Electrooptical Modulator Fabricated by Gallium Diffusion in Lithium Niobate

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***Abstract*—Mach–Zehnder modulators fabricated by gallium diffusion in y-cut lithium niobate ($LiNbO_3$) are presented. The measured halfwave voltages are 6.2 and 3.2 V when the electrode lengths are 0.4 and 0.8 cm, respectively. By calculating the overlap integral between the modulating electric and the guided optical fields, the value of the electrooptic coefficient r_{33} is found in good agreement with that of the bulk $LiNbO_3$, which indicates no significant degradation in r_{33} is induced by the in-diffused gallium atoms.**

***Index Terms*—Electrooptic coefficient, gallium-diffused waveguide, lithium niobate, Mach–Zehnder modulator.**

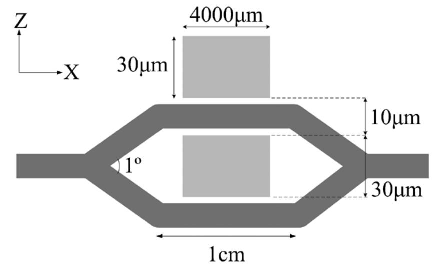

Fig. 1. Schematic diagram of the proposed gallium-diffused Mach–Zehnder interferometer.

I. Introduction

ELECTROOPTICAL (EO) device in lithium niobate ($LiNbO_3$) substrate, known for its low optical loss and driving voltage, is one of the key components in the optical communication system. Moreover, with high modulation bandwidth and good material stability, optical modulators based on $LiNbO_3$ waveguides have been widely used in high-speed optical networks. With an anisotropic electrooptic tensor, $LiNbO_3$ optical modulators are polarization sensitive so that the polarization of the input waves must be carefully controlled.

As the widely used titanium-diffused $LiNbO_3$ waveguides support both polarization states, good control of the polarizations is an important issue. To fabricate a polarization-insensitive optical modulator in $LiNbO_3$ substrate, there are two general solutions. The first one [1], [2] is independent control of the modulation for each polarization, while a complex design of electrode configuration is needed. The other one [3], [4] is to fabricate the waveguide with a propagation direction along the optical axis. However, the largest EO coefficient r_{33} is not used and thus, the driving voltage is higher.

It is known that waveguides supporting only ordinary or extraordinary waves are good alternatives. Conventionally, proton-exchange waveguides supporting only extraordinary waves are used. However, the EO coefficients are significantly reduced after the proton exchange process [5] such that an additional thermal annealing process is needed [6]. However, the annealing process is time-consuming and needs to be carefully controlled. Recently, gallium-diffused waveguides supporting only the extraordinary wave have been proposed and are good alternatives for singly polarized waveguides [7]. In this letter, the Mach–Zehnder modulators fabricated by gallium-diffusion in a y-cut $LiNbO_3$ substrate are presented. The halfwave voltage and the extinction ratio are measured. By calculating the overlap integral of the optical and modulating electric fields, the EO coefficient r_{33} in gallium-diffused waveguide is found in good agreement with that of the bulk $LiNbO_3$, which indicates no significant degradation in r_{33} is induced by the in-diffused gallium atoms.

II. Device Fabrication

To utilize the largest EO coefficient r_{33}, a Mach–Zehnder modulator is fabricated in a y-cut x-propagating $LiNbO_3$ substrate with a pair of symmetric coplanar strip electrodes. The device configuration is shown in Fig. 1. For single-mode operation, the waveguide width is chosen as 4 μm. The length of the two parallel waveguide arms is 1 cm and the full-branch angle is 1°. For simplicity, a pair of electrodes is used instead of a set of three push–pull electrodes. The length and gap width of the electrodes are chosen as 0.4 cm and 10 μm, respectively. The fabrication process is described as follows. First, the device pattern is transferred to the $LiNbO_3$ substrate by the standard photolithography process. Then, a Ga_2O_3 thin film is deposited by radio-frequency sputtering as the diffusion source. The diffusion process is performed in a furnace at 900 °C for 1.5 h. Then, the end faces are polished by diamond films. Finally, a pair of aluminum electrodes is deposited by thermal evaporation.

