Multifunctional Anisotropic Thermo-Optic Mach-Zehnder Interferometer on LNOI

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Abstract: Harnessing the strong anisotropy of lithium niobate, we have proposed a multifunctional thermo-optic Mach-Zehnder interferometer on x-cut LNOI and experimentally demonstrated its versatile configurations as a polarization-insensitive switch and a polarization beam splitter. © 2022 The Author(s)

1. Introduction

In recent years, thin-film lithium niobate (LN) on insulator (LNOI) is emerging as a promising integrated photonic platform that provides high optical confinement, strong electro-optic (EO) response, large nonlinear coefficient, wide transparency window, and long-term stability. Currently, a series of high-performance integrated functional devices have been demonstrated on LNOI, including high-quality optical cavities [1], high-speed modulators [2], and frequency combs [3]. Especially, the EO effect in LNOI makes it an ideal platform for integrated high-speed modulators. However, for static and low-speed applications, the EO effect suffers from drift effects and anomalous frequency responses [4], which requires an active feedback loop for real-time compensation. Fortunately, these adverse effects are much less observed in thermo-optic (TO) Mach-Zehnder interferometers (MZIs) on LNOI, which have been demonstrated to be a viable alternative to EO phase shifters for applications where temporal stability and repeatability are crucial. TO phase shifters feature a smaller footprint than EO phase shifters working at similar voltages, and stable phase shifts over 30 minutes have been reported [4]. Although extensively investigated for silicon photonics [5], the TO effect, especially anisotropic TO effect on the LNOI platform, which is the focus of this work, has been much less explored [6, 7].

The birefringent refractive indices n_o and n_e of LN feature quadratic temperature dependence from 300 K to 500 K [8], which is the pertinent temperature range for TO devices. Near the telecom C band, the TO coefficients for n_e and n_o are on the order of 10^{-5} K^{-1} and 10^{-6} K^{-1}, respectively, differing by nearly an order of magnitude. To harness this unique and strong anisotropic TO effect, here we propose a multifunctional MZI on the x-cut LNOI platform. The phase shifter is composed of two-section anisotropy-engineered LNOI waveguides, which can be controlled independently and simultaneously for the TE and TM polarizations by tuning the heating power of both sections. Thus, in one configuration, the incident TE and TM polarizations can be switched simultaneously by the MZI, which functions as a polarization-insensitivity switch, exhibiting low excess loss of ∼0.2–1.4 dB and crosstalk ~16–40 dB in the wavelength range of 1520–1580 nm. In another configuration, the incident TE and TM polarizations can be separated to different output ports with high extinction ratios ER_{TE} = 16–44 dB, ER_{TM} = 16.5–42 dB, which functions as a polarization beam splitter, while the excess loss for TE (EL_{TE}) is as low as 0.2–1 dB and that for TM (EL_{TM}) is 0.5–1.3 dB (1520–1580 nm). Furthermore, arbitrary splitting ratios can be achieved independently for both TE and TM polarizations. The versatile configurations of this anisotropic TO MZI for polarization handling and multiplexing may have important implications for large-scale photonic computing and interconnect.

2. Device design

Figure 1(a) shows the schematic configuration of the proposed 2×2 TO MZI, composed of two 2×2 polarizations-insensitive MMI couplers (PIMMI couplers) and two symmetric arms. Each MZI arm consists of a two-section phase shifter with a heater on top, and four 90° Euler bends. The LN thickness is 400 nm and side-wall tilt angle θ = 60°, consistent with our fabrication process. Each phase shifter (PS) consists of two sections (Section 1, Section 2) with respective lengths (L_1, L_2) and directions (y-direction, z-direction), as shown in Fig. 1(a). The PS waveguide width is 1 µm, wider than a singlemode waveguide to improve the fabrication tolerance. In PS Section 1, the light propagates along the z-direction so that the major electric (magnetic) field component of TE (TM) polarization is E_y (H_y), while in PS Section 2, the light propagates along the y-direction so that the major electric (magnetic) field component of TE (TM) polarization is E_z (H_z). With such an elegant configuration, the TO phase shift in Section 2 for the TE_0 mode is significantly larger than that for the TM_0 mode, while the phase shift in Section 1 for the TE_0 mode is significantly smaller than that for the TM_0 mode. Here, $L_1 = 1400$ µm and $L_2 = 450$ µm, sufficiently long to suppress the temperature rise required for MZI operations. Also, L_1 is much longer than L_2 because the phase shift in Section 1 is less efficient than that in Section 2. Such anisotropic TO phase shift can be readily exploited to achieve arbitrary combinations of TE_0 and TM_0 phase shifts, hence splitting ratios, by coordinated tuning of the heaters in Sections 1 and 2, enabling versatile polarization-handling functionalities with a single MZI device.

