Micro-Transfer Printed High-Speed Lithium Niobate Modulator on Silicon Nitride

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Lithium niobate integrated modulators have shown great performance when it comes to fast, low loss modulation, with multiple >100 GHz demonstrations and insertion loss below a dB. This highly desired function is missing in the silicon nitride integrated photonic platform which could be interesting for application such as datacom, light detection and ranging (LIDAR), and quantum photonics and computing. Using micro-transfer printing we are able to heterogeneously integrate these thin film lithium niobate devices on top of silicon nitride integrated circuits to create high-speed electro-optic modulators. The demonstrator device is 2 mm long with a half-wave voltage V_π of 14.8 V and an insertion loss of 3.3 dB. The device shows an extinction ratio of 39 dB and has a 3-dB Electro-Optic bandwidth of >50 GHz. We generated open eye diagram up to 70 Gb/s in this proof-of-principle demonstration paving the way towards more scalable heterogeneous integration of thin film lithium niobate on silicon and silicon nitride.

Introduction

As photonic systems advance, the demand for faster and more intricate technologies is on the rise. Exploring applications from datacom, telecom, and light detection and ranging (LIDAR) to sensors, medical devices, optical neural networks, and on-chip (quantum) computing, the need emerges to densely co-integrate diverse functionalities. While individual photonic platforms excel at specific tasks, no single integrated platform optimally performs all functions. To enhance device performance for complex integrated systems, there is a growing interest in combining different platforms to leverage their strengths.

Lithium niobate (LN) is considered an excellent material for modulators due to its exceptional Pockels coefficient, wide transparency window and minimal losses. Integrated LN modulators have successfully achieved over 100 GHz bandwidths at driving voltages compatible with CMOS technology [1,2,3]. However, lithium contamination is a barrier to the integration of thin film LN platforms into CMOS fabrication facilities. The heterogeneous integration of LN on silicon and silicon nitride (SiN) addresses this challenge, shifting LN processing to the back-end of the fabrication process.

While wafer-bonded LN has demonstrated effective modulator operation [4,5,6], it faces limitations in material efficiency, co-integration with other materials, and requires postbonding processing. Micro-transfer printing (TP), provides a solution by facilitating the integration of both fabricated devices [7] and thin films [8] in the back-end, and is a proven approach for lithium niobate applications [9,10]. This study presents a hybrid LN-on-SiN high-speed modulator fabricated using TP. It achieves a bandwidth exceeding 50 GHz and an insertion loss of 3.3 dB.

Design and Fabrication

To produce the 300 nm X-cut thin film coupons of LN for printing, the material is etched to form 2 mm by 40 µm rectangles with mechanical attachments on the sides, referred to as tethers. As shown in Figure 1c, adiabatic tapers are strategically added to both sides of the coupon to minimize transition losses from silicon nitride to LN. These tapers are designed to withstand a lateral misalignment of up to 500 nm, which is the typical accuracy of a transfer printing tool. Subsequently, the oxide layer beneath the thin film is etched away using hydrofluoric acid to release the coupon.

The suspended, free-hanging coupons are then picked up and printed using an elastomeric stamp on a SiN circuit, fabricated through e-beam lithography. Printing occurs directly on top of the SiN platform. Figure 1a depicts the Mach-Zehnder interferometer (MZI) featuring the transfer-printed LN, while Figure 1b illustrates the SiN-guided hybrid LN-on-SiN mode. For electro-optic modulation utilizing the Pockels effect, gold electrodes are introduced. These elements are designed to optimize the half-wave voltage-length product ($V\pi L$) at 6.3 Vcm. Additionally, the differential mode of the electrodes is tailored for impedance matching and velocity matching to the optical mode.

Measurements and Results

Compared to a reference SiN waveguides, the hybrid waveguides with LN coupons show a loss increase of 2.7 dB. The measured insertion loss is primarily attributed to roughness and misalignment of the tapers. Nonetheless, the tapered structure still represents an improvement over the taperless transition. The MZI structures exhibit an additional 0.6 dB loss compared to the waveguides, attributed to a 0.3 dB excess loss for each multimode interferometer.

Despite separate printing of the two MZI arms, their alignment is robust, with an extinction ratio of 39 dB near 1550 nm indicating only a 0.2 dB difference in loss between both arms. The device has a $V\pi$ of 15 V, slightly outperforming simulations, attributed to the fabrication of electrodes with a slightly smaller gap than designed. Electrode characteristics, measured up to 67 GHz (depicted in Figure 1d), closely match the desired 100 Ω impedance, and the effective index aligns with the optical group index from simulations.

