Design of Rectangular Optical Waveguide on $LiTaO_3$ Crystal Using Thermal Annealed Proton Exchange Methods

Desain Pemandu Gelombang Optik Persegi Panjang pada Kristal $LiTaO_3$ Menggunakan Metode Pertukaran Proton Terpanaskan

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Abstract

Optical waveguides are the key component for distributing optical signals with very low propagation loss in optical communication. Several type optical waveguides are established currently such as silica optical fiber. In the planar structure, planar optical waveguides are suitable for implementing to integrated optic applications. In here, rectangular optical waveguides on a planar structure with a $LiTaO_3$ crystal as the substrate are described. The optical waveguides were designed for single mode operation at infrared optical wavelength. The Marcatili method is used for designing by separated the rectangular optical waveguides into two slab optical waveguides. Design rules for the rectangular optical waveguides are discussed in this paper.

Keywords: *optical waveguide, $LiTaO_3$ crystal, proton exchange methods, Marcatili methods, optical communication.*

Abstrak

Pemandu gelombang optik adalah komponen penting untuk mendistribusikan sinyal optic dengan rugi propagasi yang sangat rendah pada komunikasi optik. Beberapa jenis pemandu gelombang optik digunakan saat ini seperti serat optic silikon. Pada struktur planar pemandu gelombang optik secara planar sesuai untuk implementasi pada aplikasi optik terintegrasi. Pada makalah ini dipaparkan tentang pemandu gelombang optik berbentuk persegi panjang pada struktur planar dengan kristal $LiTaO_3$ sebagai substrat. Pemandu gelombang tersebut dirancang untuk operasi mode tunggal pada panjang gelombang optik *infrared*. Metode Marcatili digunakan untuk perancangan dengan memisahkan pemandu gelombang persegi panjang tersebut menjadi dua buah pemandu gelombang optik *slab*. Metode perancangan untuk pemandu gelombang optik persegi panjang didiskusikan secara rinci pada paper ini.

Kata kunci: pemandu gelombang optik, kristal $LiTaO_3$, metode pertukaran proton, metode Marcatili, komunikasi optik.

I. INTRODUCTION

Optical fiber communication is going to establish rapidly to compensate for the heavy data traffic in the future [1]. By using the optical fiber network, the high quality data can be transferred with very fast of 100 Gbps through low loss optical fiber of 0.2 dB/km [2]. The optical fiber network is promising for supporting internet data transfer in the future. Several devices are required in the optical fiber networks based on optical waveguides. Planar optical waveguides are useful on the optical device by coupling to the optical fibers. The planar optical waveguides can be used also for integrated optics.

Integrated optics concern on creating simple and compact optical devices on a chip with small size [3]. The integrated optic devices are important to the optical fiber networks for high-speed communications over long distances with very low transmission loss. These devices also benefit from being immune to electromagnetic interference. Integrated optical components interface with such fibers to form devices such as Mach-Zender interferometers, amplitude and phase modulators, as well as ring resonators for digital filtering.

One of the devices is optical waveguides as the important component. The optical waveguides are used to couple light from fiber optic cables into the integrated optic devices. Basically, the optical waveguides have large refractive index at the core region and lower refractive indices at the substrate/cladding region. This allows light to be guided with very little loss inside the optical waveguide.

Two main processes of fabricating optical waveguides on a $LiTaO_3$ crystal are titanium diffusion and proton exchange methods. Both processes insert

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impurities into the $LiTaO_3$ crystal lattice. The region of the crystal containing these impurities experiences an increase in refractive index. Light can therefore be confined to this region of increased refractive index forming an optical waveguide.

The titanium diffusion methods involve depositing a thin strip of titanium on the $LiTaO_3$ crystal surface where light will be guided [4]. The device is then treated to thermal anneal at temperatures in excess of 1000 °C for a duration of ten hours or more. The thermal anneal drives the titanium source into the $LiTaO_3$ crystal, creating a diffused concentration profile of titanium ions embedded in the substrate. The inclusion of these ions in the substrate increases the refractive index of the crystal in this region, allowing light to be guided along this path.

The hydrogen proton exchange optical waveguides were first observed irregularly when forming optical waveguides by exchange of silver-lithium or thallium-lithium in a $LiTaO_3$ crystal. It was found that small amounts of water were present in the $AgNO_3$ and $HTaO_3$ melts used for these experiments, and that hydrogen-lithium exchange was the actual cause of index change requisite for forming optical waveguides. This discovery led to the use of a variety of acids as a hydrogen proton source.

