Compact photonic crystal Si-LN modulator realized by micro-transfer printing

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***Abstract*—High-density heterogeneous integration of thin-film lithium niobate is in demand for realizing compact silicon circuitry equipped with Pockels moduators. A very compact photonic crystal modulator is demonstrated. The Si-LN photonic crystal cavity shows an insertion loss of −2.6dB and an extinction ratio of >30dB. The modulator shows a tuning efficiency of 6.23 pm/V and electro-optical modulation bandwidth of 3.5GHz.**

***Keywords*—heterogeneous integration, silicon photonics, thin-film lithium niobate, micro-transfer printing**

I. Introduction

Thin-film lithium niobate (TFLN) is one of the most promising candidates for building future electro-optic modulators as it enables low-loss, ultrahigh bandwidth Pockels modulation. However, the LNOI platform itself has limited scalability and integration density. In addition, LNOI is not CMOS compatible and usually requires non-standard etching technique. The resulting ridge waveguides with sloped sidewalls also make standardization difficult and limit the smallest feature size. The Silicon-on-insulator(SOI) platform on the other hand provides unparalleled compactness, scalability, and potential for low-cost, large-volume production. The Silicon platform mostly utilizes the carrier plasma dispersion effect for modulation. While silicon modulators could be very compact and high-speed, there is a tradeoff between modulation efficiency, modulation bandwidth and insertion loss. Heterogeneous integration of TFLN enables realization of Pockels modulation in the silicon platform, expanding the available options. The heterogeneous integration of thin-film lithium niobate, combining high-performance modulation with a low-cost, highly scalable platform, could expand the range of application scenarios for lithium niobate. Heterogeneous integration of TFLN has been achieved through bonding, a process that typically necessitates substrate removal and imposes restrictions on the smallest die size. Micro-transfer printing is an emerging heterogeneous solution capable of transferring miniaturized thin-film materials and thin-film devices without including the substrate[1], [2]. Micro-transfer printing of TFLN confines all the intricate fabrication procedures on the source wafer and streamlines the production process by minimizing the processing over the target chip.

Mach–Zehnder interferometers are widely used for realizing LN modulators. Ultrahigh speed modulators are demonstrated using MZI architecture. However, the footprint of MZI modulators are usually ~cm long, which is not convenient for integration. Resonant modulators have a more compact shape and is WDM compatible. Among resonating structures, photonic crystal (PhC) cavity has the most compact shape. In addition, light travels back and forth in one direction in 1D photonic crystal cavity, which harness the most of the largest nonlinear coefficient of LN. In this paper, we demonstrated a compact Si-LN PhC modulator by micro-transfer printing of TFLN thin-film for the first time. The hybrid PhC cavity achieves single resonance over a wide spectral range. The modulator achieves efficient electro-optical tuning of 6.23 pm/V and electro-optical modulation bandwidth of 3.5GHz

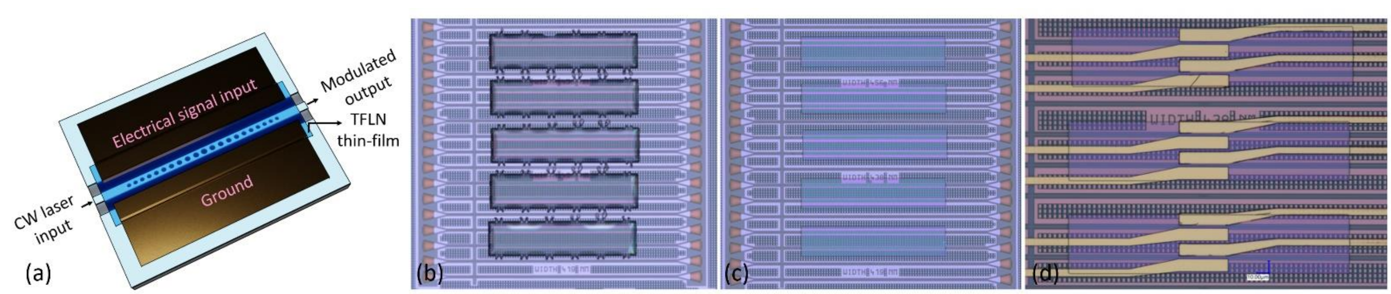

Fig. 1 (a) Schematic of the device; (b) chip with micro-transfer printed TFLN coupon; (c) chip with TFLN thin film (d) final chip.

