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Fabrication of proton-exchange optical waveguides in x-cut lithium niobate

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The fabrication and characterization of optical waveguides formed in x-cut $LiNbO_3$ by proton exchange method in benzoic acid melts have been reported. For the TE modes variation of the refractive index was found to be $\Delta n_{ex} = 0.13$ ($\lambda = 632.8$ nm). The measured optical propagation losses in single-mode waveguide at 632.8 nm wavelength ranged between 3.4 dB/cm and 4.5 dB/cm.

1. Introduction

In the past few years proton-exchange (PE) in benzoic acid developed into a very promising method for fabrication of optical waveguides on $LiNbO_3$ [1]. The main advantages of the process are that the fabrication of waveguides is relatively simple and that the end result is a high refractive index, well confined, waveguide. However, the index change is not isotropic and the extraordinary refractive index is to be modified. This means that only TE modes are guided in proton exchanged x-cut and y-cut $LiNbO_3$ and TM-mode in PE z-cut $LiNbO_3$. Although the proton exchange process produces surface damage in y-cut $LiNbO_3$ [2], it is readily used on x-cut and z-cut $LiNbO_3$. Recently, several attempts have been made to apply the process successfully even on y-cut $LiNbO_3$ [3]–[5]. This simple technique has been demonstrated for different cuts of $LiNbO_3$ crystals to fabricate various types of waveguide devices, e.g., high efficiency beam deflectors [6], second harmonic generators [7], polarizers [8], ring rezonators [9], π-arc waveguide interferometers [10], optical frequency translators [11] and acoustooptic or electrooptic modulators [12], [13].

In this paper we describe the fabrication of optical waveguides in x-cut $LiNbO_3$ crystals using proton exchange in analar benzoic acid. Well polished nonoptical quality substrates have been supplied by the Institute for Technology of Electronic Materials, Warsaw*. The obtained results show that the supplied substrates have been sufficiently good to a successful fabrication of the waveguides.

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* Those substrates were for electroacoustics applications.

2. Experimental details

Waveguide slabs were formed using *x*-cut $LiNbO_3$ substrate. The proton exchange process was carried out in open stainless steel beaker containing a molten analar benzoic acid. Benzoic acid is the most convenient organic acid. Its melting point is at 122° and a boiling point at 249°. The beaker was held in resistively heated furnace having the temperature controlled within ±0.5°C. The bath temperature ranged from 160°C to 235°C. Thermal shock does not appear to be a problem with *x*-cut crystals, but each specimen before being immersed in melted acid and after its removal was kept for 1–2 minutes over the hot acid surface in the furnace. After the exchange process the slabs were washed in methanol to remove benzoic acid excess. The proton-exchange process lasting from 5 minutes to 7 hours has been investigated.

The index change mechanism for the proton-exchange technique in $LiNbO_3$ explained as the loss of lithium ions from, and the formation of hydroxyl groups in the lithium niobate substrate can be presented by the formula [5]

$$LiNbO_3 + xH^+ \rightarrow Li_{x-1}H_xNbO_3 + xLi^+ \tag{1}$$

where the maximum value of x is 0.7 to 0.8 [14].

3. Results

The mode structure of the optical waveguides was measured by means of the conventional prism-coupler technique with crystal rutile prism at $\lambda = 632.8$ nm [15]. For multi-mode waveguides (> 4 modes), the values of the effective refractive indices n_{eff} of each observed mode were used as a data input for a computer program based on the inverse WKB approximation [16], [17], which estimates the shape of refractive index profile. The program calculates the surface refractive index n_s and the waveguide depth d at which the n_{eff} value becomes equal to the local refractive index. Figure 1 shows the typical PE waveguide refractive index profile obtained from

