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### ABSTRACT

We report the first electrooptic depolarization (TE guided wave to TM substrate modes) modulator on Y-cut LiNbO<sub>3</sub> proton-exchanged channel waveguides operating at 632.8 nm. The depolarization scattering associated with PE planar waveguides has also been consistently observed in PE channel waveguides. The phase matching condition of this scattering is  $N_{\text{eff}} \cdot \cos(\theta) = N_o$ , where  $N_{\text{eff}}$  is the effective index of the guided mode,  $\theta$  the coherent depolarization scattering angle, and  $N_o$  the ordinary index of the guiding layer. All the mode indices small than  $N_o$  can satisfy this equation. Since the proton exchange process only increases the extraordinary index of the guiding layer the TM scattered wave will automatically goes to the substrate. In this paper we use the combination of thermal annealing and external electric field to induce the coherent depolarization scattering. Tunability of the waveguide ordinary and extraordinary indices through thermal annealing provides an alternative way to reduce the drive voltage. 13.5 dB extinction ratio is achieved with 10 volt applied voltage on a modulator with 4  $\mu\text{m}$  channel width and 3 mm electrode length. The measured capacitance is 4.2 pF which gives a theoretical modulation bandwidth of 1.5 GHz.

### 2. INTRODUCTION

Lithium Niobate crystal (LiNbO<sub>3</sub>) is widely used for integrated optic devices because of its large electro-optic effect and the relative ease with which large, high quality crystals can be grown. The waveguide formation by titanium indiffusion (TI) on LiNbO<sub>3</sub> substrate had been identified to be a preferred fabrication method for many applications such as electrooptic waveguide directional coupler switch and modulator, Mach-Zehnder interferometer, acoustooptic Bragg modulator, optical computing devices, etc. The recent advance of proton exchange (PE) waveguide fabrication technique and titanium indiffusion proton exchange (TIPE) technique have increased the potential of using LiNbO<sub>3</sub> for integrated optics.

The proton-exchange process<sup>1,2</sup>, for the fabrication of optical waveguides has obvious advantages over TI process, such as simplicity, large index change, high resistance to optical damage, and the relatively low temperature at which it can be fabricated. The use of this technique on X-cut and Z-cut LiNbO<sub>3</sub> substrates has created high quality optical waveguides<sup>3</sup> and many useful devices, such as channel waveguide cut-off modulator<sup>4</sup> and second harmonic generator<sup>5</sup>, etc., have been demonstrated. However, when this technique is used on Y-cut LiNbO<sub>3</sub> with diluted benzoic acid as exchange melt, the waveguide demonstrates an interesting phenomenon<sup>6</sup>. The X-propagating guided TE wave with  $N_{\text{eff}} < N_o$  encounters very large depolarization scattering so that it is coupled to the substrate as TM radiation

modes. A good optical waveguide only occurs when  $N_{\text{eff}} > N_o$ . However, no useful application of this depolarization scattering has ever been pointed out.

We further examine this the plausible applications of PE channel waveguide on Y-cut  $\text{LiNbO}_3$ . By using thermal annealing technique, the first electrooptic depolarization (TE guided wave to TM substrate modes) modulator on Y-cut  $\text{LiNbO}_3$  proton-exchanged channel waveguide at 632.8 nm wavelength has been successfully demonstrated. The thermal annealing process greatly reduces the drive voltage. 13.5 dB extinction ratio on a modulator with 4  $\mu\text{m}$  channel width and 3 mm electrode length is presented in this paper.

