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LiNbO$_3$/Si$_3$N$_4$-Bilayer Vertical Coupler for Integrated Photonics

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Abstract: The design of a LiNbO$_3$/Si$_3$N$_4$-bilayer vertical coupler is proposed based on adiabatic transition from a thick-Si$_3$N$_4$ strip waveguide to a LiNbO3/thin-Si$_3$N$_4$ striploaded hybrid waveguide having a gross coupling loss of ~0.08 dB.

1. Introduction

Heterogeneous integration of LiNbO$_3$ on Si$_3$N$_4$ provides efficient modulation and second-order nonlinearity to ultra-low-loss photonic integrated circuits [1,2]. LiNbO$_3$ is difficult to etch so striploading the LiNbO$_3$ with Si$_3$N$_4$ to create a waveguide (Fig. 1(d-iv)) can be an attractive way of realizing the platform. However, due to the lower refractive index of Si$_3$N$_4$ (~1.99) with respect to LiNbO$_3$ (~2.21) it is not possible to confine the light in the Si$_3$N$_4$ when the LiNbO$_3$ film is present which means that adiabatic tapers and low loss transitions between areas with and without LiNbO$_3$ is challenging [3,4]. In this paper, we propose the design of a vertical mode converter where a LiNbO$_3$ thin film is wafer bonded on two stacked layers of stoichiometric Si$_3$N$_4$. Simulation results show that, the vertical mode transition can be achieved with a loss as low as ~0.04 dB.

2. LiNbO$_3$/Si$_3$N$_4$-Bilayer Structure

The wafer structure investigated is shown in Fig 1(a) and is realized by wafer bonding a 300 nm LiNbO$_3$ thin film on a two-layer Si$_3$N$_4$ wafer. After chemical mechanical polishing (CMP), the thickness of this SiO$_2$ bonding layer becomes 100 nm. Both the Si$_3$N$_4$ layers are deposited using the low-pressure chemical vapor deposition (LPCVD) technique. The bottom Si$_3$N$_4$ (740 nm) layer is thicker than the top Si$_3$N$_4$ (200 nm) layer and suitable for nonlinear photonics [5]. A 300 nm SiO$_2$ layer deposited by LPCVD separates these two Si$_3$N$_4$ layers. The bottom Si$_3$N$_4$ layer is used to fabricate the strip waveguide whereas the top Si$_3$N$_4$ layer and the wafer bonded LiNbO$_3$ layer together creates a striploaded waveguide (Fig 1(a-iv)).

The coupler can be divided into 4 sections along the propagation direction. Fig. 1(c) shows the lateral view of a single side of the coupler. Section-1 consists of only the thick-Si$_3$N$_4$ strip waveguide. Section-2 minimizes the reflection between the pure Si$_3$N$_4$ area and the hybrid strip-loaded geometry, and relaxes the alignment requirements between the bonded LiNbO$_3$ film and the bilayer Si$_3$N$_4$ structure. Section-3 is the actual vertical coupler where the mode transition occurs. Section-4 is the LiNbO$_3$ on thin-Si$_3$N$_4$ striploaded waveguide.

