Fabrication of integrated Ti:LiNbO$_3$ waveguide polarizer

Vadim Dobrusin and Shlomo Ruschin
Tel Aviv University, School of Electrical Engineering,
Department of Physical Electronics, Ramat Aviv, 61390,
Tel Aviv, Israel
E-mail: vdobrusin@netscape.net

Abstract. The design and fabrication of an integrated waveguide polarizer in z-cut LiNbO$_3$ crystals are reported. Single-polarization guiding is achieved by careful selection of Ti diffusion parameters exploiting the transverse electric/transverse magnetic (TE/TM) refractive index anisotropy. Fabricated Ti:LiNbO$_3$ waveguide polarizers of 1.5 cm length exhibit less than 0.2-dB/cm propagation loss at TM and 33-dB extinction ratio as measured at 1.55-μm wavelength. [DOI: 10.1117/1.3046714]

Subject terms: integrated optics; lithium niobate; diffusion; waveguides; polarizer.

Paper 080611LR received Aug. 7, 2008; revised manuscript received Nov. 2, 2008; accepted for publication Nov. 5, 2008; published online Dec. 24, 2008.

1 Introduction

Lithium niobate is considered a highly attractive material for production of active integrated optoelectronic components. The performance of some applications such as high-speed modulators, sensors, and gyroscope circuits are particularly dependent on precise phase and polarization control. Single-polarization guiding is desirable and in some cases even essential for their successful operation. Several methods have been reported that achieve single-polarization guiding in LiNbO$_3$ waveguides—among them, transverse electric/transverse magnetic (TE/TM) splitters,[1,2] metal cladding,[3] anisotropic overlays,[4] proton exchanged (PE) waveguides,[5] Ti:LiNbO$_3$ waveguides with incorporated PE segments,[6] and single-polarization Zn:LiNbO$_3$ waveguides.[7] Application-wise, each of these methods has its own advantages and limitations. Metal cladding, for instance, does not allow fabrication of short, high-extinction-ratio polarizers without elevating propagation losses for the passing polarization. Proton exchange is presently considered the leading technology for fabrication of waveguide polarizers with an extinction ratio of about 40 dB/cm.[6] The technique suffers, however, from relatively high propagation losses (>0.5 dB/cm) and reduction of electro-optic efficiency. Both drawbacks are usually amended by annealing processes. One main limitation of PE-based devices is their susceptibility to high temperature. High-temperature treatments (>200 °C) that are essential for production of additional layers (such as CVD-SiO$_2$ buffer for instance) are undesirable since they affect the waveguiding. Relying on higher index increase at the extraordinary polarization ($\Delta n_e > \Delta n_o$), a polarizing waveguide based on Zn in-diffusion was reported.[7] Ti in-diffusion technology is considered advantageous and is widely employed in practical and commercial devices. Therefore, a technique of incorporating polarizing properties into Ti-diffused waveguides is highly desirable. The feasibility of a polarization splitter exploiting the TE/TM mode anisotropy induced by Ti in-diffusion was predicted and simulated in the past.[2] However, the production of an integrated waveguide polarizer based solely on the Ti in-diffusion technology has not been reported so far.

Here, we present the design and a fabrication routine of a high-extinction Ti in-diffused waveguide polarizer in z-cut LiNbO$_3$ crystal. We report the attainment of fabrication conditions leading to low-loss guidance of the TM polarization in a Ti in-diffused waveguide while suppressing the TE (ordinary) polarization. The proposed method exploits the LiNbO$_3$ anisotropy and, in addition, the differential refractive index increase in TE and TM polarizations caused by the incorporation of Ti ions. It is well known that channel Ti:LiNbO$_3$ waveguides exhibit nonequal confinement for orthogonal optical polarizations. We demonstrate that careful selection of the process parameters (e.g., Ti thickness, waveguide width, as well as diffusion temperature and duration) enables fabrication of waveguides that have strong confinement for the TM mode while exhibiting leaky behavior for the TE mode. The simultaneous production of the guiding structure with a built-in polarizer in a single fabrication step utilizing the most popular waveguide fabrication technology makes this method especially attractive.

The presented technology was further applied for fabrication of various single-polarization-mode devices based on channel and ridge[8] waveguide structures of various widths. All these devices exhibited predicted single TM guidance and lack of susceptibility to slight variations of fabrication conditions.

