Monolithically Integrated Active Passive Waveguide Array Fabricated on Thin Film Lithium Niobate Using a Single Continuous Photolithography Process

Yuan Zhou, Yiran Zhu, Zhiwei Fang,* Shupeng Yu, Ting Huang, Junxia Zhou, Rongbo Wu, Jian Liu, Yu Ma, Zhe Wang, Jianping Yu, Zhaoxiang Liu, Haisu Zhang, Zhenhua Wang, Min Wang, and Ya Cheng*

This work demonstrates a robust low-loss optical interface by tiling passive (i.e., without doping of active ions) thin film lithium niobate (TFLN) and active (i.e., doped with rare earth ions) TFLN substrates for monolithic integration of passive/active lithium niobate photonics. The tiled substrates composed of both active and passive areas allow for patterning the mask of the integrated active passive photonic device at once using a single continuous photolithography process. The interface loss of tiled substrate is measured as low as 0.26 dB. Thanks to the stability provided by this approach, a four-channel waveguide amplifier is realized in a straightforward manner, which shows a net gain of 5 dB at a 1550-nm wavelength and 8 dB at a 1530-nm wavelength for each channel. The robust low-loss optical interface for passive/active photonic integration will facilitate large-scale high performance photonic devices that require on-chip light sources and amplifiers.

1. Introduction

Single crystalline lithium niobate (LN) is an attractive photonic material owing to its wide transparent window, moderately high refractive index, as well as large acousto-optic, nonlinear, and electro-optic coefficients. Turning the bulk LN crystal into thin film lithium niobate (TFLN) has further enabled the fabrication of high-performance integrated photonic devices for both classical and quantum applications, such as low-loss waveguides, high-quality microresonators, high-speed modulators, and high-efficiency optical frequency converters, etc.[1–4] To realize integrated active photonic devices, TFLN doped with rare earth ions (REI) has recently been employed to demonstrate microlasers, waveguide amplifiers, quantum emitters, and quantum memories.[5–21] Nevertheless, monolithic integration of the active devices fabricated on the REI-doped TFLN with passive TFLN photonic devices has not been demonstrated due to the challenging difficulties in achieving the high precision alignment, low-loss interfacing, and reliable bonding. To this end, the traditional strategy of active...
passive integration requires use of additional coupling elements, such as on-chip spot size converter (SSC) and lensed fiber, which leads to significant increase of complexity and cost of manufacturing and degradation of performance of the integrated devices.

In this work, we demonstrate robust low-loss optical interface for passive and active lithium niobate photonics by tiling the commercially available undoped TFLN with an REI-doped TFLN substrate before the lithographic fabrication process. Afterwards, a single continuous photolithography process is conducted for patterning the mask of the integrated devices followed by chemomechanical etching for transferring the mask pattern to the TFLN substrate. The fabrication technique, which is coined photolithography assisted chemo-mechanical etching (PLACE), has enabled fabrication of large-scale photonic devices of low propagation loss.\(^{[22]}\) Here, we demonstrate an optical interface of active passive photonic integration with an insertion loss of 0.26 dB, which has been used to produce a four-channel waveguide amplifier. The optical gain performance has been characterized in each channel of the waveguide amplifier, featuring a net gain of 5 dB at 1550-nm wavelength and that of 8 dB at 1530-nm wavelength for each channel. The device provides convincing evidence that the developed approach is of practical use for a wide range of photonic applications which require monolithic integration and low-loss interfacing of active and passive photonic devices.

