Low-Phase-Error Thin-film Lithium Niobate Optical 90° Hybrid With 4 × 4 MMI coupler

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***Abstract*—We propose and demonstrate a thin-film lithium niobate 90° optical hybrid based on 4 × 4 MMI coupler, which features low average phase error <±3° over the wavelength range of 1535-1595 nm.**

Keywords—thin-film lithium niobate, 90° optical hybrid, MMI coupler

I. Introduction

Coherent optical communication is a critical technology for achieving high-speed data transmission and enhanced spectral efficiency in data centers and network infrastructure. However, as the demand for optical communication capacity continues to increase, coherent optical transceiver (COT) systems need to meet more stringent performance requirements[1]. To address this challenge, researchers have been exploring the use of silicon on insulator platforms (SOI) due to their compatibility with CMOS technology. Nevertheless, high-speed modulation on silicon may encounter a bottleneck due to carrier plasma dispersion limitations. As an alternative platform, thin-film lithium niobate (TFLN) has emerged as a promising integrated photonic platform for its large refractive index contrast, strong electro-optic (EO) and nonlinear effects, and wide transparency window. In particular, EO modulators based on TFLN, such as the in-phase/quadrature (IQ) modulator [2], offer outstanding bandwidth, linear EO response, and low excess loss. These characteristics make TFLN a highly attractive platform for high-speed coherent optical communication [3].

Coherent detection is a method for demodulating IQ modulation signals using a 90° optical hybrid and photodetectors. The 90° optical hybrid extracts phase, amplitude, and polarization information through the interference between the signal and local oscillator light. However, there is sparse research on the use of lithium niobate (LN) 90° hybrids. Traditional LN hybrids typically use four directional couplers, resulting in a large footprint due to weak optical field confinement [4]. Consequently, these hybrids are unsuitable for compact integration.

In this work, a novel 90° optical hybrid design is presented by utilizing a 4 × 4 multimode interference (MMI) coupler on x-cut TFLN. Such device features an etched structure that enables strong optical confinement, resulting in improved performance and reduced device size. The proposed hybrid exhibits low excess loss of less than 1.25 dB, low phase errors of less than ±4.5° of over −20 dBe, and large fabrication tolerance over a wavelength range of 1535−1595 nm. This device design has significant potential for the realization of integrated transceivers on TFLN for advanced QPSK data communication, photonic imaging, and microwave photonics applications.

The project is partially supported by the National Natural Science Foundation of China (62135011; 62105286); "Pioneer" and "Leading Goose" R&D Program of Zhejiang (2022C01103), the Fundamental Research Funds for the Central Universities.

II. Design

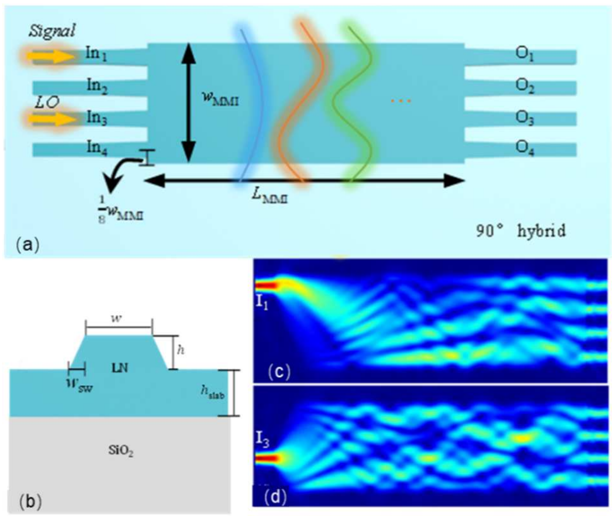

Fig. 1. (a) The conceptional illustration of proposed 90° hybrid on TFLN. (b) Cross-section of the LN waveguide. The light propagation field of the hybrid when the TE_0 mode is launched from port 1 (c) and port 3 (d), respectively.

The proposed 90° optical hybrid with a 4 × 4 MMI coupler is illustrated in Figure 1(a). It is based on a x-cut TFLN with a thickness of 360 nm and a shallow etched layer of h_{slab} = 180 nm, and has an upper cladding of air ($n_{air} \approx 1$). The width of the MMI (w_{MMI}) is set to be 9 µm, which ensures that a sufficient number of transverse electric (TE) guided modes are supported while keeping the optical loss low. During operation, the signal light and local oscillator light are launched into input ports 1 and 3 (In_1 and In_3), respectively, with corresponding electric fields denoted as E_S and E_{LO}. The cross-section of the LN waveguide is shown in Figure 1(b).

The relative phase difference between the signal and local oscillator at each of the four output ports can be calculated by subtracting the local oscillator phase ($\varphi_{\mathrm{LO},i}$) from the signal phase ($\varphi_{\mathrm{s},i}$). This yields the value $\Delta\varphi_i = \varphi_{\mathrm{LO},i} - \varphi_{\mathrm{s},i}$ (i=1, 2, …, 4). To simplify the analysis of the hybrid's performance, the O_1 output port is selected as the reference channel. The relative phase difference between the other output ports (O_i) and O_1 can then be described as $\Delta\varphi_{i1} = \Delta\varphi_i - \Delta\varphi_1$ (where i=2, 3, 4), with the ideal values of $\pi/2$, $-\pi/2$, and π for O_2, O_3, and O_4 respectively.

