

# Anomalous Attenuation and Depolarization Scattering in y-Cut LiNbO<sub>3</sub> Proton Exchanged Waveguides

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**Abstract**—A large anomalous attenuation and depolarization scattering have been observed in y-cut, x-direction propagating LiNbO<sub>3</sub> proton exchanged waveguides at 0.632  $\mu$ m wavelength. We observe this phenomenon only when the mode effective index is smaller than the ordinary index  $n_o$  ( $n_o = 2.286$ ). The effect is caused by phase-match scattering into the substrate. Exchange solutions with various mole percentages of lithium benzoate have been used and the same phenomenon has been consistently observed.

WE report here the observation at 0.632  $\mu$ m wavelength of an anomalous increase of attenuation of x-direction propagating TE guided wave modes that have  $n_{eff}$  less than the ordinary index  $n_o$  ( $n_o = 2.286$ ) in a y-cut LiNbO<sub>3</sub> proton exchanged waveguide. Following Jackel *et al.* [1], the waveguides have been fabricated by immersion of y-cut LiNbO<sub>3</sub> in benzoic acid with one mole percentage of lithium benzoate at 241°C. The number of propagating TE modes in such waveguides, varying from single to 25 modes, has been controlled by the exchange time, varying from 1 to 450 h. By means of the inverse WKB method in multimode waveguide [2], we have determined the extraordinary step-index of the guiding layer for TE modes propagating in the x-direction to be  $n'_e = 2.306$  with a substrate extraordinary index of  $n_s = 2.20$ . The  $n_{eff}$ 's of several samples at  $\lambda = 0.6328 \mu$ m have been measured by the prism coupling method; they are shown in Fig. 1. The attenuation rate of the samples has been measured by the two-prism method.

We have observed that all those modes that have  $n_{eff} < 2.286$  have large attenuation, typically from 10 to 25 dB/cm, while the modes with  $n_{eff} > 2.286$  have the normal attenuation rate of approximately 1 dB/cm. Fig. 2 illustrates the attenuation rates of the TE modes in waveguide number 2. The attenuation of the TE modes with  $n_{eff} < 2.286$  are so large that the laser power in the guided wave mode appears visually to have "walked off" from the waveguide into the substrate within a short distance of a few millimeters. When the "walked off" radiation hits the bottom of the substrate, which is typically 1 mm thick,

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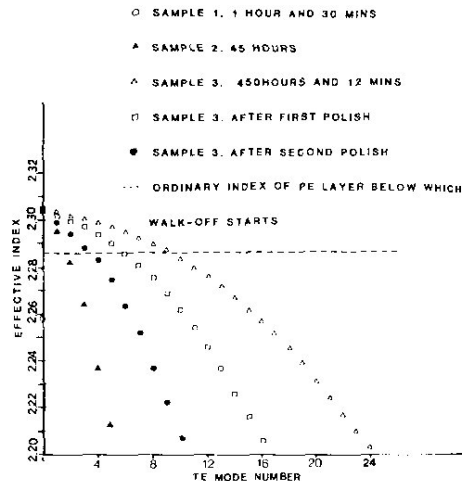


Fig. 1. Mode index of LiNbO<sub>3</sub>.

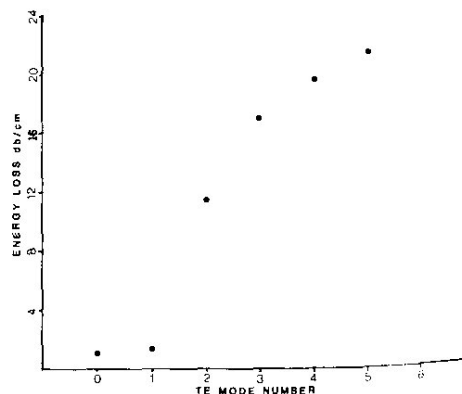
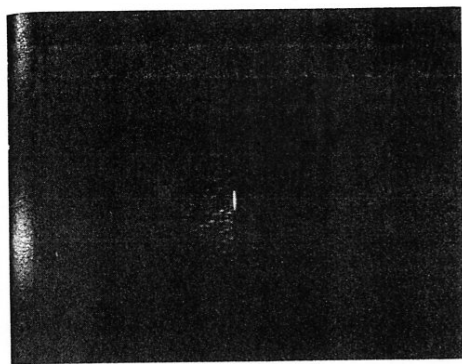


Fig. 2. Loss measurement of y-cut PE LiNbO<sub>3</sub> waveguide number 2.

