FABRICATION AND CHARACTERIZATION OF INTEGRATED OPTICAL POLARIZER FOR SENSOR APPLICATIONS

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Abstract:

APE:LiNbO$_3$ Integrated optical polarizer operating at a wavelength of 1550nm has been fabricated by optimizing waveguide parameters as well as process parameters with the help of theoretically simulations followed by some experimental studies. The polarizer guides only extraordinary polarized light (TE-mode) and an extinction ratio of >25 dB has been observed over ordinary polarized light (TM - blocked). The insertion loss of the polarizer is measured to be ~ 10 dB and can be reduced further by optimizing the process parameters. Fabrication of optical channel waveguides and its analysis mainly concentrated on the propagation loss with particular emphasis on single mode waveguide which was used in Integrated optical devices. For the fabrication of functional devices in waveguide geometries, Lithium Niobate (LiNbO$_3$) was rapidly recognized as one of the most promising alternatives. This is due to several characteristics of this crystalline material. Symmetrical Y-junction power splitter was designed through R-Soft with suitable single mode condition and simulated through Beam Propagation Method and found propagation loss with various waveguide parameters such as branching angle, width, and wavelength variation.

Keywords : Integrated Optical Polarizer, TE mode, TM mode, LiNbO$_3$

1. INTRODUCTION

Channel waveguide as shown in Fig.1.1. forms the basic structure for any integrated optical (IO) device. Hence the designing of channel waveguide is one of the fundamental requirements in designing an IO component. A typical of a substrate-type optical integrated circuit that is used in a fiber optic gyroscope is a Y-propagating optical waveguide that is fabricated on an optical crystal substrate of Lithium Niobate (LiNbO$_3$) using proton exchange method. Though two propagation modes namely, a TE mode (Transverse Electric mode) and a TM mode (Transverse Magnetic mode) are produced in a normal optical waveguide, this optical waveguide fabricated using the proton exchange method has its inherent nature that only the TE mode is formed as a guide mode or propagation mode and the TM mode is not formed as a guide mode or propagation mode[1]. In other words, the optical waveguide itself, fabricated on the optical crystal substrate of Lithium Niobate using the proton exchange method, is provided with a function of a polarizer having very high extinction ratio. As a result, when light from a light source is incident on the proton exchanged optical waveguide, only light wave of the TE mode is propagated, where as light wave of the TM mode will not be propagated and will be extinguished.

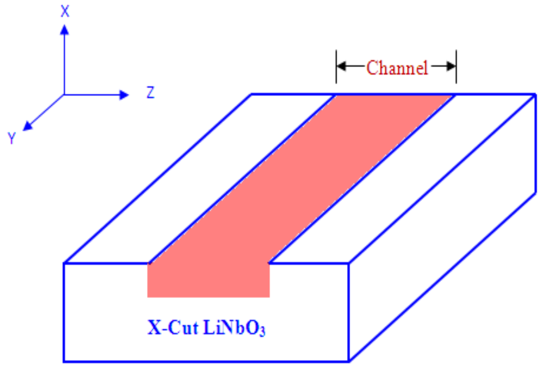


Fig 1.1. Channel waveguide

When light, of particular wavelength, propagates in a channel its behavior will be dependent on the material and geometrical properties of the waveguide. Also the behavior varies with change in wavelength. The following are the factors that effect the propagation of light in a waveguide.

- ❖ *Material parameters:*
  - Refractive index of the film
  - Refractive index of the substrate
  - Refractive index profile
  - Attenuation/Amplification factor
- ❖ *Waveguide parameters:*
  - Width
  - Thickness
  - Height of the cladding
- ❖ *Light parameters:*
  - Wavelength
  - Input power
  - Intensity profile

The following parameters that can further affect the light properties.

- Change in Refractive index inside the channel --- Δn_e.
- Thickness of the channel (depends on our choice) --- *W*.
- Depth of the waveguide (depends on fabrication parameters) --- *T*.

Now let us consider the properties of light that can be affected by the above three parameters.