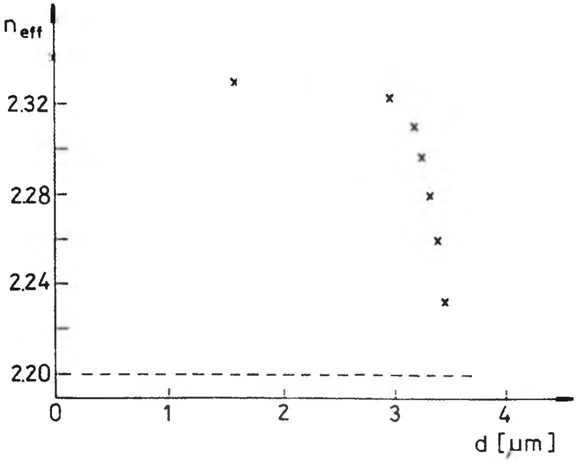

Fig. 1. Refractive index profile calculated from measured mode indices using WKB procedure for an *x*-cut sample exchanged for 290 min at 230°C

mode index measurements using the WKB method. In general, all waveguides formed in proton exchange process were found to have step-index profiles.

Since the profile produced by the proton-exchange process is step-like, the quick method of Jaussaud and Chartier [18] has been used to calculate the n_s and d of the few-mode guides (< 4 modes).

All the measurements were carried out along the y-axis in the direction of light propagation. For the above direction the maximum increment of the extraordinary refractive index was $\Delta n_{ex} = 0.134$.

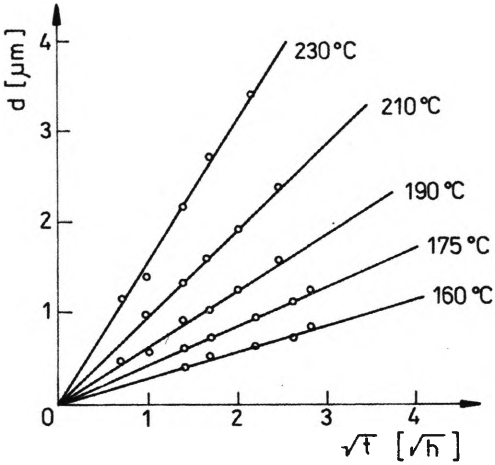

Fig. 2. Diffusion depth versus square root of time

Figure 2 shows the diffusion depth versus the exchange time. The values of the diffusion coefficient $D(T)$ for the exchange process at different temperatures were for each slab calculated from the formula

$$d = 2\sqrt{t \times D(T)} \tag{2}$$

where d is the diffusion depth, t — the exchange time, and T — the temperature of the exchange process. The mean value of $D(T)$ are shown in the Table.

The values of diffusion coefficient for PE waveguides

Temperature T [°C]	$D(T)$ [$\mu m^2/h$]
230	0.596
210	0.225
190	0.096
175	0.047
160	0.019

The plot of $D(T)$ versus T^{-1}, as shown in Fig. 3, makes it possible to calculate the usual temperature dependence for $D(T)$ according to the Arrhenius law

$$D(T) = D_0 \exp(-Q/RT) \tag{3}$$

where D_0 is the exchange process constant, R – the universal gas constant, and Q – the activation energy for the exchange process. The values of Q, and D_0 have been obtained from Fig. 3, namely:

$$D_0 = 1.05 \times 10^9 \ \mu m^2/h,$$
$$Q = 89.043 \times 10^3 \ J/mol,$$
$$Q/R = 1.071 \times 10^4 \ K.$$

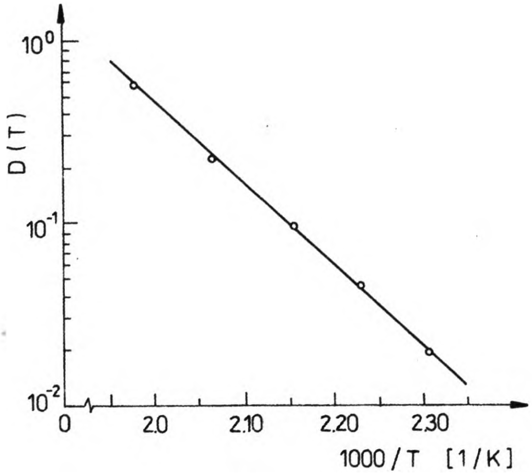

Fig. 3. Plot of ln(D) versus $1/T$

Propagation losses were measured by two-prism method on various single mode samples fabricated at different temperatures. The measured losses ranged between 3.4–4.5 dB/cm (Fig. 4). No clear correlation between propagation losses and fabrication conditions has been found.

