Zn-Diffused 1 × 2 Balanced-Bridge Optical Switch in a Y-Cut Lithium Niobate

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***Abstract*—A novel Zn-diffused 1×2 balanced-bridge optical switch fabricated in a y-cut lithium niobate has been proposed and experimentally studied for the first time. According to the experimental results, the highly polarized waveguides with the polarization extinction ratio of about 45 dB and the nondegraded electrooptic r_{33} coefficient about 30.5 pm/V can be obtained for both wavelengths of 1.32 and 1.55 μm. These encouraging results indicate that the extraordinary-polarized (polarized on the extraordinary axis of the crystal) Zn-diffused waveguides can be potentially applied to the design of an integrated optical circuit being used in the field of fiber-optic gyroscopes and cable television systems.**

***Index Terms*—Integrated optical circuit, lithium niobate (LN), optical switch, Zn-diffused.**

I. Introduction

THE scheme of optical signal modulations based on the integrated optical devices has been widely used in the filed of optical communications and sensors. Lithium niobate (LN) waveguide devices exhibiting excellent characteristics of electrooptic (EO) and nonlinear optic (NLO) can provide various functions of phase modulation, polarization rotation, and wavelength conversion [1]–[5]. In the past two decades, the commercial LN waveguide devices were mainly fabricated by using a Ti-indiffusion (TI) or a proton-exchanged (PE) method. The TI waveguides usually guide dual orthogonal polarizations due to the refractive index increase for both ordinary and extraordinary polarizations. They can be applied to the design of polarization splitter, polarization scrambler, phase modulator, and Mach–Zehnder interferometer. In contrast, the PE waveguides support an inherently extraordinary polarization with high polarization extinction ratio (PER) due to the PE process resulting in a positive and a negative change for the extraordinary and ordinary indices, respectively. Usually, a post annealing step was used to improve its EO and NLO performance [5], [6]. The annealed proton-exchanged (APE) waveguide devices were mainly fabricated on an x-cut or a z-cut substrate [4]–[6], because of the PE process suffering from surface damaged on a y-cut substrate [7]. Therefore, it is still difficult to fabricate a well y-cut APE waveguide at the near infrared wavelengths due to PE depth and concentration limitations for avoiding surface damage. Although the z-cut phase modulator has a lower switch voltage and a broader bandwidth than the x-cut one, it also requires the buffer layer of silicon dioxide (SiO_2) between the electrode and waveguide to reduce the propagation loss. As a result, the covered SiO_2 layer under the electrodes will induce the long-term reliability issues due to the dc-drift phenomenon [8]. In addition, the x-cut ones can choose without the SiO_2 layer because of the electrodes located on the both sides of the waveguides. Therefore, the commercial APE fiber gyro chip [4] or cable television (CATV) dual output modulator [9] are mainly fabricated on the x-cut substrate.

Recently, Zn-diffused and Zn-doped LN waveguides have been successfully applied to a wavelength converter and a waveguide laser based on the NLOs by pumping with sufficient power levels [10]–[12]. In comparison to the PE waveguides, the Zn-diffused waveguides have better resistance to optical damage [10], which will be expected to enhance the biasing voltage stability as used in the phase modulators with a higher input power. Meanwhile, the process-dependence guiding behaviors of Zn-diffused waveguides on the z-cut substrates also have been observed [12], [13]. Most of their efforts focus on fabricating the uniformly guiding waveguides for both polarizations to be considered using in the general waveguide amplifiers or lasers. Previously, the characteristics of Zn-diffused waveguides on the y-cut substrate at the 1.32- and 1.55-μm wavelengths have been reported in [14] and [15]. The results show that the extraordinary-polarized waveguides were fabricated under some specific process conditions, and also dependent on guiding wavelengths.

In this letter, an extraordinary-polarized Zn-diffused 1×2 balanced-bridge optical switch is successfully demonstrated on a y-cut LN. The best PERs of about 45 dB are easily achieved at a measured channel waveguide length of 1.5 cm for both wavelengths of 1.55 and 1.32 μm. With the measured mode profile and electrode configuration, the calculated values of r_{33} are 30.5 and 30.7 pm/V for 1.55- and 1.32-μm wavelengths, respectively. It implies that the Zn indiffusion process can make a singly extraordinary-polarized waveguide with nondegraded EO performance.

