

High-Speed Electro-Optical Modulation on Silicon Photonics through the Heterogeneous Integration of Lithium Niobate and Lithium Tantalate Using Micro-Transfer Printing

Tom Vanackere

Doctoral dissertation submitted to obtain the academic degrees of
Doctor of Photonics Engineering (UGent) and Docteur en Sciences de l'Ingénieur et
technologie (ULB)

Supervisors

Prof. Bart Kuyken, PhD* - Prof. Stéphane Clemmen, PhD**

* Department of Information Technology
Faculty of Engineering and Architecture, Ghent University

** Département de Physique
Faculté des Sciences, Université libre de Bruxelles

September 2026

ISBN 978-94-93570-07-8

NUR 959, 986

Wettelijk depot: D/2026/10.500/115

Members of the Examination Board

Chair

Prof. Sabine Wittevrongel, PhD, Ghent University

Other members entitled to vote

Prof. Camille-Sophie Brès, PhD, École Polytechnique Fédérale de Lausanne, Switzerland

Prof. Simon-Pierre Gorza, PhD, Université libre de Bruxelles

Yujie Guo, PhD, Ghent University

Prof. David Marpaung, PhD, Universiteit Twente, the Netherlands

Prof. Guy Torfs, PhD, Ghent University

Supervisors

Prof. Bart Kuyken, PhD, Ghent University

Prof. Stéphane Clemmen, PhD, Université libre de Bruxelles

Acknowledgements

When I tell people I am doing a PhD, the typical reaction is: 'You must be very smart!', I usually correct them, pointing out that while they aren't wrong about the 'being smart' thing, intelligence has surprisingly little to do with obtaining a PhD. Over the years, it has become abundantly clear that hard work, perseverance, and a healthy dose of masochism are far more critical.

During the seven years I spent in this group, I have grown from a naive young researcher wanting to learn all he could about the world to an ambitious senior researcher wanting to learn all he can about the world. My PhD journey was marked by early successes, and countless setbacks, unique opportunities, and steep learning curves. Beyond photonics, quantum mechanics, and material science, I learned about engineering, fabrication tolerance, and scaling, but also about leadership, priorities, and (im)balance. More than anything, I learned a lot about myself and how I interact with my environment.

Bart, thank you for welcoming me into the research group and for giving me the chance to work on this PhD. Looking back, this project brought remarkable opportunities, and I am especially grateful for your support in enabling my research visit to MIT.

Stéphane, thank you for the steady support and kindness over the years. Even though our paths crossed less frequently, your open door and pleasant conversations were always greatly appreciated.

To the members of the jury: thank you for taking the time to carefully read and evaluate this manuscript. I appreciate your insightful comments, constructive feedback, and for serving on my defense committee.

I am deeply grateful to the entire research group for their support over the years, though a few people deserve special recognition.

First, a huge thanks to Liesbet, Steven, Elif and Muneeb for all your support in the cleanroom, and to Clemens, Ewoud and Hasan for streamlining my measurements and keeping things moving. To Ilse Van Royen and Ilse Meersman: thank you for resolving all my financial issues and keeping the administrative wheels turning. And to Kristien, simply thanks for everything.

Perhaps the clearest sign that I have been here way too long is the sheer length of my office mate list. To Artur, Abdul, Awanish, Ewoud, Emmanuel, Dennis, Emiel, Tom, Robbe, Ruben, Valeria, Patrick, Nina, and Kilian: whether we shared the office for years or just a few weeks, I could always count on you to interrupt a productive working day.

To the broad and ever-changing lunch crowd: thank you to everyone who pulled up a chair over these seven years. Those mid-day breaks and random conversations were often the best part of the workday.

A special shout-out goes to the people who shaped different eras of this long road. To Camiel, Stijn Poelman, Laurens, Maximilien and Ewoud: thank you for showing me the ropes when I first started out. Stijn Cuyvers, we started this journey together and stumbled through the FWO and university administration, though I guess 'Samen uit, samen thuis' isn't an expression in your dictionary!

A big thanks to Gunther and the micro-transfer printing team. My thesis would have taken significantly longer without your feedback. To the Mayhem team (Sarah, Maximilien, Margot, Ewoud, Patrick, and Arno): thanks for teaching me to navigate the chaos.

And thanks to the colleagues and collaborators from IDLab: Arno, Olivier, and Sam, Tinus, Lucas, Jakob, Nish and Joris. Thanks for letting me use your lab and equipment and helping me throughout the years. Special thanks to Tinus for keeping me anchored when contradictory opinions left me spinning.

Thank you Tom, Jasper and Robbe for staying grounded whether we're discussing quantum computing or work ethics. To Ewoud, Camiel, Nina, and Stijn: thanks for the long evenings spent counting up board game points, only to realise (once again) that Stijn won. Also, thanks to Manuel for always capturing my good side. Finally, thanks to Lam, Antonietta and Valeria for keeping me sane and reassured.

A special thank you to the team at MIT for welcoming me into their lab during my stay. Thank you to Dirk and Artur for the inspiring discussions and guidance. Also thanks to Artur, Carlos, Jeroen, Valeria, Lydia, Hugo, and Sandro for the seamless integration into a versatile, welcoming environment across the ocean.

It probably comes as a surprise to some of the people listed here, but life is about much more than work alone. Outside of the lab, I grew significantly during these years. In a lot of ways I am still silly old me, but seven years of this journey inevitably alter who you are and how you view the world. To everyone who shared a drink, a laugh, or a conversation with me over these years, thank you for being part of the journey.

Sander, thanks for reminding me that while time moves at an alarming pace, life in Zele continues just fine.

To Tinus: thank you for acting as my interdisciplinary liaison and offering an outside perspective when academic life felt absurd.

To Floris, Luka, Tom, Emiel, Fien, Sari, and the rest of the Engineering Physics

crew: thanks for teaching me to enjoy volleyball in the rain. Tom, thanks for forwarding all those misdirected emails, hopefully there will be less confusion now that we work in different companies.

Merci, Maximilien et Charlotte: les soirées chez vous étaient toujours agréables, et je sais bien me défendre grâce à vous.

Thank you Cris and Edgar: long-distance friendships are never easy, but I'm glad you were always available when I needed to talk. And thank you Matt, for having answers to questions I couldn't ask anyone else.

A huge thank you to Christophe, Steven, Pedro and Niels, who gave me a reason to visit Antwerp more in the past two years than in the rest of my life combined.

To Jean-Mi, Laurens, Pablo, Sven and Sander: thank you for the constant support and for giving me plenty of opportunities to vent about life over movies.

Evert, thanks for hauling me over the finish line, for arriving just when I needed it most and bringing perspective when everything felt overwhelming.

Viktor, thanks for being the unmatched constant these years. Thanks for the long conversations on Discord, thanks for calling me out on my nonsense and for helping me untangle problems that existed entirely in my head.

Tot slot wil ik mijn familie bedanken. Bedankt aan mijn grootouders, nonkels, tantes, neven en nichten voor de warme thuisbasis doorheen de jaren.

En de allergrootste dankjewel aan Vake, Moeke en Bram: al meer dan dertig jaar de mensen die er onvoorwaardelijk voor mij staan. Zonder jullie steun, geduld en rustpunt was het simpelweg niet gelukt.

*Gent, April 2026
Tom Vanackere*

Contents

Acknowledgements	i
Contents	v
List of Acronyms	xi
Samenvatting	xvii
1 Inleiding	xvii
2 Schaalbare fabricage via micro-transfer printing	xviii
3 Hogesnelheid elektro-optische modulator	xx
4 Conclusie	xxi
Summary	xxiii
1 Introduction	xxiii
2 Scalable fabrication through micro-transfer printing	xxiv
3 High-speed electro-optic modulator	xxv
4 Conclusion	xxvii
1 Introduction	1
1.1 Global data traffic trends and the bandwidth bottleneck	2
1.2 Modulator figures of merit and characterisation	5
1.3 Review of integrated photonic modulator platforms	7
1.3.1 Indium phosphide modulators	8
1.3.2 Silicon modulators	9

1.3.3	Ferroelectric modulators: BTO and PZT	11
1.3.4	Organic electro-optic polymers	12
1.3.5	Plasmonic-organic hybrid modulators	13
1.3.6	A note on 2D materials (graphene)	13
1.3.7	Thin film lithium niobate and lithium tantalate	13
1.4	Lithium niobate integrated photonics	14
1.4.1	Material properties of lithium niobate	14
1.4.2	From bulk to thin-film	17
1.4.3	Lithium niobate modulators are state-of-the-art	18
1.4.4	Lithium tantalate as an alternative	19
1.5	Heterogeneous integration via micro-transfer printing	22
1.5.1	Traditional assembly	23
1.5.2	Flip-chip integration	23
1.5.3	Wafer bonding	23
1.5.4	Micro-transfer printing	24
1.6	Thesis outline	25
	List of Publications	26
2	Travelling wave amplitude modulators based on the Pockels effect	31
2.1	Pockels effect and efficient modulator waveguide design	32
2.1.1	Principle, parameters and design metrics	32
2.1.2	Numerical optimization and trade-offs between efficiency and loss	39
2.2	Efficient optical coupling: design and optimization of heterogeneous tapers	43
2.2.1	Mode coupling simulations, iterative design workflow and best practices	43
2.2.2	Final taper designs and performance	47
2.3	From phase modulation to advanced IQ architectures	50

2.3.1	Advanced modulation formats and dual-polarization operation.	54
2.4	High-speed RF design for travelling-wave modulators	59
2.4.1	The three pillars: impedance, velocity, and loss	60
2.4.2	Electrode topologies: single-ended and differential electrodes	66
2.4.3	Practical constraints: probing and measurements	72
2.4.4	Simulation workflow and results	73
3	Micro-transfer printing of lithium niobate	77
3.1	Fabrication of silicon nitride target photonic integrated circuits . .	78
3.1.1	Grating coupler and multimode interferometer design . . .	78
3.1.2	E-beam lithography and dry etching processes	78
3.2	First-generation integration: crystalline tethers	79
3.3	Second-generation integration: pillar-supported membranes	81
3.4	Third-generation integration: scalable photoresist-encapsulated process	84
4	High-speed electro-optical modulators	89
4.1	Prototype I: static characterization and proof-of-concept	90
4.1.1	Device and measurement setup	90
4.1.2	Optical performance: insertion loss and extinction ratio . .	91
4.1.3	Modulator performance: Efficiency	92
4.1.4	Problems and improvements	93
4.2	Prototype II: high-speed modulation on silicon nitride	94
4.2.1	Device and measurement setup	94
4.2.2	Optical performance: insertion loss and extinction ratio . .	95
4.2.3	Electrical performance: Impedance, loss and velocity matching	96
4.2.4	Modulator performance: Efficiency and speed	97
4.2.5	Problems and improvements	99

4.3	Prototype III: commercial silicon photonics and lithium tantalate	100
4.3.1	Device and measurement setup	101
4.3.2	Optical performance: insertion loss and extinction ratio	102
4.3.3	Electro-optical performance: efficiency	104
4.3.4	Modulator performance: high-speed characteristics	105
4.3.5	Problems and improvements	108
5	Conclusion and outlook	109
5.1	Conclusions	110
5.2	Short term future outlook	111
5.2.1	Etched Waveguides	111
5.2.2	The path towards 100 GHz and beyond	111
5.2.3	Complex modulation formats	112
5.2.4	Reliability and foundry integration for scalable production	113
5.3	Heterogeneous multi-material integration	114
5.3.1	Rationale	114
5.3.2	Expanding the photonics toolbox	114
5.4	Long term future efforts	115
5.4.1	Differential dual-waveguide architecture	115
5.4.2	High-K claddings	116
5.5	Electronic-photonic co-integration	118
5.5.1	Advantages and requirements of close co-integration	118
5.5.2	Co-design	118
6	Post Scriptum: Piezoelectrically actuated silicon-nitride-based high-speed spatial light modulator	119
6.1	Introduction	120
6.2	Results	122
6.2.1	Simulation	122

6.2.2	Design	123
6.2.3	Fabrication	127
6.2.4	Packaging	128
6.2.5	Characterization	128
6.3	Discussion	131
A	Appendix	133
A.1	Pockels modulator simulations in COMSOL with MATLAB . . .	133
A.2	Mach-Zehnder Modulator model expanded using imbalanced couplers	135
A.3	Piezo-electric resonance	136
A.4	Statement of contributions and collaborative Work	137
	References	R-1

List of Acronyms

AC	alternating current
ADC	analog-to-digital converters
AI	artificial intelligence
ALD	atomic layer deposition
AlN	aluminium nitride
APD	avalanche photodiode
APIC	atom-control photonic integrated circuit
AR/VR	augmented and virtual reality
Ar	argon
AR	augmented reality
a-Si	amorphous silicon
Au	gold
AWG	arbitrary waveform generator
balun	balanced-unbalanced
BCB	benzocyclobutene
BEOL	back-end-of-line
BER	bit error rate
BiCMOS	bipolar complementary metal oxide semiconductor
BTO	barium titanate
CL-TWE	capacitively loaded travelling wave electrodes
CMOS	complementary metal oxide semiconductor
CMP	chemical-mechanical polishing
CPD	critical point drying
CPU	central processing unit
CPW	coplanar waveguide
Cr	chromium
CW	continuous wave
DAC	digital-to-analog converters
DC	direct current
DMD	digital micromirror device
DSP	digital signal processing
EAM	electro-absorption modulator
ebeam	electron beam
EDFA	erbium doped fiber amplifier

EE	electrical-electrical
EME	eigenmode expansion
EMI	electromagnetic interference
EO	electro-optic
EOE	electrical-optical-electrical
ER	extinction ratio
ESA	electrical spectrum analyzer
FDTD	finite-difference time-domain method
FEC	forward error correction
FEM	finite elements method
FFE	feed-forward equalisation
FIB	focused ion beam
FLOPS	floating point operations per second
FoM	figure of merit
FSR	free spectral range
GaAs	gallium arsenide
GaN	galium nitride
GC	grating coupler
Ge	germanium
GLV	grating light valve
GPU	graphical processing unit
HF	hydrofluoric acid
I/O	input/output
IC	integrated circuit
IL	insertion loss
IMDD	intensity modulation/direct detection
InP	indium phosphide
IQ	in-phase/quadrature
IR	infrared
ITO	indium tin oxide
KOH	potassium hydroxide
LaMP	laser micro-packaging
LCoS	liquid-crystal-on-silicon
LDMOS	laterally-diffused metal-oxide semiconductor
LIDAR	light detection and ranging
LLM	large language model
LN	lithium niobate
LNOI	lithium niobate on insulator
LPCVD	low pressure chemical vapor deposition
LT	lithium tantalate
MBE	molecular beam epitaxy
MEMS	micro-electromechanical systems
MgO	magnesium oxide
ML	machine learning
MMI	multimode interference

MMI	multimode interferometer
MPW	multi-project wafer
mTP	micro-transfer printing
MZI	Mach-Zehnder interferometer
MZM	Mach-Zehnder modulator
NIR	near infrared
NRZ	non-return-to-zero
OOK	on-off keying
OPAMP	operational amplifier
OPO	optical parametric oscillators
OTF	optical spectral filter
PAM	pulse-amplitude modulation
PBS	polarizing beamsplitter
PCB	printed circuit board
PD	photodiode
PDFA	praseodymium-doped fibre amplifier
PDK	process development kit
PDMS	polydimethylsiloxane
PECVD	plasma-enhanced chemical vapor deposition
PIC	photonic integrated circuit
PID	proportional–integral–derivative
POH	plasmonic-organic hybrid
PRBS	pseudorandom bit sequences
PVD	physical vapor deposition
PZT	lead zirconate titanate
QAM	quadrature amplitude modulation
QCSE	quantum-confined Stark effect
QPSK	quadrature phase-shift keying
RF	radio frequency
RIE	reactive ion etching
SEM	scanning electron microscopy
SHG	second harmonic generation
Si	silicon
SiC	silicon carbide
SiGe	silicon-germanium
SiN	silicon nitride
SiPh	silicon photonics
SISCAP	semiconductor-insulator-semiconductor capacitor
SLD	superluminescent diode
SLM	spatial light modulator
SOH	silicon-organic hybrid
SOI	silicon-on-insulator
TE	transverse electric
TFLN	thin-film lithium niobate
Ti	titanium

TIA	transimpedance amplifier
TM	transverse magnetic
TPU	tensor processing unit
UTC	uni-travelling-carrier
UV	Ultraviolet
VIS	visible
VNA	vector network analyser
VR	virtual reality
WDM	wavelength division multiplexing

Samenvatting

1 Inleiding

De wereldwijde vraag naar databandbreedte ondergaat momenteel een ongeken- de stijging, gedreven door de snelle opschaling van artificiële intelligentie (AI)-clusters en de werkdruk van machinaal leren (ML). Binnen de datacenters die deze tech- nologieën aandrijven, is het knelpunt verschoven van pure rekenkracht naar de onderlinge verbindingen, ook wel interconnects genoemd, die data verplaatsen tus- sen nodes in een cluster. Hoewel siliciumfotonica is uitgegroeid tot het dominante platform voor deze optische interconnects vanwege de complementaire metaaloxide- halfgeleider (CMOS)-compatibiliteit en hoge integratiedichtheid, wordt het inhe- rent beperkt door de fysische eigenschappen van silicium (Si) zelf. Specifiek maakt het op ladingsdragers gebaseerde elektro-optische effect in silicium plasma- dispersiemodulatoren het steeds moeilijker om het lage stroomverbruik en de hoge snelheden te bereiken die vereist zijn voor de volgende generatie zendontvangers (transceivers).

In de afgelopen jaren heeft lithiumniobaat (LN) aanzienlijk momentum gewon- nen als oplossing voor deze knelpunten door efficiënte, snelle en lineaire elektro- optische modulatie te bieden, wat ideaal is voor hogesnelheidsdatatransmissie. Terwijl monolithische LN-platformen snel commerciële maturiteit naderen, evolue- ren heterogene integratietechnieken parallel om een dichtere co-integratie mogelijk te maken. De heterogene integratie van LN zou een lager energieverbruik in de fotonische circuits mogelijk maken en tegelijkertijd de totale voetafdruk van de componenten verkleinen. Bovendien wordt de integratie van LN in standaard CMOS-pilootlijnen geconfronteerd met aanzienlijke hindernissen, aangezien li- thium wordt beschouwd als een risicovolle mobiele-ionen-contaminant [1]. In de zoektocht naar schaalbare en foundry-compatibele methoden is een proces wenselijk dat zich meer aan het eind van de productielijn plaatsvindt.

In dit proefschrift hebben we het eerste micro-transfer print (mTP)-proces ontwik- keld en geoptimaliseerd voor hoogperformante ferro-elektrische kristallen, wat heeft geleid tot demonstraties op chipschaal van snelle en efficiënte Pockels-modulatoren op een siliciumfotonica-platform. Naast LN hebben we het proces ook gedemon- streerd met lithiumtantalaat (LT), wat de veelzijdigheid van het (mTP)-proces

aantoont. Het (mTP)-proces is betrouwbaar en schaalbaar, waardoor het geautomatiseerd en parallel printen van meerdere volledige siliciumfotonica-wafers vanaf een enkele LN-bronwafer mogelijk is. Het proces faciliteert sterke evanescente koppeling terwijl het bronmateriaal efficiënt wordt gebruikt en verschillende materialen heterogeen op dezelfde wafer kunnen worden geïntegreerd. In tegenstelling tot de meeste andere LN-modulatoren maakt de (mTP)-technologie een triviale implementatie van differentiële duw-trek modulatoren mogelijk door de coupons simpelweg 180° te draaien tussen het printen op beide armen. De fabricagemethode en de beste meetresultaten behaald in dit proefschrift worden hier kort samengevat.

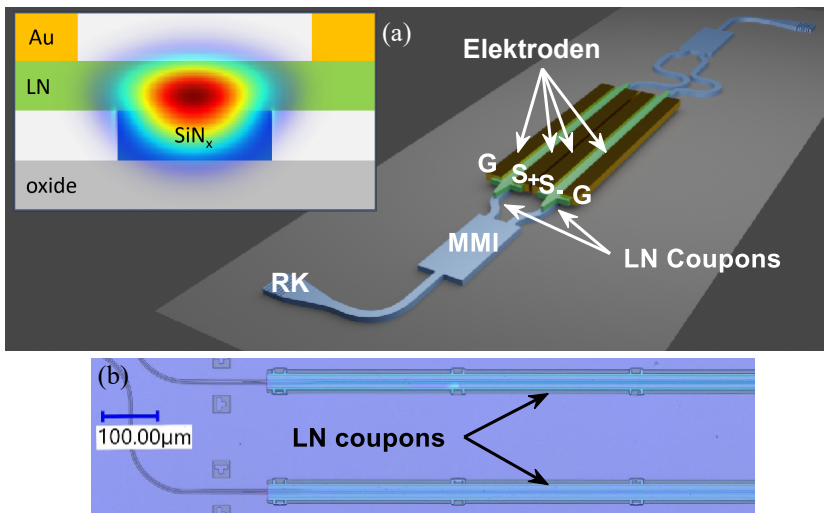
2 Schaalbare fabricage via micro-transfer printing

De grootste uitdaging van dit werk was het ontwikkelen van een methode om dunne-film LN en LT te integreren op siliciumgebaseerde circuits op een manier die zowel mechanisch stabiel als compatibel is met industriële foundry-standaarden. De fabricageprocedure evolueerde van vroege handmatige pogingen (die geplaagd werden door lage slaagkansen en het instorten van membranen door capillaire krachten) naar een robuust, schaalbaar assemblageproces. Door over te stappen van kristallijne LN-ankers en op pilaren gebaseerde ondersteuningsstructuren naar een gecontroleerde inpakking in fotoresist, werd de noodzaak voor gespecialiseerde aanpassingen aan de doelwafer, zoals het etsen van diepe gleuven, geëlimineerd. Deze laatste iteratie transformeerde de integratie van een gevoelige laboratoriumtaak naar een proces compatibel met het einde van de productielijn met een hoge slaagkans, geschikt voor het gebruik van gestandaardiseerde commerciële pilootlijnwafers, zoals het iSiPP200-platform van imec.

Het mature mTP-proces is onderverdeeld in drie hoofdfases: bronwafer preparatie, doelwafer preparatie en assemblage. Uitgaande van een commerciële LN/oxide/Si-wafer worden rechthoekige membranen (coupons genaamd, bijv. $30\text{ }\mu\text{m} \times 7\text{ mm}$) geëts met behulp van argon. Vervolgens wordt een fotoresist-inpakkingslaag aangebracht, die de mechanische ankers definieert waarmee de coupons aan het bronsubstraat vastzitten. Het onderliggende oxide wordt selectief verwijderd in een gebufferde waterstoffluoride ets, waardoor de coupons vrijhangen en klaar zijn voor opname. Deze lay-out met hoge dichtheid maakt meer dan 12.000 coupons, of 6.000 duw-trek modulatoren, op één enkele 4-inch bronwafer mogelijk, wat zorgt voor een efficiënt materiaalgebruik.

Parallel hieraan kan de doelwafer worden voorbereid. Voor de laatste demonstraties werden de doelcircuits gefabriceerd op een 200 mm siliciumfotonica-pilootplatform van imec. Deze chips bevatten passieve silicium- en siliciumnitride-componenten, waaronder roosterkoppelaars en multimodeinterferometers. Vóór het printen wordt een dunne (50 nm) laag benzocyclobuteen (BCB) op de doelwafer gespoten om als nivellerende lijmlaag te dienen.

Met behulp van een Amicra transfer-printing tool op waferschaal wordt een polydimethylsiloxaan-stempel gebruikt om de vrijhangende coupons van de bron op te pakken en op het doel te printen. De tool maakt gebruik van beeldherkenningssoftware om geautomatiseerde uitlijningsnauwkeurigheden tot ± 500 nm (3σ) te bereiken. Een cruciaal voordeel van deze methode is de mogelijkheid om differentiële duw-trek modulatoren te implementeren door simpelweg de bronwafer 180° te draaien tussen de printstappen voor de twee armen van een Mach-Zhender modulator (MZM). Na het printen wordt de fotoresist-inpakking verwijderd via zuurstofplasma, de BCB uitgehard en worden hogesnelheids-GSSG-elektroden aangebracht via lift-off. Deze overgang naar een geautomatiseerde, gestandaardiseerde procedure bood de stabiele basis die nodig was om de betrouwbare, herhaalbare prints te realiseren die essentieel zijn voor commercialisering. Om de robuustheid en veelzijdigheid van de ontwikkelde mTP-procedure verder aan te tonen, maakte de laatste en meest mature demonstratie in dit proefschrift gebruik van LT. De succesvolle integratie van LT op het imec iSiPP200-platform bewijst dat het proces niet beperkt is tot één enkel materiaal, maar kan worden toegepast op een bredere klasse van componenten en materialen. De onderstaande figuur toont het resultaat van het mTP-fabricageproces.



Figuur 1: (a) Schematische weergave van een volledige modulator component. RK: roosterkoppelaar, MMI: multimodeinterferometer. (inset) Overzicht van het hybride LN-op-SiN modeprofiel. Zowel de SiN- als de LN-laag zijn 300 nm dik. De SiN-golfgeleider is 1 μ m breed. (b) Microscopiebeeld van de geprinte LN-coupons op SiN-golfgeleiders. Komt uit [2].

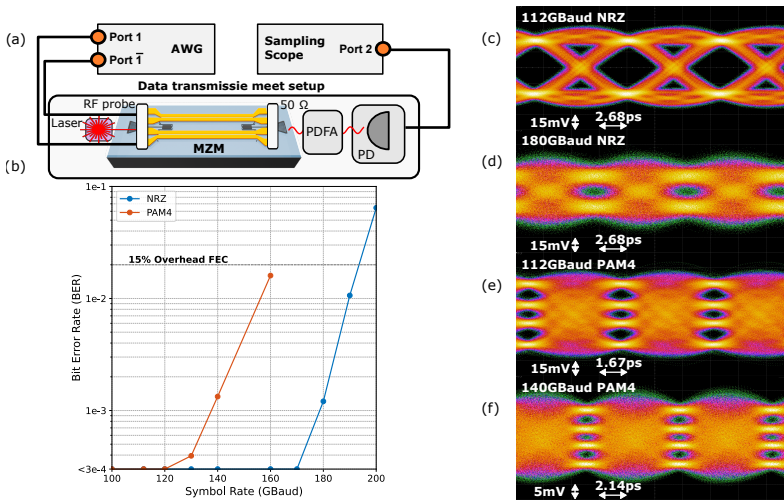
3 Hogesnelheid elektro-optische modulator

De maturiteit van de ontwikkelde mTP-procedure werd gevalideerd door de karakterisering van hogesnelheidsmodulatoren geïntegreerd op het imec iSiPP200-platform. Deze finale demonstratie dient als een hoogperformant werkend model, waarbij LT op een hoogresistief siliciumsubstraat wordt gebruikt om de bandbreedtebeperkingen van eerdere iteraties aan te pakken. Door de werking te verschuiven naar de O-band (1310 nm), tonen we de compatibiliteit van het platform met standaard datacom-golflengten aan en het potentieel om op te schalen naar de prestatiekenmerken die vereist zijn voor de volgende generatie optische interconnects.

De MZM vertoonde een halfgolfspanning V_π van 3.5 V in duw-trek configuratie, wat overeenkomt met een halfgolfspanning-lengte product ($V_\pi L$) van 2.3 V cm, een waarde die direct concurreert met monolithische LT-platformen. Ondanks een kleine fabricage-afwijking in de elektroden, vertoonde de elektro-optische sectie lage extra verliezen, met een propagatieverlies van slechts 1.0 ± 0.5 dB cm⁻¹ en overgangsverliezen van slechts 0.3 dB per transitie. Het totale insertieverlies voor de 7-mm modulator werd gemeten op 2.9 dB, wat bewijst dat het heterogene grensvlak geen significante vermogenverlies introduceert.

Frequentiedomeinmetingen met een vectornetwerkanalysator (VNA) onthulden een 3-dB elektro-optische bandbreedte van meer dan 70 GHz, waarmee effectief de meetlimiet van de apparatuur werd bereikt. Extrapolatie plaatst de werkelijke bandbreedte van de component nabij de 90 GHz. Deze prestatie is een direct resultaat van de geoptimaliseerde hybride mode en het gebruik van een hoogresistief substraat om radiofrequentie (RF)-substraatverliezen te minimaliseren.

In tijdsdomeinexperimenten demonstreerde de component hogesnelheidsdatatransmissiecapaciteiten met behulp van een 64-tap egalisatie met vooruitwerkende kracht (FFE). We bereikten succesvolle transmissie bij symboolsnelheden tot 190 GBaud non-return-to-zero (NRZ) en totale datasnelheden van 320 Gbps bij pulsamplitudemodulatie met 4 niveaus (PAM4). Deze resultaten, weergegeven in fig. 2, vormen een duidelijk werkend model demonstratie voor een via transfer-printing geïntegreerde ferro-elektrische modulator op een commercieel siliciumplatform.



Figuur 2: Datatransmissie-experiment. (a) Meetopstelling voor oogdiagram-metingen. (b) bitfoutratio (BER) in de verzonden bitsequentie voor NRZ (blauw) en PAM4 (rood) gemeten signalen. Een horizontale stippellijn geeft de drempel aan voor voorwaardse foutcorrectie (FEC) met een overhead van 15 %. Oogdiagrammen voor (c) 112 GBaud NRZ, (d) 180 GBaud NRZ, (e) 112 GBaud PAM4, (f) 140 GBaud PAM4. Bij alle figuren is correctie aan de zenderzijde en een 64-tap FFE aan de ontvangerzijde toegepast, er werd geen offline digitale post-processing uitgevoerd. Komt uit [3].

4 Conclusie

Het werk gepresenteerd in dit proefschrift toont aan dat micro-transfer printing een uitvoerbare en schaalbare strategie is voor de hoge slaagkans integratie van dunne-film ferro-elektrische kristallen op fotonische siliciumplatformen. Het onderzoek evolueerde van de ontwikkeling van een handmatig experiment op laboratoriumschaal naar een schaalbare, foundry-compatibele procedure die sub-micron uitlijningsprecisie handhaaft over duizenden coupons. Door gebruik te maken van een geautomatiseerd Amicra-assemblageproces op 200 mm imec iSiPP200-pilootlijnwafers, hebben we aangetoond dat hoogperformante modulatie kan worden bereikt zonder de schaalbaarheid van het onderliggende siliciumplatform in het gedrang te brengen.

Een belangrijk voordeel van de mTP-aanpak is de mogelijkheid om eenvoudig differentiële duw-trek modulatoren te implementeren door de bron-coupons simpelweg 180° te draaien tijdens het printproces. Dit is aanzienlijk moeilijker te realiseren met traditionele wafer-bondingstechnieken. Bovendien is de strategische overgang naar hoogresistieve siliciumsubstraten essentieel gebleken voor het onderdrukken van RF-verliezen.

Hoewel de huidige resultaten al een aanzienlijk potentieel voor hogesnelheids-datatransmissie laten zien, ligt de weg naar werking bij 100 GHz in het verder optimaliseren van het etsen van LN/LT om van hybride plaat-golfgeleiders naar rib-structuren te gaan, en in het toepassen van capacitief belaste elektrode-ontwerpen. Uiteindelijk biedt dit onderzoek het technische kader om het hoogperformante Pockels-effect van materialen zoals lithiumniobaat te combineren met de gevestigde maturiteit van de siliciumfotonica-industrie, wat dient als basis voor de volgende generatie energie-efficiënte transceivers.

Summary

1 Introduction

The global demand for data bandwidth is currently experiencing an unprecedented surge, driven by the rapid scaling of artificial intelligence (AI) clusters and machine learning (ML) workloads. Within the data centers powering these technologies, the bottleneck has shifted from raw computing power to the interconnects that move data between nodes in a cluster. While silicon photonics (SiPh) has emerged as the dominant platform of these optical interconnects due to its complementary metal oxide semiconductor (CMOS) compatibility and high integration density, it is inherently limited by the physical properties of silicon itself. Specifically, the carrier-based electro-optic effect in silicon plasma-dispersion modulators makes it increasingly difficult to achieve the high speeds and low power consumption required for next generation transceivers.

In recent years, lithium niobate (LN) is gathering significant momentum as a solution to address these bottlenecks by providing efficient, high-speed, and linear electro-optic modulation, perfect for high-speed data transmission. While monolithic LN platforms are rapidly approaching commercial maturity, heterogeneous integration techniques are evolving in parallel to enable denser co-integration. The heterogeneous integration of LN would enable lower energy consumption in the photonic circuitry while reducing the overall device footprint as well. Furthermore, the integration of LN into standard CMOS pilot lines faces significant hurdles due to the nature of lithium as a high-risk mobile-ion contaminant [1]. In search of more scalable and foundry-compatible methods a more back-end-of-line process is desirable.

In this thesis, we developed and optimized the first micro-transfer printing (mTP) process for high-performance ferroelectric crystals resulting in chip-scale demonstrations of high-speed, efficient Pockels modulators on a SiPh platform. Beyond LN we also demonstrated the process using lithium tantalate (LT) showing the versatility of the mTP process. The mTP process is reliable and scalable, allowing for automated and parallelized printing of multiple full SiPh wafers from a single LN source wafer. The process facilitates strong evanescent coupling while efficiently using the source material and allowing for different materials to be heterogeneously

integrated on the same wafer. Contrary to most other LN modulators, mTP technology allows for the trivial implementation of differential drive push-pull modulators by 'simply' rotating the coupons by 180° between the printing on both arms. The fabrication method and the best measurement results achieved in the thesis are quickly summarised here.

2 Scalable fabrication through micro-transfer printing

The primary challenge of this work was developing a method to integrate thin-film LN and LT onto silicon-based circuits that is both mechanically stable and compatible with industrial foundry standards. The fabrication workflow matured from early manual attempts (which were plagued by low yields and membrane collapse due to capillary forces) to a robust, scalable assembly process. By moving from crystalline LN tethers, and pillar-based support structures to a controlled photoresist encapsulation, we eliminated the need for specialized target-side modifications like deep-trench etching. This final iteration transformed the integration from a sensitive laboratory task into a high-yield, back-end-of-line (BEOL)-compatible process capable of utilising standardized commercial pilot-line wafers, such as imec's iSiPP200 platform.

The mature mTP process is divided into three main phases: source preparation, target preparation, and assembly. Starting from a commercial LN/oxide/Si wafer, rectangular coupons (e.g., $30\text{ }\mu\text{m} \times 7\text{ mm}$) are patterned using argon (Ar) milling. A photoresist encapsulation layer is then applied, defining mechanical tethers that secure the coupons to the source substrate. The underlying oxide is selectively removed in a buffered hydrofluoric acid (HF) release etch, leaving the coupons suspended and ready for pick-up. This high-density layout allows for over 12.000 coupons, or 6.000 push-pull modulators on a single 4-inch source wafer, ensuring efficient material utilization.

In parallel, the target wafer can be prepared. For the final demonstrations, the target circuits were fabricated on a 200 mm silicon photonics pilot platform from imec. These chips feature passive silicon (Si) and silicon nitride (SiN) components, including grating couplers and multimode interferometers (MMIs). Before printing, a thin (50 nm) layer of benzocyclobutene (BCB) is spray-coated onto the target wafer to act as a planarising adhesive.

Using a wafer-scale Amicra transfer-printing tool, a polydimethylsiloxane (PDMS) stamp is then used to pick the suspended coupons from the source and print them onto the target. The tool uses pattern recognition software to achieve automated alignment accuracies down to $\pm 500\text{ nm}$ (3σ). A key advantage of this method is the ability to implement differential push-pull modulators by simply rotating the

source wafer 180° between printing steps for the two arms of an Mach-Zehnder modulator (MZM). After printing, the photoresist encapsulation is removed via oxygen plasma, the BCB is cured, and high-speed GSSG electrodes are deposited via lift-off. This transition to an automated, standardized workflow provided the stable foundation required to achieve the reliable, repeatable printing needed for commercialisation. To further demonstrate the robustness and versatility of the developed mTP workflow, the final and most mature demonstration in this thesis utilized LT. The successful integration of LT on the imec iSiPP200 platform proves that the process is not limited to a single material, but can be applied to a broader class of devices and materials. The figure below shows the results of the mTP fabrication process.

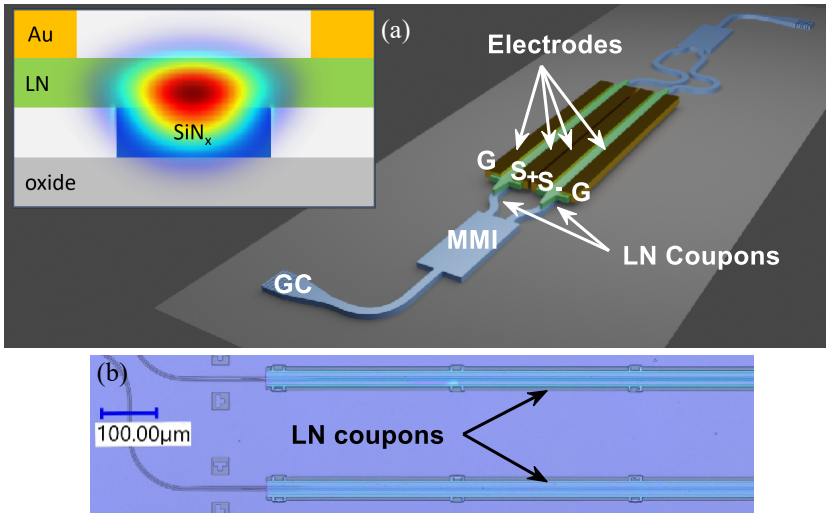


Figure 3: (a) Schematic image of a complete modulator. GC: grating coupler, MMI: multimode interferometer; (inset) Overview of the hybrid LN-on-SiN mode profile. Both the SiN and the LN layer are 300 nm thick. The SiN waveguide is 1 μm wide. (b) Microscope image of the printed LN coupons on SiN waveguides. Taken from [2].

3 High-speed electro-optic modulator

The maturity of the developed mTP workflow was validated through the characterization of high-speed modulators integrated on the imec iSiPP200 platform. This final demonstration serves as a high-performance proof-of-concept, utilising LT on a high-resistivity silicon substrate to address the bandwidth limitations observed in earlier iterations. By shifting operation to the O-band (1310 nm), we demonstrate the platform's compatibility with standard datacom wavelengths and its potential to scale toward the performance metrics required for next-generation optical

interconnects.

The MZM demonstrated a half-wave voltage V_π of 3.5 V in push-pull configuration, corresponding to a half-wave voltage-length product ($V_\pi L$) of 2.3 V cm, a value that competes directly with monolithic LT platforms. Despite a small fabrication misalignment in the electrodes, the electro-optic (EO) section exhibited low excess losses, with a propagation loss of only 1.0 ± 0.5 dB cm⁻¹ and transition losses as low as 0.3 dB per transition. Total insertion loss for the 7-mm modulator was measured at 2.9 dB, proving that the heterogeneous interface does not introduce a significant power penalty.

Frequency-domain measurements using a vector network analyser (VNA) revealed a 3-dB electro-optic bandwidth exceeding 70 GHz, effectively reaching the measurement limit of the equipment. Extrapolation places the actual device bandwidth near 90 GHz. This performance is a direct result of the optimized hybrid mode and the use of a high-resistivity substrate to minimize radio frequency (RF) substrate loss.

In time-domain experiments, the device demonstrated high-speed data transmission capabilities using a 64-tap feed-forward equalisation (FFE). We achieved successful transmission at symbol rates up to 190 GBaud non-return-to-zero (NRZ) and overall data rates of 320 Gbps pulse-amplitude modulation (PAM)⁴. These results, shown in fig. 4, represent a clear proof-of-concept demonstration for a transfer-printed ferroelectric modulator on a commercial silicon platform.

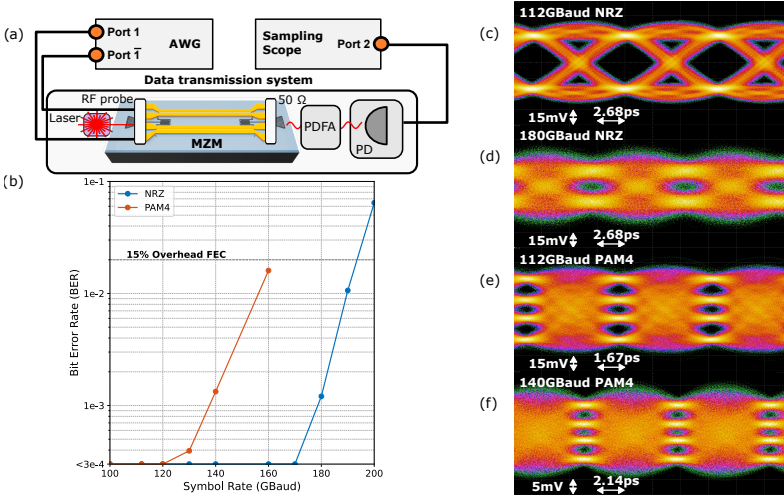


Figure 4: Data transmission experiment. (a) Measurement setup for eye-diagram measurements. (b) BER in the transmitted bit sequence for NRZ (blue) and PAM4 (red) measured signals. A horizontal dashed line indicates the threshold for FEC with an overhead of 15 %. Eye diagrams for (c) 112 GBaud NRZ, (d) 180 GBaud NRZ, (e) 112 GBaud PAM4, (f) 140 GBaud PAM4, all figures used correction at the transmitter side and a 64 tap FFE on the receiver side, however, no offline digital post-processing was done. Taken from [3].

4 Conclusion

The work presented in this thesis demonstrates that micro-transfer printing is a viable and scalable strategy for the high-yield integration of thin-film ferroelectric crystals onto silicon photonic platforms. The research progressed from the development of a manual laboratory-scale experiment to a scalable, foundry-compatible workflow that maintains sub-micron alignment precision across thousands of coupons. By utilising an automated Amicra assembly process on 200 mm imec iSiPP200 pilot-line wafers, we have shown that high-performance modulation can be achieved without compromising the scalability of the underlying silicon platform.

A key advantage of the mTP approach is the ability to easily implement differential push-pull modulators by simply rotating the source coupons 180° during the printing process. This is significantly more difficult to achieve with traditional wafer bonding. Furthermore, the strategic transition to high-resistivity silicon substrates has proven essential for suppressing RF losses.

While the current results already show significant potential for high-speed data transmission, the path toward 100 GHz operation lies in further optimizing LN/LT

etching to move from hybrid slab waveguides to rib structures and adopting capacitively loaded electrode designs. Ultimately, this research provides the engineering framework to combine the high-performance Pockels effect of materials like lithium niobate with the established maturity of the silicon photonics industry, serving as a foundation for next-generation, energy-efficient transceivers.

1

Introduction

1.1	Global data traffic trends and the bandwidth bottleneck	2
1.2	Modulator figures of merit and characterisation	5
1.3	Review of integrated photonic modulator platforms	7
1.3.1	Indium phosphide modulators	8
1.3.2	Silicon modulators	9
1.3.3	Ferroelectric modulators: BTO and PZT	11
1.3.4	Organic electro-optic polymers	12
1.3.5	Plasmonic-organic hybrid modulators	13
1.3.6	A note on 2D materials (graphene)	13
1.3.7	Thin film lithium niobate and lithium tantalate	13
1.4	Lithium niobate integrated photonics	14
1.4.1	Material properties of lithium niobate	14
1.4.2	From bulk to thin-film	17
1.4.3	Lithium niobate modulators are state-of-the-art	18
1.4.4	Lithium tantalate as an alternative	19
1.5	Heterogeneous integration via micro-transfer printing	22
1.5.1	Traditional assembly	23
1.5.2	Flip-chip integration	23
1.5.3	Wafer bonding	23
1.5.4	Micro-transfer printing	24
1.6	Thesis outline	25

List of Publications	26
---------------------------------------	-----------

Optical communication technologies form the backbone of modern information networks, connecting data centers, cloud services, and end-users around the world. As the demand for higher bandwidth and faster data rates continues to grow, the design of efficient and scalable optical components becomes increasingly critical. Among these components, electro-optic modulators are essential for converting electrical signals into optical signals with minimal loss and high speed. This chapter provides a broad overview of the technological context that motivates the work presented in this thesis. It introduces the current challenges in optical communication, outlines key performance metrics and trade-offs for modulators, reviews the material platforms available, and highlights the potential of lithium niobate and heterogeneous integration approaches that are explored in detail in the following sections.

1.1 Global data traffic trends and the bandwidth bottleneck

If I were writing this introduction at the start of my PhD, I would be discussing the steady rise in global data usage driven by industry, and business usage, and household entertainment [4]. Fixed network broadband traffic has grown approximately 16 % annually for the last few years [5], as shown in figure 1.1. I would have described how high-quality real-time video streaming and the prevalence of social media have significantly intensified our reliance on stable, high-speed connections both in the workplace and at home. Furthermore, I would have highlighted promising emerging applications like traffic safety and autonomous vehicles, Internet of Things and remote medical diagnostics to justify the need for more efficient optical transceivers (devices that convert electrical signals to optical signals) and, consequently, high-performance optical modulators.

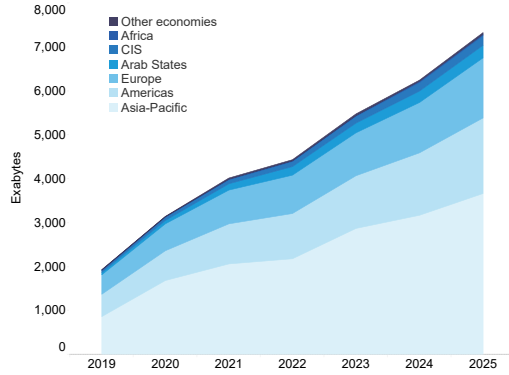


Figure 1.1: Fixed network broadband traffic usage per area expressed in exabytes (10^{18} bytes) [5].

In the last few years however, this steady growth in consumption has basically been dwarfed by the explosive rise of (generative) AI and particularly large language models (LLMs), containing now over a trillion parameters (i.e., ChatGPT-4, Gemini [6]). As a result, the compute capacity has had to drastically scale at unprecedented rates. Modern AI hardware relies on tens or maybe soon hundreds of thousands of processing units, either central, graphical or tensor processing units (CPU, GPU, or TPU) arranged in boards and racks in massive clusters. These units must be interconnected in a dense, hierarchical structure together with memory to operate more as a single distributed computer rather than isolated processors. This drastic change has somewhat shifted the bottleneck from the individual processor power to the interconnect links [7]. The performance of big computational clusters like this is no longer solely dictated by the raw floating point operations per second (FLOPS) of individual chips, but also by the ability to move data between them with minimal latency and massive bandwidth. A visualisation of this drastic change is shown in figure 1.2 [7]. As training requirements increase, the energy footprint of the underlying infrastructure has become a critical constraint. Estimates from the International Energy Agency suggest that data center electricity consumption could see a significant surge in the coming years due to the rapid scaling of AI workloads and the deployment of supporting infrastructure [8].

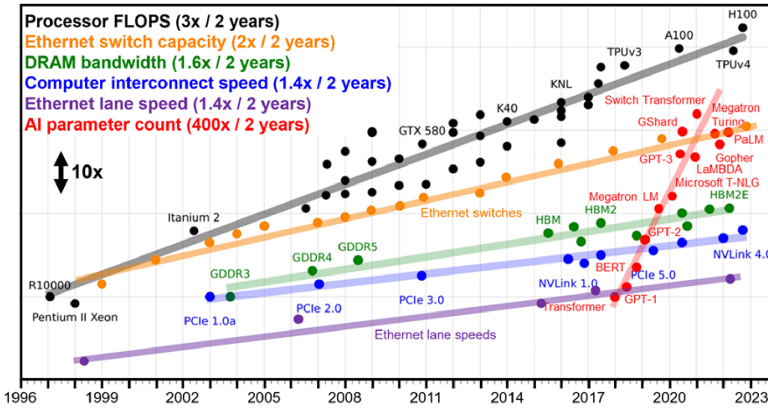


Figure 1.2: Scaling trends in computer communications on a logarithmic scale. (The absolute position of each curve on the y-axis is chosen to visually separate the curves.) [7].

As data center traffic increases, traditional copper interconnects are reaching their physical limits. At frequencies approaching 100 GHz, signal attenuation in copper traces becomes prohibitive. Optical fibers have emerged as the only sustainable solution for high-speed data transport, not just between data centers, but increasingly even for short-reach links within the racks themselves.

This transition has been enabled by the rise of photonic integrated circuits (PICs), initially developed on indium phosphide [9]. By integrating complex optical functionalities onto a single chip, the industry has significantly increased data throughput while minimizing power consumption per bit [10]. Silicon photonics, in particular, has become the dominant platform due to its compatibility with high-volume CMOS fabrication, allowing for the dense integration of waveguides, heaters, and high-speed germanium photo detectors. These detectors have already demonstrated impressive bandwidths exceeding 200 GHz [11].

However, a critical performance gap is emerging in the transmitter side of optical transceivers. Emerging optical interconnect standards, such as 1600ZR+ [12], are targeting baud rates surpassing 200 GBd. While the passive and detection components of the silicon platform are keeping pace, the electro-optic modulators are reaching their fundamental physical limits. Bridging this gap requires moving beyond traditional silicon-based modulation toward new integration strategies that can maintain high-speed operation without sacrificing the scalability of the silicon platform.

1.2 Modulator figures of merit and characterisation

The evaluation of an optical modulator is a multi-dimensional problem where the definition of “optimal” depends heavily on the target application. Modulators are evaluated using bandwidth, insertion loss, drive voltage, energy per bit, and footprint. Improving one metric often impacts others; for example, higher speed can increase insertion loss or energy consumption. Trade-offs between these parameters must be carefully balanced to meet system-level requirements. Optimal designs achieve an effective compromise between performance, power efficiency, and manufacturability.

The work laid out in this thesis specifically concerns optical modulators, and it is important to define the key parameters and figures of merit (FoM) used to describe their performance. In later chapters we will discuss design trade-offs and detail the different choices made in our devices. But let’s first set up a clear language to use within this work. The most basic metrics of an optical modulator are the half-wave voltage (V_π) and the insertion loss (IL). The half-wave voltage represents the voltage required to induce a π phase shift in the optical carrier, effectively switching the modulator between its on and off states. While this is a parameter strictly defined for phase modulators, in recent years, researchers have adopted an analogous value for amplitude modulators (such as Mach-Zehnder modulators (MZM)). While one could argue this nomenclature is used to primarily improve the initial impact of a publication, it has now become common practice to describe the voltage required for your push-pull modulator (discussed in chapter 2) to switch between the on and off states as the half-wave voltage. It is often measured at direct current (DC) or low frequencies for ease of characterisation. One typically aims for this value to be as low as possible. The lower the voltage required to switch the modulator, the easier it is to drive using CMOS or bipolar complementary metal oxide semiconductor (BiCMOS) technology. One typically shoots for values below 2 V for CMOS drivers and 3.3 V for BiCMOS drivers, though considerable nuance exists here, regarding the extent to which a modulator should be driven beyond its strictly linear operating region.