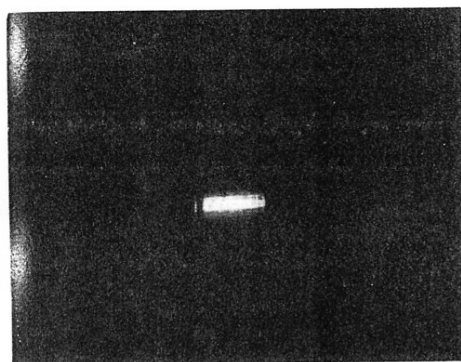
it appears as a bright streak on the bottom surface. The distance from the 90° edge of the input prism coupler to the beginning of this bright streak (i.e., the walk-off distance) depends on the  $n_{eff}$  of the mode. The walk-off angle

Fig. 3. Near fi

$\theta_i$  for a given  $n_{eff}$  of the sample is determined. This measurement is made by measuring the  $m$ -lines of the TE mode with  $n_{eff} < 2.286$  have also been observed. In the near field, concentrated walk-off radiation. When a polarization, all the TE polarization. Fig. 3 shows the TE polarization pattern observed



(a)



(b)

Fig. 3. Near field image of the polished edge. (a) With TE polarizer. (b) With TM polarizer

$\theta_s$  for a given mode (defined by the arctangent of the ratio of the sample thickness to the walk-off distance) can be determined experimentally from this walk-off distance. This measured  $\theta$  is found to be equal to  $\arcsin(n_0/n_{\text{eff}})$ .

When modes were coupled in and coupled out by prism, modes with  $n_{\text{eff}} > n_0$  have a bright spot at the center of the  $m$ -lines of the output rutile prism coupler, while modes with  $n_{\text{eff}} < n_0$  have uniformly illuminated  $m$ -lines. We have also polished one end of some of the samples and observed the end-fire radiation pattern at the output when a TE mode is excited by the prism coupler at the input. In the near field, power of all the guided wave modes is concentrated near the surface, while the pattern of the walked-off radiation is diffused and deep in the substrate. When a polarizer is inserted to examine the output radiation, all the guided wave power is in the TE polarization, while all the walk-off radiation power is in the TM polarization. Fig. 3(a) shows the near field pattern observed in the TE polarization, while Fig. 3(b) shows the near field pattern observed in the TM polarization.

We interpret the "walk-off" phenomena as created by random scattering of TE polarized radiation into TM polarized radiation. When the  $n_{\text{eff}}$  is larger than 2.286, the scattered radiation is not phase matched into any mode. Thus, the attenuation rate of the TE guided wave modes is low. When the  $n_{\text{eff}} < n_0$ , the TM radiation from the randomly scattering is now phase matched into the TM substrate modes, with their effective index in the  $x$ -direction approximately  $n_0 \sin \theta_s$ . The occurrence of the phase matching is confirmed experimentally by the measured value of  $\theta_s$ . Such a phase matching will cause a large amount of power transferred from the TE guided wave mode to the TM substrate modes, thereby creating a large attenuation rate.

We have attempted to determine the physical mechanism for the random scattering of TE radiation into TM radiation. We have examined the surface condition after ion exchange under an optical microscope at high magnification. There is no evidence of surface corrosion, as is the case of ion exchange in pure benzoic acid. We have polished a multimode waveguide. The thickness of the original guiding layer as determined by the inverse WKB method was  $11.63 \mu\text{m}$ . The thickness of the guiding layer is  $8.01 \mu\text{m}$  after the first polish and  $5.26 \mu\text{m}$  after the second polish. The same walk-off phenomena are observed after both polishing processes. Thus, we concluded that the surface corrosion was not a significant factor. It looks as if the scattering is a volume mechanism, even though we have no conclusive proof of that. We have annealed the sample after the exchange at  $400^\circ$  in wet  $\text{O}_2$  environment for 0.5–4.5 h. No change in the walk-off phenomena by the annealing has been observed. When an ion-exchanged waveguide is fabricated on  $x$ -cut  $\text{LiNbO}_3$  by the same ion exchange process, no anomalous attenuation and depolarization scattering have been observed. The  $x$ -cut  $\text{LiNbO}_3$  waveguides have typically a smaller attenuation rate than the  $y$ -cut waveguides.

We conclude that ion exchange in  $y$ -cut  $\text{LiNbO}_3$  creates a phase matched TE-to-TM conversion scattering that will lead to large attenuation rates for those TE guided wave modes with  $n_{\text{eff}} < n_0$ . This would be a further drawback of using a  $y$ -cut  $\text{LiNbO}_3$  ion exchanged waveguide. The precise mechanism for this TE-to-TM scattering is not fully understood. Clearly, the same mechanism does not exist for  $x$ -cut ion-exchanged waveguides.

#### ACKNOWLEDGMENT

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**Retzon Chen** was born in Taiwan, the Republic of China, in 1958. He received the B.S. degree in 1980 from National Tsing Hua University, Hsin Chu, Taiwan, and the M.S. degree in 1983 from the University of California, San Diego, both in physics.

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Dr. Chang is a member of the American Physical Society and a Fellow of the American Optical Society.

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