### 3. THEORY

As reported<sup>6</sup> that proton exchanged Y-cut, X-propagating  $\text{LiNbO}_3$  planar waveguide underwent an interesting phenomenon which concludes that all TE guided modes with  $N_{\text{eff}}$  smaller than or equal to  $N_o$ , ordinary index of the guiding layer, most of the guided energy, typically from 10 to 25 dB/cm, walks off into substrate modes. The "walk off" phenomenon has also been consistently observed in case of proton exchanged Y-cut  $\text{LiNbO}_3$  channel waveguides. The theoretical basis of the phenomenon is the phase matching condition of the depolarization scattering,

$$N_{\text{eff}} \leq N_o \quad (1)$$

which has been confirmed by our experiment on channel waveguides.  $N_{\text{eff}}$  and  $N_o$  designate, respectively, the effective index and the ordinary index after proton exchange. This implies that whenever this condition is satisfied, the TE guided modes will walk off to the substrate as TM radiation modes.

The working principle of the device is to employ annealing<sup>7</sup> to shift the guided mode index of PE channel waveguide from well above ordinary index of the guiding layer, to the ordinary index as close as possible. Then, we can use external voltage to change the guiding layer index such that the phase matching condition for depolarization scattering can be achieved. In order to have  $N_{\text{eff}} > N_o$ , the channel waveguide has to be multimode and operating at fundamental mode  $\text{TE}_{11}$ . For proton exchanged Y-cut, X-propagating  $\text{LiNbO}_3$  crystal plate with external applied field  $F_z$ , we have<sup>8</sup>

$$N_z(E_z, T, t) = N_e - N_e^3 \cdot r_{33} \cdot E_z / 2 - NT_e \quad (2)$$

$$N_x(E_z, T, t) = N_o - N_o^3 \cdot r_{13} \cdot E_z / 2 - NT_o \quad (3)$$

where  $N_z$  and  $N_x$  are the extraordinary and ordinary indices of the guiding layer which are function of external voltage, annealing temperature and annealing time,  $N_e$  and  $N_o$  are the extraordinary and ordinary indices of the guiding layer without influence of external perturbation,  $r_{33}$  and  $r_{13}$  the related electrooptic coefficients, and  $NT_e$  and  $NT_o$  the change of extraordinary and ordinary indices due to the influence of thermal treatment. Since the  $\text{TE}_{11}$  mode is well above cutoff, we assume that effective index of  $\text{TE}_{11}$  in this condition is equal to surface extraordinary index of the guiding layer, which is represented as

$$N_{\text{eff}11} \approx N_z \quad (4)$$

$$\begin{aligned} \Delta &= N_{\text{eff}11} - N_x \\ &\approx N_z - N_x \\ &= (N_e - N_o)^3 \cdot r_{33} \cdot E_z / 2 - (NT_e - NT_o) - \\ &= (N_e - N_o)^3 \cdot r_{33} \cdot E_z / 2 - (NT_e - NT_o) \\ &= (N_e - N_o) - 1/2(N_e^3 \cdot r_{33} - N_o^3 \cdot r_{13}) E_z - (NT_e - NT_o) \end{aligned} \quad (5)$$

The first term is due to intrinsic birefringence (after PE), second term the external bias, and the third term the thermal annealing. In case of  $E_z = 0$ , we have

$$\Delta \approx (N_e - N_o) - (NT_e - NT_o) \quad (6)$$

The proper annealing condition is that  $\Delta$  approaches but is not less than zero. In this condition, a small external voltage can be added to convert a TE well guided mode into "walk-off" substrate modes. Assuming above annealing condition has been achieved, i.e.,  $\Delta \rightarrow 0^+$ , the optimal electric field to induce depolarization scattering is

$$\frac{1}{2} \cdot (N_e^3 \cdot r_{33} - N_o^3 \cdot r_{13}) \cdot E_z = \Delta \quad (7)$$

where  $N_e$  and  $N_o$  are the extraordinary and ordinary indices after proton exchange and heat treatment, respectively. For the electrode structure shown in Fig.1,

$$V = E_z \cdot d \quad (8)$$

where  $d$  is the separation of two electrode pads. Therefore, we have

$$V = \frac{2 \cdot d \cdot \Delta}{(N_e^3 \cdot r_{33} - N_o^3 \cdot r_{13})} \quad (9)$$