### 2. Device Fabrication

Figure 1 depicts the schematic process flow of the optical interface fabrication for the integrated passive and active TFLN photonics. Firstly, we prepare both the undoped TFLN On Insulator (TFLNOI: 500-nm Z-cut TFLN/2 μm SiO\(_2\)/500 μm Si) substrate and the REI-doped TFLNOI substrate (Figure 1a) which will be further used in the tiling process. The undoped and REI-doped TFLN wafers are standard 4 inch wafers of the same size which are purchased from a manufacturer with mature technology (NANOLN, Jinan Jingzheng Electronics Co. Ltd.), the thickness error of the TFLN is within 10 nm. Before we conduct the tiling, both the doped and undoped TFLNOI substrates are coated with a 200-nm-thick chromium (Cr) film as a hard mask material for subsequent chemical mechanical polishing (CMP) process. The sidewalls of the two TFLNOI substrates around the optical interface are polished into smooth and highly vertical surfaces which are vital for achieving the low-loss interfacing. To produce TFLN substrates with flat end facets and ideal verticality, the equipment we chose is an automatic precision grinding polishing machine (Logitech DP1) and the polishing suspension is composed of cerium oxide of a particle diameter \(\approx 0.8 \mu m\). We designed and machined a metal cylinder of high flatness and parallelism as the fixture to fix the TFLN substrate, so that the surface of the polished substrate also has a high flatness, and will not chamfering the sample. It is noteworthy that the undoped and doped TFLN substrates are clamped together by two glass blocks, allowing for polishing the end facets simultaneously as the two substrates are now vertically mounted. The polishing machine is equipped with a pneumatic system for tuning the contact pressure between the sample and the polishing pad with high accuracy. The mechanical arm drives the fixture to swing back and forth, and the fixture rotates on the rotating grinding disc. In such a manner, the sample motion can be chaotic, which is necessary for achieving a uniform surface quality of the polished facets. Secondly, we tile the undoped and REI-doped TFLNOI substrates seamlessly using a home-built fixture tool. The home-built fixture is a simple tool which have two clamps to press the two TFLNOI substrates for reducing the air gap in between (Figure 1c). In this step, the undoped and REI-doped TFLNOI substrates are flip bonded on a polished glass plate with high flatness for the optimal alignment of the top surfaces of two TFLNOI.
substrates (Figure 1b). Ultraviolet (UV) glue with relatively high viscosity is applied on the bottom of the tilted TFLNOI substrates which are further placed on a quartz plate and irradiated immediately with UV light. It is quite unlikely that the glue could fill up the narrow gap between the two TFLNOI substrates (Figure 1c). Afterwards a laser welding process is conducted to permanently fix the TFLNOI substrates on the quartz support with sufficient mechanical stability and rigidity (Figure 1d). In the laser welding process, an ultrafast laser with pulse duration $\tau_p = 300$ fs, wavelength $\lambda = 1030$ nm, pulse repetition rate $f = 10$ MHZ, single pulse energy of $Q = 1 \mu J$ is used. The laser beam is focused at the glass/silicon interface using a microscope objective with a NA = 0.6. The sample is translated by a 3D stage with a translation speed of $v = 20$ mm s$^{-1}$. Thirdly, the optical waveguide patterns are produced by femtosecond laser selective direct-writing, and the following CMP process is used to transfer the waveguide pattern into the tiled TFLN (Figure 1e,f]. More fabrication details of the PLACE technique can be found in our previous work.[10,22]

Figure 2a shows a typical straight TFLN waveguide fabricated on a 500-nm-thick undoped TFLN substrate. Figure 2b,c shows integrated active passive TFLN waveguides with perpendicular and tilted interfaces. Both the doped and undoped TFLN substrates have a thickness of 500 nm before they are tiled into the integrated substrate. The angled physical contact (APC) connector in Figure 2c differs from the physical contact (PC) connector in Figure 2b for that it can reduce the back reflection by choosing the Brewster angle at the interface. Minimization of the back reflection is critical for some devices such as DFB lasers which can easily achieved with the APC connector. The PLACE process naturally forms a slope on the waveguide sidewall, resulting in ridge-shaped cross section. The detail can be found from our previous publication.[21] The schematic of the waveguide is shown in Figure 2d, where $w_0 = 1 \mu m$, $w_1 = 1.14 \mu m$, $w_2 = 4.8 \mu m$, $T_0 = 90$ nm, $T_1 = 120$ nm, $T_2 = 290$ nm. Figure 2e is a scanning electron microscopy (SEM) image of the cross-section of a TFLN waveguide fabricated by PLACE process. As shown in Figure 2f, the integrated TFLN waveguide is also characterized by SEM, and the gap at the optical interface is determined to be less than 22 nm. The Fresnel reflection loss at the interface is calculated to be less than 0.01 dB, which is much smaller than the loss caused by the different heights of the waveguides on the tiled sample.

3. Results and Discussions

We design a structure as shown in Figure 3a to measure the coupling loss between the active and passive segments of the integrated waveguide which is mainly caused by the slight misalignment in the vertical direction between the passive and active TFLN substrates. A beam splitter based on a multimode interference (MMI) coupler which can realize 50%/50% beam splitting at 1550-nm wavelength divides the beam into two beams of equal power. One waveguide arm with multiple bends with a bending radius of 300 cm passes through the interface five times, while the other waveguide arm of the same geometry only passes the interface once. We send the 1550-nm wavelength laser beam into the beam splitter and the output beam is collected by an objective lens and imaged with an infrared camera. By comparing the beam powers measured from the two output ports, the loss
caused by the extra four passings through the interface can be calculated by

\[ \alpha = -10 \log \left( \frac{P_{\text{out}1}}{P_{\text{out}2}} \right) \]  

(1)

where \( P_{\text{out}1} \) is the output power of the waveguide arm passing through the interface five times, and \( P_{\text{out}2} \) is the power of the output of the waveguide arm passing through the interface only once. For this sample, we determine that the height difference is around 60 nm. To minimize the measurement error, we repeat the measurement eight times at the different input powers and record the output powers to generate eight sets of data. The average insertion loss of the data set is 0.26 dB, and the standard deviation is 0.044 dB as shown in Figure 3b. Figure 3b also shows the simulation of the straight integrated active passive TFLN waveguides. We use the software Mode Solution in our simulation to find out the relationship between the loss and height-difference caused misalignment, and the simulation result agrees well with the experiment. It can be clearly seen that the coupling loss at the interface increases with the height difference between the passive and active waveguides. It is very encouraging from the simulation result that the interfacing loss will be less than 1 dB when the height difference is less than 160 nm, which is not difficult to ensure in today's photonic industry.