- Number of modes that can propagate inside the channel.
- How well the modes are confined inside the channel

2. Integrated Optical Polarizer : Fabrication Methodology:

Proton Exchange is a very effective process for fabrication of low-loss optical waveguides in lithium niobate ($LiNbO_3$). During this process lithium niobate is immersed in a source of porton (H^+) i.e. an acid (ex. Benzoic acid, steraic acid, or pyrophosphoric acid) or in a mixture of an acid and its lithium-salt either in molten or in liquid form. This process carried out normally at a particular temperature in the range ~ 150°C to 250°C [2]. During this process Li^+ ions diffuse out of the substrate and hydrogen ions from the acid diffuses into the substrate and occupy the vacant sites left by lithium ions. Benzoic acid is the most commonly used source for protons, because while using this acid the reaction temperature can be kept reasonably lower (150°C to 250°C) [3]. This acid does not react with most of the metals, thus giving a wide choice of mask material during waveguide fabrication. Also it is non-toxic in nature. Proton Exchange gives rise to a large increase in extraordinary refractive index (n_e) of the substrate with a sharp change in refractive index profile. Since the waveguide guides only the extra-ordinary polarized light it acts as a polarizer. During the proton exchange process crystal structure of the substrate undergoes a drastic change resulting in degradation of electro-optic and nonlinear optic properties of the material. Also the as – exchanged waveguide exhibits index instabilities over time. If these waveguides are annealed under constant oxygen flow for a given period of time hydrogen ions diffuse deep inside the material and also lithium and hydrogen ions redistribute themselves throughout the substrate. This helps to regain the original crystal structure as well as properties of the material. This process is known as annealed proton exchange process (APE). Properties of APE waveguides strongly depend on exchange conditions & subsequent annealing conditions. If the waveguide is fabricated on the surface of an X-cut $LiNbO_3$ substrate and is aligned parallel to Y-axis, it will guide only the TE polarized light.

3. Waveguide Design and Fabrication :

APE:$LiNbO_3$ integrated optical polarizer has been fabricated by optimizing waveguide parameters as well as process parameters with the help of theoretical simulations followed by some experimental studies. It has been found that waveguides support only the fundamental mode i.e. λ = 1550nm, if the waveguide width is varying within the range from 4.0μm to 6.0 μm along with suitable process parameters. The optimized single mode conditions / process parameters for APE: $LiNbO_3$ waveguides have been provided in Table 1.1.

Fabrication parameters	**Optimum value**
Channel width	4 to 6 μm
Proton Exchange Time	1 hr
Proton Exchange Temperature	175°C to 180°C
Annealing Time	1 hr
Annealing Temperature	300°C

Table 1.1. process parameters for APE:$LiNbO_3$ waveguides

X-cut Lithium Niobate wafer was thoroughly cleaned, dried and positive photoresist was coated on the positive X-plane of the wafer by a spin coater. The approximate thickness of the photoresist on the wafer was around 1.2 μm. The resist coating was followed by a soft bake of 80°C for 20 minutes. Contact printing method was used to expose the wafer. The wafer was exposed to UV-radiation (λ = 365nm) for 10 seconds to produce the pattern image on the resist. It was then developed in NaOH – based developer. After developing the wafer was rinsed in deionised water and blown dry using a N_2 air-gun. A Titanium layer was coated through out the surface of the wafer, later which was removed selectively from the wafer surface by lift-off technique. Then, proton exchange was carried out at temperature of 175°C to 180°C for one hour duration. The set up has been used for proton exchange process is shown in the fig. 1.2.

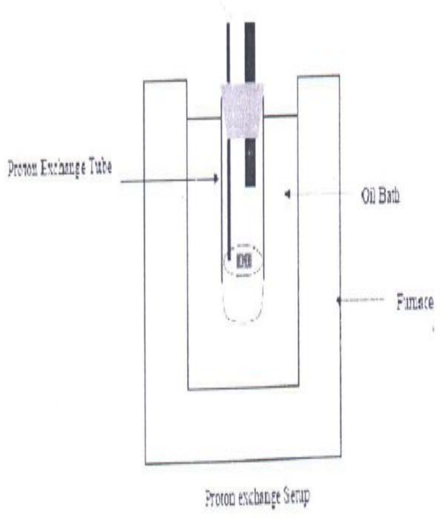


Fig. 1.2. Proton Exchange Set up

After proton exchange the sample was thoroughly cleaned in Ethanol to remove any traces of benzoic acid and then it was annealed at 300^{o}C for one hour under constant oxygen flow (2 lit/min).

