Silicon photonics: an enabler for the internet and for the life sciences

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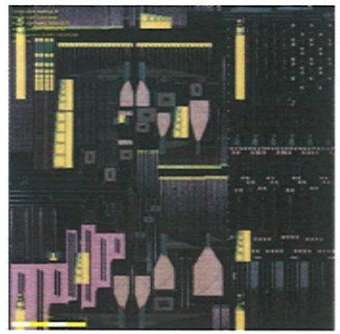
Photonics Event – June 2015 – Veldhoven

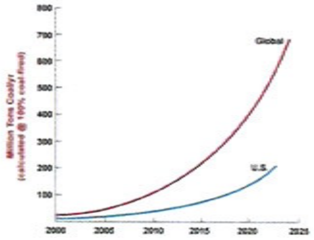
What is silicon photonics?

The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab



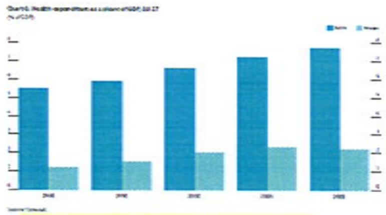
Enabling complex optical functionality on a compact chip at low cost

Why silicon photonics matters



Evolution of energy usage by datacenters

Drastic reduction of energy consumption through optical fiber interconnect and silicon photonic chips



Evolution of cost of health care

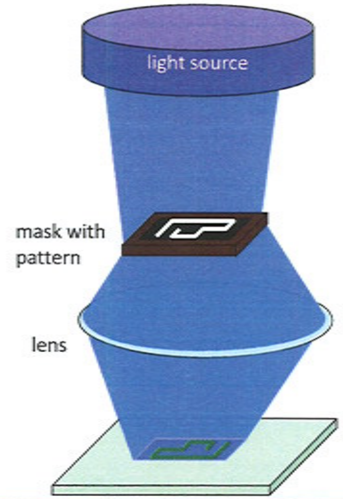
Affordable point of care solutions

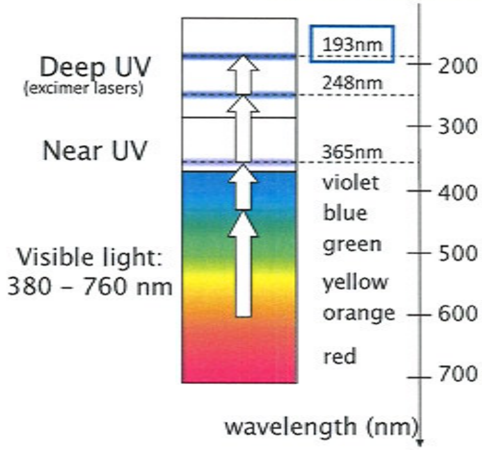
Outline

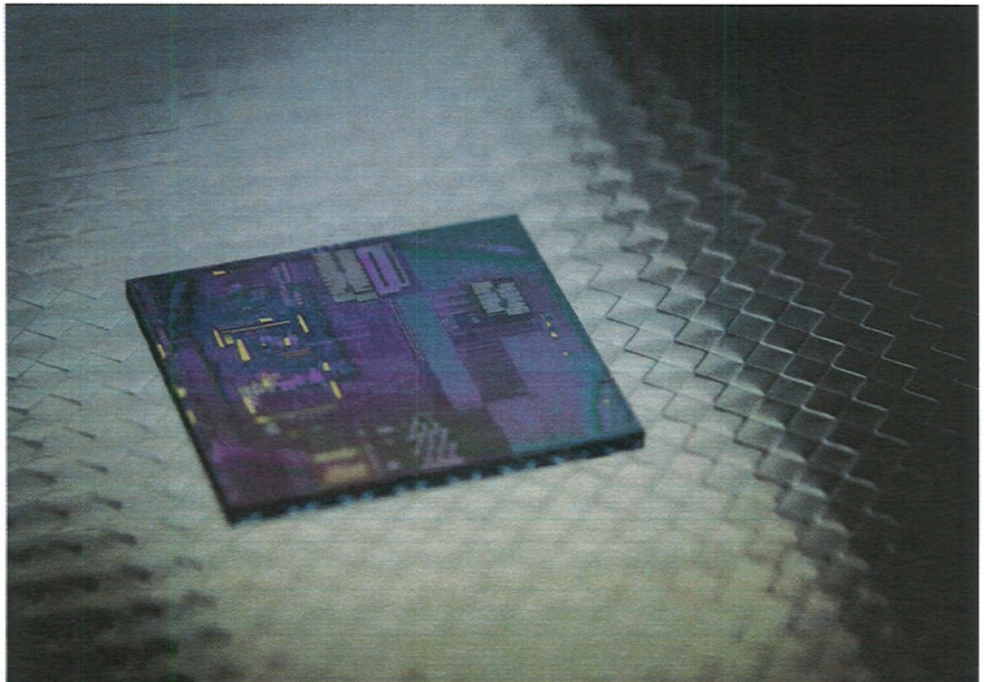
- ➡ An introduction to silicon photonics
- Biosensing and gas sensing
- Laser Doppler vibrometry and optical coherence tomography
- Spectroscopy-on-a-chip

Optical Lithography by deep UV steppers

$$\text{Resolution} = k_1 \frac{\lambda}{NA}$$

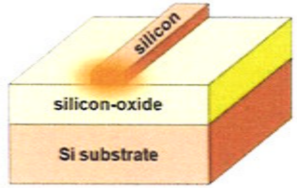


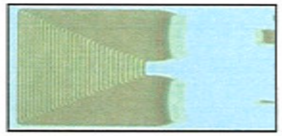


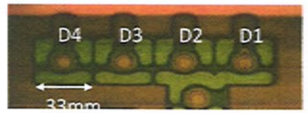


Why silicon photonics

- High index contrast ⇒ very compact PICs
- CMOS technology ⇒ nm-precision, high yield, existing fabs, low cost in volume
- High performance passive devices
- High bitrate Ge photodetectors
- High bitrate modulators
- Wafer-level automated testing
- Hierarchical set of design tools
- Light source integration (hybrid/monolithic?)
- Integration with electronics (hybrid/monolithic?)