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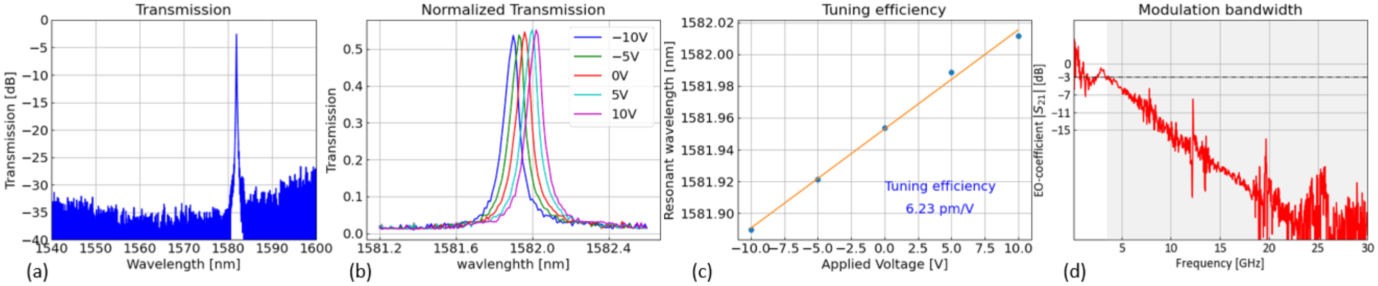

Fig. 2 (a) Optical transmission; (b) Transmission at different applied voltages; (c) Tuning efficiency; (d) Modulation bandwidth.

II. DESIGN AND FABRICATION

Fig. 1(a) shows the schematic of the device design. The device starts with a silicon circuit. The circuit is realized on a 300 mm silicon-on-insulator (SOI) wafer in a CMOS pilot line using 193 nm immersion lithography. The circuit contains silicon photonics crystal structure designed in literature[3]. The size of the 1D PhC cavity is 420 nm×11 μm. The cavity consists of periodic holes with spacing of 362 nm. The holes are symmetrically distributed around the center, and their radii are parabolically modulated, ranging from 218 nm at the center to 160 nm at the sides. The whole PhC cavity is covered with a TFLN film, which is heterogeneously integrated to the silicon chip through micro-transfer printing. To realize the heterogeneous integration, we also need to prepare a source chip, with fully suspended TFLN coupons. The fabrication of the source chip starts from a commercially available LNOI wafer. In a first step the LN-layer is patterned and etched to form a rectangular shape. After patterning and etching of the release layer, we encapsulated the LN with photoresist and after photolithography, tethers are formed for suspending the thin film. Finally, a release etch is conducted to fully suspend the TFLN coupon. Using a micro-transfer printer (X-Celeprint), the suspended TFLN coupon is picked up and transfer printed over the target chip by controlling the adhesion between the PDMS stamp and the coupon and also between the PDMS stamp and the target chip. Fig. 1(b) shows a microscope image of the TFLN coupon printed on the target chip. We micro-transfer printed multiple coupons, each with dimensions of 50 μm×230 μm, at a spacing of ∽50 μm. The TFLN coupons are micro-transfer printed in a very compact region. One could observe the tethers are nicely breaking and the film is fully attached to the target chip. After removing the resist, a TFLN film is situated on the target chip, as shown in Fig. 1(c). Finally, an E-beam lithography step was conducted to pattern the electrodes. 20nm- thick titanium and 700nm- thick gold was deposited and a metal lift-off step was conducted to finalize the fabrication of the device. The image of the final device is shown in Fig. 1(d).

III. CHARACTERIZATION

We first characterized the transmission of the device. The device demonstrates a sharp resonance at 1581nm, with transmission suppressed over a large spectral range (from 1540nm to 1600nm) as shown in Fig. 2(a). The device also demonstrates −2.6dB insertion loss, which mainly results from under coupling of the cavity. The resonance has an extinction ratio higher than 30dB.The quality factor of the resonance is around 15000.We also measured the electro-optic tuning efficiency of the cavity by applying a voltage from −10V to 10V, as shown in Fig. 2 (b). The electro-optic tuning efficiency is measured to be 6.23pm/V, as shown in Fig. 2 (c).

Finally we conducted a high-speed measurement of the device in the frequency domain. The radio frequency (RF) signal generated by the vector network analyzer (VNA, Keysight N5247b) is initially amplified and delivered to the chip through a 50GHz RF probe. CW light is input to the cavity and modulated. The modulated output is collected by a high-speed photodetector (PD, XPDV3120). The electrical output from the photodetector also undergoes amplification before being collected by the VNA. Measurement results shows the 3dB electro-optical bandwidth of the device is 3.5GHz.

IV. CONCLUSION

In summary, we demonstrated the first Si-LN PhC modulator enabled by micro-transfer printing. Dense heterogeneous integration of TFLN over compact silicon circuits are realized.

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