The theoretical results of this calculation is shown in Fig.2. As we mentioned, both  $N_e$  and  $N_o$  migrate with the heat treatment. As a consequence,  $N_e$  and  $N_o$  are two variables that need to be considered. To simplify the situation, we assumed  $N_o = 2.270$  in our theoretical calculation. The assumption is acceptable by realizing the fact that the drive voltage  $V$  is mainly changed due to the numerical value of  $\Delta$ , not the numerical value of  $N_o$ . The smaller  $\Delta$  we have, the lower drive voltage we need to switch the well guided modes into "walk-off" substrate modes. This condition, namely, smallness of  $\Delta$  value, is controlled through optimal combination of proton exchange time, temperature, and the heat treatment.

#### 4. DEVICE FABRICATION

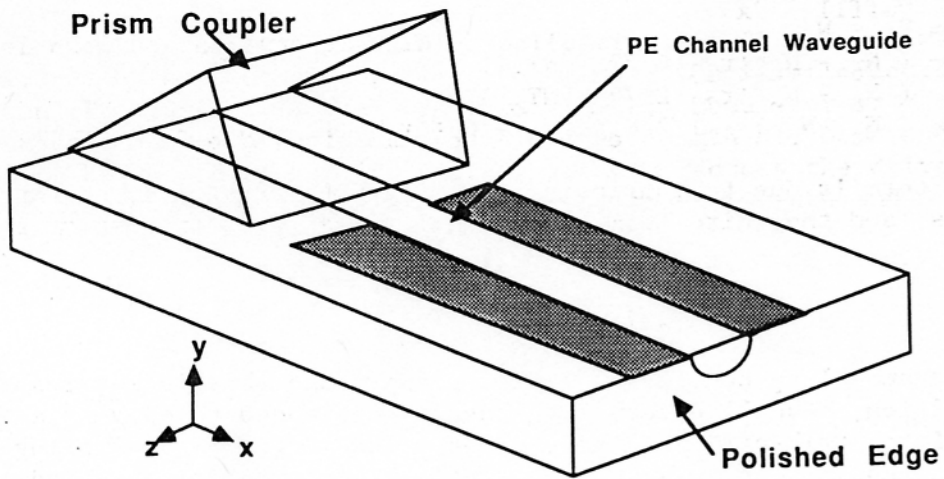


Fig.1 Device Structure of Proton Exchanged Channel Waveguide Depolarization Modulator on Y-cut, X-propagating  $\text{LiNbO}_3$

