Thermally annealed single-mode proton-exchanged channel-waveguide cutoff modulator

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We describe the first reported electro-optic cutoff modulator that utilizes a thermally annealed single-mode proton-exchanged channel waveguide in a X-cut Y-propagating $LiNbO_3$ substrate. The large changes in extraordinary refractive index obtainable by the proton-exchange process enabled us readily to form single-mode waveguides with a channel width as small as 2 μm. As a result, the voltage required for electro-optically controlled propagation cutoff was significantly reduced. Thermal annealing was used to provide fine tuning on the refractive-index changes that was in turn used to bring the waveguide to the very edge of cutoff and thus permitted further reduction in the voltage requirement. Thermal annealing was also found greatly to improve the linearity of modulation. For example, we have measured a modulation depth of 97% at a total voltage swing of only 7 V and a high linearity. In addition, no optical damage has been observed after a 2-h continuous exposure of 632.8-nm He–Ne laser light at an intensity as high as 10^4 W/cm^2.

Electro-optically induced channel guiding and cutoff modulation of a light beam in GaAs,[1,2] $LiNbO_3$,[3–6] and $KNbO_3$ (Ref. 7) substrates were reported previously. The more recent of this earlier work[5,6] utilized a titanium-indiffusion (TI) process[8] for fabrication of the waveguides in the $LiNbO_3$ substrates. In the work reported in this Letter, a proton-exchange process[9] was employed to fabricate single-mode channel waveguides of various channel widths, namely, 2, 3, and 4 μm in X-cut Y-propagating $LiNbO_3$ substrates. We have designed, fabricated, and tested a number of cutoff modulators using such proton-exchanged (PE) channel waveguides and have obtained encouraging and reproducible results. We have found it possible to bring the waveguides to the very edge of cutoff by controlling both the exchange time at a fixed exchange temperature of 245°C and the time of subsequent thermal annealing. As a result, the drive voltage required between maximum light transmission and cutoff for the resulting cutoff modulators was found to be significantly reduced. Furthermore, contrary to most of the existing modulators such as the Mach–Zehnder interferometer, the directional coupler, and total-internal-reflection and *X* modulators that exhibit a sine-squared voltage dependence of the output light intensity, the thermally annealed cutoff modulators provide an output light intensity with a significantly higher linearity. Finally, in contrast to the case of previous devices fabricated by the TI process, no optical damage has been observed in such PE devices after a continuous exposure of the He–Ne laser at 632.8-nm wavelength for 2 h at a light intensity as high as 10^4 W/cm^2. In this Letter the design and fabrication of the thermally annealed single-mode PE channel-waveguide cutoff modulator and the measured results are presented.

The design parameters and fabrication conditions of the PE channel waveguides are listed in Table 1. We note that, owing to the restriction imposed by narrow metallic apertures,[10] it was necessary to increase the exchange time from 23 to 40 min as the channel width was reduced from 4 to 2 μm. Both end faces of the X-cut Y-propagating $LiNbO_3$ plates with the PE waveguides formed were subsequently polished to facilitate end-fire coupling and near-field imaging. A single TE_{00}-mode propagation was confirmed by imaging and mapping the near-field profile of the light beam at the output endface by using a charge-coupled photodetector array. For example, the measured beam profile for the 2-μm channel waveguide is shown in Fig. 1, clearly showing a 3-dB beam cross section of approximately 2.2 μm × 1.3 μm and single-mode propagation. Single TE_{00}-mode propagation was also observed in the waveguides with 3- and 4-μm channel widths. The desired pair of parallel electrodes was subsequently added by using the lift-off technique. The electrode length was set equal to the channel length and the separation of the electrode

Table 1. Design Parameter and Fabrication Conditions for PE Channel Waveguides in X-Cut Y-Propagating $LiNbO_3$ Substrate

Parameters and Conditions	Channel Widths (μm) 2	3	4
Exchange solution	Pure benzoic acid	Pure benzoic acid	Pure benzoic acid
Exchange temperature (°C)	245	245	245
Exchange time (min)	40	30	23
Number of guided modes	1	1	1