This paper concern on design of planar optical waveguides, which serve as the basic building block for integrated optical devices. Design of the rectangular optical waveguides on a $LiTaO_3$ crystal is discussed in detail for single mode operation at 1.55 µm optical wavelength. The optical waveguides using proton exchange methods are analyzed using the Marcatili methods by separated the rectangular optical waveguide into two optical slab optical waveguides. The optical waveguide structure, modal dispersion, and field distribution are discussed with detail in this paper.

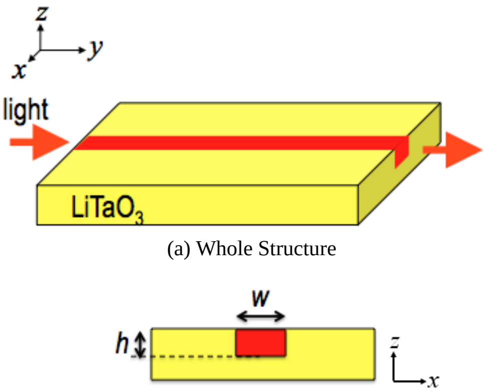
II. Structure

A rectangular optical waveguide is basically composed of a core region in region 1 as shown in Figure 1 and surrounding core regions, which are substrate and air in region 2, 3, 4, 5 as shown in Figure 1. In order to allow for guiding the optical wave, the refractive index of the core must be larger than the surrounding regions. As we know air is the lowest refractive index, which is 1 as the best cladding/ substrate. However, the air is impossible for the cladding since the waveguide core has very small size and requires other material as the support.

As shown in the Figure 1, a rectangular optical waveguide is designed on a $LiTaO_3$ crystal where core size is determined by depth of h and width of w. Refractive index of the waveguide core is slightly larger than the surrounding region, it will be discussed in detail in the next section.

III. The Sellmeier Equation

Rectangular optical waveguides can be designed on a $LiTaO_3$ crystal using proton exchange methods and thermal annealing process.Material dispersion can be calculated by Sellmeier approach with its coefficient and equation.



(a) Whole Structure

(b) Cross-sectional View

Figure 1. Structure of the Rectangular Optical Waveguide.

Sellmeier equation is an empirical relationship between refractive index and optical wavelength for a particular transparent medium. The equation is used to determine a dispersion of light in a medium. Sellmeier equation for a $LiTaO_3$ crystal can be expressed as [5]

$$n^2 = A_1 + \frac{A_2}{\lambda^2 - A_3^2} + A_4\lambda^2 \tag{1}$$

where n is the refractive index, λ is the wavelength in vacuum, and $A_{1,\,2,\,3,\,4}$ are experimentally determined by Sellmeier coefficients. The Sellmeier coefficients for the $LiTaO_3$ crystal are shown in Table 1.

TABLE I
SELLMEIER COEFFICIENCT FOR A $LiTaO_3$ CRYSTAL

	Ordinary	**Extraordinary**
A_1	4.5122	4.52999
A_2	0.0847522	0.0844313
A_3	0.19876	0.20344
A_4	- 0.0239046	- 0.0237909

Sellmeier curve of a $LiTaO_3$ crystal is shown in Figure 2, the curves for ordinary and extraordinary are represented by solid line and dashed line, respectively.

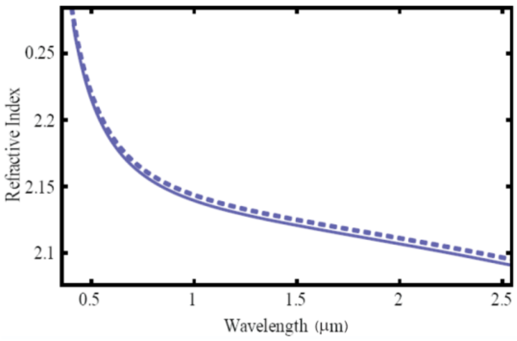
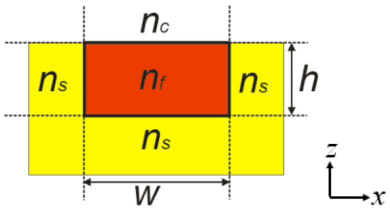


Figure 2. The Sellmeier Curve for the $LiTaO_3$ Crystal.