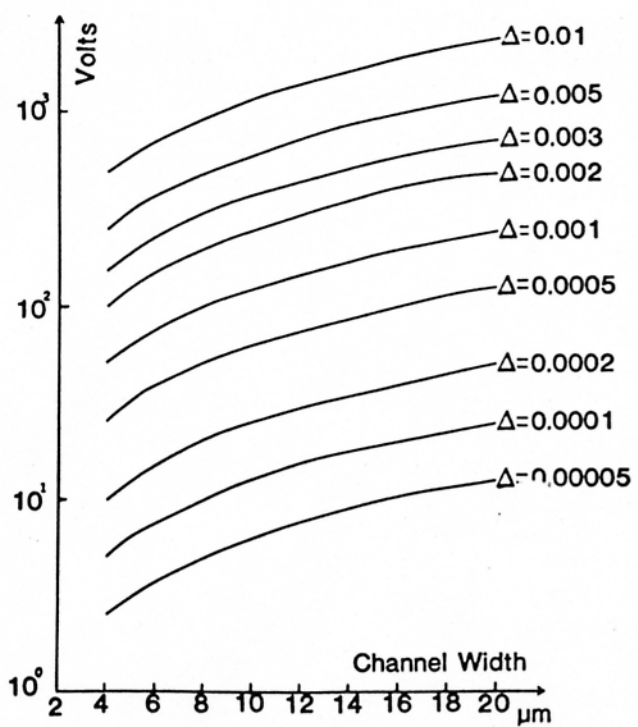


Fig.2 Drive Voltage as Function of Channel Width with  $\Delta$  as a Parameter

Channel waveguide mask with 4  $\mu\text{m}$  and 20  $\mu\text{m}$  channel widths were made through standard lithographic process. The benzoic acid ( $\text{C}_6\text{H}_5\text{COOH}$ ) with 0.5 Mol% of lithium benzoate ( $\text{C}_6\text{H}_5\text{COOLi}$ ) was used for our exchange melt to eliminate the surface damage<sup>9</sup> on Y-cut  $\text{LiNbO}_3$  substrate during the exchange. The prepared substrates were pre-heated up to the exchange temperature to prevent thermal shock. The samples were then slowly immersed in the molten exchange melt. After the exchange for a period of time determined by the guiding film thickness requirement, the samples were removed from the melt and cooled down at the room temperature. The crystal end faces were cut and polished to optical quality afterwards to expedite end fire coupling and near field imaging<sup>10</sup>. The fabricated samples were kept for more than 10 days to reach its stability<sup>10</sup> before further experiments.

We used the prism coupling method to determine the channel waveguide effective index and to control the thermal annealing time. The thermal annealing is carried out in a furnace with temperature of 400  $^\circ\text{C}$  and 1500 cc/min dry oxygen flow. The mode index decreases monotonically as the annealing time increases. After the proper heat treatment, the device was mounted and bounded on a specially designed IC chip carrier to facilitate performance measurement via edge coupling.

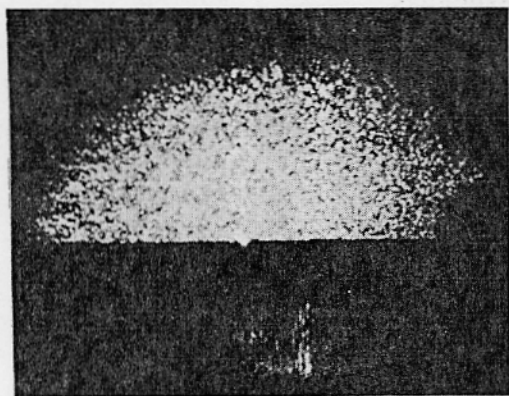
## 5. EXPERIMENTS

As reported previously, planar PE waveguides made with diluted Benzoic Acid show a vast amount of depolarization scattering which shifts the transverse electric (TE) guided modes with index smaller than  $N_o$ , i.e., ordinary index of proton exchanged  $\text{LiNbO}_3$  guides, to transverse magnetic (TM) substrate modes. The same phenomenon has been consistently observed on Y-cut  $\text{LiNbO}_3$  channel waveguides. Fig.1 shows the device structure of our proton exchanged channel waveguide depolarization modulator. The near field image of channel waveguide mode, air modes and TM substrate radiation modes are given in Fig.3. The effective indices and the walk-off angles have been measured which confirm the phase matching condition

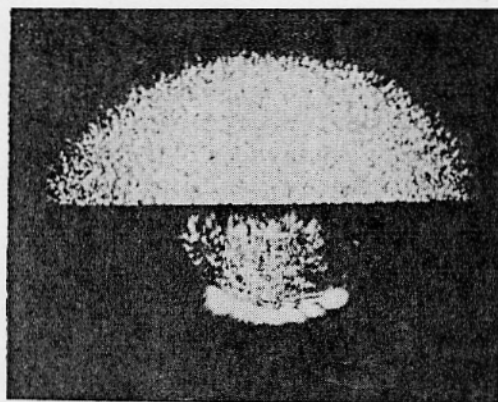
$$N_o = N_{\text{eff}} \cdot \text{Cos}(\theta)$$

is the same as that of planar PE waveguide on Y-cut  $\text{LiNbO}_3$ .