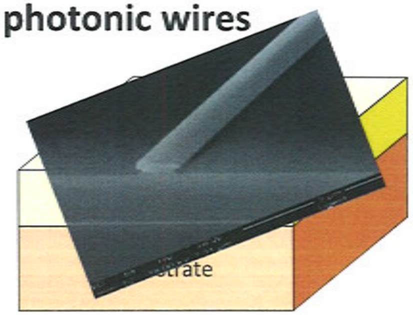


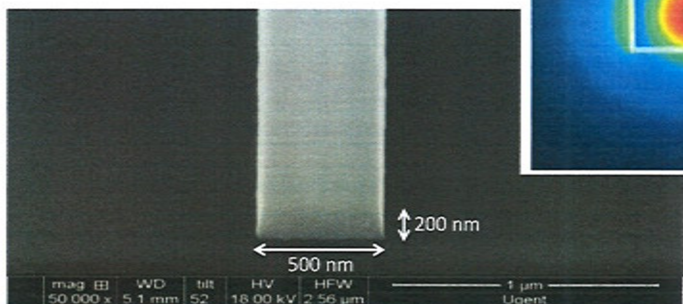


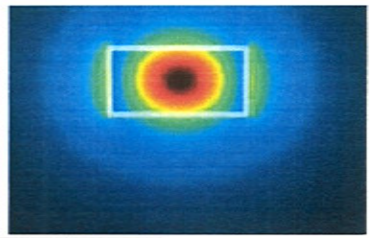


Silicon photonic wires

$n_1(=3.5) > n_2(=1.45)$

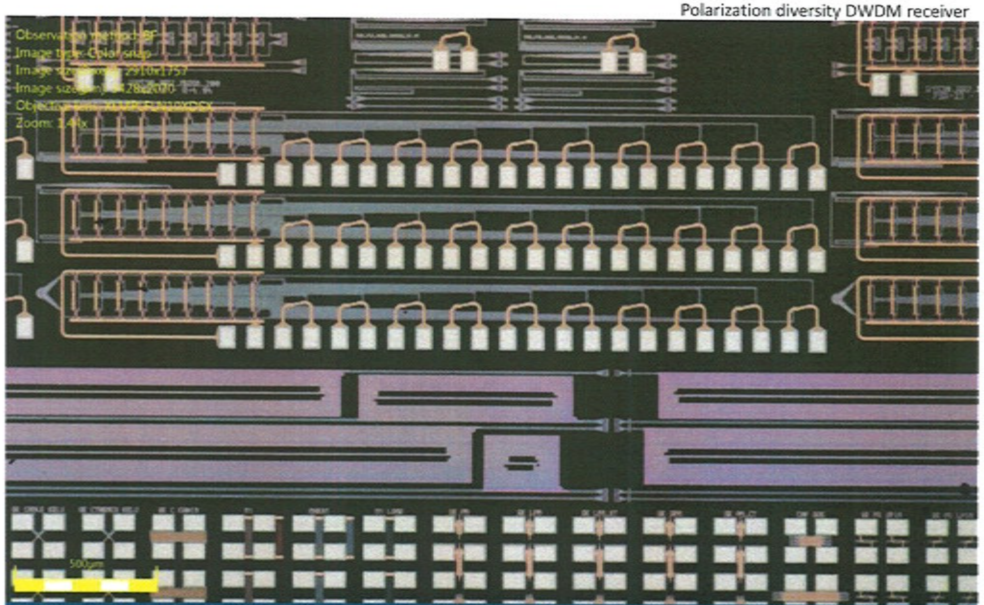




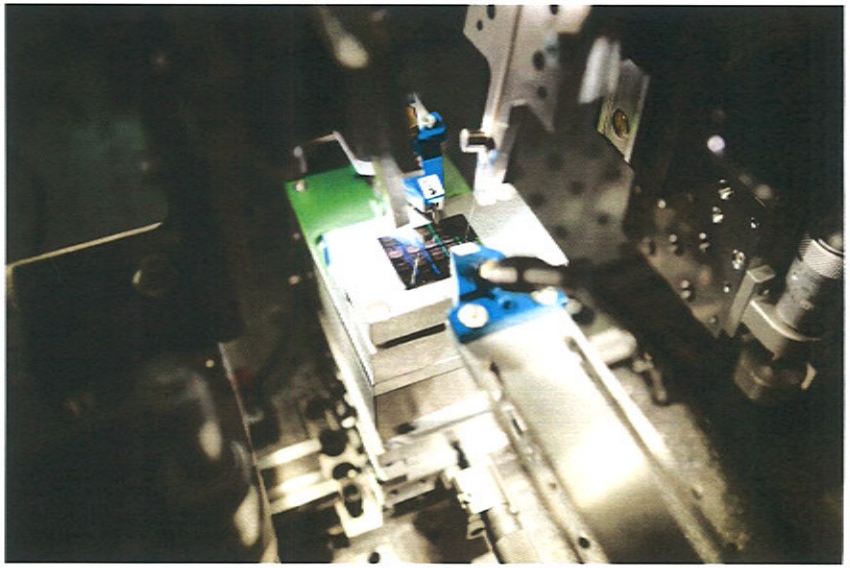


Silicon photonics chip for ultra- high bitrate communication

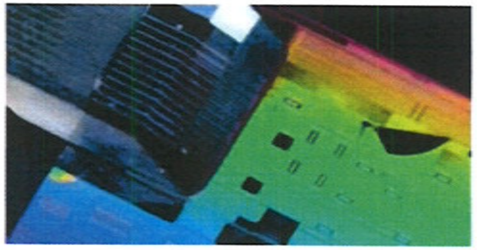
Polarization diversity DWDM receiver

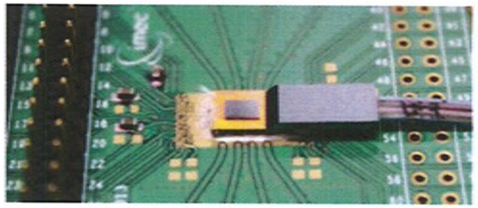


Testing photonic chips

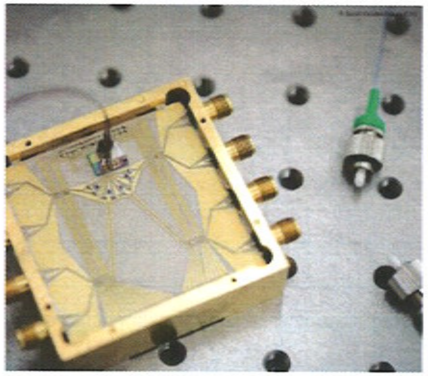


Packaging photonic chips (optical, electrical, RF, thermal)





Tyndall National Institute



Industrial take-up examples in telecom/datacom

- active optical cables (eg 4x10Gb/s on parallel fibers)
- WDM transceivers (eg 4 WDM channels x 12.5 Gb/s on single fiber)
- coherent receiver (eg 100 Gb/s PM-QPSK)
- fiber-to-the-home bidirectional transceiver (eg 12 x 2.5 Gb/s)
- monolithic receiver (eg 16x20Gb/s)
- 40Gb/s and 50Gb/s Ethernet (future: 100 and 400Gb/s)

LUCEDA PHOTONICS Finisar ST intel IBM CISCO LIGHTWIRE KOTURA SKORPIOS TeraXion LUXTERA aurrion Caliopa HUAWEI

Explorative research in silicon photonics

Bring new materials in the CMOS fab:

- Transfer printing of InP (and other III-V semiconductors) on silicon
- Direct epi-growth of InP (and other III-V semiconductors) on silicon
- Integration of graphene on silicon
- Integration of electro-optic materials (PZT, BTO,...) on silicon
- ...