The IL is typically expressed in dB and indicates the optical power loss as the light travels through the device. In academia, the focus is often limited to the specific loss accrued within the device alone, such as propagation losses, inter-layer coupling losses and metal absorption. Whereas in industrial applications, the loss from coupling light in and out of the chip is also an important factor to be taken into account. In modulators for quantum applications for example, this is often the most critical parameter; for telecom and datacom scenarios, it is primarily an economic consideration involving system trade-offs. Ultimately, it determines how much extra power and amplification are required within the optical link due to the

losses in each component.

Closely related to these two basic metrics is the physical length of the device L . This is, of course, related to the footprint of a device which is an important factor, especially in datacenters, where racks need to house vast quantities of transceivers densely packed together. Length also influences the half-wave voltage, since modulators accumulate phase change over an interaction region. They are typically characterised fundamentally by the half-wave voltage-length product ($V_\pi L$), expressed in V cm. This relationship clearly indicates that longer devices will result in lower driving voltages. However, increasing the length typically results in higher IL due to additional propagation losses, and more high-speed parasitics, which limit the overall device bandwidth.

Another important performance metric is the extinction ratio (ER), defined as the ratio of the maximum transmitted power to the minimum transmitted power according to equation 1.1. It indicates the contrast between the on and off states of the modulator and is often expressed in dB. A higher ER is typically better; while, again, quantum applications put a lot of effort into maximizing this parameter, a high ER is also beneficial in other applications since it may allow one to use less than a full V_π to drive the device and still achieve respectable extinction.

$$ER = \frac{T_{\max}}{T_{\min}} \quad (1.1)$$

For high-speed characterisation, two measurements are commonly performed. First, a frequency domain characterisation using a VNA is used to determine the small-signal characteristics often expressed in the form of an electrical or an electro-optic (EO) bandwidth S_{21} . The electrical S_{21} isolates the electrodes for characterisation of its attenuation and impedance which will be explained in section 2.4.1. The EO bandwidth indicates how the modulation amplitude at higher frequencies compares to the DC behaviour. It is expressed in dB and one typically pays most attention to two values, the 3-dB and 6-dB crossing points. There exists some confusion in the definitions here, but one should use the 20 log definition of

$$20 \log_{10} \left| \frac{I(f_{3\text{dB}})}{I(0)} \right| = -3 \text{ dB} \quad (1.2)$$

for EO optical bandwidth measurements which corresponds to the point where the detected current signal reaches half of its low-frequency value. When estimating the EO performance from purely electrical measurements (electrical-electrical (EE)), one typically considers the 6.4-dB point, particularly for modulators limited by RF losses.

A second kind of high-speed characterisation is the generation of eye-diagrams in the time domain using arbitrary waveform generators (AWG) and real-time or sampling oscilloscopes. An eye-diagram overlaps the measured points collected over a lengthy measurement of a predetermined pseudo-random bit sequence designed to contain an accurate representation of all frequency components present in truly random data. Normally only a few points per symbol period are measured, but by overlapping the data it provides an idea about all the possible signal points one would measure during operation. An example of an eye-diagram can be seen in figure 1.3. The resulting data set can give some qualitative information about the performance of the data link. It is important to realise that eye-diagrams always characterise the entire data link, and not just the modulator. They can reveal imperfections in the link, such as timing variations, signal distortion or suboptimal biasing conditions. Since the modulators discussed in this thesis are very linear we typically employ eye-diagrams simply as a demonstration of the device in an actual link. This allows us to estimate its performance at various symbol rates as the ER decreases relative to the noise in the link.

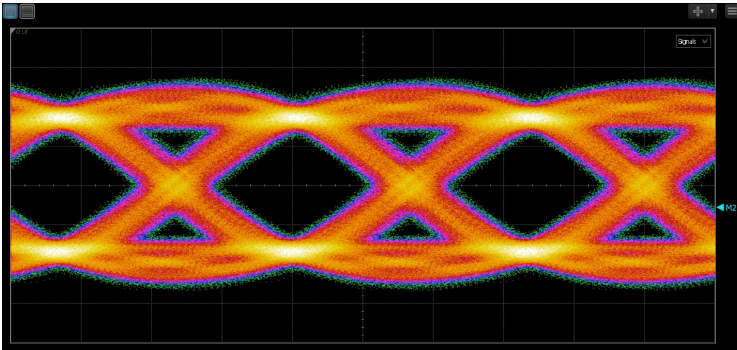


Figure 1.3: Example of eye-diagram measured at 112 GBaud using non-return-to-zero (NRZ) modulation and raised cosine pulse shaping.

1.3 Review of integrated photonic modulator platforms

Since the work in this thesis is centered around LN modulators, it is only appropriate to briefly discuss alternative modulator devices to provide the necessary context for comparison. This section is intended neither as a comprehensive review paper (see, e.g., [13, 14]) nor as a definitive ranking of current performance records; rather, it aims to qualitatively describe the different physical mechanisms and integration strategies available today. In a field as rapidly evolving as integrated

photonics, specific performance figures are often outdated faster than a thesis can be defended. Furthermore, hero results in literature can always optimize a single metric at the significant expense of other critical parameters like insertion loss, bandwidth, or drive voltage. Therefore, it is more instructive to focus on the general performance characteristics and fundamental physical limits of each platform rather than focusing on specific metric values. The following sections evaluate various material platforms based on their intrinsic physical properties and their performance when implemented in standard modulator architectures, such as the MZM. A detailed discussion of MZM operation is provided in chapter 2 and beyond. We compare the different modulator technologies according to a set of critical parameters as shown in table 1.1.

Beyond fundamental device parameters such as device length, optical loss, and bandwidth, we compare the linearity and the intrinsic amplitude or phase nature of the modulation principles. Linearity is an important parameter, particularly for advanced modulation formats beyond NRZ. These formats will be explained in detail in section 2.3.1. Linearity also plays a role in other applications, such as light detection and ranging (LIDAR) [15].

Similarly, unintended coupling between amplitude and phase modulation (spurious modulation) can introduce distortions, such as frequency chirp, which complicate their use in more advanced coherent modulation schemes. We further consider practical aspects, including the operational wavelength range and their CMOS compatibility, which is relevant for scaling considerations. Finally, we evaluate the compatibility with silicon photonics specifically, as this thesis focuses on heterogeneous integration.

1.3.1 Indium phosphide modulators

Indium phosphide (InP) was the most prominent material platform in the telecommunications industry for years, up until this year [9, 16], particularly for high-performance long-haul and metro networks. Its primary advantage is its monolithic nature, allowing the integration of high-power lasers directly with modulators on the same substrate. Amplitude modulators in the form of electro-absorption modulators (EAMs) as well as phase modulators exist in indium phosphide (InP) [17, 18], yielding different performance metrics. InP wafers are smaller and more expensive than silicon, and their integration with silicon photonics typically requires advanced bonding or micro-transfer printing strategies rather than monolithic growth.

Electro-Absorption Modulators (EAMs)

InP electro-absorption modulators (EAMs) are the workhorses of high-speed, short-

reach optics [19]. These devices operate by shifting the material's absorption edge via the quantum-confined Stark effect (QCSE) or the Franz-Keldysh effect. When an electric field is applied, the bandgap effectively shrinks, causing the material to become opaque to the operating wavelength. This mechanism allows for ultra-short device lengths (often $<100\text{ }\mu\text{m}$), which in turn leads to extremely low device capacitance and ultra-high bandwidths often exceeding 100 GHz. Because the light is modulated by being absorbed rather than by interference, EAMs are inherently amplitude modulators. While they offer high efficiency and small footprints, they suffer from moderate to high insertion loss due to the proximity of the operating wavelength to the absorption edge. Furthermore, their linearity is relatively bad due to the exponential nature of absorption, and they exhibit significant spurious phase modulation, which limits their effectiveness in complex coherent systems. Their wavelength range is also strictly limited to a narrow window near the material's bandgap around the C-band (1550 nm).

Carrier-Dispersion Phase Modulators

For applications requiring pure phase control, InP can be configured as a refractive index modulator, typically housed in an MZM [20]. These devices rely on carrier-dispersion effects and the linear electro-optic effect to change the real part of the refractive index. Because these are field-driven or carrier-depletion effects, they can achieve high bandwidths that surpass standard silicon modulators, largely due to the higher electron mobility in InP. However, they are significantly longer than EAMs because the refractive index change per volt is relatively weak, necessitating mm-scale interaction lengths to achieve a full V_π . Optical loss in these devices is primarily introduced through free-carrier absorption in the doped cladding layers required to bring the electrical signal close to the waveguide core. While they offer much better linearity and lower chirp than EAMs, their CMOS compatibility remains a significant hurdle. Beyond the inherent costs of InP substrates, these phase modulators typically require much higher drive voltages than EAMs, often exceeding the voltage limits of advanced CMOS nodes and necessitating additional amplification. Furthermore, their millimeter-scale footprint makes hybrid integration, via bonding or chiplet strategies, significantly more expensive in terms of required InP chip area compared to the compact EAM alternatives.

1.3.2 Silicon modulators

Silicon photonics has emerged as the dominant platform for high-volume data center interconnects and telecommunications, a trend highlighted by recent industry analysis suggesting 2026 as a major tipping point for the technology's market penetration [16]. The primary appeal of the platform is the native integration of

modulators within the silicon device layer of an silicon-on-insulator (SOI) wafer. This allows for absolute CMOS compatibility and massive scaling using mature 300 mm foundries, where the cost per device is minimized by the high-volume manufacturing standards of the semiconductor industry [10]. Also the material cost is significantly lower than InP.

Carrier-Dispersion Phase Modulators

Silicon modulators rely on the free-carrier plasma dispersion effect, where changes in the electron and hole densities modify both the real and imaginary parts of the refractive index. This is most commonly implemented as a p-n junction operated in depletion mode using a reverse bias voltage. This is mostly a phase modulation effect that can be turned into amplitude modulation within a Mach-Zehnder interferometer (MZI) configuration. While depletion-mode devices offer high bandwidths due to the fast sweep-out of carriers, they introduce a rigid physical trade-off: to achieve a low drive voltage (V_π), the doping concentration must be increased, which directly leads to higher optical loss through free-carrier absorption.

Alternatively, carrier injection devices utilize p-i-n junctions in forward bias to flood the waveguide core with carriers, offering much higher modulation efficiency and smaller footprints, albeit at the cost of significantly lower bandwidths limited by minority carrier lifetimes. Carrier accumulation represents a third approach, typically employing a metal-oxide-semiconductor capacitor structure. This method can achieve high efficiency without the speed limitations of carrier recombination, though it introduces challenges regarding gate oxide reliability and fabrication complexity.

In comparison to InP-based phase modulators, silicon devices generally exhibit lower intrinsic bandwidths. This is primarily attributed to the lower carrier mobility in silicon; the higher electron mobility in InP allows for faster carrier dynamics and lower series resistance, which facilitates operation at higher frequencies. Furthermore, while both platforms suffer from free-carrier absorption, the trade-off between loss and modulation efficiency is often more severe in silicon MZIs. Furthermore, as shown in table 1.1, silicon modulators are inherently long, often reaching several millimeters in length, to compensate for the relatively weak index change per carrier. Their linearity is notably low compared to other platforms because the relationship between carrier concentration and refractive index is inherently sub-linear. This nonlinearity creates signal distortion, such as eye-closure in PAM4 symbols, which must often be compensated for by complex digital signal processing (DSP). Despite these physical hurdles, the ability to operate across the O (1260-1360 nm), C (1530-1565 nm), and L-bands (1565-1625 nm) and the ease of co-integrating complex passive circuitry make silicon the baseline platform against which all emerging materials are measured.

III-V/Si hybrid

To overcome the intrinsic efficiency limits of silicon, hybrid III-V-on-Silicon integration has emerged as a key research direction. These devices often utilize a SISCAP (Semiconductor-Insulator-Semiconductor Capacitor) architecture, where an n-doped III-V membrane is heterogeneously integrated, for example through adhesive bonding, onto a p-doped Silicon waveguide. This approach leverages the significantly smaller effective mass of electrons in III-V materials (such as InGaAsP), which provides a refractive index change (Δn) approximately 17 times stronger than in Silicon for a given carrier density [21]. Furthermore, the hybrid structure addresses the phase-shift-to-loss trade-off ($\Delta n/\Delta k$); while III-V materials offer superior electron-induced effects, p-doped Silicon is utilized for the hole-accumulation layer due to its lower parasitic absorption compared to p-doped III-Vs. By combining these materials, hybrid MOS-capacitor modulators can achieve a 5-fold improvement in modulation efficiency over monolithic Silicon devices.

Silicon Germanium EAM To avoid the integration complexity of III-V materials, silicon-germanium (SiGe) EAMs have been developed [22]. These devices operate based on the Franz-Keldysh effect in Ge-on-Si epitaxial layers. When an electric field is applied across a SiGe p-i-n junction, the overlapping of wavefunctions in the triangular potential barrier allows for photon absorption at energies below the material's natural bandgap.

The primary advantage of the SiGe EAM is its compactness. Typical device lengths are nearly two orders of magnitude shorter than standard silicon MZIs, significantly reducing the lumped-element capacitance and enabling high-speed operation. Furthermore, because germanium epitaxy is already a standard module in silicon photonics foundries such as Imec's ISIPP200 platform (primarily for integrated photodetectors), SiGe EAMs offer a monolithic and CMOS-compatible path to high-density optical input/output (I/O). However, they are subject to a fundamental trade-off between the extinction ratio and insertion loss, as operating near the absorption edge inherently introduces higher optical attenuation compared to pure phase-based modulation. Additionally, the Franz-Keldysh effect is highly wavelength-dependent, typically limiting the effective operation of a single device to a narrow range within the O-band or C-band.

1.3.3 Ferroelectric modulators: BTO and PZT

Ferroelectric thin-films, specifically barium titanate (BTO) [23] and lead zirconate titanate (PZT) [24], have gained significant attention for their exceptionally high effective Pockels coefficients (r_{eff}), which can exceed 900 pm/V in optimized

BTO films [25–27]. Which is an order of magnitude higher than LN. Unlike carrier-based silicon modulators, these materials enable pure phase modulation with negligible absorption loss and high linearity.

BTO is particularly attractive for silicon photonics because it can be integrated monolithically via molecular beam epitaxy (MBE) on SOI wafers [28, 29] or even with spin coating [30], maintaining a high degree of CMOS compatibility. In contrast, PZT has a long history in micro-electromechanical systems (MEMS) and can be deposited via for example chemical solution deposition, sputtering, or spin coating [31]. While PZT offers robust ferroelectric properties and high electro-optic response, its integration into standard CMOS pilot lines is more challenging due to the potential for lead contamination. Both materials, however, suffer from challenges regarding the stability of the ferroelectric domains and the clamping effect of the substrate, which can reduce the effective electro-optic coefficient compared to bulk crystals. Despite this, their ability to provide ultra-short, low-power phase shifting makes them leading candidates for next-generation cryogenic and low-energy optical interconnects. BTO, however, exhibits a significant roll-off in its electro-optic response at higher frequencies due to the phonon contribution being unable to follow those speeds [32, 33]. Consequently, while highly efficient for low-power tuning and cryogenic applications, their advantage for ultra-high-speed data communication is limited compared other materials.

1.3.4 Organic electro-optic polymers

Organic electro-optic (EO) polymers, often used in silicon-organic hybrid (SOH) or plasmonic-organic hybrid (POH, see next section) configurations [34, 35], consist of nonlinear optical chromophores embedded within a polymer matrix. These materials provide high Pockels coefficients ($r_{33} > 300$ pm/V after high-voltage poling), significantly exceeding the value in LN. Because the nonlinearity arises from the ultra-fast displacement of π -electrons within the chromophores, these materials can support operational bandwidths well into the THz regime [36].

However, the practical implementation of EO polymers is hindered by their thermal and photochemical stability. The macroscopic alignment of chromophores is achieved through high-voltage poling near the glass transition temperature but tends to relax over time, particularly at the elevated temperatures found in data center environments. Furthermore, while they offer a path to extremely high-speed modulation, the need for protective encapsulation against oxygen and moisture adds significant complexity to the fabrication and packaging process.

1.3.5 Plasmonic-organic hybrid modulators

plasmonic-organic hybrid (POH) modulators represent the current limit of device miniaturization and operational bandwidth. By infiltrating an organic electro-optic polymer into a plasmonic slot waveguide, these devices leverage the exceptionally high $\chi^{(2)}$ nonlinearity of engineered chromophores combined with the extreme field confinement of surface plasmon polaritons [37–40].

The primary advantage of the POH approach is the sub-wavelength footprint, with active sections often shorter than 10 μm . This results in ultra-low capacitance, enabling record-breaking operational bandwidths exceeding 200 GHz and energy consumptions in the fJ/bit regime. However, they share the thermal and photochemical stability challenges inherent to organic chromophores.

1.3.6 A note on 2D materials (graphene)

While 2D materials, particularly graphene, have been extensively researched for electro-absorption and phase modulation [41–43], their practical implementation in SiPh remains limited [44, 45]. Graphene modulators offer ultra-wide bandwidths and a compact footprint by utilizing the tunable Pauli blocking effect [46, 47] or carrier-induced index changes [48]. However, these devices are plagued by high insertion losses due to the inherent semi-metallic nature of graphene and significant challenges in achieving high-quality, large-scale monolayer growth and stable electrical contacts. Given the current maturity of the thin-film lithium niobate (TFLN) and organic hybrid platforms, graphene remains primarily a subject of fundamental research rather than a near-term solution for industrial optical interconnects.

1.3.7 Thin film lithium niobate and lithium tantalate

TFLN has revolutionized the field by bringing the superior electro-optic properties of bulk LN to an integrated form factor via “smart cut” ion-slicing and wafer bonding. Unlike ferroelectric oxides such as BTO, the Pockels effect in LN is primarily electronic in origin, meaning its electro-optic coefficient ($r_{33} \approx 31 \text{ pm/V}$) remains constant well into the THz regime without the phonon-induced roll-off seen in other materials [32].

While LN is more established, LT has recently emerged as a compelling alternative due to its larger transmission window, higher optical power handling, and its availability in 8-inch wafers within standard CMOS foundry environments [49].

Both platforms offer a unique combination of high linearity and extreme bandwidths exceeding 100 GHz. However, the relatively weak Pockels coefficient necessitates long interaction lengths (often exceeding 1 cm) to achieve CMOS-compatible drive voltages, making these devices significantly larger than carrier-based silicon modulators.

Furthermore, the integration of these materials into standard CMOS pilot lines faces significant hurdles due to the nature of lithium as a high-risk mobile-ion contaminant [1]. Lithium atoms can diffuse rapidly through silicon and gate oxides, permanently shifting transistor threshold voltages and degrading performance. Consequently, TFLN processing is typically restricted to dedicated non-CMOS or “back-end-only” facilities to prevent cross-contamination of the front end of line equipment. The development of the heterogeneous integration of LN through bonding has reached a level of maturity that allows for high-yield fabrication in pilot lines.

1.4 Lithium niobate integrated photonics

Lithium niobate has long been a cornerstone of the optical communications industry, primarily in the form of bulky, discrete components. However, the recent emergence of thin-film lithium niobate (TFLN) has shifted the paradigm, allowing for the tight optical confinement and high integration densities previously reserved for integrated platforms [50, 51]. To contextualize the modulators developed in this work, it is necessary to first examine the fundamental physical and crystallographic properties of the LN crystal, as well as the fabrication techniques that enable its integrated form. A summary of the state-of-the-art in LN devices will also be included.

1.4.1 Material properties of lithium niobate

Let’s start by describing LN’s optical properties in a bit more detail since it will be required in the following sections and chapters [52]. LN is an anisotropic material with a trigonal crystal structure. For the purposes of design, this basically means that the crystal is uniaxially birefringent with the following refractive indices:

Wavelength (nm)	Ordinary Index n_o	Extraordinary Index n_e
1310	2.220	2.145
1550	2.211	2.138

Table 1.2: Refractive indices of LN at O- and C-band [53].

Table 1.1: Qualitative comparison of integrated photonic modulator platforms.

Material	Length	Optical Loss	Bandwidth	λ Range ^a	Modulation Type	Linearity	CMOS Comp.	SiPh Int.
InP (EAM)	Very Short	Moderate / High	High	O / C	Amplitude	Moderate	-	+
InP (EOM)	Moderate	Moderate	High	C + L	Phase	High	-	+
Silicon	Long	Moderate / High	Moderate / High	O / C + L	Phase	Low	+++	+++
III-V/Si Hybrid	Short	Moderate	High	O / C	Either	Low	+ ^b	+
SiGe (EAM)	Very Short	High	High	C	Amplitude	Moderate	+++	+++
BTO	Moderate	Low	Moderate	O / C + L	Phase	High	++	++
PZT	Moderate	Low	High	O / C + L	Phase	High	-	+
LN/LT	Long	Low	Very high	O / C + L	Phase	High	--	+
SOH	Short	Low	Very high	O / C + L	Phase	High	--	+
POH	Ultra short	High	Ultra-high	O / C + L	Phase	High	--	+
Graphene	Very Short	Very High	High	O / C / L	Either	Low	-	+

^a O-band (≈ 1310 nm), C-band (≈ 1550 nm), L-band (≈ 1600 nm).
Note: '/' denotes mutually exclusive device designs; '+' denotes broadband/simultaneous operation.
^b Requires heterogeneous integration.

In uniaxial materials, the extraordinary axis is typically associated with the z-axis while both the x- and y-axis are associated with the ordinary axis. One can then construct the so called index ellipsoid to calculate the refractive index when propagating in any particular direction:

$$\frac{x^2}{n_o^2} + \frac{y^2}{n_o^2} + \frac{z^2}{n_e^2} = 1 \quad (1.3)$$

Which can also be represented in the following impermeability tensor $\bar{\bar{\eta}}$:

$$\bar{\bar{\eta}} = \begin{bmatrix} \frac{1}{n_o^2} & 0 & 0 \\ 0 & \frac{1}{n_o^2} & 0 \\ 0 & 0 & \frac{1}{n_e^2} \end{bmatrix} \quad (1.4)$$

We will typically only use light propagating along the extraordinary axis of the material but, given this ellipsoid, one can calculate the effective refractive indices of both eigenmodes of light propagating at any angle with reference to the extraordinary axis. If this angle is θ , then one polarization will have the ordinary refractive index as effective index and the other polarization will have an effective refractive index according to:

$$\frac{1}{n_e^2(\theta)} = \frac{\cos^2 \theta}{n_o^2} + \frac{\sin^2 \theta}{n_e^2} \quad (1.5)$$

Lithium niobate (LN) is a popular material in optics and electronics because it has several interesting properties such as ferroelectricity and piezoelectricity. In this thesis it is however mostly interesting because of its opto-electronic property: the linear electro-optic (Pockels) effect. This effect is characterized by the Pockels coefficient r_{ij} , which describes the change in the index ellipsoid in response to an applied electric field. For LN, the primary coefficient is $r_{33} = 30.9 \text{ pm V}^{-1}$. More on the Pockels effect, how it distorts the index ellipsoid and how it's used to create modulators in the next chapter.

The material also possesses an exceptionally wide transparency window, stretching from the ultraviolet (400 nm) well into the mid-infrared (5 μm) [54]. This makes it uniquely versatile compared to silicon, which becomes opaque below 1.1 μm . Impressive demonstrations of dry-etched TFLN microring cavities have shown intrinsic Q-factors exceeding 10^7 at telecom wavelengths [55, 56]. These results imply that propagation losses are no longer a limiting factor for complex PICs, even for long delay lines or high-finesse resonators. Due to its large bandgap, two-photon absorption also does not become a problem until closer to the blue wavelengths.

As a non-centrosymmetric crystal, LN possesses a strong second-order susceptibility ($\chi^{(2)}$), which is the physical origin of both the Pockels effect and three-wave mixing processes such as second harmonic generation (SHG) and optical parametric oscillation (OPO). Furthermore, LN exhibits a non-negligible third-order nonlinearity ($\chi^{(3)}$), with a Kerr refractive index n_2 on the order of $1.8 \times 10^{-19} \text{ m}^2/\text{W}$. Although this is significantly lower than that of silicon, the combination of a high-Q factor and $\chi^{(3)}$ effects in LN resonators allows for the generation of Kerr frequency combs, providing a multi-wavelength source directly on the modulator platform.

One property that thwarts the long-term stability of modulators' bias points is an effect called "DC drift" [57, 58]. This phenomenon is attributed to the movement of mobile ions or the relaxation of charges at the interfaces between the LN film, the electrodes, and the cladding. Over time, these charges screen the applied external field, requiring an ever-increasing bias voltage to maintain the desired operating point. Feedback loops or the use of thermal phase shifters to maintain bias can solve the issue at the price of more complexity in the setup. At cryogenic temperatures this effect quickly diminishes and becomes less of an issue [59].

Another significant hurdle often mentioned in high-power or short-wavelength applications is the photorefractive effect. This is an effect where photo-excited carriers migrate and become trapped in the crystal, creating a localized space-charge field. Through the Pockels effect, this field induces a semi-permanent change in the refractive index, leading to beam or mode distortion. While LN is susceptible to this it can be mitigated by doping the crystal with magnesium oxide (MgO), which increases the conductivity and allows the trapped charges to redistribute more quickly.

Finally, the ferroelectric nature of the LN crystal is bound by the Curie temperature ($T_C \approx 1140^\circ\text{C}$), above which the material loses its non-centrosymmetric properties and, consequently, its Pockels response. This high T_C is an advantage for integration, as it allows the material to withstand high-temperature processing steps common in CMOS-compatible environments without degrading its modulation efficiency.

1.4.2 From bulk to thin-film

The transition from bulk crystals to high-index-contrast integrated circuits is primarily driven by the smart-cut process. This technique involves the implantation of helium ions into a bulk LN wafer to create a weakened "sacrificial" layer at a precise depth [60, 61]. By controlling the impact energy of the ions one can control the implantation depth. The ions create a uniform damaged layer. The implanted wafer is then flip-bonded to a handle substrate, this is typically silicon or LN itself with a

SiO_2 buffer layer. High-temperature annealing induced the damaged layer to form bubbles and allows the wafer to be cleaved along the ion-implanted zone. Further annealing and polishing is used to minimise the damage of the ion implantation on the remaining thin film. The resulting structure is a single-crystal LN thin film (typically less than $1\text{ }\mu\text{m}$ thick) on an insulator, often referred to as lithium niobate on insulator (LNOI). The schematic below illustrates the smart cut process.

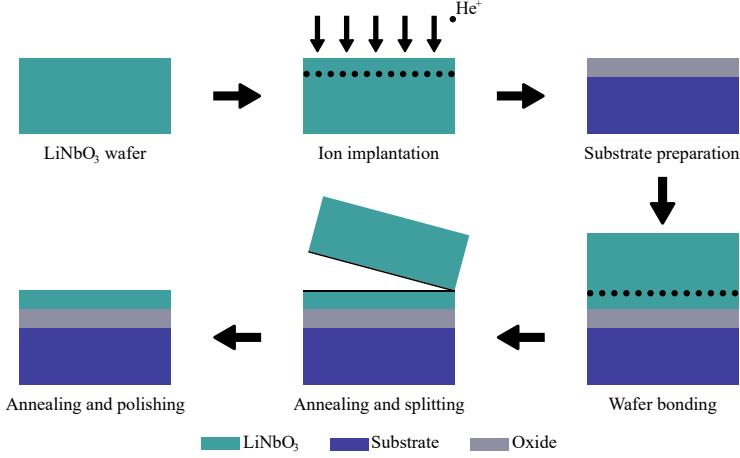


Figure 1.4: Schematic depiction of the smart cut process. [61]

Subsequent patterning is typically achieved through advanced dry etching techniques, Ar milling through reactive ion etching (RIE) is the standard method. Around 2014, this resulted in demonstrations of high-Q microdisk resonators [62] and three years later, in 2017, a microring resonator with a Q-factor up to 10^7 was shown [55], illustrating propagation losses $<3\text{ dB m}^{-1}$. After the early pioneering done by Lončar et al., several research groups and companies around the world have optimised etching processes. Modern fabrication flows utilize optimized Ar milling to produce rib waveguides with smooth, slanted sidewalls, which are critical for achieving high Q-factors and low propagation losses.

1.4.3 Lithium niobate modulators are state-of-the-art

The properties discussed in the previous section make LN a great candidate for integrated photonics applications [50, 63], ranging from passive components and modulators to quantum photonics and nonlinear wavelength converters [64, 65]. Let's now discuss some of the hallmark achievements in the field of telecom modulators [58], summarised in table 1.3. To provide a consistent comparison of

high-speed performance, table 1.3 focuses exclusively on non-resonant, traveling-wave MZMs operating in the infrared telecommunication bands (1310–1550 nm). Resonant structures, such as microring modulators or photonic crystal cavities, are omitted due to their distinct trade-offs between optical bandwidth and footprint.

Early efforts began shortly after the optimisation of the etching progress from Lončar’s group at Harvard in 2018 [66]. While bulk LN modulators had been a workhorse of the photonics industry for decades, the move to nanofabricated devices quickly proved a massive improvement in half-wave voltage was possible and the 100 GHz boundry was also quickly passed [67], though first on LN and quartz substrates.

Other research groups around the world quickly joined the effort and in the following years great progress was made in search of more mature fabrication techniques and to come closer to CMOS compatible processing. In terms of electrode design, moving to capacitively loaded travelling wave electrodes (CL-TWE) facilitated a reduction in RF loss while ensuring a close velocity and impedance match can be maintained also on silicon substrates [68–70]. Furthermore, several groups began heterogeneously integrating LN on both Si and SiN PICs [71]. Large succes has been gained from wafer bonding endeavors [72, 73], and some micro-transfer printing (mTP) examples have also been performed over the years since this work began [74, 75].

Since 2023, effort has mostly turned towards more exotic geometries or the addition of high-k claddings, more on the claddings in section 5.4.2. Efforts towards differential modulators have resulted in recent innovations [76] but no great solutions have been put forward in the literature apart from the work presented here. Around the same time, a lot of players decided to put effort into start-ups or in tech transfer to industrial players. Which has resulted in the creation of several monolythic TFLN foundries such as Hyperlight, Luxtelligence and Lightium, as well as massive effort towards heterogeneous integration of LN such as in the wafer bonding approach of Ligentec [77]. Finally, the most impressive demonstration of LN modulators still seems to come from Liu et al. at Zhejiang University who achieved very impressive results in a dual polarisation IQ setup reaching a net data rate of 1.92 Tb/s [78] already in 2022.

1.4.4 Lithium tantalate as an alternative

Before we move on to the next section concerning heterogeneous integration, it is pertinent to discuss LT. This isomorphous material to LN has come into the spotlight again in recent years as an alternative integrated platform compared to LN [49, 61]. It has seen use in other applications over the years such as RF filters

Table 1.3: Literature study of the performance of integrated LN modulators.

Ref.	Year	λ (nm)	IL (dB)	ER (dB)	V_{π} (V)	L (mm)	$V_{\pi}L$ (V·cm)	BW (GHz)	Mod. format	Rate (Gbps)	Elec. shape	Elec. config	Platform config
[66]	2018	1550	2	10	9	2	1.8	15	NRZ	22	Rect.	GSG	TFLN
[67,79]	2018	1550	<1	30	4.4	5	2.2	100	-	-	Rect.	GSG	TFLN
[67]	2018	1550	<1	30	1.4	20	2.8	>45	PAM8	210	Rect.	GSG	TFLN
[80]	2018	1550	2.9	>20	13.4	5	6.7	>106	NRZ	20	Rect.	GSG	Si/LN bonded
[81]	2019	1550	2.5	>40	5.1	5	2.5	>70	PAM4	112	Rect.	GSG	Si/LN bonded
[82]	2020	1550	13	>20	13.34	5	6.7	30.6	-	-	Rect.	GSG	SiN/LN bonded
[83]	2020	1550	1.8	>25	1.9	13	2.4	48	16QAM	320	Rect.	GSG	TFLN
[83]	2020	1550	1.45	>25	3.1	7.5	2.3	>67	-	-	Rect.	GSG	TFLN
[84]	2021	1550	-	8.5	-	10	2.74	55	NRZ	-	Rect.	GSG	Folded TFLN
[85]	2021	1550	4.7	-	3.1	10	3.1	>40	NRZ	120	Rect.	GSG	SiN loaded TFLN
[68]	2021	1550	<1	20	1.3	20	2.6	>50	-	-	CL-TWE	GSG	TFLN
[86]	2021	1550	-	17	3.5	5	1.75	>40	-	-	Rect.	GSG	TFLN
[69]	2022	1550	0.2	>20	2.2	10	2.2	>67	PAM4	112	CL-TWE	GSG	TFLN
[70]	2022	1550	5.8	>25	0.7	33	2.2	45	PAM4	200	CL-TWE	GSG	Folded TFLN
[78]	2022	1550	6.5	>20	1	23.5	-	110	400QAM	1960 ^a	CL-TWE	GSG	TFLN
[73]	2023	1550	1	33	4.3	7	3	37	PAM4	80	Rect.	GSG	SiN/LN bonded
[87]	2023	1310	16	>28	5.6	5.1	2.8	>110	-	-	Rect.	GSG	SiN/LN bonded
[12] [†]	2023	1550	3.3	39	14.8	2	3.0	>50	70	NRZ	Rect.	GSSG	mTP on SiN
[75]	2025	1550	0.97	-	2.7	9.9	2.7	28	-	-	Rect.	GSG	mTP on Si
[77]	2026	1550	4	>35	6.4	6	3.8	110	-	-	CL-TWE	GSG	SiN/LN bonded

[†] Work produced by the author's research group. ^a Net rate achieved using dual polarisation 400QAM and accounting for FEC overhead.

Note: IL: insertion loss, ER: extinction ratio, BW: 3dB electro-optic bandwidth, Rect.: Rectangular, CL-TWE: capacitively loaded travelling wave electrodes.

for 5G.

A comparison of the key material properties and high-frequency dynamics between thin-film LN and LT is outlined in table 1.4. Many of these values are not quantitative and literature isn't conclusive yet.

Table 1.4: Material and performance comparison between thin-film lithium niobate (LN) and lithium tantalate (LT).

Property / Parameter	LN	LT
EO coefficient (r_{33})	≈ 30 pm/V	≈ 30 pm/V
Birefringence ($\Delta n = n_e - n_o$)	-0.07	0.004
Curie temperature (T_C)	≈ 1140 °C	≈ 600 °C to 700 °C
Photorefractive threshold	Baseline	Elevated ($> 10\times$)
DC bias stability	Poor (drift)	Excellent [88]
Relative permittivity (ϵ_r)	Baseline	Marginally higher
Demonstrated bandwidth	> 100 GHz	Up to 110 GHz [89, 90]

Compared to LN, LT has a significantly lower birefringence of $\Delta n = n_e - n_o = 0.004$ instead of the -0.07 of LN. This simplifies circuit design and allows for much smaller bend radii. From an electro-optic standpoint, both platforms share a virtually identical dominant Pockels coefficient ($r_{33} \approx 30$ pm/V), meaning that LT does not sacrifice the low half-wave voltage-length products ($V_\pi L$) that made thin-film LN famous. In terms of RF performance, LT features a marginally higher electrical permittivity (ϵ_r), which requires slight modifications to the coplanar waveguide electrodes to maintain strict velocity matching with the co-propagating optical mode; however, its microwave loss tangent is comparable to or slightly better than LN, preventing severe high-frequency attenuation.

Its primary advantage lies in its superior optical stability [88, 91]. LT possesses a significantly higher threshold for photorefractive damage compared to undoped LN [49], making it better suited for high-power density applications or operations in the visible and near-ultraviolet regimes due to its broader transparency window. A historic bottleneck for high-speed LN modulators is bias drift, caused by the migration of charges within the cladding layers under a sustained DC bias. Recent studies have demonstrated that thin-film LT modulators exhibit vastly superior DC bias stability over extended operating times, showing significantly reduced output power fluctuations under identical high-power optical loads [88]. These values are still heavily under investigation and are possibly a result of the fabrication method and impurity concentration rather than the actual material properties.

LT also has a much lower Curie temperature (≈ 600 °C), which imposes a stricter thermal budget during fabrication. Despite this, the lower T_C can be an advantage for specific applications like periodic poling [92]. Demonstration of LT high-

speed modulators have already been shown reaching bandwidths up to 110 GHz [89, 90, 93].

These combined traits—coupled with the established commercial supply chain of 8-inch LT wafers used in the smartphone filter industry—render LT a highly compelling alternative for next-generation, stable, high-volume photonic integrated circuits.

1.5 Heterogeneous integration via micro-transfer printing

Integrated photonics is transitioning away from single-function devices to complex, multi-functional systems on a chip. Whether it is for high-speed tele- and datacom applications [94] or other applications such as LIDAR [95], sensors [96], medical devices [97] or on-chip (quantum) computing [98], modern photonic systems are becoming bigger and require multiple advanced functionalities densely co-integrated.

However, no single material platform can offer all tasks optimally. For example, Si or SiN photonics platforms offer mature fabrication, broad transparency windows, and low propagation losses [99], they lack in active properties for light generation and detection at datacom and telecom wavelengths [100]. Although Si-based modulators exist, as discussed previously, they are not as performant as other modulators such as LN modulators. To overcome these limitations, the field has moved towards heterogeneous integration techniques, this allows the combination of the best material for every function in a single system. Efficient gain from III-V materials [101, 102], high-speed detectors in germanium or III-V [103, 104] and high-speed modulation in Pockels materials, all hosted on a low-loss platform of Si or SiN.

Several methods for heterogeneous integration have been explored, each with its distinct advantages and challenges. It is important to discuss them here. Importantly, we are looking towards future commercial viability, these methods need to be scalable for mass production, as CMOS-compatible as possible while allowing for different heterogeneous integration techniques to be combined for complex functionalities on the same chip. Table 1.5 compares the different methods discussed in the following sections.

1.5.1 Traditional assembly

Before heterogeneous integration, the industry is relying on the assembling of discrete monolithic chips within a single package. This method is very prevalent in pluggable transceivers. In these systems different devices are fabricated separately: a III-V laser, a LN modulator, and an electronic driver, and then joined at the packaging level.

Optical coupling is typically achieved via free-space coupling using micro-lenses or butt-coupling. While this allows for each material to be optimized independently, it requires high-precision active alignment, which is time consuming, sequential and expensive. Furthermore, this packaging creates a significant footprint and a power consumption that is limiting for next-generation transceivers. Denser integration through co-packaged optics and heterogeneous integration promises lower power usage due to shorter electrical paths and optical losses as well as higher bandwidth and reduced latency, at the cost of thermal management issues and serviceability difficulties, often requiring to replace the entire board if a component fails.

1.5.2 Flip-chip integration

Flip-chip integration is one of the most industry-mature methods. This method brings pre-fabricated dies closer to the host circuit, usually through solder-bump technology. It leverages established monolithic fabrication techniques for III-V laser integration and allows for wafer level testing on the source wafer. This means that known good dies can be used to populate the SiPh wafer, but still in a sequential way. However, while flip-chip integration is a mature industry standard for III-V laser integration, we have not seen significant adoption for LN modulators. The large solder bumps and difficult optical coupling are the main reasons for this.

1.5.3 Wafer bonding

A more wafer level integration technique, compared to flip-chip integration, is die-to-wafer bonding or wafer-to-wafer involves the molecular bonding of the donor material directly onto the target wafer. It offers very efficient optical coupling techniques and often populates an entire wafer at once. It does require significant further processing on the target wafer, and as such, it doesn't allow for any known good die testing. For LN, this is a big issue in particular since, as mentioned, LN has to deal with high contamination risks attributed to it [1]. This means one needs significant wafer scale equipment in a back-end-of-line "contaminated" fab. Compared to flip-chip integration and micro-transfer printing, it is also wasteful in

terms of materials. Since most of the bonded wafer will be etched away after the bonding process, certainly when it comes to wafer-to-wafer bonding.

1.5.4 Micro-transfer printing

Micro-transfer printing (mTP) intends to combine the advantages of the previous techniques [105–107]. Using a elastomeric PDMS stamp, thousands of pre-fabricated devices [74, 108, 109], referred to as “coupons”, are transferred in an automated and parallel fashion onto a target PIC [110]. Future implementations are expected to enable pre-testing of these devices prior to transfer. The devices can, like in the case of this thesis, also be limited to thin films [111, 112]. More details about the fabrication follow in chapter 3.

This back-end approach allows for the parallel processing of source and target wafers. The modulators and other devices are fabricated on their monolithic platform and the functionality is verified using wafer-level testing. The printing is the final step in this process. This provides coupling that is similar in efficiency to die-to-wafer bonding while ensuring a high throughput yield, and completely isolated back-end of line process enabled by very few tools required after printing. Typically one needs only a printer and a cladding deposition tool to finish the wafers using mTP. It is also incredibly material efficient, since one is able to densely integrate the devices on the source wafer to then populate several SiPh target wafers using a single source wafer. Another advantage of the micro-transfer printing method is that it is fairly trivial to combine multiple heterogeneous materials onto the same wafer using multiple printing steps.

Other heterogeneous integration methods such as laser micro-packaging, and hetero-epitaxial growth exist but are not relevant for LN technologies, and are therefore outside of the scope of this comparison. The following table compares the methods discussed here.

Table 1.5: Technical comparison of heterogeneous integration strategies for LN on SiPh platforms.

Feature	Traditional assembly	Flip-chip integration	Wafer bonding	Micro-transfer printing
Coupling method	+ (lens)	--	++	++
CMOS comp.	++	+	-	++
Known good die	++	++	--	++
Throughput	-- (Seq.)	-- (Seq.)	++	+ (Paral.)
Material use	+	+	--	++
Multi-material	+	+	-	++
Serviceability	++	-	-	-

1.6 Thesis outline

In the following chapters, I will discuss several research aspects, including the devices that were designed, fabricated and/or measured as part of this thesis. I have chosen to group the chapters by these aspects rather than by individual devices. This way it is easier to find my thoughts and discussions concerning, for example, design or fabrication. Readers interested in a specific device are referred to the accompanying publications, which focus on individual devices in detail.

Chapter 2 discusses the theoretical and engineering foundation required to understand the remainder of the thesis. This is the main theoretical section and discusses the Pockels effect, optical coupling to heterogeneous structures, complex modulation formats and RF design principles required for high-speed operation.

Chapter 3 lays out in detail the fabrication workflow including the micro-transfer printing processes that were developed and used during the years working on this topic. It demonstrates both the SiN fabrication and the evolution of the mTP process.

In **chapter 4**, the results of the various different modulator devices are presented and discussed. All properties from passive performance to bandwidth measurements are included here.

Chapter 5 concludes the thesis while simultaneously looking ahead to several future efforts.

Chapter 6 summarizes the research performed as a visiting scientist at the Mas-

sachusetts Institute of Technology (MIT) in the group of Professor Dirk Englund. While distinct from the primary focus on mTP for datacom, this work explores a high-speed spatial light modulator based on piezoelectrically actuated silicon nitride gratings.

List of Publications

Journal Publications

- [J1] **Tom Vanackere**, Tom Vandekerckhove, Elke Claeys, John Puthenparampil George, et al. *Improvement of liquid crystal tunable lenses with weakly conductive layers using multifrequency driving*. Optics Letters, 2020.
- [J2] Kristof Reynkens, Stéphane Clemmen, Haolan Zhao, Ali Raza, **Tom Vanackere**, et al. *Gold-induced photothermal background in on-chip surface enhanced stimulated Raman spectroscopy*. Optics Letters, 2021.
- [J3] Gunther Roelkens, Jing Zhang, Laurens Bogaert, ..., **Tom Vanackere**, et al. *Micro-transfer printing for heterogeneous Si photonic integrated circuits*. IEEE Journal of Selected Topics in Quantum Electronics, 2022.
- [J4] Tom Vandekerckhove, **Tom Vanackere**, Jasper De Witte, Stijn Cuyvers, et al. *Reliable micro-transfer printing method for heterogeneous integration of lithium niobate and semiconductor thin films*. Optical Materials Express, 2023.
- [J5] **Tom Vanackere**, Tom Vandekerckhove, Laurens Bogaert, Maximilien Billet, et al. *Heterogeneous integration of a high-speed lithium niobate modulator on silicon nitride using micro-transfer printing*. APL Photonics, 2023.
- [J6] Gunther Roelkens, Jing Zhang, Laurens Bogaert, ..., **Tom Vanackere**, et al. *Present and future of micro-transfer printing for heterogeneous photonic integrated circuits*. APL Photonics, 2024.
- [J7] Ying Tan, Shengpu Niu, Maximilien Billet, Nishant Singh, Margot Niels, **Tom Vanackere**, et al. *Micro-transfer printed thin film lithium niobate (TFLN)-on-silicon ring modulator*. ACS Photonics, 2024.
- [J8] Peter Ossieur, Bart Moeneclaey, Gertjan Coudyzer, ..., **Tom Vanackere**, et al. *Integrated photonics and electronics for optical transceivers supporting AI/ML applications*. IEEE Journal of Selected Topics in Quantum Electronics, 2025.

- [J9] Margot Niels, **Tom Vanackere**, Tom Vandekerckhove, Stijn Poelman, et al. *Centimetre-scale micro-transfer printing to enable heterogeneous integration of thin film lithium niobate with silicon photonics*. Optical Materials Express, 2025.
- [J10] Margot Niels, Ewoud Vissers, **Tom Vanackere**, Arno Moerman, et al. *Demonstration of lithium niobate integration on a 200-mm silicon photonics wafer using transfer printing*. Optics Letters, 2025.
- [J11] **Tom Vanackere**, Artur Hermans, Ian Christen, Christopher Panuski, et al. *Piezoelectrically actuated silicon-nitride-based high-speed spatial light modulator*. Nature Communications, 2025.
- [J12] Margot Niels, **Tom Vanackere**, Ewoud Vissers, Tingting Zhai, et al. *A high-speed heterogeneous lithium tantalate silicon photonics platform*. Nature Photonics, 2026.

International Conference Proceedings

- [C1] **Tom Vanackere**, Maximilien Billet, Camiel Op de Beeck, Stijn Poelman, et al. *Micro-transfer printing of lithium niobate on silicon nitride*. In European Conference on Optical Communications (ECOC), 2020.
- [C2] Stijn Cuyvers, **Tom Vanackere**, Tom Vandekerckhove, et al. *High-yield heterogeneous integration of silicon and lithium niobate thin films*. In Conference on Lasers and Electro-Optics (CLEO), 2022.
- [C3] Jasper De Witte, Zhe Liu, Atefeh Shadmani, **Tom Vanackere**, et al. *Micro-transfer printing for the heterogeneous integration of single-photon sources on SiN*. In IEEE Photonics Society Benelux Chapter, 2023.
- [C4] **Tom Vanackere**, Tom Vandekerckhove, et al. *Micro-Transfer Printed High-Speed Lithium Niobate Modulator on Silicon Nitride*. In IEEE Photonics Society Benelux Chapter, 2023.
- [C5] Maximilien Billet, **Tom Vanackere**, et al. *Filling the gap of silicon nitride photonic platform functionalities using micro-transfer printing*. In Advanced Photonics Congress, 2023.
- [C6] Jing Zhang, Laurens Bogaert, ..., **Tom Vanackere**, et al. *Photonic integrated circuits realized using micro-transfer printing*. In PIERS, 2023.
- [C7] Margot Niels, Maximilien Billet, Tom Vandekerckhove, **Tom Vanackere**, et al. *Micro-Transfer Printing for cm-scale Heterogeneous Integration of Lithium Niobate*. In IEEE Photonics Society Benelux Chapter, 2023.

- [C8] Tom Vandekerckhove, **Tom Vanackere**, et al. *Pillar-based high-yield heterogeneous integration of lithium niobate and gallium phosphide thin films*. In Conference on Lasers and Electro-Optics (CLEO), 2023.
- [C9] **Tom Vanackere**, Tom Vandekerckhove, Laurens Bogaert, ..., Bart Kuyken. *High-speed lithium niobate modulator on silicon nitride using micro-transfer printing*. In Conference on Lasers and Electro-Optics (CLEO), 2023.
- [C10] Tom Vandekerckhove, **Tom Vanackere**, Jasper De Witte, Isaac Luntadila Lufungula, et al. *High-efficiency second harmonic generation in heterogeneously-integrated periodically-poled lithium niobate on silicon nitride*. In European Conference on Lasers and Electro-Optics (CLEO Europe), 2023.
- [C11] Peter Ossieur, Bart Moeneclaey, Joris Lambrecht, ..., **Tom Vanackere**, et al. *High speed transceivers beyond 1.6 Tb/s for data centre networks*. In European Conference on Optical Communications (ECOC), 2023.
- [C12] Ying Tan, Margot Niels, Maximilien Billet, **Tom Vanackere**, et al. *Heterogeneously integrated Si-LN microring modulator based on transfer-printing method*. In European Conference on Optical Communications (ECOC), 2023.
- [C13] Margot Niels, Maximilien Billet, Tom Vandekerckhove, **Tom Vanackere**, et al. *Scalable cm-scale Micro-Transfer Printing for Heterogeneous Integration of Lithium Niobate*. In Frontiers in Optics, 2023.
- [C14] Margot Niels, Maximilien Billet, Tom Vandekerckhove, **Tom Vanackere**, et al. *Characterisation of Centimetre-Scale Micro-Transfer Printed Lithium Niobate on a Silicon Nitride platform*. In IEEE Photonics Society Benelux Chapter, 2024.
- [C15] Maximilien Billet, **Tom Vanackere**, Tom Vandekerckhove, Margot Niels, et al. *Recent progress in heterogeneous integration on the silicon nitride platform using micro-transfer printing*. In SPIE OPTO, 2024.
- [C16] Ying Tan, Joris Van Kerrebrouck, **Tom Vanackere**, et al. *Compact photonic crystal Si-LN modulator realized by micro-transfer printing*. In IEEE Silicon Photonics Conference (SiPhotonics), 2024.
- [C17] Tom Vandekerckhove, Ruben Van Assche, ..., **Tom Vanackere**, et al. *Highly-Selective Etching of Micro-Transfer-Printed Thin-Film Lithium Niobate for Low Coupling Losses*. In Conference on Lasers and Electro-Optics (CLEO), 2024.