For exchange process the refractive index profile is step like as shown in the figure 1.3(a). Annealing is done by heating the exchanged wave-guide in the temperature range 300^{0}C. As a result, protons diffuse further into the crystal, thus lowering the concentration and increasing the thickness of the wave-guide. In this case the refractive index no longer be step like. It becomes graded index profile (figure 1.3.(b)).

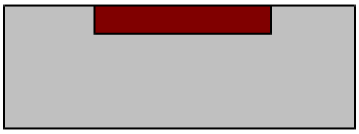


Fig 1.3(a). Proton exchanged waveguide

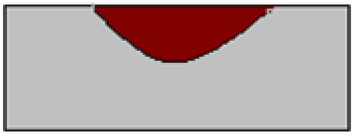


Fig. 1.3 (b).Annealed wave-guide

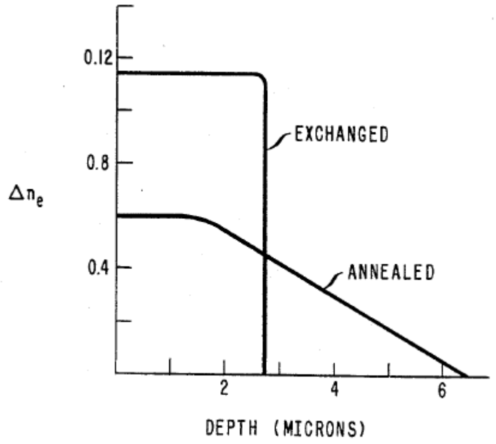


Fig. 1.4. Depth Vs Δn_e

4. Characterization:

After waveguide fabrication, the sample was diced and edges were optically polished perpendicular to the waveguide axis. Then various optical characterizations were performed for the given set of optical waveguides. The setup used for characterization is shown in fig. 1.5.

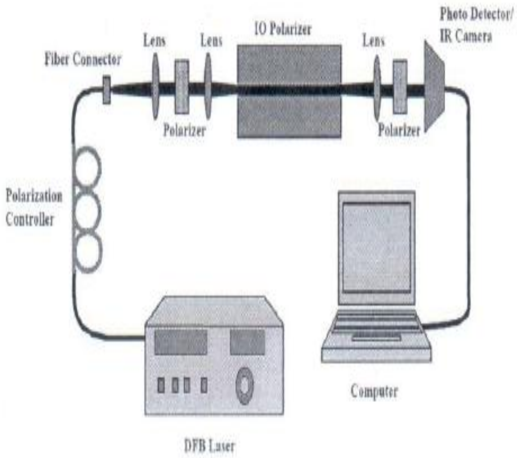


Fig. 1.5 Experimental setup for characterization

A tunable DFB laser source has been used for waveguide characterization. The wavelength tuning range of this laser source is from 1510 to 1590 nm. Initially, the chip was tested with ordinary He-Ne laser to check the output of the fabricated device. Finally, the chip testing was done with tunable laser source and optical spectrum analyzer to observe the splitting of the power.