Here, the phase errors ($\Delta\theta_i$) of the 90° optical hybrid are described as the deviation between $\Delta\varphi_{i1}$ and C_{i} ($\pi/2, -\pi/2, \pi$), which is given as following,

$$\Delta\theta_i = \Delta\varphi_{i1} - C_{\mathrm{i}}\ , \text{ i=2,3,4} \tag{1}$$

To characterize the performance of the hybrid, a Mach-Zehnder interferometer (MZI) structure is employed. The input light is evenly divided using a 1×2 3-dB MMI and then propagates through the unequal delay line arms before interfering in the 90° hybrid. In order to achieve optimal self-imaging of the 4 × 4 MMI coupler, it is necessary to ensure that the beat length L_π satisfies the following condition:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} = \frac{\lambda}{2(n_0 - n_1)}, \tag{2}$$

where β_0, β_1 are the propagation constant of TE_0 and TE_1 mode, λ is the operation wavelength, n_0 and n_1 are the effective mode refractive index of TE_0 and TE_1 mode respectively. Based on these parameters, the theoretical length of 4 × 4 MMI coupler (L_{MMI}) will be $\frac{3}{4}L_\pi$. The spacing between the adjacent access ports is set to 1/4 of the effective width of the multimode waveguide (w_{eMMI}), which include Goos-Hänchen shift (GHS) and side wall width (w_{sw}). The GHS is calculated ~0.27 μm for each side, which is significant for the shallow etched TFLN ridge waveguide, and the w_{sw} is 0.1 μm. The width of the waveguide is determined to be 0.9 μm in order to ensure good optical field confinement and quasi single-mode operation in the delay line region, while allowing for small bend radii of 40 μm and maintaining low bending loss (< 0.1 dB/cm). To minimize reflection and mode mismatch loss at the junction, adiabatic linear taper sections are introduced with a length of 10 μm and varying widths from 0.9 μm to 1.2 μm between the 4 × 4 MMI section and the access waveguides. The minimum gap between the adjacent taper waveguides is set to 1.2 μm. The calculated MMI length (L_{MMI}) is approximately 107 μm.

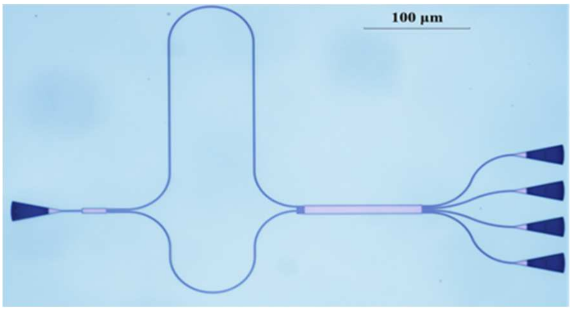

Fig. 2. Optical microscope image of the fabricated device.

The proposed devices were fabricated on an x-cut TFLN wafer, which featured a 360-nm-thick top LN layer and a 4.7-μm-thick buried oxide layer. The structure was patterned using an electron beam lithography (EBL) system, and a 180 nm thick LN layer was etched using inductively coupled plasma reactive ion etching (ICP-RIE) technology. The fabricated device was imaged using a microscope, as is shown in Fig. 2. Efficient chip-fiber coupling was achieved using grating couplers with a period of 1 μm, a duty cycle of 41%, and an incident angle of 10°.

The performance of the 90° hybrid was verified by measuring the MZI transmission spectra from 1535 to 1595 nm for each port, as shown in fig. 3(a). To obtain these spectra, the loss of two grating couplers and one 1 × 2 MMI coupler was subtracted and the results were normalized. The 4 × 4 MMI coupler used in the experiment had an excess loss ranging from 0.55 dB to 1.25 dB across the wavelength range of 1535 to 1595 nm, as illustrated in fig. 3(b). The measured extinction ratio was found to be larger than 25 dB, indicating high splitting uniformity. To further characterize the phase errors between two channels, $\Delta\theta_i$ can be calculated from the transmission spectra, which can be expressed as follow,

$$\Delta\theta_i = \frac{2\pi\Delta\lambda_i}{\mathrm{FSR}}, \tag{4}$$

Where $\Delta\lambda_i$ is the wavelength spacing between the minima of the spectra of output ports i and 1, and FSR is the free spectrum range. The phase error of the 90° optical hybrids was estimated by comparing the measured values with the corresponding theoretical values mentioned earlier. Figure 3(c) shows the extracted phase error, which indicates an excellent phase controllability of the hybrids, with an average absolute value of around 2°.

III. Results

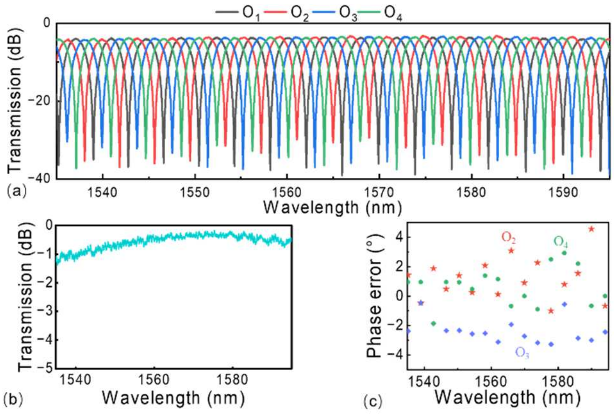

Fig. 3. (a) The measured normalized transmission spectra of four ports; (b) the excess loss of the fabricated 90° hybrid; (c) the phase error.

In conclusion, we have proposed and demonstrated a 90° hybrid with 4 × 4 MMI coupler on x-cut TFLN. By introducing etched ridge waveguide in TFLN, reduced device size as well as improved device performance efficiency. The overall footprint of the proposed device is about 9 μm × 107 μm. A high performance 90° hybrid has been achieved with measured low excess loss of <1.25 dB and average phase error less than ±3° over the wavelength range of 1535 –1595 nm. Such devices will be expected to be utilized in the integration of the proposed device with high-speed PD, high-speed EO modulators and hybrid integrated lasers to realize a fully integrated coherent transceiver chip on TFLN.

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