2 Design Considerations

Understanding of the mode geometry is essential for the design of a waveguide polarizer with a high extinction ratio. The guidance in the Ti:LiNbO$_3$ waveguide was simulated by applying the diffusion model[9] and the beam propagation method. Based on material properties and known physical constants, the refractive index change was evaluated as a function of four main fabrication parameters, namely, Ti strip width and thickness as well as diffusion duration and temperature. The calculated index profile was then used in a commercial beam propagation simulator (RSoft, Inc.) for generation of the mode profile guided by the 3-D Ti in-diffused channel waveguide. The calculations of light propagation were performed for a 1.5-cm-long straight waveguide by applying a 0.2-μm grid across the x-y plane (e.g., cross section) and a 5-μm-grid along the propagation z direction. The reported diffusion routine was determined by searching for the maximal anisotropy between TE and TM modes while iterating the preceding procedure for fabrication parameters varying within practical boundaries. It was found that the refractive index change near the surface for the TM mode is more than 2 times higher than for the TE mode, if the postdiffusion profile is calculated for the Ti strip of 9.5 μm width and 600 A thickness in-diffused during 8.5 h at 1000 °C. The corresponding TE and TM modes simulated at 1550-nm wave-

0091-3286/2008/$25.00 © 2008 SPIE

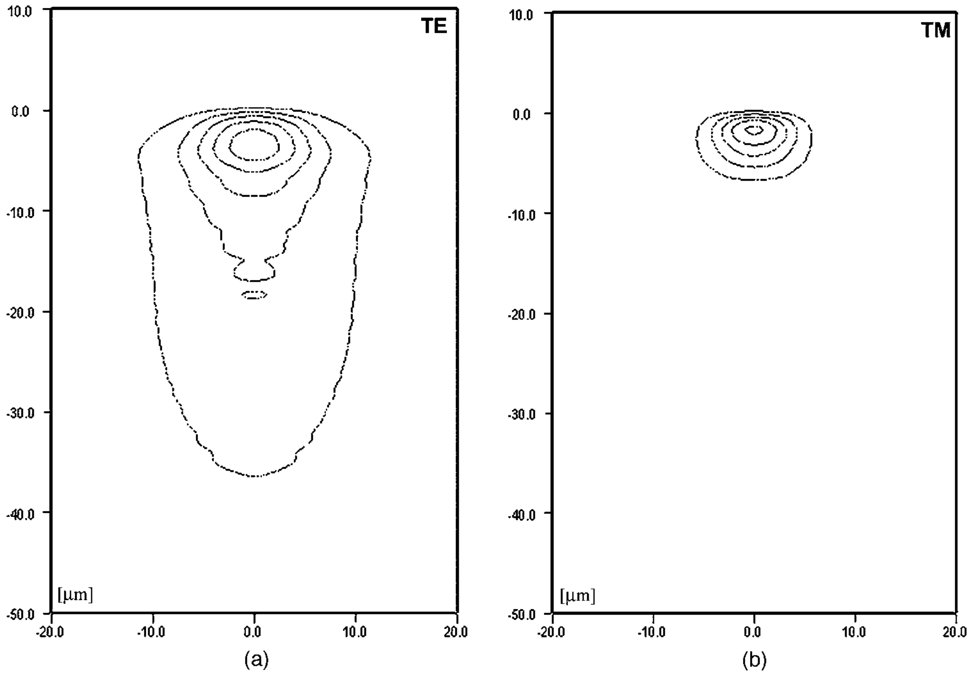

Fig. 1 Simulated intensity distribution of (a) TE and (b) TM modes at 1.55 μm.

length are presented in Fig. 1. The results clearly indicate well-confined single-mode guidance for the TM mode and an enlarged appearance of the TE mode due to weak confinement. Such a weakly confined mode, if present, is expected to be very susceptible to scattering loss.