Outline

An introduction to silicon photonics

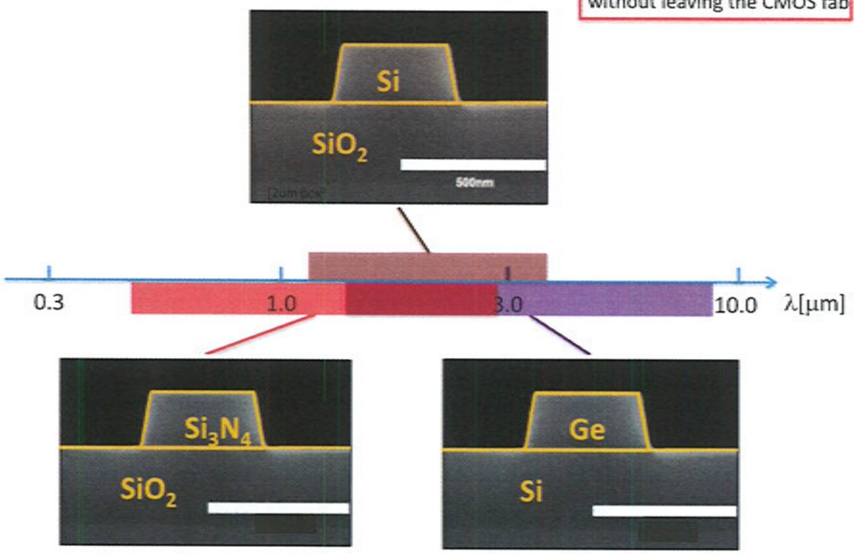
➡ Biosensing and gas sensing

Laser Doppler vibrometry and optical coherence tomography

Spectroscopy-on-a-chip

Silicon photonics: extending the wavelength range

without leaving the CMOS fab



R. Soref, Nature Photonics 2010

Biosensors

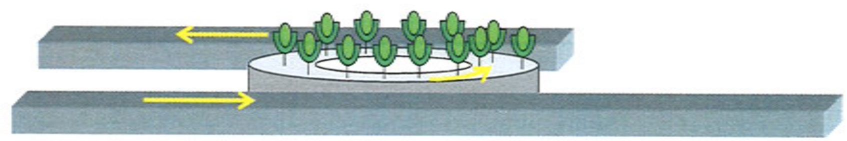
Detect presence and concentration of

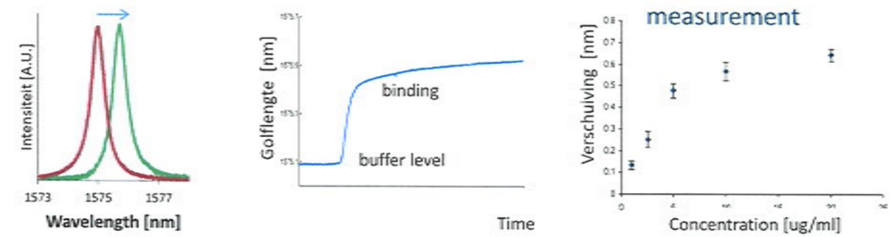
- Proteins
- Viruses
- Bacteria
- DNA
- ...

Two classes:

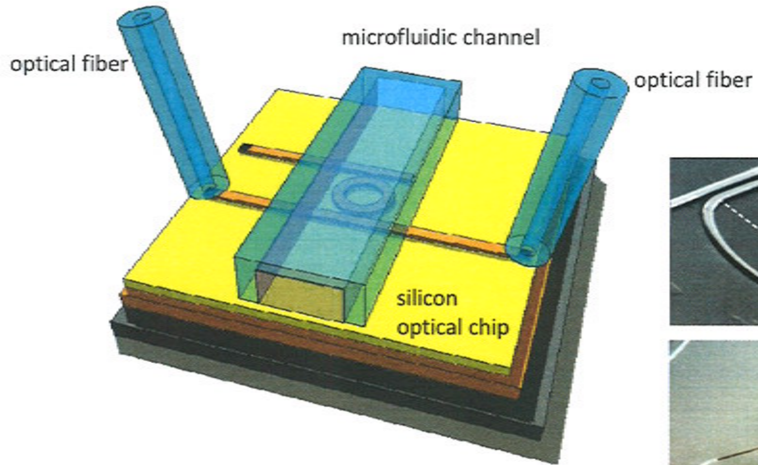
- Labeled: detection of label bound to biomolecule
- Label-free: direct detection of biomolecule

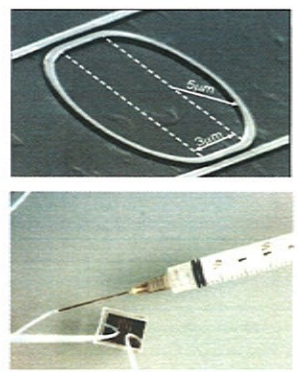
Label-free ring resonator biosensor



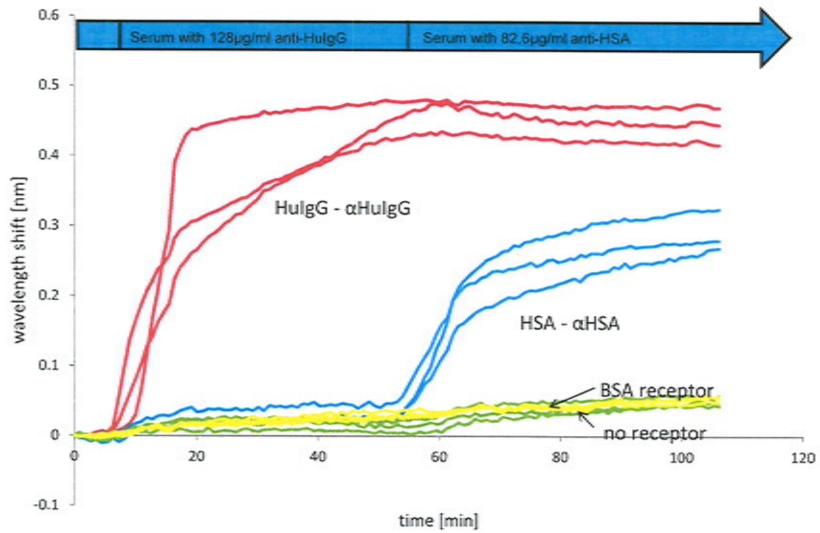


Lab-on-chip concept



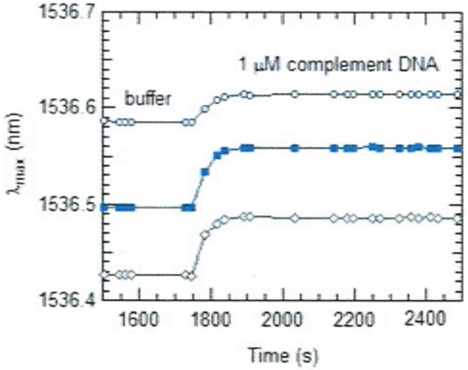


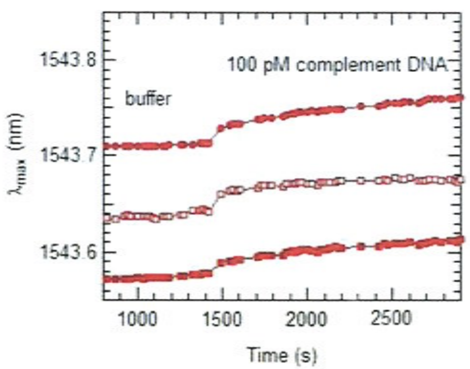
Multiplex sensing results



K. De Vos et al, Optics Express (2007)

DNA hybridisation

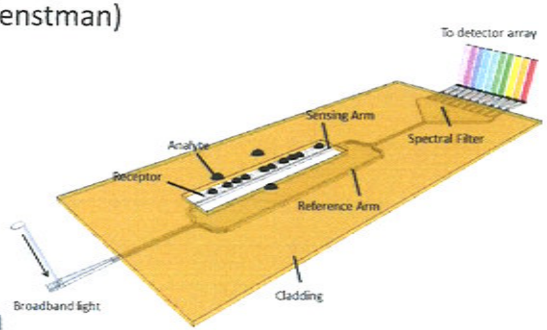




Concentrations down to 100 pM can be detected

Pocket project (FP7)

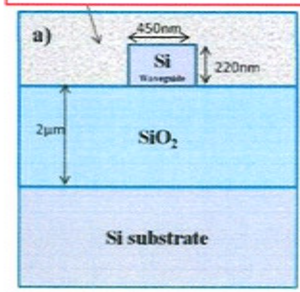
- Detection of **Tuberculosis** biomarkers in urine
- SiN PIC-platform in visible: cheaper sources and detectors
- Cheap readout: broadband source + sensor + on-chip spectrometer
- Coordinator: UGent (P. Bienstman)
- Spin-off plans

