Novel Optical Polarization Splitter in Lithium Niobate

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Abstract
A tunable Y-branch Ni:$LiNbO_3$ polarization (mode) splitter with a ridged input arm is presented. The ridge is used to lower the tuning voltage and thus enhance the tuning flexibility of the polarized fields. To improve the confinement of Ni-indiffused waveguide, Zn and Ni are both diffused at the same time. To use the electro-optic modulation, the polarization splitter is implemented in a Z-cut Y-propagating $LiNbO_3$. Experimental results show that the tuning voltage can be reduced by a factor of about 1/3 with a ridge of height 2μm. The measured extinction ratio is 21dB for the transverse electric (TE) mode and 18dB for the transverse magnetic (TM) mode.

1. Introduction
Integrated optical polarization splitters are essential in such applications as the heterodyne interferometers or coherent communication system sensitive to the variation of polarization. According to the operational principles, the splitters are divided into two categories: mode interference and mode sorting effect. The mode interference manipulates the difference in phase velocity between different polarizations. A typical illustration is the directional coupler [1], where the coupling lengths of different polarizations, separation of the coupled waveguides, and thereby the difference of the refractive indices are carefully considered to achieve high extinction ratio. Although the directional coupler is advantageous for its economical use of device area, it suffers from the operation over a narrow range of wavelength and the stringent fabrication tolerances such as lithographical misalignment and metallic lateral diffusion error. The alternative is to use the mode sorting effect, mostly taking the shape of a Y-branch (Fig. 1(a)) [2], to split different polarizations of the guided wave. The basic idea is to differentiate the two arms of the Y-branch in their refractive indices for individual polarizations to propagate preferentially along the arms with the closest refractive indices. In practical application, those, which use the Y-branch structure, have a larger fabrication tolerance [3]. Goto and Yip [3] first used an asymmetric Y-branch with its waveguide branches made of different fabrication techniques, namely, the proton exchange (PE) and the titanium

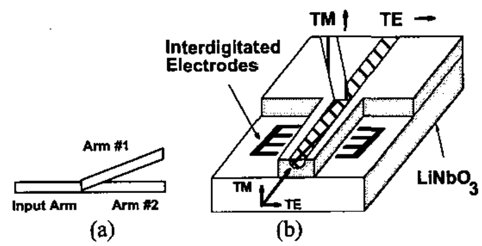

Fig. 1 Y-branch polarization splitter (a) basic structure and (b) electrode and ridge structure

indiffusion (TI). As the fabricated device is based on the adiabatic mode conversion of the extraordinary polarization modes, i.e., the partial mode sorting effect, a careful design of the waveguide pattern for a specific index distribution is then required to obtain the maximum extinction ratios. Recently, novel mode splitters based on the complete mode sorting effect were realized by using branching waveguides supporting only TE or TM modes [4]. The measured extinction ratios are greater than 20 dB for the fundamental or higher-order TE and TM modes due to the inherent single polarizations of the waveguides. In this work, the Y-branch TE-TM mode splitter based on complete mode sorting is concatenated to a TE-TM mode converter to become a tunable polarization splitter (Fig. 1(b)). The TE-TM mode converter is simply formed by extending the input arm with a pair of interdigitated electrodes deposited on both sides. To lower the applied voltage and therefore, enhance the tuning flexibility, a ridge structure is etched to increase the overlap of the optical and electric field. The Y-branch is fitted into the Z-cut, Y-propagating $LiNbO_3$ substrate to use the electro-optical modulation offered by the material. A homogeneous scheme of using both Zn and Ni diffusion to fabricate the TE, TM, and TE-TM waveguide branches reconciles the disturbance of crystalline and the mode mismatch expected in the reported work [5]. Using Zn as part of the diffusion metal not only improves the rather poor confinement of the Ni-indiffused (NI) waveguide but also enhances the anti-photorefractive capability of the waveguide.