The fiber-waveguide coupling losses were estimated as 0.78 dB for TM and 1.86 dB for TE modes, suggesting a nonsignificant difference in their coupling efficiencies. The losses were calculated for a SM fiber with 10.5-μm mode-field diameter. The performed simulations show that mode profiles are not susceptible to typical equipment-related variations of diffusion parameters, implying good reproducibility of the results. However, the substantial modification of one or more diffusion parameters leads to production of waveguides with excellent guidance for both TM and TE polarizations.[8]

3 Waveguide Fabrication

A sample was prepared from a congruent double-side-polished z-cut 3-inch $LiNbO_3$ wafer of 1-mm thickness supplied by Crystal Technology, Inc. After cleaning, the $-z$ side of the sample was subjected to photolithographic patterning with negative-tone photoresist. The pattern consisted of a series of straight waveguides of 9.5-μm width and 1.5-cm length aligned along the crystallographic y axis. Then, 600 Å of Ti was deposited by e-gun over the patterned surface. Residual Ti was removed by the lift-off technique. The sample was subjected to Ti in-diffusion at 1000 °C in wet O_2 atmosphere inside a three-zone furnace. The Li out-diffusion was suppressed by 1 lit/min wet O_2 flow and partial pressure created inside a Pt crucible, where the specimen was enclosed for 8.5 h. Slow overnight cooling in dry O_2 atmosphere took place, reoxidizing the $LiNbO_3$ and preventing waveguide breakdown due to superposition of pyro- and piezo-electric effects. Finally, the sample was polished at the edge.

4 Waveguide Characterization

Inspection of the near-field light irradiated from the fabricated series of waveguides was performed with a Vidicon camera and a 40× micro-objective lens. For each waveguide, a well-confined single TM mode was observed. The mode geometry and dimensions were consistent with the simulation results for TM polarization presented in Fig. 1. However, the TE mode was not detected by IR camera under 0 dBm input condition.

The propagation losses for guided TM mode in channel $Ti:LiNbO_3$ waveguides were evaluated by the Fabry-Pérot method using a fiber-chip-fiber setup. The polishing quality of the waveguide-terminating facets enabled good visibility of Fabry-Pérot resonances inside the straight guiding sections. Scanning the resonator transmission by a tunable source within the 1545.0 to 1545.2-nm wavelength range, the intensity variations were measured as function of the wavelength, as shown in Fig. 2.

The results, evaluated from the measured modulation depth,[10] revealed propagation losses of less than 0.2 ± 0.15 dB/cm for quasi-TM polarization. Most likely, the losses were significantly lower, because the calculations were based on ideal reflectance from the $LiNbO_3$-air interface, while the real facets were evidently imperfect. Imperfection of the waveguide and fiber facets also contributed to 2.8 dB total fiber-chip-fiber loss measured for TM mode. The results were then validated by comparing the calculated and measured free spectral range (FSR) of the waveguide resonator. This was done to ensure that the measured modulation depth resulted from the internal waveguide resonance and was not imposed by the fiber-waveguide cavity. The calculated and measured values of FSR were both equal to 55.6 pm.

Utilizing the same fiber-chip-fiber setup with an incorporated in-line fiber polarizer and polarization controller,

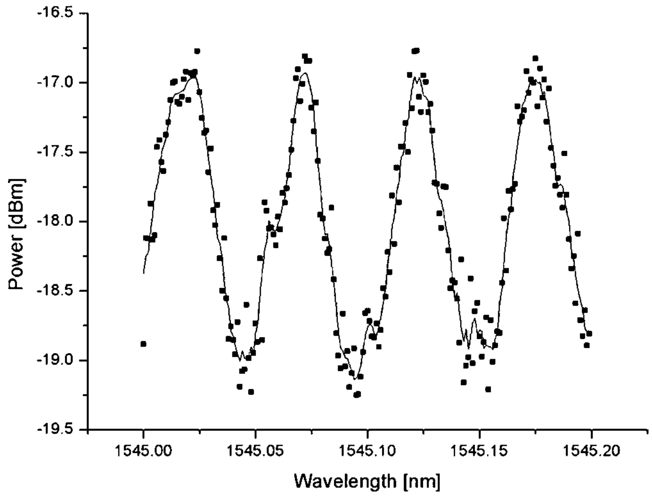

Fig. 2 Measured Fabry-Pérot resonance for TM mode.

the transmission of the two orthogonal polarization modes was measured. An extinction ratio of 33 dB was observed by finding maxima and minima of intensity while changing the state of the polarization by controller. The exclusive transmission of the quasi-TM mode was further confirmed by means of a fiber-chip-polarimeter setup. Then, spectral