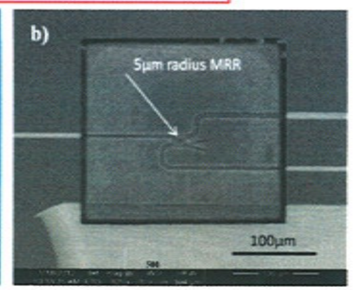


Selective, reversible and fast ammonia gas detection

Application: breath analysis

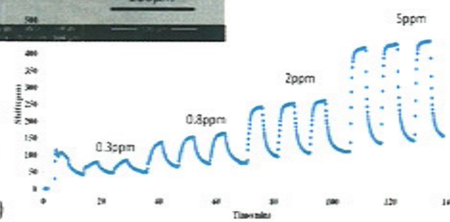
Microporous silica layer, pores: 2nm; porosity: 45%
Functionalized for ammonia-selectivity





Sensitivity down to 100ppb demonstrated

No interference from H_2O and CO_2



N. Yebo et al, Optics Express, 20(11), pp. 11855 (2012)

Outline

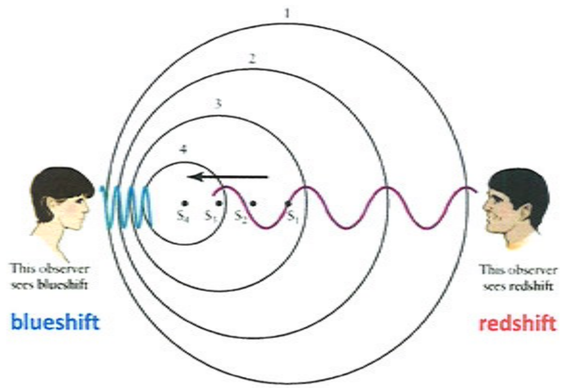
An introduction to silicon photonics

Biosensing and gas sensing

➡ Laser Doppler vibrometry and optical coherence tomography

Spectroscopy-on-a-chip

Doppler effect



$$\frac{\Delta f_{opt}}{f_{opt}} = \frac{2v_{target}}{c}$$

Example:

v_{target} =15 cm/s

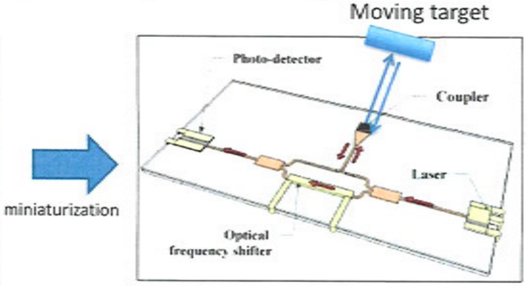
c= 30 cm/ns

Δf/f = 10^{-9}

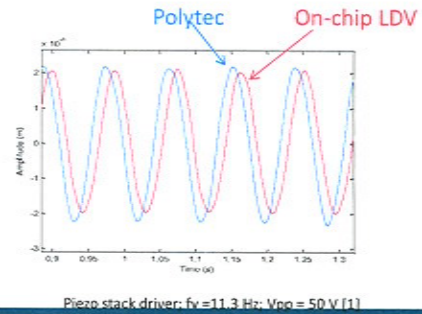
Δf = 100-1000 kHz

Laser Doppler Vibrometer: measuring the velocity of a surface

Polytec OFV-534 LDV sensor head.



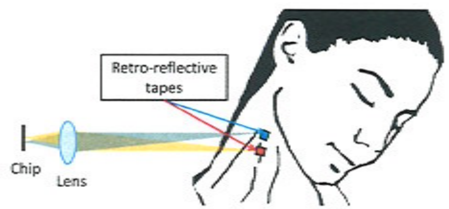
Doppler effect: $\frac{\Delta f_{opt}}{f_{opt}} = 2\frac{v_{target}}{c}$

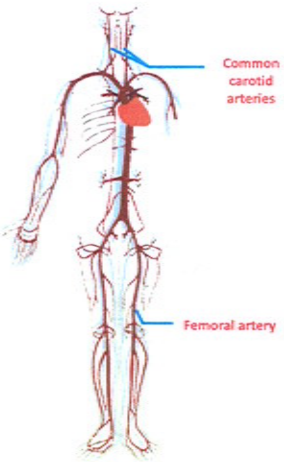


Y. Li et al, Optics Express (2013)

Pulse wave velocity measurement

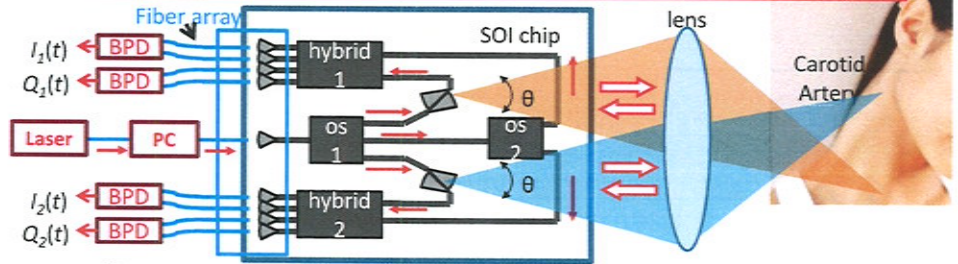
- pulse wave velocity: measure for aortic stiffness, an important marker for atherosclerosis
- gold standard: carotid-femoral PWV
- not practical for general practitioner
- hence: move to local carotid PWV measurement

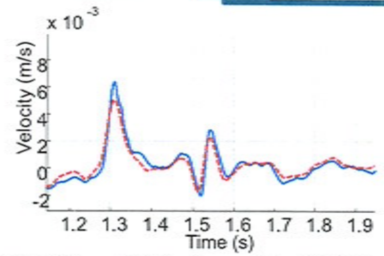


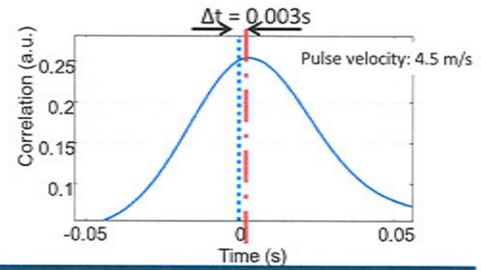


LDV-measurement of blood pulse velocity

Blood pulse velocity: increases when blood vessels become stiffer due to atherosclerosis







Y. Li, et al, Biomedical Optics Express, 4(7), p.1229(2013)

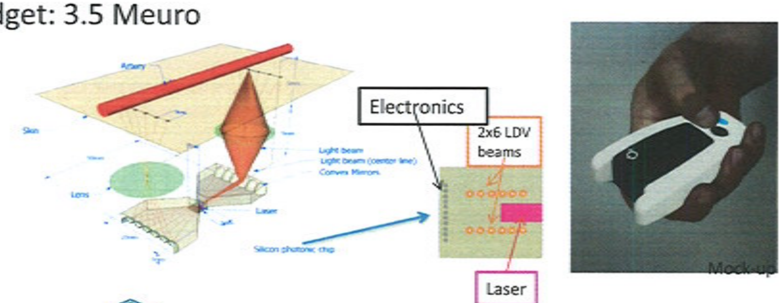
CARDIS project (Horizon 2020)