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2. NI Waveguides

TI waveguides have the advantage of low propagation loss; however, an outdiffusion layer near the $LiNbO_3$ surface is often formed. Optical fields guided by TI channel waveguides will be affected by the unwanted planar waveguide. Some techniques are then needed to suppress it. Moreover, decrease in the bulk electro-optic coefficients at diffusion temperature above 950°C was also observed. Thus, other materials for indiffusion should be considered. Schmidt found that the planar NI waveguides made at 800°C can support random polarization waves [6]. The measured propagation loss is less than 1 dB/cm, which makes Ni a good alternative diffusant for making waveguide in $LiNbO_3$. The typical fabrication process for an NI waveguide used in our laboratory is described as follows. First, a Ni strip of thickness 100 to 400 Å, width 4 to 12 μm, depending on the input laser wavelength, is prepared on a Z-cut $LiNbO_3$ chip of area about 12mm×6mm by the lift-off technique. Then, the waveguide pattern is diffused in a furnace at 650-900°C for 0.4 to 7 hr. As Ni is a diffusant more active than the commonly used Ti, a shorter diffusion time or lower diffusion temperature has to be used. Outdiffusion of Li_2O is then less important compared with that of TI. From our experience, when diffusing at 1000°C for 1 hr, 950°C for 2 hr, and 900°C for 6 hr, no significant outdiffusion layer was observed at the 632.8 nm wavelength. Moreover, as the melting point of Ni is lower than that of Ti, a preoxidation step for Ni at 400°C for about 1 hr is necessary to prevent from increasing the waveguide width. After diffusion, the end faces of the samples are polished for optical characterization. The optical measurement is performed at the wavelength 632.8 nm with a He-Ne laser. The NI waveguide can be made on either one of the three cuts of $LiNbO_3$. For the Z-cut substrate just described, TE modes have ordinary polarizations, and TM modes, extraordinary polarizations. To know the waveguide polarization is dependent on the diffusion temperature and the diffusion time, planar waveguides made of Ni layers of the same thickness (100Å) are fabricated at temperatures varying from 650°C to 900°C. The measured polarizations are shown in Table 1. The interesting behavior of the process-dependent polarization can be explained with the aid of Fig. 2. As the diffusion time is short, the Ni concentration is high near the surface (Fig.2 (a)), and the relation $\Delta n_e > \Delta n_o > 0$ is valid from Fig. 2 (b), where Δn_e and Δn_o are the index changes of ordinary and extraordinary indices. In principle, both ordinary and extraordinary modes can be supported by the waveguide. However, the waveguide is not wide enough for the ordinary mode, and it is then cut off. On the contrary, when the diffusion time is long

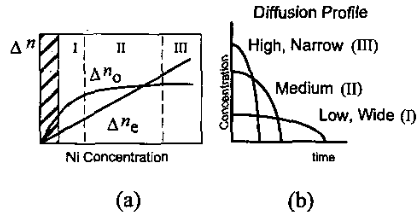

Fig.2 Ni-indiffused waveguide (a) index change and (b) Ni profile

enough, the Ni concentration becomes low near the surface (Fig. 2(b)) and the relation $\Delta n_o > \Delta n_e \approx 0$ (Fig. 2(a)) becomes valid. The waveguide is now wide enough to support both polarizations, but Δn_e is too small to meet the requirement of an extraordinary polarization. Therefore, only the ordinary polarization exists. For Ni concentration within the range mentioned above, the index changes and the waveguide width are large enough; hence, both polarizations can be successfully supported. Thus, a fabrication process that can control the waveguide width and the Ni concentration will determine the guided wave polarization. In our experiment, Zn-indiffused (ZI) waveguides were also found to have the similar process-dependent polarization behavior. However, their propagation losses are higher than those of NI waveguides, and therefore are not chosen for making devices.

Table 1 Process-dependent polarization of planar NI waveguides at the 632.8nm wavelength.

Temp. (°C)	Time (hr)	Polarization
650	4.5~7	TM
800	1~6	TE-TM
900	0.4~3	TE-TM
900	4~6	TE

Ni layer thickness 100Å

3. Y-Branch TE-TM Mode Splitters

The TE-TM mode splitter considered in this paper is essentially an asymmetric Y-branch that consists of a main and two branch waveguides as shown in Fig. 1(a). The main waveguide supports random polarization, and the two branch waveguides supporting single-TE and single-TM mode. The random polarization waveguide can be fabricated by TI, NI, ZI, etc. For the single-ordinary polarization waveguides, the existing fabrication methods are NI and Zn-and-Ni indiffusion (ZNI). However, those for the extraordinary are NI, ZI, ZNI, PE, magnesium-induced lithium outdiffusion (MILO) [4], etc. Any combination of the above waveguides can possibly be used as a TE-TM mode splitter. For simplicity, only polarization splitters with NI and ZNI waveguides are discussed.