III. Measurement and Results

For optical characterization, a He–Ne laser of wavelength 632.8 nm is coupled through a polarizer to the end face of the Mach–Zehnder interferometer. A symmetric triangular voltage

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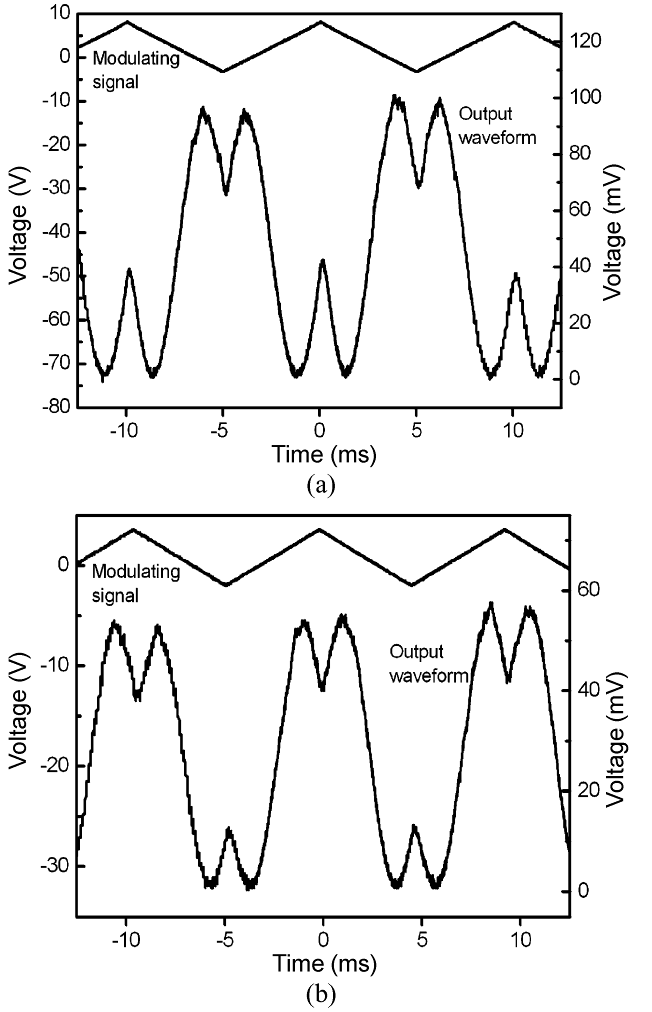

Fig. 2. Optical response of the Mach–Zehnder modulator driven by a symmetric triangular voltage signal with a pair of (a) 4- and (b) 8-mm-long electrodes.

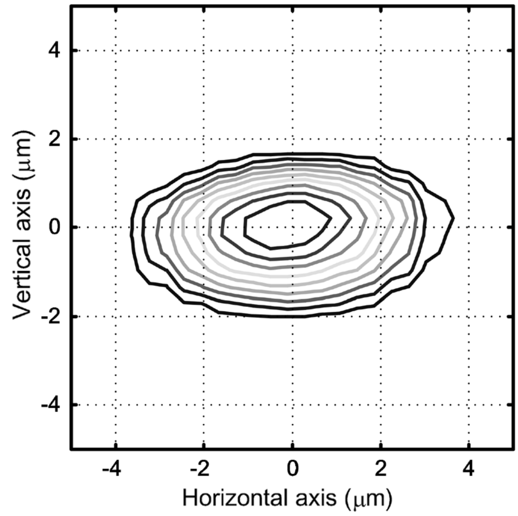

Fig. 3. Optical field intensity contours of the modulator.

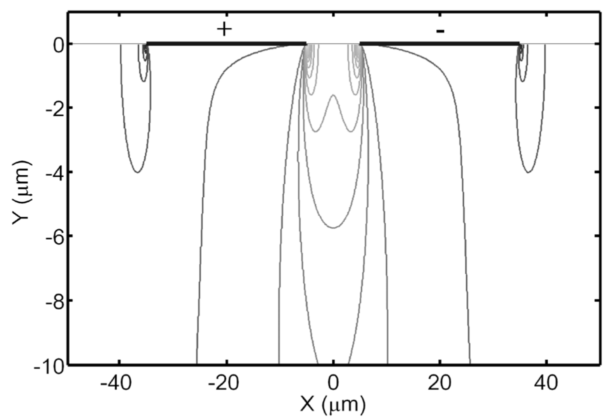

Fig. 4. Simulated electric field contour profiles of a modulator with an applied voltage.

signal is then applied to the electrodes. The applied voltage waveform and modulated output signals are displayed on an oscilloscope as shown in Fig. 2. The halfwave voltage (V_π) and the extinction ratio are measured to be 6.2 V and 20.8 dB, respectively. Another modulator with a pair of 0.8-cm-long electrodes is also fabricated for comparison. The halfwave voltage and the extinction ratio are measured to be 3.2 V and 21.4 dB, respectively. Note that, as the gallium-diffused waveguides have been shown to support only extraordinary waves [7], the output power of ordinary waves can hardly be detected.

