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Efficient and Broadband Trident Spot-size Convertor for Thin-Film Lithium Niobate Integrated Device

Xuerui Liang, Li Fu, Qianchen Yu, Zhenfeng Xue, Xiaodong Shi, Yaoqin Lu, Honggang Chen, Bo Zhang, Yong Luo, Qianggao Hu, Haiyan Ou, Weidong Ma

***Abstract*—Thin-film lithium niobate on insulator (LNOI) has recently emerged as a promising platform for high-speed optical communication devices. For practical applications, an efficient, polarization-insensitive, misalignment-tolerant and broadband fiber-to-chip optical coupler is necessary. In this paper, we present a fiber-to-chip edge coupler based on trident spot-size convertor (SSC). Experiment shows 1.18/1.10 dB per facet low loss at 1550 nm for TE/TM polarization respectively. A relatively large alignment tolerance (AT) has also been demonstrated. Over a broadband wavelength range from 1490 nm ~ 1640 nm, the edge coupler exhibits a maximum loss of 1.30 dB, a wavelength dependent loss (WDL) of 0.23 dB for TE mode and a polarization dependent loss (PDL) of 0.33 dB when coupled to a single mode fiber (SMF) with a mode field diameter (MFD) of ~6 μm.**

***Index Terms*—Edge Coupler, Thin-film Lithium Niobate, Spot size convertor**

I. INTRODUCTION

A high-performance optical modulator with a CMOS-compatible drive voltage, a large electro-optic (EO) bandwidth, a low optical insertion loss and compatibility with large-scale manufacturing is one of the crucial optical communication devices being pursued. Over the last two decades, significant progress in various material platforms, including the lithium niobate (LN) [1], polymer [2], indium phosphide [3], silicon [4] have been made. Recently, the thin film LN attracts more intention from both research institutions and industry and is considered as a promising photonic integrated circuits (PICs) platform for ultra-high-speed applications. In fact, LNOI-based integrated devices have recently been demonstrated with outstanding performance, such as ultra-low-loss resonators, optical frequency combs, EO modulators, frequency converters [5~8], etc. However, a major challenge for practical applications of LNOI is the lack of a highly efficient, polarization independent, large alignment tolerance and broadband SSC, due to the large mode mismatch between the optical fiber and LNOI optical waveguide. Increasing the optical coupling facet mode size is therefore important not only to enable LNOI PICs devices with low insertion loss, but also to improve the alignment tolerance for package and component assembly.

To realize fiber-chip coupling, two main solutions are designed: grating couplers and horizontal edge coupler. Grating couplers with insertion loss of ~3 dB or higher and 3 dB bandwidth ~30 nm have been demonstrated [9,10]. But it is limited by its narrow bandwidth and polarization-dependence. Efficient edge couplers with multiple tapers have been fully validated in silicon photonics [11,12]. The gap between the multiple tapers varies gradually, which offers another degree of freedom to improve the coupling performance, including the mode distribution and mode confinement. However, it’s not suitable for LN rib waveguide since rib tapering only push the optical mode to the LN slab. Recently, a bilayer inverse tapered edge couplers have been demonstrated with higher coupling efficiency and larger optical wavelength bandwidth. In [13], an on-chip LN bilayer inversely tapered mode size converter was demonstrated and ~2 μm lensed single mode fiber-to-chip coupling losses lower than 1.7 dB/facet was achieved. In [14], the edge coupler consists of a bilayer inversely tapered waveguide in LNOI and a SU8 polymer waveguide. The light was coupled into and out of the chip by the lensed fiber with a MFD of 3 μm. The coupling loss is 0.5 - 1.7 dB/facet in a C-band (1530 nm ~ 1565 nm). In [15], an edge coupler for LNOI devices through combining a bilayer inversed taper with silicon oxynitride (SiON) cladding waveguide is demonstrated. A coupling loss 1.5 dB ~ 0.4 dB per facet for TE/TM light in 1500 nm ~ 1600 nm was achieved, when coupled with an ultra-high numerical aperture fiber (UHNAF) of which MFD is about 3.2 μm. In [16], an edge coupler employing novel staircase structure for LNOI modulators is proposed. The simulated results show a coupling loss of 1.9 dB over a wavelength of 1510 nm ~ 1630 nm and a PDL of 10 dB at 1550 nm when coupled to 3.2 μm UHNAF. Although promising results have been achieved, fabrication process of the edge couplers is complicated and the MFD is not large enough to couple with

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standard, cleaved optical fiber.

