論文79-16-2-3

Fabrication of a $LiNbO_3$ Single-Mode Optical Waveguide
($LiNbO_3$ 單一모드 光導波管의 製作)

朴 東 徹*
(Park, Dong Chul)

要 約

집적광학 도파관을 만들기 위해 $LiNbO_3$ substrate 내로 전위원소인 Ti를 확산시켰다. Li_2O out-diffusion 모드를 제거 시킴으로써 단일 모드 도파관이 제작 될 수 있었다. 특성 측정에는 He-Ne 레이저($\lambda = 0.6328 \mu m$)와 프리즘 결합 방법이 사용되었다.

Abstract

Deposited film of a transition metal, Ti was diffused into $LiNbO_3$ crystals to form integrated optical waveguides. By suppressing Li_2O out-diffusion, single-mode waveguides could be constructed. Measurements on characteristics were performed dy using the prism coupling technique and a He-Ne laser. ($\lambda = 0.6328 \mu m$)

1. Introduction

Recent intensive researches on optical communication have revealed the need for high speed integrated optical devices such as modulators, switches, and deflectors. For this purpose, $LiNbO_3$ and $LiTaO_3$ are very often used as substrate materials, because of their excellent electro- , and acousto-optic properties. The optical waveguides have been made by out-diffusion of Li_2O[1], in-diffusion of transient metal ions (Ti, V, and Ni)[2], ion implantation[3], rf-sputtering[4], and epitaxial growth by melting[5] techniques.

Single-mode optical waveguides are fundamental and absolutely needed, if we are to build single-mode optical communication systems. Furthermore, they are essential in fabricating directional-coupler-type modulators or switches. But if the largest r_{33} component of the electro-optic coefficient of $LiNbO_3$ is to be utilized, it is not easy to get a single-mode waveguide, because of the out-diffusion process, which arises during the in-diffusion process and makes an undesirable planar waveguide layer.

In this work, attempts to obtain single-mode waveguides were made by the method of thermal diffusion of Ti into y-cut $LiNbO_3$ substrates.

2. Waveguide Formation Process

The formation of optical waveguides involves the in-diffusion of the evaporated Ti metal film into $LiNbO_3$ substrate. This widely used in-diffusion method

---

* 正會員, 忠南大學校 電子教育工學科
(Dept. of Electronic Engineering Education, Chungnam National Univer.)

接受日字；1979年 1月 26日

easily provides single-mode, low-loss 3-dimensional waveguides.

The surface of the substrate was finely polished, and then Ti films up to the 300 Å thickness was deposited onto the substrate by thermal evaporation at a pressure of $3\sim5\times10^{-7}$ Torr and at a substrate-heater temperature of 150 ℃. The deposited substrate was pushed into a furnace at a rate of 50 ℃/min to 980 ℃ and diffused 4.5 hours in Ar atmosphere flowing 20 l/hour (to prevent metal oxidation). It was pulled out at the same rate, and then cooled naturally in air.

3. Suppression of the Out-diffusion Modes

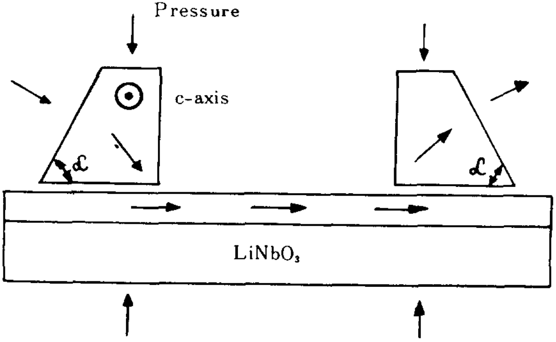
A major difficulty in waveguide formation by metal in-diffusion is that, at high diffusion temperature (nearly 1000 ℃) substrates suffer the loss of loosely bound Li_2O through a surface out-diffusion process. The existence of a planar out-diffusion waveguide would introduce excess crosstalk between channels in directional couplers. In the out-diffusion waveguides the refractive index change occurs only in n_e, while in the in-diffusion waveguides it occurs both in n_e and n_o. Therefore, the Li_2O out-diffusion plays no role when r_{13} electro-optic coefficient is used.

In order to use the largest r_{33} coeffient the out-diffused layer should be suppressed. Suppression techniques were published by Miyazawa[6] (with Li_2CO_3 powder), Chen[7] (with $LiNbO_3$ powder), and Ranganath[8] (with Li_2O chunk).