For a Mach–Zehnder modulator, the halfwave voltage is written as [8]

$$V_\pi = \frac{\lambda G}{n^3 r_{33} \Gamma L} \tag{1}$$

where λ is the operating wavelength, n is the refractive index of the waveguide, L is the length of the electrodes, and Γ is the overlap integral between the optical and modulating electric fields as defined by the following equation [9]:

$$\Gamma = \frac{G}{V} \frac{\iint E_{\rm op}^2(x,y) E_{\rm el}(x,y) dx dy}{\iint E_{\rm op}^2(x,y) dx dy} \tag{2}$$

where G is the gap between the electrodes, V is the applied voltage, $E_{\rm op}(x,y)$ is the optical field, and $E_{\rm el}(x,y)$ is the electric field. Fig. 3 shows the measured optical field intensity contours of the modulator. The simulated electric field is shown in Fig. 4. In this case, Γ and n are found to be 0.7465 and 2.206, respectively. As a result, the calculated values of r_{33} are 30.84 and 31.84 pm/V for the 0.8- and 0.4-cm-long electrodes, respectively. Thus, good agreement between the estimated and bulk values of r_{33} is obtained, indicating that no significant degradation in r_{33} is induced by the in-diffused gallium atoms in $LiNbO_3$ substrate. In addition, the total loss of the device, characterized by comparing the transmitted power of a modulator and a straight-channel waveguide on the same substrate, is about 3.4 dB. To achieve a lower driving voltage, push–pull electrodes and ridge waveguide structure [10] have been demonstrated to be an effective solution. Moreover, the device length can be shortened by introducing a simplified coherently coupled bending structure [11] to the Y-branch region of the Mach–Zehnder modulator.

It is known that the value of r_{33} in the proton-exchanged waveguide is severely degraded to one tenth of its bulk value [5]. Even with an additional postexchanged annealing process,

TABLE I
COMPARISON OF GALLIUM-DIFFUSED AND PROTON-EXCHANGED OPTICAL WAVEGUIDES IN LITHIUM NIOBATE

Parameter	Gallium-diffusion [7]	Proton-exchange	Annealed proton-exchange
Index distribution	Graded	Step	Graded
Maximum index change	10^{-2}~10^{-3}	10^{-1}	10^{-2}
Propagation loss (dB/cm)	0.2~0.9(y-cut)	0.5(x-cut) [12] 3(y-cut) [13] 0.25(z-cut) [14]	0.15(x-cut) [15] 0.15(z-cut) [14]
Annealing Process	No	No	Yes
r_{33} degradation	No	90% degradation [5]	25% degradation [6]

only 75% restoration of r_{33} can be obtained [6]. A comparison of gallium-diffused, proton-exchanged, and annealed proton-exchanged optical waveguides in lithium niobate is listed in Table I. It can be seen that gallium-diffused waveguides are good alternatives for making EO devices for practical application.

IV. CONCLUSION

The EO coefficient r_{33} of the gallium-diffused waveguide on $LiNbO_3$ substrate is investigated. A Mach–Zehnder optical modulator is fabricated by the gallium-diffused waveguide in a y-cut, x-propagating $LiNbO_3$ substrate with a pair of symmetric coplanar strip electrodes. The halfwave voltages are measured to be 6.2 and 3.2 V for 0.4- and 0.8-cm-long electrodes, respectively. Good agreement between the estimated and theoretical values of r_{33} indicates that no significant degradation in EO effect is induced by the gallium atoms diffused into $LiNbO_3$ substrate. Moreover, with the low propagation loss, singly guided polarization, and high EO coefficient, gallium-diffused waveguides are demonstrated to be suitable for EO-device application.

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