In this paper, we demonstrate a broadband LNOI edge coupler based on the triplex waveguide structure that can match a commercial cleaved SMF with a MFD of ~6 μm. The device is cladded by SiO_2 simply. The measured fiber-to-chip coupling loss of 1.18/1.10 dB per facet for TE/TM light is achieved at 1550 nm. For TE mode, the coupling loss is lower than 1.3 dB and WDL is 0.23 dB over 1490 nm ~ 1640 nm. By adopting a triplex SSC, an alignment tolerance for 1 dB additional insertion loss of ±3 μm in Z directions and ±2 μm in X directions for TE mode has been demonstrated.

II. Device Design

Fig.1(a) shows the schematic diagram of the LNOI edge coupler. The proposed edge coupler is composed of a LN transition waveguide and a trident SSC with optimized parameters. The LN transition waveguide and LN trident SSC is connected with a slab taper. The LN transition waveguide transfer the light from the etched rib waveguide to bottom slab layer. The cross section of trident SSC varies gradually to achieve better mode overlap and index matching between optical fiber. The device has two symmetrical cladding layers functioning as optical mode extension layer. The mode field distributions of fundamental TE mode along the different region of edge coupler are shown in Fig.1(a). It shows the mode field at transition waveguide, slab taper and tip of trident SSC respectively. With our optimal design, the mode size in the tip of trident SSC matches well with 6 μm single mode fiber and a high coupling efficiency of 86% is achieved in simulation.

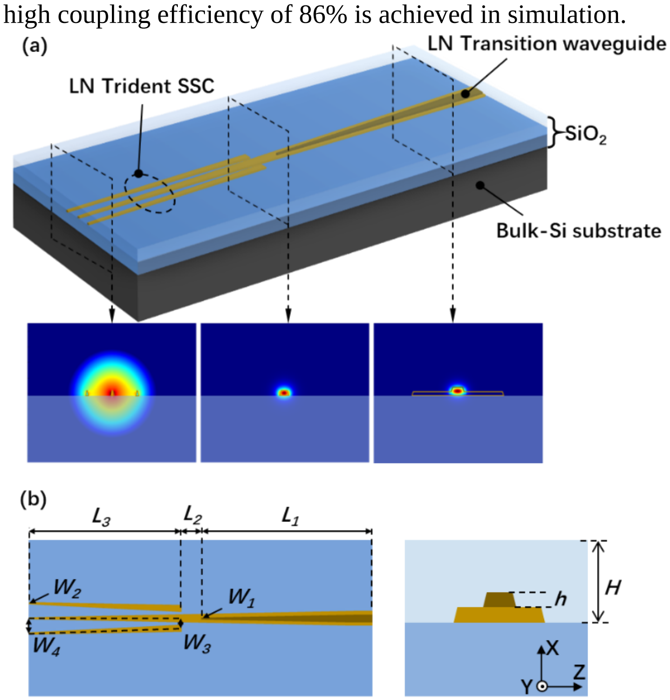

Fig. 1. (a) Schematic diagram of the designed LNOI edge coupler. (b) Top view and cross section of the edge coupler.

The top view and cross section of the edge coupler are shown in Fig.1(b). A top adiabatic taper is designed to taper the normal LN rib waveguide width of 1.2 μm down to a 0.1 μm tip width (W_1) with a rib height of 300 nm (h) over a length of 300 μm (L_1). The slab taper narrows down from 1.2 μm to 0.8 μm wide over a length of 150 μm (L_2) to obtain a stable fundamental mode in slab layer. These parameters are optimized using the finite-difference time domain (FDTD) simulations. As shown in Fig.2 (a), W_1 should be small enough to achieve low mode conversion loss from top transition waveguide to bottom slab taper. Considering the fabrication precision, W_1 is selected as 0.1 μm. According to the simulated results in Fig.2 (b), the coupling efficiency increases gradually along the trident SSC length L_3 and reaches a plateau finally. Considering the size of edge coupler device, L_3 is determined to be 300 μm. As shown in Fig.2(c), the peak coupling efficiency is at tip width W_2 = 0.12 μm. The mode size will decrease rapidly as W_2 increases or expand to an ellipse as W_2 decreases which worsens its mode overlap with the optical fiber. Therefore, the tip width of trident SSC is chosen to be 0.12 μm to reach a relatively high coupling efficiency.

