

Electro-optic depolarization switch on y -cut LiNbO_3 proton-exchanged channel waveguides

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We report the first electro-optic depolarization (TE guided mode to TM substrate modes) switch on y -cut LiNbO_3 proton-exchanged channel waveguides operating at 632.8 nm. Tunability of the waveguide ordinary and extraordinary indices through thermal annealing provides an alternative way to reduce the drive voltage. An extinction ratio of 13.5 dB is achieved with 10 V applied voltage on a switch with 4 μm channel width and 3 mm electrode length. The measured capacitance of the electrode is 4.2 pF, which gives a theoretical modulation bandwidth of 1.5 GHz in a 50 Ω lumped electrode structure.

We present here a novel electro-optic switch by utilizing the volume depolarization scattering centers associated with proton-exchanged (PE) y -cut LiNbO_3 plates.¹ 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 LiNbO_3 guides, to transverse magnetic (TM) substrate modes. The same phenomenon has been consistently observed on y -cut LiNbO_3 channel waveguides. The phase-matching condition for this scattering is²

$$N_o = N_{\text{eff}} \cos(\Upsilon), \quad (1)$$

where N_{eff} is the effective index of guided mode, N_o is the ordinary index of the LiNbO_3 plate, and Υ is the walk-off angle of the TM substrate mode. All the guided modes with $N_{\text{eff}} < N_o$ can satisfy this equation. Since the guided index can be perturbed by the thermal annealing process,³ the phase-matched depolarization scattering can be induced by proper heat treatment. Figure 1(a) shows the near field of a guided mode with $N_{\text{eff}} = 2.284$ after proton exchange (0.5 mol % lithium benzoate, 240 $^\circ\text{C}$ for 30 h). The mode index is larger than N_o . Therefore, no depolarization scattering is observed. After 210 min of thermal annealing at 400 $^\circ\text{C}$ and 1500 cc/min dry oxygen flow, the guided-mode index changed from 2.284 to 2.260 which is smaller than N_o . The original well guided TE light [Fig. 1(a)] in this condition is coherently scattered to the TM substrate modes as shown in Fig. 1(b). The measured throughput intensity is at least 20 dB less than the original.

The working principle of this electro-optic switch is to employ thermal annealing as a perturbation tool to shift the mode index of well guided mode to a value very close to the ordinary index of the guiding layer, i.e., very close to the phase-matching condition. Once this condition is achieved, external voltage is applied to change the guiding layer index such that the coherent depolarization scattering caused by the phase-matching condition [Eq. (1)] can be achieved. To form a PE waveguide with $N_{\text{eff}} > N_o$ it has to be a multimode guide. Accordingly, the switch we present here is a multimode device operating in the TE_{11} mode. The device structure is shown in Fig. 2. The purpose of doing prism coupling is to measure the optimal N_{eff} value so that the proper heat treatment process is correctly determined. Thermal anneal-

ing changes both the ordinary and extraordinary indices of the guiding layer. Experimentally, optimal heat treatment is needed to shift the effective index of TE_{11} to the boundary of N_o . The extraordinary and ordinary indices of a y -cut, x -propagating PE LiNbO_3 crystal plate with external E field along the z direction are

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

and

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

respectively; where N_z and N_x are the extraordinary and ordinary indices of the guiding layer which are functions of the external E field, annealing time, and temperature; N_e and N_o are the intrinsic extraordinary and ordinary indices of the guiding layer without the influence of external perturbation; r_{33} and r_{13} are the related electro-optic coefficients; and $N T_e$ and $N T_o$ are the extraordinary and ordinary index changes due to the influence of thermal treatment. The optimal annealing condition is employed so that only the effective index of the lowest order mode, TE_{11} , is just above N_o . Since the TE_{11} mode index is well above the cutoff condition, we assume that the effective index of TE_{11} , i.e., $N_{\text{eff}11}$ in this condition, is equal to the surface index of the extraordinary index of the guiding layer, which is represented as