3. Mode Transition Mechanism & Simulation Results

The optical mode in the thick-Si$_3$N$_4$ strip waveguide (Section-1) is shown in Fig. 1(d-i). While propagating from the Section-1 to Section-2 a very small portion of optical field is exposed to the LiNbO$_3$ thin film which is visible from both the mode field shown in Fig. 1(d-ii) and the field profile along the propagation direction shown in Fig. 1(c-i). The amount of field leakage to LiNbO$_3$ in Section-2 is so small that the power loss for mode transition from Fig. 1(d-i) to Fig. 1(d-ii) is almost negligible. The vertical adiabatic transition of the mode occurs in Section-3. The width of the thick-Si$_3$N$_4$ strip waveguide is 2 μm which is linearly tapered down to 200 nm whereas the width of the thin-Si$_3$N$_4$ is fixed to 1.5 μm. Fig. 1(b) depicts the top view of the coupler where the taper can be easily seen. From Fig. 1(f) it is clear that, when the width of the thick-Si$_3$N$_4$ narrows down to ~1.4 μm the effective index of the thick- Si$_3$N$_4$ strip waveguide (with LiNbO$_3$ misalignment) matches with the mode of the LiNbO$_3$/thin-Si$_3$N$_4$ stripload hybrid structure. In Fig. 1(d-iii) the optical field distribution of the mode is shown. The thick-Si$_3$N$_4$ strip waveguide is further narrowed down to 200 nm to fully transfer the mode to the LiNbO$_3$/thin-Si$_3$N$_4$ hybrid structure. The mode field looks like Fig 1(d-iv) when the optical field propagates to the end of the taper (starting point of Section-4). Fig. 1(c-ii) shows the smooth transition of the mode from the thick-Si$_3$N$_4$ layer to the LiNbO$_3$/thin-Si$_3$N$_4$ hybrid structure. A length sweep was performed for the taper (Section-3) which is shown in Fig. 1(e). The optical loss for a taper length of 700 μm is ~0.04 dB.
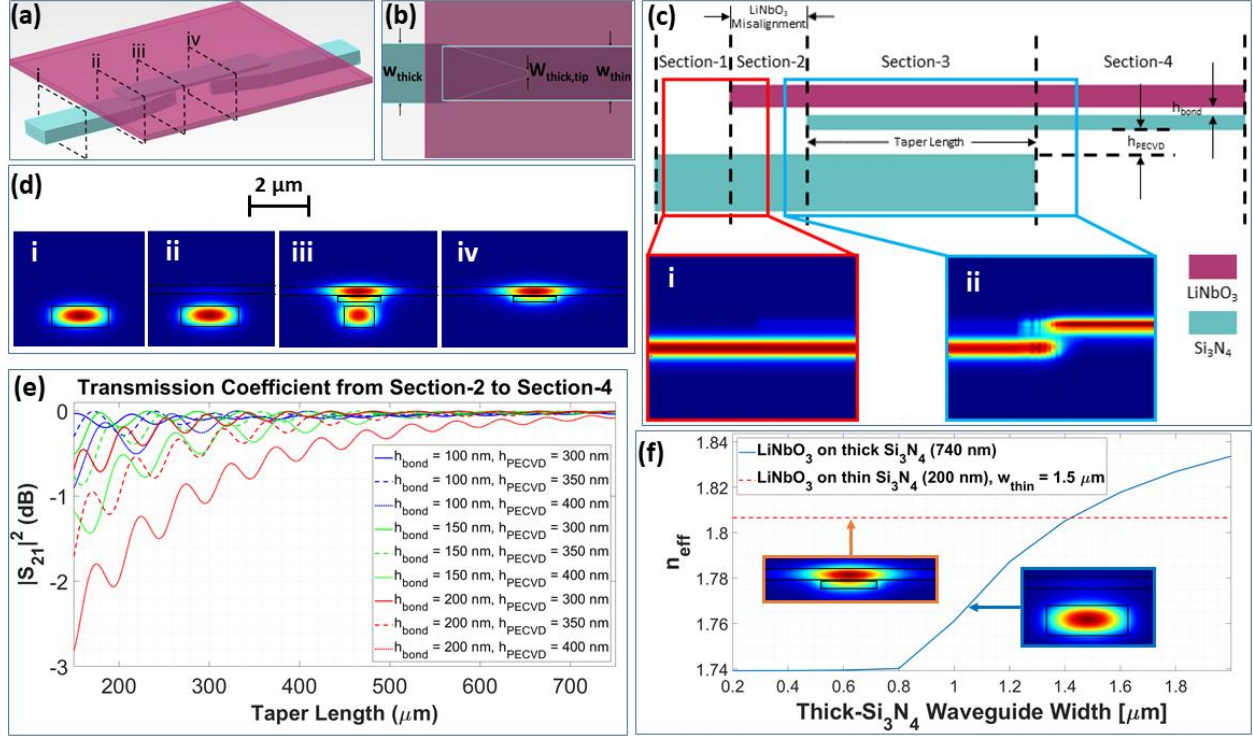
Fig. 1: (a) 3D image & (b) top view of the vertical coupler. (c) Lateral view of the coupler. Inset (i) & (ii) shows the lateral electric field distribution when the light enters from Section-1 to Section-2 & Section-2 to Section-3 respectively. (d) Mode field at different positions of the coupler (i, ii, iii & iv). (e) Transmission coefficients of a single side of the coupler for different coupling lengths and different SiO_2 thicknesses. (f) Effective index matching condition.

4. Tolerance to Fabrication Imperfections

The performance of the coupler was investigated as function of the fabrication uncertainty of the polished layers, i.e. the distance between the two Si_3N_4 layers and the top Si_3N_4 and $LiNbO_3$. Results are shown in Fig. 1(e) and shows a 0.11 dB tolerance of 100 nm for both layers.

5. Summary

We designed an ultra-low loss $LiNbO_3/Si_3N_4$-Bilayer Vertical Coupler which does not require etching of $LiNbO_3$. A total coupling loss of ~0.08 dB for a taper length of 700 μm was calculated from the simulations.

6. References

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