The suppression effect was tested by using either $LiNbO_3$ powder or Li_2O chunk. But the substrate, which was packed in $LiNbO_3$ powder and diffused, was proved so rough that only Li_2O chunk was used to eliminate the out-diffused layer.

Two y-cut $LiNbO_3$ substrates with no Ti layers were prepared. One (sample 1) was diffused only in Ar atmosphere to generate the out-diffused layer, and the other (sample 2) was diffused under Li_2O, which was about 5 cm upstream from the substrate and kept in a platinum crucible, in Ar atmosphere to eliminate the out-diffused layer.

Excitation of the waveguide modes was carried out by the prism coupling technique. TiO_2 (Rutile) prisms were used, and the contact between the waveguide and the prism was locally pressed with special prism holders. The experimental set-up is shown in Fig. 1.



	prism	$LiNbO_3$
n_e	2.872	2.203
n_o	2.584	2.295
α	51°	

Fig. 1. Experimental set-up.

TE polarized light was applied to the waveguide. The view of the mode spectrum on the output screen was seen at the proper angle of the incident beam. The existence of the guided modes could be recognized by the m-lines (mode lines) on the screen. While one guided mode was observed with sample 1, no guided mode was observed with sample 2. This means that the out-diffusion mode was suppressed by using Li_2O chunk.

4. Mode Dispersion Curves

In 1969 Marcatili[9] analyzed mode dispersion relations of rectangular dielectric waveguides. Though Marcatili's modal analysis is relative simple, it does not agree well to the circular harmonic computer analyis of Goell[10] for modes near cutoff. Knox and Toulios[11] analyzed this same problem by introducing the effective refractive index method. Their approach gives somewhat closer agreement than Marcatili's method to Goell's for modes near cutoff. Hocker and Burns[12] compared these three methods by plotting modal dispersion curves.

In this work modal analysis was done by using the effective refractive index method. Let us assume that the diffused Ti layer in $LiNbO_3$ is that of Fig. 2(a). In the effective refractive index method the structure in Fig. 2(a) is analyzed by conventional planar waveguide techniques as shown in Fig. 2(b) and (c).

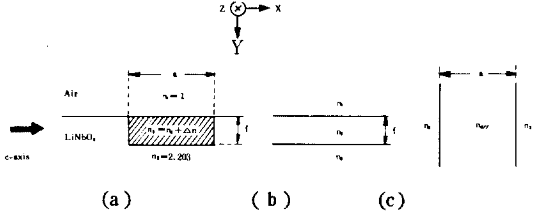


Fig. 2.(a) Configuration of the diffused waveguide.
(b) A planar waveguide with equivalent confinement in the y direction.
(c) A planar waveguide with equivalent confinement in the x direction. n_{eff} is the effective index of the mode in guide (b)

n_{eff} in guide (c) is the effective refractive index of the mode in guide (b) and given by

$$n_{eff}=k_z/k$$

where $k=2\pi/\lambda$ is the free space wave number and k_z is the wave number in the z-direction (propagation constant) of guide (b).

n_{eff} is defined as below:

$$n_{eff}'=k_z'/k$$

where k_z' is the propagation constant of guide(c). This k_z' is taken as the propagation constant of guide (a).

The plotted mode dispersion curves for TE modes and an aspect ratio(a:f)of 2:1 are shown in Fig. 3.

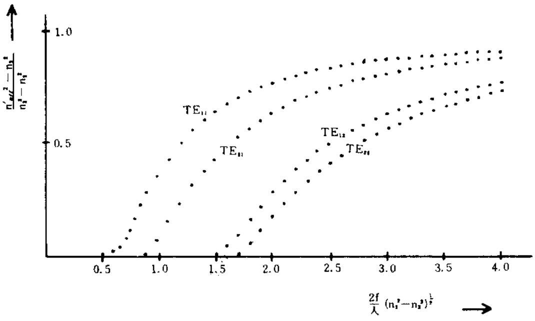


Fig. 3. Mode dispersion curves for rectangular waveguides (a= 2f).

5. Realization of a Single-mode Waveguide

As a single-mode waveguide, a $3\mu m$-wide waveguide with 150 Å-thick Ti layers was fabricated on a y-cut $LiNbO_3$ under Li_2O chunk(sample 3).