- [C18] Tom Vandekerckhove, **Tom Vanackere**, et al. *Deterministic Phase-Matching of Micro-Transfer-Printed Periodically-Poled Lithium Niobate Waveguides*. In Conference on Lasers and Electro-Optics (CLEO), 2024.
- [C19] **Tom Vanackere**, Tom Vandekerckhove, Maximilien Billet, ..., Bart Kuyken. *Towards scalable heterogeneous integration of thin-film lithium niobate on silicon photonics using microtransfer printing*. In **Invited** SPIE Photonics Europe, 2024.
- [C20] Jasper De Witte, Zhe Liu, Atefeh Shadmani, **Tom Vanackere**, et al. *SiN/GaAs quantum photonic platform with efficient fiber-coupling*. In Quantum 2.0, 2024.
- [C21] Margot Niels, Maximilien Billet, Tom Vandekerckhove, **Tom Vanackere**, et al. *Characterisation of Micro-Transfer Printed cm-Scale Lithium Niobate on a Silicon Nitride Platform*. In Pacific Rim Conference on Lasers and Electro-Optics (CLEO-PR) , 2024.
- [C22] Ying Tan, Shenpu Niu, **Tom Vanackere**, et al. *Heterogeneous integration of thin-film lithium niobate and silicon photonics via micro-transfer printing*. In International Conference on Information Optics and Photonics (CIOP), 2024.
- [C23] Ying Tan, Nishant Singh, ..., **Tom Vanackere**, et al. *Micro-transfer printed Si-LN Bragg Grating modulator*. In Conference on Lasers and Electro-Optics (CLEO), 2025.
- [C24] **Tom Vanackere**, Margot Niels, Ewoud Vissers, Tingting Zhai, et al. *Lithium tantalate high-speed modulators on a silicon photonics platform*. In **Post-Deadline** Conference on Lasers and Electro-Optics (CLEO), 2025.
- [C25] Margot Niels, **Tom Vanackere**, et al. *High-speed lithium tantalate-based silicon photonic modulators*. In European Conference on Lasers and Electro-Optics (CLEO europe) , 2025.
- [C26] Jakob Declercq, Shengpu Niu, Margot Niels, ..., **Tom Vanackere**, et al. *320 Gb/s Unamplified Transmission Using 100 GHz Ge PD and TFLN MZM on a Foundry-Compatible SiPh Platform Co-Packaged with Traveling-Wave Drivers and TIAs*. In **Post-Deadline** European Conference on Optical Communications (ECOC), 2025.
- [C27] Margot Niels, Ewoud Vissers, **Tom Vanackere**, et al. *Wafer-scale integration of lithium niobate on a silicon photonics 200-mm platform*. In IEEE Photonics Conference (IPC), 2025.

- [C28] Lam Tran, Dongbo Wang, ..., **Tom Vanackere**, et al. *Microtransfer printing for heterogeneous integrated active devices on silicon nitride platforms*. In SPIE OPTO, 2026.

Patents

- [P1] Tom Vandekerckhove, **Tom Vanackere**, Gunther Roelkens, Stéphane Clemmen, Bart Kuyken. *Micro-transfer printing of thin films*. WO2024042016A1, 2023.
- [P2] **Tom Vanackere**, Guy Torfs, Bart Kuyken. *An integrated electro-optic modulator and method of manufacturing thereof*. WO2026037588A1, 2025.

2

Travelling wave amplitude modulators based on the Pockels effect

2.1	Pockels effect and efficient modulator waveguide design . . .	32
2.1.1	Principle, parameters and design metrics	32
2.1.2	Numerical optimization and trade-offs between efficiency and loss	39
2.2	Efficient optical coupling: design and optimization of heterogeneous tapers	43
2.2.1	Mode coupling simulations, iterative design workflow and best practices	43
2.2.2	Final taper designs and performance	47
2.3	From phase modulation to advanced IQ architectures . . .	50
2.3.1	Advanced modulation formats and dual-polarization operation.	54
2.4	High-speed RF design for travelling-wave modulators . . .	59
2.4.1	The three pillars: impedance, velocity, and loss	60
2.4.2	Electrode topologies: single-ended and differential electrodes	66
2.4.3	Practical constraints: probing and measurements . . .	72
2.4.4	Simulation workflow and results	73

Over the course of this thesis, I have simulated and designed a wide range of modulators, exploring different layer stacks, materials, and guiding principles, certainly more than initially planned, as fabrication processes evolved throughout the project. Many of these designs were ultimately not implemented, but the work provided valuable insights into proper high-speed modulator design. While there are plenty of modulator designs possible I will stick to the principles and designs relevant to travelling wave amplitude modulators based on the Pockels effect. These devices will be based on Mach-Zehnder interferometer (MZI) architectures to create a Mach-Zehnder modulator (MZM).

2.1 Pockels effect and efficient modulator waveguide design

2.1.1 Principle, parameters and design metrics

The linear description of a material using its refractive index is a first order approximation that is often enough to describe plenty of optical phenomena such as refraction, total internal reflection, absorption, and dispersion. It is however not a full description. Optical materials are fundamentally nonlinear. This implies that their response will become dependent on the intensity of the light. These nonlinearities can cause a myriad of effects such as harmonic generation, self-focusing, soliton formation, and phase modulation. For a more comprehensive treatment of nonlinear optical phenomena, the reader is referred to standard textbooks on nonlinear optics, such as Boyd [113].

To describe these nonlinear effects one typically looks at the polarisation vector $\mathbf{P}$ to characterize the material's total dipole moment. Which appears in the definition of the displacement field in Maxwell's Equations

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \quad (2.1)$$

where ε_0 is the vacuum permittivity. Typically one describes the polarisation linearly as follows $\mathbf{P} = \varepsilon_0 \chi^{(1)} \mathbf{E}$. If the potential well of electrons was perfectly harmonic this would be an accurate description. This turns out to not really be the case, in reality things like electron-electron interactions and strong force interactions with the nucleus cause the potential well to become anharmonic, illustrated in figure 2.1 such that it is more accurate to write the nonlinear polarisation as follows:

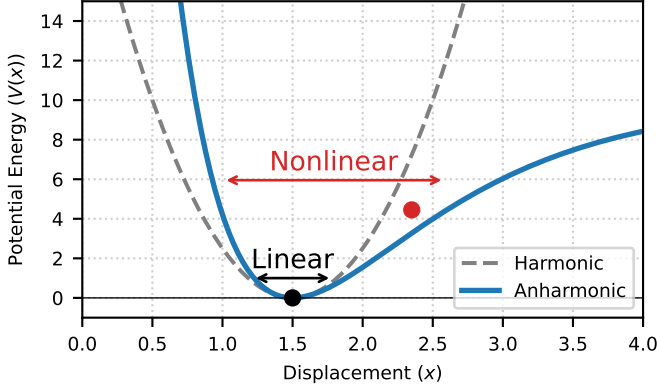


Figure 2.1: Comparison of the ideal harmonic potential (dashed gray) and the realistic anharmonic potential (blue). The black and red arrows indicate the electron oscillation range in the linear and nonlinear regimes, respectively. In the nonlinear regime, the electron samples the asymmetrical regions of the well, leading to a non-sinusoidal polarization response and the generation of higher-order harmonics.

$$\mathbf{P} = \epsilon_0 (\chi^{(1)} \mathbf{E} + \chi^{(2)} \mathbf{E}^2 + \chi^{(3)} \mathbf{E}^3 + \dots) \quad (2.2)$$

This equation now contains nonlinear polarisation terms with second- and third-order nonlinearity coefficients $\chi^{(2)}$ and $\chi^{(3)}$. Due to symmetry reasons, second-order nonlinearities only appear with reasonable magnitude in certain non-centrosymmetric materials (such as LN) while third-order nonlinearities are present in most materials to a reasonable degree. This interaction can occur between electrical fields at the exact same frequency such as in second harmonic generation but it can also be between fields at different frequencies such as in sum-frequency generation. Here we will mostly focus on the second order nonlinearity and even more specifically on the Pockels effect, also called the linear electro-optic effect. The Pockels effect is a second order nonlinear effect that enables the interaction between an RF field and an optical field. It is however most often described simply by saying that the refractive index at optical frequencies changes based on the applied RF field over the material. Simplified, the change in refractive index Δn can be written as follows:

$$\Delta n \simeq -\frac{1}{2} n^3 r E \quad (2.3)$$

where n is the unmodified refractive index, r is the Pockels coefficient and E is the applied electrical field. In reality, since it is a second order nonlinear effect and thus requires a breaking of centrosymmetric symmetry, Pockels materials are not isotropic, and the effect will be dependent on the material orientation,

the polarization of the light and the applied electrical field. In order to describe this mathematically we have to make use of tensor formalism. Looking at the impermeability tensor for LN $\bar{\eta}$ from equation 1.4, we can describe the change in refractive index according to

$$\eta_{ij} = \eta_{ij}^{(0)} + \sum_k r_{ijk} E_k \quad (2.4)$$

with r_{ijk} the pockels coefficient tensor. This tensor should be real and symmetric which allows one to simplify it from a 3x3x3 tensor r_{ijk} to a 6x3 tensor r_{hk} using a contracted notation as follows

$$h = \begin{cases} 1 & \text{for } ij = 11, \\ 2 & \text{for } ij = 22, \\ 3 & \text{for } ij = 33, \\ 4 & \text{for } ij = 23 \text{ or } 32, \\ 5 & \text{for } ij = 13 \text{ or } 31, \\ 6 & \text{for } ij = 12 \text{ or } 21. \end{cases} \quad (2.5)$$

In this formalism the change in permeability due to the pockels effect can be written as such

$$\begin{bmatrix} \Delta(\eta)_1 \\ \Delta(\eta)_2 \\ \Delta(\eta)_3 \\ \Delta(\eta)_4 \\ \Delta(\eta)_5 \\ \Delta(\eta)_6 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}. \quad (2.6)$$

For many crystals, the symmetry in the crystal structure causes most terms to be zero or equal to each other. In the case of LN which is a class 3m crystal, we end up with a matrix as follows

$$\begin{bmatrix} \Delta(\eta)_1 \\ \Delta(\eta)_2 \\ \Delta(\eta)_3 \\ \Delta(\eta)_4 \\ \Delta(\eta)_5 \\ \Delta(\eta)_6 \end{bmatrix} = \begin{bmatrix} 0 & r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{42} & 0 \\ r_{42} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}. \quad (2.7)$$

The coefficients for LN are summarised in table 2.1.

In LN modulators one mostly uses the r_{33} component since it is easiest to access and large. To visualise the effect of applying an electric field one can write out the new impermeability tensor in the form of an altered index ellipsoid:

$$\begin{aligned} \frac{x^2}{n_o^2} + \frac{y^2}{n_o^2} + \frac{z^2}{n_e^2} + r_{22}E_yx^2 + r_{22}E_yy^2 + r_{13}E_zx^2 + r_{13}E_zy^2 \\ + r_{33}E_zz^2 + 2r_{42}E_yyz + 2r_{42}E_xxz - 2r_{22}E_xxy = 1 \end{aligned} \quad (2.8)$$

	Electro-optic coefficient (pm V ⁻¹)
r_{13}	9.6
r_{22}	6.8
r_{33}	30.9
r_{42}	32.6

Table 2.1: Pockels coefficients of LN [113].

This is quite complex. As an example we can only apply an electric field along the z-axis. This results in:

$$\left(\frac{1}{n_o^2} + r_{13}E_z\right)(x^2 + y^2) + \left(\frac{1}{n_e^2} + r_{33}E_z\right)z^2 = 1 \quad (2.9)$$

This ellipsoid is still oriented the same as the original ellipsoid but the length of the axis' have changed. Just like all nonlinear effects, the pockels effect can usually be considered to be small, so we can use a Taylor expansion to write

$$\frac{1}{n_o^2(E_z)} = \frac{1}{n_o^2} + r_{13}E_z \Rightarrow n_o(E_z) \simeq n_o - \frac{1}{2}n_o^3r_{13}E_z \quad (2.10)$$

$$\frac{1}{n_e^2(E_z)} = \frac{1}{n_e^2} + r_{33}E_z \Rightarrow n_e(E_z) \simeq n_e - \frac{1}{2}n_e^3r_{33}E_z \quad (2.11)$$

Which looks very similar to the simplified equation 2.3. Before we move on to the more specific case of our integrated on-chip devices, this simple formula can be used to calculate the half-wave voltage-length product $V_\pi L$. If we assume the electric field is applied uniformly between two electrodes at a distance d the electric field can be written as $E_z = V/d$. Let's also assume the optical field has a polarisation parallel to the extraordinary z-axis to be able to exploit the stronger r_{33} component. A schematic view of this device is shown in figure 2.2. After propagating a distance L the wave has thus accumulated a phase change due to the electric field according to

$$\Delta\phi = \Delta n \frac{\omega L}{c} = \frac{\omega n_e^3 r_{33} V L}{2cd} \quad (2.12)$$

Or thus for the half-wave voltage-length product:

$$V_\pi L = \frac{2cd\pi}{\omega n_e^3 r_{33}} \quad (2.13)$$

Important in this equation, the $V_\pi L$ does not only reduce due to a larger pockels coefficient but also due to a larger refractive index and a higher optical frequency. Because of this, modulators in the visible are often much more efficient than

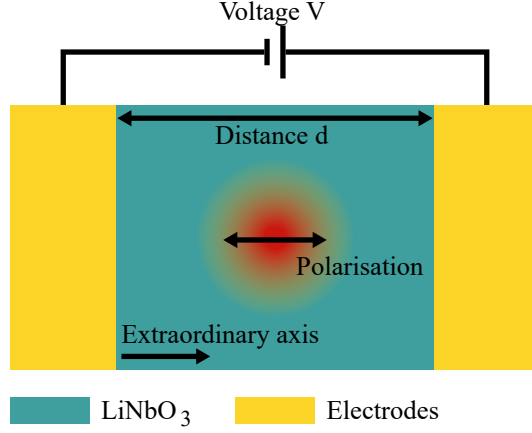


Figure 2.2: Schematic cross-section of an ideal bulk LN modulator.

modulators in the near infrared (NIR). It is also clear that reducing the distance between the electrodes increases the efficiency of the modulator.

When trying to apply this description to integrated waveguides we run into some nuanced differences. Mainly the light is no longer uniformly distributed in a single nonlinear material and also the electric field is no longer uniform. In order to model this accurately and predict the modulator efficiency a more precise description of the optical and electric fields is required. This is best done with a mode description. For this we move to the frequency domain and for the moment stick to a linear description according to the following formulas:

$$\nabla \times \mathbf{H}(\mathbf{r}, \omega) = j\omega\epsilon_0 n(\mathbf{r})^2 \mathbf{E}(\mathbf{r}, \omega) \quad (2.14)$$

$$\nabla \times \mathbf{E}(\mathbf{r}, \omega) = -j\omega\mu_0 \mathbf{H}(\mathbf{r}, \omega) \quad (2.15)$$

In which we have assumed a constant cross section such that the solutions can be written according to

$$\mathbf{E}(\mathbf{r}, \omega) = \mathbf{E}(x, y, \omega) e^{-j\beta(\omega)z} \quad (2.16)$$

$$\mathbf{H}(\mathbf{r}, \omega) = \mathbf{H}(x, y, \omega) e^{-j\beta(\omega)z}. \quad (2.17)$$

Where the dependence in the propagation direction z is reduced to a phase factor $e^{-j\beta(\omega)z}$. We call these solutions eigenmodes and each has their own characteristic propagation constant $\beta(\omega)$. Typically, the set of eigenmodes is orthogonal and

complete and can be split up in a discrete number of guided modes and a continuous spectrum of radiating modes. As a result any electric field distribution can be decomposed as a sum of these fields:

$$\tilde{\mathbf{E}}(\mathbf{r}, \omega) = \sum_{\mu} A_{\mu} \mathcal{E}_{\mu}(x, y, \omega) e^{-j\beta_{\mu}(\omega)z} + \sum_{\zeta} \int_{\beta} A_{\zeta, \beta} \mathcal{E}_{\zeta, \beta}(x, y, \omega) e^{-j\beta z} d\beta \quad (2.18)$$

For ideal waveguides the orthogonality implies that there is no coupling between the modes. Due to fabrication variation and roughness there can always be some coupling between modes, but with proper fabrication, sufficient tapering and careful waveguide bends this can often be kept to a minimum. It is then reasonable to assume that in most cases only a single mode will be meaningfully excited.

In order to describe a change in the refractive index due to the electro-optic Pockels effect we will consider an interaction between a microwave field $\mathbf{E}_{mw}$ and an optical field $\mathbf{E}_{opt}$. For more thorough explanations there are sources such as [114], but in general we can state the following

$$\Delta n_{\text{eff}} \approx \frac{c\varepsilon_0 \iint_{-\infty}^{+\infty} [n(\mathbf{r}) \Delta n(\mathbf{r}) \mathbf{E}_{opt}(x, y)] \cdot \mathbf{E}_{opt}^*(x, y) dx dy}{\iint_{-\infty}^{+\infty} \Re \{ \mathbf{E}_{opt}(x, y) \times \mathbf{H}_{opt}^*(x, y) \} \cdot \mathbf{e}_z dx dy} \quad (2.19)$$

where due to perturbation theory terms in $\Delta n(\mathbf{r})^2$ have been left out. In this formula we basically see an overlap integral of the optical electric field with the changed refractive index. and a poynting vector integral for normalization. In most integrated waveguide structures not all materials will have the same or even significant Pockels coefficients. Because of this we can limit the first integral over the material that has a significant Pockels coefficient [115].

$$\Delta n_{\text{eff}} \approx \frac{c\varepsilon_0 n_{\text{thin film}}^4 \iint_{\text{thin film}} \Delta n(x, y) |\mathbf{E}_{opt}(x, y)|^2 dx dy}{\iint_{-\infty}^{+\infty} \Re \{ \mathbf{E}_{opt}(x, y) \times \mathbf{H}_{opt}^*(x, y) \} \cdot \mathbf{e}_z dx dy} \quad (2.20)$$

We can then insert the change in refractive index similarly described in equation 2.11 to find

$$\Delta n_{\text{eff}} \approx - \frac{c\varepsilon_0 n_{\text{thin film}}^4 r_{33} V_0 \iint_{\text{thin film}} \frac{\mathbf{E}_{mw, x}(x, y)}{V_0} |\mathbf{E}_{opt, x}(x, y)|^2 dx dy}{2 \iint_{-\infty}^{+\infty} \Re \{ \mathbf{E}_{opt}(x, y) \times \mathbf{H}_{opt}^*(x, y) \} \cdot \mathbf{e}_z dx dy} \quad (2.21)$$

A normalisation voltage V_0 is added to the microwave field and serves the same purpose as the pointing vector integral in the denominator for the optical field. You will have noticed that the microwave electric field component in this equation is x while it was z in 2.11, this is due to the relative orientation of the crystal with reference to the waveguide direction. Most successful LN modulators use x -cut LN since it allows us to access the large r_{33} coefficient with TE polarized light and simple electrodes left and right of the waveguide in the same or approximately the same plane. An example geometry is shown in figure 2.3. Modulators using z -cut LN exist [58] but will not be discussed here.

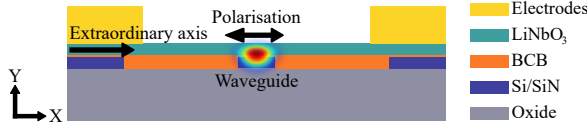


Figure 2.3: Schematic cross-section of an example waveguide based LN modulator. The mode profile calculated from COMSOL is shown in the waveguide.

Using this Δn_{eff} it is relatively easy to calculate the half-wave voltage-length product $V_\pi L$. We define the situation in which the phase change compared to the situation without an electric field is π radians:

$$\begin{aligned}
 k_0 \Delta n_{\text{eff}} L &= \pi \\
 k_0 \Delta n_{\text{eff},1V} V_\pi L &= \pi \\
 V_\pi L &= \frac{\pi}{k_0 \Delta n_{\text{eff},1V}} \\
 V_\pi L &= \frac{\lambda}{2 \Delta n_{\text{eff},1V}}
 \end{aligned} \tag{2.22}$$

where $k_0 = \frac{2\pi}{\lambda}$ is the wavevector of light.

Now that we know how to judge the efficiency, we can talk about what actually affects it. There are three main geometries that we studied, though many variations of each have existed. I will show them here quickly from a geometrical perspective such that we can discuss the various parameters in the future without any confusion. Most of the early work was performed on homemade chips starting from a blank SiN wafer purchased from Lionix. This 300 nm thick SiN provided the guiding layer while a slab of LN was placed on top to provide the Pockels material as shown in figure 2.4(a). The etching left air gaps in-between the waveguide and the SiN slab, these trenches were often filled with BCB before printing. Later work started focusing more on etched LN waveguides to confine the light, which could be placed

either on another waveguide as is the case in figure 2.4(b) which represents some of our work on the 800 nm SiN platform from Ligentec, or placed on oxide such as in figure 2.4(c). In these cases the presence of an oxide layer in-between the SiN and the LN or the LN and the electrodes can significantly affect the correct functioning of both passive components and the modulator. The widths and thicknesses of most layers and structures are important optimisation parameters while designing the device.

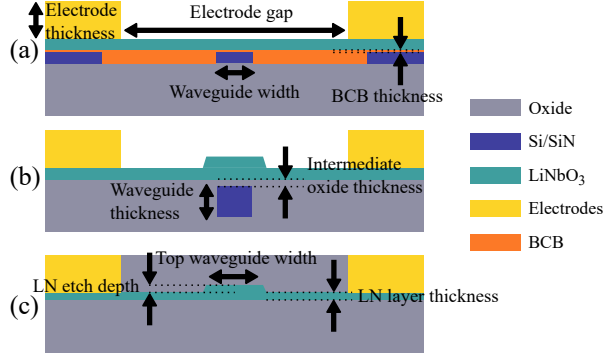


Figure 2.4: Schematic cross-sections of some common modulator waveguide geometries we worked with. (a) Full processing on a Lionix wafer. (b) Post-processing on a Ligentec wafer. (c) Post-processing on an ideal commercial wafer.

2.1.2 Numerical optimization and trade-offs between efficiency and loss

In order to calculate and optimize the efficiency of the electro-optic modulators we used a finite elements method (FEM) simulation in the commercial software COMSOL. By calculating the electric field over the waveguide between two electrodes and the optical mode in the waveguide we are able to accurately calculate the integral in equation 2.21 and plug it into equation 2.22 to estimate the half-wave voltage-length product $V_{\pi}L$. COMSOL for example makes this numerical integration easy as the two fields of widely different wavelengths are calculated on the same triangular grid in the FEM.

An example geometry can be seen in figure 2.5. Depending on the meshing, it can take COMSOL only 30 seconds to calculate an accurate field profile for both the electric and optical fields. Once the fields are calculated a simple integral can evaluate the resulting $V_{\pi}L$. This can be done in COMSOL itself. I used the MATLAB interface for COMSOL to not only do these final calculations but also to loop, evaluate and plot the results for the COMSOL simulations automatically. A

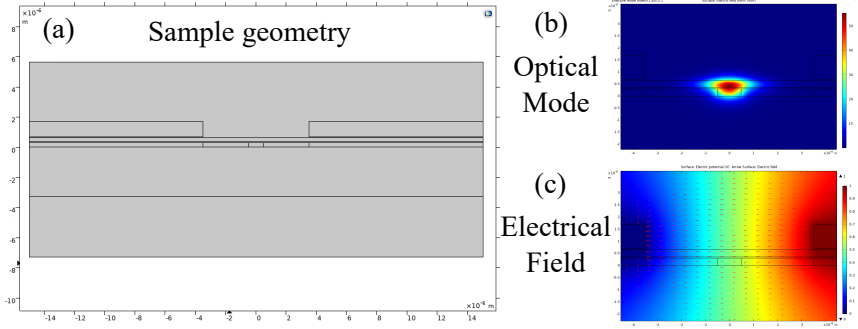


Figure 2.5: Screenshots from the COMSOL GUI. (a) An example Waveguide geometry. (b) The simulated optical mode. (c) The simulated electric potential with corresponding electric field lines.

simple example is shown in appendix A.1.

This model spits out three relevant values. The effective refractive index n_{eff} , the half-wave voltage-length product $V_{\pi}L$, and the optical loss α_{opt} . Researchers sometimes want to optimise for $V_{\pi}L\alpha_{\text{opt}}$ since this would generate the best modulator compared to optical losses. This however does not work well particularly if the fabrication losses (roughness, imperfections) aren't modeled in the simulation software, or if one wants to prioritise one figure of merit (FoM) compared to another. Since the only losses that are modeled in the simulation is the absorption in the electrodes, we have to take into account that other losses can be present.

The most important factor in the optimisation process can be considered a trade-off between modulator efficiency (low $V_{\pi}L$) and optical losses (low α_{opt}). Due to the structure of the overlap integral 2.21 it is clear that more overlap between the electric and optical fields will increase the modulator efficiency. However, since the electric field is confined by metallic electrodes this implies also more overlap with the electrode materials. These electrodes typically have very high losses in the optical domain, thus increased overlap induces an increase in the α_{opt} . This is a delicate balance since device requirements often heavily rely on these two critical figures of merit. One wants the device to be as efficient as possible while keeping the loss below a certain desired threshold which can be very limiting in the case of quantum applications. What makes this trade-off even more difficult is the difference in the way they scale. The efficiency scales mostly linear with the electrode gap (think of the $E_z = V/d$ in the simplified case) while the losses scale exponentially with the electrode gap due to the nature of the decaying evanescent tail of guided modes in waveguides. Adding on top the fabrication variation of widths and alignments, this quickly becomes the most critical part in both design

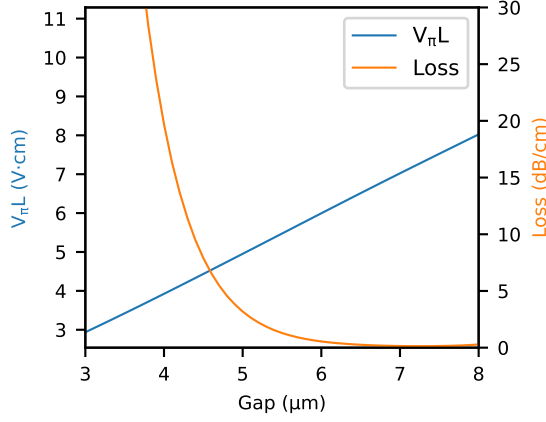


Figure 2.6: Plot of the influence of the electrode gap in figure 2.4(a) on the half-wave voltage-length product $V_{\pi}L$ and optical loss α_{opt} .

and fabrication. As an example, the plot in figure 2.6 shows the influence of the electrode gap on both the modulation efficiency $V_{\pi}L$ and the optical loss α_{opt} .

While these geometries contain plenty of parameters we are often limited by applications, fabrication or suppliers in selecting values for these parameters. These limitations can often severely limit optimisation choices in the design process, but these limits also facilitate a more simple design process that doesn't require the simulation and optimisation of every possible parameter. This is a good thing since for every parameter you need to consider for the optimisation the search space becomes exponentially larger.

The best example of this is the wavelength, while technically speaking you could design a modulator for every possible wavelength, the market and existing technology has converged to certain wavelengths that are frequently being used for other, more limiting, physical reasons than modulator efficiency. The lowest optical fiber loss and zero dispersion in optical fiber points at 1550 nm and 1310 nm respectively are often fixed requirements for telecom or datacom applications, while a wavelength in the visible where atom transitions, often used in quantum photonics, are situated (i.e. transition in Rb Atoms near 780 nm [116]) are also sometimes non negotiable. That being said, in general Pockels modulators often become more efficient at shorter wavelengths. It is clear from formula 2.22 that the $V_{\pi}L$ reduces as the wavelength decreases but it's even stronger than that. The change in refractive index also increases in multiple ways, further reducing the $V_{\pi}L$. This can be seen from equation 2.21. Firstly, in most materials the refractive index increases as the wavelength decreases (except in specific windows where ionic, electronic or

phononic resonances occur). This is amplified here by the fourth power of $n_{\text{thin film}}^4$ in equation 2.21. Furthermore, as the wavelength decreases the mode volume often also decreases, this increased confinement not only ensures that the overlap integral which scales nonlinearly with $|\mathbf{E}(x, y)|^2$ will drastically increase (if the integral scaled linearly with the optical field, the mode confinement would not significantly change the value of the integral due to the normalisation in the denominator) but also typically allows a designer to place the electrodes closer to the waveguide without inducing significant optical losses. Thus increasing the electric field strength $\mathbf{E}_{\text{mw},x}(x, y)$. All of these factors cause a quite drastic increase in efficiency as a function of reduced wavelength.

In our exploratory, proof of principle research, we often wanted to keep things simple for the sake of rapid experimentation and ease of fabrication. So often we settle on layer thicknesses early on due to other restraints from multi-project wafer (MPW) providers, chips/wafers available in our cleanroom, customer demands, and even fabrication restrictions. Because of this, most optimisations came down to determining the influence of widths on the modulation efficiency. In reality we focussed on the waveguide width and the width of the electrode gap. There are more widths to consider, such as the width of the electrodes, the width of the trenches next to waveguides, and more. But simulations, experiments and common sense intuition have confirmed that these barely influence the efficiency of the devices, past a certain practical width for guiding, contacting, etching, deposition,... So we will not look into them further.

The thickness of the electrodes is definitely an important parameter for the RF characteristics of the modulators. But in terms of the efficiency and the loss it barely matters. The design of the high-speed electrodes is a critical factor in good modulator design and can be the most difficult part. Therefore it is lucky that a parameter like the electrode thickness doesn't notably affect the other FoM's and can be optimised for high-speed functionality specifically.

The vertical placement of the electrodes is also not an obvious choice. Plenty of groups have placed electrodes deep inside the cladding [82, 87] or on top of a partial cladding [117]. While there are advantages and disadvantages for these positions and particularly their fabrication. We have currently stuck to placing the electrodes directly on top of the transfer printed LN. This purely from a fabrication perspective. For future prototypes where more intricate fabrication can be permitted, there is definitely merit to exploring placing them for example below the waveguide.

2.2 Efficient optical coupling: design and optimization of heterogeneous tapers

In the story of mTP, the coupling between the host material's waveguides and the transfer-printed structure is an essential part of the design. If one would suddenly introduce the source material in the target stack without any adjustment, like in figure 2.4a, a loss of approximately 1.7-2.0 dB can be expected per facet (in the case of LN for example). Adiabatic coupling often yields the best results but can take up a lot of space and requires thin structures. In the different prototypes, several tapers were designed since the internal structure or coupon layout changed. To design these tapers properly, numerical modeling in Lumerical has been used. Plenty of research exists on designing the mathematically best adiabatic taper, but when you are limited by the fabrication and alignment requirements of micro-transfer printed devices you want to keep it as simple as possible. The taper design has to fulfill two main criteria aside from the high transmission. It should be short and robust in order to allow the easy pick up and print without it breaking or bending. Furthermore, it should also continue to function within the 500 nm 3σ alignment accuracy of the transfer printing tool. The transmission of printed coupons depending on the alignment influences the performance of modulators beyond some additional losses. If both arms of the MZM have a different transmission, the interference at the MMI will not be perfect anymore resulting in a lower maximum transmission below 100% and higher minimum above 0%.

2.2.1 Mode coupling simulations, iterative design workflow and best practices

To simulate a proper taper in a feasible time limit, an eigenmode expansion (EME) solver works very well. Since adiabatic tapers vary only slowly along the propagation direction, but can end up being incredibly long, it makes sense to simulate propagating modes rather than the entire electromagnetic field. The structure is thus divided in a few (but sufficient) cross sections where the electromagnetic modes are calculated. By allowing those modes to propagate and then calculating the overlap with modes in the next cross section, the computation time is significantly reduced compared to a full three dimensional simulation. One can then sweep the length of each section to find a low-loss transition. This should be done a couple of times, since the results of one section may influence the others. After a few of iterations, a consistent and short design can typically be found. A more detailed explanation of an EME solver is available [118].

As an example, let's consider one of our mTP devices. We never measured this

design but it is a good pedagogical example. Typically the light will be coupled into the chip using the target's native guiding layers such as Si or SiN, to couple the light into the LN one then slowly introduces the LN material using a fine taper tip, and then tapers down the original guiding layer to the final desired width, which can include tapering it away fully. An example top view and side cross-section are shown in figure 2.7. Here the light was coupled into the 800 nm SiN layer through a grating coupler (GC) and needs to be transitioned into a LN rib waveguide with a total height of 600 nm and an etch depth of 300 nm. Afterwards the SiN waveguide is tapered down from an initial width of $3\text{ }\mu\text{m}$ to a 900 nm width.

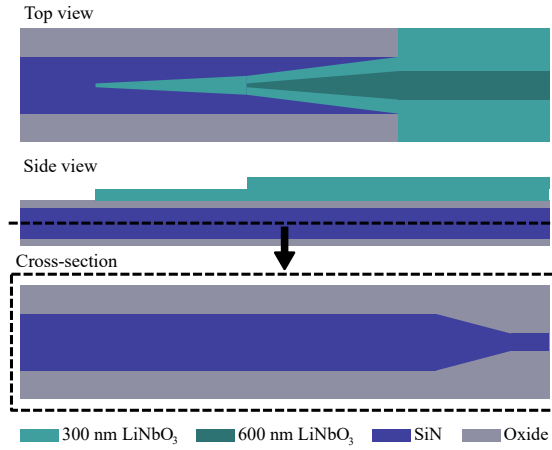


Figure 2.7: Schematic example of a taper structure. A top view, a side view and a cross-section to show all the different layers.

First I simulate the interfaces specifically, to figure out the starting and goal widths of all layers. Moreover, it allows you to calculate the best possible transmission your taper should have. Since, if tapered slowly enough, the only losses should come from the interfaces (and absorption). The narrow tips are often limited by the fabrication limitations and would like to be kept as thin as possible to reduce transition loss. The wide ends can be influenced by the desired final waveguide width, by the width at which the mode no longer interacts with the boundaries, or even by the required misalignment tolerance. In this example, we start the native SiN waveguide at $3\text{ }\mu\text{m}$. This is much wider than the single mode width of the 800 nm waveguide. But it allows for a more misalignment tolerant taper design. The mode is large and introducing the LN taper tip a little bit off center doesn't cause as much change in the transmission as with thinner waveguides. By simulating the three transition shown in figure 2.8 you can already determine the best possible loss your taper could get. This quickly gives you an idea whether it is

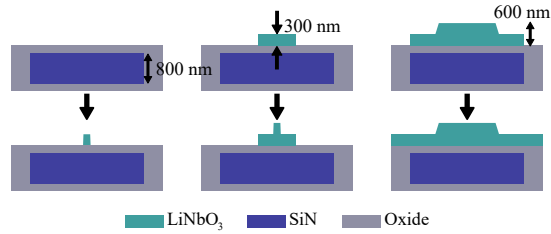


Figure 2.8: Schematic example of the taper facets. At each of these three facets, the light experiences an instantaneous change in the mode shape. This comes with unavoidable losses that limit the best transmission you can achieve.

worth designing the taper like this and which fabrication constraints are the limiting factors in your design.

One then needs to determine the actual design of the taper section in-between the facets. An initial design can easily be extracted from the EME simulation. With an example geometry in place, one can run the simulation and calculate the mode decomposition in the different cross sections of the taper. Once the modes are calculated it is easy to calculate the mode propagation in the system even while adjusting the length of the sections. A sweep of each section can then be performed to determine the minimal length required to eliminate mode coupling. It is however critical to find not only a length at which the transmission is high, but a length at which the oscillations in the transmission have stopped. An oscillating transmission as a function of section length is an indication of multimodal excitation and means you are not making an adiabatic coupler but rather a glorified MMI. Normally there should be a clear reduction in the oscillation strength as the section length is increased, indicating that less of the light is coupled to a higher order mode. An example of this is shown in figure 2.9. If this is not the case, even for absurd lengths ($> 200\lambda$) it is often an indication that the other modes were excited before the segment you are sweeping. Either at the interface or a previous section. Because of this it is important to have simulated the facet transitions first. If they predict a minimum loss of 3% then it will be impossible to have a taper that adiabatically couples more than 97% of the light. If your sweep indicates this anyway, it means there is an MMI-like section earlier in the propagation path. It is very good practice to go over each segment in your taper multiple times iteratively selecting the shortest adiabatic point in the sweep. After two or three iterations the sweeps should become consistent and either no longer have oscillations meaning everything is adiabatic. Or the oscillations will be constant indicating the multimodal behaviour is generated at facets rather than in taper sections.

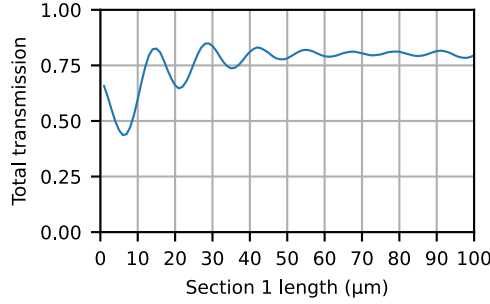


Figure 2.9: Plot of a typical length sweep in a EME simulation. From the reducing oscillations you can deduce that at lengths shorter than $40\text{ }\mu\text{m}$ the taper is too short and therefor exciting higher order modes. But since the oscillations don't disappear completely there is most likely another place where some higher order modes are excited, most likely a taper tip. Taken from [2].

Another great diagnostics tool is looking at the overall mode excitation in different cells along the propagation direction of the taper. This can show you where issues arise. Is a second mode suddenly getting excited in the cell after an interface? You need to adjust that interface if possible or live with this multimodal excitation. Is a second mode gradually being excited over multiple cells as show in figure 2.10? Tapering slower in that section will almost certainly fix this issue.

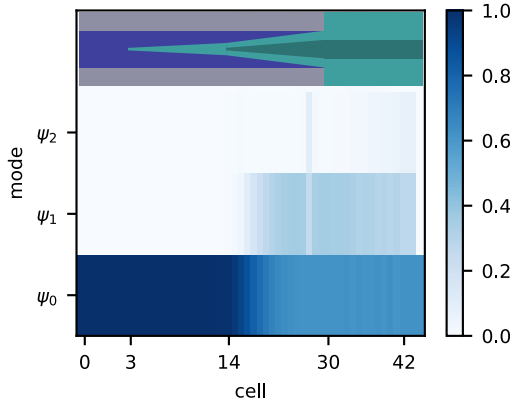


Figure 2.10: Plot of the excited modes in the different cells along the propagation of the taper. This taper is tapered too fast between cells 14 and 30 which is clear from the excitation of higher order modes. The legend for the inset schematic is the same as in figure 2.7

To further reduce the taper length, it typically helps to make an effective index map. This can help you map out which segments of each material should overlap

to create the shortest taper. But due to the alignment requirements of the micro transfer printing process we often kept the designs relatively simple, tapering only one material at a time. Even then, it is frequently possible to find a design that is limited mainly by taper tip losses with barely any losses in the adiabatic region.

Taking into account possible misalignment of transfer printed structures is also not trivial. Considering the ± 500 nm 3σ alignment accuracy boasted by most micro-transfer printing tools, all structures should be designed with this fabrication tolerance in mind. One can simply check if the structure you designed still functions sufficiently at some offset, but it is often efficient to optimize the structure at a small offset to begin with, and see if you can achieve high efficiency there. Be careful, with sufficient asymmetry due to offset, taper structures can sometimes start behaving like polarization rotators instead of simple tapers.

Using all these sweeping and diagnostics tools, allows you to determine which parts of tapers are the problematic parts, which parts can be tapered quickly and which should be lengthened to ensure adiabatic coupling. Using these techniques all tapers for this paper were designed.

2.2.2 Final taper designs and performance

The end results of the three prototype designs are shown below. The simulated losses and measured losses are in reasonable agreement. Fabrication of tapers (and certainly taper tips) is not straightforward. The offset strongly influences the results, and it is not trivial to measure with an optical microscope.

In the very first iteration of the modulator, no taper was implemented at all. The device used a 300 nm SiN platform from Lionix on a $3.3\text{ }\mu\text{m}$ oxide layer. In this device we simply printed a 300 nm rectangular coupon of LN on the waveguide using a thin BCB adhesive layer. This prototype was the first demonstration of the printing process and simply no effort was put into the coupling. Both simulations and measurements showed that this sudden transition from a 300 nm SiN ridge waveguide to a hybrid mode causes a loss of approximately 1.7-2.0 dB per facet. This hybrid mode is essentially a 600 nm rib waveguide with an etch depth of 300 nm, formed by placing the 300 nm LN slab on top of the SiN waveguide layer. This cross section is shown in 2.4(a).

The second prototype was built using the same layer stack. However, this time a taper was designed for the device. In order to transition from a mode confined in the 300 nm SiN waveguide layer to the hybrid mode shown in Fig. 2.11(a), adiabatic tapers on each side were added. The taper is shown in Fig. 2.11(b) and consist of two linear sections with a total length of only $45\text{ }\mu\text{m}$. Because the mode changes

fastest in the first section, it is designed to slowly taper linearly from a taper tip between 100-200 nm to 1 μm over 30 μm . After which the second section tapers much more quickly to 3 μm . This second section is only 15 μm long, at which point the entire slab can be introduced without generating reflections. In order to increase the transmission in case of misalignment, the SiN waveguide is also locally tapered to a 3 μm width at the transition sections. The simulated transmission as a function of misalignment for two different taper tip widths is shown in Fig. 2.11(c). The taper tip was fabricated wider than in the design and we ended up with a taper tip of 300 nm, as seen in the figure this doesn't significantly reduce the transmission if everything is perfectly aligned but makes the taper considerably less resilient to misalignment. Unless we are able to fabricate very narrow taper tips, simulations tell us that lengthening the taper does little to increase the transmission at larger misalignment since the reduced transmission is caused by the excitation of higher order modes and reflections at the facets. This taper would have less than 0.25 dB loss if perfectly aligned and fabricated. As will be discussed in more detail in the results, these showed a loss around 2.7 dB per coupon, mostly attributed to the wider taper tip and misalignment.

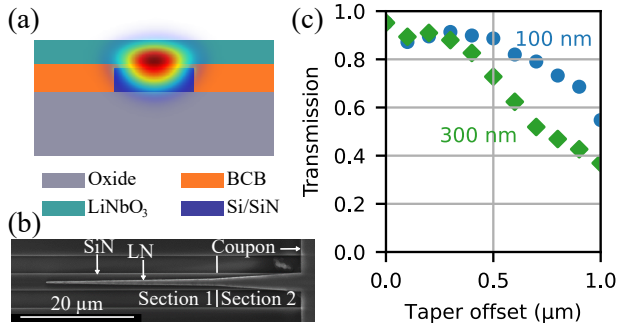


Figure 2.11: Taper design for the second prototype. (a) Schematic cross section of the wafer layer stack (b) SEM image of the fabricated and printed taper. (c) Simulation of the taper transmission efficiency as a function of printing offset for two different taper tip widths: the preferential 100 nm, and the realised 300 nm. Taken from [2].

The third prototype has a completely different layer stack. Let's first mention that for reasons discussed later in chapter 4, we made this device using lithium tantalate (LT) instead of LN. It uses an adjusted ISIPP200N stack from IMEC. The relevant parts of this layer stack for us are a 300 nm SiN layer on top of a 220 nm Si layer. The Si layer is used for most components while the SiN layer facilitates efficient edge coupling and can be used as a low loss waveguide layer. In this device we print the LT coupon on top of these two layers using a thin 20 nm layer of BCB and use both passive layers to facilitate a smooth transition to the LT hybrid

waveguide without the need for a taper in the coupon structure. Due to the high refractive index of Si and the relative distance between the buried Si waveguide and the LT coupon printed on top, the coupon doesn't need a taper. Suddenly introducing the LT layer on top of the 500 nm oxide cladding doesn't influence the mode profile at all. The intermediate layer of 300 nm SiN (150 nm above the Si and 70 nm below the LT layer) is then used to couple the light into the LN layer and facilitate the same hybrid waveguide structure as in the previous prototype.

Figure 2.12 shows a 3D schematic of the taper structure and where the light is positioned in the different parts of the adiabatic taper. This taper was designed to simply couple to a layer of 300 nm LT in the hybrid waveguide mode. This taper first introduces the LT layer on top of the 380 nm wide Si waveguide. Shortly after the SiN layer is introduced and tapers from 150 nm to 900 nm width rather quickly over 5 μm . Over the course of the next 200 μm the Si layer is slowly tapered away until it suddenly disappears after the 150 nm wide taper tip is reached. Since the design was made for a hybrid waveguide design without a rib waveguide in the LT, the SiN waveguide never disappears.

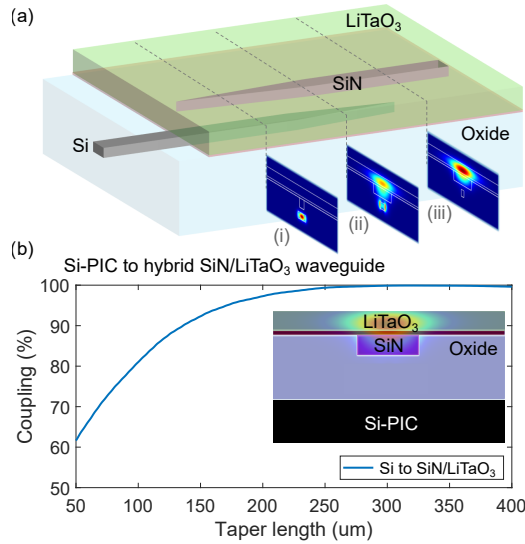


Figure 2.12: Transition from the Si waveguide to the hybrid modulator. (a) Schematic of the tri-layer adiabatic transition: mode profiles in the regions of interest are added. (b) Expected transmission from a fully etched Si waveguide to a hybrid SiN/LiTaO₃ phase modulator; (inset) and cross-section of the passive stack of an MZM arm. Taken from [3].

In later designs, the SiN also completely tapers to a tip and disappears to couple completely into a LN layer for more efficient modulation. The measurement of

these devices falls outside of the scope of this thesis. This tri-layer structure results in an alignment indifferent structure, since all the etched waveguide structures are fabricated in the highly precise ISIPP200N platform. And even in the subsequent cases where a LN rib waveguide is introduced, the taper was relatively robust due to this more complex taper design compared to the ± 500 nm 3σ alignment accuracy of the micro-transfer printing tools.

While no single “perfect” taper design exists, this methodology provided a practical balance between rigor and efficiency. With the coupling problem under control, the remainder of this chapter focuses on modulation schemes and RF design.

2.3 From phase modulation to advanced IQ architectures

The Pockels effect causes a phase change in your light. This has plenty of applications such as gyroscopes, time lenses, Optical Coherence Tomography (OCT), and more. We will even discuss its use in more complex modulation schemes later in this very section but, in practice, people often want to convert this phase modulation into intensity modulation. This is because detectors fundamentally detect optical intensity, and measuring the phase requires additional processing steps. Using an MZI one can easily convert the phase modulation of the Pockels modulator into intensity modulation which is when we generally call it an MZM. While there are plenty of implementations of MZMs they typically split the light in two different paths, called arms, adding a phase change to those arms and then recombining the light into one output. The interference between the light of both arms causes a change in intensity that depends on the phase difference between both arms. We now describe this down mathematically to better understand their functionality, starting with the ideal case and progressively adding more detail. We can describe the symmetrical, lossless splitter (often an MMI, y-splitter, or directional coupler) using the following matrix

$$\begin{bmatrix} E_{\text{out},1} \\ E_{\text{out},2} \end{bmatrix} = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} E_{\text{in}} \quad (2.23)$$

If we do nothing except recombining the light we get the following expression:

$$\frac{E_{\text{out}}}{E_{\text{in}}} = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} = 1 \quad (2.24)$$

We can add the phase modulators to both arms, which will allow for a phase and thus voltage dependent output.

$$\frac{E_{\text{out}}}{E_{\text{in}}} = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} e^{-j\phi_1} & 0 \\ 0 & e^{-j\phi_2} \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} = \frac{1}{2} (e^{-j\phi_1} + e^{-j\phi_2}) \quad (2.25)$$

This can then be converted to an intensity pattern that will be measurable:

$$\frac{I_{\text{out}}}{I_{\text{in}}} = \left| \frac{E_{\text{out}}}{E_{\text{in}}} \right|^2 = \cos^2 \left(\frac{\phi_1 - \phi_2}{2} \right) \quad (2.26)$$

This is the simplest modulator formula that explains an MZM, it clearly demonstrates the cosine square relation between the phase difference of the light in both arms and the measured intensity. I glossed over the fact that it is often efficient in terms of area, energy and performance to modulate both arms instead of just one. From this expression it is clear that if the phase change introduced in both arms is identical, no actual intensity modulation will be observed. Rather, it is conventional and easiest to modulate both arms equally but opposite. When you slow down light in one arm, you speed up the light in the other arm. This type of device is rightfully called a push-pull modulator. This seems obvious but is also a not so trivial requirement specifically in LN Pockels modulators. More on this in the next section concerning RF design.

While the intensity is purely a function of the phase difference, the electric field itself carries an additional term that can be easily overlooked. By factoring out the average phase, we can rewrite the field expression as:

$$\frac{E_{\text{out}}}{E_{\text{in}}} = e^{-j\frac{\phi_1 + \phi_2}{2}} \cos \left(\frac{\phi_1 - \phi_2}{2} \right) \quad (2.27)$$

The exponential term represents a global phase shift applied to the entire pulse as it is modulated. In optical communications, the time-derivative of this phase is known as chirp. If the modulator is not operated in a perfectly balanced push-pull manner ($\phi_1 = -\phi_2$), the center frequency of the optical carrier will shift during the transition between bits. This parasitic frequency modulation causes the pulse to broaden or compress as it propagates through dispersive fiber, limiting the reachable transmission distance or bandwidth [119]. A common metric to quantify this is the chirp parameter α , defined as:

$$\alpha = \frac{\phi_1 + \phi_2}{\phi_1 - \phi_2} \quad (2.28)$$

In an ideal push-pull configuration, where the phase changes are equal and opposite, the sum $\phi_1 + \phi_2$ becomes zero. Consequently, the chirp parameter $\alpha = 0$, resulting in a "chirp-free" signal. This is one of the primary reasons why achieving a symmetric push-pull drive is so critical in high-speed LN modulators, and why differential drive modulators are non-trivial to achieve as discussed later in section 2.4.2.

It is valuable to replace the phase change by an expression in terms of the applied voltage relative to the half-wave voltage $\phi_1 = \pi \frac{V_1}{V_\pi}$ and $\phi_2 = \pi \frac{V_2}{V_\pi}$.

$$\begin{aligned} \frac{I_{\text{out}}}{I_{\text{in}}} &= \left| \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} e^{-j\pi \frac{V_1}{V_\pi}} & 0 \\ 0 & e^{-j\pi \frac{V_2}{V_\pi}} \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} \right|^2 \\ &= \cos^2 \left(\frac{\pi}{2V_\pi} (V_1 - V_2) \right) \end{aligned} \quad (2.29)$$

Presuming the structure is nicely symmetrical we can replace the voltages $V_1 = +\frac{V}{2}$ and $V_2 = -\frac{V}{2}$, where it is assumed that the voltage is oscillating around ground. This might seem weird to engineers used to different modulators but LN Pockels modulators don't need a DC-bias, even if they did, as explained in the introduction, the DC-drift effect would nullify any DC-bias applied to the modulator.

$$\begin{aligned} \frac{I_{\text{out}}}{I_{\text{in}}} &= \left| \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} e^{-j\pi \frac{V}{2V_\pi}} & 0 \\ 0 & e^{j\pi \frac{V}{2V_\pi}} \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} \right|^2 \\ &= \cos^2 \left(\frac{\pi V}{2V_\pi} \right) \end{aligned} \quad (2.30)$$

Now, in practice this comes with some issues. No matter how perfect your fabrication, with modulators of this size there will always be a small random phase difference between both arms due to slight differences in arm length, waveguide width,... Because of this, any fabricated device will be at a somewhat random point in the cosine square period. This is not ideal, since for linearity reasons it is best to operate a modulator around its quadrature point as shown in figure 2.13. At this point in the cosine square pattern the intensity change is as linear as possible as a function of the voltage change. Typically, one would correct this by applying a DC-bias to move the modulator to the nearest quadrature point (using some proportional-integral-derivative (PID) controller the DC-drift effect can somewhat be avoided). Alternatively a heater can be added to achieve the same goal. All of these make experiments significantly more complex which is why we often opted for a different strategy.