Goal: develop a prototype for a point-of-care LDV device

12 LDV systems on a single photonic chip

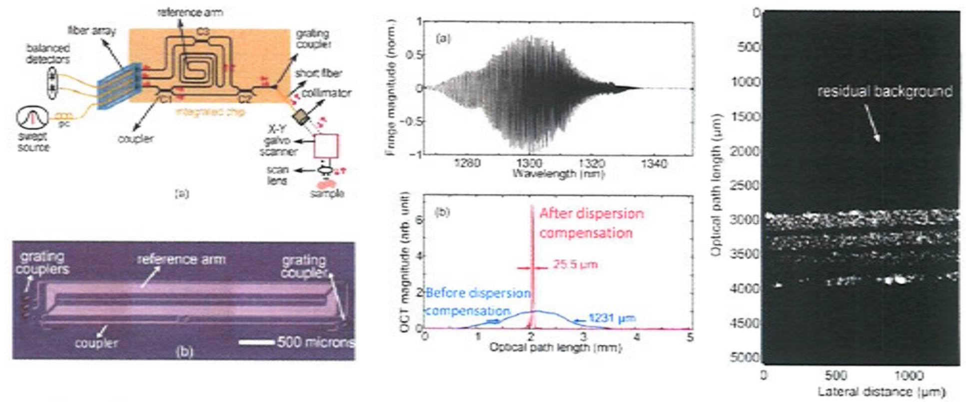
Timeframe: 2015-2018

Budget: 3.5 Meuro



imec UNIVERSITEIT GENT Medtronic SIOS Tyndall National Institute

Silicon photonics circuit for swept source OCT

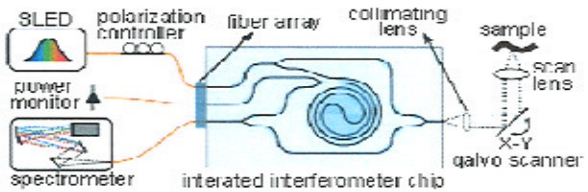


Silicon chip: 0.75 × 5 mm² (waveguide loss: 0.35 dB/cm)
Reference arm with 13 cm physical length (50.4 cm optical length)
Sensitivity: −62 dB with 115 µW power delivered to the sample
Axial resolution: 25 µm (limited by bandwidth of fiber-chip grating couplers)

UNIVERSITY OF AMSTERDAM

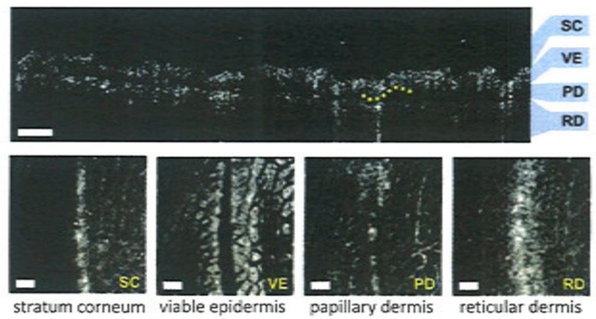
G. Yurtsever et al, Optics Letters 2014

Si_3N_4/SiO_2 circuit for Fourier domain OCT



LioniX
MEDIZINISCHE UNIVERSITÄT WIEN

Si_3N_4/SiO_2 waveguides (TriPleX) on silicon chip: 10 × 33 mm²
Waveguide loss: 0.14 dB/cm
Reference arm with 19 cm physical length
Sensitivity: −65 dB with 100 µW power delivered to the sample



G. Yurtsever et al, Biomedical Optics Express (2014)

Outline

An introduction to silicon photonics

Biosensing and gas sensing

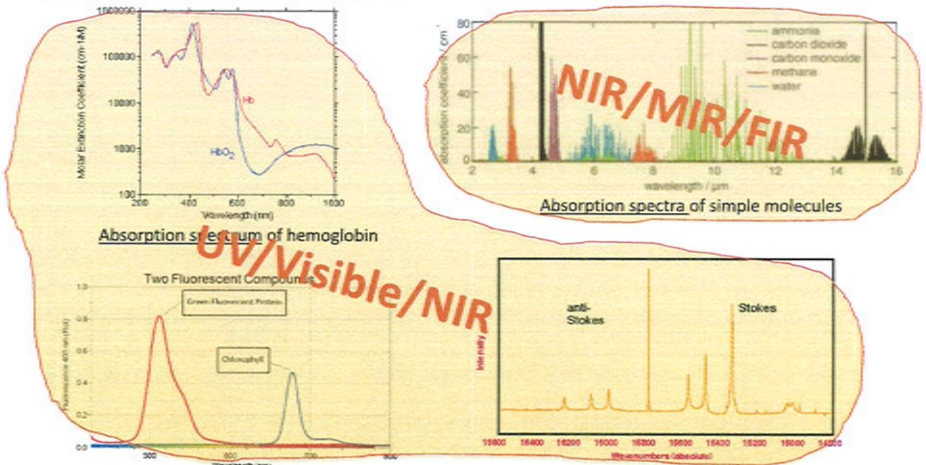
Laser Doppler vibrometry and optical coherence tomography

