Characterisation of Centimetre-Scale Micro-Transfer Printed Lithium Niobate on a Silicon Nitride Platform

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Abstract

For many years, photonic integrated circuits have been developed using CMOS-compatible materials like silicon (Si) and silicon nitride (SiN). This compatibility ensures low-loss operation, easy integration with electronic components, and the use of established manufacturing processes. Although these materials are well-suited for passive optical components, they lack certain features such as a high Pockels coefficient and intrinsic $\chi^{(2)}$ nonlinearity. To introduce these capabilities, it's possible to integrate other materials with the CMOS-compatible platforms.

In this study, we present a method for integrating centimetre-long thin-film lithium niobate (TFLN) devices onto a SiN substrate using micro-transfer printing (µTP). We evaluate the performance of these integrated TFLN devices by measuring their loss and assessing their electro-optic properties.

1. Introduction

For many years, photonic integrated circuits have been created on CMOS-compatible platforms like silicon (Si) or silicon nitride (SiN). This makes integration with electronic components easier and enables processing in already existing foundries. While these platforms outclass others for passive structures, they often miss critical components like gain or photodetection. Also, these platforms have negligible intrinsic second-order nonlinearity are missing.
Lithium niobate (LN) on the other hand also offers promising features, including low loss, nonlinearity, acousto-optic, pyro-electric and strong electro-optic effects [1], that could fill this gap by being heterogeneously integrated. Integrating e.g. LN modulators onto CMOS-compatible platforms could therefore allow for efficient optical modulation for advanced communication systems.

In the past, various techniques to integrate a material in a SiN platform have been proposed: flip-chip bonding, where a prefabricated device is directly bonded to the target wafer; epitaxial growth, where a full layer of the device material is grown on the target wafer, after which the device is patterned; die-to-wafer or wafer-to-wafer bonding, where the device material is first bonded on the target wafer, then the substrate is removed and the device is patterned. Micro-transfer printing (µTP) is a more recently developed technique [2], where devices are fabricated on a source wafer and then pick-and-placed to a target wafer. This method allows for batch fabrication and testing of devices on a source wafer before back-end integrating them to the target wafer (known-good die principle) without disrupting processing lines of the target wafers. For LN specifically, mostly bonding [3, 4] has been used to combine the two platforms. Sporadically, flip-chip bonding [5] and also µTP [6, 7, 8, 9] were used. Transfer printing, which preserves CMOS foundry processes, facilitates large-scale, cost-effective manufacturing while incorporating nonlinear functionality on the chip, enhances the accessibility of the LN platform [10].

Earlier research showcased the potential of transfer-printed LN for high-speed modulating a SiN platform [7]. Nonetheless, there remains room to enhance the modulator efficiency. Since the half wave voltage is directly inversely proportional to the interaction length, scaling up the length of printed devices consequently reduces the power consumption, leading to a competitive heterogeneous CMOS platform. However, dealing with heterogeneous integration of up to cm-scale devices remains challenging. Here we demonstrate integration of such devices on SiN while maintaining decent propagation losses.

2. Micro-transfer printing of cm-scale lithium niobate thin films on SiN waveguides

Up to a centimetre long LN coupons are prepared and transfer printed on a SiN platform using the process developments reported in [11]. The design is altered to minimise the reflection at the facets and angled facets are introduced. With these coupons, both hybrid LN/SiN propagation loss test structures and modulators are populated.

To estimate the propagation losses in the hybrid LN/SiN platform, coupons with different lengths are printed on identical SiN waveguides, as shown in Figure 1a. By using this cut-back method, only the length of the LN is differed. In this way, the propagation losses attributed to the LN can be derived from transmission measurements. All lengths of coupons are printed twice to have a backup and estimate the reproducibility.

In a second test, the facet losses are examined by printing several shorter coupons in series. A different amount (three and seven) was printed on the dedicated structures. By doing so, it can both be compared to the reference and each other. Figure 1b shows the chip after printing those structures. Both printing routines where, in this case, carried out without any adhesive layer.