4.1. Mode-profile measurement:

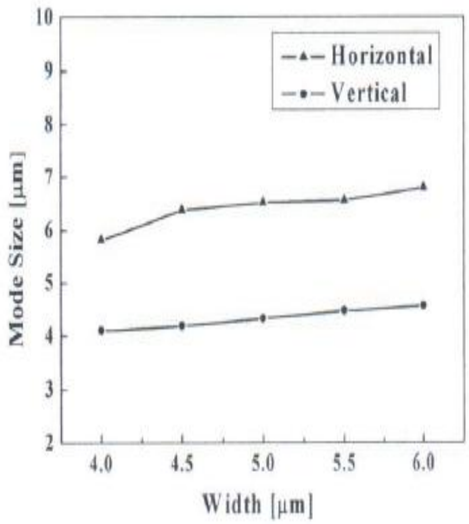


Fig. 1.6(a) waveguide width vs TE mode size at λ=1550nm

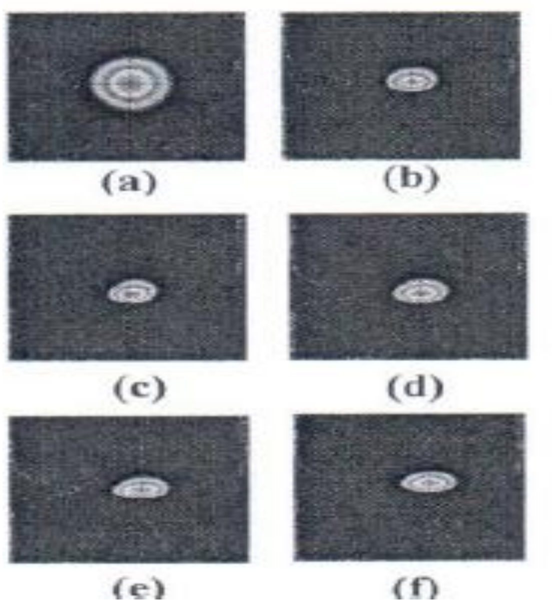
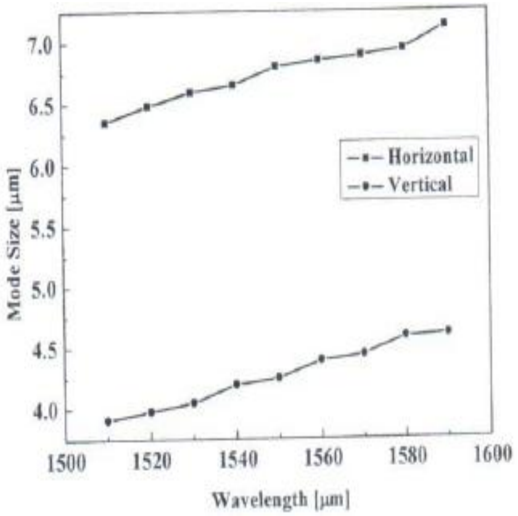


Fig. 1.6(b). TE mode profile for (a). fiber and for waveguides (b). w = 4μm, (c). w=4.5μm (d). w=5μm (e). w=5.5μm (f). w= 6 μm

Guided mode profiles were measured and the mode – sizes were subsequently estimated by comparison with the measured mode-profiles of standard single-mode fiber. Horizontal and vertical TE mode size have been plotted as a function of waveguide width at λ = 1550nm with a TE- polarized beam at the input. It is evident that the mode size is almost constant for all waveguides along the vertical direction. This is because all waveguides have same proton exchange and anneal parameters, so they have almost similar depth. However, mode size in the horizontal direction increases with the increase in waveguide width. TE mode profiles of waveguides at λ = 1550nm is shown in fig. 1.6(b). The waveguides up to width of 6 μm have been observed to support single mode as per the design.

4.2. Wavelength dependency :

The waveguides were tested for wavelength ranging from 1510 to 1590 nm. Mode profiles at λ = 1510 nm and 1590 nm are shown in fig.1.7(b). It is observed that the waveguides behave as single mode for wavelength up to λ =1590 nm and its wavelength cut off is beyond λ = 1590 nm. Variation of TE mode size as a function of wavelength is shown in fig. 1.7(a). Horizontal and vertical mode size increases with increase in wavelength.