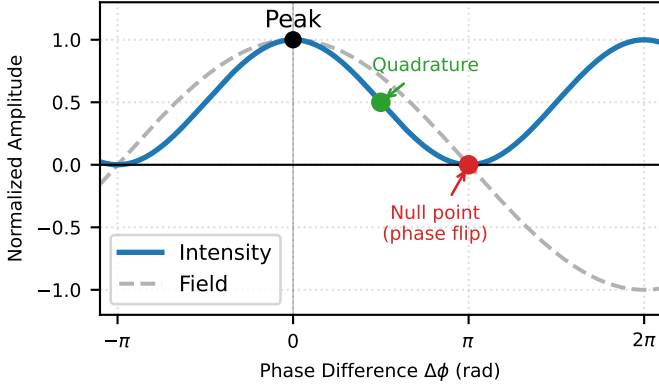


Figure 2.13: Transmission characteristics of a MZM as a function of the phase difference. The quadrature point represents the region of maximum linearity for intensity modulation (OOK). The Null point is the bias condition for coherent modulation; the optical intensity is suppressed while the field amplitude (dashed line) crosses zero, enabling 180° phase-shifting via small voltage swings around the null.

By intentionally introducing a significant path length difference between both modulator arms, we can control the bias point by adjusting the wavelength of the laser within a couple of nanometer window, something the lasers in our lab (Santec TSL-510) can do very easily and precisely. The phase introduced by this path length difference is $\phi = \beta(\lambda)\Delta L = \frac{2\pi n_{\text{eff}}}{\lambda} \Delta L$, considering the typical wavelengths and effective refractive indices in LN waveguides, this formula quickly indicates a path length difference of around 100 μm will cause the quadrature point around 1550 nm to be within less than 10 nm of the centre wavelength. We can introduce this into the equation as follows:

$$\begin{aligned} \frac{I_{\text{out}}}{I_{\text{in}}} &= \left| \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & e^{+j\pi \frac{V}{2V_{\pi}}} \end{bmatrix} \begin{bmatrix} e^{-j(\pi \frac{V}{2V_{\pi}} + \beta(\lambda)\Delta L)} & 0 \\ 0 & e^{+j\pi \frac{V}{2V_{\pi}}} \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} \right|^2 \\ &= \cos^2 \left(\frac{\pi V}{2V_{\pi}} + \frac{\beta(\lambda)\Delta L}{2} \right) \end{aligned} \quad (2.31)$$

The additional wavelength-dependent phase term makes the experiments significantly simpler without diminishing the result quality.

Another factor that comes into play is loss. Both arms will have a certain amount of loss that is ideally kept to a minimum but does still influence the device in interesting ways, due to the interference nature of the device. We can add the loss in both arms using factors a_1 and a_2 . The expression becomes the following:

$$\begin{aligned}
\frac{I_{\text{out}}}{I_{\text{in}}} &= \left| \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & \sqrt{a_2} e^{+j\pi \frac{V}{2V_\pi}} \end{bmatrix} \begin{bmatrix} \sqrt{a_1} e^{-j(\pi \frac{V}{2V_\pi} + \beta(\lambda)\Delta L)} & 0 \\ 0 & \sqrt{a_2} e^{+j\pi \frac{V}{2V_\pi}} \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} \right|^2 \\
&= \frac{1}{4} \left[a_1 + a_2 + 2\sqrt{a_1 a_2} \cos\left(\pi \frac{V}{V_\pi} + \beta(\lambda)\Delta L\right) \right]
\end{aligned} \tag{2.32}$$

This result indicates some interesting behaviour. We can calculate the following general results. The maximum transmission, in the case of constructive interference becomes:

$$T_{\text{max}} = \frac{1}{4} (a_1 + a_2 + 2\sqrt{a_1 a_2}) = \frac{1}{4} (\sqrt{a_1} + \sqrt{a_2})^2 \tag{2.33}$$

The minimum transmission in case of destructive interference becomes:

$$T_{\text{min}} = \frac{1}{4} (a_1 + a_2 - 2\sqrt{a_1 a_2}) = \frac{1}{4} (\sqrt{a_1} - \sqrt{a_2})^2 \tag{2.34}$$

which results in an ER of:

$$\text{ER} = \frac{T_{\text{max}}}{T_{\text{min}}} = \frac{(\sqrt{a_1} + \sqrt{a_2})^2}{(\sqrt{a_1} - \sqrt{a_2})^2} = \left(\frac{\sqrt{a_1} + \sqrt{a_2}}{\sqrt{a_1} - \sqrt{a_2}} \right)^2 \tag{2.35}$$

It is first good to see that if the loss is nicely balanced ($a_1 = a_2$) the minimum transmission remains zero and the extinction ratio can be infinite. However, when there is even a small imbalance in the loss of both arms ($a_2 = a_1(1 - \varepsilon)$) the ER quickly diminishes in a quadratic manner ($\text{ER} \approx \frac{16}{\varepsilon^2}$). This shows the importance of reproducible fabrication in devices like this. In the appendix A.2 I quickly elaborate on the case of imbalanced optical splitters, but since this was not used during the thesis it is therefore not mentioned here.

In the next section we will discuss more advanced modulation formats that do more than "turning the light on and off" in order to transmit more data quickly.

2.3.1 Advanced modulation formats and dual-polarization operation.

Modulators for applications in telecom and datacom try to transmit as much information as possible as quickly as possible. In the next section we will go into the details around the quick part, but we can first discuss the information part. In our mostly digital infrastructure information is stored as bits. And the obvious

way of transmitting bits using a modulator is to turn the light on if you want to transmit a 1 and turn it off if you want to transmit a 0. However, people have implemented a myriad of other strategies to transmit more information per symbol, usually multiple bits, at the same time. We call these strategies modulation formats. I will not explain all modulation formats, and all possible ways you could encode data on light using a modulator but for the purposes of understanding the results of this thesis I will quickly introduce some of the most interesting formats for our research.

The idea of these more complex formats is to have more than 2 possible measurement results per symbol which are then assigned 2 or more bits of data. PAM4 stands for 4-level Pulse Amplitude Modulation and simply adds intermediate power levels in-between completely on or off. This allows one to then encode 2 bits per power level. With 3 bits there are now 8 possible combinations, it is therefore not very far fetched to make a PAM8 modulation format as well, dividing the available ER into 8. These modulation formats work by only modulating the intensity of light and can be implemented using a simple MZM as discussed previously and only require a normal photodetector at the receiver side. They are called intensity modulation/direct detection (IMDD). However, in order for the information to be transmitted without errors the different power levels need to be clearly distinguishable. Because of this, only low noise signals with high ER modulators are able to transmit PAM8 encoded data without introducing a large amount of errors. Figure 2.14 shows a schematic representation of 5 different modulation formats. Including the simple on-off keying (OOK) also sometimes called PAM2, PAM4 and PAM8.

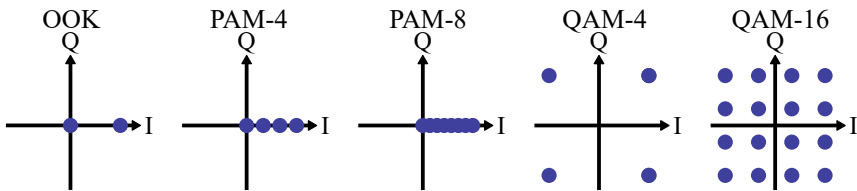


Figure 2.14: Schematic representation of some example modulation formats (a) OOK, (b) PAM4, (c) PAM8, (d) QAM4, (e) QAM16.

From the way the graphs in figure 2.14 are made it is clear that there is another degree of freedom in phase space that hasn't been used yet. By moving beyond pure intensity modulation, it becomes possible to exploit the optical phase as an additional degree of freedom. Phase modulation is orthogonal to amplitude modulation and allows information to be encoded without changing the average optical power. This naturally leads to coherent modulation formats also known as

in-phase/quadrature (IQ) modulation formats, which combine phase and amplitude control to increase the information density per symbol. Pockels modulators are great candidates for these coherent modulator devices since they fundamentally are phase modulators. Common examples of this are called quadrature phase-shift keying (QPSK) also called QAM-4 or for example QAM-16 shown in figure 2.14d and e.

In order to achieve coherent modulation, one can still use MZMs but you will need to combine two of them in a circuit as shown in figure 2.15. The optical input is first split into two branches before modulating each with independent MZMs. Then one branch is given a 90° optical phase shift. The modulated fields in both branches are therefore orthogonal to each other in phase space and can be combined again without loss of information.

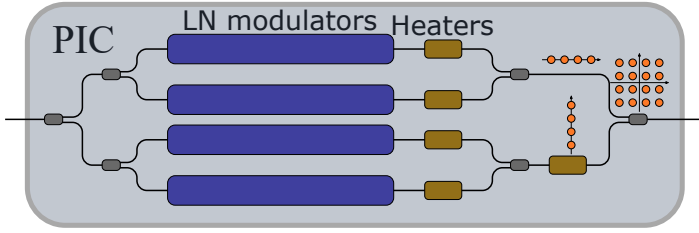


Figure 2.15: Schematic representation of an integrated IQ modulator chip

We can write the signal $S_{IQ}(t)$ after the IQ modulator as follows:

$$S_{IQ}(t) = I(t) \cos \omega_c t - Q(t) \sin \omega_c t, \quad (2.36)$$

where ω_c is the carrier optical frequency, and $I(t)$ and $Q(t)$ are the individual in-phase and quadrature symbol streams, respectively.

Using phasor notation this can be written as,

$$\tilde{S}_{IQ}(t) = I(t) + jQ(t), \quad (2.37)$$

In the case of QAM-4 these signals are each binary values $I, Q \in \{-\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\}$ resulting in four different possible results in phase space:

$$\tilde{S}_{IQ}(t) = \pm \frac{1}{\sqrt{2}} \pm j \frac{1}{\sqrt{2}}, \quad (2.38)$$

These values are chosen this way such that they are normalised and at maximum transmission $|\tilde{S}_{IQ}(t)|^2 = 1$. In case of more elaborate IQ modulation schemes

amplitude modulation is again added in. For QAM16 for example, the individual modulated symbol streams $I(t)$ and $Q(t)$ are individual PAM4 signals resulting in 16 possible normalized constellation points. Each individual component choosing independently from $I, Q \in \{-\frac{1}{\sqrt{2}}, -\frac{1}{3\sqrt{2}}, \frac{1}{3\sqrt{2}}, \frac{1}{\sqrt{2}}\}$.

In order to achieve this type of modulation efficiently, one should bias the separate MZMs at the minimum transmission point (null point is shown in figure 2.13) rather than the quadrature point and one requires double the swing since completely changing the field between full transmission with opposite phases requires $2V_\pi$, in contrast to the simple intensity modulator. That being said, due to the sinusoidal nature of MZMs you already achieve over 70% of the modulation depth with just once V_π [120].

This does now also encounter another issue at the receiver side. Since the information of the signal is encoded in the complex field, we cannot simply detect the signal using a photodetector which is phase agnostic. A coherent receiver is used to retrieve both the phase and amplitude information of the field from the optical signal. The signal is combined in four distinct channels with a local oscillator at the carrier frequency of the signal using an optical hybrid. This optical hybrid is just a 2x4 or even 4x4 MMI that causes a 90° phase shift between the output of the different arms.

If we write the input fields of the signal and the local oscillator as follows:

$$\begin{aligned}\tilde{E}_S(t) &= \sqrt{P_S} \tilde{S}_{IQ}(t), \\ \tilde{E}_{LO} &= \sqrt{P_{LO}} e^{j\phi_{LO}},\end{aligned}\tag{2.39}$$

Then the four different outputs of the optical hybrid will have the form:

$$\begin{aligned}\tilde{E}_1 &= \frac{1}{2}(\tilde{E}_S + \tilde{E}_{LO}) \\ \tilde{E}_2 &= \frac{1}{2}(\tilde{E}_S + j\tilde{E}_{LO}) \\ \tilde{E}_3 &= \frac{1}{2}(\tilde{E}_S - \tilde{E}_{LO}) \\ \tilde{E}_4 &= \frac{1}{2}(\tilde{E}_S - j\tilde{E}_{LO})\end{aligned}\tag{2.40}$$

When these are detected by a photodiode with responsivity $\mathcal{R}$, we get:

$$\begin{aligned}
 i_1 &= \frac{1}{4} \mathcal{R} (P_S |\tilde{S}_{IQ}(t)|^2 + P_{LO} + 2\sqrt{P_S P_{LO}} \Re(\tilde{S}_{IQ}(t) e^{-j\phi_{LO}})) \\
 i_2 &= \frac{1}{4} \mathcal{R} (P_S |\tilde{S}_{IQ}(t)|^2 + P_{LO} + 2\sqrt{P_S P_{LO}} \Im(\tilde{S}_{IQ}(t) e^{-j\phi_{LO}})) \\
 i_3 &= \frac{1}{4} \mathcal{R} (P_S |\tilde{S}_{IQ}(t)|^2 + P_{LO} - 2\sqrt{P_S P_{LO}} \Re(\tilde{S}_{IQ}(t) e^{-j\phi_{LO}})) \\
 i_4 &= \frac{1}{4} \mathcal{R} (P_S |\tilde{S}_{IQ}(t)|^2 + P_{LO} - 2\sqrt{P_S P_{LO}} \Im(\tilde{S}_{IQ}(t) e^{-j\phi_{LO}}))
 \end{aligned} \tag{2.41}$$

These all contain large factors that are proportional to the detected power of the signal and local oscillator. This is where a coherent detector utilizes balanced photodiodes to subtract the quadratic terms that don't contain any phase information. By placing photodetectors 1-and-3 and 2-and-4 in a balanced photodiode configurations such that the photocurrents are subtracted, we obtain the following two results.

$$\begin{aligned}
 i_I &= i_1 - i_3 \\
 &= \mathcal{R} \sqrt{P_S P_{LO}} \Re(\tilde{S}_{IQ}(t) e^{-j\phi_{LO}}) \\
 &= \mathcal{R} \sqrt{P_S P_{LO}} (I(t) \cos \phi_{LO} + Q(t) \sin \phi_{LO}) \\
 i_Q &= i_2 - i_4 \\
 &= \mathcal{R} \sqrt{P_S P_{LO}} \Im(\tilde{S}_{IQ}(t) e^{-j\phi_{LO}}) \\
 &= \mathcal{R} \sqrt{P_S P_{LO}} (Q(t) \cos \phi_{LO} - I(t) \sin \phi_{LO})
 \end{aligned} \tag{2.42}$$

This linear combination of $I(t)$ and $Q(t)$ might look familiar, it is a rotation around the origin of the intended constellation diagram relative to the phase difference between the signal laser and the local oscillator.

$$\begin{bmatrix} i_I \\ i_Q \end{bmatrix} = \mathcal{R} \sqrt{P_S P_{LO}} \begin{bmatrix} \cos \phi_{LO} & \sin \phi_{LO} \\ -\sin \phi_{LO} & \cos \phi_{LO} \end{bmatrix} \begin{bmatrix} I(t) \\ Q(t) \end{bmatrix}. \tag{2.43}$$

This means that the coherent receiver with balanced photodiodes recovers the IQ signal up to a global rotation. It is the role of digital signal processing (DSP) to estimate the ϕ_{LO} numerically in order to retrieve the original constellation diagram. This can be done through calibration and training but will have to continue to track changes due to noise and phase drift. However, there is also the factor $\sqrt{P_S P_{LO}}$ in the balanced photodiode formula 2.42. Due to the current scaling with the power of the local oscillator, it basically means the signal is boosted by a local oscillator gain. Moreover, the large DC currents in the photodetectors are cancelled due to the balanced configuration, this further increases the sensitivity of the detector

and transimpedance amplifier (TIA) structure. This is a fundamental advantage of coherent receivers compared to IMDD, which enables longer range transmission and detection of weaker signals.

However, this comes at a cost in terms of system requirements. These systems require narrow linewidth lasers for both the signal and local oscillator, precise optical hybrids and good balanced photodiodes. Additionally, the electronics for high-speed analog-to-digital conversion and DSP are also very demanding. The power consumption in coherent systems is therefore higher than in IMDD systems.

There is one more degree of freedom that is easily accessible to increase the data rate: polarization. When moving towards dual-polarization operation, the complexity doubles again. Two IQ modulators are used, one for each polarization. The total achievable data rate scales accordingly, which is why such structures are intended for high-end telecom transceivers and coherent optical systems. An example structure is shown in figure 2.16.

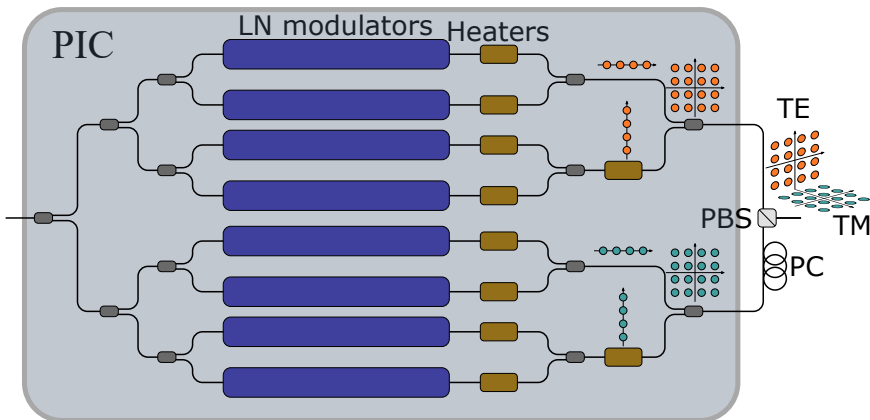


Figure 2.16: Schematic representation of a dual-polarisation IQ modulator

2.4 High-speed RF design for travelling-wave modulators

For high-speed modulation, it's not enough to have a good optical design, the RF side matters just as much. The optical part is usually well-behaved and easy to simulate. Good RF design takes into account the impedance, to avoid reflections, and velocity matching, to maximize modulation efficiency, as well as the electrical losses and modal behaviour. These can sometimes interact in non-intuitive ways.

The simulations for this part of the thesis was done mostly by Arno Moerman, IDLab EM, Ghent University - imec, with input from Sam Lemey and Olivier Caytan from the same group, and me. While the underlying electromagnetic expertise resides with these collaborators, the following discussion provides a synthesis of the critical design principles and insights gained throughout this interdisciplinary optimization process.

A travelling wave modulator refers to modulators that are so fast and so long that one can not really consider the electrodes to be what is often called a lumped element. In lumped element modulators one can consider the entire electrode to be at the same voltage at all times. Instead, in a travelling wave modulator, a voltage will be applied at a certain place (where the probe or wirebonds are attached) and will propagate along the length of the electrodes like a wave, in a similar manner to an optical waveguide. Since the optical signal does the same thing in the dielectric waveguide, these two waves should be moving in the same direction and the relative velocity at which they do so matters for the efficiency of the device. Before we dive into the simulations, it is first important to understand how impedance matching, velocity matching and RF losses together determine the performance of a travelling wave modulator. A quick top down example of a travelling wave modulator with high-speed electrodes is shown in figure 2.17. Some good more complete sources are available [51, 121]

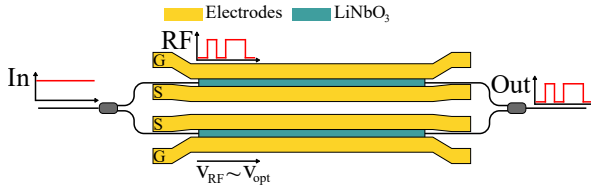


Figure 2.17: Schematic of a travelling wave modulator using a ground-signal-signal-ground electrode configuration.

2.4.1 The three pillars: impedance, velocity, and loss

In order to get efficient high-speed travelling wave modulation there are three main parameters that have to be optimized: characteristic impedance, velocity matching, and RF attenuation. The conceptually simplest is the characteristic impedance. The impedance mismatch between the driver or load impedance and the characteristic impedance of the transmission line determines how much power effectively enters your modulator and how much power is reflected at the end of the modulator. The voltage reflection coefficient for a wave moving from one structure to the next is written as:

$$\Gamma_{12} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (2.44)$$

In the ideal matched situation $Z_2 = Z_1$ the electrical signal is entirely entering the modulator and nothing is reflected at the load impedance. Typical impedances for drivers and other high-speed electronics are 50 Ω , 75 Ω , or 100 Ω . As an example, if the driver has a 50 Ω impedance but your transmission line only has 40 Ω characteristic impedance you immediately lose $\pm 11\%$ of the voltage amplitude you try to apply which is reflected back into the driver. Similarly, the load impedance can cause reflection of the signal wave, interfering with the intended wave pattern. The characteristic impedance of the transmission line is also frequency dependent. This can cause issues at higher or lower frequencies but it can also be used intentionally to flatten the response over a larger frequency range since as we show below, RF losses typically increase at higher frequencies which can be partially offset using for example inductive peaking.

Next, we discuss the travelling wave aspect of the modulator. As a good rule of thumb a modulator should be considered travelling wave once it is longer than 1/10th of the RF wavelength [121] (in the transmission line, so take the effective refractive index into account). Shorter electrodes can often be described using lumped elements; longer electrodes should be designed with travelling waves in mind, as a distributed effect. In this case, we have two separate waves co-propagating in the same direction along two parallel waveguides: a dielectric waveguide for the optical wave and a metallic waveguide (transmission line) consisting of multiple electrodes for the electrical wave. The electrical wave is adjusting the optical refractive index of the dielectric waveguide temporarily. If the light is travelling at the same velocity and constantly ‘feels’ the intended refractive index change the modulator is working perfectly as a low-speed lumped elements modulator would. If the optical wave is however propagating at a different velocity relative to the electrical wave, it will either outrun or fall behind the electrical wave and might ‘feel’ the refractive index change intended for the previous or next bit in the sequence (or a transition in-between). An illustration of this runoff effect can be seen figure 2.18, including how the later part of the modulator is undoing some of the earlier phase change.

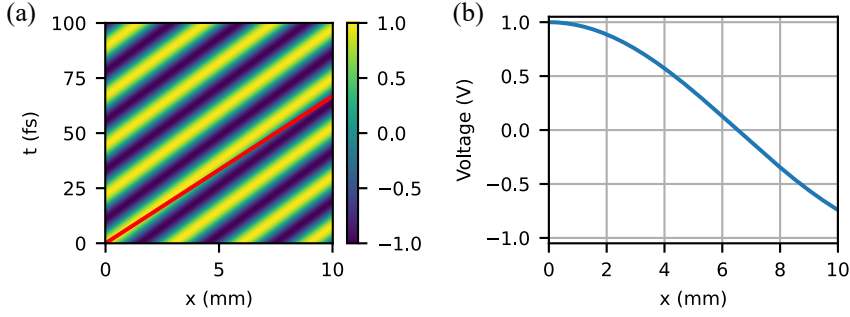


Figure 2.18: Illustration of the effect velocity matching has on the modulator in a lossless case with significant velocity mismatch. (a) The color illustrates the voltage at each time and location in the modulator, the red line is the propagation line of the optical wave. (b) The voltage experienced by the optical wave as it propagates along the modulator, the later part of the modulator is not only inefficient, it is undoing some of the phase accumulated in the first half.

This will thus reduce the modulation efficiency of the modulator compared to DC switching. To obtain good travelling wave modulation, the phase velocity of the transmission line determined by n_{RF} should be matched as closely as possible to the group velocity of the optical wave determined by n_g [121, 122]. Most literature compares the RF phase velocity to the optical group velocity, but there are other sources that extend this definition to use the group velocity of the RF wave [79]. The effect of the velocity mismatch on the modulator efficiency can be encapsulated in the following formula (no losses or reflections are considered here, [122]):

$$S_{21}^{EOE}(\omega_{RF}) \propto e^{-j\frac{\omega_{RF}}{c}n_g l} \frac{1}{l} \int_0^l e^{j\frac{\omega_{RF}}{c}(n_g - n_{RF})z} dz, \quad (2.45)$$

where $S_{21}^{EOE}(\omega_{RF})$ is the electro-optical transfer function of the modulator at angular modulation frequency ω_{RF} , c is the speed of light in vacuum, and l is the length of the modulator. This can be solved to find that the modulator efficiency scales as a sinc function

$$S_{21}^{EOE}(\omega_{RF}) \propto \frac{1}{2} e^{-j\frac{\omega_{RF}}{c}(n_g + n_{RF})\frac{l}{2}} \text{sinc}\left(\frac{\omega_{RF}}{c}(n_g - n_{RF})\frac{l}{2}\right), \quad (2.46)$$

It's clear that the longer the device, the higher the frequency or the higher the velocity mismatch, the worse the device will function. The 3-dB bandwidth is given by

$$f_{3dB} = \frac{1.39c}{\pi l |n_g - n_{RF}|}. \quad (2.47)$$

The third important parameter is the RF losses. If there are high electrical losses on the transmission line then the later parts of the modulator will induce a significantly smaller index change than the earlier parts. We can add the RF power attenuation α_{RF} to the formula 2.45 above to find:

$$S_{21}^{EOE}(\omega_{RF}) \propto e^{-j\frac{\omega_{RF}}{c}n_g l} \frac{1}{l} \int_0^l e^{j\frac{\omega_{RF}}{c}(n_g - n_{RF})z - \frac{\alpha_{RF}}{2}z} dz, \quad (2.48)$$

It is important to note that n_{RF} , and α_{RF} are both frequency dependent. While this equation can be worked out into a closed form, the integral representation illustrates the distributed nature of the RF attenuation along the electrodes. As a result, the stronger the RF attenuation and the longer the device, the more the high-frequency response is suppressed. A small counterintuitive point here is that the overall performance of the modulator tends to be higher than what you'd expect from simply adding the effects of loss and velocity mismatch. This can be explained by considering that the regions of the device where the RF amplitude is already attenuated contribute less to the mismatch problem, partially mitigating the combined penalty of loss and velocity mismatch. This mitigating effect and an example behaviour for the velocity mismatch and the RF loss are shown in figure 2.19. Together, velocity mismatch and RF loss define the electro-optic bandwidth, which fundamentally limits how fast and long a high-speed modulator can be.

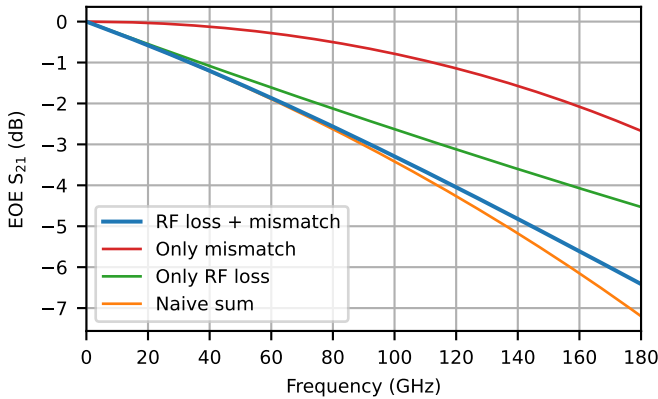


Figure 2.19: Illustration of the impact of some arbitrary RF loss and velocity mismatch on the bandwidth of a travelling wave modulator. The naive sum illustrates what would happen if you don't integrate the mismatch and RF loss together.

Substrate resistivity and performance implications

An extremely important factor in the performance for the electrodes at higher frequencies is the substrate resistivity. In metal electrodes the resistivity typically scales as a square root function of the frequency $\propto \sqrt{\omega_{\text{RF}}}$ if resistive heating is the main cause for loss. This is simply explained by the current density being forced into a thinner and thinner edge around the metal due to the skin effect [123]. In short, high-speed currents are forced out of the center of the conductor due to eddy currents, only the outer skin carries the current in a layer with a $1/e$ depth δ of:

$$\delta \approx \sqrt{\frac{2\rho}{\omega\mu}} \quad (2.49)$$

where ρ is the resistivity of the metal, ω is the angular frequency of the signal, μ is the permeability of the metal. Which results in the effective conductor area scaling (A_{eff}) as a layer around the outside and the resistance scaling as

$$R \propto \frac{1}{A_{\text{eff}}} \propto \frac{1}{\delta} \propto \sqrt{f}. \quad (2.50)$$

During our first high-speed measurements, however, we noticed that the loss did not behave this way. It seemed to contain a major contribution from dielectric losses. The figures below show the behaviour of the RF losses for different resistivities.

To determine the origin of these losses we fabricated four different samples to compare the effect of the metal stack and the substrate on the losses. The figures 2.20a-d compare loss measurements of the four test samples with the loss measurement of the working device from our second demonstration (further explained in chapter 4.2). Each of the test results is plotted in red with the gray background showing the reference device. The calibration of the measurement involving the test devices is different from the calibration of the reference device and much noisier than the reference device, therefore results at higher frequencies are somewhat inaccurate. Figure 2.20a and b show the results of a similar layer stack as the reference device, which includes a silicon substrate, $3.3 \mu\text{m}$ of buried oxide and a 300 nm SiN layer. The device length in 2.20a is the same as the reference device (2.0 mm) while the device in 2.20b is 9.0 mm long. These devices did not have the LN slab or the etched SiN waveguide but this shouldn't influence the results a lot. Corrected for the device length all three devices behave similar with a rapid increase in the loss below 10 GHz after which the loss almost plateaus. Figures 2.20c and d show results from the same electrode design fabricated on a glass substrate rather than a SiN chip. They show a remarkably different behaviour, which looks significantly closer to a $\propto \sqrt{\omega_{\text{RF}}}$ function. The difference between the two samples is the thickness of the titanium (Ti) adhesive layer used in the fabrication of the $1.0 \mu\text{m}$ thick gold electrodes. The device in figure 2.20c has the conventional 15 nm Ti, while the device in 2.20d had only a flash deposition

of 1-2 nm of Ti. The difference between figure 2.20c and 2.20d is small and probably not very meaningful with this measurement accuracy, the loss does seem slightly better at high frequencies in the device with less Ti. These plots point to the loss being influenced by one of the materials in the chip layer stack, not just the metals. Since the silicon substrate is not a high-resistivity substrate we think that the increased losses (in figure 2.20 a and b) are ohmic losses in the substrate.

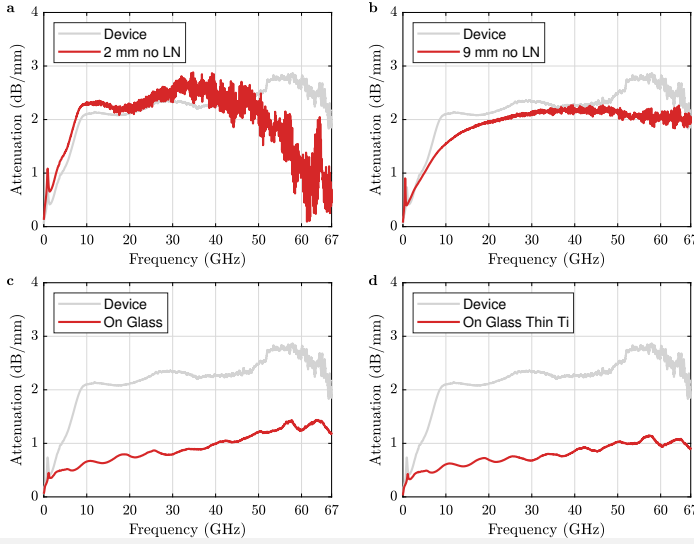


Figure 2.20: Comparison measurements of RF losses in different structures using 1.0 μm thick gold electrodes, in red: (a) a 2 mm electrode on the same SiN layer stack but without patterned waveguides or printed LN, (b) a 9 mm electrode on the same SiN layer stack but without patterned waveguides or printed LN, (c) a 9 mm electrode on a glass substrate, (d) a 9 mm electrode on a glass substrate, but with a thinner layer of titanium in the metal stack. The grey lines in all figures are the RF losses from the device in the main manuscript. Taken from [2].

For further validation we implemented the layer stack into CST Studio Suite® and set the resistivity of the substrate to $5 \Omega\text{cm}$. This value is based on an estimate we got from the provider of the commercial SiN wafers (Lionix). CST allows us to determine from which material the losses originate. The simulation results plotted in figure 2.21 show that the measured losses qualitatively agree very well with the simulated loss, and to some extent also quantitatively. Furthermore, the breakdown of the losses clearly indicate that they are mainly originating from the dielectric layers and the silicon specifically (CST places any non metal in the dielectrics). The metallic losses are significantly lower and scale according to the expected square root of the frequency. It is clear from these simulations and measurements that a high-resistivity substrate is

critical for a high-speed modulator.

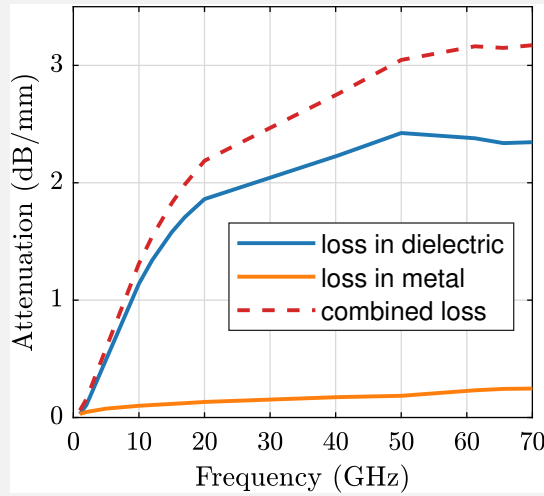


Figure 2.21: Simulation results obtained through CST microwave studio. RF loss breakdown for an approximate layer stack used in our device. Taken from [2].

2.4.2 Electrode topologies: single-ended and differential electrodes

While the previous sections treated impedance, velocity matching, and RF attenuation as separate design constraints, in practice they are all strongly influenced by the electrode topology. The transmission line geometry determines the field distribution, achievable impedance, effective RF index, and RF losses. More than that, it determines the compatibility with drivers [124]. Two configurations are most commonly used: single-ended and differential transmission lines.

In a single-ended design, the RF signal is applied between the middle electrode and the other two electrodes, an example geometry is shown in figure 2.22a. These designs often use three electrodes, it is therefore often referred to as a GSG electrode indicating the ground-signal-ground nature of the electrodes. This configuration offers a relatively simple layout and straightforward impedance control, often targeting the $50\ \Omega$ used by many high-speed drivers and measurement instruments.

Differential designs instead drive two electrodes with equal amplitude and opposite polarity. Here there are two commonly used designs. GSSG and GSGSG electrode configurations using either four or five actual electrodes as shown in figure 2.22b

and c. These are commonly designed for $100\ \Omega$ impedance operation to match differential drivers. GSGSG configurations are more standard in tools since the middle ground electrode simplifies design and usage by isolating the two signal electrodes from each other. Allowing the structure to be used as two single-ended devices in case that is required at the cost of extra footprint due to the fifth contact pad required.

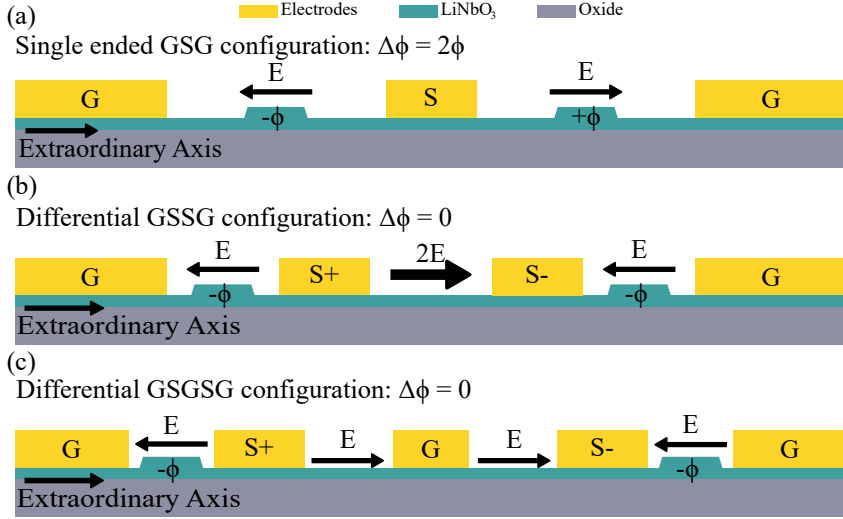


Figure 2.22: Schematic representation of different RF electrode configurations. (a) Single ended GSG electrodes, (b) Differential GSSG electrodes, (c) Differential GSGSG electrodes. The electric field direction, extraordinary axis and phase change is noted in each structure. Here, E denotes the characteristic electric field magnitude within the modulation slots. For schematic clarity, the field vector between the differential signal electrodes is represented as $2E$ to reflect the doubled potential difference ($V_{S+} - V_{S-} = 2V$), noting that the exact local field strength scales with the relative electrode spacing.

Push-pull realization in lithium niobate

It is important to acknowledge the different advantages and disadvantages these configurations offer Pockels based LN modulators compared to the historically more mature silicon based carrier-depletion modulators. In general, push-pull operation halves the voltage required for operation. Instead of using the full V_{pi} on a single arm one can now use half of V_{pi} on both arms. Even in differential drive configuration, this reduces the power consumption since power scales with the square of the voltage, having half the voltage twice is better than having the full voltage once. Moreover, the supply voltage required is halved as well.

Historically this has led to the choice of differential drive for silicon modulators.

Silicon based carrier depletion modulators require a reverse bias in both arms to operate in push-pull configuration. This cannot be done using GSG electrodes and therefore uses differential drive electrodes with separate bias voltages on both signal electrodes to obtain push-pull operation, where the choice leads to multiple advantages. Aside from the voltage advantages for the modulators themselves, the choice for differential drive modulation also brings some vital advantages for the driver. Differential drivers have improved linearity thanks to the cancellation of even order harmonics [124]. Moreover, these differential drivers also have improved tolerance to electromagnetic interference (EMI) or power supply noise. Differential drivers are also a more natural design choice since parasitics and currents flowing to the ground plane can be avoided due to the anti-symmetrical nature of the driver. When one arm requires current the other arm can provide it, there is no need to draw it all from the supply nets [125]. Reduced parasitics can improve the high-speed characteristics and bandwidth of these differential drivers. These benefits must be weighed against the increased design complexity, increased power usage and the multimodal challenges discussed below.

Due to the field mode between the electrodes and the lack of a need for a bias, it is natural to obtain push-pull configuration with a uniform LN orientation in single-ended GSG electrodes. This is not possible in differential drive LN modulators. Since these are based on the field in-between the electrodes, one has to break the symmetry of the modulator in some way to achieve push-pull operation using differential drive modulators. This can be done by placing the optical waveguides in different slots of the electrode configuration as shown in figure 2.23. Driving an asymmetrical modulator has the problem of changing the eigenmodes away from the useful "common mode/differential mode" eigenmodes to a new set of eigenmodes that show a mix of both characteristics, this typically causes some chirp in-between the two arms of the modulator, which has to be taken into account to achieve extremely high-speed operation. One might want to use the higher voltage naturally formed in the middle of the signal electrodes in a GSSG design as shown in figure 2.22a, but that causes even worse chirp.

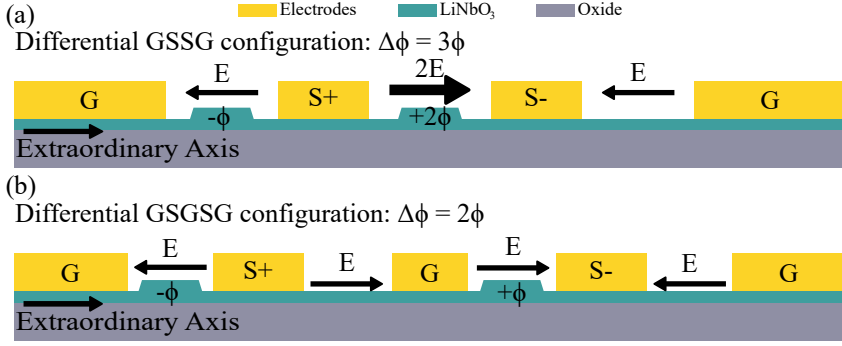


Figure 2.23: Schematic representation of different asymmetrical RF electrode configurations for LN push-pull operation. (a) Differential GSSG electrodes with a waveguide in-between the signal electrodes, (b) Differential GSGSG electrodes with asymmetrical waveguide placement. The electric field direction, extraordinary axis and phase change is noted in each structure. Here, E denotes the characteristic electric field magnitude within the modulation slots. For schematic clarity, the field vector between the differential signal electrodes is represented as $2E$ to reflect the doubled potential difference ($V_{S+} - V_{S-} = 2V$), noting that the exact local field strength scales with the relative electrode spacing.

The least invasive way of solving the asymmetry is by reversing the orientation of the LN crystal in the two active arms. This is the method we used in our high-speed devices. This doesn't noticeably change the symmetry of the electrical field while still enabling push-pull operation in a single differentially driven device. In our case, the mTP technique allows us to simply rotate half of the coupons by 180° to accomplish the reorientation of the extraordinary axis as shown in figure 2.24. This is a unique advantage of the mTP technique allowing simple fabrication of differentially driven LN modulators.

This can also be done by poling one of the waveguides, poling a structure with a waveguide completely is however not trivial. Poling of rib waveguide structures often doesn't pole the waveguide itself, and only poles the slab underneath [92]. This would allow the differential device to function, but depending on the completeness of the poling it will have a reduced efficiency. Significant research effort has been dedicated to the realization of poling across the entire device structure, including the waveguide regions [126]. Poling before etching the waveguide is however possible [127] but rare. Other, way more complex methods of enabling differential drive modulators have also been attempted using delay lines for example [76], though these methods are not actually differential according to the conventional definition.

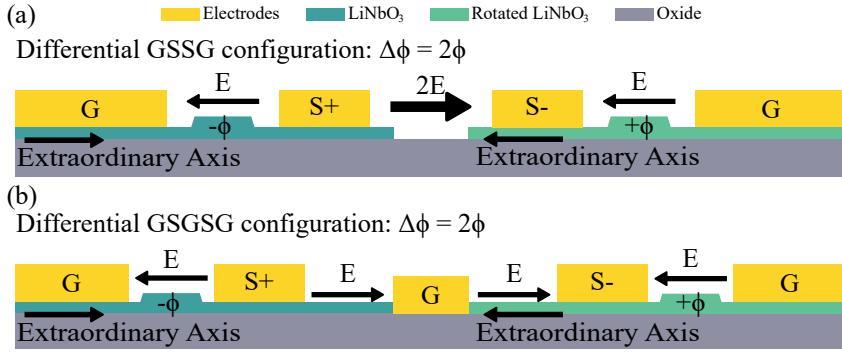


Figure 2.24: Schematic representation of different RF electrode configurations for LN push-pull operation. (a) Differential GSSG electrodes with rotated LN coupon, (b) Differential GSGSG electrodes with rotated LN coupon. The electric field direction, extraordinary axis and phase change is noted in each structure.

Modal behaviour

The choice of topology introduces significant differences in quasi-TEM modal behaviour. Differential electrode configurations are by default multimodal. In general any coplanar waveguide (CPW) electrode configuration has a number of modes equal to the number of separate electrodes minus one, in the ideal case all grounds are one electrode. This for example means that a GSG configuration ideally has only a single mode $2 - 1 = 1$, and a GSSG or GSGSG configuration has $3 - 1 = 2$ modes.

The single mode in the single-ended design is ideal, and the mode is exactly the mode we want to use. The differential configurations have a common mode one typically doesn't want to use, and a differential mode which is the one we want to use. Since the modes are orthogonal, in a straight waveguide structure they should not be able to mix simply during propagation. The clue is 'simply' to excite the correct modes using the driver; land the probes correctly, make sure the differential signal from the driver or arbitrary waveform generator (AWG) arrives perfectly in sync.

However, in practice the ground electrodes are separate metal lines that are typically only connected at the start and end of the transmission lines. Because of this, a single-ended electrode has $3 - 1 = 2$ modes, and the differential lines have either $4 - 1 = 3$ modes in a GSSG configuration and $5 - 1 = 4$ modes in a GSGSG configuration. This can for example cause an additional differential mode to appear in the eigenmode solution. Correctly exciting the ideal mode in differential transmission lines is difficult. One will typically excite some linear combination of the differential eigenmodes that exist in the structure. These different modes

have different mode profiles, and propagation constants (real and imaginary). Thus influencing the electro-optic efficiency, RF losses and drifting away from each other during propagation along the several wavelength long transmission line. This causes fringes to be measured in both the electrical frequency response and the electro-optical frequency response. Due to each mode having a different characteristic impedance it is virtually impossible to terminate each mode correctly at the end of the transmission line causing some of the modes to reflect back at the load impedance.

A solution to this problem is to intermediately connect the ground electrodes using a thin metal wire [121, 128–131]. By connecting the ground electrodes frequently (compared to the wavelength of the highest frequency component in the signal), one can ensure that the ground electrodes remain at the same voltage along the entire travelling wave electrode and reduce the number of eigenmodes that exist in the single-ended and differential electrode configuration back to the easy to use and ideal 1 and 2 modes respectively.

Designing these electrodes is again a balancing act. GSG electrode designs typically require a thin signal electrode ($<10\text{ }\mu\text{m}$) to ensure the characteristic impedance is close to $50\text{ }\Omega$, which drives up the current density in the thin metal line, increasing the loss. In differential electrodes one can match the characteristic impedance ($100\text{ }\Omega$) a bit easier while still keeping the signal electrodes relatively wide. Signal electrodes in excess of $25\text{ }\mu\text{m}$ are possible allowing for lower current densities and lower RF losses. The oxide thickness below and above the electrodes significantly influences the velocity of the electrical wave. In a lot of our air clad devices the RF wave was often a bit too fast for the optical wave. By adding cladding you indeed first slow down both waves but after the cladding is thicker than what the optical wave can see, adding more cladding only slows down the RF wave allowing you to match the velocities again. It is important to mention capacitively loaded electrodes. These are more complex electrodes with significantly more design parameters as shown in figure 2.25 [69]. While more complex, they do allow for better control of the three important parameters separately. We did not look into them for this thesis [70].

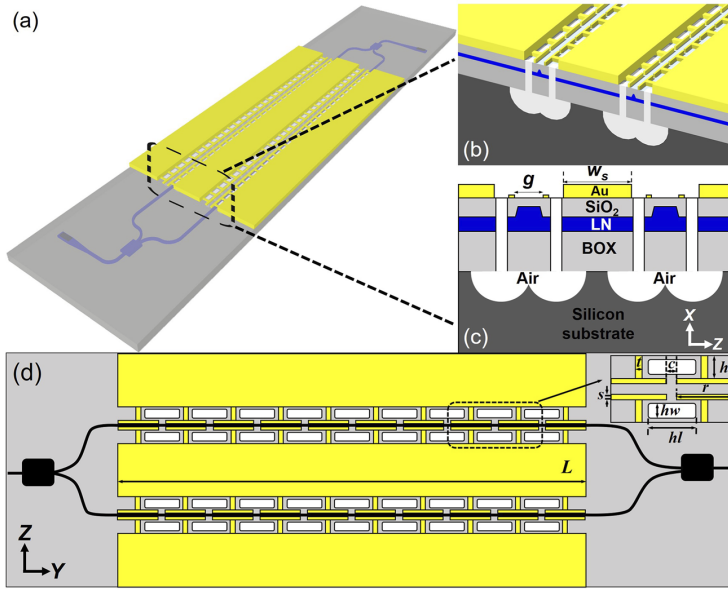


Figure 2.25: Schematic representation of capacitively loaded travelling wave electrodes (CL-TWE) with undercut etching of the silicon substrate [69].

Ultimately, for LN modulators compared to carrier diffusion based silicon modulators, the advantages of differential signaling are mostly driver-related rather than electro-optical. There is a clear industrial consensus favoring differential driving configurations for high-speed optical interconnects, which mTP is uniquely able to answer. If one was free from historical context and existing technology, able to design a complete system from scratch, I think the trade-off between single-ended and differential drive would be mostly dependent on the driver characteristics, the footprint, and the power consumption rather than actual modulator characteristics.

2.4.3 Practical constraints: probing and measurements

A final consideration that is not very fundamental, but still matters in practice, is the measurement equipment needed for these devices. Single-ended configurations can be measured using a single high-speed input and output while differential devices typically need up to two input and output ports depending on the type of measurement that is required. This is currently not trivial and equipment often becomes very expensive for four port testing. To go beyond 70 GHz one typically uses range extenders which are only single-ended currently. State-of-the-art VNAs now do offer four port configurations exceeding 70 GHz. A single-ended setup

could be used for differential measurements by using a balanced-unbalanced (balun), but these are also difficult to find and expensive at these high-speeds. In theory, a differential device can also be characterised electrically by measuring the arms independently including the cross talk terms and then using single-ended to mixed mode S-parameter conversion equations mentioned below but this does not work for electrical-optical-electrical measurements since phase information and cross talk cannot be retrieved from this measurement. And even then, in practice this can never be accurate with just single-ended equipment due to calibration issues and cable movement.

Table 2.2: Single-ended to mixed-mode S-parameter conversion equations, S_{ij} represent single port S-parameters, 1 and 3 are the input ports, 2 and 4 are the respective output ports, S_{ABij} represent differential port S-parameters, 1 is the input port, 2 is the output port, C and D stand for Common and Differential modes respectively [132]

Single-ended to Mixed-mode S-parameter Conversion Equations			
Differential–Differential		Common–Differential	
$S_{DD11} = \frac{1}{2}(S_{11} - S_{13} - S_{31} + S_{33})$		$S_{DC11} = \frac{1}{2}(S_{11} + S_{13} - S_{31} - S_{33})$	
$S_{DD21} = \frac{1}{2}(S_{21} - S_{23} - S_{41} + S_{43})$		$S_{DC21} = \frac{1}{2}(S_{21} + S_{23} - S_{41} - S_{43})$	
$S_{DD12} = \frac{1}{2}(S_{12} - S_{14} - S_{32} + S_{34})$		$S_{DC12} = \frac{1}{2}(S_{12} + S_{14} - S_{32} - S_{34})$	
$S_{DD22} = \frac{1}{2}(S_{22} - S_{24} - S_{42} + S_{44})$		$S_{DC22} = \frac{1}{2}(S_{22} + S_{24} - S_{42} - S_{44})$	
Differential–Common		Common–Common	
$S_{CD11} = \frac{1}{2}(S_{11} - S_{13} + S_{31} - S_{33})$		$S_{CC11} = \frac{1}{2}(S_{11} + S_{13} + S_{31} + S_{33})$	
$S_{CD21} = \frac{1}{2}(S_{21} - S_{23} + S_{41} - S_{43})$		$S_{CC21} = \frac{1}{2}(S_{21} + S_{23} + S_{41} + S_{43})$	
$S_{CD12} = \frac{1}{2}(S_{12} - S_{14} + S_{32} - S_{34})$		$S_{CC12} = \frac{1}{2}(S_{12} + S_{14} + S_{32} + S_{34})$	
$S_{CD22} = \frac{1}{2}(S_{22} - S_{24} + S_{42} - S_{44})$		$S_{CC22} = \frac{1}{2}(S_{22} + S_{24} + S_{42} + S_{44})$	

Ultimately, the choice between single-ended and differential electrodes represents a trade-off between simplicity and modulation efficiency, and should be made in the context of the targeted bandwidth, drive electronics, and integration platform.