3. Loss and half-wave voltage measurements

After printing and removing the coupon encapsulation, the aforementioned structures are measured. Transmission measurements are carried out at a wavelength of 1550 nm and the results are collected in the graphs below (see Figure 2), where only the values for the successfully printed coupons are displayed. The printing yield in this case was 90%. The deleted entry showed much lower transmission due to several brakes in the coupon.

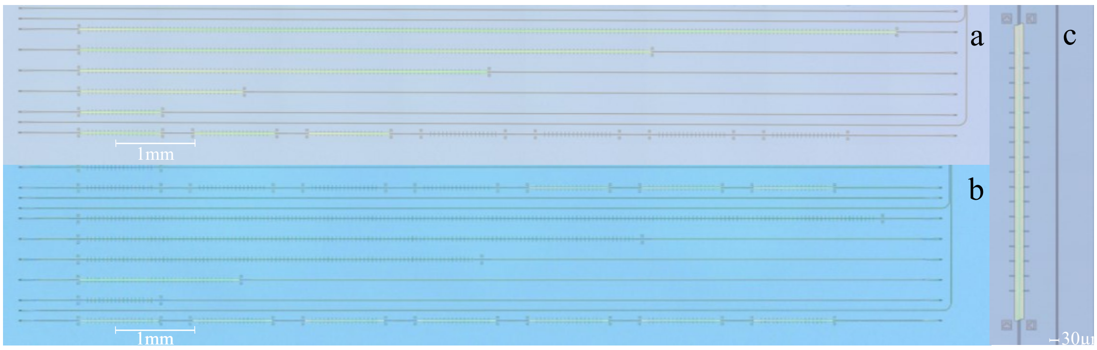

Figure 1: Printing of loss structures for measuring propagation losses (a) and facet losses (b) and a zoomed version of a 1mm coupon (c)

When the values for the first measurement run are plot (Figure 2a), a linear fit is added for the average of each coupon length. The gradient of this fit shows propagation losses of about 0.9 dB/cm. The second measurement run (Figure 2b) shows the transmission power with respect to the amount of facets of the coupons in the chain. Comparing all different arrangements, the facet losses are 1.8 dB/facet on average.

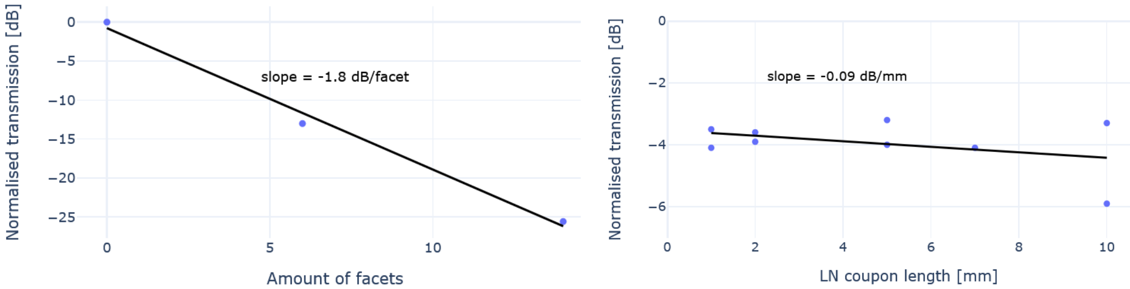

Figure 2: measurements to deduce the transmission loss and facet loss of the LN/SiN patform

With these sufficiently low propagation losses, integrated LN modulators with long light-matter interaction on a CMOS-compatible platforms are possible. Therefore, we can validate the electro-optic effect by building a heterogeneous SiN/LN unbalanced Mach-Zehnder modulator (MZM) with a cavity length of one centimetre. The printing results (after encapsulation removal) are shown in Figure 3a and a close up in Figure 3c. After printing, the coupons are metalized by adding a 15 nm thick titanium adhesion layer with a micron of gold on top of it as displayed in Figure 3b and a close up in Figure 3d. The cross-section of the full stack is illustrated in Figure 4a.
The gap between the two metal traces is around 5.8 µm. This gap width was chosen to make the electro optic effect act as strong as possible (resulting in a low half-wave voltage length product ($V_\pi L$)), while avoiding extra propagation loss due to the metals, even if the fabrication would not be perfect.