➡ Spectroscopy-on-a-chip

Optical spectroscopy: fingerprint for molecular sensing

Probing the photon-electron coupling in molecules

Probing the photon-phonon coupling in molecules



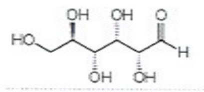
Absorption spectrum of hemoglobin

Absorption spectra of simple molecules

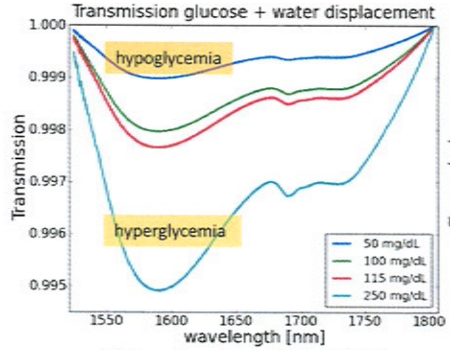
Fluorescence spectrum of GFP

Raman spectrum of CCl_4

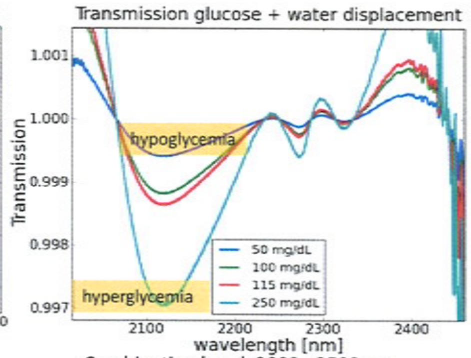
Glucose absorption spectroscopy



Objective: Continuous Glucose Monitoring by means of subcutaneous implant



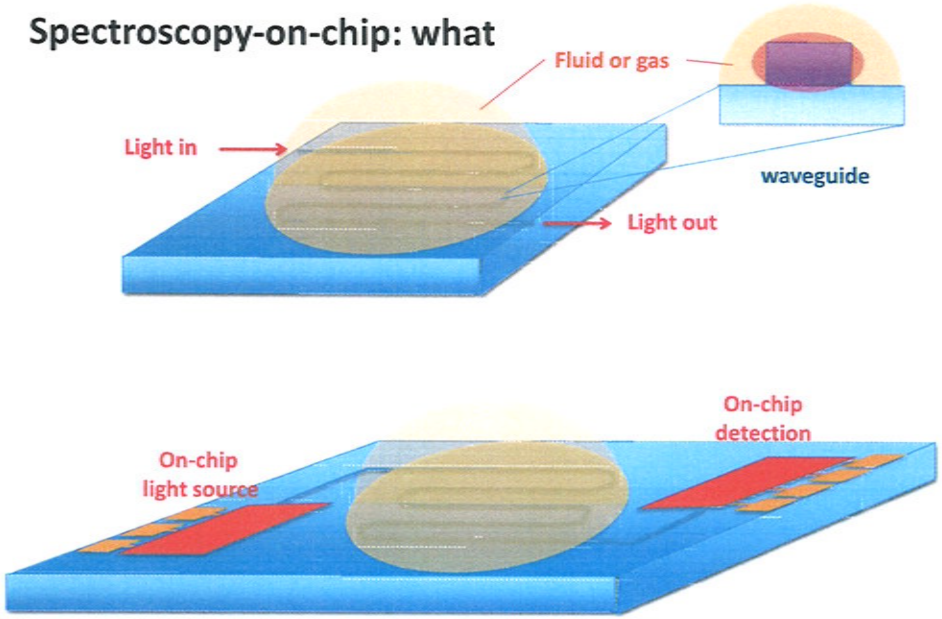
First overtone band: 1500 - 1800 nm



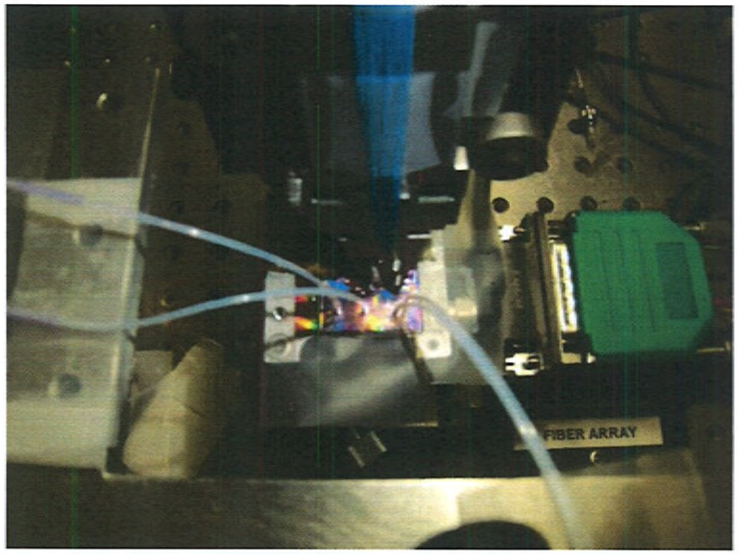
Combination band: 2000 - 2500 nm

For glucose sensing in humans (3-15 mM): Largest change in transmission is 0.5 %
Required sensitivity : 0.02%

Spectroscopy-on-chip: what



View of the chip



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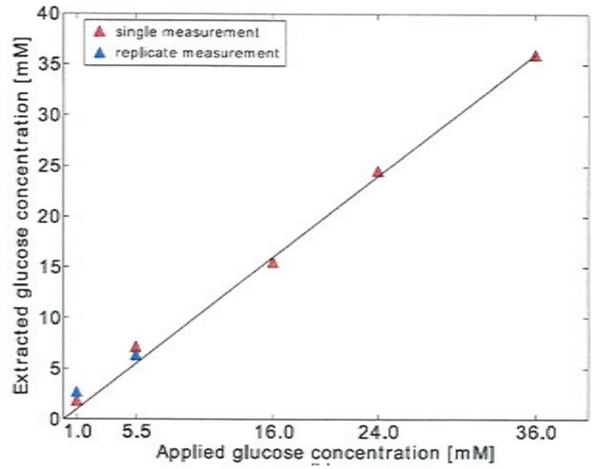
Spectroscopy-on-a-chip

➡ Absorption spectroscopy for glucose detection

Raman spectroscopy

Glucose absorption spectroscopy: proof-of-concept

Use measured spectrum of 36 mM solution as the basic vector



Demonstrated sensitivity of 1mM

E. Ryckeboer et al, Biomedical Optics Express (2014)

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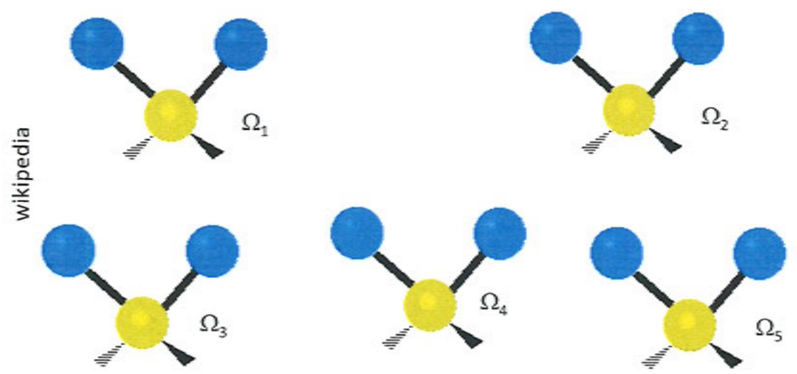
Spectroscopy-on-a-chip

- Absorption spectroscopy for glucose detection

➡ Raman spectroscopy

Molecular vibrations: fingerprint for chemical composition

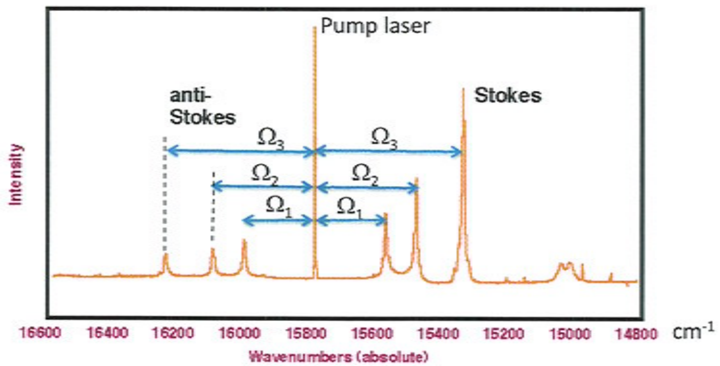


Some modes of vibrations of methylene group - CH_2-

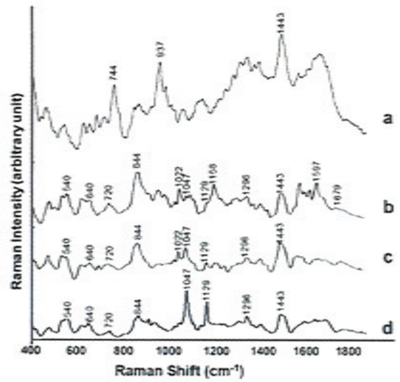
Typical vibration frequencies: several tens of THz

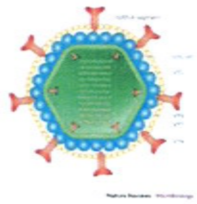
Raman spectroscopy

Raman spectrum of CCl_4



Raman spectra of viruses





C. Fan et al, Detecting Food- and Waterborne Viruses by Surface-Enhanced Raman Spectroscopy, Journal of Food Science Vol. 75, Nr. 5, 2010

Raman signal strength

Typical molecular scattering cross-section: 10^{-29} cm^2

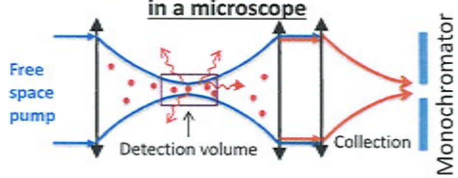
After propagation through 1 cm of 100% dense analyte, one photon is scattered for 10^6- 10^7 input photons

Ways to deal with the weak signals

- use strong pumps
  - unpractical, expensive, damage
- use long integration times
  - unpractical
- surface enhanced Raman scattering (SERS) using rough gold surfaces or nanoparticles
  - poor reproducibility of spectra, probing of nm-sized volumes
- coherent anti-stokes Raman scattering (CARS)
  - nonlinear; needs two lasers or supercontinuum source