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

After some theoretical calculations, it is easy to show that the drive voltage needed to bring the TE_{11} well guided mode to the TM coherently scattered substrate mode is

$$V = \frac{2d\Delta}{(N_z^3 r_{33} - N_x^3 r_{13})}, \quad (5)$$

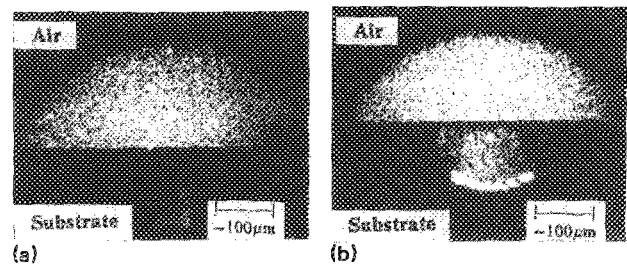


FIG. 1. Near-field profiles of the TE_{11} guided mode: (a) before annealing, $N_{\text{eff}} = 2.284$; (b) after annealing, $N_{\text{eff}} = 2.260$.

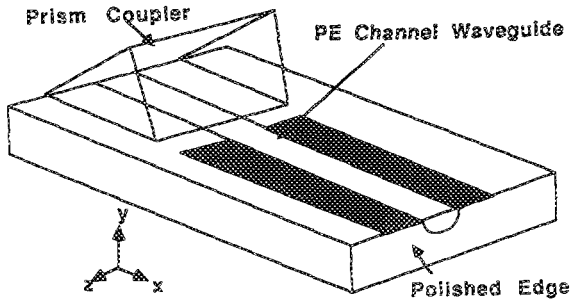


FIG. 2. Device structure of proton-exchanged channel waveguide depolarization switch on y -cut, x -propagating LiNbO_3 .

where d is the separation of two electrode pads and

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

The theoretical results of the drive voltage as a function of channel width is shown in Fig. 3 with Δ as a parameter. The channel width is equal to the electrode gap for all the devices fabricated. The ordinary index of the guiding layer is also a function of annealing process; therefore, both N_e and N_x migrate with the heat treatment. As a consequence, N_e and N_o are two variables that need to be considered. The measured effective indices of the TE_{11} mode of various samples are around 2.270 when the depolarization scattering is first observed. This result implies that $N_x \sim 2.270$, which is the value we used to plot Fig. 3. It is clear, based on Eq. (5), that the smaller Δ we have, the lower drive voltage we need to switch the well guided mode into "walk-off" TM substrate modes. This condition, namely, smallness of Δ value, is carefully controlled through the optimal combination of proton-exchange time, temperature, and heat treatment condition.

Channel waveguides with various widths from 4 to 20 μm were made. The exchange time needed to generate the same TE_{11} mode index in different samples is a function of channel width.⁴ The annealing furnace is kept at 400 °C and 1500 cc/min dry oxygen flow. The effective index of the TE_{11} mode and the drive voltage versus throughput intensi-

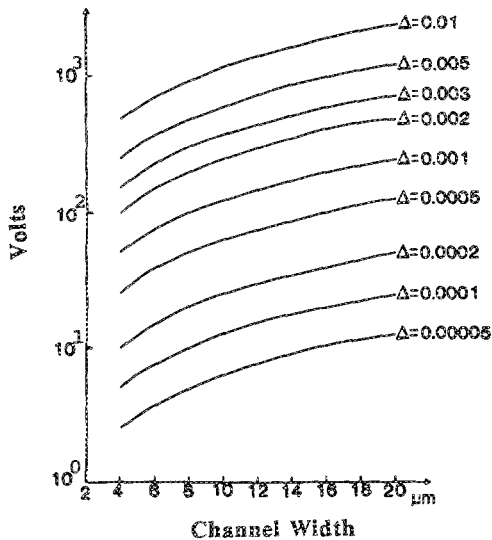


FIG. 3. Drive voltage as function of channel width with d as a parameter.

TABLE I. Device parameters of depolarization switch F-6.