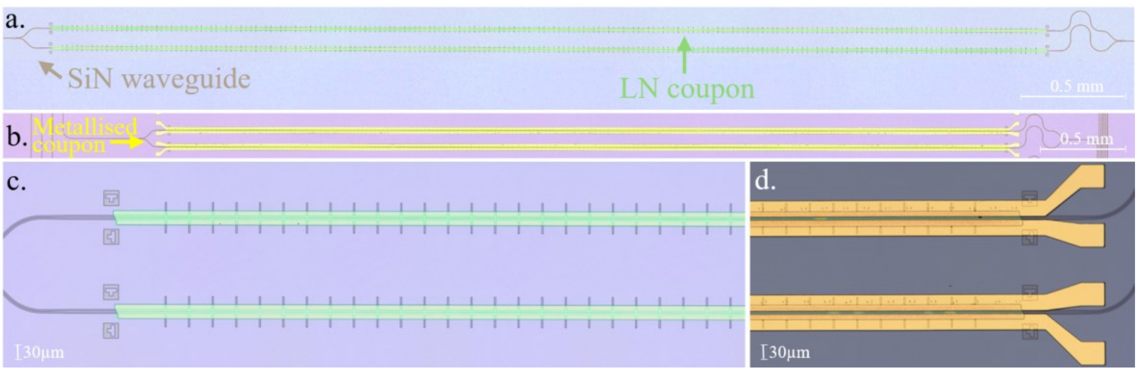

Figure 3: The centimetre long MZM after printing (a, c) and post-processing (b, d)

With these parameters, a half-wave voltage (V_π) of about 3 V is expected [12]. The actual V_π is measured using the setup shown in Figure 4b, where the laser source is coupled into the MZM and the outcoming light is measured by a power meter (PM). In the meantime, the electrodes are steered by bringing a low frequency electrical signal of 100 Hz to the electrodes through probes. Both the electrical signal from the signal generator (SG) and the measured optical output signal from the PM are then fed to an oscilloscope (OSC) to be recorded. In post processing of the data, the logged transmission power and input power can be plotted with respect to each other, to deduce a V_π of 3.2 V, as displayed in

Figure 4c. This Value is close to the expected V_π, which indicates that the measured modulation is obtained through the electro-optic effect.

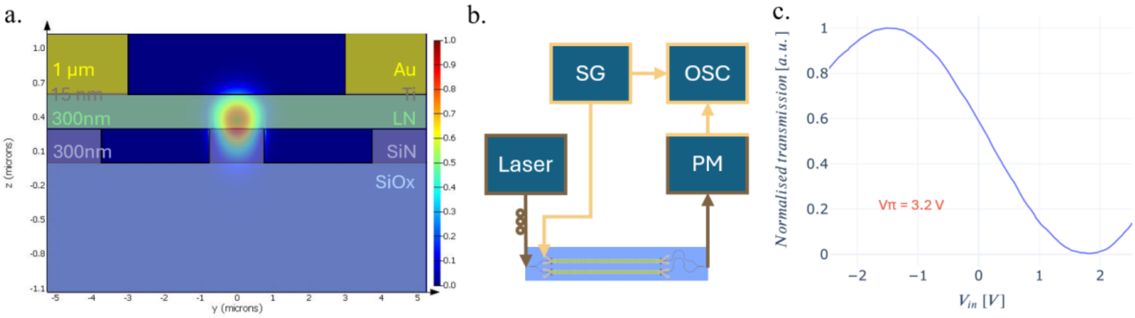

Figure 4: Cross-section of the heterogeneous LN/SiN platform after post-processing (a), measurement setup used to measure the Vπ (b) and output power as a function of the applied voltage, from which the Vπ can be found (c)

4. Conclusion and outline

In this paper, cm-scale µTP of LN is demonstrated by characterising the losses in a heterogeneous LN/SiN platform and showcasing a low V_π MZM. The transmission and transition losses are 0.9 dB/cm and 1.8 dB respectively. The latter can still be improved by using a tapered structure or a more advanced CMOS platform. A V_π of 3.2 V was shown for the demonstrated centimetre long unbalanced MZM at 100 Hz. To verify the electro-optic nature of the modulation, the modulator will be measured at higher speeds.

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