Vertical mode transition in hybrid lithium niobate and silicon nitride-based photonic integrated circuit structures

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This Letter presents an optical mode transition structure for use in Si3N4/LiNbO3-based hybrid photonics. A gradual modal transition from a Si3N4 waveguide to a hybrid Si3N4/LiNbO3 waveguide is achieved by etching a terrace structure into the sub-micrometer thick LiNbO3 film. The etched film is then bonded to predefined low pressure chemical vapor deposition Si3N4 waveguides. Herein we analyze hybrid optical devices both with and without the aforementioned mode transition terrace structure. Experimental and simulated results indicate that inclusion of the terrace significantly improves mode transition compared to an abrupt transition, i.e., a 1.78 dB lower mode transition loss compared to the abrupt transition. The proposed transition structure is also applied to the design of hybrid Si3N4-LiNbO3 micro-ring resonators. A high-quality factor (Q) resonator is demonstrated with the terrace transition which mitigates undesired resonances.

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The integration of electro-optic (EO) LiNbO3 with passive Si photonics has attracted significant interest in the optical communication community [1–10]. Hybrid devices have the potential to realize many photonic devices by means of combining the desirable properties of dissimilar materials: tunable micro-ring resonators [3,5,6], Mid-IR modulators [7], Mach–Zehnder modulators [1], and wavelength converters [10]. The heterogeneous integration of LiNbO3 with Si on insulator (SOI) is currently at the forefront of hybrid LiNbO3 device research [1,3,5–7,9,10]. This is likely due to the low material cost of Si, established SOI fabrication technology, and the high index contrast between Si and LiNbO3, which facilitates low complexity optical mode designs [9]. An equivalently simple solution for fabricating Si3N4/LiNbO3 hybrid EO devices has yet to be implemented despite the ultra-low propagation loss [11–13], high power handling capabilities [14], and wide transparent spectrum [13] that high-quality low pressure chemical vapor deposition (LPCVD) Si3N4 possesses. One of the major challenges of designing this Si3N4/LiNbO3 hybrid device is in achieving a low loss optical mode transition from the Si3N4 waveguide to hybrid Si3N4/LiNbO3 [2]. Bonding LiNbO3 directly on the top of the predefined Si3N4 waveguide imposes a significant mode transition loss at the interface due to reflections caused by a substantial disparity in effective indices and mode profiles between Si3N4 and hybrid Si3N4/LiNbO3 guided optical modes. A tapered Si3N4 mode transition has been implemented with success [8], but the device fabrication is complex and requires precise alignment during bonding.

In this work, we present a simplified but efficient mode converter structure to obtain a low transition loss from the Si3N4 waveguide to the hybrid Si3N4/LiNbO3 structure. With the application of the mode transition structure, a hybrid Si3N4/LiNbO3 single bus micro-ring resonator has been demonstrated. Our process uses commercial-off-the-shelf (COTS) LPCVD Si3N4 on quartz, and thin film LiNbO3 on insulator (LNOI) wafers. The general process flow is as follows: fabricate passive Si3N4 waveguides, etch terrace structures into the LiNbO3, and then bond the two structures together. Some advantages of our approach are that it facilitates a low-loss transition, allows for relaxed alignment requirements during the bonding process, and conserves the high-cost thin film LiNbO3 wafer by selectively bonding only in the desired location of the photonic circuit. This paper is organized by first presenting a simulation of the hybrid waveguide and mode transition structure, then discussing the device fabrication and characterization.

The passive hybrid photonic device proposed in this Letter consists of three types of optical waveguide structures: standalone Si3N4 ridge waveguides for optical input and output, a hybrid (Si3N4/LiNbO3) EO waveguiding region suitable for hosting active devices, and a mode transition structure residing between the standalone Si3N4 and hybrid waveguide sections, shown in Fig. 1.

