Micro-transfer-printed InP-based Membrane Photonic Devices on Thin-film Lithium Niobate Platform

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Abstract Micro-transfer-printed InP-based membrane devices are fabricated on thin-film lithium niobite (TFLN). For ultra-low coupling loss (~1.0 dB), we use an InP inverse taper waveguide covered with stress-controlled SiON film. We demonstrate 128-Gbit/s NRZ signal modulation using a TFLN Mach-Zehnder modulator integrated with a membrane laser. ©2023 The Authors

Introduction

Thin-film lithium niobate (TFLN) has attracted much attention as a promising platform for high-speed and compact optical modulators, as well as nonlinear optical integrated circuits for optical sensing and computing applications [1]. The integration of InP-based photonic devices such as laser diodes (LDs), semiconductor optical amplifiers (SOAs), and photodetectors (PDs) on TFLN is highly desired to scale-up chip functionality to the level of state-of-the-art Si photonic chips.

Various techniques for integration on the TFLN platform have been demonstrated, such as hybrid integration [2-4], wafer bonding [5], and micro-transfer printing (μTP) [6], as shown in Table I. Hybrid integration using flip-chip bonding is one of the most mature methods because it can use conventional high-power LD chips. However, it requires high alignment accuracy for both horizontal and vertical directions, which results in a relatively large coupling loss between LDs and TFLN waveguides (~5.2 dB in ref. [2]). The wafer bonding method offers the benefits of wafer-level productivity and precise alignment. However, since TFLN devices still have a much larger footprint than InP-based devices, the wafer-scale process does not appear to be a cost-effective solution. To overcome these problems, the μTP is a suitable way because densely-fabricated InP-based photonic devices on an InP substrate can be transferred to a large TFLN platform.

In this work, we demonstrate a heterogeneous integration of electrically-pumped membrane LDs [7] and SOAs on TFLN platforms by μTP. Due to the low coupling loss (~1.0 dB) between the InP-based membrane photonic devices and the TFLN waveguides, mW-class output power LD and low-power-consumption SOA on a TFLN platform are achieved. A 128-Gbit/s non-return-to-zero (NRZ) signal modulation is also demonstrated with a TFLN Mach-Zehnder modulator (MZM) and an integrated membrane LD.

Device design and fabrication

Figure 1(a) shows a schematic of a membrane LD and SOA transfer-printed on a TFLN wafer; the LD and SOA coupons are integrated by transferring them to where the overcladding layer of the prefabricated TFLN chip has been removed. Figure 1(b) shows a schematic diagram

Table I: Typical parameters comparison of reported electrically pumped LNOI lasers.

<table>
<thead>
<tr>
<th>Integration Method</th>
<th>$I_T$ [mA]</th>
<th>Output power (RT)</th>
<th>Operating temperature</th>
<th>Coupling loss</th>
<th>Device configuration (Dynamic operation)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>μTP</td>
<td>1.7</td>
<td>2.7 mW @ 30 mA (w/o MZM)</td>
<td>RT-80°C</td>
<td>~ 1.0 dB</td>
<td>LD + MZM (128-Gbit/s NRZ modulation)</td>
<td>This work</td>
</tr>
<tr>
<td>Hybrid</td>
<td>60</td>
<td>60 mW @ 1000 mA (w/o MZM)</td>
<td>RT</td>
<td>5.2 dB</td>
<td>LD + MZM (Small-signal response)</td>
<td>[2]</td>
</tr>
<tr>
<td>Hybrid</td>
<td>100</td>
<td>2.5 mW @ 300 mA</td>
<td>RT</td>
<td>--</td>
<td>RSOA + Ring resonators</td>
<td>[3]</td>
</tr>
<tr>
<td>Hybrid</td>
<td>80</td>
<td>3.7 mW @ 200 mA</td>
<td>RT</td>
<td>3-4 dB</td>
<td>RSOA + Ring resonators + PPLN</td>
<td>[4]</td>
</tr>
<tr>
<td>Wafer bonding</td>
<td>80</td>
<td>1.3 mW @ 150 mA</td>
<td>RT</td>
<td>--</td>
<td>SOA + DMR mirror</td>
<td>[5]</td>
</tr>
<tr>
<td>μTP</td>
<td>85</td>
<td>0.77 mW @ 160mA</td>
<td>RT-60°C</td>
<td>--</td>
<td>SOA + Optical filter</td>
<td>[6]</td>
</tr>
</tbody>
</table>
of a membrane distributed-reflector (DR) laser coupon, consisting of a distributed feedback (DFB) active section and a distributed Bragg reflector (DBR). The output channel waveguide has an inverse taper structure that is covered with stress-controlled SiON film (n = 1.50) to protect the output waveguide during the μTP process. Figure 1(c) shows a cross-section of the laser section, where a TFLN waveguide is underneath the laser active region. A six-period InGaAlAs-based multiple-quantum-well (MQW) with a photoluminescence peak wavelength of 1.26 μm is used for the active region. The detailed structure and μTP process are almost the same as in previous studies [7-10]. Figure 1(d) shows the cross-section of a TFLN MZM. We used an x-cut TFLN wafer with a 600-nm thick TFLN layer and 2.0-μm-thick buried oxide (BOX) layer.

