Optica Applicata, Vol. XIV, No. 3, 1984

Optical waveguides formed in *Y*-cut $LiNbO_3$ crystals by Ti indiffusion in stationary air atmosphere

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The paper presents a method of producing slab and strip (multi- and single-mode) optical waveguides in *Y*-cut $LiNbO_3$ crystals by Ti indiffusion in presence of $LiNbO_3$ powder in stationary air atmosphere in closed but nonhermetic system. The required guide parameters were controlled only by adjusting the Ti film thickness under fixed diffusion temperature and duration. The dependence of the guide characteristics (for TE and TM polarized light propagating in both directions parallel and perpendicular to the optical axis of crystal) on the titanium metal film thickness has been investigated in detail. The method of refractive index profile evaluation is described. The results of light attenuation measurements for the fabricated waveguides are also presented.

1. Introduction

Single crystals of lithium niobate possess excellent electro-optic and acousto-optic properties and much work has been done in recent years in the development of active integrated optical devices in this material. Thin film modulators, deflectors, switches, filters, polarization controllers have been demonstrated [1]. In particular, the formation of waveguides in $LiNbO_3$ by Ti-diffusion has received much attention [2, 3, 4]. A problem which has almost universally plagued the fabrication of waveguides by this process is the simultaneous production, accompanying the outdiffusion of Li_2O, of a surface guide for light polarized along the *c*-axis [5]. This is an important problem especially in the fabrication of strip waveguides because excess cross talk occurs between channels and butt coupling efficiency to single mode optical fibres is impaired due to loss

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of energy to the planar waveguide modes. Several techniques to eliminate or compensate for the effects of outdiffusion have been reported [5, 6, 7], however most of these methods complicate the diffusion process and some of them cause degradation of the sample surface quality [6].

In this paper, we describe the technique of producing optical slab (multi- and single-mode) waveguides by Ti diffusion into Y-cut $LiNbO_3$ crystals; this method is a new variant of the process first proposed by ESDAILE [7]. The required guide parameters are controlled only by adjusting the Ti film thickness d_{Ti} under fixed diffusion temperature T and time t; d_{Ti} can be measured with a great accuracy, contrary to the remaining parameters T and t (the diffusion process usually starts before the temperature in a furnace reaches the desired value).

We discuss (for TE and TM light polarizations and for both X and Z directions of light propagation) the effect of Ti metal film thickness on the change of the refractive index profile in the produced waveguides. In particular, we report the influence of the incomplete penetration of Ti (from the thin film covering a crystal substrate) into $LiNbO_3$, on the shape of the refractive index profile of the produced optical waveguide. We also describe the experimental and computational methods of evaluating the optical properties of the waveguides.

2. Production of Ti:$LiNbO_3$ waveguides

Thin Ti metals layers (0.065, 0.050, 0.035, 0.020 and 0.010 μm thick) were deposited on Y-cut $LiNbO_3$ substrates by thermal evaporation technique. Their thickness were monitored during the deposition process using quartz-crystal oscillator and then measured by means of an interference microscope with an accuracy of ± 0.002 μm.

The used diffusion arrangement is diagrammed in Fig. 1. A box (muffle) type furnace containing closed (unhermetically) Al_2O_3 ceramic crucible was used instead of the standard tube furnace. The crucible was partly filled with $LiNbO_3$ powder in order to maintain a sufficient Li_2O vapour pressure which should suppress the outdiffusion process from the $LiNbO_3$ crystal substrates. The crystals covered with Ti films were placed in the crucible in a way which prevents them from touching the powder; at the temperature the diffusion was carried out, it was found that lithium niobate powder sintered to the surfaces of the $LiNbO_3$ substrates. The gas phase in the furnace was stationary air. Diffusion of Ti into $LiNbO_3$ was performed at the temperature of 1000°C for 6 hours; the elapsed time was measured, beginning with the moment the temperature in the furnace reached 950°C. The diffusion temperature (1000°C) was chosen using the following datum:

Propagation losses for Ti:$LiNbO_3$ waveguides decrease as diffusion temperature increases [8]. However, electro-optic coefficients degrade if the temperature of the technological process exceeds 1000°C [9]. After the heating was turned off, the samples in the furnace were naturally cooled to room temperature.