We first conduct a parametric study to investigate the impact of the Si3N4 ridge thickness and width, as well as LiNbO3’s thickness on mode confinement in the LiNbO3 and device bending radius. Our primary interest is finding...
an optimal device structure that maximizes the mode confinement in the LiNbO$_3$ and does not introduce excessive bending loss in the hybrid waveguide. The device is designed to support a single TE-polarized fundamental mode at a wavelength of 1550 nm. The proposed device is simulated using commercial Lumerical Mode solver software. The design parameters include Si$_3$N$_4$ core width of $W_{Si3N4}$, core thickness of $T_{Si3N4}$, and the x-cut LiNbO$_3$ film thickness of $T_{LN}$. Figure 2(a) shows the simulated confinement factor map, which visualizes the optical mode confinement factor in LiNbO$_3$ ($\Gamma_{LN}$) as function of $W_{Si3N4}$ and $T_{LN}$ for 200 nm $T_{Si3N4}$. We define $\Gamma_{LN}$ as the ratio of the power residing in the LiNbO$_3$ compared to the total power present in the hybrid guided mode. The confinement factor falls by $\sim$10% as $W_{Si3N4}$ rises from 0.5 to 2 $\mu$m because of increased mode confinement in the Si$_3$N$_4$ core, while $\Gamma_{LN}$ increases by 20% from 300 to 800 nm LiNbO$_3$ thickness as it pulls the light from Si$_3$N$_4$ due to its higher index. However, the bending radius significantly increases for the thicker LiNbO$_3$, as shown in Fig. 2(b), due to the lack of optical mode confinement in the Si$_3$N$_4$ core region. Furthermore, a thinner LiNbO$_3$ film will help to reduce mode transition loss from standalone Si$_3$N$_4$ to the hybrid device. A thinner and narrower loading Si$_3$N$_4$ strip provides a higher optical confinement factor, however, it results in lower index contrast in the horizontal direction, leading to increased bending loss. By considering the above tradeoff study, a hybrid waveguide with a cross section of a 1.7 $\mu$m wide and 200 nm thick Si$_3$N$_4$ strip loaded to a 300 nm thick LiNbO$_3$ is chosen, which can support a more compact bending radius of $\sim$250 $\mu$m, higher mode confinement in LiNbO$_3$ of 0.63, and lower mode transition loss.

As the thin film LiNbO$_3$ is locally bonded to the Si$_3$N$_4$ waveguide, an efficient mode transition from the Si$_3$N$_4$ waveguide to the hybrid waveguide is required. To this end, a mode converter structure is designed to achieve a low transition loss from the Si$_3$N$_4$ waveguide to the hybrid Si$_3$N$_4$/LiNbO$_3$ waveguide region. For low loss transition, we etch the edge of the LiNbO$_3$ film in two steps to form a terrace shape as shown in Fig. 1, top inset. The terrace LiNbO$_3$ film is bonded on the top of the Si$_3$N$_4$ waveguide. The terrace structure has only a step shape in the optical mode propagation direction and is uniform in the other direction. Such a feature eliminates any critical alignment requirement during the bonding process. For reference, a LiNbO$_3$ sample without a terrace transition structure is also investigated. Full 3D EM simulation of the coupling devices are simulated using Lumerical 3D FDTD simulation software. Figure 3 shows the intensity profile of the mode transition from the Si$_3$N$_4$ to the hybrid waveguides. In the non-etched rectangular LiNbO$_3$, due to the discontinuity of the high index of LiNbO$_3$ substrate, large scattering or reflection from the coupling is observed. The simulated mode transition loss per interface is 2.67 dB for non-etched LiNbO$_3$, shown in Fig. 3(a). By introducing our proposed two-step transition this transition loss can be reduced to 0.81 dB. The gradual mode transition at three different locations in the terrace structure indicated as (i), (ii), and (iii) in Fig. 3(b) are shown in Figs. 3(c)–3(e). As the LiNbO$_3$ thickness increases, more light is confined in the LiNbO$_3$ cladding region. The height of each step is 100 nm,
and regions (i) and (ii) are each 5 μm in length, making the total length of the transition region 10 μm.

A schematic of the fabrication process is shown in Fig. 4. Silicon nitride waveguide fabrication begins with a commercial LPCVD Si₃N₄ on a quartz wafer (Mark Optics). The 200 nm thick LPCVD layer offers a homogeneous refractive index, uniform thickness, chemical stability, and low optical absorption at our operational wavelength. A 90 nm thick Cr layer is deposited on the insulating substrate to mitigate the charging phenomenon during e-beam lithography. Device features are defined in an AR-N 7520 negative tone resist using e-beam lithography.