The design of the four-channel waveguide amplifier is illustrated in Figure 4a, which consists of four Er\(^{3+}\)-doped spiral waveguides connected by an MMI beam splitter. The concentration of Er\(^{3+}\) ions in the LN waveguides is 1 mol\%. The four waveguide amplifiers are fabricated on Er\(^{3+}\)-doped TFLN while the three MMI couplers are fabricated on the undoped TFLN. Figure 4b shows the digital picture of the integrated device, the length of each Er\(^{3+}\)-doped waveguide is 2.1 cm. The output beam profile of the waveguides is also captured by an objective and imaged onto an infrared camera. As shown in the false-color insets of Figure 4c, the 1550-nm wavelength beams in the four Er\(^{3+}\)-doped waveguides are all in the fundamental mode with a uniform intensity distribution.

The pump-and-signal method was applied to measure the gain in the four-channel waveguide amplifiers array as shown in Figure 5a. A C-band continuously tunable laser (CTL 1550, TOP-TICA Photonics) is used as the signal source. The polarization states of both the pump and signal lasers are adjusted using inline fiber polarization controllers (PC). A wavelength division multiplexers (WDM) at the output port of the integrated amplifier to inject the pump laser and collect the signal laser. The pumping is realized with backward injection rather than the bidirectional injection, because the MMIs are designed around for the signal wavelengths. The amplified signal is measured by an optical spectrum analyzer (OSA: AQ6370D, YOKOGAWA). The power of the 1530 and 1550 nm coupled to the waveguide is about 13 eW, while the output power of the 1530 and 1550 nm decreases to \( \approx 10 \) eW after taking into account the MMI loss, interface loss, and waveguide propagation loss. The photograph of the Er\(^{3+}\)-doped TFLN waveguide amplifier array under the pumping with a 980 nm diode laser is shown in Figure 5b, demonstrating the strong green upconversion fluorescence along the four spiral waveguides. Figure 5c,d demonstrates the net gain of the
integrated amplifier as a function of the injected pump power at the signal wavelengths at 1550 and 1530 nm under the backward pumping, respectively. In both cases a rapid increase of the gain with the increasing pump power is observed, which is followed by a slow gain saturation at the higher pump power. We also observed obvious gain even under the low pumping power, because the population inversion of the Er\(^{3+}\) ions is far from saturation under the low pumping power. Specifically, the maximum internal net gain for the 1550 nm signal reaches about 5 dB and that for the 1530 nm signal reaches about 8 dB, corresponding gain coefficient of 2.4 dB cm\(^{-1}\) for the 1550 nm and 3.8 dB cm\(^{-1}\) for the 1530 nm. The gain coefficients are lower than our previous work, because the pump laser is injected only from the one end of the waveguide amplifier rather than injected from both ends of the waveguide as our previous work.\(^{[14]}\) In addition, there is about 0.5–1 dB variation of the gain between the four channels which should be a result of the imperfections in the fabrication process of the waveguide amplifier as well as the different coupling efficiencies of the pump laser at the four ports. On the whole, there is quite uniform in the four waveguide amplifiers, and it shows the stability in the fabrication process as the four waveguide amplifiers are designed to have the same parameters. This multichannel waveguide amplifier is expected to contribute to the high-power output from onchip amplifiers by coherent beam combination.

4. Conclusion

In summary, we demonstrate a robust low-loss optical interface for monolithic integration of passive and active TFLN photonics by tiling the undoped and REI-doped TFLN substrates followed with a single continuous photolithography fabrication process. We achieve a coupling loss of 0.26 dB at the waveguide interface. Furthermore, a four-channel waveguide amplifier array is fabricated, showing a net gain of 3 dB at 1550-nm wavelength and 8 dB at 1530-nm wavelength in each Er\(^{3+}\)-doped waveguide.
respectively. The strategy of tiling passive and active TFLN substrates to form low-loss optical interfaces for the monolithic integration of passive and active TFLN photonics offers advantages in its high scalability, high reliability, high production rate, and cost effectiveness.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

optical interface, photolithography, photonic integrated circuits, thin film lithium niobate, waveguide amplifier

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