The parameters of two working prototypes are given in Table 1. Their fundamental mode effective indices are higher than but close to the substrate ordinary index. The applied voltage is used to lower the waveguide effective indices through electrooptic effect so that depolarization scattering can occur and therefore intensity modulation is thus achieved. Fig.4 and Fig.5 give the throughput intensities versus different bias voltages. The extinction ratios, namely,  $(I_{\text{max}} - I_{\text{min}})/I_{\text{max}}$ , are 86% within 350 volts for device B-2 and 95.5% within 10 volts for device F-6. Fig.6 shows the throughput intensity profile of sample F-6 under different switching voltages through CCPD (Charge Coupled Photo Detector) array. The measured capacitance of device F-6 is 4.2 pF. A modulation bandwidth of 1.5 GHz is theoretical feasible with a 50 Ohm lumped electrode structure.



(a)



(b)

Fig.3 Near Field Profiles; (a) Before Annealing,  $N_{eff}=2.284$ ,  
(b) After Annealing,  $N_{eff}=2.260$

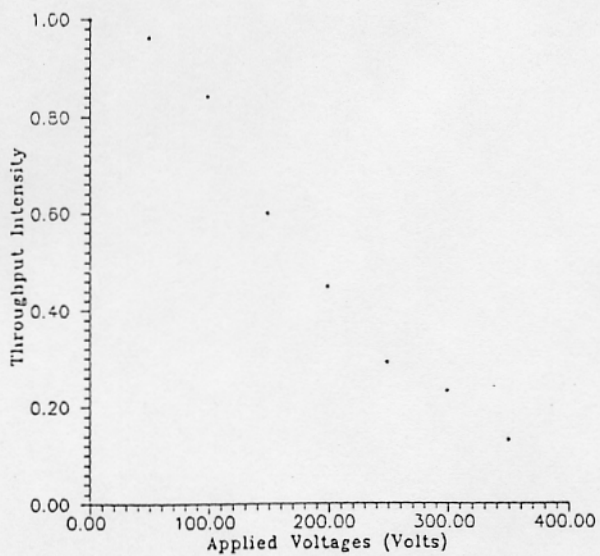


Fig.4 Transfer Curve of Device #B-2

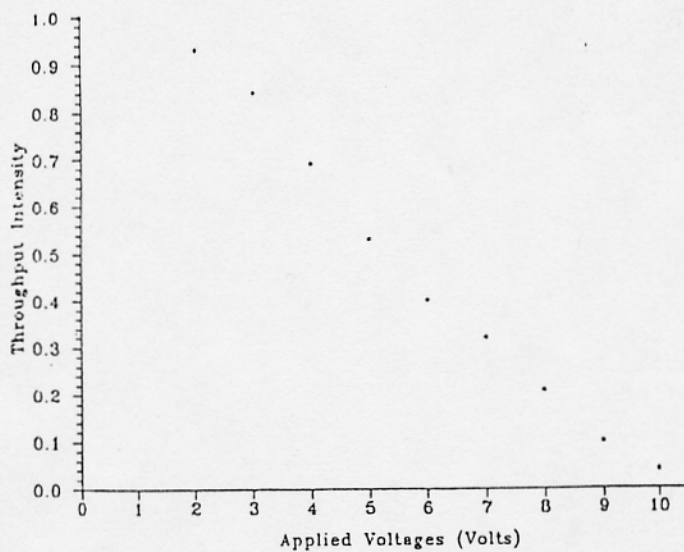


Fig.5 Transfer Curve of Device #F-6

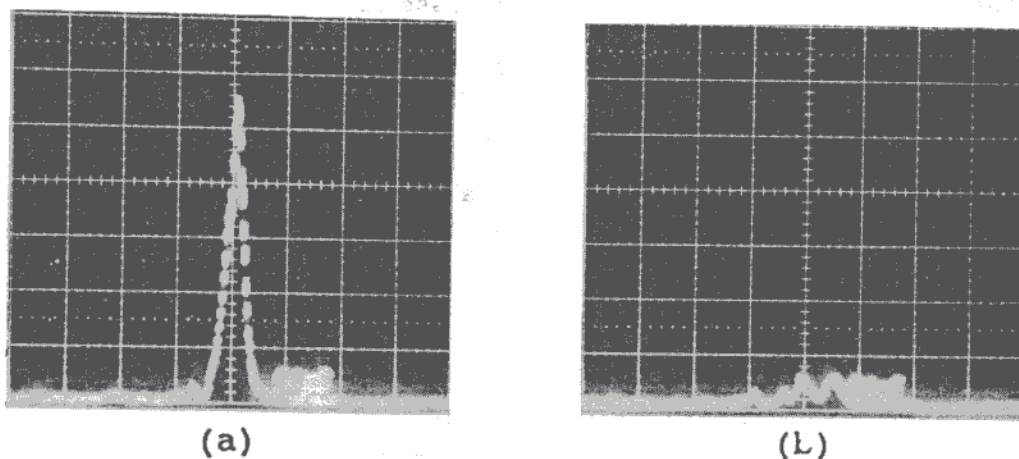


Fig.6 Near Field Profile of Device F-6; (a) V=0 volt, (b) V=10 volts

Table 1

Device Parameters of Depolarization Modulators  
on Y-Cut, X-Propagating,  $\text{LiNbO}_3$  Channel Waveguide

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20  $\mu\text{m}$  Channel Width (Sample B-2)

Electrode Length	3.0 mm
Exchange Time	30 Hours
Exchange Temperature	235°C
Annealing Temperature	400°C
Dry Oxygen Flow	1500cc/min
Annealing Time	1 Hour
Electrode Materials	Cr/Al

4  $\mu\text{m}$  Channel Width (Sample F-6)

Electrode Length	3.0 mm
Exchange Time	30 Hours
Exchange Temperature	235°C
Annealing Temperature	400°C
Dry Oxygen Flow	1500cc/min
Annealing Time	1 Hour and 19 Mins.
Electrode Materials	Cr/Al