Asset of waveguide based Raman spectroscopy

Free space excitation and collection in a microscope

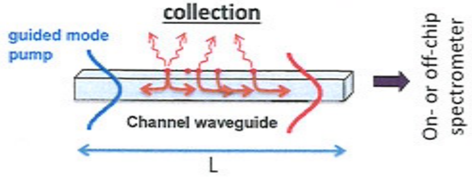


- Large étendue from particle cloud: ⇒ Resolution - sensitivity - size compromise for the spectrometer
- In a confocal microscope:

Raman Scattering cross section

$$\frac{P_{coll}}{P_{pump}} = 2\frac{\lambda_0}{n}\rho\sigma_{scat}$$

Waveguide-based excitation and collection



- Cloud couples to single waveguide mode: smallest possible étendue! ⇒ Optimal performance of spectrometer

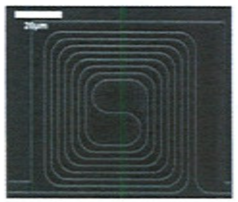
$$\frac{P_{coll}}{P_{pump}} = L\eta_0\rho\sigma_{scat}$$

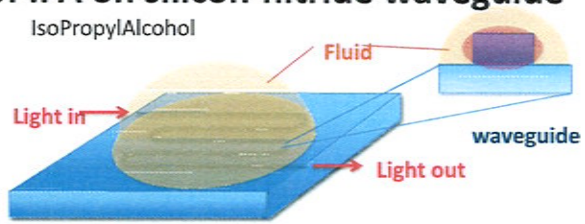
Main asset

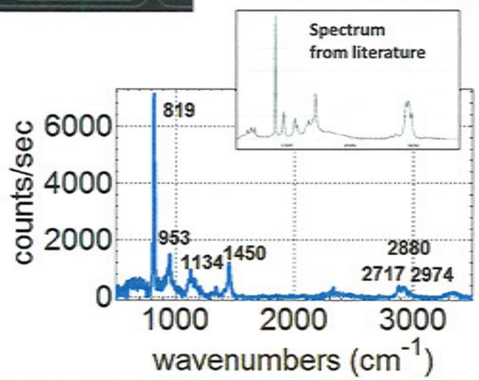
$$\eta_0 = \frac{\pi^2}{n}\frac{\kappa^2 n_\varepsilon^2}{\lambda_0^2}\frac{\int_{clad} d\bar{r}\,|E(\bar{r}_0)|^2}{\left(\iint \varepsilon_0\varepsilon(\bar{r})|E(\bar{r})|^2\,d\bar{r}\right)^2}$$

Raman spectrum of IPA on silicon-nitride waveguide

IsoPropylAlcohol



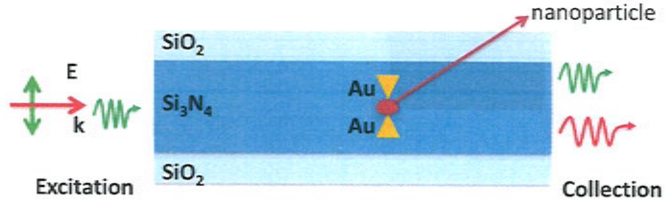




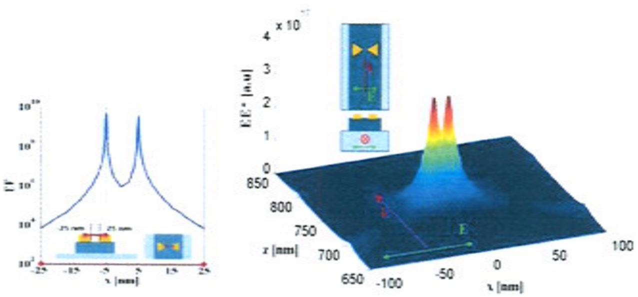
Efficiency of collection >25x better than in Raman microscope

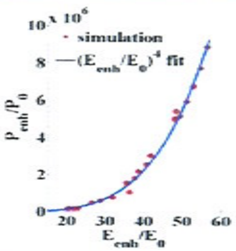
A. Dhakal et al, Opt Lett. (2014)

Nanoplasmonic enhancement on Si_3N_4 waveguide



Enhancement of Raman scattering scales with $|E|^4$



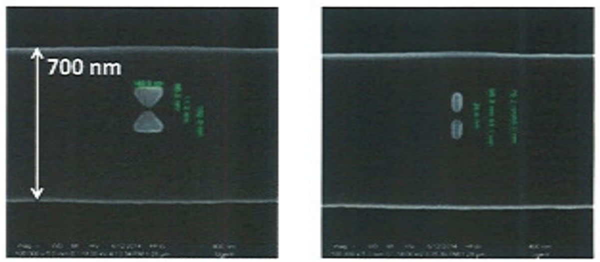


F. Peyskens et al, CLEO, CM2F.5 (2013)

On-chip nanoplasmonic antennas

Fabricated nanoplasmonic antennas (by e-beam lithography):

- gaps of ≈ 10 nm can be achieved
- all antennas are integrated on top of a 700 nm single-mode Si_3N_4 waveguide



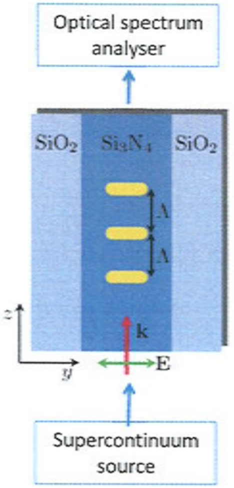
Excitation of an array of nanoplasmonic antennas on a single-mode waveguide

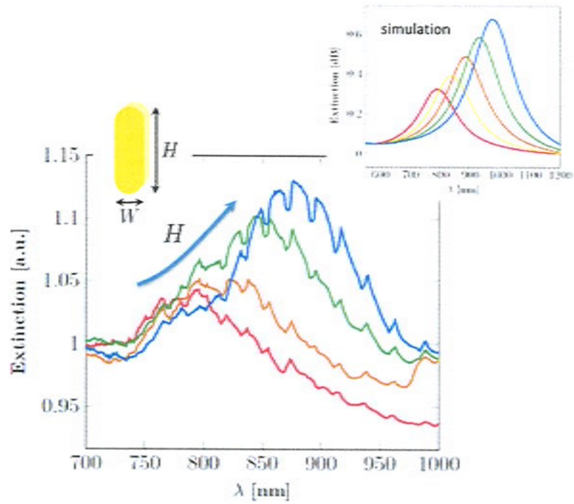
Pump attenuation by a single antenna: up to 25%!! → very efficient use of pump power

F. Peyskens et al, to be published

Extinction spectra of on-chip nano-antennas

Example: experimental single-rod antenna resonance as a function of height



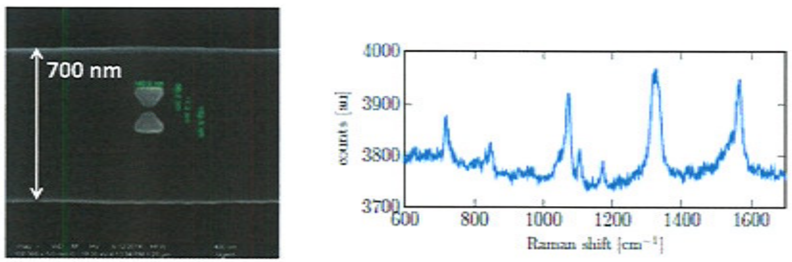


F. Peyskens et al, Optics Express 2015

On-chip nanoplasmonic antennas for enhanced Raman

Fabricated nanoplasmonic antennas (by e-beam lithography):