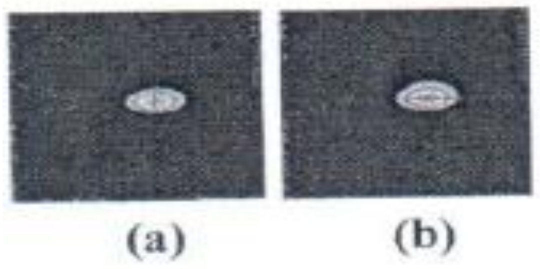


Fig. 1.7(a). wavelength vs TE mode size for Fig. 1.7(b). TE mode profile at (a). λ = 1510 nm Waveguide width w = 6 μm(b). λ = 1590

4.3. Propagation Loss :

The main cause for propagation losses in any straight waveguides are due to absorption and scattering from material in homogeneities and boundary imperfections. This 'smoothing' does not occur in the fabrication of an integrated device, which is produced as a 1:1 copy of a master mask set. Consequently, scattering losses are much higher in integrated optics. However, all forms of loss vary considerably, depending on the precise nature of the waveguide. Propagation loss was measured using Fabry-Perot resonance method. The measured losses are plotted in fig 1.6. The minimum waveguide loss ~ 2.2 dB/cm, has been obtained for the channel widths of 5.5 µm and 6 µm. This large waveguide loss can be attributed to surface roughness,. Propagation loss was also measured for waveguide width w = 6µm for various wavelength from λ = 1520 nm to λ = 1590 nm.

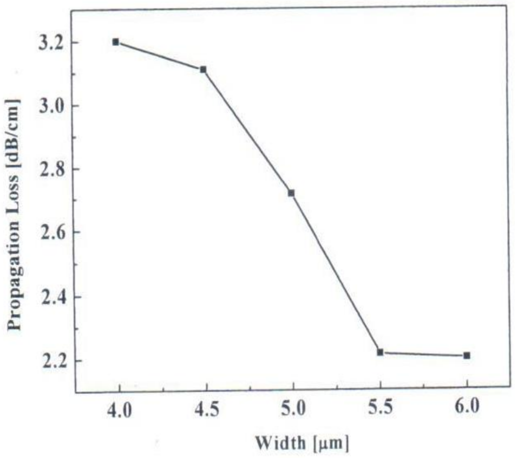


Fig. 1.8 Waveguide width vs. propagation loss for TE mode at λ = 1550 nm

4.4. Polarization Dependency :

Fabricated X-cut APE:$LiNbO_3$ IO polarizer supports only TE mode polarization. The light was coupled through the waveguides, once by maximizing input power for TE mode and then for TM mode. The transmitted output power was measured for TE and TM mode respectively, and compared subsequently. Polarization dependent loss has been calculated for waveguides with different widths and these have been shown in the table 1.2. The observed values for various width of waveguides λ = 1550 nm are given in Table 1.2.

Input power = 5.2 mW		
Waveguide Width(µm)	Input Mode– TE mode	Input Mode– TM mode
	Waveguide loss (dB)	Waveguide loss (dB)
4.0	12.29	47.35
4.5	10.88	47.16
5.0	10.53	47.62
5.5	10.00	46.75

6.0	9.31	46.55

Table 1.2. polarization dependency for waveguide at λ = 1550 nm

The losses are inclusive of coupling loss, propagation loss, Fresnel reflection loss and any other losses. To avoid any variation in above mentioned losses, measurements for TE as well as TM mode were taken without disturbing the alignment. However, input power was tuned to the maximum using polarization controller for both modes to ensure that only one mode is available at input.

Insertion loss was measured by the formula **$I_L = 10 \text{ Log}_{10}(P_2 / P_1)$ dB.**

Insertion loss was almost constant from 1500 to 1600 nm, it was noted to be 0.1 dB by simulation at 1550nm. The extinction ratio between TM and TE was found from the losses calculated above and is better (>35dB) than the ITU-T standard (>30 dB). It has been observed that all the waveguides support single mode and guide only the TE-polarized light (> 35dB extinction ratio) over the wavelength range 1510 nm to 1590 nm. A typical mode size of 4.6 µm x 6.5 µm has been measured for a 6-µm waveguide at λ = 1550 nm and the total insertion loss has been estimated to be ~ 9 dB.

5. Conclusions :

Integrated optical polarizer has been successfully fabricated with an extinction ratio >35 dB operating in the wavelength range of 1510 nm to 1590 nm. The insertion loss of the polarizer is estimated to be ~ 9 dB, which needs to be improved by further optimization of the waveguide / process parameters.

6. *References:*

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7. *Figures and Tables:*

Tables :