Small signal measurements reveal a 3 dB bandwidth exceeding 50 GHz, with measurements hitting the noise floor due to the large $V\pi$ beyond this point (Figure 1e). The system successfully transmits up to 70 Gb/s NRZ with a BER below KP4-FEC. Bit error rates (BER) for different bit rates are presented in Figure 1f, alongside an example eye at 56 Gb/s (BER=1.4e-7).

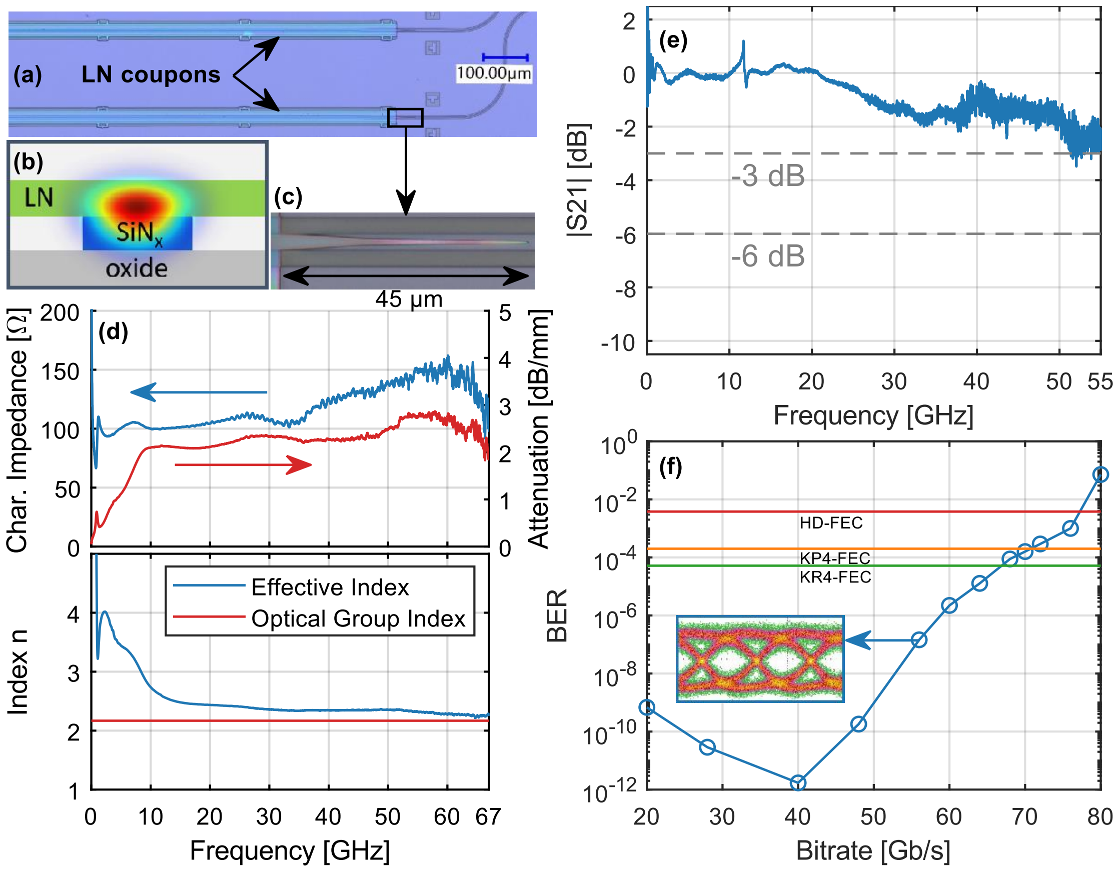

Figure 1: (a) Microscope image of half of the printed LN coupons in the Mach-Zehnder structure. (b) Hybrid SiN/LN mode profile (c) Zoom of the taper (d) Electrical parameters of the differential mode in the electrodes. (e) Small signal response of the modulator (f) NRZ bit error rates of the eye diagrams generated using the modulator compared to bit error rates required for conventional forward error corrections.

Conclusions

We report on the fabrication of a high-speed hybrid LN-on-SiN modulator using micro-transfer printing, demonstrating a bandwidth exceeding 50 GHz. The incorporation of adiabatic LN tapers enhances the coupling efficiency of the SiN-to-LN transition, resulting in a measured 3.3 dB insertion loss and a 39 dB extinction ratio. The performance can be improved with longer coupons, and more detailed design of the electrodes.

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