According to the Baues'[13] measurement on the diffusion profile, the diffusion depth f under the nearly same formation process can be assumed about $1.5\mu m$ for y-cut $LiNbO_3$. And from Naitoh's[14] empirical relations between Δn and d(Å) in TE modes, the following relation can be derived.

$$\Delta n=4.636\times10^{-5}\times d(\text{Å})\ \text{for}\quad \lambda=0.6328\mu m$$

where d(Å) is the thickness of the deposited Ti layers.

These two results are applied to calculate the x-axis value of the dispersion graph in Fig. 3.

$$f=1.5\mu m$$

$$\Delta n=4.636\times10^{-5}\times150\approx0.007$$

$$\frac{2f}{\lambda}(n_3^2-n_2^2)^{\frac{1}{2}}=\frac{2\times1.5}{0.6328}(2.210^2-2.203^2)^{\frac{1}{2}}$$

$$\approx 0.83$$

This means the fabricated waveguide can be considered as a single-mode waveguide.

TE polarized light was applied to sample 3. The mode spectrum of sample 3 was a single bright line, while that of the waveguide, which was fabricated without Li_2O, has several m-lines.

With sample 3, loss measurement was made by varying the position of the output prism relative to the fixed input prism and measuring the output power as a function of separation of the two prisms. The output power was measured with a photonmultiplier.

The measured waveguide losses were about 6 dB/cm and are plotted in Fig. 4.

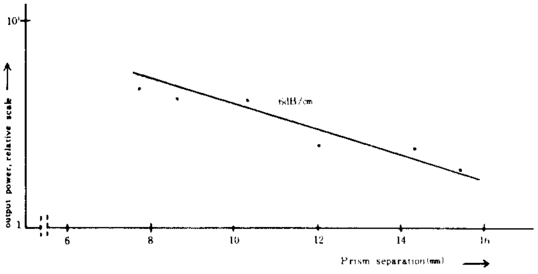


Fig. 4. Loss measurements.

6. Conclusion and Comments

In this paper, fabrication technology of the integrated optical single-mode waveguides is mainly presented. With this technology many integrated optical devices such as modulators, switches, and logic elements can be developed. But reproducibility is the kev point of fabricating such devices because of their very small dimensions. By using high purity $LiNbO_3$ crystals the waveguide losses and optical damage phenomena[15] may be reduced.

For further work followings are suggested:

1) Derivation of empirical relations between $\triangle n$ and Ti thickness
2) Precise measurement of the angle of m-lines to analyze each mode

This work is a part of the research, which was carried out during my stay at the Ruhr-university Bochum in W. Germany.

Reference

1. P. Kaminow and J. R. Carruthers, Appl. Phys. Lett. 22, 326 (1973).
2. J. M. Hammer and W. Phillip, Appl. Phys. Lett. 24, 545 (1974).
3. E. Garmire, H. Stoll, Y. Yariv, and R. G. Hunsperger, Appl. Phys. Lett. 21, 87 (1972).
4. S. Takada, M. Ohnishi, H. Hayakawa, and N. Mikoshiba, Appl. Phys. Lett. 24, 490 (1974).
5. S. Miyazawa, Appl. Phys. Lett. 23, 198 (1973).
6. S. Miyazawa, R. Guglieme and A. Carenco, Appl. Phys, Lett. 31, 742 (1977).
7. B. U. Chen and A. C. Pastor, Appl. Phys. Lett. 30, 570 (1977).
8. T. R. Ranganath and S. Wang, Appl. Phys. Lett. 30, 376 (1977).
9. E. A. J. Marcatili, Bell Syst. Tech. J. 48, 2071 (1969)
10. J. E. Goell, Bell Syst. Tech. J. 48, 133 (1969).
11. R. M. Knox and P. P. Toulios, Proceedings of MRI Symposium on Submillimeter Waves, J. Fox, Ed. (Polytechnic press, Brooklyn, 1970).
12. G. B. Hocker and W. K. Burns, Appl. Opt. 16, 113 (1977).
13. P. Baues, Information from the Research Laboratories of Siemens AG.
14. H. Naitoh, M. Nunoshita and T. Nakayama, Appl. Opt. 16, 2546 (1977).
15. M. K. Barnoski and J. F. Lotspeich, Proceedings of the Integrated Optics Conference, Salt Lake City, Utah (1976).

◇