For the samples covered with Ti films 0.065 μm and 0.050 μm thick it was found that milky rough layers appeared on the top of the $LiNbO_3$ during the diffusion process. Taking into account other reports, it seems probable that the described rough lasers contain Ti-Nb-O compounds [10] and Li-Ti-O compounds [2]; because of the roughness of the layers surfaces and the high refractive index of the constituent materials ($n_e = 2.9$ and $n_0 = 2.6$ for TiO_2 according to [3]), it was impossible to couple light, via rutile prism, into these waveguides. The described difficulties disappeared after careful polishing of the surfaces of the samples.

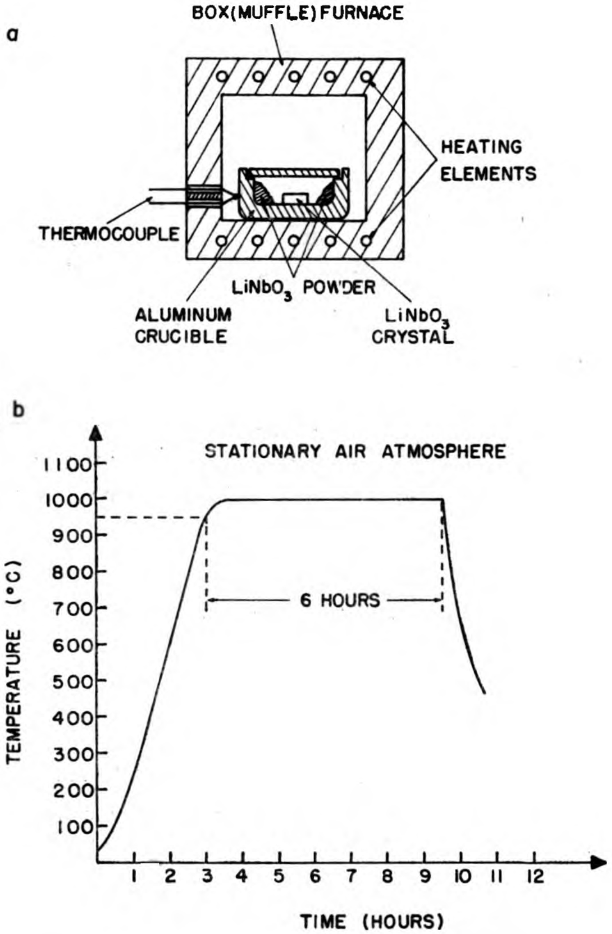


Fig. 1. Schematic representation of the diffusion system. The furnace system (a), temperature as a function of time (b)

Using the technique described above, it was possible to fabricate slab optical waveguides, both multi- and single-mode. This was established by observainvestigations were performed in order to check if the Li_2O outdiffusion was really prevented by our new process.

In the conditions identical to the ones in which the waveguides were formed, the $LiNbO_3$ crystal substrate, not covered with titanium film, was also annealed; in this crystal the out-diffusion modes did not exist. Also, as a test, we fabricated some channel waveguides. Stripes of titanium metal 3–10 μm wide and 0.010 μm thick were formed using the standard thermal evaporation and lift-off technique. After diffusion, the ends of the samples were polished to allow end-fire coupling. The near-field patterns of light emerging from the guides were examined; the characteristic effects of Li_2O out-diffusion on the field pattern [5, 8] were not observed either.

3. Determination of optical properties of Ti:$LiNbO_3$ slab waveguides

3.1. Refractive index profile in waveguides

The effective refractive indices n_{ef} for TE and TM modes (at 0.6328 μm He-Ne laser) were determined with an accuracy of about ± 0.0008 by measuring the synchronous coupling angles of the modes. Effective refractive index measurement data, for some of the produced waveguides, are summarized in the Table. The obtained values of n_{ef} were then used to define the refractive index profiles $n(y)$ in waveguides.