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In the two transfer curves shown (Fig.5 & 6) most of the guided energy is scattered into TM substrate modes which are phase-matched to the TE<sub>11</sub> guided mode. Both N<sub>e</sub> and N<sub>o</sub> of the guiding layer are changed during the heat treatment. Consequently, optimal annealing condition to induce small Δ value and thus low drive voltage is not easy to obtain. Measured drive voltages for ~10 dB extinction ratio of different devices vary from three hundred volts to ten volts with only a very small variation of annealing time (+5 minutes). As far as the control of the drive voltage is concerned, a thermally annealed cutoff modulator<sup>4</sup> more easily achieves low voltage due to the fact that only the extraordinary index change is involved in the drive voltage formula.

## 6. DISCUSSION

In this experiment, the electrode separation was set equal to the channel width in all the devices and there was no buffer layer such as SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> between waveguide and electrode. PE Y-cut, X-propagating waveguides only provide TE guided modes due to the increase of N<sub>e</sub> and decrease of N<sub>o</sub> during PE. As we know, for TE guided mode, the electric field is parallel to the waveguide surface. The guided wave energy penetrating into the electrode is negligible. Therefore, the closeness of the waveguide edge to the electrode and the ignoring of the buffer layer will not increase the propagation loss significantly.

Before we did the thermal annealing, the walk off modes were well confined. We observed a bright streak came out of the substrate. However, after annealing process, the walk-off modes were not as sharp as before. The coherent scattering angle spreaded out. This result implies that ordinary index is also not a sharp step index. The phase matching angle under this condition became wide as we observed. This phenomenon has been consistently observed in all the thermally annealed depolarization modulators built on Y-cut, X-propagating, proton-exchanged LiNbO<sub>3</sub> channel waveguides. The mode instability of the proton exchanged devices can be eliminated through the utilization of heat treatment. This is a beneficial side effect of thermal annealing which is a fine tuning tool to optimize the device performance.