A major challenge when considering the integration of TFLN and InP-based devices is the difficulty of optical coupling due to the large refractive index difference between these materials. In our previous work [10], we used shallow ridge InP waveguides for optical coupling with Si waveguides to make them easy to fabricate. However, in the case of an LN waveguide, we need to further reduce the effective refractive index of the InP output waveguide. Figure 2(a) shows the calculated fill factor in the InP layer for various slab heights as a function of the InP ridge waveguide width. This indicates that the use of inverse channel waveguides (i.e., 0-nm slab thickness) is particularly important for SOA integration where undesired laser oscillation must be suppressed. Figure 2(b) shows a schematic diagram of a coupler section between a TFLN waveguide and an InP taper waveguide. The width of the InP taper waveguide linearly decreases from 0.5 to 0.1 μm, whereas that of the TFLN waveguide is 2.8 μm. After the optical mode is transferred to the TFLN waveguide, the width of the TFLN taper waveguide linearly decreases from 2.8 to 0.8 μm. Figures 2(c)-(e) show calculated mode profiles at each point indicated in Fig. 2(b).

Figure 3(a) shows a microscope image of a transfer-printed membrane LDs and TFLN MZM array. The MZM arm is 8 mm long. The close-up of LD section is shown in Fig. 3(b). Figure 3(c) shows a cross-section of the membrane LD with a transmission electron microscope (TEM). Extracted misalignment between a TFLN waveguide and an InP inverse taper waveguide was about 150 nm, which is an acceptable value for efficient optical coupling.

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**Fig. 1:** Schematic diagrams of (a) transfer-printed membrane devices on TFLN platform, (b) coupon of membrane LD, and cross-sections of (c) LD/SOA coupon on TFLN waveguide, and (d) TFLN MZM.

**Fig. 2:** (a) The effective refractive index of membrane devices for each thickness of the slab layer, h, and tip width, w. (b) The detailed structure of a coupler section and (c)-(e) simulated mode profiles of each cross-section.

**Fig. 3:** (a), (b) Microscope images of fabricated membrane devices integrated with TFLN MZM and (c) a cross-sectional TEM images of the coupler section.
Membrane LDs on TFLN waveguide
First, we fabricated a membrane LD ($L_{DFB} = 200 \mu$m) on a TFLN waveguide and measured the output light versus bias current (L-I curve) at a temperature range of 25-80°C to evaluate its static characteristics without MZM, as shown in Fig. 4(a). The threshold current was 1.7, 2.8, and 5.7 mA at 25, 50, and 80°C, respectively. The maximum optical power received by a large-area PD was about 2.7 mW at 25°C. We also measured a reference membrane LD integrated on the BOX layer, and the output power was measured through the InP output waveguide. By comparing these results, we can estimate the coupling loss between the membrane LD and the TFLN waveguide to be about 1.0 dB, which is much lower than in previous studies [2-6]. Figure 4(b) shows the lasing spectra at 25, 50, and 80°C, where the bias current was around 30 mA. Single-mode operations with side mode suppression ratios (SMSR) of up to 35-40 dB were realized at each operating temperature. The kinks in the L-I curve and ripples in the spectrum are due to the reflection at the TFLN chip facet, which can be suppressed by integrating a high-coupling efficiency edge coupler [11].

TFLN Mach-Zehnder modulator integrated with membrane LDs and SOAs
Next, we fabricated a membrane SOA ($L_{SOA} = 140 \mu$m) integrated with a TFLN MZM. Figures 5 (a)-(b) show measured optical spectrum amplified by the membrane SOA and extracted optical gains of the SOA as a post-amplifier for each injection current, respectively. Here, the fibre input power was -7 dBm and the fibre coupling loss was -6 dB. A maximum optical gain of 8.3 dB was obtained at an injection current of 10 mA, showcasing a high energy efficiency for our membrane SOA. This is due to the low coupling losses achieved by using inverse taper waveguides. In addition, undesired laser oscillation due to internal reflections are sufficiently suppressed as shown in Fig. 5(a), allowing membrane SOAs to be placed at any position on the TFLN circuit.

Conclusions
We have demonstrated heterogeneous integration of membrane LDs and SOAs on a TFLN platform using $\mu$TP. We have achieved an ultra-low loss optical coupling (~1.0 dB) between the LDs and TFLN waveguides. We have also confirmed a 128-Gbit/s NRZ signal modulation with a TFLN MZM and an integrated membrane LD. These results indicate that heterogeneous integration of membrane devices using $\mu$TP is promising for manufacturing TFLN PICs for optical communications and other applications.

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References


