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Optimization of Ti-indiffused $LiNbO_3$ Optical Waveguide for Fiber Coupling

Han-Young Lee*, Woo-Seok Yang, and Woo-Kyung Kim

Optical Telecommunication Research Center, Korea Electronics Technology Institute, Pyungtaek-si, 451-865 Kyunggi-do, KOREA

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The structure of Ti:$LiNbO_3$ optical waveguide with a mode size far different from that of single mode optical fiber has been optimized by tapering the waveguide ends. This work was focused on determining the optimized sets of parameters for the fabrication of low-loss Ti indiffused optical waveguides in $LiNbO_3$. Numerical and analytical modeling were applied to simulate the guiding quality and to determine the mode sizes. Based on these modeling results, new waveguide structures with tapered ends have been defined, fabricated and characterized in the respect of the coupling of fiber to Ti-indiffused $LiNbO_3$ waveguide.

OCIS codes : 230.4110, 230.7390, 230.7020, 230.2090, 230.3120

I. INTRODUCTION

Ti-indiffused $LiNbO_3$ optical waveguide devices are most commonly used planar integrated optical devices to exploit electro-optic and acousto-optic properties for optical telecommunication and sensing applications [1]. Since the Ti:$LiNbO_3$ waveguide is produced by a diffusion process, the refractive index in the cross section of the waveguide is dispersively changing and its profile is not circular. Consequently, the mode shape of the Ti:$LiNbO_3$ single mode waveguide strip is elliptical but not symmetrical. The optical field overlap between a Ti:$LiNbO_3$ waveguide and single mode optical fiber is not as high as for the silica optical waveguide which is surrounded by silica clad with lower refractive index, which results in a step refractive index gradient-like optical fiber. The coupling loss due to the mode size mismatching between the Ti:$LiNbO_3$ waveguide and optical fiber contributes to the total insertion loss of a device and should be minimized as the integrated devices are getting more complicated. The reflection loss caused by the refractive index difference between Ti indiffused lithium Niobate and silica optical fiber should be also considered for the maximum coupling.

Several investigations have been reported for the coupling of Ti:$LiNbO_3$ waveguide to single mode fiber [2-6]. Recently, mode size converter technology is a key issue in silica planar circuits since the width of silica waveguides gets narrower to increase integration density [7-9]. Fukuma et. al. [6] obtained a minimum fiber-waveguide-fiber insertion loss of 3.8 dB at 1.15 μm wavelength under various waveguide diffusion parameters, which value includes propagation loss for a 1 cm long Ti:$LiNbO_3$ waveguide and Fresnel refection loss at the two fiber-waveguide interfaces. Alferness et. al. [3] have formulated a model to calculate the vertical and horizontal mode size and fabricated waveguides under a variety of Ti strip thickness and width to obtain an optimized waveguide with fiber-waveguide coupling loss of 0.35 dB at 1.32 μm wavelength.

In this paper, we propose Ti:$LiNbO_3$ waveguide with a tapered structure at both the ends for a maximum coupling of waveguide to fiber. A straight waveguide chip, whose ends were mirror-like polished, was used as a Fabry-Perot resonant cavity to measure the propagation loss of Ti:$LiNbO_3$ waveguide itself, independent of the fiber-waveguide alignment efficiency. The TE and TM mode sizes were measured as a function of Ti metal strip width. Based on the mode size measurement results of straight Ti:$LiNbO_3$ waveguides, the waveguide structure was modified to have appropriate tapered ends.

II. MODELING OF SINGLE MODE $LiNbO_3$ WAVEGUIDE

In order to calculate the mode sizes and the propagation constants of guided modes in Ti-indiffused waveguides in $LiNbO_3$, the wave equation given by [10]

$$\left[\alpha_x^{-2}\frac{\partial^2}{\partial x^2}+\alpha_y^{-2}\frac{\partial^2}{\partial y^2}+n^2(x, y)k_0^2-\beta^2\right]\Phi(x, y)=0 \tag{1}$$

should be solved. The coordinate system is chosen in such a way that the waveguide is oriented along the z-axis, and the y-axis is perpendicular to the substrate surface. k_0 is the vacuum wave number and β is the propagation constant of the mode with the field distribution Φ (x, y). n(x, y) is the refractive index profile determined by the fabrication parameters. The factor α depends on the polarization. For TE modes $\alpha_x = n_z/n_x$ and $\alpha_y = 1$. n_x and n_z are the refractive indices along the respective directions. Similarly, for TM-polarized modes, $\alpha_x = 1$ and $\alpha_y = n_z/n_y$.

