Research Article

Fabrication of Proton-Exchange Waveguide Using Stoichiometric LiTaO₃ for Guided Wave Electrooptic Modulators with Polarization-Reversed Structure

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Optical waveguides were fabricated on z-cut stoichiometric LiTaO₃ (SLT) by using the proton-exchange method. The surface index change for the extraordinary ray on the SLT substrate resulting from the proton exchange was 0.017, which coincided well with congruent LiTaO₃ substrates. The proton exchange coefficient in the SLT was 0.25×10^{-12} cm²/s. The application of the SLT waveguide to a quasi-velocity-matched travelling-wave electrooptic modulator with periodically polarization-reversed structure is also reported.

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1. Introduction

Recently, optical-quality stoichiometric LiNbO₃ (SLN) and stoichiometric LiTaO₃ (SLT) crystals have been attracting a lot of interest due to their excellent characteristics as a material for optical functional devices; small coercive electric field for polarization reversal, excellent nonlinear optic (NLO) and electrooptic (EO) characteristics, and small defect density [1–5]. Several studies on the optical wavelength conversion devices using NLO effects in SLN and SLT have been reported, however, there are few reports on their applications to EO devices. In particular, a guided-wave optical modulator based on SLT has not been yet reported, as far as we know. One main reason, we believe, is that waveguide fabrication methods have not been established for SLT. SLT exhibits a large tolerance for optical damage and small birefringence which can be controlled precisely. These features are attractive for applications to advanced NLO and EO devices.

In this report, we present the fabrication of proton exchange waveguides in z-cut SLT substrates. The measured surface refractive index change for an extraordinary ray, Δn_e , was $\Delta n_e = 0.017$, which was in good agreement with the reported value in congruent LiTaO₃ [6]. The application to

high-speed traveling-wave EO modulators using SLT with periodic polarization reversal for quasi-velocity-matching is also reported.

2. Waveguide Fabrication

Z-cut stoichiometric LiTaO₃ (SLT) wafers from Oxide Corporation were used in this study. For the fabrication of the proton exchange waveguides, the standard exchange technique using melted benzoic acid was used [6]. The temperature of the melted benzoic acid for the proton exchange was set at 240 degrees centigrade. During the proton exchange process, the temperature of the melted benzoic acid was kept within 240 ± 0.1 degrees centigrade by use of a proportional-integral-derivative (PID) temperature controller. Several slab waveguides were fabricated using SLT with three different proton exchange times set at 4, 9, and 24 hours.

The effective indices of the TM-guided modes in the fabricated slab waveguides were measured by using the prism coupling method with a standard rutile prism coupler at a wavelength of 633 nm. The measured results are plotted in Figure 1 with the dispersion curves of TM-guided modes. Figure 2 shows the relationship between the proton exchange

FIGURE 1: Measured effective index values with TM-guided wave mode dispersion curves.

thickness and the square root of the exchange time. From the measurement results, we obtained the surface index change, Δn_e , for the extraordinary ray and the exchange coefficient, D_{ex} , in the SLT by the proton exchange with benzoic acid at 240 degrees centigrade. We defined the exchange coefficient D_{ex} by use of the depth d of the proton-exchanged layer from the surface and the proton exchange time t_{ex} as the following equation:

$$d = 2\sqrt{D_{ex}t_{ex}}. \quad (1)$$

The obtained results are summarized in Table 1. For comparison, the reported surface index change value and exchange coefficient in CLT [6] are also shown in Table 1. The surface index change value in SLT coincided with the reported one of CLT by the proton exchange with benzoic acid at 249 degrees centigrade [6]. On the other hand, the exchange coefficient in SLT at 240 degrees centigrade was about 30% larger than that in CLT at 249 degrees centigrade. In other words, the velocity of the proton exchange in SLT was slightly faster compared with CLT. This might come from the small defect density of SLT. From the measured surface refractive index change and the depth of the exchanged layer, we can derive the proton exchange condition for SLT in order to obtain a single-mode channel optical waveguide at a designed wavelength.

3. Fabrication of Quasi-Velocity-Matched Electrooptic Modulator

Utilizing the proton exchange single-mode optical waveguide of SLT, we tried to fabricate the quasi-velocity-matched (QVM) electrooptic (EO) modulators with traveling-wave electrodes and periodically polarization-reversed structure [7]. The basic structure of the device is shown in Figure 3. It consists of a single-mode channel waveguide formed by the proton exchange method and traveling-wave coplanar electrodes fabricated on a z-cut SLT substrate with an SiO_2 buffer layer. A periodically polarization-reversed structure is

TABLE 1: The surface refractive index change Δn_e and the exchange coefficient D_{ex} in the proton exchange slab waveguides of SLT and CLT.

	Δn_e	$D_{ex} (10^{-12} \text{ cm}^2/\text{s})$
Stoichiometric LiTaO_3 (benzoic acid, 240 degrees)	0.017	0.25
Congruent LiTaO_3 [6] (benzoic acid, 249 degrees)	0.017	0.184

FIGURE 2: Proton exchange thickness as a function of the square root of exchange time in the measured samples.

also fabricated through the substrate for the quasi-velocity-matching between the lightwaves propagating in the optical waveguide and the modulation microwave traveling along the coplanar electrodes.