- gaps of ≈ 10 nm can be achieved
- all antennas are integrated on top of a 700 nm single-mode Si_3N_4 waveguide



Raman spectrum of NitroThyoPhenol (NTP) bound to the gold nano-antenna

F. Peyskens et al, unpublished

Conclusion

Silicon photonics:

Mature technology in CMOS-fab, low cost in high volume

High index contrast: miniaturisation, Purcell effect, high field confinement

Strong industrial traction for telecom/datacom applications

From visible to mid-IR

Many new materials integrated on silicon

Very large potential for:
- lab-on-chip applications (biosensors, Raman-sensors)
- body implants (glucose sensors)
- point-of-care instruments (breath analysis, pulse wave velocity, OCT)

Acknowledgements

Photonics Research Group
professors P. Bienstman, W. Bogaerts, G. Morthier, G. Roelkens, N. Le Thomas, D. Van Thourhout

many postdocs and PhD's

IMEC CMOS process line
and ePIXfab www.epixfab.eu

Funding and collaborations through national and EU research projects

Collaborations:
C. Detavernier (UGent), A. Skirtach (UGent), J. Martens (KULeuven), W. Drexler (MUVienna), T. Van Leeuwen (UAmsterdam), P. Van Dorpe (imec)

Program Photonics Event 2015 - Vision, Robotics & Mechatronics 2015

Thursday June 4

BRABANTZAAL PhotonicsNL Conference	BARONIEZAAL Independent	ROOM 19 Vision, Robotics & Mechatronics	ROOM 20 Photonics
09:45-09:55 - BRABANTZAAL **Opening** *Bart Verbeek, PhotonicsNL*			
09:55-10:25 - BRABANTZAAL **Advanced photonic technologies for monitoring cerebral oxygen metabolism and blood flow** *Alessandro Torricelli, Associate Professor, Politecnico di Milano - Department of Physics*			
10:25-10:50 **Visit expo**			
10:50-11:05 **Exosomes enlightened** *Edwin van der Pol, Postdoc researcher, Academic Medical Center, University of Amsterdam*	10:50-11:35 **RoboNED DUO presentation – Robotics and Healthcare** *Prof. dr. Tinie Kardol, Chairman of governing board at care institution Vughterstede* *Dr. Marcel Heerink, Associate professor at Hogeschool Windesheim Flevoland*	10:50-11:10 **Actieve stereovisie: de toegangssleutel tot robuuste industriële 3D-visietoepassingen** *Koenraad Van de Veere, CEO, Phaer bvba*	10:50-11:10 **NTS' 25+ years of experience in design and construction of optomechatronical systems** *Theo Scholten, Operations Manager NTS-Optel*
11:05-11:20 **Needless Needles: non-invasive blood analysis on premature babies** *Nienke Bosschaart, Postdoc, Twente University*			
11:20-11:35 **Biomedical application of light scattering: detection of field carcinogenesis** *Arjen Amelink, Senior Scientist, TNO*		11.15-11.35 **Smart Vision for Drones in Civil Applications** *Jaap van de Loosdrecht, Professor Computer Vision, Centre of Expertise Computer Vision NHL University of Applied Sciences*	11.15-11.35 **Optical coherence tomography for material characterization** *Ping Liu, Postdoc researcher, Aerospace Non-Destructive Testing Laboratory, TU Delft*
11:35-11:55 **Visit expo**			
11:55-12:10 **Combined photoacoustic and ultrasound modulated optical tomography for quantitative imaging** *Altaf Hussain, Researcher, Biomedical Photonic Imaging group, University of Twente*	11:55-12:40 **RoboNED Workshop: Flexible manufacturing and robotization – "Cooperative robots are going to make production of small series profitable"**	11:55-12:15 **ToF ... cross linked !** *Luc Mertens, Onderzoeksleiding, Universiteit Antwerpen*	11:55-12:15 **PNO Photonics Innovation Services** *Jose Pozo, Lead Consultant Photonics Technology, PNO Consultants*
12:10-12:25 **Real-time tissue diagnosis during lung biopsy procedures using Diffuse Reflectance Spectroscopy** *Jarich W. Spliethoff, Clinical Research Scientist/ PhD candidate, Netherlands Cancer Institute/ Philips ResearchNKI*			
12:25-12:40 **Nonlinear optical imaging as a diagnostic tool for cutaneous squamous cell carcinoma** *Giju Thomas*		12:20-12:40 **The pursuit of exceptioneel 3D sensor design** *Lucien Vieugels, LMI Technologies BV*	12:20-12:40 **Benefit of Beam Profiling and Power or Energy Measurement** *Sven Kern, Sales Germany, Ophir Spiricon Europe GmbH*
12:40-13:50 **Lunch & visit expo**			
13.50-14.20 - BRABANTZAAL **Silicon photonics: an enabler for the internet and for the life science** *Roel Baets, Ghent University - Imec*			
14.25-14.40 **Biosensing platform based on micro-ring resonators for sensitive and label-free protein detection** *Bart de Boer, Senior Scientist, TNO*	14.25-15.10 **RoboNED DUO presentation – Autonomous vehicles in agriculture settings** *Allard Martinet MSc., Managing Director at Probotiq BV* *Dr. ir. Maurice Kwakkernaat, Sr. scientist specialist, TNO Automotive and group leader of the Cooperative Vehicle Systems group*	14:25-14:45 **Adaptive Vision Technologies; For non-conditioned environments or products** *Richard Vialle, Algemeen Directeur, Beltech B.V.*	14:25-14:45 **Supercontinuum lasers for life science and bio-instrumentation** *Sascha Häuser, Regional Sales Manager, EMEA, NKT Photonics GmbH*
14:40-14:55 **Optical trapping, manipulation and Raman spectroscopy of (bio-)particles with photonic devices** *Jaap Caro, Delft University*			
14:55-15:10 **Photonic Integrated Circuits for biophotonic applications: manipulating visible light** *Douwe Geuzebroek, VP marketing & Sales, XiO Photonics*		14:50-15:10 **Voor- en nadelen van offline robots programmeren** *Björn Hoeven, Consultant cards PLM Solutions*	14:50-15:10 **Key Enabling Technologies - Nano, Micro, New Materials and Photonics in NRW** *Dirk Kalinowski, Project manager Photonics, Cluster NanoMicroMaterialsPhotonics.NRW*
15:10-15:30 **Visit expo**			
15:30-15:45 **Widely tunable laser source for gas sensing applications** *Sylwester Latkowski, Postdoctoral researcher, TU/e*	15:30-16:15 **Workshop: Mechatronicus - wat wordt de volgende stap?** *Theo Bookelmann, System Architect, TEGEMA* *Martin van Acht, directeur, TEGEMA*	15:30-15:50 **"Controlled Growing"** *Sven Rusch, Sales & support, Aris BV*	15:30-15:50 **Smart positioning with piezo electric elements** *Hubert Muenzer, mechOnics ag*
15:45-16:00 **Roadmap for photonic integration technologies** *Katarzyna Ławniczuk, JePPIX coordinator, JePPIX – TU/e*			
16:00-16:15 **BlackGEM: an optical robotic telescope array** *Marc Klein-Wolt, Assistant Professor, Radboud University Nijmegen*		15:55-16:15 **Making modern factories more efficient with intelligent mobile robots** *Paul van der Vorst, Business Development Manager, Europe, Clearpath Robotics*	15:55-16:15 **New Optical CMOS Sensors for Time Correlated Detection** *Werner Brockherde, Head of Department Optical Sensor Systems, Fraunhofer IMS*
16:15-17:00 **Networking drinks**			