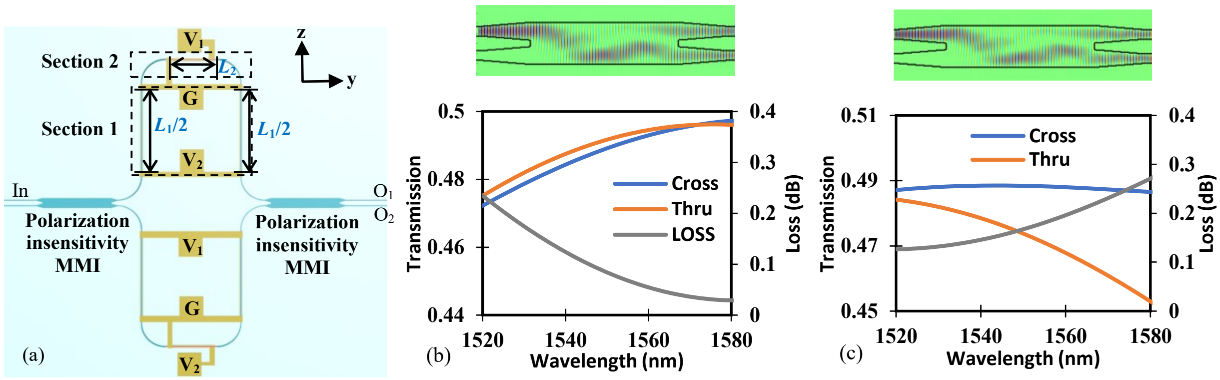

Fig. 1. Schematic configurations of the proposed MZI device. (a) Overview. (b) and (c) The simulated light propagation, the calculated power-splitting ratios, and the excess loss of the designed PIMMI coupler for (b) TE_0, and (c) TM_0 modes.

The PIMMI couplers serving as 3-dB splitters are critical for the MZI performance. To achieve polarization insensitivity, the multimode beating lengths in the MMI coupler must be equal for both TE and TM polarizations. Accordingly, the beat length difference between both polarizations is calculated as a function of MMI coupler width (w_{MMI}), for the coupler thickness of 400 nm. The calculation results indicate that polarization insensitivity is obtained when $w_{MMI} = 4.5$ µm. To guarantee singlemode propagation, the width of the input/output waveguide is set to be 600 nm. Then further structural design optimization is performed using 3D finite-difference time-domain (3D-FDTD) method. The optimized MMI coupler length (L_{MMI}) is 56.81 µm. Figures 1(b) and (c) show the simulated optical field propagation in the optimized MMI coupler operating at 1550 nm for the TE_0 and TM_0 modes, respectively. The calculated transmission spectra for the TE_0 and TM_0 modes at the cross and through ports are also shown in Fig. 1(b) and (c). Evidently, for TE_0, the power-splitting ratio varies between 47.3%:47.6% and 49.8%:49.5% with low non-uniformity of 0.12–0.25 dB across the entire 60 nm bandwidth. For TM_0, the power-splitting ratio varies between 48.7%:48.4% and 48.7%:45.5% with low non-uniformity of 0.03–0.14 dB across the entire 60 nm bandwidth.

3. Device fabrication and characterizations

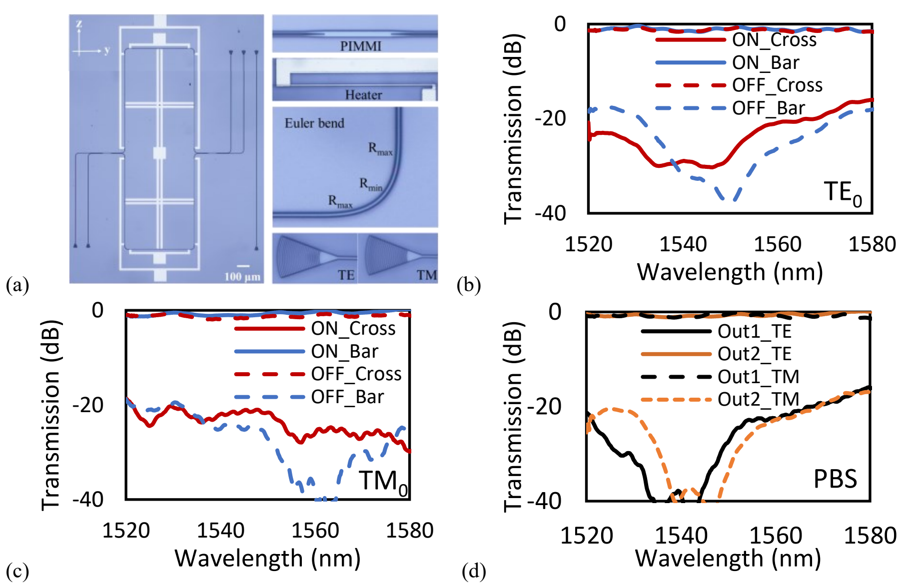

Fig. 2. MZI device fabrication and characterizations. (a) Optical microscope image of the MZI device. Transmission spectra at the cross/bar ports of the polarization-insensitive switch in the Off/On states for (b) TE_0 and (c) TM_0 modes. (d) Transmission spectra of the polarization beam splitter.