The distance between waveguides at beginning (W_3) and tip end (W_4) of trident SSC is well optimized with respect to optical coupling efficiency together with the misalignment tolerance. As shown in Fig.3 (a), a relatively larger misalignment tolerance is achieved at W_4 = 1.95 μm. In the contour map as shown in Fig.3 (b), '×' mark represents selected parameters for trident SSC: W_3 = 1.2 μm when W_4 = 1.95 μm to achieve maximum coupling efficiency.

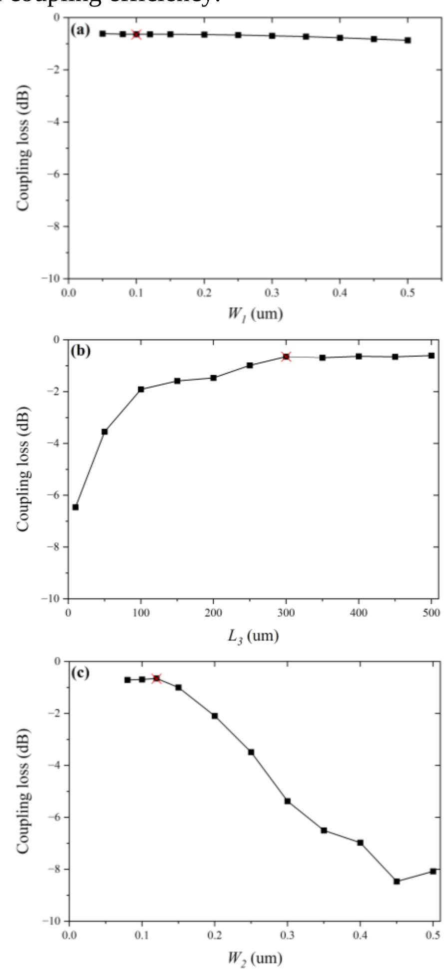

Fig. 2. Calculated coupling loss versus (a) W_1 (b) L_3 (c) W_2 of the edge coupler.

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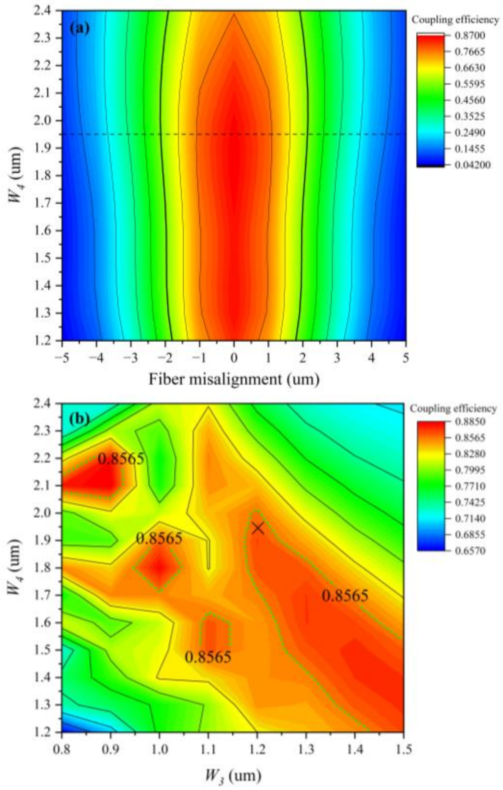

Fig. 3. Simulated coupling efficiency versus (a) W_4 and fiber misalignment (b) W_3 and W_4 of the trident SSC where '×' marks the selected parameters.