Electrode length	3.0 mm
Exchange solution	0.5% lithium benzoate
Exchange time	30 h
Exchange temperature	235 °C
Annealing temperature	400 °C
Dry oxygen flow	1500 cc/min
Annealing time	1 h and 19 min
Electrode materials	Cr/Al

ty were measured after every 5–20 min of heat treatment. The mode index decreases monotonically as the annealing time increases. When the TE_{11} mode index is far from the phase-matching value, the throughput intensity does not change even with a few hundred volts applying across the electrode pair. The change of the effective index provided by external E field is much smaller than that provided by annealing. Therefore, accurate control of the Δ value has to be achieved first through proper proton exchange and annealing process. Measurement of the effective indices and the throughput intensity versus applied voltage gives a standard criterion to determine whether the optimal annealing condition has been achieved. Among all the samples we made, the best result we achieved is sample F-6. The device parameter of this depolarization switch is shown in Table I. The drive voltage needed for this device is 10 V and the measured extinction ratio is 13.2 dB. The near-field profiles of this device with and without the external voltage are shown in Figs. 4(a) and 4(b), which correspond to the profiles at $V = 0$ and $V = 10$ V, respectively. In Fig. 4(b) most of the guided energy is scattered into TM substrate modes which are phase matched to the TE_{11} guided mode. Both N_e and N_o 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 200 to 10 V with only a very small variation of annealing time (± 5 min). As far as the control of the drive voltage is concerned, a thermally annealed cutoff modulator⁵ more easily achieves low drive voltage due to the fact that only the extraordinary index change is involved in the drive voltage formula. The measured capacitance of device F-6 is 4.2 pF. A modulation bandwidth of 1.5 GHz is theoretically feasible with a 50 Ω lumped electrode structure. As mentioned previously in this letter, the device we are presenting here is a multimode waveguide operating in the TE_{11}

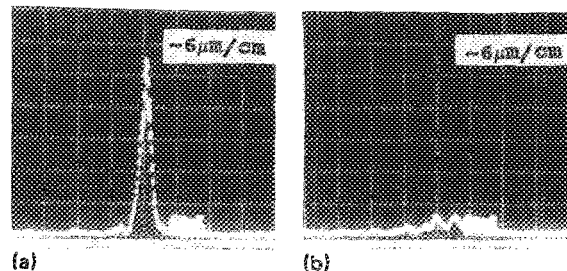


FIG. 4. Near-field profile of device F-6: (a) $V = 0$ V; (b) $V = 10$ V.

mode. The selective mode coupling from laser light to TE_{11} guided mode is achieved by choosing the proper prism coupling angle. End-fire coupling can also be used to input the laser light into the TE_{11} guided mode. The laser light TEM_{00} is an even function which can be strongly coupled only into the TE_{11} mode when the profiles and the center maximum of these two modes are well overlapped.^{6,7}

In summary, we report here the first electro-optic depolarization switch on y -cut, x -propagating PE $LiNbO_3$ channel waveguide. The phase-matching condition is caused by the proper combination of external drive voltage and annealing condition. A drive voltage as low as 10 V is achieved for 13.2 dB extinction ratio on a 4 μm channel waveguide device with 3 mm interaction length. The theoretical result shows that the drive voltage is linearly dependent on Δ , i.e., $(N_e - N_o) - (NT_e - NT_o)$. Since both ordinary and extraordinary indices change during the heat treatment pro-

cess, the control of the drive voltage in this depolarization switch is harder than can be achieved by using a thermally annealed cutoff modulator on PE $LiNbO_3$ channel waveguide reported.⁵ The measured capacitance is 4.2 pF; therefore, 1.5 GHz modulation bandwidth is expected in a 50 Ω impedance-matched lumped electrode structure.

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¹R. T. Chen and W. S. C. Chang, *IEEE J. Quantum Electron.* **QE-22**, 880 (1986).

²R. T. Chen, Ph.D. dissertation, Department of Electrical Engineering, University of California, 1988.

³J. L. Jackel and C. E. Rice, *Proc. Soc. Photo-Opt. Instrum. Eng.* **460**, 43 (1984)

⁴N. A. Sanford and W. C. Robinson, *Opt. Lett.* **10**, 1990 (1985).

⁵R. T. Chen and C. S. Tsai, *Opt. Lett.* **11**, 546 (1985).

⁶C. Vasallo, *IEEE J. Quantum Electron.* **QE-13**, 165 (1977).

⁷W. B. Joyce and B. C. Deloach, *Appl. Opt.* **23**, 4187 (1984).