The resist patterns are transferred into the underlying Cr using Cl₂ (45 sccm)/O₂ (2 sccm) inductively coupled plasma (ICP) reactive-ion etching. Afterward, the device pattern is transferred into the Si₃N₄ layers using a SF₆ (5 sccm)/C₄F₈ (5 sccm)/Ar (90 sccm) etch. Then, the excess photoresist, Cr, and other etching byproducts are removed using O₂ plasma clean and wet chemical cleaning processes. Fabricated Si₃N₄ structures are shown in Fig. 5(a); their measured dimensions for height and width are 200 nm and 1.7 μm, respectively. Along with straight waveguides, micro-ring resonators are fabricated on Si₃N₄. Figure 5(a) shows the top-down view of the fabricated micro-ring and its coupling region. A thin film LiNbO₃ is etched to produce the simulated mode transition structure. The x-cut LNOI wafers are purchased from Nanoln; the wafers consist of a 300 nm-thick LiNbO₃ device layer affixed to a 500 μm-thick fused silica handle. A 120 nm chromium layer is sputtered on the thin film LiNbO₃ as a hard mask, then the positive resist is spin-coated and patterned by UV-lithography to define the first level of the mode transition structure. The pattern is then transferred to the substrate using Cr dry etching, as mentioned above, followed by time multiplexed LiNbO₃ etching by CF₄ (6 sccm)/N₂ (28 sccm)/O₂ (5 sccm) plasma dry etch. The etch rate of x-cut LiNbO₃ is ~32 nm/min in a 600 W plasma under 400 W bias, and the surface roughness is ±8 nm. The remaining photoresist and Cr mask layer are removed by the wet etching solution. The second etch height is fabricated in the same fashion. Figure 5(b) shows the SEM image of the final mode transition structure after the two steps have been defined. The levels described in the Fig. 5(b) are comparable to the levels defined in Fig. 1. Level 1 is the thinnest part of the transition region which is 100 nm thick, level 2 is the 200 nm thick middle section, and level 3 is the 300 nm thick section which is the bonding surface of the LiNbO₃. Next, we bond the Si₃N₄ and LiNbO₃ samples together indirectly with Benzocyclobutene (BCB) [15] procured from DOW. A ~250 nm thick BCB layer is spun over the top of the Si₃N₄ device layer, and the BCB is diluted with mesitylene to reduce spin on thickness. The BCB coated wafer is then soft baked for 1 min at 150°C, to let the excess solvent evaporate. The BCB coated Si₃N₄ substrate is placed into a nitrogen purged vacuum oven for precurat at ~180°C for 5 min, resulting in a BCB thickness of ~230 nm, leaving a ~30 nm bonding layer between the LiNbO₃ and Si₃N₄ devices. The thin film’s LiNbO₃ substrate is bonded face down on top of the target Si₃N₄ wafer using the flip-chip bonder. A bonding weight of 9,000 g is applied through the bond-head. The sample is under load for 150 s at 150°C. The bonded wafer stack is placed back into a nitrogen purged vacuum oven set at 200°C for 15 h to complete the polymerization of the BCB. Finally, the waveguide end-facet is prepared by a dicing and polishing technique for efficient fiber coupling. Figures 5(c) and 5(d) show the microscopic images of the bonded devices.

The hybrid waveguides are characterized using a tunable semiconductor laser near 1550 nm. Transverse electric polarized light is edge coupled into and out of the Si₃N₄ waveguide via polarization maintaining lensed fibers. Exiting light is directed into a photodetector then a transimpedance amplifier. The optical intensity as a function of wavelength can then be observed on an oscilloscope. Figure 6 shows the measured insertion loss spectra for three 1.3 cm long devices: a standalone Si₃N₄ reference waveguide, a hybrid waveguide with a mode transition structure, and a hybrid waveguide without transition structure. The hybrid waveguides consist of 0.4 cm long input and output Si₃N₄ waveguides with a 0.5 cm long hybrid region residing in between. The hybrid transition loss can be obtained by comparing the measured insertion loss spectra of the three different waveguides.

At 1550 nm, the measured mode transition loss difference per interface between the two hybrid waveguides is 1.78 dB, which is comparable to our simulation result. This implies the mode transition loss of ~0.81 dB per interface for the terrace transition structure. The total insertion loss can be further
reduced by introducing a top cladding layer at the input/output Si3N4 waveguides and thinning the Si3N4 core dimension [12,16]. This, however, leads to the larger footprint of the photonic devices [12]. A single micro-ring of 250 μm radius with a single bus waveguide is fabricated and characterized with and without the mode transition terrace structure. The measured transmission spectrum for TE polarization is scanned using a Keysight tunable laser near 1550 nm. The hybrid ring without the terrace mode transition structure exhibits a mode transition loss of ~0.81 dB from Si3N4 to the hybrid Si3N4/LiNbO3 waveguide. This improved the mode transition loss by 1.78 dB in comparison to when steps are absent. Hybrid micro-ring resonators with and without mode transition are compared, and a clean spectrum of single FSR and a smooth mode transition are demonstrated by introducing the mode transition structure.

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