The refractive index change due to the indiffusion of Ti is related to the Ti concentration c in different ways for the extraordinary and the ordinary polarization: $\delta n_{e,633} = Ec_{Ti}$, $\delta n_{o,633} = |Fc_{Ti}|^{\gamma}$ with constants of $E = 1.2 \times 10^{-23}$ cm^3, $F = 0.13 \times 10^{-24}$ cm^3 and $\gamma = 0.55$. The refractive index distribution in Ti:$LiNbO_3$ strip waveguides at a certain wavelength λ can be expressed as below by using the refractive index change at $\lambda = 633$ nm, which is driven based on a Fick type diffusion law.

$$\delta n_e = \frac{0.839\lambda^2}{\lambda^2 - 0.0645}\delta n_{e,633} \tag{2}$$

$$\delta n_o = \frac{0.8\lambda^2}{\lambda^2 - 0.08066}\delta n_{o,633} \tag{3}$$

where δn_e and δn_o are the refractive index change for the extraordinary and the ordinary polarization, respectively. The index profile discussed above is deduced from experimental investigations of the Ti concentration and of the dispersion of this index increase. However, this profile does not match exactly the experimental investigations of mode sizes. There may be additional contributions to the change of the refractive index especially in narrow stripe structures. They may, for example, arise due to stress in the crystal induced by the indiffusion as in the case of stress-induced $LiNbO_3$ optical waveguide. It is considered from comparisons of experimentally and theoretically determined mode sizes that a better agreement can be driven when only about 70 - 80% of the evaporated Ti thickness is applied for the calculation.

There is no analytical solutions for the wave equation with the above described refractive index profiles. Therefore, either numerical or approximate methods should be approached. The finite element method (FEM) is a well-known technique to solve such differential equations. Although the FEM gives exact solutions within the numerical accuracy, it is often helpful to have an approximate analytical solution as well. As will be described later, overlap integrals with the fiber profile were calculated in order to optimize fiber-waveguide coupling. For this purpose, an analytical description of the mode field allows a fast computation even for a large variation of fabrication parameters. The Gauss-Hermite-Gauss method (GHG) was used for an approximate analytical solution as described in [11]. The mode fields of the fundamental mode are approximated by a Gaussian function in the lateral direction and by a Hermite-Gaussian function in the depth direction, i.e. the mode field is approximated by

$$\Phi(x, y) = \psi(x)\varphi(y) \tag{4}$$

with

$$\psi(x) = \sqrt{\frac{2}{\sqrt{\pi}w}}\exp\left(-\frac{2x^2}{w^2}\right)$$
$$\varphi(y) = \frac{2}{\sqrt{d\sqrt{\pi}}}\frac{y}{d}\exp\left(-\frac{y^2}{2d^2}\right) \tag{5}$$

where w and d are horizontal and vertical mode field diameters, respectively. There are only two free parameters w and d in using this approximate solution. Besides the fundamental mode, even the first higher order mode with an asymmetric lateral field distribution can be calculated. For this purpose, the Gaussian function $\Psi(x)$ has to be replaced by a Hermite-Gaussian function.

The objective of the calculations performed in this work was first to determine appropriate parameter sets for single mode waveguiding. Therefore, the Ti layer thickness and the waveguide width were varied for two different diffusion conditions (1030℃ and 1060℃ for 9 hours). The calculations were performed using the FEM method for an optical wavelength, λ =1550 nm. In order to quantify the guiding quality, the normalized guiding parameter b defined by

$$b = \frac{n_{eff}^2 - n_{sub}^2}{n_{\max}^2 - n_{sub}^2} \tag{6}$$

was calculated. n_{eff}, n_{sub}, and n_{max} are the effective index of the mode, the refractive index of the substrate and the maximum refractive index at the waveguide surface, respectively. The results of the calculations for TM polarized modes in z-cut $LiNbO_3$ and TE polarized modes in x-cut $LiNbO_3$ are shown in Fig. 1 and Fig. 2, respectively. Those modes correspond to the extraordinary wave for each crystal directions and are mostly used to exploit electro-optic properties of lithium niobate crystal. The normalized parameters b for the fundamental and first higher order mode are plotted as a function of the stripe width, i.e. the width of the Ti stripe before indiffusion. Curves for stripe thicknesses ranging from 40 nm to 100 nm are given.