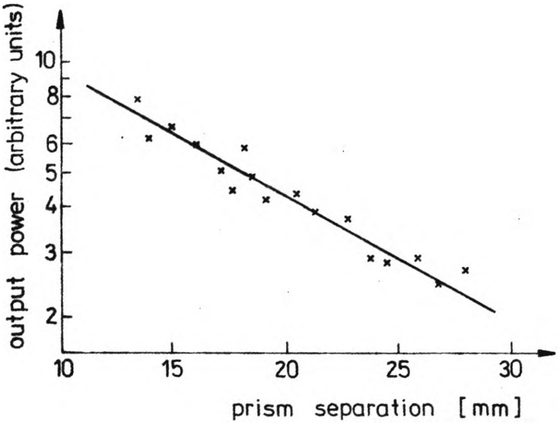

Fig. 4. Loss measurement for an x-cut sample (estimated losses 3.4 dB/cm)

Instabilities of the refractive index in waveguides at room temperature have been examined for nearly ten months. The examination was carried out every day during one month and then every week. The measured effective mode indices demonstrate that the index profile of proton-exchange waveguides is not stable but evolves as

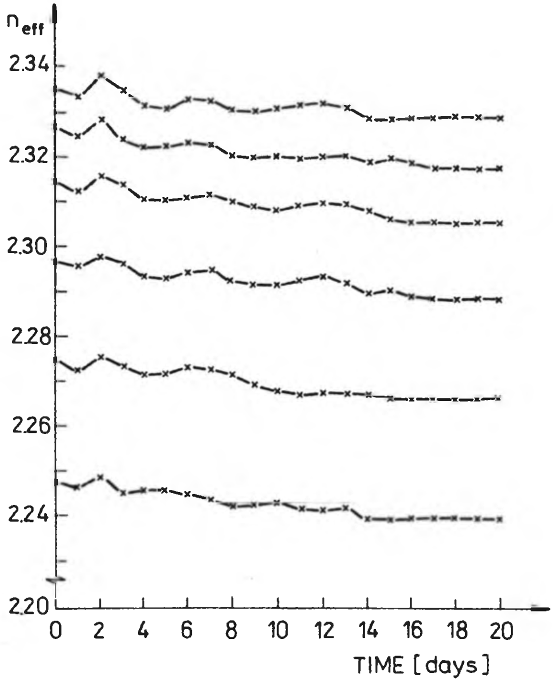

Fig. 5. Variation of effective mode indices as a function of time for a waveguide exchanged for 3 hours at 230°C. Accuracy of the measurement is 4×10^{-4}

a function of time. This effect for a multi-mode sample is shown in Fig. 5. It can be clearly seen that the effective indices undergo rapid daily changes during about 16 days. The general shape of this variation follows a function which comprises a slow damping component superimposed on an oscillating function the period of which is not well defined. After about 16 days the relaxation vanished and the measured values of n_{eff} were included in the experimental errors (4×10^{-4}).

4. Conclusions

The proton exchange process is very simple, requiring low temperature and rather not complicated installations. The temperature stabilization enables us to produce waveguides with exact parameters, such as diffusion depth and numbers of modes by process period and temperature changes.

The waveguides, though being fabricated on nonoptical quality substrates, have good parameters for optoelectronics applications, their index change Δn is high of about 0.13 and propagation losses are relatively low.

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Производство оптических волноводов в $LiNbO_3$ со срезом *x* методом ионного обмена

В работе представлен простой метод производства оптических волноводов $LiNbO_3$ на *x*-срезе путем обмена ионов H^+ с ионами Li^+ основы в расплаве бензойной кислоты. Обнаружено, что максимальное изменение показателя преломления света в оптических волноводах $LiNbO_3$ на *x*-срезе.