II. Fabrication and Experiment Results

The device, two edge couplers connected by a 5 mm long rib waveguides, is fabricated on a 600 nm thick X-cut LN thin film with 4.7 μm thick buried silica layer (NANOLN). In the first step, the LN rib waveguide is defined by electron beam lithography (EBL) with hydrogen silsesquioxane (HSQ) resist and formed through 300 nm-deep inductively coupled plasma etching (ICP) [8]. The Argon plasma is used to physically etch 300nm LN. The ICP etcher is from SPTS with coil power of 100 W, platen power of 1200 W, chamber pressure of 5 mTorr, and the substrate is set at 20 degrees C. After a second layer EBL alignment and 300 nm-deep etch into LN slab, the LN slab taper and trident SSC are defined. The waveguides are then cladded by depositing a 5 μm SiO_2 layer by using plasma-enhanced chemical vapor deposition (PECVD). Fig.4 shows images of the edge coupler we fabricated.

The fabricated device is tested by end-butt coupling via two SMFs with MFD of 6.3 μm (Corning HI 1060 FLEX). The spectral response of device is measured by using a broad band light source (Keysight 8164B: 1490 nm ~ 1640 nm), a polarization controller (Keysight N7786) and an optical spectrum analyzer (Keysight N7745A). Micro-ring resonators are fabricated and measured. The linewidths are 5.2 pm for TE mode and 4.8 pm for TM mode with a Lorentz fit to the resonance, shown in Fig.5. Then 0.5 dB/cm propagation loss of the LN rib waveguide is confirmed for both polarizations. This indicates that the 5 mm long straight rib waveguides have a propagation loss of 0.25 dB. Therefore, the overall insertion loss and PDL that we measured is dominantly due to fiber-to-chip edge coupling loss.

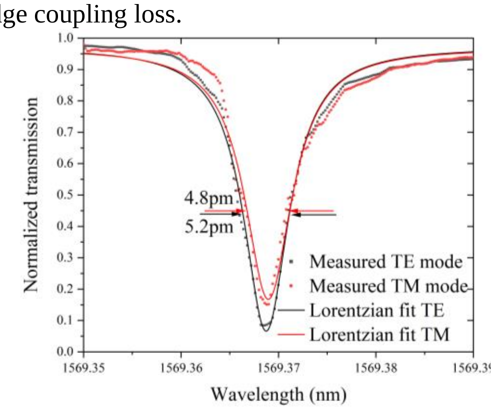

Fig.5. Normalized transmission spectrum of ring resonators.

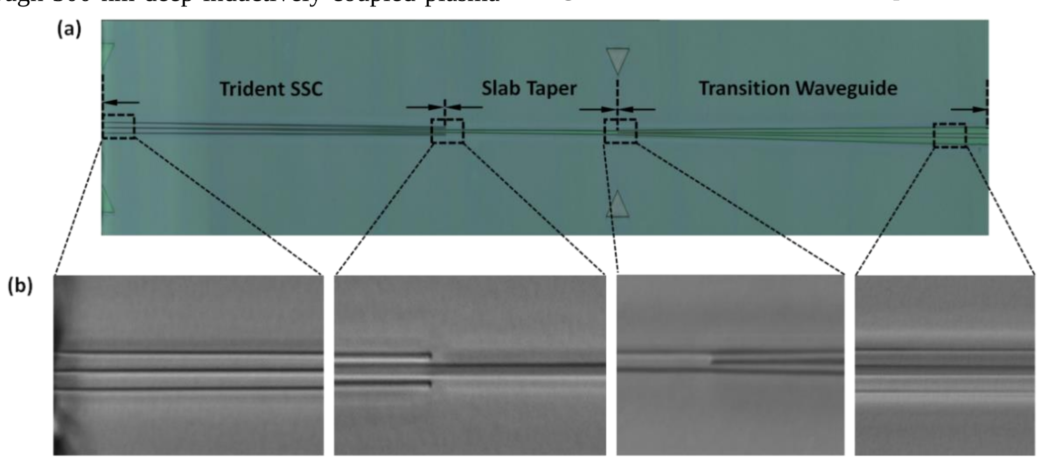

Fig.4. (a) Top view of the fabricated edge coupler. (b) SEM of the edge coupler including end tip in trident SSC, the beginning in trident SSC, tip end of transition waveguide and the rib waveguide.