2.4.4 Simulation workflow and results

CST Microwave Studio® was the obvious choice for modeling this. In the optical simulations we often simulated a single arm of the modulator since that is the only relevant part. However, in the electrical simulations obviously the entire modulator and sometimes even neighbouring modulators should be modelled. One can then do simulations in different ways, modal analysis is a helpful way of understanding the electromagnetic properties, and modelling the full modulator in 3D voltage can predict the electrical velocity, the characteristic impedance and the RF loss of the

electrodes at each frequency. Some strict external boundaries were the electrode gap for electrodes which surround an optical waveguide. This was always decided beforehand from electro-optical simulations in COMSOL[®] based on efficiency and optical losses. And due to the availability of some preexisting 125 μm pitch GSSG configuration drivers from our colleagues of IDLab Design, Ghent University - imec, we also designed the MZM for compatibility with these devices.

Our first device had no RF design whatsoever and we only measured it at DC voltages. The second device was fabricated on the Lionix platform, which includes a 3.3 μm thick buried oxide layer underneath the 300 nm layer of SiN. And the devices were air cladded. From modulation efficiency simulations in COMSOL[®] the electrode gap was fixed at 6 μm . We prioritised impedance matching the differential mode to the 100 Ω impedance of the driver and minimize RF losses, while keeping the velocity matching close up to 100 GHz. The impedance matching is achieved by changing the electrode width and height, while the velocity matching is ensured by optimizing the buried oxide thickness. The resulting design was ground and signal electrodes of each 35 μm wide, 1 μm thick and a pitch of 200 μm between both arms. The electrodes are then fitted with a short fan-out taper to the contact pads with a pitch of 125 μm . It is important to point out that this 1 μm thickness of the electrodes is fixed by the upper limit of our lift-off fabrication process, otherwise a thicker electrode would probably have been chosen.

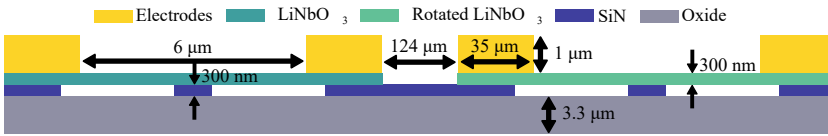


Figure 2.26: Schematic representation of the RF electrode parameters in the second device iteration.

The third device was fabricated using LT on a dedicated run of imec with a layer stack close to the ISIPP200N platform. And again the design was made to function with a pre-existing GSSG differential driver with a contact pad pitch of 125 μm . From electro-optic simulation we settled on a 6 μm gap between the signal and ground electrodes for efficient modulation while keeping a safe distance that even with some offset in the lift-off process the optical losses wouldn't be too high. From RF simulation we then settled on signal widths of 33 μm and 60 μm ground electrodes. A pitch of 137 μm between the two MZM arms was chosen for printing purposes. In this design we used a high-resistivity silicon substrate as discussed in section 2.4.1.

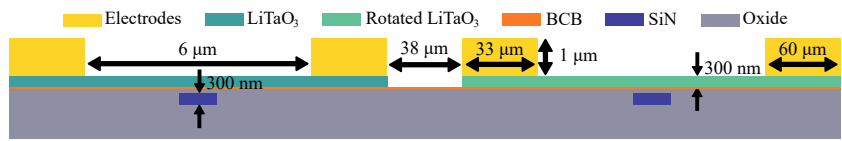


Figure 2.27: Schematic representation of the RF electrode parameters in the third device iteration.

3

Micro-transfer printing of lithium niobate

3.1	Fabrication of silicon nitride target photonic integrated circuits	78
3.1.1	Grating coupler and multimode interferometer design	78
3.1.2	E-beam lithography and dry etching processes	78
3.2	First-generation integration: crystalline tethers	79
3.3	Second-generation integration: pillar-supported membranes	81
3.4	Third-generation integration: scalable photoresist-encapsulated process	84

The integration of thin-film LN onto silicon-based photonic circuits presents significant mechanical challenges, due to the thin membrane and the need for precise alignment. This chapter details the evolution of the fabrication and integration workflow developed to overcome these hurdles. To provide the necessary context for this development, we first discuss the design and in-house fabrication of the SiN target chips used for the first two prototypes. The integration process then matured through three distinct iterations: starting with a manual, LN-tether-based approach, moving to a pillar-supported method to enhance structural stability, and finally transitioning to an automated, photoresist-tethered process compatible with commercial pilot-line wafers. By documenting these iterations, this chapter highlights

the transition from laboratory-scale proof-of-concepts to a high-yield, scalable integration strategy suitable for high-speed electro-optic modulation.

3.1 Fabrication of silicon nitride target photonic integrated circuits

For the initial two prototypes, also the SiN chip was designed and fabricated in-house. They were made using wafers from Lionix, with a 300 nm layer of low pressure chemical vapor deposition (LPCVD) SiN and a 3.3 μm thick layer of silicon oxide underneath. Rather than developing new fabrication recipes, I implemented the group's established process, making only minor adjustments specific to the modulator geometry. I did not focus on further optimization, since the designs were already well-characterized and any small variations could be calibrated out.

3.1.1 Grating coupler and multimode interferometer design

The GC and MMI are standard components, yet their specific design details make a big difference. Using earlier designs from within the group as a starting point, the structures were optimized in Lumerical to adjust parameters like grating period and duty cycle to balance bandwidth and efficiency for the specific thickness of BCB expected after the printing and curing process.

The GC is designed in 2D to allow for rapid optimization using a built-in particle swarm algorithm in Lumerical. In the first design a 100 nm layer of BCB was envisioned. The design for the GC functioning at a wavelength of 1550 nm then used a pitch of 1.2 μm with a duty cycle of 52 %. In the second device we aimed at a device without BCB layer on top and thus adjusted the design to a pitch of 1.24 μm with a duty cycle of 77 %. The 1x2 MMIs were designed using EME simulations, optimizing insertion loss. Both designs had a width of 8 μm and utilized 2 μm wide input and output waveguides. The length was tuned from 37 μm for the BCB-clad prototype to 34.2 μm for the air-clad design. These designs provided reliable test points for the integrated devices and allowed consistent optical characterization between fabrication runs.

3.1.2 E-beam lithography and dry etching processes

The SiN designs are simply fabricated using electron beam (ebeam) lithography. ARP6200 ebeam resist is spin coated, exposed and developed using n-amyl acetate. The resulting pattern is transferred to the SiN layer using a CF_4 and SF_6 based dry

etching in a reactive ion etching (RIE) tool for five to eight minutes. The remaining resist is then rinsed off to finalize the SiN chip.

With the target chips fabricated, the focus shifts to the integration via micro-transfer printing. This process was not static; it evolved through three successive iterations aimed at enhancing the yield and printing quality. In the following three sections, I outline how the lessons learned from each iteration informed the next, ultimately leading to a significantly improved and high-performing modulator integration.

3.2 First-generation integration: crystalline tethers

The first attempts at integrating lithium niobate used 1 mm long coupons held by narrow tethers in the LN layer. This approach looks fragile but worked. It allowed for quick testing of the bonding, waveguide, and material quality. The coupons often collapsed in the drying process due to capillary forces. Significant effort and time was dedicated to trying all sorts of adjustments to reinforce the coupons, or reduce the capillary forces. Printing was difficult and fiddly, requiring a certain *fingerspitzengefühl* to use a specific misalignment in the stamp with reference to the often collapsed coupon to pick it up completely without breaking it. Although this method wasn't scalable, it proved that the transfer process could yield functional optical devices and established the basic workflow for later refinements.

Before performing the mTP process, first both source and target chip are prepared separately. The main elements of the fabrication process are shown schematically in figure 3.1. The source sample is purchased commercially from NanoLN and consists of a 300 nm functional layer of LN on top of a 2 μ m buried oxide layer on a LN substrate. Using a standard process of contact Ultraviolet (UV) lithography and lift-off, a chromium (Cr) hard mask is deposited and defined. An Ar milling recipe in the RIE is used to transfer the pattern of rectangles and tethers shown in figure 3.1 (a) into the LN. The 60 μ m by 1 mm rectangle is called the coupon, and is connected to the rest of the sample through its tethers. The extraordinary axis of the LN crystal is aligned along the short side of the rectangle to ensure optimal modulation efficiency when light propagates along the coupon. Next, the buried oxide layer underneath the LN coupon is selectively etched away by dipping the sample in HF (d). After the release process the coupon is held in place suspended due to the support of the tethers. After the release etch the sample is dried using critical point drying (CPD) to avoid the capillary forces associated with drying. Depending on the coupon width, the number of tethers and the tether width, some coupons exited the CPD tool suspended and some collapsed onto the surface. This often happened without breaking. The 300 nm thin LN simply bends down creating a slope of 2 μ m down to the substrate which is not affected by the HF etchant.

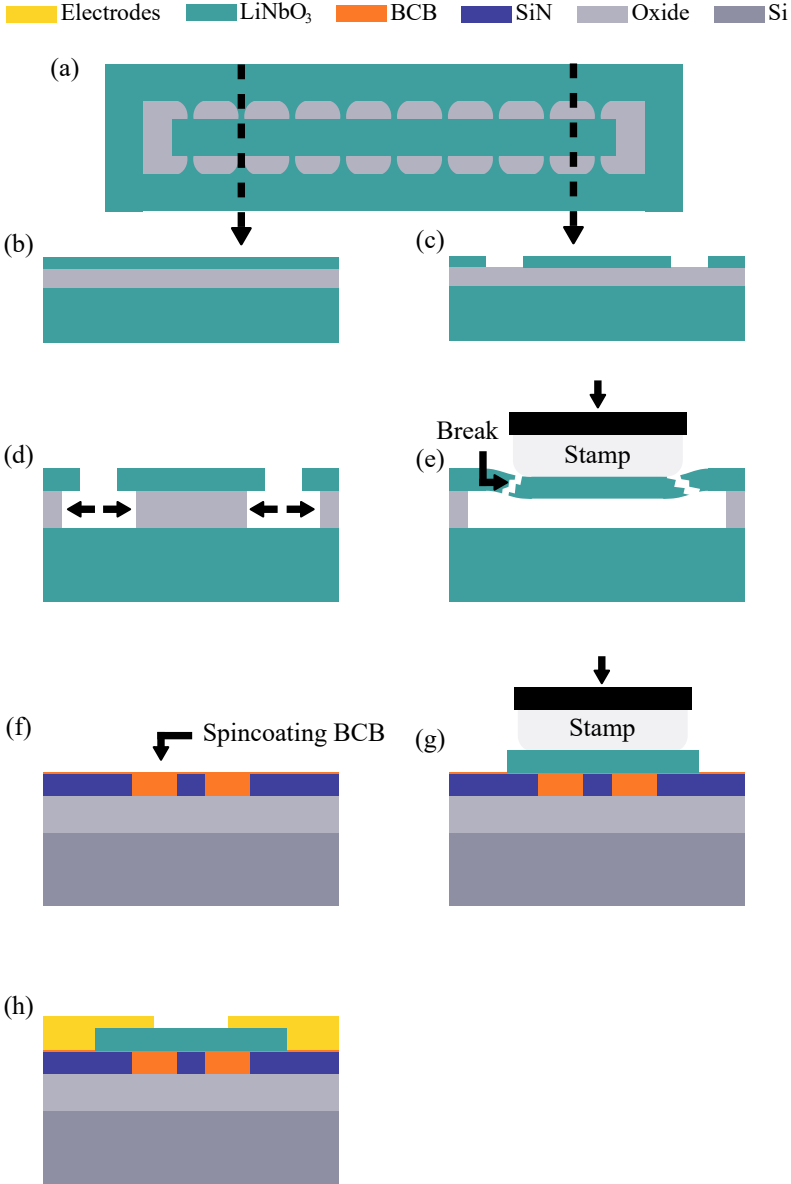


Figure 3.1: Schematic representation of the mTP process flow. (a) Top view of the coupon on patterned on the target. (b) Cross-section of the coupon at a tether as shown by the dotted line. (b) Cross-section of the coupon not at a tether as shown by the dotted line. (d) Release etch of the coupon. (e) Picking up the coupons using a stamp to break the tethers. (f) The target is prepared by spincoating a thin layer of BCB. (g) The coupon is printed on top of the waveguide structure. (h) Electrodes are patterned using lift-off.

The fabrication of the target circuit was explained in the previous section, but before printing a layer of approximately 100 nm of BCB polymer is spin-coated on top of the target sample after which it is pre-baked at 150° Celsius to prepare it for the printing process. Subsequently, the source and target samples are loaded and aligned in the transfer-printing tool. An elastomeric stamp (Polydimethylsiloxane, PDMS) with the approximate shape of the coupon is slowly pressed against the target coupon after which it is quickly elevated. Elastomers have increased adhesion when moving quickly. During the rapid upwards acceleration, the adhesion to the elastomer stamp is sufficiently strong to cause the thin tethers to break and the coupon to detach from the source sample. It is then moved to the target where it is aligned and pressed against the sample. When slowly retracting the stamp, the adhesion force is again weaker, allowing the coupon to stick to the BCB on the target. The resulting hybrid waveguide guides a mode that is partially inside of the SiN waveguide and partially inside of the LN slab as shown schematically in figure 3.1 (h). As I mentioned, this process didn't always work exactly as advertised. If the released coupons were collapsed, they were relatively stuck to the substrate. But by aligning the stamp during pick up to touch some of the sloped, under-etched sections, I was able to regularly pick up the entire coupon which simply followed the suspended section. This process had a low yield of probably around 25 %, but that was enough for a first prototype. Since the coupons here are simple rectangular slabs, there is no precise alignment required to create a good hybrid mode. A simple lift-off step adds gold electrodes to create the modulation section. The resulting device is shown in figure 3.2.

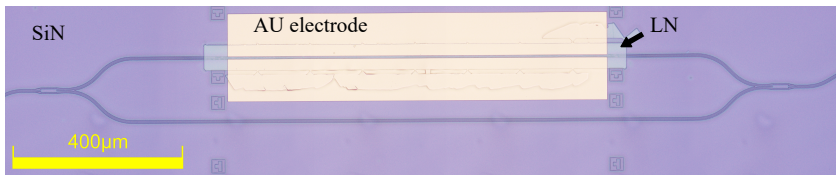


Figure 3.2: Microscope image of the finished mTP device. Taken from [133].

3.3 Second-generation integration: pillar-supported membranes

A first breakthrough came by providing periodic support to the coupon through pillars of photoresist through the coupon. This idea from Tom Vandekerckhove makes it possible to print artificially large areas of LN as long as you are willing to etch trenches in the target wafer and can tolerate periodic holes in the material every

20-30 μm . Often waveguides can simply be routed in-between the holes such that they are not a limiting factor. Areas up to 500 μm by 1000 μm have been printed this way [134], and nothing indicated that this was the size limit. The second prototype was also fabricated this way.

The 300 nm x-cut LN source chip is deposited with a 500 nm amorphous silicon (a-Si) hard mask using plasma-enhanced chemical vapor deposition (PECVD). A layer of ARP6200 ebeam resist is then exposed and patterned with rectangular coupons with a length of 2 mm and a width of 30 μm . They include the taper structures discussed in section 2.2.2 and tethers to keep the coupon mechanically connected to the rest of the chip during release. The tethers include a mechanical fuse or 'crack barrier' in order to prevent the breaking tether to also break the entire coupon [135]. The pattern is then transferred into the a-Si hard mask using a CF_4 and SF_6 based dry etching recipe in an RIE tool. After clearing away the remaining ebeam resist the pattern is then again transferred from the hard mask into the LN layer using an Ar milling recipe. A potassium hydroxide (KOH) dip ensures the remainder of the hard mask is removed before a short HF dip etches away about 1 μm of oxide underneath the LN (see figure 3.3.3). This partial etching creates the mold for the photoresist pillars. The encapsulation is then added and simultaneously creates support structures extending underneath the coupon as shown in figure 3.3.4. There was no noticeable difference between coupons in which the taper was encapsulated or free hanging without encapsulation. A final HF dip then etches away the remainder of the buried oxide layer resulting in suspended coupons held in place by the tethers and support pillars. The optical structures on the target chip are again prepared as explained in section 3.1 but deep trenches that can hold the support pillars during the printing process need to be added to the target chip in a separate UV lithography and etching step to ensure the coupons can be printed flat on the optical surface [105, 134]. The process is shown schematically in figure 3.3.

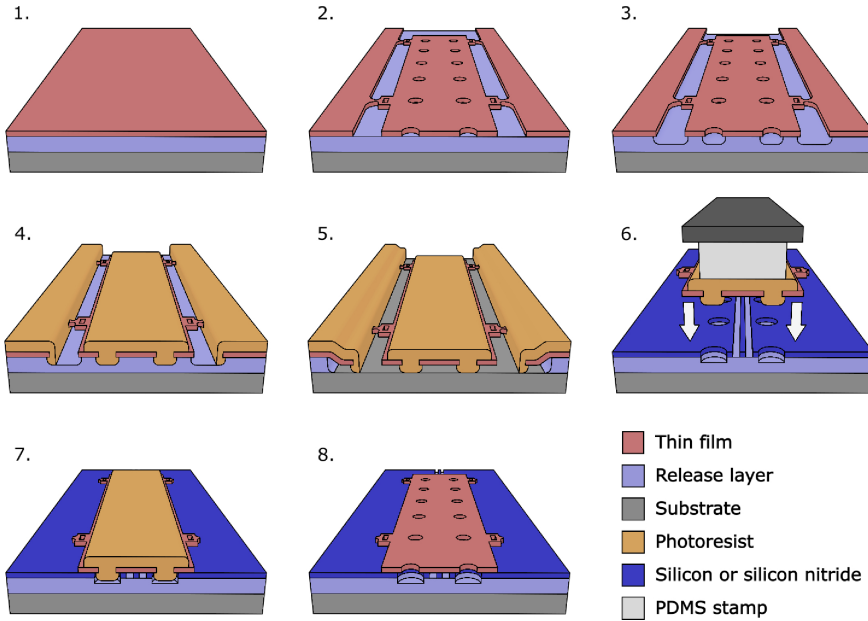


Figure 3.3: Schematic illustration of the pillar method. (1) Initial thin film LN wafer. (2) The coupon including holes for pillars is etched in the LN layer. (3) A short HF dip etches molds for the resist encapsulation and pillars. (4) The resist encapsulation fills the molds. (5) After the release etch the coupon is supported by the pillars. (6) During printing the pillars are aligned with corresponding trenches in the target. (7) The coupon printed on the target. (8) After removing the encapsulation, a clean LN layer remains on the target. Taken from [134].

When both chips are ready they are loaded and aligned for the transfer printing tool. No BCB layer is used in this process. The alignment is far more critical due to the narrow tapers now included in the structure. Going back and forth between the two sides of the coupon and slowly adjusting the X and Y alignment on one side, and the angle on the other side, allows one to obtain alignment on both sides within ± 500 nm given sufficient patience. One has to remember to rotate the source chip 180° after printing one arm on each of the modulators, to ensure push-pull functionality as explained in section 2.4.2. The result after printing is shown in figure 3.4. The chip made for this test had a printing yield of 27 out of 32 coupons, but the method can yield near 100 % printing success. This increased yield did however come at the cost of an additional etching step in the target to pattern the trenches. After the printing step an oxygen plasma step cleans the photoresist encapsulation. Due to an imperfect etching process for the LN the taper tip was wider than expected at around 300 nm. One more UV lithography step, metalization and lift-off are used to define the high-speed electrodes using 15 nm Ti and 1 μ m gold (Au). Also in this step, we noticed a small misalignment after processing.

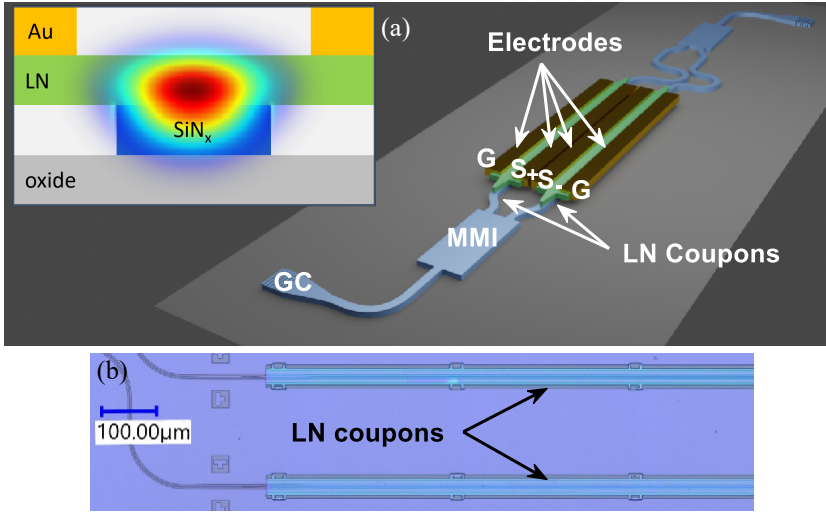


Figure 3.4: (a) Schematic image of a complete modulator. GC: grating coupler, MMI: multimode interferometer. (inset) Overview of the hybrid LN-on-SiN mode profile. Both the SiN and the LN layer are 300 nm thick. The SiN waveguide is 1 μm wide. (b) Microscope image of the printed LN coupons on SiN waveguides. Taken from [2].

3.4 Third-generation integration: scalable photoresist-encapsulated process

Further process development by Margot Niels and Maximilien Billet aimed to remove the need for the periodic support and the etching of the trenches in the target to find a procedure that is compatible with CMOS BEOL processing. By closely controlling the photoresist encapsulation and the temperature treatment, it was possible to come to a reliable scalable process for narrow 30 μm coupons of currently up to 1.2 cm long. We also moved away from homemade target chips and printed on devices fabricated on a subset of the commercial SiPh platform iSiPP200 from imec. For this specific test we printed LT instead of LN, demonstrating the process is robust enough to work for both materials.

We again start from a 300 nm thin film LT wafer purchased commercially from NanoLN, with a 2 μm buried oxide layer and a Si substrate. The process is shown schematically in figure 3.5. Similar to before an a-Si layer is deposited and used as a hard mask. The coupons of, in this case, 30 μm by 7 mm rectangles are first patterned in UV photoresist, then transferred to the a-Si hard mask and then again transferred to the LT using Ar milling RIE. These coupons are simple rectangles

as no taper structure (the taper is defined in the target only) or tethers are defined in the LT layer. A KOH dip removes the remaining a-Si hard mask. A second, slightly larger rectangle is then etched into the oxide layer underneath down to the Si substrate using UV lithography and a CF_4 and SF_6 based dry etching recipe. A photoresist encapsulation layer is then added and patterned with mechanical tethers to the substrate using another UV lithography step. These tethers support the suspended LT membrane when in the next step a buffered HF solution is used to etch away the oxide layer in the release process. The suspended coupons are then ready for the transfer process. The picture from 3.5.f shows the final result. The $30\text{ }\mu\text{m}$ by 7 mm coupons are defined closely together with a density of $1.5\text{ membranes/mm}^2$, and for a 4-inch wafer, the total number of membranes would be more than 12 000. This makes efficient use of the expensive electro-optic material.

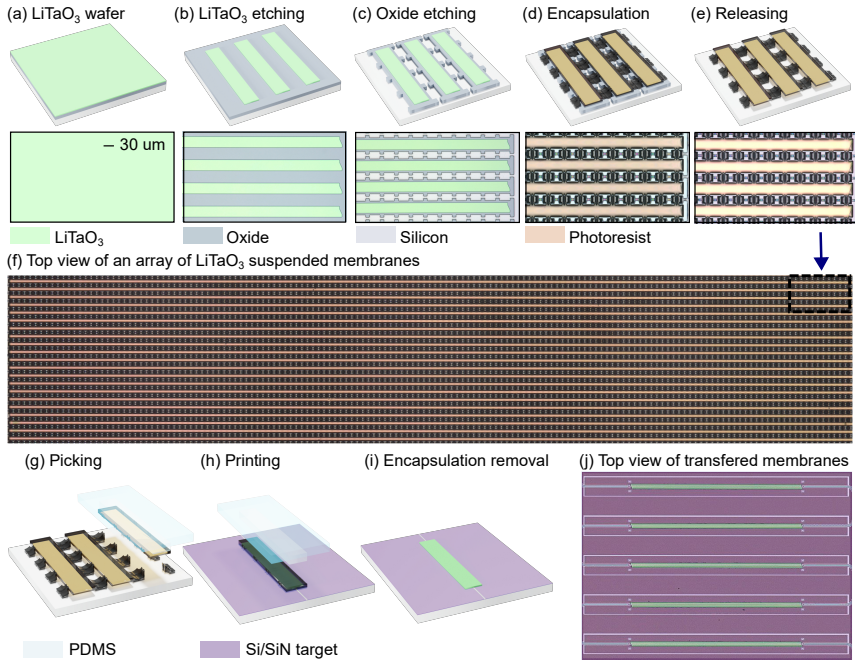


Figure 3.5: Description of the successive steps for the fabrication and printing of suspended LT membranes with a schematic representation as well as a microscope picture. (a) LT (300 nm) / oxide ($2\text{ }\mu\text{m}$) / Si wafer (substrate) starting point. (b) Patterning of the LT membranes. (c) Patterning of the oxide release layer. (d) Photoresist mechanical encapsulation of the structures. (e) Undercutting (releasing) of the oxide layer, making the structures suspended. (f) Top view of the sample with suspended LT. (g) picking of the suspended LT. (h) Printing of the LT on a pre-processed external chip. (i) Encapsulation removal. (j) Top view of a few successfully printed LT membranes. Taken from [3].

The target platform is now a standardized commercial pilot platform (imec iSiPP200). We implemented simple MZM structures on a customized passive-only run from imec which didn't include the germanium (Ge) layer or any of the metal layers. Si and SiN process development kit (PDK) components and layers were used for the routing, grating couplers, 1x2 MMIs, and heaters. The SOI layer is 220 nm with two etch depths available (70 nm and 220 nm). The 300 nm LPCVD nitride is available in a full etch format. Everything is cladded in oxide and planarised. We used the Si layer for all the passive components in the MZM structure. The SiN layer is only used for coupling to the LT structure as explained in section 2.2.2. The resulting architecture is shown in figure 3.6a. A thin adhesive layer of approximately 50 nm BCB is spray coated on the wafer before the printing process can begin.

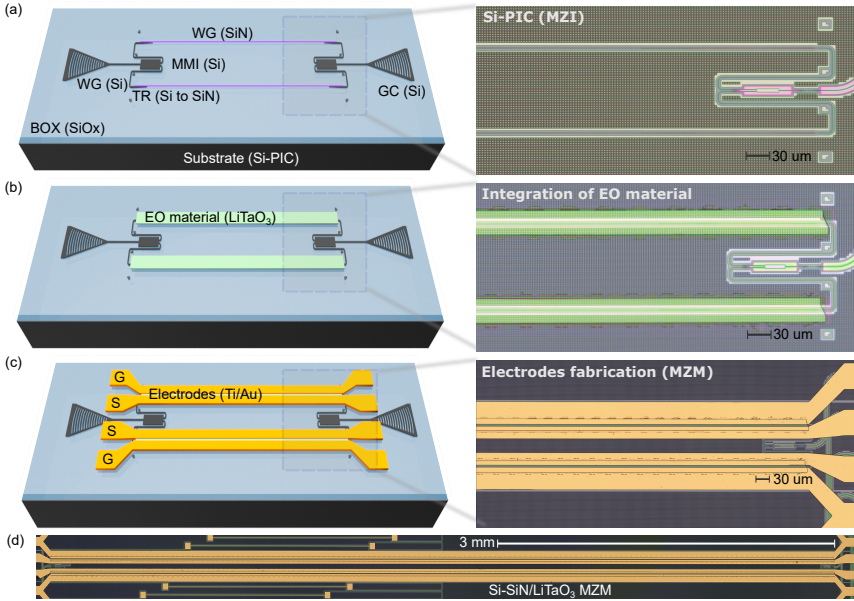


Figure 3.6: Integration flow of LT on a Si-PIC. (a) Architecture of the passive Si and SiN circuitry and corresponding optical microscope picture. WG: waveguide, BOX: buried oxide, TR: transition, GC: grating coupler, MMI: multimode interferometer, MZI: Mach-Zehnder interferometer. (b) Architecture of the hybrid modulator after the integration of the LT and corresponding optical microscope picture. (c) Architecture of the MZM after the fabrication of the electrodes and corresponding optical microscope picture. G: ground, S: signal. (d) Overview of a 7-mm-long heterogeneous Si and SiN/LT MZM. Taken from [3].

During the printing process, hybrid mode waveguides are again formed using LT slabs printed on top of the SiN waveguides. Both arms of the MZM are populated

with coupons that are 180° rotated coupons to ensure push-pull functionality in GSSG electrode configurations. In this iteration, a PDMS stamp of the correct size is used to transfer the coupons in an automated fashion. The wafer scale transfer printing tool from Amicra allows for the use of pattern recognition and automated alignment tools to facilitate the printing of an entire wafer on it's own after the first alignment is done. This now allows for automated printing of hundreds of coupons in a row with alignment accuracies down to ± 500 nm (3σ). After printing the photoresist encapsulation is removed using a oxygen plasma step in the RIE tool before the BCB is cured for 90 min at 280°. The final step is to deposit 50 nm of Ti and 1 μ m of Au and using a lift-off process define the GSSG electrodes and contact pads. Figure 3.6 shows both schematic figures of the structure as microscope images.

Over the course of these three iterations, the integration process for thin-film LN/LT on silicon-based platforms was successfully transformed from a manual, low-yield proof-of-concept into a scalable, automated assembly flow. By fine tuning tether designs and supports structures, the constraints on the target chip fabrication were minimized, enabling compatibility with commercial pilot-line platforms like imec's iSiPP200. This evolution in fabrication maturity not only improved the structural integrity and alignment precision of the hybrid devices but also provided a stable foundation for the high-performance modulators discussed in the following sections. With the devices successfully integrated and the electrodes defined, the focus of the next chapter shifts to the experimental characterization of these modulators, assessing their static and high-speed performance.

4

High-speed electro-optical modulators

4.1	Prototype I: static characterization and proof-of-concept .	90
4.1.1	Device and measurement setup	90
4.1.2	Optical performance: insertion loss and extinction ratio	91
4.1.3	Modulator performance: Efficiency	92
4.1.4	Problems and improvements	93
4.2	Prototype II: high-speed modulation on silicon nitride . .	94
4.2.1	Device and measurement setup	94
4.2.2	Optical performance: insertion loss and extinction ratio	95
4.2.3	Electrical performance: Impedance, loss and velocity matching	96
4.2.4	Modulator performance: Efficiency and speed	97
4.2.5	Problems and improvements	99
4.3	Prototype III: commercial silicon photonics and lithium tantalate	100
4.3.1	Device and measurement setup	101
4.3.2	Optical performance: insertion loss and extinction ratio	102
4.3.3	Electro-optical performance: efficiency	104
4.3.4	Modulator performance: high-speed characteristics . .	105
4.3.5	Problems and improvements	108

This chapter discusses the characterization of the three main prototypes developed during this work. As a direct result of the improvements in fabrication and design detailed previously, the devices evolved from short, inefficient, and slow early-stage prototypes to the long, efficient, high-speed modulators realized in the final iteration.

4.1 Prototype I: static characterization and proof-of-concept

The goal of the first demonstration was to validate the mTP process. It was crucial to determine whether the high Pockels coefficient and low optical loss would remain after the complex fabrication process. For this we designed simple straight waveguide sections and MZMs but we only printed coupons on one arm of the modulator structures. This ensured working devices would be present even with low printing yields. The electrodes were simple rectangular pads, the only parameters optimized were the half-wave voltage-length product $V_{\pi}L$ and the propagation loss added due to absorption in the metal electrodes.

4.1.1 Device and measurement setup

The first demonstration of micro-transfer printed layers of thin film LN was on an in-house SiN integrated platform using a wafer from Lionix. The 300 nm slab layer of LN forms a waveguide together with the 300 nm SiN waveguide underneath with widths ranging from 1.3 μm to 1.5 μm . In these hybrid structures the light is guided by the patterned SiN structures while a significant portion of the mode resides in the LN slab on top. The device is air cladded, with a layer of approximately 100 nm BCB. Underneath the waveguide is a 2 μm layer of buried oxide on top of a Si substrate. The MZMs use 1x2 MMI structures and light is coupled into the structures using GCs and optical fibers. The electrodes are probed using single probes and a voltage is applied using a Keithley voltage source. Light is generated using a Santec laser at 1550 nm and detected using a Newport Power meter. A polarisation controller is added to ensure transverse electric (TE)-polarized light is entering the chip. A diagram of the setup is shown in figure 4.1.

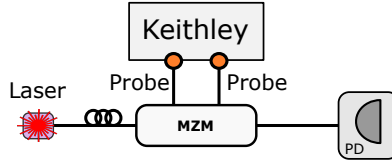


Figure 4.1: Schematic of the measurement setup used for the first demonstration. No high-speed probes or other equipment is used in this case.

4.1.2 Optical performance: insertion loss and extinction ratio

To evaluate the quality of the LN coupons, the MZM structures were analysed before the electrodes were deposited. After transfer printing a LN coupon on one of the arms of the MZM, the induced group index shift effectively creates an unbalanced MZI. A sweep of the laser wavelength will thus reveal the interferometer pattern. We normalized the measurements using an MZI that does not have a coupon printed on it, this way all losses not associated with the coupon are eliminated. The normalized results of a device using a SiN waveguide of $1.4\text{ }\mu\text{m}$ width are shown in figure 4.2. The plot indicates a typical MZI pattern with a free spectral range (FSR) of approximately 12 nm and an ER of 12.0 dB. By assuming the loss in the arm without a coupon is zero, the loss in the other arm can be calculated, using equation 2.35, to be around 4 dB. This early demonstration only printed one coupon length with varying quality so it is difficult to distinguish between propagation loss and transition loss at the interface. finite-difference time-domain method (FDTD) simulations predict transition losses of around 2.0 dB/facet, indicating the propagation losses most likely remain minimal.

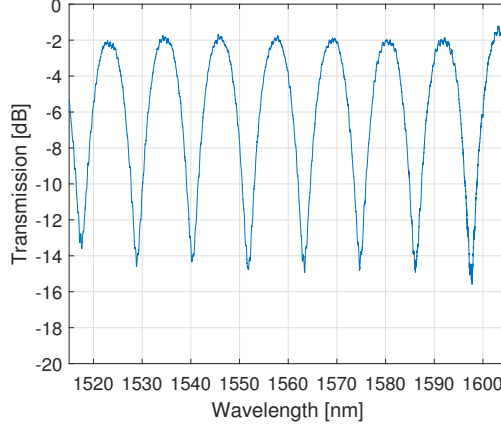


Figure 4.2: Transmission spectrum of an integrated MZI with a micro-transfer printed LN coupon on one arm of the interferometer. No electrodes or bias voltage is present here. Taken from [133].

4.1.3 Modulator performance: Efficiency

After the passive measurement the Ti/Au electrodes are patterned and the electro-optic performance is measured. The electrodes are 500 nm thick, 0.9 mm long and have a $6.5\ \mu\text{m}$ gap to optimize the $V_\pi L$ without spurious additional losses. After normalizing the IL of around 7 dB at 1550 nm the electro-optic measurement results are shown in figure 4.3. A large portion of the losses are due to imperfect MMI splitters.

The two curves in figure 4.3 (a) show the measurement at bias voltages of $-36\ \text{V}$ and $24\ \text{V}$, confirming that significant modulation is achieved. Figure 4.3 (b) shows the phase difference as a function of the bias voltage at 1550 nm. From a fit we estimate a half-wave voltage-length product $V_\pi L = 5.5\ \text{V cm}$. This somewhat outperforms the simulated $6.0\ \text{V cm}$. This is likely due to a small electrode misalignment resulting in stronger fields but also higher than intended optical losses. The linear phase response across both positive and negative bias voltages confirms the dominant role of the Pockels effect, validating the material's suitability for subsequent high-speed operation.

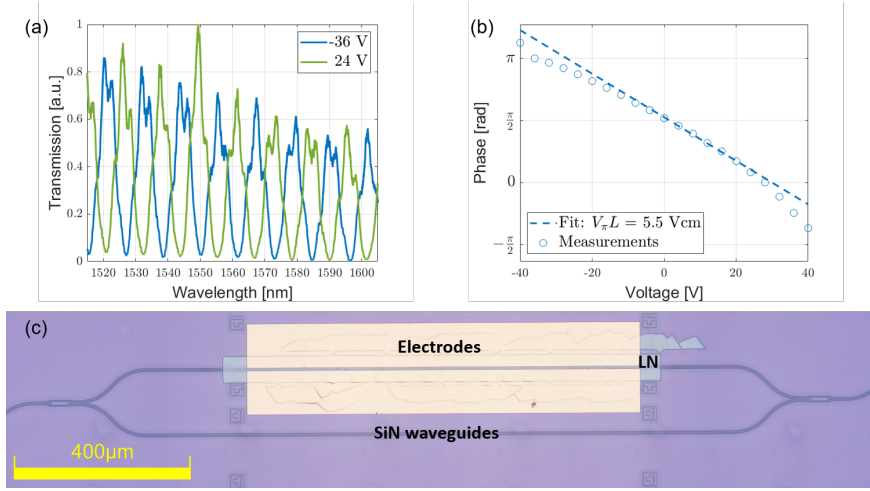


Figure 4.3: (a) Transmission spectra at two different bias voltages for an MZM with a micro-transfer printed LN coupon on one arm of the interferometer. (b) Phase difference between the light in both arms as a function of the bias voltage, extracted from measurements at a wavelength of 1550 nm. (c) Microscope image of the MZM used for electro-optical modulation. Taken from [133].

4.1.4 Problems and improvements

This first demonstration achieved its purpose of validating the mTP technology for LN onto a SiN platform. The measured $V_{\pi}L$ and losses closely matched the simulated values, confirming that the material properties remain intact throughout the heterogeneous integration process. However, several limitations were identified that are addressed in subsequent prototypes.

The IL seemed dominated by the 2.0 dB/facet transitions, the implementation of adiabatic tapers in the next generation will lead to a significantly improved coupling efficiency. Increasing the length of the devices will significantly improve their functionality, but that requires the better fabrication processes of the latter iterations. Finally, high-speed functionality was not even a consideration in this first iteration. Later iterations will optimize the electrode design and measure the high-speed performance.

4.2 Prototype II: high-speed modulation on silicon nitride

The second iteration aimed to make a high-speed version of the modulator and reduce the transition losses at the coupon facets. The printing method had evolved to the pillar method at this point and the chip is designed to work with a GSSG driver chip from our colleagues at IDLab. The device was designed to work at 100 GHz. This device is 2 mm long, has an IL of 3.3 dB and a half-wave voltage ($V_\pi = 14.8$ V). We were able to measure a 3-dB bandwidth of over 50 GHz which allowed us to generate 70 Gb/s NRZ data.

4.2.1 Device and measurement setup

The device consists of two phase modulators sections combined with two 1-by-2 MMIs to form a MZM in a push-pull configuration. A schematic image of the in-house fabricated device is shown in figure 4.4a. Etched tapers are fabricated at both sides of the coupon to reduce the transition losses. Both arms are intentionally made imbalanced to ensure easy measurements by sweeping the wavelength to find the quadrature point. The 300 nm thick SiN layer is used to fabricate the grating couplers for in- and out-coupling. The transfer-printed x-cut LN slabs on top of the 1 μ m wide SiN waveguide form hybrid waveguides as shown in figure 4.4. This hybrid mode at 1550 nm has significant overlap with the LN. Four electrodes of 15 nm Ti and 1 μ m Au are placed on both sides of each waveguide. Simulations in COMSOL Multiphysics® minimizing the $V_\pi L$ while keeping the propagation loss insignificant resulted in a $V_\pi L$ of 6.0 V cm at an electrode gap of 6 μ m. The completed push-pull device should thus show a $V_\pi L$ of 3.0 V cm.

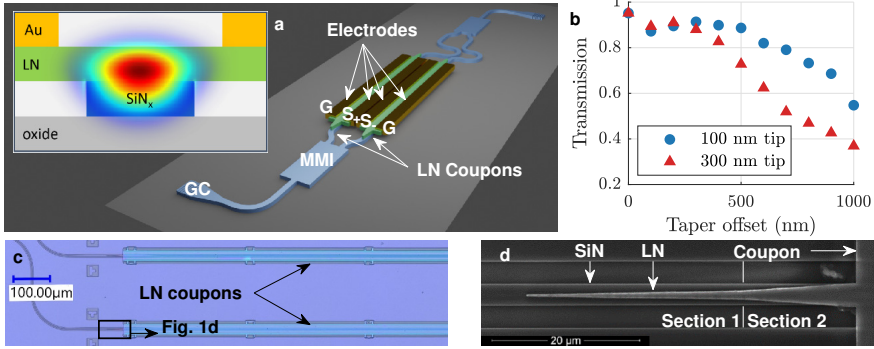


Figure 4.4: (a) Schematic image of the complete device. (inset) Overview of the hybrid LN-on-SiN mode profile. Both the SiN and the LN layer are 300 nm thick. The SiN waveguide is 1 μm wide. (b) Simulation results of the 45 μm long bilinear taper as a function of the taper tip width and alignment offset. (c) Microscope image of the printed LN coupons on SiN waveguides. (d) SEM image of the LN taper. Taken from [2].

The electrodes are also designed for high-speed operation in a ground-signal-signal-ground (GSSG) electrode configuration in the interest of matching it to a specific driver chip in the future. The CST Studio Suite[®] simulations impedance match the differential mode to 100 Ω by adjusting the electrode width and thickness to 35 and 1 μm , the velocity matching is achieved at a buried oxide thickness of 3.3 μm . short fan-out tapers and contact pads are fitted to the electrodes to allow probing with a pitch of 125 μm . Measurements are performed using individual fibers to couple light from the Santec laser at 1550 nm into the chip. Electronic probing is this time done using high-speed GSSG probes from Picoprobe.

4.2.2 Optical performance: insertion loss and extinction ratio

The passive performance of the device is measured first. An additional insertion loss of 2.7 dB is measured between structures without printed coupons and structures with printed coupons. The total loss of the MZM structure is measured at 3.3 dB, due to an additional 0.3 dB loss per MMI (measured in cascaded MMI structures). While the 2.7 dB per coupon is worse than expected from the taper simulations that indicate a loss of 0.25 dB, it is still better than coupling into the LN coupons without tapering. The reduced efficiency can be the result of wider taper tips, misalignment during printing, or from sidewall roughness due to an unoptimized etch recipe. Figure 4.4b shows that misaligned tapers with a taper tip of 300 nm are significantly more detrimental for coupling than the designed 100 nm.

A wavelength sweep of the MZM transmission shows an extinction ratio of 39 dB

near 1550 nm. Figure 4.5a shows a transmission spectrum. The nitride chip was designed with an imbalanced MZI design resulting in a FSR of 9.5 nm. While the insertion loss exceeded the simulated values, the high ER of 39 dB demonstrates excellent modal symmetry between the two arms, indicating that the fabrication and printing variances were consistent across the interferometer.

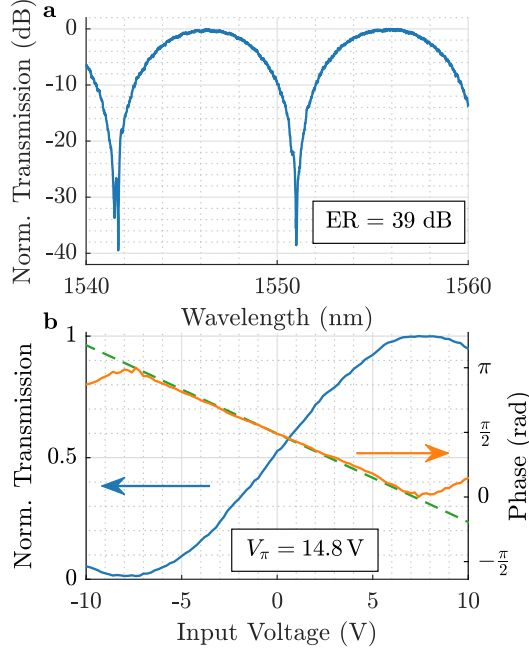


Figure 4.5: Low frequency measurement results. (a) Normalized wavelength sweep of the MZI structure, the free spectral range is 9.5 nm and the extinction ratio is 39 dB. (b) Output power as a function of the applied voltage (blue line). Extracted phase change depending on the applied voltage (orange line), fitted linear phase change resulting in a V_π of 14.8 V. (green striped line) Taken from [2].

4.2.3 Electrical performance: Impedance, loss and velocity matching

Using a VNA (Keysight N5247A PNA-X) the electrical performance is characterised up to 67 GHz. After calibration using a calibration substrate we extract the S-parameters up to the contact pads. The extracted electrical characteristics of the differential mode are shown in figure 4.6. The characteristic impedance of the transmission line is close to the desired 100 Ω . The electrical losses of the modulator are high as shown in figure 4.6a. As explained in section 2.4.1, an attenuation of this shape around 2 dB/mm is expected for chips with normal silicon

substrates and high ohmic losses, and should be improved significantly by moving to a high-resistivity substrate. Also the effective index of the differential mode is calculated from these measurements and is relatively close to the index of the optical mode as is shown in figure 4.6b.

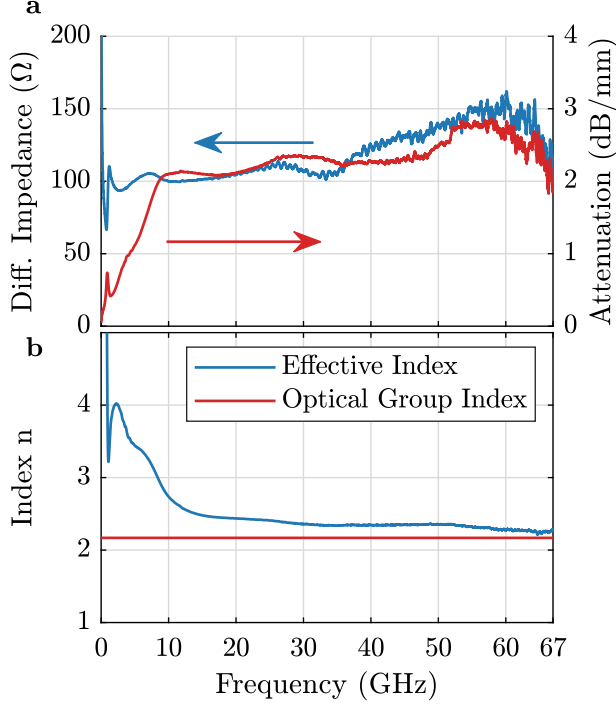


Figure 4.6: High-speed electrical characteristics. (a left) The characteristic impedance of the differential transmission line as a function of the modulation frequency. (a right) Electrical attenuation as a function of the modulation frequency. (b) Effective electrical index as a function of the modulation frequency, the red line is the target optical group index. Taken from [2].

4.2.4 Modulator performance: Efficiency and speed

To measure the modulation efficiency we first modulate at a lower frequency of 100 MHz. the voltage sweep around the quadrature point indicates a V_π of 14.8 V as shown in figure 4.5b. The measured device has a length of 2 mm in push-pull configuration. This indicates a $V_\pi L$ close to the simulated 3.0 V cm for the MZM.

The device is subsequently characterised at higher speeds in both the frequency and time domain. For the frequency domain we used a setup as shown schematically

in figure 4.7a. Again a Santec laser (Santec TSL-510) is used as a continuous wave (CW)-source at 1550 nm. The light is sent through a polarisation controller before coupling to the chip using a grating coupler. One percent of the light is tapped off to a Newport power meter to continuously monitor the transmission during the measurement. The rest of the light is amplified using an erbium doped fiber amplifier (EDFA) (Keopsys CEFA-C-HG) followed by an optical spectral filter (OTF) set to 2 nm optical bandwidth (Santec OTF-350) to filter out some of the noise generated by the EDFA. A 70 GHz uni-travelling-carrier (UTC) photodiode (XPDV3120R) is used to detect the light. The modulator is probed on both sides using GSSG probes, on one side it is connected to the VNA but contrary to the electrical measurement, this time the other side is terminated using high-speed 50 Ω terminations. We calibrate the setup by de-embedding the frequency response of the cables, probes and photodiode (PD). The resulting measurement is shown in figure 4.7b. The modulator has a 3-dB bandwidth exceeding 50 GHz. Due to the high V_π the signal quickly hits the noise floor of the VNA. There is a small feature around 11.8 GHz which is due to a piezo-electrical resonance that is explained in more detail in appendix A.3.

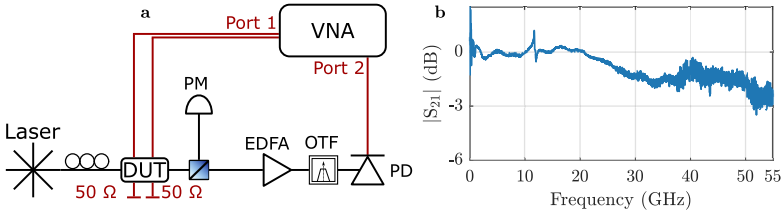


Figure 4.7: (a) Schematic overview of the measurement setup used to perform the frequency domain measurements. (PM = Power Meter, EDFA = Erbium Doped Fiber Amplifier, OTF = Optical Tunable Filter, PD = Photodiode, VNA = Vector Network Analyser, DUT = Device Under Test) (b) Measured $|S_{21}|$ as a function of the modulation frequency, obtained by using the setup in (a). The measurement hits the noise floor around 55 GHz. Taken from [2].

The setup is then adjusted for the time domain measurements. Instead of the VNA we now use a differential signal generated by an AWG (Keysight M8196A) which is first amplified electrically before it enters the chip using the RF probe. A second electrical amplification stage is added after the photodiode before the signal is measured on a sampling scope (Keysight N1000A DCA-X). The setup is shown schematically in figure 4.8a. All three stages of amplification (electrical before modulation and after detection, and optical through an EDFA) are needed to generate a visible signal on the sampling scope. Using a laser output power of 20 mW we are able to generate up to 70 Gb/s NRZ eyes using raised cosine signals with a BER below KP4-FEC after equalization of the high-speed modulator input

(AWG + cables + electrical pre-amplification). Figure 4.8b shows the different error rates as a function of modulation speed. The electrical back-to-back measurement and eyes of the 56 Gb/s and 70 Gb/s points are also included. The EDFA is needed in these measurements due to a loss of around 18 dB from both gratings combined. We estimate that the 4.4 V peak-to-peak input signal at 56 Gb/s will result in an approximate extinction ratio of 3.7 dB between the 1 and 0 levels at the output of the chip. The measurement could be significantly improved using better grating couplers or horizontal coupling. The noise of the unmodulated light that has gone through the EDFA increases from 24 mV on the sampling scope (PD thermal noise) to 64 mV (PD thermal noise + EDFA noise), severely reducing the quality of the eye diagrams. Furthermore, the electrical amplifiers, AWG and sampling scope are also reaching their speed limit at the highest bit rates as seen from the reduced input eye quality at 70 Gb/s in figure 4.8c.