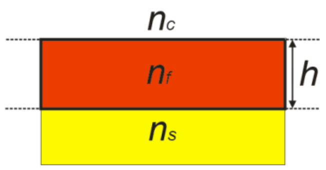
In this paper, rectangular optical waveguide are designed in infrared optical wavelength of 1.55 µm using thermal annealed proton exchange methods. The proton exchange method optical waveguides are operated Transverse Magnetic (TM) mode only. Design of the optical waveguide will be discussed in detail.

IV. Modal Dispersion

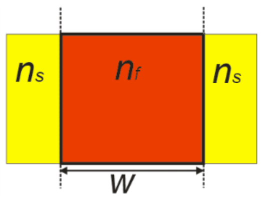
Generally, planar optical waveguides have two types, which are slab/two dimensional (2D) waveguides and rectangular/three dimensional (3D) waveguides. Rectangular optical waveguides can be designed using Marcatili method. In the Marcatili method, a rectangular optical waveguide is separated by two slab optical waveguides in the horizontal (W) and vertical (H) as illustrated in Figure 3. The film region of n_f is the largest than surrounding regions of n_s and n_c. Furthermore, fields in film region vary in an oscillatory manner in the x and y directions, while fields in outer regions decay exponentially from boundaries. Optical fields in the four corners are very weak and can be ignored completely in the consideration.



a. Rectangular Waveguide.



b. Slab Waveguide H.



c. Slab Waveguide W.

Figure 3. Analysis Methods of the Rectangular Optical Waveguide.

Dispersion relations for the slab waveguide H as shown in Figure 3 (a) and the slab waveguide W as shown in Figure 3 (b) are expressed as following equations respectively by [5], [6].

$$kh\sqrt{n_f^2 - N_1^2} = m\pi + \tan^{-1}\left(\frac{n_f^2}{n_s^2}\sqrt{\frac{N_1^2 - n_s^2}{n_f^2 - N_1^2}}\right) + \tan^{-1}\left(\frac{n_f^2}{n_c^2}\sqrt{\frac{N_1^2 - n_c^2}{n_f^2 - N_1^2}}\right) \quad (2)$$

$$kw\sqrt{N_1^2 - N_2^2} = m\pi + \tan^{-1}\left(\sqrt{\frac{N_2^2 - N_s^2}{N_1^2 - N_2^2}}\right) + \tan^{-1}\left(\sqrt{\frac{N_2^2 - N_s^2}{N_1^2 - N_2^2}}\right) \quad (3)$$

where k is the wave number of lightwave, n_f is the refractive index of waveguide core, n_s is the refractive index of waveguide substrate, n_c is the refractive index of waveguide cladding, m is the mode number, h is the core height/depth, w is the core width, and N is the effective index.

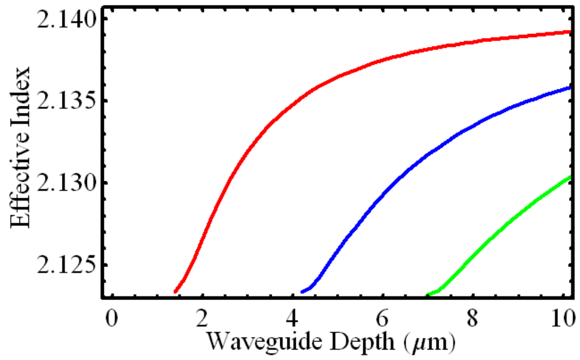


Fig. 4 Effective Index as a Function of Core Depth (*h*).

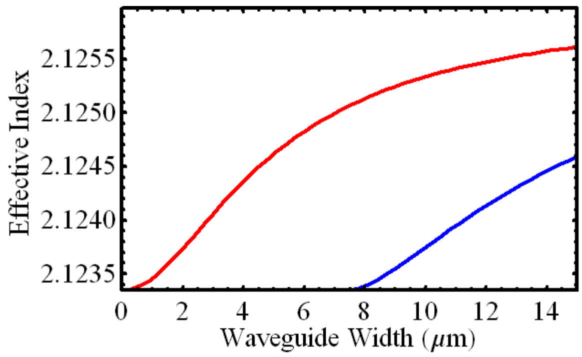
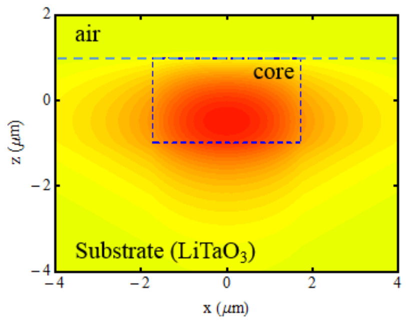