4. Design and fabrication

Fig.1 (b) shows the configuration of the proposed TE-TM mode splitter. It consists of three waveguide branches: 1) the ridged input waveguide supporting both TE and TM modes between a pair of interdigitated electrodes, 2) TE branch following the input branch straightly and supporting only TE-mode wave, 3) TM branch bending from the input waveguide at an angle of 0.5° and supporting only the TM-mode wave. The width of all waveguides is 8μm suitable for single mode propagation at an operating wavelength of 1.55μm for either TE or TM mode. Because of the phase matching requirements and large birefringence of lithium niobate, the mode conversion efficiency is highly wavelength dependent and thus requires the interdigitated electrode of period Λ satisfying

$$2\pi|N_{TE} - N_{TM}|/\Lambda = 2\pi/\lambda_0 \qquad (1)$$

where λ_0 is the vacuum wavelength, N_{TE} and N_{TM} are effective indices of TE and TM mode, respectively. In this case, the estimated $|N_{TE} - N_{TM}|$ is 0.0734 leading to the electrode period Λ=21μm. The electrode gap is 18μm and the total length is 4mm. The fabrication parameters of the waveguide branches are listed in Table 2. The fabrication process steps are illustrated as shown in Fig. 3. A layer of 4500Å-thick titanium is deposited on the substrate as the mask for proton exchange. Submerge the chip in benzoic acid at 240°C for 6 hr and subsequently etch it with hydrofluoric acid to reveal the ridge structure. The measured ridge height is about 2μm. A layer of 200Å-thick Ni and 550Å-thick Zn is sequentially deposited on the substrate first to form a Zn-Ni alloy strip on top of the ridge and the TE waveguide branch. Another 100Å-thick Ni and 1300Å-thick Zn strip is superimposed only on the input section and then the chip is oxidized and diffused in the furnace. The oxidation is necessary to prevent the metallic strip from distortion due to the abruptly rising temperature. For this device, the oxidation process is carried out at 400°C for 1.5 hr. Next, a 200Å-thick Ni and a 650Å-thick Zn metallic strip are deposited to make the TM bending branch and then repeat the diffusion. Finally, a 3000Å-thick aluminum is deposited and periodic electrode patterned photoresist is lithographically transformed to form the etch mask. The chip is then submerged in the phosphoric acid to pattern the periodic electrode.

5. Results and conclusion

The fabricated tunable ridged TE-TM mode splitter is characterized with a distributed-feedback laser at a wavelength of 1.55μm by end-fire coupling. The output optical field contour profiles are captured by a charge-coupled-device camera. Fig. 4 shows the results of a TM and TE mode input, respectively. The extinction ratios are 18dB for the TM mode and 21 dB for the TE mode. Fig. 5 shows the dependence of the normalized power on the applied voltage, as the input is TM, TE, or both TE and TM modes. As can be seen from the figure, about 30% of TM is converted into TE at 60V rather than 90V (reduced by a factor of about 1/3) as is in the case of the planar (without the ridge) polarization splitter. Conversion efficiency as high as 50% can be obtained when the applied voltage is 100V. That suggests using the ridge structure can efficiently reduce the intolerably high operation voltage found in the planar tunable polarization splitter, and therefore, increases the voltage-tuning flexibility. Details of the application of the devices will be of great interest in the future.