As we have mentioned previously, due to the physical origin causing the phase-matched depolarization scattering, the depolarization modulator must be a multi-mode waveguide with fundamental mode operation. In the case of edge coupling with laser light operating at TE<sub>00</sub> mode, it is important to match the phase and amplitude profile of the input light source with that of the guided mode. With anti-reflection coating on the coupling edge, the coupling efficiency Q<sub>mn</sub> of TE<sub>mn</sub> mode is equal to<sup>11</sup>

$$Q_{mn} = \frac{|\langle \psi_{mn} | \psi_1 \rangle|^2}{\langle \psi_{mn} | \psi_{mn} \rangle \cdot \langle \psi_1 | \psi_1 \rangle} \quad (10)$$

where  $\psi_{mn}$  represents the mode profile of TE<sub>mn</sub> guided mode and  $\psi_1$  the input laser mode profile at the coupling interface<sup>12</sup>. Usually,  $\psi_1$  is an even function for well collimated TE<sub>00</sub> laser light source. The guided mode  $\psi_{mn}$  can be approximately written as<sup>13</sup>



$$\psi_{mn} = \exp^{-i(kx-\omega t)} \begin{cases} \text{COS}(m \cdot k_y \cdot Y) \cdot \text{COS}(n \cdot k_z \cdot Z) & m, n \text{ even} \\ \text{COS}(m \cdot k_y \cdot Y) \cdot \text{SIN}(n \cdot k_z \cdot Z) & m \text{ even, } n \text{ odd} \\ \text{SIN}(m \cdot k_y \cdot Y) \cdot \text{COS}(n \cdot k_z \cdot Z) & m \text{ odd, } n \text{ even} \\ \text{SIN}(m \cdot k_y \cdot Y) \cdot \text{SIN}(n \cdot k_z \cdot Z) & m, n \text{ odd} \end{cases} \quad (11)$$

where  $k_z = \pi/a$  and  $k_y = \pi/b$ ;  $a$  and  $b$  are the width and the depth of the waveguide respectively. In this representation, we put the origin at the center of the waveguide. It is clear from Eq.(10) and (11) that only the fundamental mode,  $TE_{11}$ , will be excited dominantly. The coupling efficiency of higher order mode with odd function mode profile will be negligible. The higher order mode with even function mode profile can only be coupled with very small portion of the energy due to the cancellation of the overlap integral<sup>14</sup>. Therefore, even though this is a multi-mode device with fundamental mode operation, we can still achieve high coupling efficiency to the fundamental mode. In addition, multi-mode implies that the cross section of fundamental mode is bigger than that of single mode device. This also facilitates our coupling and thus increases the coupling efficiency.

## 7. CONCLUSION

We report here the first electrooptic depolarization modulator on Y-cut, X-propagating PE  $\text{LiNbO}_3$  channel waveguide. The phase matching condition is caused by the proper combination of external drive voltage and annealing condition. Drive voltage as low as 10 volts is achieved for 13.5 dB extinction ratio on a  $4 \mu\text{m}$  channel waveguide device with 3 mm interaction length. The theoretical result shows that the drive voltage is linearly dependent on  $\Delta$ , i.e.,  $(N_e - N_o) - (NT_e - NT_o)$ . Since both ordinary and extraordinary indices change during the heat treatment process, the control of the drive voltage in this depolarization modulator is harder than that can be achieved by using a thermally annealed cutoff modulator on PE  $\text{LiNbO}_3$  channel waveguide reported<sup>4</sup>. The measured capacitance is 4.2 pF, therefore, 1.5 GHz modulation bandwidth is expected in a 50 Ohm impedance-matched lumped electrode structure.

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