Table. Effective refractive index measurement data for slab waveguides diffused for 6 hours at 1000 °C in stationary air atmosphere

No. of sample	d_{Ti} [μm]	Mode order m	n_m^{ef}			
			X prop.		Z prop.	
			TE modes	TM modes	TE modes	TM modes
1	0.065	0	2.2132	2.2913	2.2910	2.2907
		1	2.2071	2.2878	2.2874	2.2871
		2	2.2049	—	—	—
		3	2.2045	—	—	—
		4	2.2039	—	—	—
2	0.050	0	2.2090	2.2894	2.2895	2.2890
		1	2.2053	—	—	—
		2	2.2045	—	—	—
		3	2.2039	—	—	—
3	0.035	0	2.2066	2.2888	2.2893	2.2888
		1	2.2031	—	—	—
4	0.020	0	2.2042	2.2875	2.2881	2.2879
		1	2.2030	—	—	—
5	0.010	0	2.2023	2.2865	2.2869	2.2866

To determine the extraordinary index of refraction profiles of the waveguides No. 1 and 2 we applied the modified LWKB method [11]. This procedure enables $n(y)$ to be evaluated by data sets (y_m, n_m^{ef}) (m-mode order, y_m — turning point of m-order mode). These sets were used to find the analytical form of the refractive index profile by the least mean-square method.

For the waveguides named above it was impossible to approximate $n(y)$ by means of typical functions (linear, exponential, Gaussian, erfc, second-order polynomial). Taking into account the information [2, 3, 10] concerning the mechanism of Ti diffusion into $LiNbO_3$, we approximated $n(y)$ using a *double Gaussian* function

$$n(y) = n_b + \frac{1}{2}\Delta n \exp\left[-\left(\frac{y}{D_1}\right)^2\right] + \exp\left[-\left(\frac{y}{D_2}\right)^2\right] \tag{1}$$

where:

n_b — bulk substrate extraordinary refractive index,
n_s — refractive index on the waveguide surface,
$\Delta n = n_s - n_b$.

The extraordinary refractive index profile of the waveguide No. 2 is shown in Fig. 2.

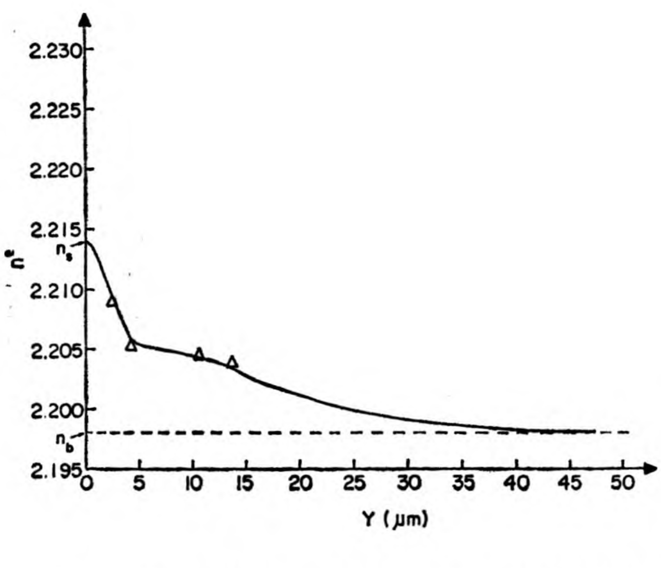


Fig. 2. *Double Gaussian* extraordinary refractive index profile of the slab optical waveguide formed with 0.050 μm thick Ti metal film

The ordinary index of refraction profile $n(y)$ of waveguide No. 1 may probably also be approximated by a *double Gaussian* function. However, because of an insufficient number of measured date, this hypothesis could not be verified. Thus, remembering that only part of the whole amount of Ti (from the thin film/diffusion source) penetrated into the substrate during the process we decided to use the erfc function (the case of *continuous source* diffusion), for $n(y)$ approximation. The parameters of this function were computed by a numerical solution of the following system of four equations:

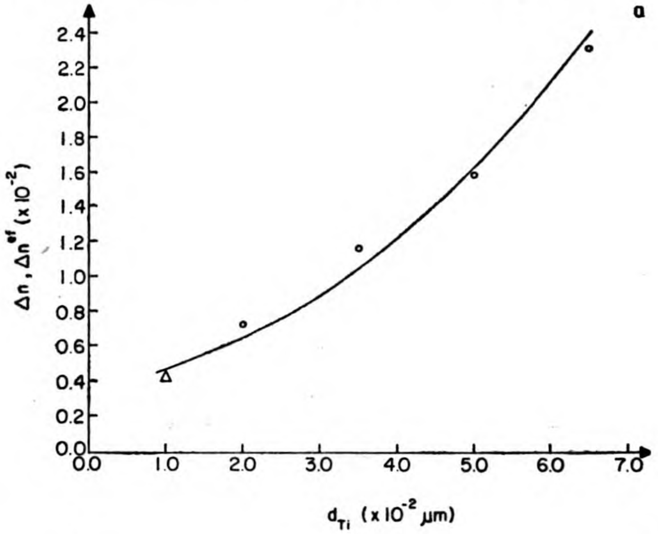
$$\left.\begin{aligned} &k_0\int\limits_0^{y_m}[n^2(y)-(n_m^{ef})^2]^{\frac{1}{2}}\,dy = n\left(m+\frac{1}{4}\right)+\arctan\varrho\left[\frac{(n_m^{ef})^2-1}{n_s^2-(n_m^{ef})^2}\right]^{\frac{1}{2}} \qquad (2a)\\ &e_n^{ef} = n_b+\Delta n\,\mathrm{erfc}\left(\frac{y_m}{D}\right) \qquad (2b)\end{aligned}\right\}$$

where: $m = 0, 1$

k_0 — light wave number in vacuum

$$\varrho = \begin{cases} 1 & \text{for TE modes}\\ n_s^2 & \text{for TM modes}\end{cases}$$

((2a) is a characteristic equation for gradient slab waveguides).



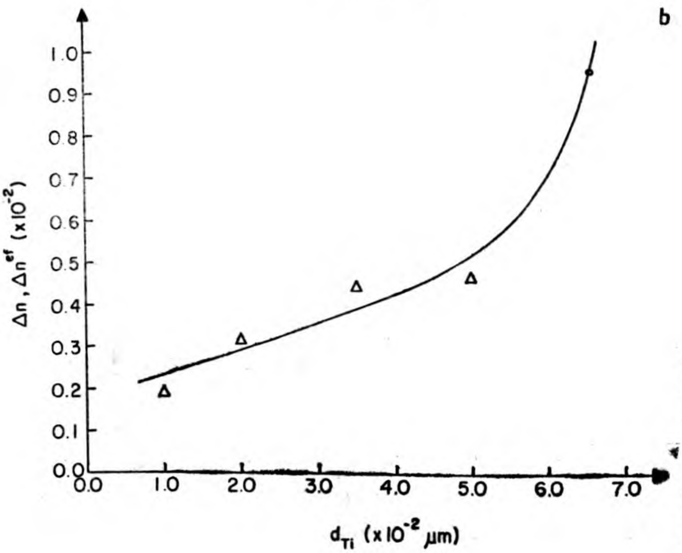


Fig. 3. Relation between refractive index change and titanium film thickness: extraordinary refractive index change (a), ordinary refractive index change (b). ○ — $\Delta n = n_s - n_b$, △ — $\Delta n^{ef} = n^{ef} - n_b$

Both waveguides No. 3 and No. 4 supported only two TE modes in the X direction. Appearance (during the diffusion process) of the residual layers on top of the substrates did not occur so we decided to approximate the extraordinary index of refraction profiles by Gaussian function (the case of ***limited source*** diffusion). The parameters of this function were computed, as in the previously mentioned case, by solving the system of equations (2) (in (2b) the erfc function is replaced by a Gaussian function: $n_m^{ef} = n_b + \Delta n \exp\left[-\left(\frac{y_m}{D}\right)^2\right]$. The results of our calculations are illustrated in Fig. 3 (for the waveguides which supported at least two modes $\Delta n = n_s - n_b$ was obtained as a function d_{Ti}, while for the single-mode waveguides the relations between $\Delta n^{ef} = n^{ef} - n_b$ and d_{Ti} were shown).