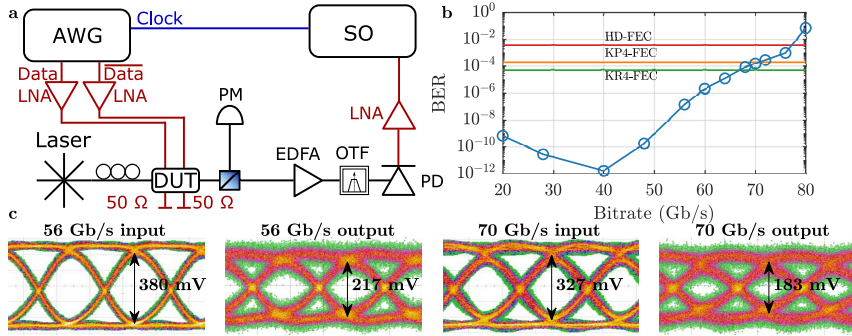


Figure 4.8: (a) Schematic overview of the measurement setup used to perform the time domain measurements. (AWG = Arbitrary Waveform Generator, SO = Sampling Oscilloscope, LNA = Low Noise Amplifier, PM = Power Meter, EDFA = Erbium Doped Fiber Amplifier, OTF = Optical Tunable Filter, PD = Photodiode, DUT = Device Under Test) (b) Bit error rate measured by using the setup in (a) as a function of the bitrate. KR4-FEC, KP4-FEC, and HD-FEC are included as a reference. (c) Electrical back-to-back and resulting electro-optically generated eye diagrams for 56 and 70 Gb/s. The electrical back-to-back eyes were attenuated by 20 dB before entering the sampling oscilloscope. The Q factors of these eyes are from left to right: 12.18, 5.13, 6.85, 3.60. Taken from [2].

4.2.5 Problems and improvements

This second iteration succeeded in demonstrating the high-speed functionality of the mTP technology. A measured 3-dB bandwidth exceeding 50 GHz ensures the modulation is based on the Pockels effect and indicates the potential for much higher speeds. Additionally, the IL was improved by using coupons with integrated tapers, although the losses remain higher than simulated values.

The most effective way to improve the V_π is by increasing the interaction length. We are confident that coupons up to at least 1 cm can be printed to significantly reduce the V_π . For these longer devices, ohmic losses must be addressed by transitioning to a high-resistivity substrate. Furthermore, higher quality fabrication of the grating couplers and passive components will facilitate better characterization at speeds beyond the 55 GHz limit of the current setup. These specific improvements together with scalability form the basis of the third and final prototype discussed in the next section.

4.3 Prototype III: commercial silicon photonics and lithium tantalate

The third and final iteration of the modulator was strongly aimed at demonstrating the scalability of the mTP process. Both improving the printing process to a scalable and automated process, and using a commercial photonics platform as a target. The timing of this demonstration came at the same time as some hype began to grow around the use of LT as a modulator material. Because of this, we used the same printing method for LN to demonstrate the ease with which mTP can be used for different materials while also riding the hype for the publication.

The resulting device shows a bandwidth exceeding the 70 GHz limit of the equipment and is estimated to reach 90 GHz. The modulator exhibits a voltage-length product $V_\pi L$ of 2.3 V cm which is comparable to the monolithic LT results shown in [49]. The total insertion loss of the 7 mm coupons is 2.9 dB most of which is the result of misaligned electrodes causing absorption losses in the metal (1.6 dB). The device was successfully used for data modulation up to 190 GBd highlighting the potential of this approach for next-generation high-speed photonic applications.

4.3.1 Device and measurement setup

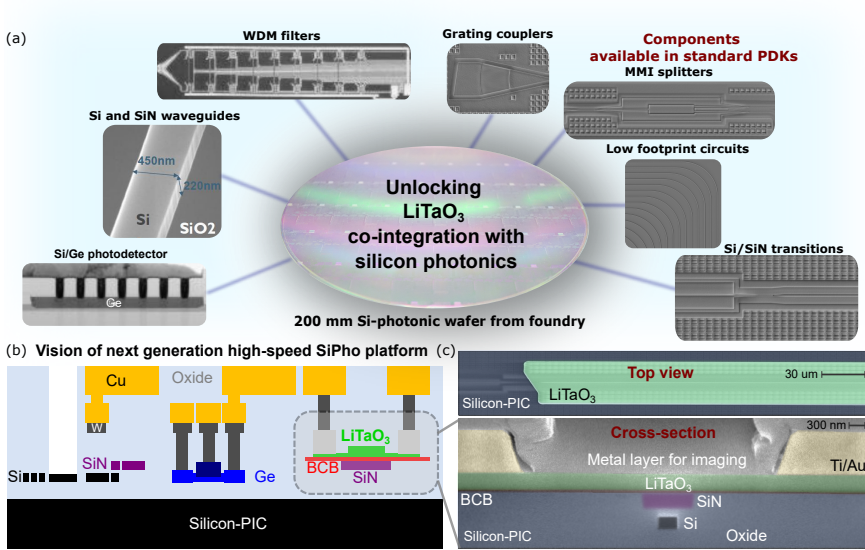


Figure 4.9: Next generation high-speed silicon photonic platform. (a) Generic view of a state-of-the-art Si-PIC platform with its basic components. (b) View of the vision of a high-speed Si-PIC's cross-section: next to the components already offered, lithium tantalate modulators need to be integrated. (c) SEM (colourised) picture after the integration of LT on a Si-PIC and FIB cross-section (colourised) of a heterogeneous electro-optic device on a Si-PIC. Taken from [3].

The final device demonstrated in this work is based on the commercial pilot platform (imec iSiPP200) which contains a 220 nm SOI layer and a 300 nm LPCVD nitride layer. The hybrid waveguide consists of the SiN waveguide with the 300 nm LT slab on top. A thin layer of approximately 50 nm of BCB is also used. The device is measured using a fiber array with a pitch of 127 nm. The electrodes are probed using high-speed GSSG probes similar to the previous iteration. A big change in this device is that the working wavelength shifted to O-band (1310 nm) in order to comply with the demands from data centers.

The design used the existing PDK of the platform and new PDK components were made for the amplitude and phase modulators, including design rules, to ensure full compatibility with the platform. Figure 4.9 shows the platform and the included mTP structures. This back-end compatible process enables the co-integration of all the critical components of the imec platform and the new functionality of the LT structures.

4.3.2 Optical performance: insertion loss and extinction ratio

For the optical characterisation we use an O-band tunable laser and detector. A polarisation controller is used to ensure the TE mode is excited. A reference waveguide is measured in order to calibrate out the grating coupler contributions. The transmission spectrum of the MZM is plotted in figure 4.10a. The spectrum shows an FSR of approximately 4 nm with an extinction ratio near 1310 nm of around 28 dB. The insertion loss of these chips is around 6.7 dB.

2.9 dB of this is associated with the high-speed electro-optic modulator section. From measurements on devices with different lengths we are able to distinguish between propagation losses and coupling losses. Samples S1 and S2 in table 4.1 each couple into and out of the hybrid waveguide structure once while propagating for respectively 0.66 mm and 6.66 mm. Additionally, we fabricated structures that continuously coupled in and out of the hybrid waveguide structure underneath one and the same coupon. Samples S3 and S4 have the same propagation length in the hybrid structure, but sample S4 couples in and out of the hybrid waveguide 14 times instead of once, resulting in 28 transitions. Comparing the losses in these four samples and taking the propagation losses in Si waveguides into account, it allows us to estimate the propagation loss to be around 1.0 ± 0.5 dB cm⁻¹ and the transition loss to be around 0.3 ± 0.1 dB per transition. The measurement values are stated in table 4.1 below. For our device with 7 mm long coupons and 6.66 mm long propagation inside of the electro-optic structure. This results in coupling losses of 0.6 dB and propagation losses of 0.7 dB. The remaining 1.6 dB loss in the 2.9 dB loss associated with the high-speed electro-optic modulator section is due to a 0.6 μ m misalignment of the metal electrodes observed in the FIB cut. This was confirmed in COMSOL simulations since no test structures are present for this fabrication fluke.

Test structure	# of coupons	Propagation length in LT (mm)	# of transitions	Propagation loss in Si (dB)	Transmission (dB)
S1	1	0.6	2	0.2 ± 0.01	-8.2 ± 0.2
S2	1	6.6	2	0.2 ± 0.01	-8.8 ± 0.2
S3	1	0.3	2	0.4 ± 0.01	-8.1 ± 0.2
S4	1	0.3	28	2.5 ± 0.04	-16.8 ± 0.2

Table 4.1: Description and measured transmission for all test structures needed to determine the propagation loss and transition loss of the LT slabs.

The remaining 3.8 dB of insertion loss can be attributed to the PDK components also used in the design. The losses of all components are listed in table 4.2. The MMI splitters introduce 0.8 dB in total and a slightly excessive amount of Si routing

that could have been used for heaters but wasn't also adds significant loss (3.0 dB). These numbers are measured from process control structures on the same chip.

Label	Component	Loss in the MZM
C1	MMI splitters	0.8 ± 0.2
C2	Si routing inside MZM	3.0 ± 0.4
C3	Transitions (Si to SiN/LT)	0.6 ± 0.2
C4	EO section (SiN/LT)	0.7 ± 0.3
C5	Metal misalignment	1.6 ± 0.1

Table 4.2: Measurement of the loss for each component of the MZM, allowing to extract the contribution to the insertion loss from the Si-PIC PDK (C1 and C2) and the back-end integration process (C3, C4 and C5).

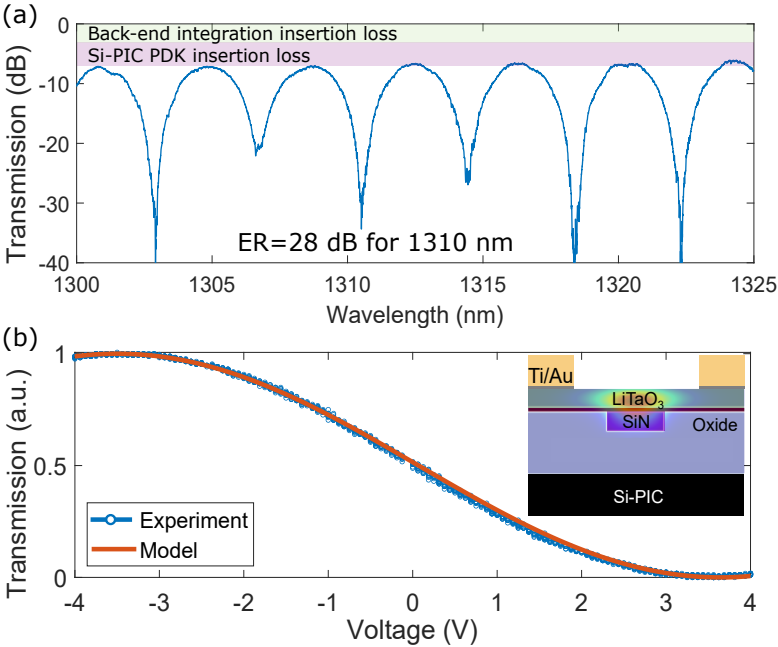


Figure 4.10: Quasi-DC characterisation of the modulator. (a) Measurement of the modulator transmission as a function of wavelength (b) Normalised transmission of the modulator as a function of applied voltage as well as the simulated response, and (inset) cross-section of the full stack of an MZM arm. Taken from [3].

Figure 4.11 shows wavelength sweeps of four different devices on the same wafer after normalizing for the grating coupler losses. All four devices show similar MZI

spectra with an ER of >25 dB. This illustrates the stability of the printing process.

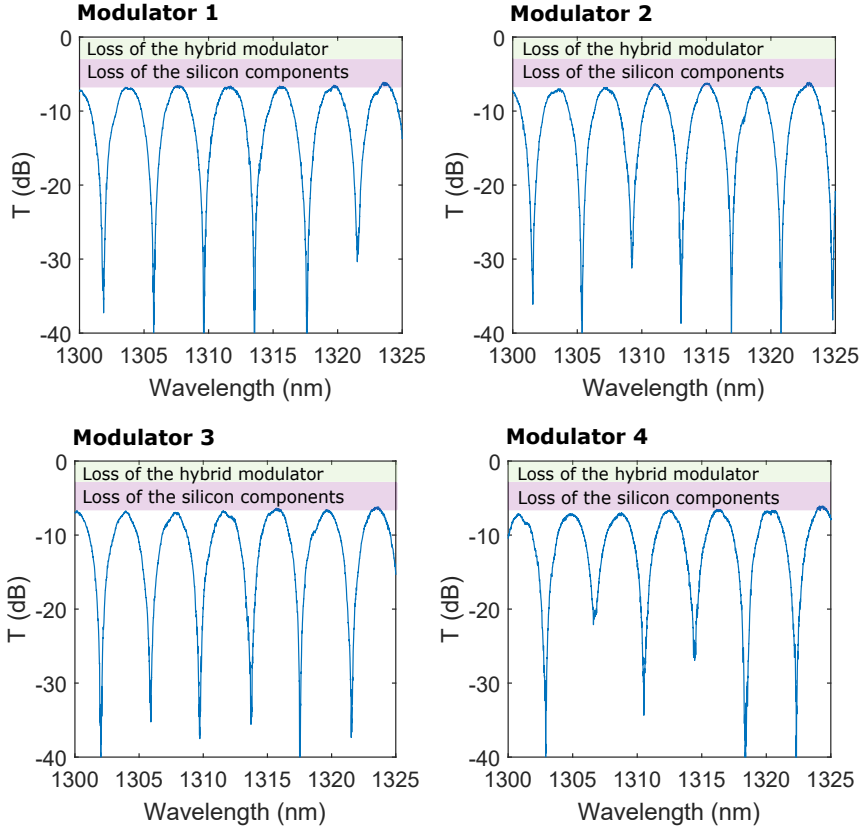


Figure 4.11: Transmission (T) measurements for four fabricated MZMs. The losses from the grating couplers and external routing are removed. The insertion loss contribution from the Si-PIC components ($C1$ and $C2$ from table 4.2) and the contribution of the back-end integration process ($C3$, $C4$ and $C5$ from table 4.2) are described on top of the graphs. Taken from [3].

4.3.3 Electro-optical performance: efficiency

Further characterisation was done by measuring the half-wave voltage (V_π). We drove the device using a 100 kHz triangular wave from a signal generator. The wavelength of the tunable laser is set to a quadrature point close to 1310 nm. An RF probe and a fiber array supply the electrical and optical signal respectively. A

photo detector connected to an oscilloscope is used to measure the output signal. The results for modulating a single MZM arm are shown in figure 4.10b. A V_π of 7 V for the single arm indicates a V_π of 3.5 V for the device in push-pull operation. Considering the device length, the resulting half-wave voltage-length product $V_\pi L = 2.3$ V cm which is consistent with other recent publication of LT modulators [49, 88]. It corresponds well with the simulations in COMSOL.

4.3.4 Modulator performance: high-speed characteristics

We perform two separate high-speed experiments, a frequency domain experiment and a time domain experiment. First, frequency domain characterisation using a VNA is used to determine the 3-dB bandwidth of the modulator while simultaneously comparing the performance of a normal silicon substrate and a high-resistivity substrate. In order to confirm the prediction laid out in section 2.4.1, two samples with different substrates are fabricated and measured. This measurement and comparison is performed both purely electrically as well as in a full electro-optic setup. The measurement setups and results of both of these measurements are shown in figure 4.12. The electrical measurement simply lands GSSG probes on both sides of the device and connects them to the VNA, schematically shown in 4.12a (EE). Due to the capabilities of the VNA only a single arm could be measured at the same time. While this gives somewhat skewed results as explained in section 2.4.3, the results in figure 4.12b still clearly show the significant effect the substrate resistivity has on the modulator performance at higher speeds.

The full electro-optic setup shown in figure 4.12c (electrical-optical-electrical (EOE)) adds a tunable laser, a high-speed photo diode and $50\ \Omega$ terminations to prevent electrical reflections at the far side of the modulator. Also in this case, a single arm was measured simultaneously. The signal from the photodiode is sent to the VNA shown in figure 4.12d. After compensating for the probe and detector characteristics the high-resistivity substrate sample exhibits a 3-dB bandwidth in excess of 70 GHz, which also corresponds to the bandwidth of the VNA, photo detector, and electrical cables.

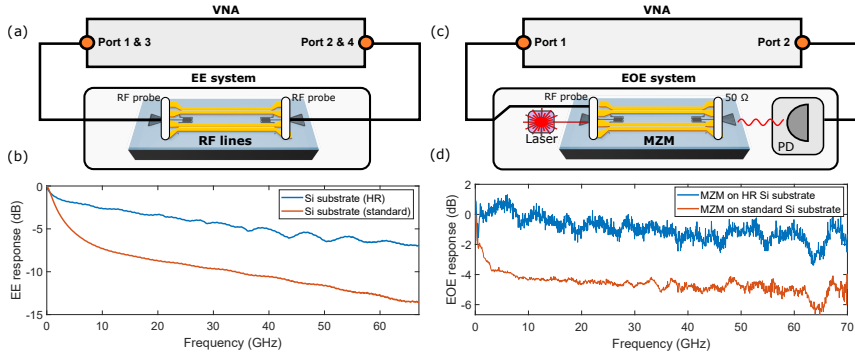


Figure 4.12: High-speed characterisation of the modulator. (a) Measurement setup (EE system) for the RF line frequency response characterisation. (b) Results showing the comparison using regular Si substrate and high resistivity substrate. (c) Measurement setup (EOE system) for the modulator frequency response characterisation. (d) Results showing the comparison for a modulator integrated on a platform using a regular Si substrate and high resistivity substrate. Taken from [3].

Secondly, the device was characterised in the time domain. As a demonstration, the device is utilised in a link to transmit data for which the setup is presented in figure 4.14a. A differential signal, generated by a 256 GS/s AWG, is applied to the device using a GSSG probe. A second probe is used to terminate the device on the opposite side of the transmission line with two $50\ \Omega$ loads to prevent electrical reflections. The optical signal is amplified using a praseodymium-doped fibre amplifier (PDFA) before being detected by a high-speed photodetector. The detected signal is subsequently recorded using a sampling oscilloscope.

To optimise the transmission, the link is characterised to facilitate the equalisation of the signal generated by the AWG. As such, clear eye diagrams are generated. Figure 4.13 shows the measured frequency response of the data transmission link (magnitude in a. and phase in b.), which is compensated at the AWG side. A noticeable performance drop-off is observed in the link characterisation around 70 GHz, attributed to the bandwidth limitations of the electrical cables, RF probes, the high-speed photodetector and the AWG. All transmitted signals are based on standardised pseudorandom bit sequences (PRBS, in this case: PRBS-15).

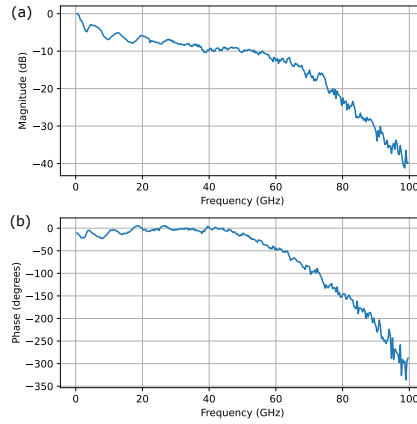


Figure 4.13: Data transmission link characterisation. (a) Amplitude and (b) phase characteristic of the data transmission link, used to generate eye diagrams. Taken from [3].

A 64-tap FFE algorithm is applied at the receiver end, using the sampling oscilloscope's software to enhance the received signal. 4.14.b presents the measured BER derived from the generated eye diagrams using both NRZ and PAM4 formats. A dashed line indicates the BER threshold for a FEC algorithm with an overhead of 15 %. Taking this as a limit 190 GBaud NRZ and 320 GBit/s PAM4 were achieved. The lower limit of the plot, at 3×10^{-4} , indicates the error rate threshold below which statistically significant assessments could not be made, due to the limited number of bits transmitted during the demonstration. Figure 4.14 also includes representative eye diagrams, all of which incorporate FFE.

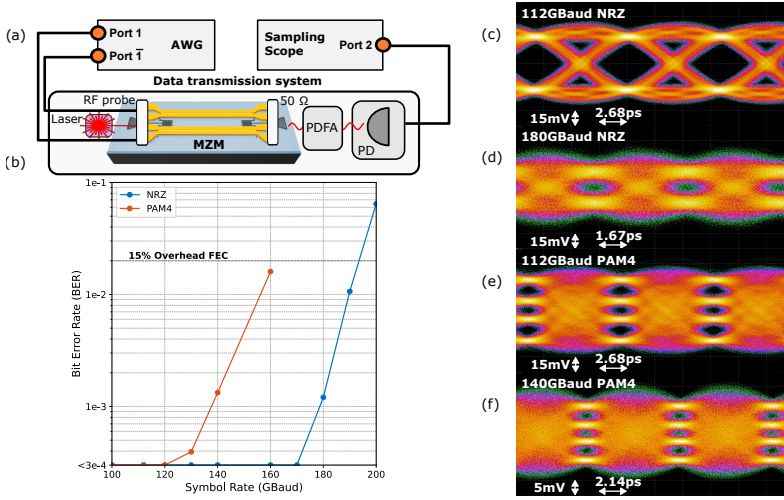


Figure 4.14: Data transmission experiment. (a) Measurement setup for eye-diagram measurements. (b) BER in the transmitted bit sequence for NRZ (blue) and PAM4 (red) measured signals. A horizontal dashed line indicates the threshold for FEC with an overhead of 15 %. Eye diagrams for (c) 112 GBaud NRZ, (d) 180 GBaud NRZ, (e) 112 GBaud PAM4, (f) 140 GBaud PAM4, all figures used correction at the transmitter side and a 64 tap FFE on the receiver side, however, no offline digital post-processing was done. Taken from [3].

4.3.5 Problems and improvements

The device accomplished the goal of demonstrating the viability and scalability of the mTP process. At the same time it demonstrated the flexibility of transferring the a process to different material like LT. The transfer of LT to a 200 mm commercial silicon photonics platform with minimal insertion loss confirms the validity of these goals. It also facilitates the integration of mTP technology like these high-speed modulators with high quality PDK components in existing commercial platforms.

The MZM exhibits a bandwidth exceeding 70 GHz with a voltage-length product of 2.3 V cm which is comparable to other demonstrated LT technologies. High quality etching of LT is possible [49] and would allow for patterned LT waveguides to be transferred instead of slabs. The resulting increased confinement together with improved electrode design would allow for modulators with higher bandwidths exceeding 100 GHz and lower half-wave voltage-length products to be fabricated (< 1.8 V cm). Also the transition losses can be further improved, adiabatic coupling section can reach efficiencies up to 99 % in simulation. Even with the limitations of the current design high-speed transmission experiments reaching symbol rates of 190 GBaud NRZ and 160 GBaud PAM4 were possible.

5

Conclusion and outlook

5.1	Conclusions	110
5.2	Short term future outlook	111
5.2.1	Etched Waveguides	111
5.2.2	The path towards 100 GHz and beyond	111
5.2.3	Complex modulation formats	112
5.2.4	Reliability and foundry integration for scalable production	113
5.3	Heterogeneous multi-material integration	114
5.3.1	Rationale	114
5.3.2	Expanding the photonics toolbox	114
5.4	Long term future efforts	115
5.4.1	Differential dual-waveguide architecture	115
5.4.2	High-K claddings	116
5.5	Electronic-photonic co-integration	118
5.5.1	Advantages and requirements of close co-integration	118
5.5.2	Co-design	118

Over the past years, we have gone from concept sketches to functional traveling-wave modulators fabricated using micro-transfer printing. Along the way, we have tested different materials, coupling strategies, and fabrication methods, not all of which worked, but all of which taught us something. The main achievement is

showing that heterogeneous integration using micro-transfer printing is not just a lab curiosity: it can yield high-speed, efficient modulators on foundry-compatible platforms. In order to reach a finished product, there is still work to be done on stability, scaling, and reproducibility, but the path forward is now much clearer.

5.1 Conclusions

The work presented in this thesis has demonstrated the viability and successful development of a heterogeneous integration platform for thin-film LN/LT on silicon photonics. Using mTP technology, we transitioned fundamental proof-of-concept experiments to high-performance, industry-compatible modulators. This maturation was characterized by three distinct generations of prototypes, each improving specific fabrication and performance bottlenecks. The following table summarizes the technological developments achieved across the three main prototypes.

Table 5.1: Comparison of the three modulator prototype iterations developed in this work.

Feature	Prototype 1	Prototype 2	Prototype 3
Active Material	LN	LN	LT
Target Platform	In-house SiN	In-house SiN	imec iSiPP200
Printing Strategy	LN side tethers	Pillar method	Resist encapsulation
Coupon transition	No taper	Etched LN taper	PDK-compatible taper
Coupon Length	1 mm	2 mm	7 mm
$V_\pi L$	5.5 V cm	3.0 V cm	2.3 V cm
Substrate Type	Standard Si	Standard Si	High-resistivity Si
Bandwidth	DC	50 GHz	> 70 GHz

More explicitly we established a mTP process that is somewhat material agnostic, allowing for both LN and LT to be printed with reliable success. Repeated printing while showing reproducible measurement results in terms of IL and ER while printing on a commercial 200-mm platform shows the potential of this technology. A critical evolution was the move towards high-resistivity substrates to enable the high-speed operation of the modulator. The demonstration of simple differential devices reaching symbol rates in excess of 190 GBaud places mTP firmly on track of becoming a next-generation heterogeneous integration technique.

5.2 Short term future outlook

5.2.1 Etched Waveguides

A major limitation of these prototypes was the lack of high-quality LN etching. While we etched coupons and tapers, the process was never optimized for waveguide-quality sidewalls. Using hybrid slab waveguides reduces the effective Pockels effect because too much light remains in the SiN layer, which is not electro-optically active.

Optimizing the etching to create rib waveguides could lower the half-wave voltage-length product by up to 40 %. This efficiency boost improves all other metrics: a shorter device reaches higher speeds because RF attenuation and velocity mismatch both scale with length. Furthermore, propagation loss becomes less of a factor in a shorter interaction region. Since transfer printing pre-etched LN circuits has already been demonstrated without issues, this is the logical next step, either through refining in-house etching or partnering with a foundry.

5.2.2 The path towards 100 GHz and beyond

Achieving bandwidths of 100 GHz and beyond is a prerequisite for the large-scale adoption of this technology in next-generation transceivers. While this has been a design goal since the second iteration, reaching 100 GHz might still be possible with similar designs but going beyond these speeds requires moving beyond simple rectangular electrodes.

Capacitively loaded traveling-wave electrodes, as shown in Figure 5.1 [69, 70], offer a more promising route to the 140 GHz to 180 GHz range. These designs decouple the electrical and optical overlap constraints, allowing for wider electrodes that reduce RF skin-effect losses while maintaining precise velocity and impedance matching.

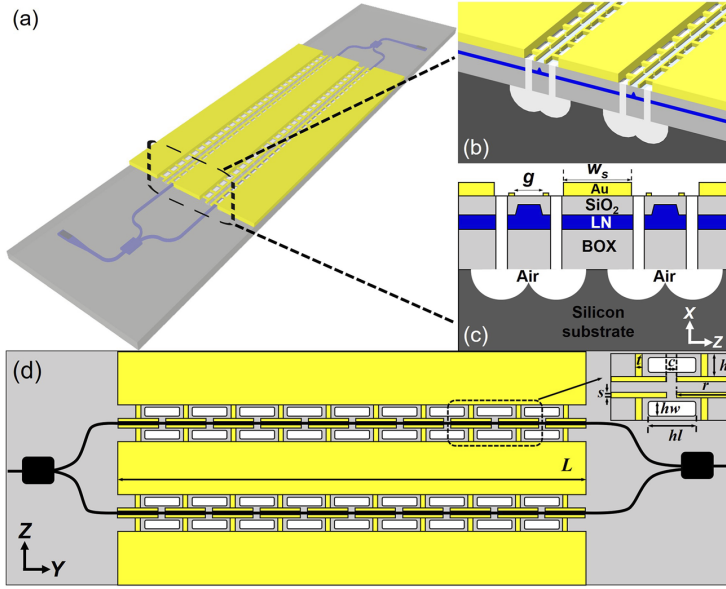


Figure 5.1: Schematic representation of capacitively loaded travelling wave electrodes (CL-TWE) with undercut etching of the silicon substrate [69].

Furthermore, substrate management will become critical at these frequencies. Although transitioning to high-resistivity silicon alleviated significant losses in the third prototype, parasitic surface conduction at the Si/SiO₂ interface can still lead to significant Ohmic losses regardless of the bulk resistivity [136–138]. To address this, completely undercutting the modulator to remove the silicon substrate in the active region may be necessary. It is a technique already employed by several competing heterogeneous platforms as also shown in figure 5.1. Future work must involve high-frequency simulations and substrate-engineering experiments to determine if such structural modifications are required to suppress these interface-related losses.

5.2.3 Complex modulation formats

The next logical step for modulators is to move beyond simple on/off intensity modulation NRZ. High-capacity telecommunication standards now rely almost exclusively on complex formats like PAM4 and QAM, which require precise and stable control over both phase and amplitude. While the devices developed in this work were designed with the linearity and bandwidth required for these formats, they have not yet been characterized for IQ modulation formats.

Expanding our efforts to include IQ measurements presents significant challenges regarding the experimental infrastructure. Characterizing 100 GBaud QAM signals requires dedicated hardware, incredibly phase stable setups, and advanced digital signal processing that is currently lacking from our research group. Future work should look to implement the required infrastructure for this characterization to be performed properly.

5.2.4 Reliability and foundry integration for scalable production

For mTP to transition from lab-scale demonstrations to commercial production, the focus must shift toward long-term reliability and supply chain integration. A primary concern is the environmental and operational stability of the devices: it must be determined if the BCB bonding layer and the ferroelectric membranes can survive prolonged thermal cycling and exposure to high optical power without performance degradation.

Furthermore, achieving high-throughput fabrication requires a robust foundry-based supply chain. This involves sourcing high-quality, pre-processed source wafers and target Si-PIC wafers from established foundries. The micro-transfer printing process has now been demonstrated to print reliable and automated on a wafer-scale tool in our lab capable of maintaining sub-micron alignment across thousands of coupons but must itself be transitioned to large scale fabrication facilities. Integrating pre-etched waveguides and complex electrodes, as discussed previously, will only be viable if the placement accuracy is high enough to ensure consistent coupling efficiency across the entire wafer.

Complementary to these fabrication efforts, a transition to standardized and automated measurement protocols is essential. Currently, characterizing high-speed performance is a manual, time-intensive process. For a scalable product, we need automated testing of both passive structures and high-speed modulation across entire wafers. Establishing these rigorous measurement routines is essential for a rational comparison between different fabrication batches and for identifying the statistical yield of the integration process. Conducting these tests alongside rigorous accelerated aging experiments represents the final hurdle to achieving large-scale adoption of this heterogeneous technology.

5.3 Heterogeneous multi-material integration

5.3.1 Rationale

To fully exploit the potential of mTP, a convincing demonstration of a single target chip combining multiple coupons from different source materials in one working circuit is still required. While mTP may ultimately outperform wafer bonding in material efficiency, its true advantage, in my opinion, lies in the close co-integration of heterogeneous materials.

Our differential drive modulators have already partially demonstrated this flexibility by rotating the crystal axis in each arm, this is much more difficult with wafer-bonding. A “true” multi-source demonstration, however, would go further by placing active III-V gain sections, electro-optic modulators, and passive filters on the same SiN-on-Si platform in a single fabrication flow.

5.3.2 Expanding the photonics toolbox

There’s a lot more that could be done with this. The material-agnostic nature of the mTP process can be exploited to achieve some incredible feats on a single chip.

- **Transceivers:** Printing III-V gain sections, such as InP or GaAs [105], directly alongside LN modulators would enable fully integrated, high-speed heterogeneous transmitters without the need for external fiber-coupled lasers. Adding onto that the high-speed Germanium photodiodes of for example the ISIPP platform or even some III-V detectors also printed on the sample [139], a full transceiver on a single chip is conceivable.
- **Heterogeneous Quantum Accelerators:** Quantum photonic circuits have notoriously strict requirements: they want deterministic single-photon sources, extremely low-loss passives, high-speed, low-noise optical switches, and specialised single-photon detectors. mTP allows us to “cherry-pick” the best materials for each, printing InAs quantum dot sources [140] next to low-loss SiN delay lines, high-efficiency LN frequency converters [141] and superconducting nanowire single-photon sources, to realize fully integrated quantum processors that are currently impossible to build on a single monolithic platform.
- **On-Chip OPOs and Frequency Combs:** The combination of III-V gain and the strong $\chi^{(2)}$, $\chi^{(3)}$, or Pockels nonlinearity of LN provides a path toward on-chip Optical Parametric Oscillators (OPOs), EO combs and frequency combs. This would enable the generation of new wavelengths (e.g., visible light from

an IR pump) or stabilized multi-wavelength sources for wavelength division multiplexing (WDM) systems, all within a compact footprint that avoids the stability issues of benchtop nonlinear optics.

That being said, it is important to acknowledge that the field of advanced electronic-photonic packaging is evolving rapidly. In recent years, chip-to-chip coupling techniques, such as high-accuracy flip-chip bonding and automated edge coupling, have seen significant performance improvements. These advancements raise valid questions regarding whether mTP remains the “only” solution for the close integration of diverse, optimized materials.

5.4 Long term future efforts

5.4.1 Differential dual-waveguide architecture

Over the past years, close collaboration with the high-speed electronics group has led to the conception of a novel modulator geometry for LN devices. The idea originated from the observation that, in conventional ground–signal–signal–ground (GSSG) traveling-wave electrode configurations, only the voltage difference between a single signal electrode and ground is typically exploited for phase modulation. As a result, the full differential voltage available between the two signal electrodes remains unused, limiting the achievable modulation efficiency. As discussed previously in section 2.4.2, placing a waveguide in the middle breaks the field symmetry and introduce unwanted chirp.

To address this limitation, I investigated an alternative architecture that incorporates two parallel LN waveguides, positioned symmetrically between the two signal electrodes as shown in figure 5.2. By poling the waveguides with opposite ferroelectric orientations, the electro-optic phase shifts induced by the electric field in each arm add constructively, despite the local field distribution being the same in both regions. This approach enables the modulator to directly harness the complete inter-signal voltage swing inherent to the GSSG structure. The device layout must, however, be designed carefully: the two waveguides must remain sufficiently separated to avoid optical coupling, and the electrodes must be placed far enough from the optical modes to prevent excess absorption losses.

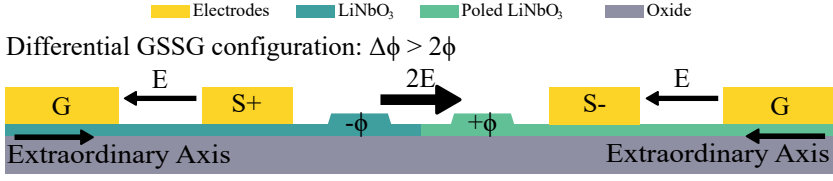


Figure 5.2: Schematic cross section of the dual-waveguide architecture.

Preliminary simulations indicate that the resulting device concept enhances the effective modulation strength by up to 20-30 % and thus offers the potential to reduce the half-wave voltage-length product ($V_\pi L$) compared to standard single-ended and differential drive geometries. Such an improvement would again compound into additional improvements towards speed and insertion loss typical with shorter devices. This is only a preliminary analysis and RF simulations are required to assess the high-speed viability of this geometry.

5.4.2 High-K claddings

Another promising direction for improving modulator performance lies in the use of high-permittivity (high- κ) dielectric claddings around the RF electrodes and the LN waveguides [117, 142–144] such as Al_2O_3 , HfO_2 , or TiO_2 . Conventional thin-film LN modulators typically rely on SiO_2 or air cladding, which provide good optical confinement but offer limited control over the microwave field distribution. In particular, the strong permittivity mismatch between the dielectric layers, and the LN film constrains the overlap between the RF and optical modes, thereby limiting the achievable modulation efficiency. Figure 5.3 [142] shows the field distributions in case of a normal low- κ cladding like air or oxide compared to the field distribution using a high- κ cladding. This is completely analogous to the field distributions in capacitors with different media inside.

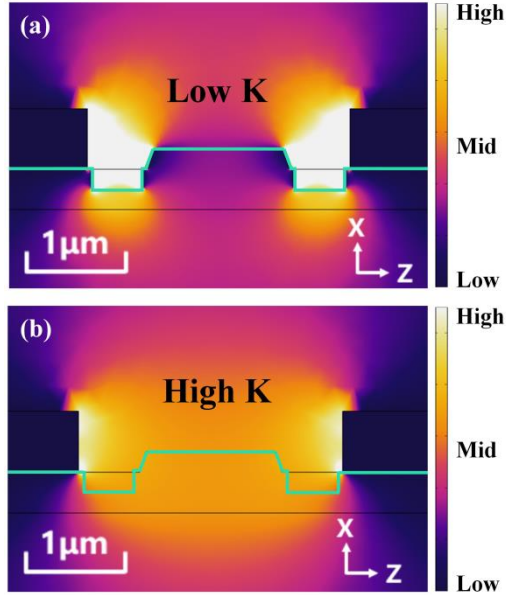


Figure 5.3: Simulated x-component of the RF field distribution of the thin film LN modulator cross-section (a) with low- κ cladding, (b) with high- κ cladding [142].

Integrating a high- κ material can substantially modify the RF field profile. Because the electric field preferentially concentrates in the highest-permittivity regions, introducing a high- κ cladding more evenly distributes the microwave field over the LN waveguide (i.e. the region containing the Pockels coefficient). This increases the electro-optic overlap integral without requiring a reduction in electrode spacing.

However, most high- κ materials also exhibit relatively high refractive indices, complicating their use as claddings. If the mode is less confined, this negatively influences the electro-optic overlap integral from equation 2.22 as well as increases the risk of absorption in the metal electrodes. Optical quality high- κ claddings are also not easy to come by and could introduce additional optical loss to the waveguide. By definition they will increase the capacitance of the electrodes and could complicate impedance tuning and high-speed operation. Typically the optical wave is too slow and increasing the group index of the electrical mode is a good thing but a more detailed analysis will be in order.

5.5 Electronic-photonic co-integration

5.5.1 Advantages and requirements of close co-integration

The electrical interfaces are typical sources of parasitic capacitances, inductances and losses. Bringing the electronics physically closer (through co-packaged drivers, flip-chip bonding, or transfer printing drivers) could reduce those parasitics while improving overall bandwidth. The requirements are strict: impedance control, thermal management, and signal integrity all have to be considered. But the potential benefits are worth it: tighter integration could turn these printed modulators into practical, low-power, and scalable building blocks for next-generation transceivers.

5.5.2 Co-design

Ultimately, no optical modulator lives in isolation, it needs a driver, and it will be working with a detector, TIA, digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) and more. If I learned anything from working with the high-speed electronics people, it's that these fields are deep and contain incredible nuance and technical knowledge. When you talk to people from a different field, you often instinctively simplify your explanation. You strip down an incredibly complex system into a few manageable terms that even a layperson can understand. While this is natural and has its uses, I think it limits the overall performance of combined systems. Thorough and detailed understanding of neighboring devices can lead to significant advantages in these extremely high-tech and cutting edge engineering challenges. Designing a modulator to work with an existing driver, or designing a driver to work with an existing modulator, are fine strategies for proofs of concepts. But true co-design and listening to the reasoning for decisions in each other's design will lead to the real improvements.

Interdisciplinary research spanning photonics, high-speed electronics, and advanced packaging, is essential for translating device-level improvements into system-level performance. With such co-integration, these modulators can underpin the next generation of high-bandwidth, energy-efficient transceivers.

6

Post Scriptum: Piezoelectrically actuated silicon-nitride-based high-speed spatial light modulator

6.1	Introduction	120
6.2	Results	122
6.2.1	Simulation	122
6.2.2	Design	123
6.2.3	Fabrication	127
6.2.4	Packaging	128
6.2.5	Characterization	128
6.3	Discussion	131

This chapter presents work conducted during a research stay at the Massachusetts Institute of Technology (MIT) within the Research Laboratory of Electronics (RLE) in the group of professor Dirk Englund. The content is a reproduction of a paper published together with Arthur Hermans in Nature Communications [145] with minor adjustments.

This project was a collaborative effort involving the full author list. I focused on the final phase of the project to perform the optical FDTD simulations and free space

physical measurements. It is included to show the results and explore a different kind of modulator.

6.1 Introduction

Devices that have the ability to control multiple optical modes at high speeds are revolutionizing many fields of science and technology, including laser ranging [146], quantum information processing [147], imaging [148, 149], optogenetics [150], artificial intelligence [151, 152], and augmented and virtual reality (AR/VR) [153, 154]. In particular, the availability of multimodal and/or high-speed light modulators has been instrumental in the rapid advancement of atom-based quantum technology over the last years [147, 155–158]. Optical control of atomic quantum systems poses the following requirements: (R1) operation at a design wavelength of choice in the visible (VIS) to NIR spectrum, (R2) a scalable technology with a high channel density ($> 100 \text{ mm}^{-2}$), (R3) a high modulation speed ($> 100 \text{ MHz}$), and (R4) a high extinction ratio ($> 20 \text{ dB}$). This motivates the development of a new modulator technology, meeting these requirements to continue driving progress. Requirement (R1) stems from the fact that many optical transitions in atoms or atom-like emitters in solids lie in the VIS to NIR wavelength range. VIS to NIR wavelength operation is also essential for bioimaging [159, 160], optogenetics [150], and AR/VR [153]. Requirement (R2), a scalable technology with a high channel density, originates from the need to individually control hundreds to thousands of atoms to unlock quantum technology's full potential. High modulation speeds (R3) and high extinction ratios (R4) are required to optically control the state of atoms or atom-like emitters with high fidelity in a short time compared to the lifetime of the state [158]. A high-extinction and high-channel-density optical control technology acting as an ultrafast spatial light modulator is also an immediate benefit to the varied fields of research which already rely on devices with thousands to millions of times slower modulation rates.

Table 6.1 compares state-of-the-art multichannel light modulator technologies in terms of requirements (R1)–(R4). None of the existing technologies meets all requirements. spatial light modulators (SLMs) operating in the VIS to NIR range based on MEMS [161–163] and liquid crystals [164, 165] are commercially available, but their modulation rates are limited. In the infrared (IR) wavelength range, alternative SLM technologies with $> 1 \text{ MHz}$ modulation rates have been explored based on electrical gating of graphene [166, 167], the Pockels effect in organic electro-optic molecules [168–170] and dielectric thin films [171], the quantum-confined Stark effect in III-V semiconductor quantum-well-based material [172, 173], and charge carrier effects in indium tin oxide (ITO) [174] and silicon

[175, 176]. The refractive index changes associated with these fast effects tend to be small, thus long interaction lengths are needed to realize devices with a high modulation efficiency. To create compact, free-space-coupled devices, one therefore often relies on optically resonant structures, such as metasurfaces [166, 167, 169, 173, 174], Fabry-Perot cavities [172], resonant waveguide gratings [168, 170, 175], or photonic crystal cavities [176].

Table 6.1: Comparison of multichannel light modulator technologies in terms of requirements (R1)–(R4).

Technology	R1	R2	R3	R4
Liquid-Crystal-on-Silicon (LCoS) [164, 165]	✓	✓	✗	✓
Digital Micromirror Device (DMD) ^a [161]	✓	✓	✗	✓
Grating Light Valve (GLV) ^a [162]	✓	✓	✗	✓
Atom-control Photonic Integrated Circuit (APIC) ^b [158]	✓	✗	✓	✓
Electro-optic silicon-organic metasurface [170]	✗	✗	✓	✗
Silicon photonic crystal cavities with free-carrier modulation [176]	✗	✓	✓	–
Technology presented in this work	✓	✓	✓	✓

^a MEMS device

^b SiN PIC with aluminium nitride (AlN) piezoelectric actuators

To fulfill requirements (R1)–(R4), we introduce an SLM technology based on piezoelectrically actuated SiN resonant waveguide gratings (Fig. 6.1). The piezoelectric actuators induce strain in the gratings, resulting in a shift of the resonant wavelengths and thereby realizing free-space-coupled modulators. This technology not only enables SLMs with $\mathcal{O}(\text{MHz})$ to $\mathcal{O}(\text{GHz})$ modulation rates, it also operates in the VIS to NIR wavelength range. Moreover, our devices are fabricated on 200 mm diameter silicon wafers using deep UV optical lithography and CMOS-compatible, low-temperature processes. Hence, we can fabricate the piezoelectric actuators and resonant waveguide gratings directly on top of electronics to drive the devices [177] or on (multiple) metal layers to enable large-scale electrical interconnects. These integration schemes are advantageous for the commercial production of large-scale SLMs.

Our work builds on a platform developed at Sandia National Laboratories consisting of a SiN optical waveguide layer on top of an AlN-based piezoelectric actuation layer [178]. While previous works on this platform focused on photonic integrated circuits [158, 178–180], here we demonstrate densely packed free-space-coupled modulators arranged in a 4×4 grid with a high fill factor of $\sim 96\%$ as a proof of concept for scalable SLM technology (Fig. 6.1). To boost the modulation efficiency of our devices we not only make use of optically resonant devices,

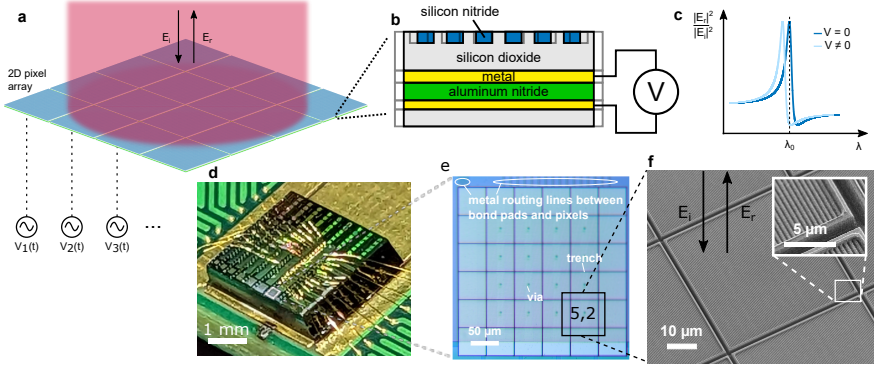


Figure 6.1: Concept and device images. **a, b**, Concept figure of our SLM technology based on piezoelectrically actuated SiN resonant waveguide gratings. The piezoelectric actuators are based on AlN thin films. **c**, Device operation principle. Applying a voltage shifts the reflection spectrum. **d**, Chip with 4×4 SLM wire bonded to a PCB. See Methods for packaging details. **e**, Microscope image of 4×4 SLM with a $50 \mu\text{m}$ pixel pitch and $1 \mu\text{m}$ wide trenches in between pixels. **f**, SEM image showing a grating surrounded by trenches. Taken from [145].

namely resonant waveguide gratings [181], but we also take advantage of the mechanical resonances of our pixels, which greatly enhances the piezoelectrically induced displacement [182]. Resonant waveguide gratings, also known as guided mode resonant gratings or waveguide-mode resonant gratings, couple light incident at specific wavelengths, incidence angles, and polarization to leaky guided modes, giving rise to resonances in the reflection and transmission spectra (in amplitude and phase) [181].

6.2 Results

6.2.1 Simulation

We use Ansys Lumerical's 2D FDTD solver for optical simulations. We run the simulation for two orthogonal polarizations. Afterwards, we use transfer matrix multiplication to implement the beamsplitter and wave plates together with the simulations of both polarizations. Our simulation takes into account the Gaussian shape of the excitation and collected beams. To directly compare the simulation with the measurement, we implement the same normalization method. We perform a simulation without the grating structure to simulate the effect of reflection from the aluminum layer with the silicon dioxide and SiN layers on top (E_{ref}). The resulting simulation is able to capture the entire measurement setup to accurately

predict the results. An example field profile from the grating is shown below.

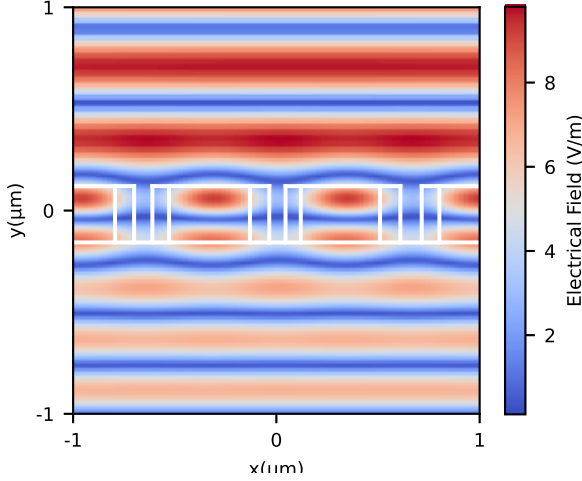


Figure 6.2: Field profile of the TE polarized light in the structure at a wavelength of 800 nm. The white lines depict the edges of the SiN and silicon dioxide structures. The grating is only partly filled with oxide due to deposition limitations. Taken from [145].

6.2.2 Design

We designed our SiN resonant waveguide gratings to operate at a wavelength λ of ~ 780 nm (R1), with a pitch Λ of 0.490 μm for a SiN thickness of 0.3 μm . The simulated reflection spectrum of our gratings, $R[\text{dB}] = 10 \times \log_{10} \left(\frac{|E_{\text{out}}(\lambda)|^2}{|E_{\text{ref}}(\lambda)|^2} \right)$, in Fig. 6.4a shows a steep dip at a wavelength of ~ 800 nm with an extinction ratio > 50 dB (R4) with respect to the reflection at ~ 770 nm. We test our devices in a cross-polarized light setup, as schematically depicted below.

Linearly polarized light from a Ti:sapphire laser is sent through a polarizing beam-splitter and rotated 45° through the use of a half-wave plate. The light then impinges perpendicularly onto the resonant waveguide gratings. The TE and transverse magnetic (TM) polarizations in the light experience a different amplitude and phase change during the reflection such that when the light passes through the wave plates again, the resulting polarization has changed. When the reflected light then hits the polarizing beamsplitter, part of it is reflected to the detector rather than transmitted back to the laser. The detector is a high-speed avalanche photodiode (APD). By adjusting the voltage over the piezoelectric layer, we can change the amplitude and phase change both polarizations experience during reflection and control the

portion of the light that is reflected by the beamsplitter.

For the measurement of the reflection spectrum, we replaced the Ti:sapphire laser with a superluminescent diode (SLD), and sent the light to a spectrometer instead of an APD. To normalize the measurement of the reflection spectrum, we also measured the reflection spectrum from a uniform area of the chip that does not include the grating structure, where the light is simply reflected back by the aluminum electrode layer.