The MZI devices have been fabricated on an x-cut LNOI wafer with a 400-nm-thick top LN layer and a 3-μm-thick buried oxide layer. First, the MZI was patterned by electron beam lithography (EBL) and argon-based inductively coupled plasma (ICP) etching. Then, a second EBL was utilized to fabricate the sputtered Ti/Au electrodes and microheaters, which consist of a 100-nm-thick Ti layer and 5-nm-thick Au layer. The microscope image of the fabricated MZI device is shown in Fig. 2(a).

Figures 2(b) and 2(c) show the measurement results for the MZI as a polarization-insensitive switch. From the transmission spectra at the cross/bar ports of the MZI in the Off/On states, the excess loss and the extinction ratio are about 0.2–1.4 dB and 16–40 dB, respectively, in the wavelength range of 1520–1580 nm. For the Off state, the heater power P_1 = 9.5 mW and P_2 = 54 mW are used, while for the On state, the heater power P_1 = 35 mW and P_2 = 178 mW are used.

We also characterize the MZI as a polarization beam splitter, as shown in Figure 2(d). From the transmission spectra, for both polarizations, the extinction ratios are ER_{TE} = 16–44 dB and ER_{TM} = 16.5–42 dB, while the excess losses are as low as EL_{TE} = 0.2–1 dB and EL_{TM} = 0.5–1.3 dB in the wavelength range of 1520–1580 nm. In this case, the heater power P_1 = 107 mW and P_2 = 109 mW are used. In addition, it is expected to significantly reduce the heating power of our device with thermal isolation trenches.

4. Conclusion and discussions

In conclusion, we proposed a multifunctional anisotropic TO MZI on x-cut LNOI. Harnessing the unique and strong anisotropic TO effect of LN, we have demonstrated its versatile configurations as a polarization-insensitive switch and a polarization beam splitter. The incident TE and TM polarizations can be switched simultaneously by the MZI, which functions as a polarization-insensitive switch, exhibiting low excess loss of ~0.2–1.4 dB and crosstalk ~16–40 dB in the wavelength range of 1520–1580 nm. In addition, the incident TE and TM polarizations can be separated to different output ports with high extinction ratios ER_{TE} = 16–44 dB and ER_{TM} = 16.5–42 dB, which functions as a polarization beam splitter. Furthermore, arbitrary splitting ratios can be achieved independently for both TE and TM polarizations. Such unprecedented multifunctional anisotropic MZI will be an important part of the versatile integrated LNOI photonic platform, which may have important implications for large-scale polarization multiplexing photonic computing and interconnect.

Acknowledgement

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References

[1] M. Zhang, C. Wang, R. Cheng, A. Shams-Ansari, and M. Lončar, "Monolithic ultra-high-Q lithium niobate microring resonator," *Optica* **4**, 1536-1537 (2017).

[2] M. He, M. Xu, Y. Ren, J. Jian, Z. Ruan, Y. Xu, S. Gao, S. Sun, X. Wen, L. Zhou, L. Liu, C. Guo, H. Chen, S. Yu, L. Liu, and X. Cai, "High-performance hybrid silicon and lithium niobate Mach–Zehnder modulators for 100 Gbit s−1 and beyond," *Nature Photonics* **13**, 359-364 (2019).

[3] M. Zhang, B. Buscaino, C. Wang, A. Shams-Ansari, C. Reimer, R. Zhu, J. M. Kahn, and M. Lončar, "Broadband electro-optic frequency comb generation in a lithium niobate microring resonator," *Nature* **568**, 373-377 (2019).

[4] M. Xu, M. He, H. Zhang, J. Jian, Y. Pan, X. Liu, L. Chen, X. Meng, H. Chen, Z. Li, X. Xiao, S. Yu, S. Yu, and X. Cai, "High-performance coherent optical modulators based on thin-film lithium niobate platform," *Nature Communications* **11**, 3911 (2020).

[5] L. Song, T. Chen, W. Liu, H. Liu, Y. Peng, Z. Yu, H. Li, Y. Shi, and D. Dai, "Toward calibration-free Mach-Zehnder switches for next-generation silicon photonics," *Photon. Res.* **10**, 793-801 (2022).

[6] G. Chen, H.-L. Lin, and A. J. Danner, "Highly efficient thermal tuning interferometer in lithium niobate thin film using air bridge," *IEEE Photonics Journal* **13**, 1-9 (2021).

[7] X. Liu, P. Ying, X. Zhong, J. Xu, Y. Han, S. Yu, and X. Cai, "Highly efficient thermo-optic tunable micro-ring resonator based on an LNOI platform," *Opt. Lett.* **45**, 6318-6321 (2020).

[8] L. Moretti, M. Iodice, F. G. Della Corte, and I. Rendina, "Temperature dependence of the thermo-optic coefficient of lithium niobate, from 300 to 515 K in the visible and infrared regions," *Journal of Applied Physics* **98**, 036101 (2005).