II. Experiments

Fig. 1(a) displays the schematic diagram of a 1×2 balanced-bridge optical switch, which consists of a Y-branch splitter, a phase modulator, and a directional coupler. The switch is similar to a Mach–Zehnder interferometer with two output ports. The waveguide width is 8 μm and the splitting angle is 2° in the Y-branch. The gap width g between two adjacent waveguides of a directional coupler is 6 μm and the parallel coupling length l is 0.5 mm. The length of modulation

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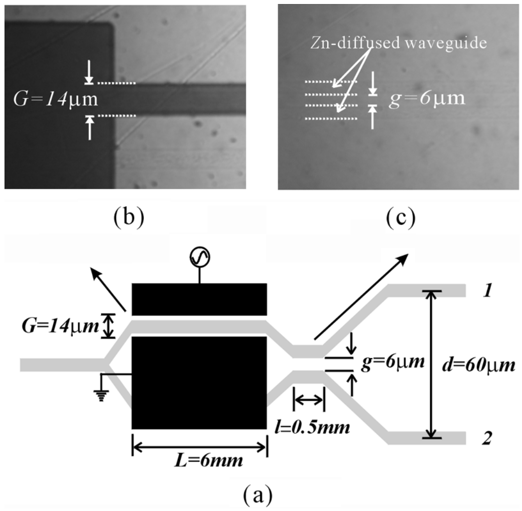

Fig. 1. (a) Schematic diagram of a 1×2 balanced-bridge optical switch; (b) and (c) surface photographys of fabricated device.

electrode L is 6 mm and the gap width G between the electrodes is 14 μm. The distance d between the centers of two output waveguides is 60 μm. To enhance adhesion between a Zn film and substrate, the predeposition of a Ni layer of 5 nm was done for all Zn-deposited samples, which was originally proposed by Twu *et al.* [14]. This method also has been easily replicated to fabricate the Zn-diffused waveguides by several recent studies [12], [13]. Especially, the high photorefractive damage resistance waveguides, even with the codiffusion of Ni atoms, were successfully demostrated in a z-cut periodically poled LN [12]. In this experiment, a 50-nm Zn film with predeposition Ni film of 5 nm was deposited over the substrate by thermal evaporation. Then, the waveguide pattern was formed by a lift-off technique. After thermal diffusion of 850 °C for 100 min, and substrate end faces polished, an Al electrode of thickness of 300 nm was deposited and patterned. The laser light sources of 1.32 and 1.55 μm individually coupled into the front end face of waveguide with a $40\times$ lens and the output beams were imaged onto an InGaAs photodetector or a charge-coupled device camera also with a $40\times$ lens. The switching voltage of fabricated device was determined by measuring the corresponding relations between input electrical signals and optical response curves.

III. Results and Discussion

To make a single-polarized waveguide or a waveguide polarizer, the performance is determined mainly by the PER, which is simply defined as PER $= 10\log(P_{\mathrm{TE}}/P_{\mathrm{TM}})$, where P_{TE} and P_{TM} are the output transverse-electric (TE) and transverse-magnetic (TM) wave powers while keeping the same power intensities for both incident polarizations, respectively. The measured values are 45 and 48 dB at channel length of 1.5 cm for wavelengths of 1.32 and 1.55 μm, respectively. Moreover, the measured propagation loss of the TE-polarized waveguide is of about 0.9 dB/cm by using a cut-back method for both wavelengths. Unlike the APE waveguide polarizers without bandwidth limited for all guiding modes, the best Zn-diffused waveguide polarizer is wavelength dependent and

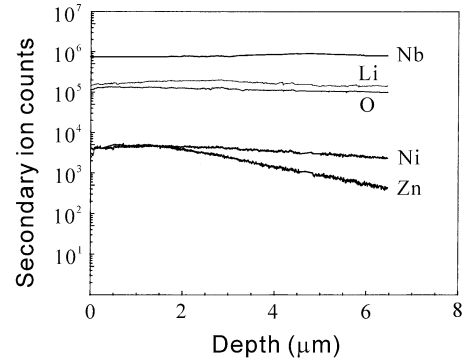

Fig. 2. SIMS depth profiles of Ni, Zn, and Li contents in a y-cut LN substrate after codiffusion of Zn and Ni films (50 nm/5 nm) at 850 °C for 100 min.