In the device design, we set the peak modulation frequency as 15 GHz and the operational light wavelength as 633 nm for the prototype device. The required length for each polarization-reversed and nonreversed region L for the quasi-velocity-matching is given by the following equation [7]:

$$L = \frac{c}{2f_m(n_m - n_g)}, \quad (2)$$

where n_g is the group index of the lightwaves propagating in the waveguide, n_m is the effective index of the modulation microwave traveling along the electrodes, and c is the light-wave velocity in vacuum. In order to obtain a single-mode channel waveguide at 633 nm, we designed the waveguide core width as $3 \mu\text{m}$ and the waveguide core depth as $0.7 \mu\text{m}$. From the reported wavelength dispersion characteristics of the refractive index of SLT [4] and calculated waveguide dispersion characteristics, we obtained the group index value of the lightwaves propagating in the waveguide as $n_g = 2.30$ at a wavelength of 633 nm. The effective index of the modulation microwave was also calculated as $n_m = 4.55$ from the dielectric constants of SLT and the structure of the coplanar asymmetric electrodes with a hot electrode of $14 \mu\text{m}$ in width and an electrode separation of $33 \mu\text{m}$. As a result,

FIGURE 3: Structure of QVM EO modulator with periodically polarization-reversed structure.

FIGURE 4: Calculated modulation frequency dependence of the QVM modulator when the polarization reversal period is $2L = 8.88$ mm and the total electrode length is $L_t = 31$ mm.

the length for the polarization-reversed and nonreversed region for the quasi-velocity-matching was obtained as $L = 4.44$ mm for the peak modulation frequency at 15 GHz from (2). The calculated frequency response of the QVM modulator is shown in Figure 4 when the electrode length for modulation L_t is set as 7 times that of L ($L_t = 31$ mm).

The designed device was fabricated using z-cut SLT as shown in Figure 5. Firstly, the periodic polarization reversal pattern with a period of $2L = 8.88$ mm was fabricated on a 0.4 mm thick z-cut SLT substrate by use of the pulse voltage applying method. The electric field required for the polarization reversal was rather small (~ 3.3 kV/mm) compared with standard CLT substrates (~ 22 kV/mm). Next, the single-mode channel waveguide was fabricated on the periodically poled SLT by using the proton exchange method. The waveguide core width was $3 \mu\text{m}$ and the core depth was set as $0.7 \mu\text{m}$. The periodically-poled Cr-masked SLT substrate for the fabrication of the channel waveguide with a width of $3 \mu\text{m}$ was immersed into the melted benzoic acid at 240 degree centigrade for 90 minutes. After the removal of the Cr film, a $0.1 \mu\text{m}$ thick SiO_2 buffer layer was deposited on the waveguide by sputtering. Finally, $2 \mu\text{m}$ thick Al asymmetric coplanar electrodes were fabricated onto the waveguide by use of EB deposition and a standard

FIGURE 5: Fabrication sequence of the QVM EO modulator.

photolithography technique. The hot electrode width was set as $14 \mu\text{m}$ and the electrodes separation was set as $33 \mu\text{m}$, where the intrinsic impedance of the electrodes became 50Ω . The electrode length for modulation L_t was 31 mm, which corresponded with 3.5 times the polarization reversal period $2L$.

Both ends of the waveguides were cut and polished for light-beam coupling. The total device length was 42 mm and the optical insertion loss of the device was about 25 dB including the coupling losses at both ends. We believe that the relatively large optical loss will be reduced by a thermal annealing process as with the proton exchange CLT waveguides (annealed proton exchange process). Microwave characteristics of the fabricated electrodes were measured by use of a network analyzer and good microwave responses of SLT (almost the same as CLT) were confirmed.

The optical spectrum of the modulated lightwave from the fabricated device was measured by use of a scanning Fabry-Perot interferometer. The measured modulation frequency dependence of the fabricated QVM EO modulator is shown in Figure 6. The band modulation characteristic was confirmed. The peak modulation frequency was in good agreement with the designed frequency of 15 GHz. We think that the dip in the modulation index at 14 GHz in Figure 5

FIGURE 6: Measured modulation frequency dependence of the fabricated modulator.

was due to the effect of the substrate resonance mode, which could be reduced by changing the size of the substrate and the coupling of the microwave signal to the electrodes.

4. Discussion and Conclusion

Basic characteristics of the proton exchange waveguide in SLT and the fabrication condition of a single-mode waveguide were obtained. However, the optical loss in the fabricated waveguide was large (~ 25 dB in the 42 mm waveguide with coupling loss). In addition, it is well known that the proton exchange process might degrade the Pockels effect. Thermal annealing is rather effective in reducing the optical loss and recovering the Pockels effect. We have also tried to do the thermal annealing of the fabricated proton exchange SLT waveguides with the standard annealing condition for the proton exchange CLT waveguides (250–400 degrees centigrade, ~ 1 hour). However, after annealing, the guiding characteristics became poor and the output beam spot from the end of the waveguide could not be observed. It might come from the large diffusion velocity, and some specific techniques like rapid thermal annealing might be necessary to realize good annealing conditions.

In conclusion, we fabricated the proton-exchanged waveguide on z-cut stoichiometric SLT. The measured surface index change for the extraordinary ray was $\Delta n_e = 0.017$, which coincided well with congruent LiTaO_3 substrates. The proton exchange coefficient in SLT was $D_{\text{ex}} = 0.25 \times 10^{-12} \text{ cm}^2/\text{s}$. Some interesting applications include EO modulators with advanced functions using the polarization reversal and optical waveguide technologies.

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