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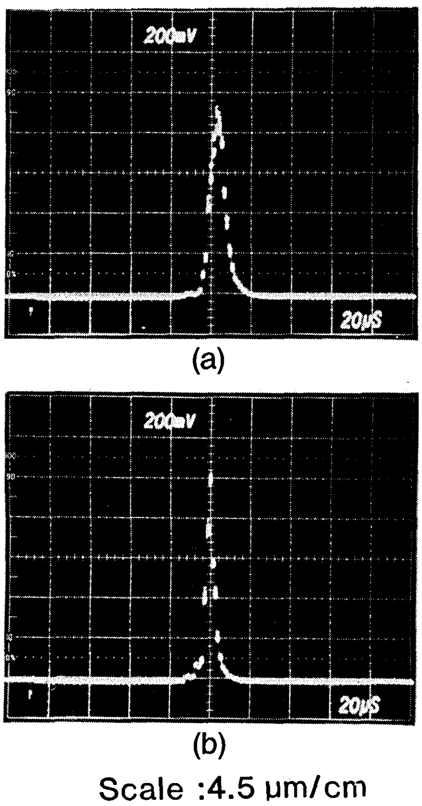

Fig. 1. Profile of a single-mode PE channel waveguide in $LiNbO_3$. (a) Horizontal, (b) vertical.

pair equal to the channel width in all devices. The configuration of the complete device is shown in Fig. 2. It is to be noted that, in contrast to the TI devices previously reported,[5,6] only a single uniform section of channel waveguide is involved in the present device. As a result, design and fabrication of the present device are considerably simpler. Propagation cutoff, and thus intensity modulation, are provided through electro-optical control of the extraordinary refractive index N_e using the coefficient r_{33}. Curve A of Fig. 3 shows the output light intensity as a function of dc drive voltage for the device with a 2-μm channel width and a 5-mm electrode length that was measured before thermal annealing. It is seen that a voltage swing from −10 to +6 V was required to switch the modulator from maximum transmission to cutoff, resulting in a modulation depth of 98%. Here the modulation depth is defined as $[1 - (I_{min}/I_{max})] \times 100\%$, where I_{max} and I_{min} designate, respectively, the maximum and the minimum output light intensities.

A further reduction in the drive voltage could be accomplished by bringing the effective refractive index of the guided mode N_{eff} to be practically identical to the substrate index. This was facilitated by thermal annealing of the devices at 300°C for 7.0 min in accordance with the fact that subsequent thermal annealing after the PE process would cause the index profile to shift from a stepped distribution to a graded distribution with a lower index on the surface.[11] Assuming that the resulting electric field E in the channel waveguide is given by $2V/\pi d$, in which V and d designate, respectively, the applied voltage and separation of the parallel electrode pair, we have derived the drive voltage that is required to bring the waveguide to the edge of cutoff:

$$V \approx \left(\frac{N_{eff}^2 \Delta N}{r_{33} N_e^4 N_s}\right)(\pi d), \tag{1}$$

where N_e has been defined previously, N_{eff} is the effective waveguide index, N_s (=2.20 at 0.632-μm wavelength) is the substrate index, and $\Delta N \equiv N_{eff} - N_s$. Note that in this calculation the highest wave number in the two transverse directions is approximately 7.3×10^8/cm and is, thus, neglected when compared with that in the propagation direction, namely, 2.2×10^9/cm. Based on expression (1), the drive voltage as a function of the electrode separation has been plotted using the logarithmic scale in Fig. 4 with N_{eff} as a parameter. It is to be noted that this set of plots was generated using the electro-optic (EO) coefficient r_{33} (=30.9×10^{-12} m/V) for bulk $LiNbO_3$. Although a reduced EO effect in PE $LiNbO_3$ was suggested previously,[12,13] this degradation is yet to be confirmed with the device reported here. At any rate, the general shape of the drive-voltage–electrode separation plot will remain the same regardless of the numerical value used for r_{33}. It is clear that the drive voltage required for cutoff can be reduced considerably by shifting the

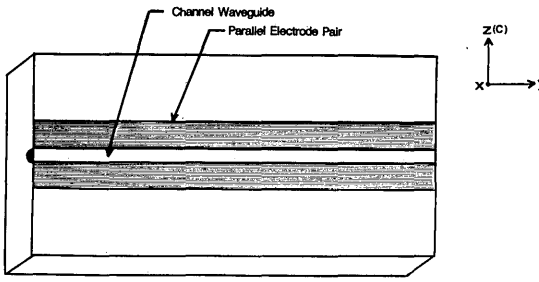

Fig. 2. Single-mode PE channel-waveguide cutoff modulator in X-cut Y-propagating $LiNbO_3$.