There was only a little influence of the diffusion temperature on the b parameters. The guiding was only

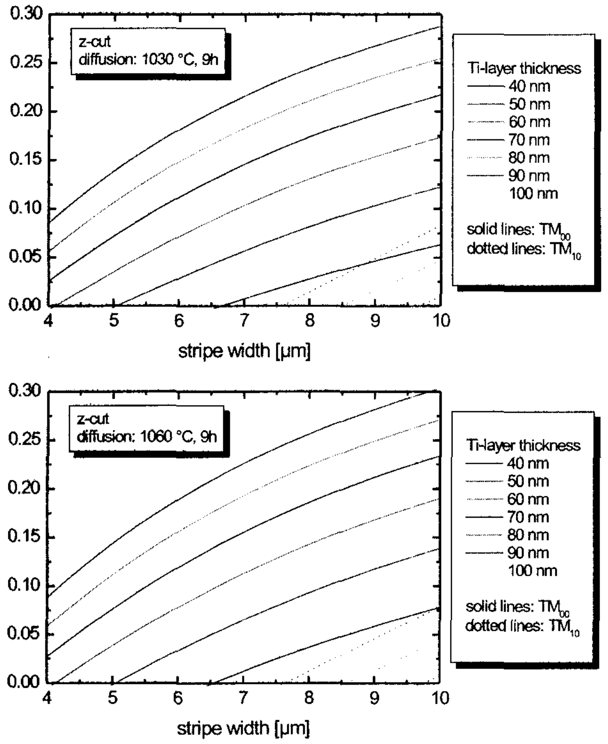

FIG. 1. Calculated guiding parameter b as function of stripe width for TM-modes in z-cut Ti-diffused optical stripe waveguides. Curves for different thicknesses of the Ti-layer are shown. A 9 hour long diffusion at 1030℃ (upper diagram) and 1060℃ (lower diagram) has been assumed.

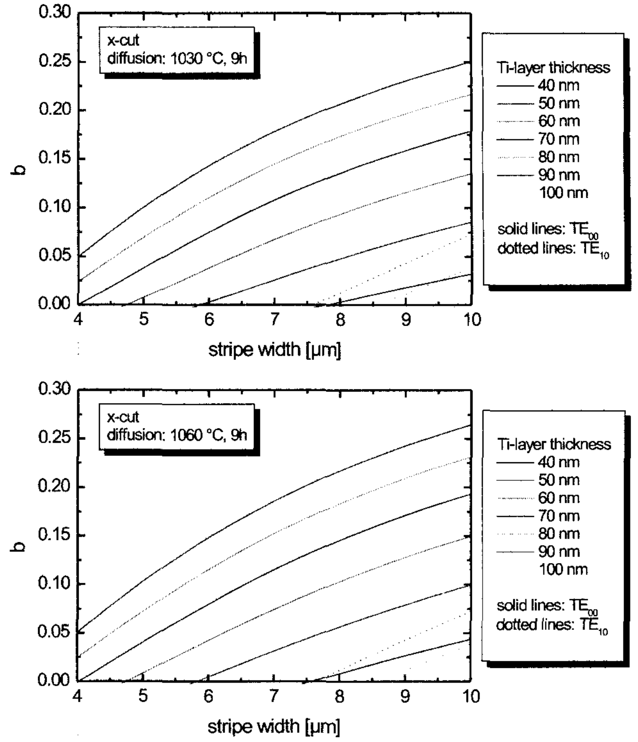

FIG. 2. Calculated guiding parameter b as function of stripe width for TE-modes in x-cut Ti-diffused optical stripe waveguides. Curves for different thicknesses of the Ti-layer are shown. A 9 hour long diffusion at 1030℃ (upper diagram) and 1060℃ (lower diagram) has been assumed.