3.2. Light attenuation measurements

The attenuation a of the slab Ti:$LiNbO_3$ waveguides was determined using measurements obtained with the system presented in Fig. 4. The intensity variations of the light decoupled from the polished end of the waveguide were recorded as a function of the prism coupler distance from this end. It is known [12] that the prism coupling efficiency is highly influenced by the width of the air gap separating the prism from the guide; the gap width being adjusted by the clamping of both elements. In turn, the clamping force may be controlled

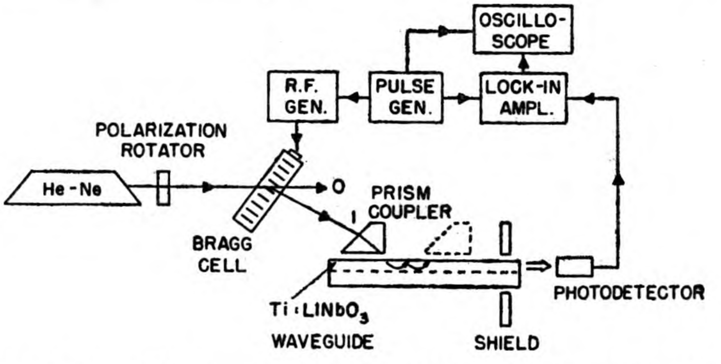


Fig. 4. Block diagram of system used for measuring light attenuation in slab Ti:$LiNbO_3$ waveguides

on the basis of the pattern of interference fringes visible at the prism base. The above method was used to control the efficiency of light coupling into the waveguide. To improve the optical signal-to-noise ratio, the laser light was modulated by acousto-optic Bragg cell operating at 40 MHz; the first order diffracted beam was introduced into the waveguide. The experimental method used allowed us to determine the value of a with an accuracy of ± 0.2 dB.

We observed that in all the waveguides produced the propagation paths of guided light were not visible and a took the value of about 1 dB/cm.

4. Conclusions

The results can be summarized in the following way:

— The presented method of Ti: $LiNO_3$ slab and strip waveguides production enables us to take precautions against the typical guide defects caused by outdiffusion of Li_2O.

— Assuming a constant (not precisely defined) temperature and duration of the Ti diffusion process and adjusting only the (precisely measured) titanium film thickness, we are able to form low-loss ($\sim$1 dB/cm) multi- and single-mode slab waveguides with the required optical properties (number of supported modes, values of the effective refractive indices).

— The described computational methods allow us to determine the refractive index profiles of the waveguides supporting two or more modes.

— According to our knowledge, we present the first report describing the evident influence of the incomplete penetration of Ti (from the thin film/diffusion source) into $LiNbO_3$ crystal substrate on the shape of the refractive index profile of the formed waveguide. In this case, the refractive index profile assumes a complex form which may be approximated by *double Gaussian* function.

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Received January 17, 1984

Формирование оптических световодов в кристаллах $LiNbO_3$) со срезом Y путем диффузии Ti в постоянных атмосферных условиях

В статье представлен метод изготовления планарных и полосатых световодов (одно- и многомодовых) в кристаллах $LiNbO_3$ со срезом Y путем диффузии Ti. Описан, кроме того, примененный метод предупреждения нежелаемых эффектов, связанных с диффундированием LiO_2 из кристаллов

$LiNbO_3$. Световоды с заданными оптическими свойствами формировались путем изменения толщины пласта Ti (источник диффузии) при установленных остальных параметрах (температура и продолжительность) процесса диффузии. Представлен метод определения профиля коэффициента преломления света в волноводах Ti : $LiNbO_3$, ведущих по крайней мере два световодовых мода. Подробно обсуждено влияние толщины пласта Ti на изменение коэффициента преломления света и затухание световодов.

Перевела Малгожата Хейдрих