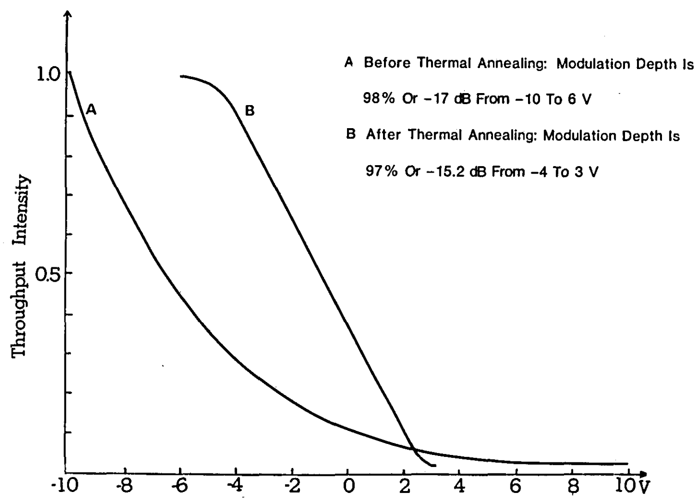

Fig. 3. Modulation curve of the device with a 2-μm channel width and a 5-mm interaction length.

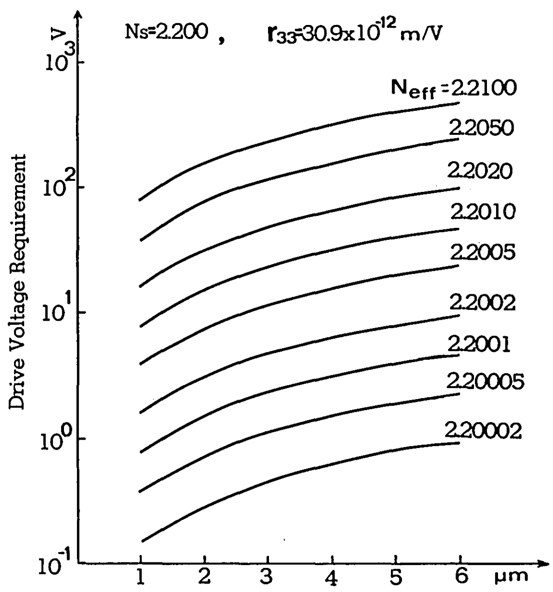

Fig. 4. Cutoff voltage versus parallel electrode separation with effective waveguide index as a parameter.

effective index of the waveguide mode to a value that is close to the substrate index. Plot B of Fig. 3 shows the experimental demonstration of this drive-voltage reduction through thermal annealing using the same cutoff modulator that was used to generate plot A. It is seen that a 97% modulation depth was obtained at a total voltage swing of only 7 V, namely, from −4 to +3 V. This plot also shows a distinct improvement in the linearity of the modulation after thermal annealing. The desirable effects of thermal annealing, namely, reduction in the drive voltage and improvement in the linearity of modulation, were consistently observed in all six devices of identical design and fabrication conditions. A complete set of measurements for each device was carried out within a few hours. This significant improvement in modulation linearity implies that, owing to redistribution of the mode profile, the linearity between the scattering loss at the guiding-layer–substrate interface and the drive voltage was greatly increased. The physical mechanism for this experimental observation is yet to be established. Another major benefit of thermal annealing is elimination of the instability in the guided mode index that was often observed in the PE waveguides.[14,15] This enhancement in waveguide stability through annealing was also confirmed in the PE cutoff modulator just described. Finally, the measured throughput of the cutoff modulator was −24 dB. This measured value is to be compared with the calculated value of −21 dB that consists of the mode-mismatch loss (−13.5 dB) based on the beam profile shown in Fig. 1, the measured propagation loss (–6 dB) in the channel waveguide, and the calculated reflection losses (–1.50 dB) at both endfaces.

In summary, single-mode EO cutoff modulators with desirable performance characteristics have been realized for the first reported time by using thermally annealed PE channel waveguides in X-cut Y-propagating $LiNbO_3$ substrates. Such PE cutoff modulators are simpler to design and fabricate than those utilizing a three-section TI channel waveguide.[5,6] The PE time required for single-mode channel-waveguide formation is about 1 order of magnitude shorter than that for the TI guides, while the induced change in extraordinary refractive index in the PE guides is 1 order of magnitude higher. Furthermore, both the drive voltage and the linearity in the modulation curve are significantly improved after thermal annealing. For example, the PE device with a 2-μm channel width and a 5-mm electrode length has demonstrated the requirement of a voltage swing of only 7 V from total transmission to cutoff and a much improved linearity after heat treatment. Finally, in contrast to the TI devices that often suffer from the photorefractive effect (under zero external electric field) and the concomitant optical damage at a relatively low light intensity, resistance to the optically induced refractive-index instability in the PE devices was found to be much greater. For example, no optical damage was observed even after a 2-h continuous exposure of the 632.8-nm-wavelength He–Ne laser at a light intensity as high as 10^4 W/cm^2. This intensity threshold is at least 1 order of magnitude higher than that for the TI devices.

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