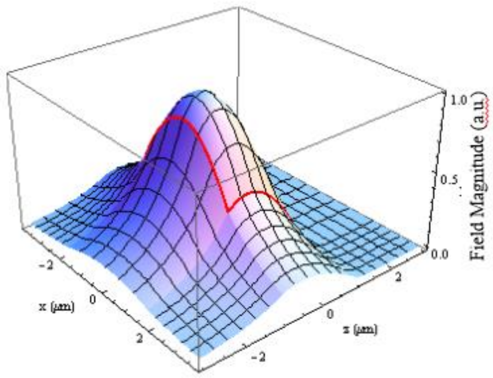
Fig. 5 Effective Index as a Function of Core Width (*w*).

As mentioned before, the rectangular optical waveguide is designed on a $LiTaO_3$ crystal using thermal annealed proton exchange method and operated for 1.55 μm optical wavelength. Refractive index of a $LiTaO_3$ crystal at the designed wavelength can be calculated using Equation 1. Calculated refractive index of the $LiTaO_3$ crystal is 2.12. By using the proton exchange methods on the $LiTaO_3$ crystal, refractive index of the core is larger 0.017 than the substrate refractive index [7]. Therefore, refractive index of the core becomes 2.137. As a result, modal dispersion of the designed optical waveguide can be calculated using Equations (2) and (3). Dispersion curve for the slab waveguide H as a function of the waveguide core depth (h) is shown in Figure 4. Based on result of the calculated modal dispersion, the depth/height of the optical waveguide core is determined less than 4 μm for single mode operation in 1.55 μm optical wavelength. When the height is set 2 μm, the modal dispersion for slab waveguide (*w*) as a function to the waveguide width is shown in Figure 5. We can see that the width of the optical waveguide core must be set less than 7 μm for single mode operation at 1.55 μm optical wavelength.

As summary based on the calculated result, a $LiTaO_3$ optical waveguide with annealing proton exchange method for single mode operation in 1.55 μm optical wavelength can be obtained using waveguide core size of 2x7μm. In addition, multimode operation can be designed also by considering modal dispersion.



(a) Contour Curve in Cross-sectional View



(b) Curve in 3-D View

Figure 6. Field Distribution of the Designed Optical Waveguide.

V. OPTICAL FIELD DISTRIBUTION

Optical field profiles of the rectangular optical waveguide can be calculated using the Maxwell equations [8], [9]. The optical field in core region is a sinusoidal function and the optical fields in outer sides of the core region are expressed as an exponential function to decay. Field distribution of the designed optical waveguide is shown in Figure 6.

The calculated field distribution with contour curve in the xz-plane is shown in Figure 6 (a). We can see that strong fields are confined in the waveguide core with single mode. A 3-D curve for the calculated field distribution is also shown in Figure 6 (b) where the y-axis is the field magnitude with arbitrary unit (a.u.). Clear strong fields are illustrated in the 3-D curve.

The rectangular optical waveguide for single mode operation at 1.55 µm optical wavelength is designed with 2 µm-depth waveguide core and 4 µm-width waveguide core. The designed optical waveguide are fabricated on a $LiTaO_3$ crystal using annealed proton exchange methods. The fabrication process will be discussed in the other paper.

CONCLUSION

We have discussed regarding design of rectangular optical waveguide on a $LiTaO_3$ crystal using proton exchange method with thermal annealing process. The optical waveguide was designed using the Marcatili method by separating rectangular optical waveguide into two slab optical waveguides. The modal dispersion and field profiles of the designed optical waveguide were discussed for single mode operation at 1.55 µm optical wavelength. Based on the result, single mode rectangular optical waveguide on a $LiTaO_3$ crystal can be obtained when waveguide core size is 2 µm-depth and below 7 µm-width. TM mode optical fields are operated in the annealed proton exchange optical waveguide on a $LiTaO_3$ crystal.

Fabrication processes of the designed optical waveguide using standard lithography process will be reported later in other paper. Measurement of the optical waveguide characteristics using simple measurement setup will be also reported later.

Planar optical waveguidesare promising for integrated optic applications such as optical interconnects for high-speed data transfer, optical sensor for precise measurement, and so on. Compact optical devices can be obtained based on the planar optical waveguide with large bandwidth and high speed for transferring data.

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