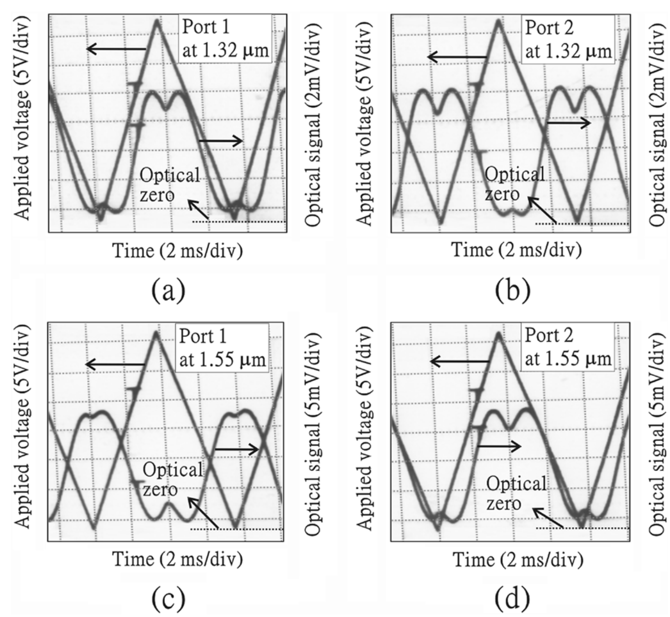

Fig. 3. Measured response curves for (a) the output port 1 at 1.32 m, (b) the output port 2 at 1.32 m, (c) the output port 1 at 1.55 m, and (d) the output port 2 at 1.55 m, where the sinusoidal curves are the optical signals (2 mV/div at 1.32 m and 5 mV/div at 1.55 m) and the triangular curves are the applied-voltage signals (5 V/div).

bandwidth limited. In a real application, the PER value can easily reach 60 dB at a typical length of an integrated optical chip longer than 2 cm, which is comparable with the traditional APE waveguide of about 60 dB, and sufficient to suppress the unwanted cross-polarization disturbance. In Fig. 1(b), the top view photograph of the fabricated device shows a good alignment process in the electrode region. The top view photograph of the coupler region indicates that there is no clear surface residual onto the waveguide as shown in Fig. 1(c). The $1/e$ Zn diffusion depth was found from secondary ion mass spectroscopy (SIMS) data to be 6.5 μm, as shown in Fig. 2. The constant concentration profile of Li contents shows that there is no out-diffusion during the thermal process at 850 °C for 100 min. Fig. 3(a) and (b) gives the measured response curves at two output ports for 1.32 μm, and the measured switching voltage is 17 V. Fig. 3(c) and (d) gives the measured response curves for 1.55 μm, and the measured switching voltage is 22.5 V. The sinusoidal curves are the optical signals and the triangular curves are the applied-voltage signals (5 V/div), and exhibit a good switching performance. The output power levels of the two ports are almost the same, and the sinusoidal curves also show a good inverse relation due to the power transferred periodically between two ports. With the measured mode profile and electrode configuration, the calculated values of r_{33} are 30.5 and 30.7 pm/V for 1.55 and 1.32 μm, respectively. The Zn-diffused waveguide exhibits r_{33} coefficient comparable to the conventional TI waveguides. Especially, without the chemical process for removing the protective masks as being used only in the APE waveguides, the Zn-diffused ones can save production cost and have a higher product throughput. In addition, similar to the x-cut (y-propagation) EO device, the y-cut (x-propagation) Zn-diffused switch is possible to suppress the dc-drift because there is no buffer layer under the electrodes [8]. Although only one phase modulator is used in this device, in real applications, multiple phase modulators with faster EO response can be easily implemented by a suitable design of electrode arrangements [4], [9], [16].

IV. Conclusion

In summary, a novel Zn-diffused 1 × 2 balanced-bridge optical switch has been experimentally evaluated on a y-cut LN substrate. It shows that the Zn indiffusion process can make an extraordinary-polarized waveguide with a nondegraded EO property at the near infrared wavelengths (1.32–1.55 μm). Similar to the conventional APE waveguides, the proposed waveguide device presents a simple and economical process for fabrications of extraordinarily polarized phase modulators. It will be of a great potential to be possibly applied to the design of gyro-chip and CATV dual output modulator in the near future.

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