Table 2 Fabrication parameters of waveguide branches

Polarization (Mode)	Thickness (Ni)	Thickness (Zn)	Diffusion Temp.
TM	200Å	650Å	850°C
TE	200Å	550Å	950°C
TE & TM	200Å(1st) 100Å(2nd)	550Å(1st) 1300Å(2nd)	950°C

Diffusion Time = 1.5hr

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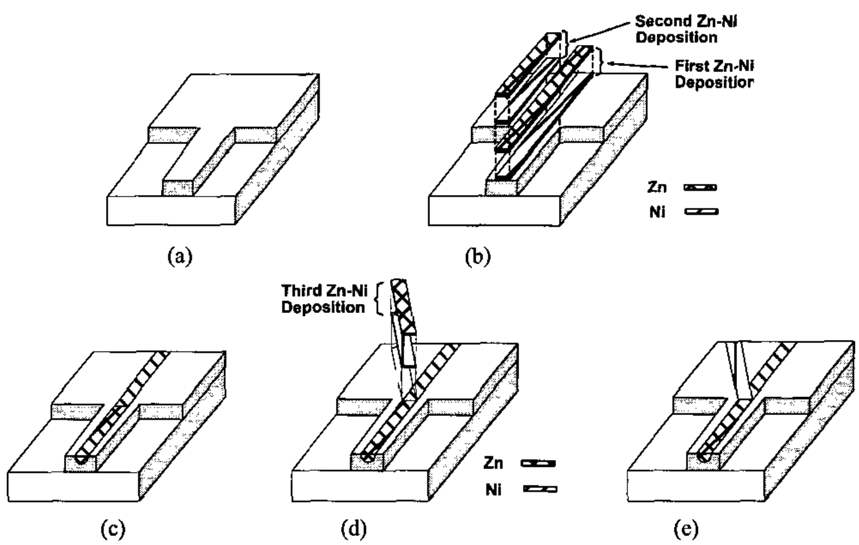

Fig. 3 Process steps for the fabrication of the polarization splitter (a) ridge formation, (b) first and second Zn-Ni strip deposition, (c) diffusion, (d) third Zn-Ni strip deposition, and (e) diffusion

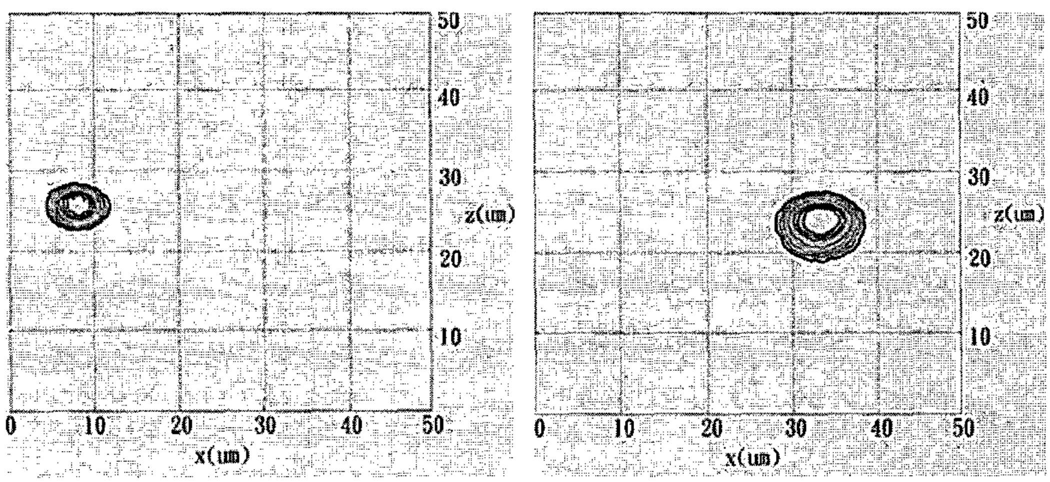

Fig. 4 Output contour profiles (a) TM input (b) TE input

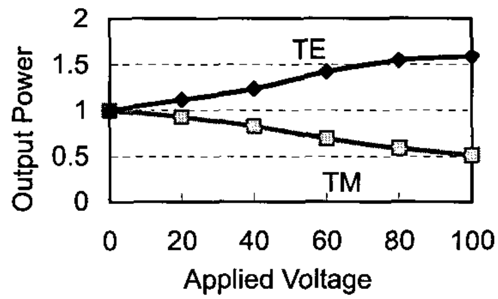

Fig. 5 Tuned TE/TM power vs. the applied voltage