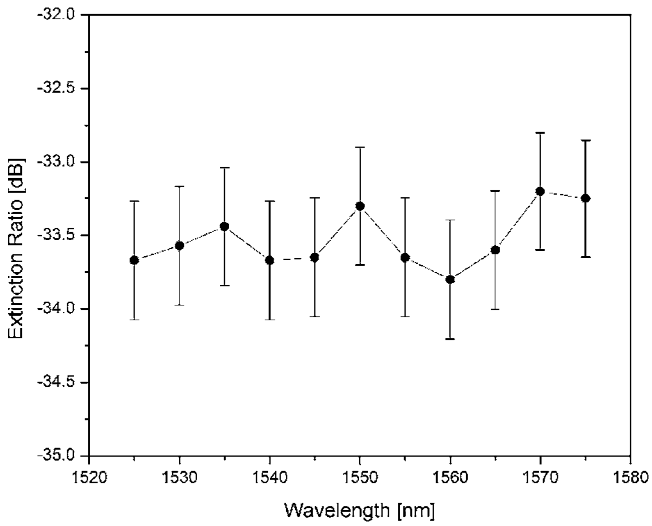

Fig. 3 Polarizing extinction ratio measured at various wavelengths.

response of the waveguide polarizer across the C-band was tested by measuring the extinction ratio at various wavelengths in the range. The results presented in Fig. 3 emphasize the lack of spectral dependence. Although slight fluctuation can be noticed, all experimental data is still in the error range from the average.

5 Conclusions

The design and single-step fabrication routine of a high-extinction Ti in-diffused waveguide polarizer in z-cut $LiNbO_3$ crystal were reported. The effect responsible for the polarizing action is higher index increase at the extraordinary polarization as compared to the ordinary one. The simulations we performed still reveal the existence of an enlarged cross-section mode for the TE polarization. The fact that the TE mode was not distinctly observed may be attributed to its leaky propagation as well as to additional effects[11] that may increase the difference between the two modifications of the refractive index.

References

1. W.-H. Hsu, K.-C. Lin, J.-Y. Li, Y.-S. Wu, and W.-S. Wang, "Polarization splitter with variable TE–TM mode converter using Zn and Ni codiffused $LiNbO_3$ waveguides," *IEEE J. Sel. Top. Quantum Electron.* **11**(1), 271–277 (2005).
2. J. J. G. M. van der Tol and J. H. Laarhuis, "A polarization splitter on $LiNbO_3$ using only titanium diffusion," *J. Lightwave Technol.* **9**(7), 879–886 (1991).
3. T. Takano and J. Hamasaki, "Propagating modes of a metal-clad-dielectric-slab waveguide for integrated optics," **QE-8**(2), 206–212 (1972).
4. M. Papuchon, M. Enard, K. Thyagarajan, and M. Vatoux, "Anisotropic polarizers for Ti:$LiNbO_3$ strip waveguides," in *Seventh Topical Meeting on Integrated and Guided-Wave Optics. Technical Digest*, IEEE Cat. No. 84CH1997-6, pp. WC5/1–4 (1984).
5. U. Hempelmann, H. Herrmann, G. Mrozynski, V. Reimann, and W. Sohler, "Integrated optical proton exchanged TM-pass polarizers in $LiNbO_3$: modelling and experimental performance," *J. Lightwave Technol.* **13**(8), 1750–1759 (1995).
6. P. G. Suchoski, T. K. Findakly, and F. G. Leonberger, "Low-loss high-extinction polarizers fabricated in LiNbO3 by proton exchange," *Opt. Lett.* **13**(2), 172–174 (1988).
7. R. C. Twu, C. C. Huangand, and W. S. Wang, "Zn indiffusion waveguide polarizer on a y-cut $LiNbO_3$ at 1.32-μm wavelength," *IEEE Photonics Technol. Lett.* **12**(2), 161–163 (2000).
8. V. Dobrusin, S. Ruschin, and L. Shpisman, "Fabrication method of low-loss large single-mode ridge Ti:LiNbO3 waveguides," *Opt. Mater.* **29**(12), 1630–1634 (2007).
9. E. Strake, G. P. Bava, and I. Montrosset, "Guided modes of Ti:$LiNbO_3$ channel waveguides: a novel quasi-analytical technique in comparison with a scalar finite-element method," *J. Lightwave Technol.* **6**(6), 1126–1135 (1988).
10. R. Regener and W. Sohler, "Loss in low-finesse Ti:$LiNbO_3$ optical waveguide resonators," *Appl. Phys.* **36**, 143–147 (1985).
11. S. L. Kwiatkowski and A. R. Mickelson, "Nearly cut-off modes caused by diffusion in lithium niobate," *J. Appl. Phys.* **76**, 5877–5885 (1994).