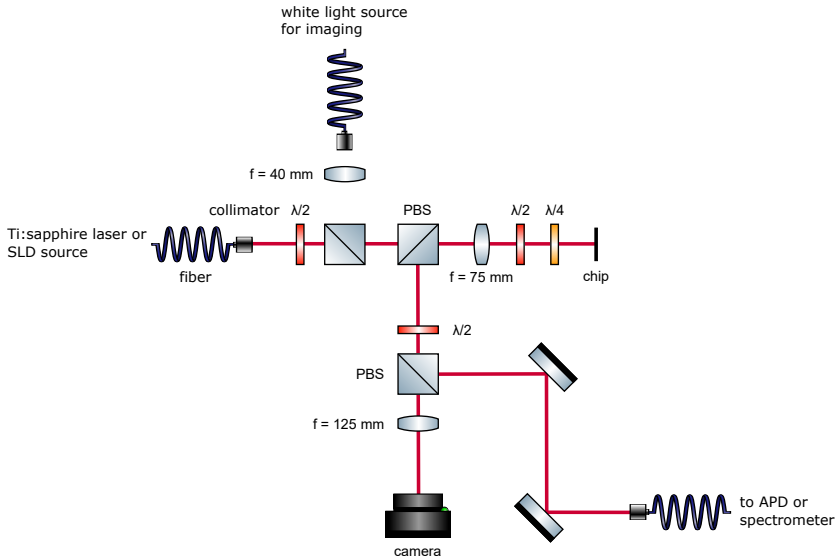


Figure 6.3: Schematic of the setup we used for characterization of our spatial light modulators. PBS: polarizing beamsplitter, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate. Taken from [145].

Our simulation of the reflection spectrum captures the cross-polarized testing setup. The steep dip in the reflection spectrum results from the phase difference between TE and TM polarized reflected light shifting from 0 to π while the reflection amplitude of TE and TM fields remain similar (Fig. 6.4c), where TE polarized light corresponds to the electric field being parallel to the grating lines. When the TE and TM polarized light waves reflected off the grating are in phase with equal amplitude, the reflected light is polarized at 0° before the polarizing beamsplitter and no light is reflected towards the detector. For a phase difference of π all light is reflected. Notably, the effective interferometer governing this effect is contained within $\sim 1 \mu\text{m}$ of thickness of the device, requiring no long-pathlength stabilization.

A decrease in grating pitch blue-shifts the wavelength of the dip in the reflection

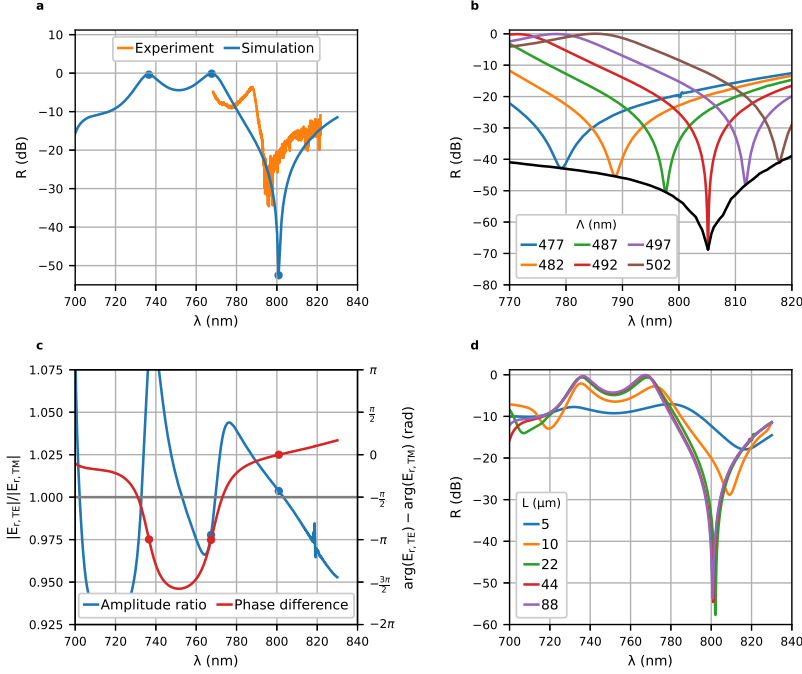


Figure 6.4: Device design, optical. **a**, Simulated reflection spectrum compared to the measured spectrum, with $R[\text{dB}] = 10 \times \log_{10} \left(\frac{|E_{out}(\lambda)|^2}{|E_{ref}(\lambda)|^2} \right)$. **b**, Influence of the grating pitch Λ on the reflection spectrum. These simulations are all for a duty cycle of 63 %. **c**, The simulated amplitude ratio and phase difference between TE and TM polarized reflected waves. The dots indicate the wavelengths at which there is a 0 and $-\pi$ phase differences, corresponding to the minima and maxima in **a**. **d**, Simulation of reflection spectrum for different grating sizes L . For a fair comparison the Gaussian input beam was rescaled such that the $1/e$ field full width is kept at 45 % of the grating size. This way, equal proportions of the input beam interact with the grating structure for all pixel sizes. Taken from [145].

spectrum (Fig. 6.4b). A pitch of 492 nm gives a maximum extinction ratio of > 60 dB. The reduced extinction ratio at different pitches results from the ratio between the TE and TM reflection amplitudes being further away from 1 where the phase difference is 0.

The resonant waveguide gratings are made of silicon nitride with a silicon oxide cladding. These materials are transparent in the visible and near-infrared wavelength range. Therefore, we can freely alter the design to shift the wavelength of operation within this transparency range. As an example, figure. 6.5 shows the simulated reflection spectrum for a grating pitch of $0.27 \mu\text{m}$, with a resonance at ~ 470 nm. When reducing the grating pitch, it is important to keep fabrication limits in mind. Fabrication limits depend on the foundry you are working with and the technology

and toolset they have available. 193 nm deep UV lithography is a widely available technology in commercial foundries that allows patterning of sub-100 nm features [183], enabling the pitches needed for blue wavelength gratings. The exact feature size depends not only on pitch but also the duty cycle of the grating, e.g. for a 100 nm minimum feature size and 0.27 μm pitch, you can fabricate duty cycles in between 37 % and 63 % (the simulation shown below is for a duty cycle of 63 %).

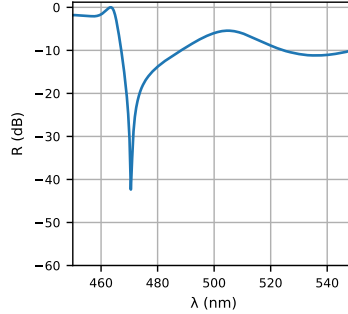


Figure 6.5: Simulated reflection spectrum of a grating (pitch of 0.27 μm) designed for a shorter working wavelength. Taken from [145].

Our simulations take into account the finite size of the gratings and the incident light beam. While the fabricated and tested devices have a grating size L of 49 μm (Fig. 6.1e), simulations indicate that we could reduce the size down to $\sim 20 \mu\text{m}$ without significant changes in extinction ratio and the overall shape of the reflection spectrum (Fig. 6.4d), resulting in even higher channel densities (R2).

The material platform with which we are working allows fabrication of undercut devices (see section 6.2.3), giving us an additional degree of freedom in engineering the mechanical device properties. We can produce pixels of length L supported by a pillar of size l underneath (schematically shown in Fig. 6.6a, SEM image in Fig. 6.6b), where L and l can be chosen freely for every pixel. The pillar also contains electrical vias between the piezoelectric actuator and a bottom metal routing layer, connecting the pixels to bond pads (see Fig. 6.1d and 6.1e). Fig. 6.6c shows the simulated mechanical mode with an eigenfrequency f_r of 5.9 MHz for a device with $L = 49 \mu\text{m}$ and $l = 10 \mu\text{m}$. This closely matches the resonance observed experimentally, Fig. 6.7b and 6.7c. By altering the pixel and pillar size L and l , we can set the mechanical resonance to a frequency of choice (Fig. 6.6d).

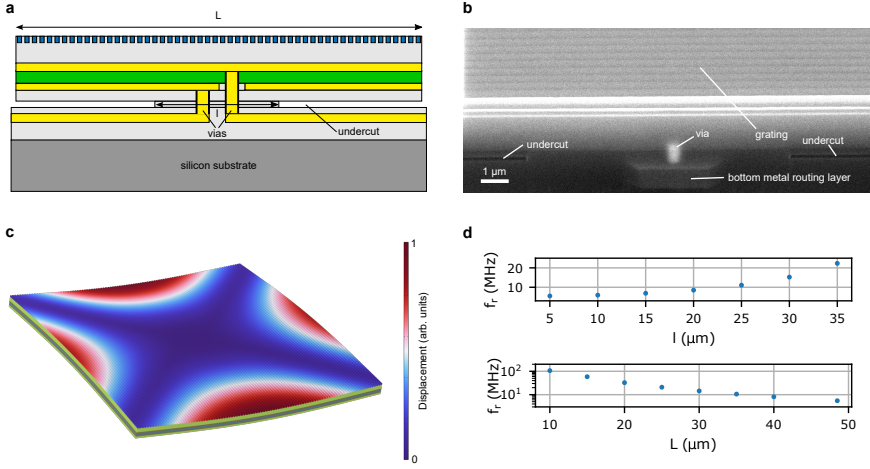


Figure 6.6: Device design, mechanical. **a**, Schematic cross-section of a released device with grating size L . Released devices are undercut and anchored to the substrate with a silicon dioxide pillar, with diameter l , in the middle of the grating. **b**, SEM image of a cross-section of a released device (at an angle of 57.5°). We used focused ion beam milling (FIB) to create a hole in the device so we could image the cross-section. This is an image of the middle of a grating, where it is anchored to the substrate. **c**, Simulated mechanical mode with an eigenfrequency f_r of 5.9 MHz for a released device with $L = 49 \mu\text{m}$ and $l = 10 \mu\text{m}$. Simulated in COMSOL. **d**, Simulated eigenfrequency f_r as a function of pillar diameter l for grating size $L = 49 \mu\text{m}$ (top) and simulated f_r as a function of L for $l = 5 \mu\text{m}$ (bottom). Taken from [145].

6.2.3 Fabrication

Our devices consist of a SiN optical waveguide layer on top of an AlN-based piezoelectric actuation layer with a silicon dioxide optical buffer layer in between [178–180]. The devices are fabricated on 200 mm diameter silicon wafers at Sandia National Laboratories using deep UV optical lithography. Low-temperature, CMOS-compatible processes are used for thin-film deposition, namely PECVD: for amorphous silicon, SiN and oxide deposition and physical vapor deposition (PVD): for AlN and metal deposition. There are three metal layers in the stack to enable device actuation. From bottom to top, these are: a routing layer which we use to connect each of the pixels to bond pads, a bottom electrode layer, and a top electrode layer. In between the two electrode layers there is the AlN layer; together these comprise the piezoelectric actuation layer. The bottom electrode layer is separated from the routing layer by a silicon dioxide buffer. The three metal layers are connected by vias. Throughout the process flow, chemical-mechanical polishing (CMP) is used for planarization. In between the bottom electrode layer and routing layer there is also a patterned amorphous silicon layer to enable undercutting of

devices. After having processed the entire device stack, a release etch in XeF_2 gas removes the amorphous silicon to create undercut devices. The XeF_2 gas can reach the amorphous silicon layer through deep, etched trenches.

6.2.4 Packaging

We dice the wafers into chips and wire bond them to printed circuit boards (Fig. 6.1d). The devices with 4×4 pixels have 17 bond pads, 1 pad for a shared ground and 16 pads for the signals applied to each of the pixels. Each of our PCBs contains 16 operational amplifiers (OPAMPs) (Texas Instruments THS3491) to individually address 16 pixels. The OPAMPs provide a voltage gain of 5, have a 900 MHz bandwidth, and a ± 16 V supply voltage. Ganged microscale RF plugs (Samtec) connect the PCBs to signal generators.

6.2.5 Characterization

Fig. 6.7a and 6.4a show the measured reflection spectrum of a grating and its agreement with simulations, with a measured extinction ratio > 20 dB (R4). We measure the modulation amplitude A and speed of the packaged devices by reflecting laser light off a pixel and detecting the reflected light (with electric field E_{out}) on a fast photodiode (Fig. 6.7e), which is connected to an electrical spectrum analyzer (ESA). When applying an alternating current (AC) voltage to the illuminated pixel, a peak appears on the ESA at the applied AC frequency f , as anticipated for our piezoelectrically actuated device. The height of this peak, i.e. the modulation amplitude A , depends on the laser wavelength. Fig. 6.7a overlaps the reflection spectrum with the modulation amplitude as a function of wavelength λ . The peak of the modulation amplitude occurs where the slope in the reflection spectrum is steepest (~ 791 nm). The devices have an optical bandwidth of several nanometers (8 nm peak to trough of resonance, 3 dB bandwidth of 2.3 nm in the modulation amplitude measurement). This corresponds to photon-lifetime-limited modulation bandwidths on the order of 1 THz, which does not pose a limitation for the envisaged applications. Moreover, the target applications typically only require modulators with narrowband operation at a discrete set of wavelengths (e.g. a set wavelengths corresponding to certain atomic transitions). Our modulator technology is very well suited to accommodate this requirement. Either one can use separate modulator chips designed to operate at different wavelengths, or pixels designed to operate at different wavelengths can be integrated on the same chip (in separate chip areas or interleaved).

Fig. 6.7b compares the modulation amplitude and speed for two different types of devices, released and unreleased. Released devices are undercut and anchored

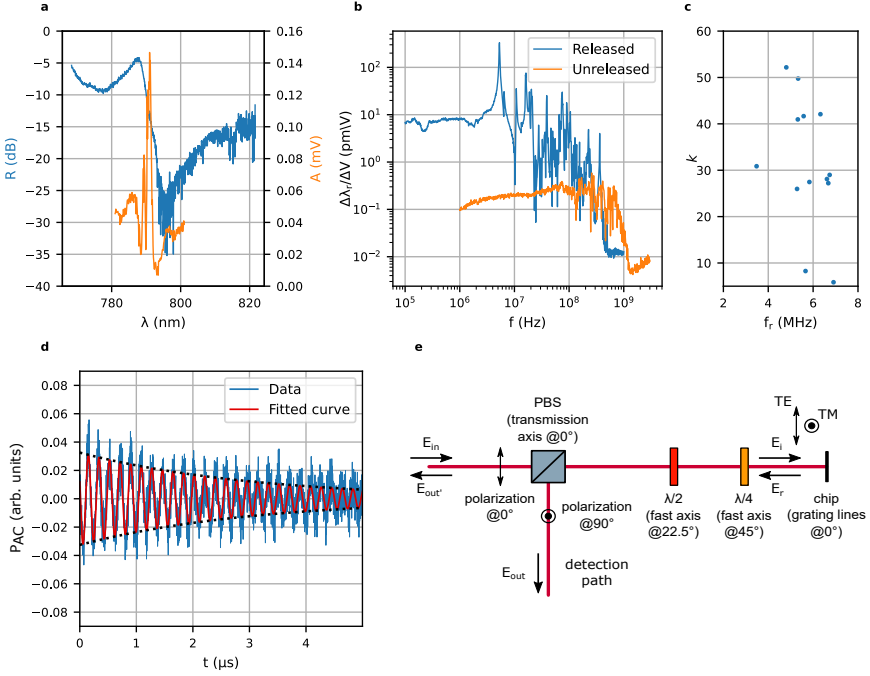


Figure 6.7: Device characterization. **a**, The reflection spectrum of the grating (blue) overlapped with the modulation amplitude A as a function of wavelength (orange), measured on an unreleased device at a fixed AC frequency f of 20 MHz for a peak-to-peak voltage of 10 V. **b**, Wavelength shift $\Delta\lambda_r/\Delta V$ versus AC frequency f for a released and unreleased device. We used a detector with a 3 dB bandwidth of DC-400 MHz for the released device and 5-1000 MHz for the unreleased device. **c**, Measurement of the different mechanical resonance frequencies f_r for each pixel of the strong resonance around 5 MHz and the associated enhancement factor k . 13 of the 16 pixels were functioning in this device. All measurements were done at a wavelength of 791 nm. **d**, Ringdown measurement of the mechanical mode at ~ 5 MHz of a released device. For this measurement we first apply an AC frequency at resonance, then we switch it off and observe how the AC-coupled photodiode signal P_{AC} decays over time t on an oscilloscope. Fitting gives a ringdown time τ of 3.1 μ s. **e**, Schematic depiction of our cross-polarized light setup. PBS: polarizing beamsplitter, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate. Taken from [145].

to the substrate with a $10\mu\text{m}$ wide silicon dioxide pillar in the middle of the pixel (see Fig. 6.6b for an SEM image of a device cross-section). Unreleased devices have no undercut. The goal of releasing is to make the devices more mechanically compliant, resulting in lower drive voltages for the same level of induced strain. Additionally, released devices have high-quality-factor mechanical resonances. Resonant enhancement reduces the required drive voltage even further. Fig. 6.7b shows the wavelength shift $\Delta\lambda_r/\Delta V$ of the reflection spectrum versus the applied

AC frequency f for a released and unreleased grating. We calculate the wavelength shift from the measured modulation amplitude and the slope of the reflection spectrum. The numerous peaks and troughs in Fig. 6.7b are attributed to mechanical resonances [184, 185]. The more compliant nature of the released devices results in low-frequency wavelength shifts that are more than an order of magnitude larger compared to the unreleased devices. It also leads to the appearance of mechanical resonances at lower frequencies. Finite element analysis confirms the existence of mechanical resonances and identifies the mechanical mode at $f_r \approx 5$ MHz for the released device (Fig. 6.6c). The resonance at $f_r \approx 5$ MHz gives a large wavelength shift of $4 \times 10^2 \text{ pm V}^{-1}$, which corresponds to an enhancement of a factor $k = \frac{(\Delta\lambda_r/\Delta V)_{f_r}}{(\Delta\lambda_r/\Delta V)_{DC}} \approx 50$ compared to the low-frequency shift. Up to a frequency of ~ 100 MHz, the data shows wavelength shifts larger than the low-frequency response for the released device (R3). The stiffer nature of the unreleased device shifts the resonances to higher frequencies. Up to ~ 700 MHz, wavelength shifts are comparable to the low-frequency response. The frequency response measurements are limited by the photodetector bandwidths (DC-400 MHz for the released device and 5-1000 MHz for the unreleased device measurement) and the 900 MHz bandwidth of the voltage amplifiers on the printed circuit boards.

From the frequency response measurements (Fig. 6.7b) and the measured reflection spectrum (Fig. 6.7a), we can estimate the voltages required to shift the spectrum by 8 nm, that is, the wavelength difference between the trough and peak in the spectrum. We find a voltage of ~ 20 V for a released device at the ~ 5 MHz mechanical resonance and $\sim 1 \times 10^3$ V off-resonance (100 kHz driving frequency). For an unreleased device, we estimate a voltage of $\sim 40 \times 10^3$ V off-resonance (at 10 MHz). We recognize that the off-resonance and unreleased device voltages are high in this proof-of-concept demonstration and suggest ways of lowering these significantly in section 6.3. Also, we note that several technologies exist today to deliver voltages in the $\mathcal{O}(10 \text{ V})$ to $\mathcal{O}(\text{kV})$ range at $\mathcal{O}(\text{MHz})$ to $\mathcal{O}(\text{GHz})$ frequencies, such as Si laterally-diffused metal-oxide semiconductor (LDMOS) [186], silicon carbide (SiC) [187], and gallium nitride (GaN)-based devices [188].

Fig. 6.7d shows the ringdown measurement of the mechanical mode at ~ 5 MHz for a released device. Fitting the data gives a ringdown time τ of $3.1 \mu\text{s}$. This corresponds to a mechanical Q -factor of $Q_m = \frac{\omega_m \tau}{2} = 52$ ($\omega_m = 2\pi \times 5.3 \text{ MHz}$) [189]. This is in good agreement with the enhancement factor of ~ 50 observed in the frequency response measurement, as expected for a harmonic oscillator.

Pixel-to-pixel fabrication-induced variations lead to differences in resonance frequencies and enhancement factors, e.g. variations in pixel size, layer thicknesses, and depth of the undercut. For the pixels in our 4×4 device, we determined the mechanical resonance frequencies f_r of the strong resonance around 5 MHz and the

associated enhancement factor k (Fig. 6.7c). The average resonance frequency is 5.7 MHz (standard deviation of 0.9 MHz) and the average enhancement factor is 32 (standard deviation of 13). Established post-fabrication trimming techniques such as laser trimming [190] and FIB milling [191] can be used to tune up the resonances. A possible approach for closed-loop laser trimming consists of combining the trimming laser, probe laser (to be modulated by the device), and imaging optics in a single optical system, as has been demonstrated for photonic crystal cavities [176] and ring resonators [158]. Image recognition methods can locate the pixel edges to be trimmed [190]. We can parallelize laser trimming of multiple pixels by e.g. using a liquid crystal SLM to generate arrays of laser spots and photodetector arrays for probe laser detection.

6.3 Discussion

One of the main challenges ahead is to reduce the voltages required to achieve high-extinction-ratio modulation. We see several ways to achieve this. Firstly, we can use a piezoelectric material with an enhanced response. Scandium aluminum nitride, for instance, has a piezoelectric response up to 5 times larger compared to AlN [192]. Secondly, we can use optical resonators with reduced optical linewidths. Recently, a SiN-based resonant waveguide grating with a linewidth of only ~ 0.7 μm at 779 nm has been demonstrated [193]. Vertically coupled photonic crystal cavities with high quality factors are another promising candidate. These have been demonstrated in silicon with linewidths < 10 μm at a wavelength of 1.6 μm [176]. Silicon nitride photonic crystal cavities with linewidths down to 0.1 μm at 760 nm have been reported [194], though these were not vertically coupled. By combining narrow-linewidth optical resonators with piezoelectric materials with an enhanced response, we can potentially reduce the drive voltages by three to four orders of magnitude. A significant reduction in linewidth will increase the need for post-fabrication optical resonance tuning, as the resonant wavelength is likely to deviate from the target operating wavelength. This is a common problem in integrated optics for which multiple solutions have been reported, e.g. laser trimming [158, 176] and on-chip heaters [158, 195].

Another challenge is to get all the required electrical driving signals onto the SLM chip as we scale up the number of pixels. In our proof-of-concept device we use wire bonds. The number of wire bonds is limited by the available chip perimeter. For example, on a 1 cm by 1 cm chip, for a pixel size of 50 μm and a typical bond pad spacing of 100 μm , we can fit 40 000 pixels, but only 400 bond pads around the chip perimeter. One approach to increase the number of electrical inputs is to make use of through-silicon vias [196] and bond the SLM chip to an interposer.

This interposer could also hold electronic driving integrated circuits (ICs). An even more advanced solution is to integrate some of the electronics on the SLM chip.

We see many potential applications for this SLM technology. Depending on the target application, we can configure our modulator technology in different ways. For instance, driving the modulators at a strong mechanical resonance generates strong sidebands to the incident laser light (the sidebands could be resonant with an atomic transition). The generation of these sidebands can be switched on and off (individually controlled for every pixel) with response times on the order of microseconds, with the exact response time depending on the mechanical quality factor. This has applications in the optical control of atomic systems, where one wishes to address certain atomic transitions in large-scale arrays of atoms, ions, or solid-state color centers [158]. We can use different mechanical resonances to generate sidebands at different frequencies or engineer the pixels to alter the mechanical resonances, e.g. by varying the grating size or the depth of the undercut. Laser trimming [176, 190] or focused ion beam milling [191] can alter the resonance frequencies post-fabrication.

Predictable time-varying and even periodically repeating light patterns can be generated in the far field [184] by driving each of the pixels at a particular mechanical resonance frequency, enabling low-voltage driving, with a particular phase. The generated pattern will depend on the chosen frequencies and phases. This concept has been described for photonic integrated circuit phased arrays [184] and has applications in atom control [197], display technology [198], and laser ranging [199]. The proposed SLM technology enables MHz speeds, compared to conventional MEMS laser scanners limited to sub-MHz speeds [198].

Our modulator technology could even generate arbitrary waveforms requiring the full device bandwidth (i.e. not only driving at resonance frequencies) by using signal equalization techniques to compensate for the non-flat frequency response. Signal equalization has been demonstrated for photonic integrated circuit modulators with mechanical resonances in the MHz to GHz range [185].

In conclusion, we have presented a scalable high-channel-density, high-speed modulator technology operating in the visible to near-infrared spectrum. This technology has the potential to drive progress across various fields in science and technology, including large-scale coherent optical control of atomic quantum systems.



Appendix

A.1 Pockels modulator simulations in COMSOL with MATLAB

This appendix details the numerical workflow used to calculate the electro-optic overlap and half-wave voltage ($V_{\pi}L$) discussed in section 2.1.2. To facilitate rapid parameter sweeps and automated mode selection, the simulations were performed using the COMSOL Multiphysics LiveLink for MATLAB interface. This approach allows for the programmatic control of geometry, meshing, and solvers, as well as the post-processing of complex surface integrals across large design spaces.

First the model is loaded and opened so you can tweak it if needed. Then some constants are defined in SI units. We can then set the value of parameters in the model using `model.param.set()`. One can then use simple loops in matlab to explore the desired parameter space. One then runs the same steps as COMSOL usually does through the `model.geom().run`, `model.mesh().run` and `model.study().run` commands.

We then calculate the two 2D surface integrals using `mphint2(model,'es.Ex*ewfd.Ex*conj(ewfd.Ex)','surface','selection',[6])` where we take care to only integrate along the extraordinary axis of the material because of the strong tensor component in the Pockels effect. We also ensure the integration is only done where

the LN material is present since light that doesn't overlap with the Pockels material will not contribute.

The optical mode solver finds multiple modes, and this calculation can be done for each of them. We have to select through them to find the correct mode. Typically they are ordered by effective refractive index and we want a TE mode with a high index, often this will be the last mode (20 in this case) but sometimes TM modes are found with higher refractive indices at which point we have to filter through the modes using some selection criteria depending on the situation, in this case it's quite rudimentary by looking for a $V_{\pi}L < 60$ Vcm through $V_{\pi}L_{TE} > 60$. Not only will this filter out TM modes with barely any x-component in the electric field, it will also filter out even TE modes since the opposite nodes in the mode will cancel out in the overlap integral.

Listing A.1: Simple example of the MATLAB script to control the COMSOL interface

```

1  model = mphload('StaticSimulator.mph','model');
2  mphlaunch model
3
4  c = 299792458; % m/s
5  mu_0 = 4*pi*1e-7; % H/m
6  eps_0 = 1/(mu_0*c^2); % F/m
7  ne_thin_film = 2.1376; % 1550 nm
8  % ne_thin_film = 2.1451; % 1310 nm
9  wvl = 1550e-9; % m
10 r33_thin_film=30.9*10^(-12); % m/V
11
12 model.param.set('Electrode_gap', '6.0 [um]');
13 model.param.set('Waveguide_width', '900 [nm]');
14 model.param.set('BCB_thickness', '50 [nm]');
15
16 model.geom('geom1').run;
17 model.mesh('mesh1').run;
18 model.study('std1').run;
19
20 neff_g=mphglobal(model,'ewfd.neff');
21 Modenumber=20;
22 neff=neff_g(Modenumber);
23 integral_TE_g = mphint2(model,'es.Ex*ewfd.Ex*conj(ewfd.Ex)','
    surface','selection',[6])./mphint2(model,'real(ewfd.Ex*conj(
    ewfd.Hy)-ewfd.Ey*conj(ewfd.Hx))','surface');
24 integral_TE = integral_TE_g(Modenumber);
25
26 Delta_n_eff_TE=-(c*eps_0*(ne_thin_film^4)*r33_thin_film*
    integral_TE/2); % 1/V
27 VpiL_TE=abs(wvl/(2*Delta_n_eff_TE))*100; % Vcm
28 loss=-40*pi*imag(neff)/(wvl*log(10))/100; %dB/cm
29 VpiLalpha=VpiL_TE.*loss;
30
31 while (Modenumber > 15) && (VpiL_TE > 60)
32     Modenumber = Modenumber-1;
33     integral_TE = integral_TE_g(Modenumber);
34

```

```

35 Delta_n_eff_TE=-(c*eps_0*(ne_thin_film^4)*r33_thin_film*
    integral_TE/2); % 1/V
36 VpiL_TE=abs(wvl/(2*Delta_n_eff_TE))*100; % Vcm
37 neff=neff_g(Modenumber);
38 loss=-40*pi*imag(neff)/(wvl*log(10))/100; %dB/cm
39
40 VpiLalpha=VpiL_TE.*loss;
41 end
42 if Modenumber == 15
43     Neff=nan;
44     Loss=nan;
45     VpiL=nan;
46 else
47     Neff=neff;
48     Loss=loss;
49     VpiL=VpiL_TE;
50 end

```

Once we can accurately model a geometry and extract the relevant parameters from it, we can go exploring the parameter space. At this point any optimisation algorithm can be used, I typically used simple for loops searching the parameter space either completely or in rough and fine steps, saving the three important values n_{eff} , $V_{\pi}L$, and α_{opt} for each configuration. Depending on the situation we then often filtered the results based on the maximum value of the α_{opt} before then selecting the lowest $V_{\pi}L$. For a two dimensional search space this could look like this:

Listing A.2: Simple example of the MATLAB script to analyse the COMSOL data

```

1 MaxLoss=0.01;% 0.01; %dB/cm
2 Mask=Loss<MaxLoss;
3 FilteredVpiL=VpiL;
4 FilteredVpiL(~Mask) = nan;
5 [BestVpiL1,I1]=min(FilteredVpiL);
6 [BestVpiL,I2]=min(BestVpiL1);
7 BestWidth=Widths(1,I1(I2));
8 BestGap=Gaps(1,I2);

```

A.2 Mach-Zehnder Modulator model expanded using imbalanced couplers

For completeness and since it can sometimes be useful to explain measurements that are 'better than expected' I include the math for a MZM when the couplers are not perfectly balanced. We can define the power splitting ratios of the input and output splitter according to $\kappa : 1 - \kappa$ and $\kappa' : 1 - \kappa'$, and the field thus uses the square root of these.

$$\begin{aligned}
\frac{I_{\text{out}}}{I_{\text{in}}} &= \left| \begin{bmatrix} \sqrt{\kappa'} & \sqrt{1-\kappa'} \end{bmatrix} \begin{bmatrix} \sqrt{a_1} e^{-j(\pi \frac{V}{2V_\pi} + \beta(\lambda)\Delta L)} & 0 \\ 0 & \sqrt{a_2} e^{+j\pi \frac{V}{2V_\pi}} \end{bmatrix} \begin{bmatrix} \sqrt{\kappa} \\ \sqrt{1-\kappa} \end{bmatrix} \right|^2 \\
&= \kappa\kappa' a_1 + (1-\kappa)(1-\kappa') a_2 \\
&\quad + 2\sqrt{\kappa\kappa'(1-\kappa)(1-\kappa') a_1 a_2} \cos\left(\pi \frac{V}{V_\pi} + \beta(\lambda)\Delta L\right)
\end{aligned} \tag{A.1}$$

Resulting in the following maximum and minimum transmissions,

$$T_{\text{max}} = \left(\sqrt{\kappa\kappa'\eta_1} + \sqrt{(1-\kappa)(1-\kappa')\eta_2} \right)^2 \tag{A.2}$$

$$T_{\text{min}} = \left(\sqrt{\kappa\kappa'\eta_1} - \sqrt{(1-\kappa)(1-\kappa')\eta_2} \right)^2 \tag{A.3}$$

and the ER can then be written as:

$$\text{ER} = \left(\frac{\sqrt{\kappa\kappa'\eta_1} + \sqrt{(1-\kappa)(1-\kappa')\eta_2}}{\sqrt{\kappa\kappa'\eta_1} - \sqrt{(1-\kappa)(1-\kappa')\eta_2}} \right)^2. \tag{A.4}$$

If an imbalance in the loss cannot be avoided an intentional imbalanced splitting ratio can be used to still aim to achieve a high extinction ratio.

A.3 Piezo-electric resonance

The electro-optical response function shown in Fig. 4(b) of the main manuscript shows a small kink near 12 GHz. We are fairly sure this is a piezo-electrical resonance in the LN. Even though we order 300 nm LN layers, in reality the LN layer is around 280 nm thick in the x-direction (it varies between 270-290 nm over the entire wafer). The speed of sound in that direction in LN is:

$$v = \sqrt{\frac{c_{11}}{\rho}} = \sqrt{\frac{2.030 \times 10^{11} \text{ Ncm}^3}{m^2 4.65g}} = 6.62 \times 10^3 \frac{m}{s} \tag{A.5}$$

Here, both the elastic constant c_{11} and density ρ have been taken from [200]. For flat materials with uniform height the lowest resonance frequency for thickness-extension can be found using:

$$f = \frac{v}{2 \times T} = \frac{6.62 \times 10^3 m}{s \times 2 \times 280 \times 10^{-9} m} = 11.827 \text{ GHz} \tag{A.6}$$

Where v is the speed of sound in the material and T is the thickness of the thin dimension of the material layer. The value calculated from equation (A.6) agrees very well with the kink in the measured electro-optic response found at 11.83 GHz, as shown in Supp. Fig. A.1. Further confirmation of the piezo-electrical origin of the resonance is the fact that it is not visible in the purely electrical measurements.

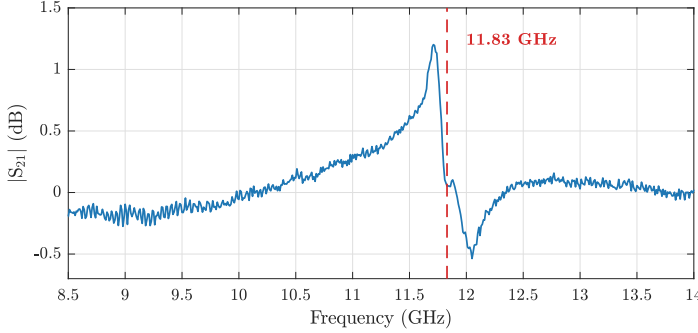


Figure A.1: Zoom in of the resonance in the $|S_{21}|$ graph of the electro-optical response. The marker indicates the resonance. Taken from [2].

A.4 Statement of contributions and collaborative Work

The research presented in this thesis involved collaborative efforts across various cleanroom fabrication stages and high-frequency design iterations. To provide clarity on the division of labor, Table A.1 outlines the specific tasks, design steps, and fabrication processes performed by colleagues, collaborators, or external foundries for each prototype generation.

Table A.1: Overview of specific fabrication, design, and layout contributions from collaborators.

Prototype	Process / Task	Contributor
Prototype 1	Electron-beam lithography	Stijn Poelman
	Metal deposition	Steven Verstuyft
Prototype 2	Electron-beam lithography	Stijn Poelman
	Metal deposition	Steven Verstuyft
	RF design	Arno Moerman, Olivier Caytan
Prototype 3	SiPh platform fabrication	imec
	RF design	Arno Moerman, Olivier Caytan
	Layout engineering	Ewoud Vissers
	Cleanroom post-processing	Margot Niels, Maximilien Billet, Tingting Zhai, Patrick Nenezic
	Metal deposition	Steven Verstuyft

References

- [1] Annika F. Wandesleben, Delphine Truffier-Boutry, Frédérique Glowacki, Agnès Royer, Maximilian Lederer, Benjamin Lilienthal-Uhlig, and Carla Vogt. *Influences and Diffusion Effects of Lithium Contamination during the Thermal Oxidation Process of Silicon*. Advanced Engineering Materials, 26(13):2400396, 2024.
- [2] T. Vanackere, T. Vandekerckhove, L. Bogaert, M. Billet, S. Poelman, S. Cuyvers, J. Van Kerrebrouck, A. Moerman, O. Caytan, N. Singh, S. Lemey, G. Torfs, P. Ossieur, G. Roelkens, S. Clemmen, and B. Kuyken. *Heterogeneous integration of a high-speed lithium niobate modulator on silicon nitride using micro-transfer printing*. APL Photonics, 8(8):086102, August 2023.
- [3] Margot Niels, Tom Vanackere, Ewoud Vissers, Tingting Zhai, Patrick Nenezic, Jakob Declercq, Cédric Bruynsteen, Shengpu Niu, Arno Moerman, Olivier Caytan, et al. *A high-speed heterogeneous lithium tantalate silicon photonics platform*. Nature Photonics, pages 1–7, 2026.
- [4] Erik Agrell, Magnus Karlsson, A R Chraplyvy, David J Richardson, Peter M Krummrich, Peter Winzer, Kim Roberts, Johannes Karl Fischer, Seb J Savory, Benjamin J Eggleton, Marco Secondini, Frank R Kschischang, Andrew Lord, Josep Prat, Ioannis Tomkos, John E Bowers, Sudha Srinivasan, Maité Brandt-Pearce, and Nicolas Gisin. *Roadmap of optical communications*. Journal of Optics, 18(6):063002, may 2016.
- [5] International Telecommunication Union. *Measuring Digital Development: Facts and Figures 2025*, 2025. Accessed: 2026-04-03.
- [6] Epoch AI. *AI Models Dataset*, 2026. Accessed: 2026-04-03.
- [7] Guilhem de Valicourt, Pete Pupalakis, Randy Giles, Marco Lamponi, Lukas Elsinger, Shawn Liu, Brett Sawyer, Jon Proesel, Son Thai Le, Eugene Ho, Karen Liu, Zhihui Zhu, Steve Corteselli, Laurent Alloine, Chris Daunt, Mark Ferriss, Behzad Rahmani, Fred Warning, Ashok Bruno, Siamak Abbaslou,

- Mehdi Zaman, Zeyu Pan, George Fischer, Gannon Reichert, John George, Utku Alakusu, Jeb Binkley, Issac Martinez, Karel van Acoleyen, Faezeh Fesharaki, Suzanne Paul, Vaishnavi Karra, Tu Nguyen, Nikitha Machineni, Andrew Sullivan, Daniel Assumpcao, and Peter Winzer. *1.6-Tbps low-power linear-drive high-density optical interface for machine learning/artificial intelligence*. Opt. Express, 33(7):15338–15354, Apr 2025.
- [8] International Energy Agency. *Energy and AI*, 2025. Licence: CC BY 4.0.
- [9] Anat Sneh and Christopher R. Doerr. *Indium Phosphide-Based Photonic Circuits and Components*. In Integrated Optical Circuits and Components. CRC Press, 1999. Num Pages: 77.
- [10] Xuetong Zhou, Dan Yi, David W. U. Chan, and Hon Ki Tsang. *Silicon photonics for high-speed communications and photonic signal processing*. npj Nanophotonics, 1(1):1–14, July 2024. Publisher: Nature Publishing Group.
- [11] S. Lischke, A. Peczek, J. S. Morgan, K. Sun, D. Steckler, Y. Yamamoto, F. Korndörfer, C. Mai, S. Marschmeyer, M. Fraschke, A. Krüger, A. Beling, and L. Zimmermann. *Ultra-fast germanium photodiode with 3-dB bandwidth of 265 GHz*. Nature Photonics, 15(12):925–931, December 2021. Publisher: Nature Publishing Group.
- [12] Karl Gass. *OIF adds a short-reach design to its 1600ZR/ ZR+ portfolio*.
- [13] Abdul Rahim, Artur Hermans, Benjamin Wohlfeil, Despoina Petousi, Bart Kuyken, Dries Van Thourhout, and Roel G. Baets. *Taking silicon photonics modulators to a higher performance level: state-of-the-art and a review of new technologies*. Advanced Photonics, 3(2):024003, 2021.
- [14] Yixin Yan, Haoran Zhang, Xiaolei Liu, Liuxing Peng, Qian Zhang, Guangbin Yu, Qing Wu, and Haitao Li. *Recent Progress in Electro-Optic Modulators: Physical Phenomenon, Structures Properties, and Integration Strategy*. Laser & Photonics Reviews, 19(3):2400624, 2025.
- [15] Viacheslav Snigirev, Annina Riedhauser, Grigory Lihachev, Mikhail Churaev, Johann Riemensberger, Rui Ning Wang, Anat Siddharth, Guan hao Huang, Charles Möhl, Youri Popoff, et al. *Ultrafast tunable lasers using lithium niobate integrated photonics*. Nature, 615(7952):411–417, 2023.
- [16] LightCounting. *Research Note: 2026 - The Year of Silicon Photonics*. Research note, LightCounting Market Research, 2024. Accessed: March 25, 2026.

- [17] Jae-Hoon Han, Frederic Boeuf, Junichi Fujikata, Shigeki Takahashi, Shinichi Takagi, and Mitsuru Takenaka. *Efficient low-loss InGaAsP/Si hybrid MOS optical modulator*. Nature Photonics, 11(8):486–490, 2017.
- [18] Tatsuro Hiraki, Takuma Aihara, Koichi Hasebe, Koji Takeda, Takuro Fujii, Takaaki Kakitsuka, Tai Tsuchizawa, Hiroshi Fukuda, and Shinji Matsuo. *Heterogeneously integrated iii-v/si mos capacitor mach-zehnder modulator*. Nature Photonics, 11(8):482–485, 2017.
- [19] José Manuel Estarán, Haik Mardoyan, Filipe Jorge, Oskars Ozolins, Aleksejs Udalcovs, Agnieszka Konczykowska, Muriel Riet, Bernadette Duval, Virginie Nodjiadjim, Jean-Yves Dupuy, Xiaodan Pang, Urban Westergren, Jiajia Chen, Sergei Popov, and Sébastien Bigo. *140/180/204-Gbaud OOK Transceiver for Inter- and Intra-Data Center Connectivity*. Journal of Lightwave Technology, 37(1):178–187, January 2019. Conference Name: Journal of Lightwave Technology.
- [20] Hiroshi Yamazaki, Munehiko Nagatani, Hitoshi Wakita, Yoshihiro Ogiso, Masanori Nakamura, Minoru Ida, Hideyuki Nosaka, Toshikazu Hashimoto, and Yutaka Miyamoto. *IMDD Transmission at Net Data Rate of 333 Gb/s Using Over-100-GHz-Bandwidth Analog Multiplexer and Mach-Zehnder Modulator*. Journal of Lightwave Technology, 37(8):1772–1778, April 2019. Conference Name: Journal of Lightwave Technology.
- [21] Tatsuro Hiraki, Takuma Aihara, Koichi Hasebe, Koji Takeda, Takuro Fujii, Takaaki Kakitsuka, Tai Tsuchizawa, Hiroshi Fukuda, and Shinji Matsuo. *Heterogeneously integrated III-V/Si MOS capacitor Mach-Zehnder modulator*. Nature Photonics, 11(8):482–485, Aug 2017.
- [22] Srinivasan Ashwyn Srinivasan, Marianna Pantouvaki, Shashank Gupta, Hong Tao Chen, Peter Verheyen, Guy Lepage, Gunther Roelkens, Krishna Saraswat, Dries Van Thourhout, Philippe Absil, et al. *56 Gb/s germanium waveguide electro-absorption modulator*. Journal of Lightwave Technology, 34(2):419–424, 2016.
- [23] *A manufacturable platform for photonic quantum computing*. Nature, 641(8064):876–883, 2025.
- [24] Koen Alexander, John P. George, Jochem Verbist, Kristiaan Neyts, Bart Kuyken, Dries Van Thourhout, and Jeroen Beeckman. *Nanophotonic Pockels modulators on a silicon nitride platform*. Nature Communications, 9(1):3444, 2018.
- [25] Felix Eltes, Marcel Kroh, Daniele Caimi, Christian Mai, Youri Popoff, Georg Winzer, Despoina Petousi, Stefan Lischke, J Elliott Ortmann, Lukas

- Czornomaz, et al. *A novel 25 Gbps electro-optic Pockels modulator integrated on an advanced Si photonic platform*. In 2017 IEEE International Electron Devices Meeting (IEDM), pages 24–5. IEEE, 2017.
- [26] Felix Eltes, Christian Mai, Daniele Caimi, Marcel Kroh, Youri Popoff, Georg Winzer, Despoina Petousi, Stefan Lischke, J. Elliott Ortmann, Lukas Czornomaz, Lars Zimmermann, Jean Fompeyrine, and Stefan Abel. *A BaTiO₃-Based Electro-Optic Pockels Modulator Monolithically Integrated on an Advanced Silicon Photonics Platform*. *J. Lightwave Technol.*, 37(5):1456–1462, Mar 2019.
- [27] Felix Eltes, Gerardo E Villarreal-Garcia, Daniele Caimi, Heinz Siegwart, Antonio A Gentile, Andy Hart, Pascal Stark, Graham D Marshall, Mark G Thompson, Jorge Barreto, et al. *An integrated optical modulator operating at cryogenic temperatures*. *Nature Materials*, 19(11):1164–1168, 2020.
- [28] Alexander A. Demkov and Agham B. Posadas. *Ferroelectric BaTiO₃ for Electro-Optic Modulators in Si Photonics*. *IEEE Journal of Selected Topics in Quantum Electronics*, 30(4: Adv. Mod. and Int. beyond Si and InP-based Plt.):1–13, 2024.
- [29] J. Elliott Ortmann, Felix Eltes, Daniele Caimi, Norbert Meier, Alexander A. Demkov, Lukas Czornomaz, Jean Fompeyrine, and Stefan Abel. *Ultra-Low-Power Tuning in Hybrid Barium Titanate-Silicon Nitride Electro-optic Devices on Silicon*. *ACS Photonics*, 6(11):2677–2684, 2019.
- [30] Ewout Picavet, Enes Lievens, Kobe De Geest, Hannes Rijckaert, Edgar Gutierrez Fernandez, Oier Bikondoa, Eduardo Solano, Petriina Paturi, Nishant Singh, Tinus Pannier, Jiayi Liu, Xin Yin, Dries Van Thourhout, Jeroen Beeckman, and Klaartje De Buysser. *Integration Of Solution-Processed BaTiO₃ Thin Films with High Pockels Coefficient on Photonic Platforms*. *Advanced Functional Materials*, 34(37):2403024, 2024.
- [31] Ewout Picavet, Kobe De Geest, Enes Lievens, Hannes Rijckaert, Tom Vandekerckhove, Eduardo Solano, Davy Deduytsche, Laura Van Bossele, Dries Van Thourhout, Klaartje De Buysser, and Jeroen Beeckman. *Solution-Processed Pb(Zr,Ti)O₃ Thin Films with Strong Remnant Pockels Coefficient*. *ACS Applied Materials & Interfaces*, 16(31):41134–41144, 2024. PMID: 39077874.
- [32] Inhwan Kim, Therese Paoletta, and Alexander A. Demkov. *Nature of electro-optic response in tetragonal BaTiO₃*. *Phys. Rev. B*, 108:115201, Sep 2023.
- [33] Daniel Chelladurai, Manuel Kohli, Joel Winiger, David Moor, Andreas Messner, Yuriy Fedoryshyn, Mohammed Eleraky, Yuqi Liu, Hua Wang, and

- Juerg Leuthold. *Barium titanate and lithium niobate permittivity and Pockels coefficients from megahertz to sub-terahertz frequencies*. Nature Materials, 24(6):868–875, 2025.
- [34] Christian Koos, Wolfgang Freude, Daria Kohler, Johannes Milvich, Clemens Kieninger, and Heiner Zwickel. *Silicon organic hybrid (SOH) and silicon-nitride-organic hybrid (SiNOH) integration: From electro-optic modulators to visible-wavelength lasers*. In Integrated Optics: Devices, Materials, and Technologies XXVI, page PC120040B. SPIE, 2022.
- [35] Luca Alloatti, Robert Palmer, Sebastian Diebold, Kai Philipp Pahl, Baoquan Chen, Raluca Dinu, Maryse Fournier, Jean-Marc Fedeli, Thomas Zwick, Wolfgang Freude, et al. *100 GHz silicon–organic hybrid modulator*. Light: Science & Applications, 3(5):e173–e173, 2014.
- [36] Stefan Wolf, Heiner Zwickel, Wladislaw Hartmann, Matthias Lauermann, Yasar Kutuvantavida, Clemens Kieninger, Lars Altenhain, Rolf Schmid, Jingdong Luo, Alex K.-Y. Jen, Sebastian Randel, Wolfgang Freude, and Christian Koos. *Silicon-Organic Hybrid (SOH) Mach-Zehnder Modulators for 100 Gbit/s on-off Keying*. Scientific Reports, 8(1):2598, April 2018. Publisher: Nature Publishing Group.
- [37] Marco Eppenberger, Andreas Messner, Bertold Ian Bitachon, Wolfgang Heni, Tobias Blatter, Patrick Habegger, Marcel Destraz, Eva De Leo, Norbert Meier, Nino Del Medico, Claudia Hoessbacher, Benedikt Baeuerle, and Juerg Leuthold. *Resonant plasmonic micro-racetrack modulators with high bandwidth and high temperature tolerance*. Nature Photonics, 17(4):360–367, April 2023. Publisher: Nature Publishing Group.
- [38] C. Haffner, W. Heni, Y. Fedoryshyn, J. Niegemann, A. Melikyan, D. L. Elder, B. Baeuerle, Y. Salamin, A. Josten, U. Koch, C. Hoessbacher, F. Ducry, L. Juchli, A. Emboras, D. Hillerkuss, M. Kohl, L. R. Dalton, C. Hafner, and J. Leuthold. *All-plasmonic Mach–Zehnder modulator enabling optical high-speed communication at the microscale*. Nature Photonics, 9(8):525–528, August 2015. Publisher: Nature Publishing Group.
- [39] Maurizio Burla, Claudia Hoessbacher, Wolfgang Heni, Christian Haffner, Yuriy Fedoryshyn, Dominik Werner, Tatsuhiko Watanabe, Hermann Massler, Delwin L. Elder, Larry R. Dalton, and Juerg Leuthold. *500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics*. APL Photonics, 4(5):056106, May 2019.
- [40] Benedikt Baeuerle, Wolfgang Heni, Claudia Hoessbacher, Yuriy Fedoryshyn, Ueli Koch, Arne Josten, Tatsuhiko Watanabe, Christopher Uhl, Horst Hettrich, Delwin L. Elder, Larry R. Dalton, Michael Möller, and Juerg Leuthold.