The measured transmission spectrum of the fabricated edge coupler over a broadband wavelength range (1490 nm ~ 1640 nm) is shown in Fig.6. For the cleaved fiber with a 6.3 μm MFD, the best coupling loss is measured to be 0.98 dB/facet at wavelength of 1565 nm. In the broadband wavelength range, the WDL is less than 0.3 dB for TE mode and 0.5 dB for TM mode. The measured coupling loss is better than practical value of silicon photonic edge coupler with silicon nitride transition to 6 μm MFD in CMOS foundry [17,18]. Based on the flatness and curve trend of the transmission spectrum, it's expected the edge coupler has a coupling loss lower than 1.5 dB/facet in the whole S+C+L+U band (1460 nm ~ 1675 nm). The designed edge coupler also shows a 2.5 dB coupling loss with SMF-28 cleaved fiber over the broadband wavelength and PDL lower than 0.5 dB.

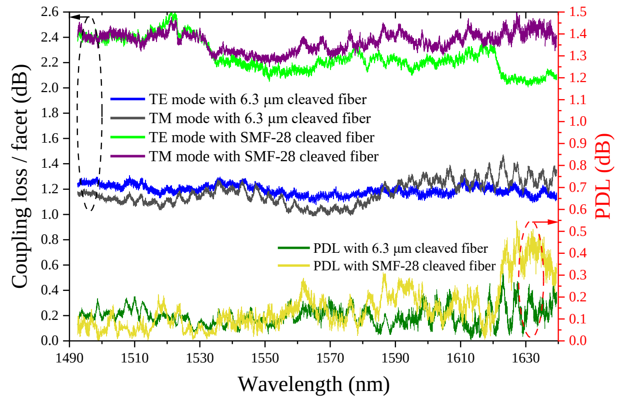

Fig.6. Transmission spectrum of fabricated device in a broadband wavelength.

The tolerance of the alignment between the edge coupler and the cleaved fiber with 6.3 μm MFD is scanned over ±4 μm in the horizontal (Z) and vertical plane (X) for both TE and TM modes, as shown in Fig.7. The measured alignment tolerance for 1 dB additional insertion loss is ±3 μm in Z directions for TE mode and in X directions for TM mode. The designed edge coupler shows a dependence of PDL less than 0.5 dB on the fiber-to-chip misalignment over ±2 μm. Finally, the performance of the designed LNOI edge coupler is summarized in Table I. Compared with other edge couplers in [13~16], the designed edge coupler shows a relatively larger MFD and better alignment tolerance, which will significantly simplify the device package and increase the reliability in practical applications.

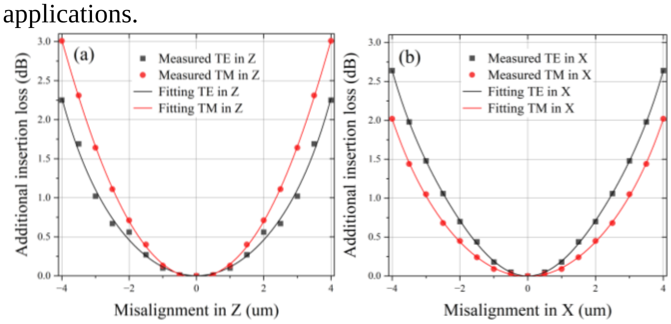

Fig.7. Dependence of coupling loss on fiber-chip misalignment in X and Z.

TABLE I

COMPARISON OF THE FIBER-TO-CHIP EDGE COUPLER IN LNOI

SMF	MFD (μm)	Coupling loss/facet (dB)	Wavelength range (μm)	AT (1dB)	Ref.
Lensed	~2	1.7~2.5	1.48~1.58	±1.0 μm	[13]
Lensed	3	0.5~1.7	1.53~1.57	±1.5 μm	[14]
Lensed	3.2	0.54~1.5	1.50~1.60	-	[15]
Lensed	3.2	1.6~1.9	1.51~1.63	-	[16]
Cleaved	~6	0.98~1.47	1.49~1.64	±3 μm	This work

IV. CONCLUSION

A highly efficient, polarization independent, large alignment tolerance and broadband fiber-to-chip edge coupler has been designed and fabricated based on the LNOI platform. The edge coupler consists of transition waveguide, slab taper and trident SSC, fabricated by a two-step dry etching process and cladded by SiO_2 simply. The proposed edge coupler shows low coupling loss of 1.18 dB/facet at 1550 nm and 0.5 dB bandwidth greater than 150 nm when coupled to a commercial cleaved SMF. The designed edge coupler is the fundamental component for broadband LNOI integrated device with low insertion loss.

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