- 120 GBd plasmonic Mach-Zehnder modulator with a novel differential electrode design operated at a peak-to-peak drive voltage of 178 mV*. Optics Express, 27(12):16823–16832, June 2019. Publisher: Optica Publishing Group.
- [41] Chenghan Wu, Tom Reep, Steven Brems, Didit Yudistira, Joris Van Campenhout, Inge Asselberghs, Cedric Huyghebaert, Marianna Pantouvaki, Zheng Wang, and Dries Van Thourhout. *Graphene-Based Silicon Photonic Electro-Absorption Modulators and Phase Modulators*. IEEE Journal of Selected Topics in Quantum Electronics, 30(4: Adv. Mod. and Int. beyond Si and InP-based Plt.):1–11, July 2024. Conference Name: IEEE Journal of Selected Topics in Quantum Electronics.
- [42] Ming Liu, Xiaobo Yin, Erick Ulin-Avila, Baisong Geng, Thomas Zentgraf, Long Ju, Feng Wang, and Xiang Zhang. *A graphene-based broadband optical modulator*. Nature, 474(7349):64–67, June 2011. Publisher: Nature Publishing Group.
- [43] Marco Romagnoli, Vito Sorianello, Michele Midrio, Frank H. L. Koppens, Cedric Huyghebaert, Daniel Neumaier, Paola Galli, Wolfgang Templ, Antonio D’Errico, and Andrea C. Ferrari. *Graphene-based integrated photonics for next-generation datacom and telecom*. Nature Reviews Materials, 3(10):392–414, October 2018. Publisher: Nature Publishing Group.
- [44] Ming Jin, Ziyi Wei, Yanfang Meng, Haowen Shu, Yuansheng Tao, Bowen Bai, and Xingjun Wang. *Silicon-Based Graphene Electro-Optical Modulators*. Photonics, 9(2), 2022.
- [45] Vito Sorianello, Michele Midrio, Giampiero Contestabile, Inge Asselberghs, Joris Van Campenhout, Cedric Huyghebaert, I Goykhman, AK Ott, AC Ferrari, and Marco Romagnoli. *Graphene-silicon phase modulators with gigahertz bandwidth*. Nature Photonics, 12(1):40–44, 2018.
- [46] Marco A. Giambra, Vito Sorianello, Vaidotas Miseikis, Simone Marconi, Alberto Montanaro, Paola Galli, Sergio Pezzini, Camilla Coletti, and Marco Romagnoli. *High-speed double layer graphene electro-absorption modulator on SOI waveguide*. Opt. Express, 27(15):20145–20155, Jul 2019.
- [47] Elham Heidari, Hamed Dalir, Farzad Mokhtari Koushyar, Behrouz Movahhed Nouri, Chandraman Patil, Mario Miscuglio, Deji Akinwande, and Volker J. Sorger. *Integrated ultra-high-performance graphene optical modulator*. Nanophotonics, 11(17):4011–4016, 2022.
- [48] Haowen Shu, Zhaotang Su, Le Huang, Zhennan Wu, Xingjun Wang, Zhiyong Zhang, and Zhiping Zhou. *Significantly high modulation efficiency of*

- compact graphene modulator based on silicon waveguide*. Scientific reports, 8(1):991, 2018.
- [49] Chengli Wang, Zihan Li, Johann Riemensberger, Grigory Lihachev, Mikhail Churaev, Wil Kao, Xinru Ji, Junyin Zhang, Terence Blesin, Alisa Davydova, Yang Chen, Kai Huang, Xi Wang, Xin Ou, and Tobias J. Kippenberg. *Lithium tantalate photonic integrated circuits for volume manufacturing*. Nature, 629(8013):784–790, May 2024. Publisher: Nature Publishing Group.
- [50] Andreas Boes, Lin Chang, Carsten Langrock, Mengjie Yu, Mian Zhang, Qiang Lin, Marko Lončar, Martin Fejer, John Bowers, and Arnan Mitchell. *Lithium niobate photonics: Unlocking the electromagnetic spectrum*. Science, 379(6627):eabj4396, 2023.
- [51] Di Zhu, Linbo Shao, Mengjie Yu, Rebecca Cheng, Boris Desiatov, C. J. Xin, Yaowen Hu, Jeffrey Holzgrafe, Soumya Ghosh, Amirhassan Shams-Ansari, Eric Puma, Neil Sinclair, Christian Reimer, Mian Zhang, and Marko Lončar. *Integrated photonics on thin-film lithium niobate*. Advances in Optics and Photonics, 13(2):242–352, June 2021. Publisher: Optica Publishing Group.
- [52] Cheng Wang, Mian Zhang, and Marko Lončar. *High-Q Lithium Niobate Microcavities and Their Applications*, chapter Chapter 1, pages 1–35.
- [53] David E. Zelmon, David L. Small, and Dieter Jundt. *Infrared corrected Sellmeier coefficients for congruently grown lithium niobate and 5 mol. % magnesium oxide-doped lithium niobate*. J. Opt. Soc. Am. B, 14(12):3319–3322, Dec 1997.
- [54] *Basic Nonlinear Optical Crystals*, pages 5–74. Springer New York, New York, NY, 2005.
- [55] Mian Zhang, Cheng Wang, Rebecca Cheng, Amirhassan Shams-Ansari, and Marko Lončar. *Monolithic ultra-high-Q lithium niobate microring resonator*. Optica, 4(12):1536–1537, Dec 2017.
- [56] Kevin Luke, Prashanta Kharel, Christian Reimer, Lingyan He, Marko Loncar, and Mian Zhang. *Wafer-scale low-loss lithium niobate photonic integrated circuits*. Opt. Express, 28(17):24452–24458, Aug 2020.
- [57] Jeffrey Holzgrafe, Eric Puma, Rebecca Cheng, Hana Warner, Amirhassan Shams-Ansari, Raji Shankar, and Marko Lončar. *Relaxation of the electro-optic response in thin-film lithium niobate modulators*. Optics Express, 32(3):3619–3631, January 2024. Publisher: Optica Publishing Group.

- [58] Mian Zhang et al. *Integrated lithium niobate electro-optic modulators: when performance meets scalability*. *Optica*, 8(5):652–667, May 2021.
- [59] Hana K. Warner, Yuqi Zhao, Yu Zhang, Mian Zhang, and Marko Lončar. *DC-stable thin-film lithium niobate modulator at liquid nitrogen temperatures*. *Opt. Lett.*, 50(17):5398–5401, Sep 2025.
- [60] Payam Rabiei and Peter Gunter. *Optical and electro-optical properties of submicrometer lithium niobate slab waveguides prepared by crystal ion slicing and wafer bonding*. *Applied Physics Letters*, 85(20):4603–4605, 11 2004.
- [61] Yixin Zhu and Qing Wan. *Lithium niobate/lithium tantalate single-crystal thin films for post-moore era chip applications*. *Moore and More*, 1(1):6, August 2024.
- [62] Cheng Wang, Michael J. Burek, Zin Lin, Haig A. Atikian, Vivek Venkataraman, I-Chun Huang, Peter Stark, and Marko Lončar. *Integrated high quality factor lithium niobate microdisk resonators*. *Opt. Express*, 22(25):30924–30933, Dec 2014.
- [63] Amirmahdi Honardoost, Kamal Abdelsalam, and Sasan Fathpour. *Rejuvenating a Versatile Photonic Material: Thin-Film Lithium Niobate*. *Laser & Photonics Reviews*, 14(9):2000088, 2020.
- [64] Juanjuan Lu, Joshua B. Surya, Xianwen Liu, Alexander W. Bruch, Zheng Gong, Yuntao Xu, and Hong X. Tang. *Periodically poled thin-film lithium niobate microring resonators with a second-harmonic generation efficiency of 250,000%/W*. *Optica*, 6(12):1455–1460, 2019.
- [65] Cheng Wang, Carsten Langrock, Alireza Marandi, Marc Jankowski, Mian Zhang, Boris Desiatov, Martin M. Fejer, and Marko Lončar. *Ultrahigh-efficiency wavelength conversion in nanophotonic periodically poled lithium niobate waveguides*. *Optica*, 5(11):1438–1441, Nov 2018.
- [66] Cheng Wang, Mian Zhang, Brian Stern, Michal Lipson, and Marko Lončar. *Nanophotonic lithium niobate electro-optic modulators*. *Opt. Express*, 26(2):1547–1555, Jan 2018.
- [67] Cheng Wang, Mian Zhang, Xi Chen, Maxime Bertrand, Amirhassan Shams-Ansari, Sethumadhavan Chandrasekhar, Peter Winzer, and Marko Lončar. *Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages*. *Nature*, 562(7725):101–104, 2018.

- [68] Prashanta Kharel, Christian Reimer, Kevin Luke, Lingyan He, and Mian Zhang. *Breaking voltage–bandwidth limits in integrated lithium niobate modulators using micro-structured electrodes*. *Optica*, 8(3):357–363, Mar 2021.
- [69] Gengxin Chen, Kaixuan Chen, Ranfeng Gan, Ziliang Ruan, Zong Wang, Pucheng Huang, Chao Lu, Alan Pak Tao Lau, Daoxin Dai, Changjian Guo, and Liu Liu. *High performance thin-film lithium niobate modulator on a silicon substrate using periodic capacitively loaded traveling-wave electrode*. *APL Photonics*, 7(2):026103, 02 2022.
- [70] Gengxin Chen, Kaixuan Chen, Junwei Zhang, Ranfeng Gan, Lu Qi, Xuancong Fan, Ziliang Ruan, Zhenrui Lin, Jie Liu, Chao Lu, Alan Pak Tao Lau, Daoxin Dai, Changjian Guo, and Liu Liu. *Compact 100GBaud driverless thin-film lithium niobate modulator on a silicon substrate*. *Opt. Express*, 30(14):25308–25317, Jul 2022.
- [71] Lin Chang, Martin H. P. Pfeiffer, Nicolas Volet, Michael Zervas, Jon D. Peters, Costanza L. Manganelli, Eric J. Stanton, Yifei Li, Tobias J. Kippenberg, and John E. Bowers. *Heterogeneous integration of lithium niobate and silicon nitride waveguides for wafer-scale photonic integrated circuits on silicon*. *Opt. Lett.*, 42(4):803–806, 2017.
- [72] Mikhail Churaev, Rui Ning Wang, Annina Riedhauser, Viacheslav Snigirev, Terence Blésin, Charles Möhl, Miles H. Anderson, Anat Siddharth, Youri Popoff, Ute Drechsler, Daniele Caimi, Simon Hönl, Johann Riemensberger, Junqiu Liu, Paul Seidler, and Tobias J. Kippenberg. *A heterogeneously integrated lithium niobate-on-silicon nitride photonic platform*. *Nature Communications*, 14(1):3499, June 2023. Publisher: Nature Publishing Group.
- [73] Ziliang Ruan, Kaixuan Chen, Zong Wang, Xuancong Fan, Ranfeng Gan, Lu Qi, Yiwei Xie, Changjian Guo, Zhonghua Yang, Naidi Cui, and Liu Liu. *High-Performance Electro-Optic Modulator on Silicon Nitride Platform with Heterogeneous Integration of Lithium Niobate*. *Laser & Photonics Reviews*, 17(4):2200327, 2023.
- [74] Zhibo Li, Jack A. Smith, Mark Scullion, Nils Kolja Wessling, Loyd J. McKnight, Martin D. Dawson, and Michael J. Strain. *Photonic integration of lithium niobate micro-ring resonators onto silicon nitride waveguide chips by transfer-printing*. *Opt. Mater. Express*, 12(11):4375–4383, Nov 2022.
- [75] Toshiya Murai, Rai Kou, Guangwei Cong, Masahiko Imai, Kazumasa Takabayashi, and Koji Yamada. *1.1-cm-long thin-film lithium niobate Mach-*

- Zehnder modulator with low driving voltage integrated by micro-transfer printing*. Opt. Express, 33(18):38258–38267, Sep 2025.
- [76] Gengxin Chen, Ziliang Ruan, Haiqiang Wei, Haohua Wang, Yanting Zhou, Kaixuan Chen, Kangping Zhong, Changjian Guo, and Liu Liu. *First Demonstration of Differential-Drive Push-Pull Modulators on Thin-Film Lithium Niobate*. Laser & Photonics Reviews, 19(19):e00018, 2025.
- [77] Arif Rahman, Forrest Valdez, Vipretuo Mere, Camiel Op de Beeck, Pieter Wuytens, and Shayan Mookherjea. *Integration of Hybrid Thin-Film Lithium Niobate Electro-Optic Modulators on a Wafer-Scale Silicon Nitride Photonics Platform*. Journal of Lightwave Technology, 44(5):1822–1831, 2026.
- [78] Mengyue Xu, Yuntao Zhu, Fabio Pittalà, Jin Tang, Mingbo He, Wing Chau Ng, Jingyi Wang, Ziliang Ruan, Xuefeng Tang, Maxim Kuschnerov, Liu Liu, Siyuan Yu, Bofang Zheng, and Xinlun Cai. *Dual-polarization thin-film lithium niobate in-phase quadrature modulators for terabit-per-second transmission*. Optica, 9(1):61–62, Jan 2022.
- [79] Cheng Wang, Mian Zhang, Xi Chen, Maxime Bertrand, Amirhassan Shams-Ansari, Sethumadhavan Chandrasekhar, Peter Winzer, and Marko Lončar. *100-GHz Low Voltage Integrated Lithium Niobate Modulators*. In Conference on Lasers and Electro-Optics. Optical Society of America, 2018.
- [80] Peter O. Weigel, Jie Zhao, Kelvin Fang, Hasan Al-Rubaye, Douglas Trotter, Dana Hood, John Mudrick, Christina Dallo, Andrew T. Pomerene, Andrew L. Starbuck, Christopher T. DeRose, Anthony L. Lentine, Gabriel Rebeiz, and Shayan Mookherjea. *Bonded thin film lithium niobate modulator on a silicon photonics platform exceeding 100 GHz 3-dB electrical modulation bandwidth*. Opt. Express, 26(18):23728–23739, Sep 2018.
- [81] Mingbo He, Mengyue Xu, Yuxuan Ren, Jian Jian, Ziliang Ruan, Yongsheng Xu, Shengqian Gao, Shihao Sun, Xueqin Wen, Lidan Zhou, Lin Liu, Changjian Guo, Hui Chen, Siyuan Yu, Liu Liu, and Xinlun Cai. *High-performance hybrid silicon and lithium niobate Mach-Zehnder modulators for 100 Gbit/s-1 and beyond*. Nature Photonics, 13(5):359–364, May 2019. Publisher: Nature Publishing Group.
- [82] Nicholas Boynton, Hong Cai, Michael Gehl, Shawn Arterburn, Christina Dallo, Andrew Pomerene, Andrew Starbuck, Dana Hood, Douglas C. Trotter, Thomas Friedmann, Christopher T. DeRose, and Anthony Lentine. *A heterogeneously integrated silicon photonic/lithium niobate travelling wave electro-optic modulator*. Optics Express, 28(2):1868–1884, January 2020. Publisher: Optica Publishing Group.

- [83] Mengyue Xu, Mingbo He, Hongguang Zhang, Jian Jian, Ying Pan, Xiaoyue Liu, Lifeng Chen, Xiangyu Meng, Hui Chen, Zhaohui Li, et al. *High-performance coherent optical modulators based on thin-film lithium niobate platform*. Nature communications, 11(1):1–7, 2020.
- [84] Jinyao Hu, Chijun Li, Changjian Guo, Chao Lu, Alan Pak Tao Lau, Pengxin Chen, and Liu Liu. *Folded thin-film lithium niobate modulator based on a poled Mach–Zehnder interferometer structure*. Opt. Lett., 46(12):2940–2943, Jun 2021.
- [85] Xingrui Huang, Yang Liu, Zhiyong Li, Zhongchao Fan, and Weihua Han. *High-performance and compact integrated photonics platform based on silicon rich nitride–lithium niobate on insulator*. APL Photonics, 6(11):116102, 11 2021.
- [86] Ye Liu, Heng Li, Jia Liu, Su Tan, Qiaoyin Lu, and Weihua Guo. *Low V_π thin-film lithium niobate modulator fabricated with photolithography*. Opt. Express, 29(5):6320–6329, Mar 2021.
- [87] Forrest Valdez, Viphetuo Mere, Nicholas Boynton, Thomas A. Friedmann, Shawn Arterburn, Christina Dallo, Andrew T. Pomerene, Andrew L. Starbuck, Douglas C. Trotter, Anthony L. Lentine, Ashok Kodigala, and Shayan Mookherjee. *Buried-Electrode Hybrid Bonded Thin-Film Lithium Niobate Electro-Optic Mach-Zehnder Modulators*. IEEE Photonics Technology Letters, 35(11):633–636, 2023.
- [88] Keith Powell, Xudong Li, Daniel Assumpcao, Letícia Magalhães, Neil Sinclair, and Marko Lončar. *DC-stable electro-optic modulators using thin-film lithium tantalate*. Optics Express, 32(25):44115–44122, December 2024. Publisher: Optica Publishing Group.
- [89] Chengli Wang, Dengyang Fang, Alexander Kotz, Grigory Lihachev, Mikhail Churaev, Zihan Li, Adrian Schwarzenberger, Xin Ou, Christian Koos, and Tobias Kippenberg. *Ultrabroadband thin-film lithium tantalate modulator for high-speed communications*, October 2024. arXiv:2407.16324 [physics].
- [90] Junyin Zhang, Chengli Wang, Connor Denney, Johann Riemensberger, Grigory Lihachev, Jianqi Hu, Wil Kao, Terence Blésin, Nikolai Kuznetsov, Zihan Li, Mikhail Churaev, Xin Ou, Gabriel Santamaria-Botello, and Tobias J. Kippenberg. *Ultrabroadband integrated electro-optic frequency comb in lithium tantalate*. Nature, pages 1–8, January 2025. Publisher: Nature Publishing Group.

- [91] Haohua Wang, Xinke Xing, Ziliang Ruan, Jiayang Yu, Kaixuan Chen, Xin Ou, and Liu Liu. *Optical switch with an ultralow DC drift based on thin-film lithium tantalate*. Optics Letters, 49(18):5019–5022, September 2024. Publisher: Optica Publishing Group.
- [92] Anna Shelton, C. J. Xin, Keith Powell, Jiayu Yang, Shengyuan Lu, Neil Sinclair, and Marko Loncar. *Robust Poling and Frequency Conversion on Thin-Film Periodically Poled Lithium Tantalate*. 2025.
- [93] Fei Huang, Xiaowan Shen, Siyuan Wang, Haochen Xu, Hongxuan Liu, Zexu Wang, He Gao, Xinmin Yao, Hengzhen Cao, Bin Chen, Xijie Wang, Jizhi Zhang, Zhile Wu, Mingyu Zhu, Hongzhi Xiong, Weike Zhao, Huan Li, Zejie Yu, Liu Liu, Yaocheng Shi, and Daoxin Dai. *Toward Large-Scale Photonic Chips Using Low-Anisotropy Thin-Film Lithium-Tantalate*. Advanced Science, n/a(n/a):2410345. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1002/advs.202410345>.
- [94] Amir H Atabaki, Sajjad Moazeni, Fabio Pavanello, Hayk Gevorgyan, Jelena Notaros, Luca Alloatti, Mark T Wade, Chen Sun, Seth A Kruger, Huaiyu Meng, et al. *Integrating photonics with silicon nanoelectronics for the next generation of systems on a chip*. Nature, 556(7701):349–354, 2018.
- [95] Christopher V Poulton, Matthew J Byrd, Peter Russo, Benjamin Moss, Oleg Shatrovoy, Murshed Khandaker, and Michael R Watts. *Coherent LiDAR with an 8,192-element optical phased array and driving laser*. IEEE Journal of Selected Topics in Quantum Electronics, 28(5: Lidars and Photonic Radars):1–8, 2022.
- [96] Wouter J Westerveld, Md Mahmud-Ul-Hasan, Rami Shnaiderman, Vasilis Ntziachristos, Xavier Rottenberg, Simone Severi, and Veronique Rochus. *Sensitive, small, broadband and scalable optomechanical ultrasound sensor in silicon photonics*. Nature Photonics, 15(5):341–345, 2021.
- [97] Pao Tai Lin, Hao-Yu Greg Lin, Zhaohong Han, Tiening Jin, Rachel Millender, Lionel C Kimerling, and Anu Agarwal. *Label-free glucose sensing using chip-scale mid-infrared integrated photonics*. Advanced Optical Materials, 4(11):1755–1759, 2016.
- [98] Jianwei Wang, Fabio Sciarrino, Anthony Laing, and Mark G Thompson. *Integrated photonic quantum technologies*. Nature Photonics, 14(5):273–284, 2020.
- [99] Abdul Rahim, Eva Ryckeboer, Ananth Z Subramanian, Stéphane Clemmen, Bart Kuyken, Ashim Dhakal, Ali Raza, Artur Hermans, Muhammad Muneeb,

- Sören Dhoore, et al. *Expanding the silicon photonics portfolio with silicon nitride photonic integrated circuits*. Journal of lightwave technology, 35(4):639–649, 2017.
- [100] Wim Bogaerts, Martin Fiers, and Pieter Dumon. *Design challenges in silicon photonics*. IEEE Journal of Selected Topics in Quantum Electronics, 20(4):1–8, 2013.
- [101] Wai Kit Ng, Yu Han, Kei May Lau, and Kam Sing Wong. *Broadband telecom emission from InP/InGaAs nano-ridge lasers on silicon-on-insulator substrate*. OSA Continuum, 2(11):3037–3043, 2019.
- [102] Bahawal Haq, Sulakshna Kumari, Kasper Van Gasse, Jing Zhang, Agnieszka Gocalinska, Emanuele Pelucchi, Brian Corbett, and Gunther Roelkens. *Micro-transfer-printed III-V-on-silicon C-band semiconductor optical amplifiers*. Laser & Photonics Reviews, 14(7):1900364, 2020.
- [103] Feng Xiao, Qin Han, Han Ye, Shuai Wang, and Fan Xiao. *InP-based high-speed monolithic PIN photodetector integrated with an MQW semiconductor optical amplifier*. Japanese Journal of Applied Physics, 61(1):012005, 2022.
- [104] Meint Smit, Kevin Williams, and Jos van der Tol. *Past, present, and future of InP-based photonic integration*. APL Photonics, 4(5):050901, 2019.
- [105] Gunther Roelkens, Jing Zhang, Laurens Bogaert, Maximilien Billet, Dongbo Wang, Biwei Pan, Clemens J. Kruckel, Emadreza Soltanian, Dennis Maes, Tom Vanackere, Tom Vandekerckhove, Stijn Cuyvers, Jasper De Witte, Isaac Luntadila Lufungula, Xin Guo, He Li, Senbiao Qin, Grigorij Muliuk, Sarah Uvin, Bahawal Haq, Camiel Op de Beeck, Jeroen Goyvaerts, Guy Lepage, Peter Verheyen, Joris Van Campenhout, Geert Morthier, Bart Kuyken, Dries Van Thourhout, and Roel Baets. *Micro-Transfer Printing for Heterogeneous Si Photonic Integrated Circuits*. IEEE Journal of Selected Topics in Quantum Electronics, 29(3: Photon. Elec. Co-Inte. and Adv. Trans. Print.):1–14, May 2023. Conference Name: IEEE Journal of Selected Topics in Quantum Electronics.
- [106] John Justice, Chris Bower, Matthew Meitl, Marcus B Mooney, Mark A Gubbins, and Brian Corbett. *Wafer-scale integration of group III–V lasers on silicon using transfer printing of epitaxial layers*. Nature Photonics, 6(9):610–614, 2012.
- [107] Brian Corbett, Ruggero Loi, Weidong Zhou, Dong Liu, and Zhenqiang Ma. *Transfer print techniques for heterogeneous integration of photonic components*. Progress in Quantum Electronics, 52:1–17, 2017.

- [108] Bahawal Haq, Sulakshna Kumari, Kasper Van Gasse, Jing Zhang, Agnieszka Gocalinska, Emanuele Pelucchi, Brian Corbett, and Gunther Roelkens. *Micro-Transfer-Printed III-V-on-Silicon C-Band Semiconductor Optical Amplifiers*. *Laser & Photonics Reviews*, 14(7), 2020.
- [109] John Justice, Chris Bower, Matthew Meitl, Marcus B. Mooney, Mark A. Gubbins, and Brian Corbett. *Wafer-scale integration of group III–V lasers on silicon using transfer printing of epitaxial layers*. *Nature Photonics*, 6(9):610–614, 2012.
- [110] Gunther Roelkens, Jing Zhang, Laurens Bogaert, Emadrezza Soltanian, Maximilien Billet, Ali Uzun, Biwei Pan, Yang Liu, Evangelia Delli, Dongbo Wang, Valeria Bonito Oliva, Lam Thi Ngoc Tran, Xin Guo, He Li, Senbiao Qin, Konstantinos Akritidis, Ye Chen, Yu Xue, Margot Niels, Dennis Maes, Max Kiewiet, Tom Reep, Tom Vanackere, Tom Vandekerckhove, Isaac Luntadila Lufungula, Jasper De Witte, Luis Reis, Stijn Poelman, Ying Tan, Hong Deng, Wim Bogaerts, Geert Morthier, Dries Van Thourhout, and Bart Kuyken. *Present and future of micro-transfer printing for heterogeneous photonic integrated circuits*. *APL Photonics*, 9(1):010901, January 2024.
- [111] Maximilien Billet, Luis Reis, Yoan Léger, Charles Cornet, Fabrice Raineri, Isabelle Sagnes, Konstantinos Pantzas, Grégoire Beaudoin, Gunther Roelkens, Francois Leo, and Bart Kuyken. *Gallium phosphide-on-insulator integrated photonic structures fabricated using micro-transfer printing*. *Opt. Mater. Express*, 12(9):3731–3737, Sep 2022.
- [112] John McPhillimy, Benoit Guilhabert, Charalambos Klitis, Martin D Dawson, Marc Sorel, and Michael J Strain. *High accuracy transfer printing of single-mode membrane silicon photonic devices*. *Optics Express*, 26(13):16679–16688, 2018.
- [113] R.W. Boyd and D. Prato. *Nonlinear Optics*. Academic Press, 2008.
- [114] Christian Koos. *Nanophotonic Devices for Linear and Nonlinear Optical Signal Processing*. PhD thesis, 2007.
- [115] Christian Koos, Juerg Leuthold, Wolfgang Freude, Manfred Kohl, Larry Dalton, Wim Bogaerts, Anna Lena Giesecke, Matthias Lauermann, Argishti Melikyan, Sebastian Koeber, Stefan Wolf, Claudius Weimann, Sascha Muehlbrandt, Kira Koehnle, Joerg Pfeifle, Wladislaw Hartmann, Yasar Kutuvantavida, Sandeep Ummethala, Robert Palmer, Dietmar Korn, Luca Alloati, Philipp Claudius Schindler, Delwin L. Elder, Thorsten Wahlbrink, and Jens Bolten. *Silicon-Organic Hybrid (SOH) and Plasmonic-Organic Hybrid (POH) Integration*. *Journal of Lightwave Technology*, 34(2):256–268, 2016.

- [116] Mark Saffman. *Quantum computing with atomic qubits and Rydberg interactions: progress and challenges*. Journal of Physics B: Atomic, Molecular and Optical Physics, 49(20):202001, 2016.
- [117] Ahmed Shariful Alam and J. Stewart Aitchison. *Optimization of a Broadband Lithium Niobate-Barium Titanate Hybrid Modulator With Low Half-Wave-Voltage-Length Product*. IEEE Photonics Journal, 15(6):1–7, 2023.
- [118] Ansys Lumerical. *EigenMode Expansion (EME) solver introduction*, 2024. Ansys Optics Documentation.
- [119] Govind P Agrawal. *Fiber-optic communication systems*, volume 222. John Wiley & Sons, 4th edition, 2010.
- [120] Jochem Verbist. *Compact and Low-Power Silicon Photonic Transceivers for Inter and Intra Data Center Optical Interconnects*. PhD thesis, Ghent University, Ghent, Belgium, 2021.
- [121] Jeremy Witzens. *High-speed silicon photonics modulators*. Proceedings of the IEEE, 106(12):2158–2182, 2018.
- [122] Tinus Pannier, Lucas Van Severen, Marijn Werbrouck, and Peter Ossieur. *Small-signal system-level analysis of traveling-wave Mach-Zehnder modulators*. Opt. Express, 34(8):14445–14464, Apr 2026.
- [123] Terry C. Edwards and Michael B. Steer. *Foundations for Microstrip Circuit Design*. Wiley-IEEE Press, Hoboken, NJ, 4 edition, 2016.
- [124] Behzad Razavi. *Design of Analog CMOS Integrated Circuits*. McGraw-Hill, 2001.
- [125] Paul R Gray and Robert G Meyer. *Analysis and design of analog integrated circuits*. In Symposium on Medical Informatics (WAMI, DRME), volume 325, page 3912.
- [126] C. A. A. Franken, S. S. Ghosh, C. C. Rodrigues, J. Yang, C. J. Xin, S. Lu, D. Witt, G. Joe, G. S. Wiederhecker, K. J. Boller, and M. Lončar. *Milliwatt-level UV generation using sidewall poled lithium niobate*. 2025.
- [127] Haiwei Chen, Xinyu Zhang, Zhilin Ye, Xin Chen, ChunYu Huang, Peng Zhan, Xin Ou, Shining Zhu, and Xiaopeng Hu. *Continuous-wave second-harmonic generation of green light in periodically poled thin-film lithium tantalate*. Opt. Lett., 50(4):1125–1127, Feb 2025.
- [128] Ran Ding, Yang Liu, Yangjin Ma, Yisu Yang, Qi Li, Andy Eu-Jin Lim, Guo-Qiang Lo, Keren Bergman, Tom Baehr-Jones, and Michael Hochberg. *High-Speed Silicon Modulator With Slow-Wave Electrodes and Fully Independent*

- Differential Drive*. Journal of Lightwave Technology, 32(12):2240–2247, 2014.
- [129] Clayton R Paul. *Analysis of multiconductor transmission lines*. John Wiley & Sons, 2nd edition, 2008.
- [130] Hao Xu, Xianyao Li, Xi Xiao, Zhiyong Li, Yude Yu, and Jinzhong Yu. *Demonstration and Characterization of High-Speed Silicon Depletion-Mode Mach–Zehnder Modulators*. IEEE Journal of Selected Topics in Quantum Electronics, 20(4):23–32, 2014.
- [131] Ke Li, David J Thomson, Shenghao Liu, Weiwei Zhang, Wei Cao, Callum G Littlejohns, Xingzhao Yan, Martin Ebert, Mehdi Banakar, Dehn Tran, et al. *An integrated CMOS–silicon photonics transmitter with a 112 gigabaud transmission and picojoule per bit energy efficiency*. Nature Electronics, 6(11):910–921, 2023.
- [132] Bert Simonovich. *A Guide for Single-Ended to Mixed-Mode S-Parameter Conversions*. Signal Integrity Journal, July 2020. Technical feature, published in SIJ July 2020 print issue, page 18.
- [133] Tom Vanackere, Maximilien Billet, Camiel Op de Beeck, Stijn Poelman, Gunther Roelkens, Stéphane Clemmen, and Bart Kuyken. *Micro-Transfer Printing of Lithium Niobate on Silicon Nitride*. In 2020 European Conference on Optical Communications (ECOC), pages 1–4, 2020.
- [134] Tom Vandekerckhove, Tom Vanackere, Jasper De Witte, Stijn Cuyvers, Luis Reis, Maximilien Billet, Günther Roelkens, Stéphane Clemmen, and Bart Kuyken. *Reliable micro-transfer printing method for heterogeneous integration of lithium niobate and semiconductor thin films*. Opt. Mater. Express, 13(7):1984–1993, Jul 2023.
- [135] Stijn Cuyvers, Tom Vanackere, Tom Vandekerckhove, Stijn Poelman, Camiel Op de Beeck, Jasper De Witte, Artur Hermans, Kasper Van Gasse, Nathalie Picqué, Dries Van Thourhout, Gunther Roelkens, Stéphane Clemmen, and Bart Kuyken. *High-Yield Heterogeneous Integration of Silicon and Lithium Niobate Thin Films*. In 2022 Conference on Lasers and Electro-Optics (CLEO), pages 1–2, 2022.
- [136] A.C. Reyes, S.M. El-Ghazaly, S. Dorn, M. Dydyk, and D.K. Schroder. *Silicon as a microwave substrate*. In 1994 IEEE MTT-S International Microwave Symposium Digest (Cat. No.94CH3389-4), pages 1759–1762 vol.3, 1994.
- [137] Mohan Shen, Likai Yang, Yuntao Xu, and Hong X. Tang. *Parasitic conduction loss of lithium niobate on insulator platform*. Applied Physics Letters, 124(10):101107, 03 2024.

- [138] Nur Zatil Ismah Hashim. *Au-compensated high resistivity silicon for low loss microwave devices-suppression of parasitic surface conduction effect*. PhD thesis, University of Southampton, 2015.
- [139] Dennis Maes, Sam Lemey, Gunther Roelkens, Mohammed Zaknounge, Vanessa Avramovic, Etienne Okada, Pascal Szriftgiser, Emilien Peytavit, Guillaume Ducournau, and Bart Kuyken. *High-speed uni-traveling-carrier photodiodes on silicon nitride*. APL Photonics, 8(1):016104, 01 2023.
- [140] Jasper De Witte, Atefeh Shadmani, Zhe Liu, Andraz Debevc, Tom Vandekerckhove, Marcus Albrechtsen, Rüdiger Schott, Arne Ludwig, Janez Krč, Gunther Roelkens, Leonardo Midolo, Bart Kuyken, and Dries Van Thourhout. *Integrated emitters with CMOS-compatible tuning for large scale quantum SiN photonic circuits*, 2025.
- [141] Tom Vandekerckhove, Jasper De Witte, Lisa De Jaeger, Ewoud Vissers, Sofie Janssen, Peter Verheyen, Neha Singh, Dieter Bode, Martin Davi, Filippo Ferraro, Philippe Absil, Sadhishkumar Balakrishnan, Joris Van Campenhout, Dries Van Thourhout, Günther Roelkens, Stéphane Clemmen, and Bart Kuyken. *A Scalable Quadratic Nonlinear Silicon Photonics Platform With Printable Entangled Photon-Pair Sources*. Laser & Photonics Reviews, 20(3):e01357, 2026.
- [142] N. Chen, Y. Yu, K. Lou, and T. Chu. *Ultra-high efficiency electro-optic modulator on thin-film lithium niobate*. In 49th European Conference on Optical Communications (ECOC 2023), volume 2023, pages 1632–1635, 2023.
- [143] Nuo Chen, Kangping Lou, Yalong Yu, Xuanjian He, and Tao Chu. *High-Efficiency Electro-Optic Modulator on Thin-Film Lithium Niobate with High-Permittivity Cladding*. Laser & Photonics Reviews, 17(11):2200927, 2023.
- [144] A. S. Alam and J. S. Aitchison. *Low Half-Wave-Voltage Lithium Niobate Modulator Using High-K Dielectric Material Cladding*. In Optica Advanced Photonics Congress 2022, page JTU2A.9. Optica Publishing Group, 2022.
- [145] Tom Vanackere, Artur Hermans, Ian Christen, Christopher Panuski, Mark Dong, Matthew Zimmermann, Hamza Raniwala, Andrew J Leenheer, Matt Eichenfield, Gerald Gilbert, et al. *Piezoelectrically actuated silicon-nitride-based high-speed spatial light modulator*. Nature Communications, 2025.
- [146] J. Park, B. G. Jeong, S. I. Kim, D. Lee, J. Kim, C. Shin, C. B. Lee, T. Otsuka, J. Kyoung, S. Kim, K.-Y. Yang, Y.-Y. Park, J. Lee, I. Hwang, J. Jang, S. H. Song, M. L. Brongersma, K. Ha, S.-W. Hwang, H. Choo, and B. L. Choi. *All-solid-state spatial light modulator with independent phase and amplitude*

- control for three-dimensional LiDAR applications*. Nature Nanotechnology, 16:69–76, 2021.
- [147] Sepehr Ebadi, Tout T. Wang, Harry Levine, Alexander Keesling, Giulia Semeghini, Ahmed Omran, Dolev Bluvstein, Rhine Samajdar, Hannes Pichler, Wen Wei Ho, Soonwon Choi, Subir Sachdev, Markus Greiner, Vladan Vuletić, and Mikhail D. Lukin. *Quantum phases of matter on a 256-atom programmable quantum simulator*. Nature, 595(7866):227–232, 2021.
 - [148] Volodymyr Nikolenko, Brendon Watson, Roberto Araya, Alan Woodruff, Darcy Peterka, and Rafael Yuste. *SLM microscopy: scanless two-photon imaging and photostimulation using spatial light modulators*. Frontiers in Neural Circuits, 2:5, 2008.
 - [149] Seokchan Yoon, Moonseok Kim, Mooseok Jang, Youngwoon Choi, Wonjun Choi, Sungsam Kang, and Wonshik Choi. *Deep optical imaging within complex scattering media*. Nature Reviews Physics, 2:141–158, 2020.
 - [150] Emiliano Ronzitti, Cathie Ventalon, Marco Canepari, Benoît C Forget, Eirini Papagiakoumou, and Valentina Emiliani. *Recent advances in patterned photostimulation for optogenetics*. Journal of Optics, 19(11):113001, 2017.
 - [151] Ying Zuo, Yujun Zhao, You-Chiuan Chen, Shengwang Du, and Junwei Liu. *Scalability of All-Optical Neural Networks Based on Spatial Light Modulators*. Physical Review Applied, 15:054034, 2021.
 - [152] Liane Bernstein, Alexander Sludds, Christopher Panuski, Sivan Trajtenberg-Mills, Ryan Hamerly, and Dirk Englund. *Single-shot optical neural network*. Science Advances, 9(25):eadg7904, 2023.
 - [153] Chenliang Chang, Kiseung Bang, Gordon Wetzstein, Byoungcho Lee, and Liang Gao. *Toward the next-generation VR/AR optics: a review of holographic near-eye displays from a human-centric perspective*. Optica, 7(11):1563–1578, 2020.
 - [154] Tao Zhan, Kun Yin, Jianghao Xiong, Ziqian He, and Shin-Tson Wu. *Augmented Reality and Virtual Reality Displays: Perspectives and Challenges*. iScience, 23(8):101397, 2020.
 - [155] K. Wright, K. M. Beck, S. Debnath, J. M. Amini, Y. Nam, N. Grzesiak, J.-S. Chen, N. C. Pienti, M. Chmielewski, C. Collins, K. M. Hudek, J. Mizrahi, J. D. Wong-Campos, S. Allen, J. Apisdorf, P. Solomon, M. Williams, A. M. Ducore, A. Blinov, S. M. Kreikemeier, V. Chaplin, M. Keesan, C. Monroe, and J. Kim. *Benchmarking an 11-qubit quantum computer*. Nature Communications, 10:5464, 2019.

- [156] Ian Christen, Thomas Propson, Madison Sutula, Hamed Sattari, Gregory Choong, Christopher Panuski, Alexander Melville, Justin Mallek, Cole Brabec, Scott Hamilton, P. Benjamin Dixon, Adrian J. Menssen, Danielle Braje, Amir H. Ghadimi, and Dirk Englund. *An integrated photonic engine for programmable atomic control*. Nature Communications, 16:82, 2025.
- [157] T. M. Graham, Y. Song, J. Scott, C. Poole, L. Phuttitarn, K. Jooya, P. Eichler, X. Jiang, A. Marra, B. Grinkemeyer, M. Kwon, M. Ebert, J. Cherek, M. T. Lichtman, M. Gillette, J. Gilbert, D. Bowman, T. Ballance, C. Campbell, E. D. Dahl, O. Crawford, N. S. Blunt, B. Rogers, T. Noel, and M. Saffman. *Multi-qubit entanglement and algorithms on a neutral-atom quantum computer*. Nature, 604:457–462, 2022.
- [158] Adrian J. Menssen, Artur Hermans, Ian Christen, Thomas Propson, Chao Li, Andrew J. Leenheer, Matthew Zimmermann, Mark Dong, Hugo Larocque, Hamza Raniwala, Gerald Gilbert, Matt Eichenfield, and Dirk R. Englund. *Scalable photonic integrated circuits for high-fidelity light control*. Optica, 10(10):1366–1372, 2023.
- [159] Jeff W Lichtman and José-Angel Conchello. *Fluorescence microscopy*. Nature Methods, 2:910–919, 2005.
- [160] Seokchan Yoon, Seo Young Cheon, Sangjun Park, Donghyun Lee, Yeeun Lee, Seokyoung Han, Moonseok Kim, and Heebeom Koo. *Recent advances in optical imaging through deep tissue: imaging probes and techniques*. Biomaterials Research, 26:57, 2022.
- [161] Larry J. Hornbeck. *Digital Light Processing for high-brightness high-resolution applications*. In Ming Hsien Wu, editor, Projection Displays III, volume 3013, pages 27–40. International Society for Optics and Photonics, SPIE, 1997.
- [162] David M. Bloom. *Grating Light Valve: revolutionizing display technology*. In Ming Hsien Wu, editor, Projection Displays III, volume 3013, pages 165 – 171. International Society for Optics and Photonics, SPIE, 1997.
- [163] Omer Tzang, Eyal Niv, Sakshi Singh, Simon Labouesse, Greg Myatt, and Rafael Piestun. *Wavefront shaping in complex media with a 350 kHz modulator via a 1D-to-2D transform*. Nature Photonics, 13:788–793, 2019.
- [164] Douglas J. McKnight, Kristina M. Johnson, and Roylenn A. Serati. 256×256 liquid-crystal-on-silicon spatial light modulator. Applied Optics, 33(14):2775–2784, 1994.

- [165] Zichen Zhang, Zheng You, and Daping Chu. *Fundamentals of phase-only liquid crystal on silicon (LCOS) devices*. Light: Science & Applications, 3:e213, 2014.
- [166] Kebin Fan, Jonathan Suen, Xueyuan Wu, and Willie J. Padilla. *Graphene metamaterial modulator for free-space thermal radiation*. Optics Express, 24(22):25189–25201, 2016.
- [167] Beibei Zeng, Zhiqin Huang, Akhilesh Singh, Yu Yao, Abul K. Azad, Aditya D. Mohite, Antoinette J. Taylor, David R. Smith, and Hou-Tong Chen. *Hybrid graphene metasurfaces for high-speed mid-infrared light modulation and single-pixel imaging*. Light: Science & Applications, 7:51, 2018.
- [168] Ileana-Cristina Benea-Chelmsus, Maryna L. Meretska, Delwin L. Elder, Michele Tamagnone, Larry R. Dalton, and Federico Capasso. *Electro-optic spatial light modulator from an engineered organic layer*. Nature Communications, 12:5928, 2021.
- [169] Xinyu Sun, Hongyan Yu, Niping Deng, Dasai Ban, Guolei Liu, and Feng Qiu. *Electro-optic polymer and silicon nitride hybrid spatial light modulators based on a metasurface*. Optics Express, 29(16):25543–25551, 2021.
- [170] Ileana-Cristina Benea-Chelmsus, Sydney Mason, Maryna L. Meretska, Delwin L. Elder, Dmitry Kazakov, Amirhassan Shams-Ansari, Larry R. Dalton, and Federico Capasso. *Gigahertz free-space electro-optic modulators based on Mie resonances*. Nature Communications, 13:3170, 2022.
- [171] Alexei Smolyaninov, Abdelkrim El Amili, Felipe Vallini, Steve Pappert, and Yeshaiah Fainman. *Programmable plasmonic phase modulation of free-space wavefronts at gigahertz rates*. Nature Photonics, 13:431–435, 2019.
- [172] T. L. Worchesky, K. J. Ritter, R. Martin, and B. Lane. *Large arrays of spatial light modulators hybridized to silicon integrated circuits*. Applied Optics, 35(8):1180–1186, 1996.
- [173] Jongwon Lee, Seungyong Jung, Pai-Yen Chen, Feng Lu, Frederic Demmerle, Gerhard Boehm, Markus-Christian Amann, Andrea Alù, and Mikhail A. Belkin. *Ultrafast Electrically Tunable Polaritonic Metasurfaces*. Advanced Optical Materials, 2(11):1057–1063, 2014.
- [174] Yao-Wei Huang, Ho Wai Howard Lee, Ruzan Sokhoyan, Ragip A. Pala, Krishnan Thyagarajan, Seunghoon Han, Din Ping Tsai, and Harry A. Atwater. *Gate-Tunable Conducting Oxide Metasurfaces*. Nano Letters, 16(9):5319–5325, 2016.

- [175] Yi-Chen Shuai, Deyin Zhao, Yonghao Liu, Corey Stambaugh, John Lawall, and Weidong Zhou. *Coupled Bilayer Photonic Crystal Slab Electro-Optic Spatial Light Modulators*. IEEE Photonics Journal, 9(2):7101411, 2017.
- [176] Christopher L. Panuski, Ian Christen, Momchil Minkov, Cole J. Brabec, Sivan Trajtenberg-Mills, Alexander D. Griffiths, Jonathan J. D. McKendry, Gerald L. Leake, Daniel J. Coleman, Cung Tran, Jeffrey St Louis, John Mucci, Cameron Horvath, Jocelyn N. Westwood-Bachman, Stefan F. Preble, Martin D. Dawson, Michael J. Strain, Michael L. Fanto, and Dirk R. Englund. *A full degree-of-freedom spatiotemporal light modulator*. Nature Photonics, 16:834–842, 2022.
- [177] Yoon Ho Daniel Lee and Michal Lipson. *Back-End Deposited Silicon Photonics for Monolithic Integration on CMOS*. IEEE Journal of Selected Topics in Quantum Electronics, 19(2):8200207, 2013.
- [178] P. R. Stanfield, A. J. Leenheer, C. P. Michael, R. Sims, and M. Eichenfield. *CMOS-compatible, piezo-optomechanically tunable photonics for visible wavelengths and cryogenic temperatures*. Optics Express, 27(20):28588–28605, 2019.
- [179] Mark Dong, Genevieve Clark, Andrew J. Leenheer, Matthew Zimmermann, Daniel Dominguez, Adrian J. Menssen, David Heim, Gerald Gilbert, Dirk Englund, and Matt Eichenfield. *High-speed programmable photonic circuits in a cryogenically compatible, visible–near-infrared 200 mm CMOS architecture*. Nature Photonics, 16:59–65, 2022.
- [180] Mark Dong, David Heim, Alex Witte, Genevieve Clark, Andrew J Leenheer, Daniel Dominguez, Matthew Zimmermann, Y Henry Wen, Gerald Gilbert, Dirk Englund, and Matt Eichenfield. *Piezo-optomechanical cantilever modulators for VLSI visible photonics*. APL Photonics, 7(5):051304, 2022.
- [181] Giorgio Quaranta, Guillaume Basset, Olivier J. F. Martin, and Benjamin Gallinet. *Recent Advances in Resonant Waveguide Gratings*. Laser & Photonics Reviews, 12(9):1800017, 2018.
- [182] Bei-Bei Li, Lingfeng Ou, Yuechen Lei, and Yong-Chun Liu. *Cavity optomechanical sensing*. Nanophotonics, 10(11):2799–2832, 2021.
- [183] Newport. *Deep UV Photolithography*. <https://www.newport.com/n/deep-uv-photolithography>.

- [184] Mark Dong, Julia M. Boyle, Kevin J. Palm, Matthew Zimmermann, Alex Witte, Andrew J. Leenheer, Daniel Dominguez, Gerald Gilbert, Matt Eichenfield, and Dirk Englund. *Synchronous micromechanically resonant programmable photonic circuits*. Nature Communications, 14:7716, 2023.
- [185] Y. Henry Wen, David Heim, Matthew Zimmermann, Roman A. Shugayev, Mark Dong, Andrew J. Leenheer, Michael R. Miller, Gerald Gilbert, Mikkel Heuck, Matt Eichenfield, and Dirk R. Englund. *Strain-concentration for fast, compact photonic modulation and non-volatile memory*. Optica, 11(11):1511–1518, 2024.
- [186] Ted Johansson and Jonas Fritzin. *A review of watt-level CMOS RF power amplifiers*. IEEE Transactions on Microwave Theory and Techniques, 62(1):111–124, 2013.
- [187] Asger Bjørn Jørgensen, Thore Stig Aunsborg, Szymon Beczkowski, Christian Uhrenfeldt, and Stig Munk-Nielsen. *High-frequency resonant operation of an integrated medium-voltage SiC MOSFET power module*. IET Power Electronics, 13(3):475–482, 2020.
- [188] S. Krause, P. Brückner, M. Dammann, and R. Quay. *High-Power-Density AlGaIn/GaN Technology for 100-V Operation at L-Band Frequencies*. In 2019 IEEE International Electron Devices Meeting (IEDM), pages 17.4.1–17.4.4, 2019.
- [189] J. D. Thompson, B. M. Zwickl, A. M. Jayich, Florian Marquardt, S. M. Girvin, and J. G. E. Harris. *Strong dispersive coupling of a high-finesse cavity to a micromechanical membrane*. Nature, 452:72–75, 2008.
- [190] Yuxian Liu, Qiancheng Zhao, Dacheng Zhang, and Jian Cui. *Automatic Pico Laser Trimming System for Silicon MEMS Resonant Devices Based on Image Recognition*. IEEE Transactions on Semiconductor Manufacturing, 36(2):260–267, 2023.
- [191] Alexandra Efimovskaya, Danmeng Wang, and Andrei M. Shkel. *Mechanical trimming with focused ion beam for permanent tuning of MEMS dual-mass gyroscope*. Sensors and Actuators A: Physical, 313:112189, 2020.
- [192] Morito Akiyama, Toshihiro Kamohara, Kazuhiko Kano, Akihiko Teshigahara, Yukihiro Takeuchi, and Nobuaki Kawahara. *Enhancement of Piezoelectric Response in Scandium Aluminum Nitride Alloy Thin Films Prepared by Dual Reactive Cosputtering*. Advanced Materials, 21(5):593–596, 2009.
- [193] Jie Fang, Rui Chen, David Sharp, Enrico M. Renzi, Arnab Manna, Abhinav Kala, Sander A. Mann, Kan Yao, Christopher Munley, Hannah Rarick,

- Andrew Tang, Sinabu Pumulo, Yuebing Zheng, Vinod M. Menon, Andrea Alù, and Arka Majumdar. *Million-Q free space meta-optical resonator at near-visible wavelengths*. Nature Communications, 15:10341, 2024.
- [194] Taylor K. Fryett, Yueyang Chen, James Whitehead, Zane Matthew Peycke, Xiaodong Xu, and Arka Majumdar. *Encapsulated Silicon Nitride Nanobeam Cavity for Hybrid Nanophotonics*. ACS Photonics, 5(6):2176–2181, 2018.
- [195] Joris Van Campenhout, William M. J. Green, Solomon Assefa, and Yurii A. Vlasov. *Integrated NiSi waveguide heaters for CMOS-compatible silicon thermo-optic devices*. Optics Letters, 35(7):1013–1015, 2010.
- [196] Jintao Wang, Fangcheng Duan, Ziwen Lv, Si Chen, Xiaofeng Yang, Hongtao Chen, and Jiahao Liu. *A Short Review of Through-Silicon via (TSV) Interconnects: Metrology and Analysis*. Applied Sciences, 13(14):8301, 2023.
- [197] Mark Dong, Matthew Zimmermann, David Heim, Hyeonrak Choi, Genevieve Clark, Andrew J. Leenheer, Kevin J. Palm, Alex Witte, Daniel Dominguez, Gerald Gilbert, Matt Eichenfield, and Dirk Englund. *Programmable photonic integrated meshes for modular generation of optical entanglement links*. npj Quantum Information, 9:42, 2023.
- [198] Sven T. S. Holmström, Utku Baran, and Hakan Urey. *MEMS Laser Scanners: A Review*. Journal of Microelectromechanical Systems, 23(2):259–275, 2014.
- [199] Xiaosheng Zhang, Kyungmok Kwon, Johannes Henriksson, Jianheng Luo, and Ming C. Wu. *A large-scale microelectromechanical-systems-based silicon photonics LiDAR*. Nature, 603:253–258, 2022.
- [200] RS Weis and TK Gaylord. *Lithium niobate: Summary of physical properties and crystal structure*. Applied Physics A, 37:191–203, 1985.