slightly better for wider stripes diffused at higher temperature. This weak dependence on the diffusion temperatures is apprehensible in terms of the overall amount of Ti atoms, and hence the integral refractive index change, i.e. the index change summated over the waveguide cross section is constant. A different behavior would be expected for ordinary polarized modes. Due to the nonlinear dependence of the refractive index change on the Ti concentration a significantly better guiding can be expected for diffusion at higher temperature, as the average Ti concentration is smaller in this case. According to the calculations, there exists a relatively wide parameter range where single mode guiding can be achieved. For instance, with a 600Å thick Ti layer the single mode range covers stripe widths from about 4 mm to more than 10 mm.

III. FIBER TO WAVEGUIDE COUPLING

In order to minimize the coupling loss at the transition between the optical fiber and the waveguide, the overlap of two mode field distributions must be maximized. It was assumed for the coupling loss calculations that an optical fiber has a circularly symmetric Gaussian-shaped mode field. According to the specification of the Corning SMF-28 fiber, the mode field diameter MFD is 10.4 ± 0.8 μm, which corresponds to the intensity full width at half maximum (FWHM) of 6.1 μm. To begin with, the coupling losses were calculated using the GHG approximation for the waveguides. This has the advantage that an analytical solution of the overlap integral is obtainable. The sizes of the waveguide modes were calculated as the strip width and the thickness of the Ti layer were varied, optimizing the center position of the fiber in order to yield the minimum coupling loss. The results of these calculations are shown in Fig. 3 and Fig. 4.

In the diagrams above, the loss in dB is plotted as function of the stripe width and the layer thickness. The minimum loss was obtained in narrow stripes with thin Ti layer for both the crystal orientations. However, higher propagation losses are expected in such a narrow stripe width since the modes are very close to the cut-off condition. Using a deeper diffusion (1060℃ instead of 1030°) yields smaller losses. This is due to the fact that the vertical mode size increases with diffusion depth and, hence, the overlap integral gets

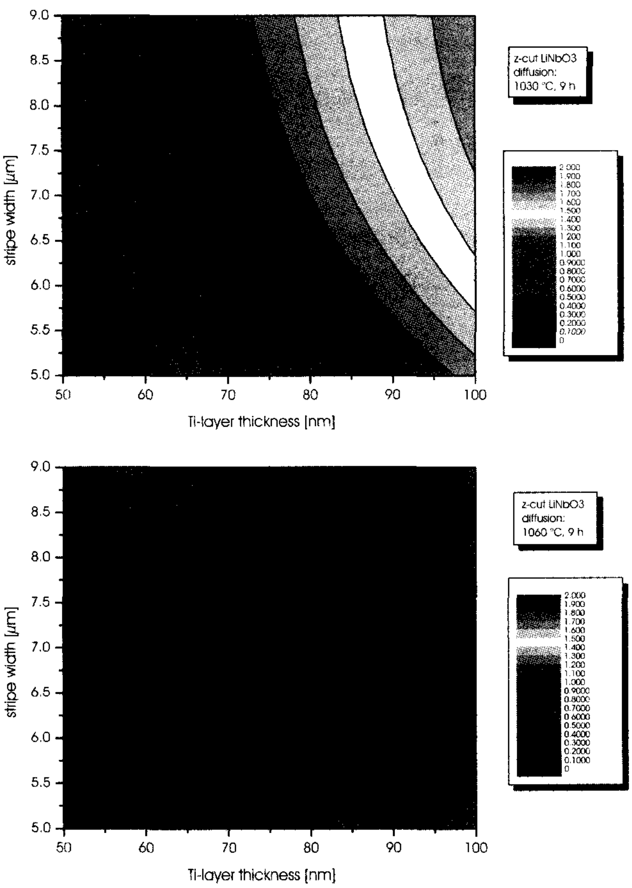

FIG. 3. Calculated coupling loss in dB due to mode size mismatch for coupling between Corning SMF-28 fiber and Ti-diffused waveguides in z-cut $LiNbO_3$ as function of Ti-stripes width and layer thickness. Upper diagram: diffusion at 1030℃, 9 hours; lower diagram: diffusion at 1060℃, 9 hours.

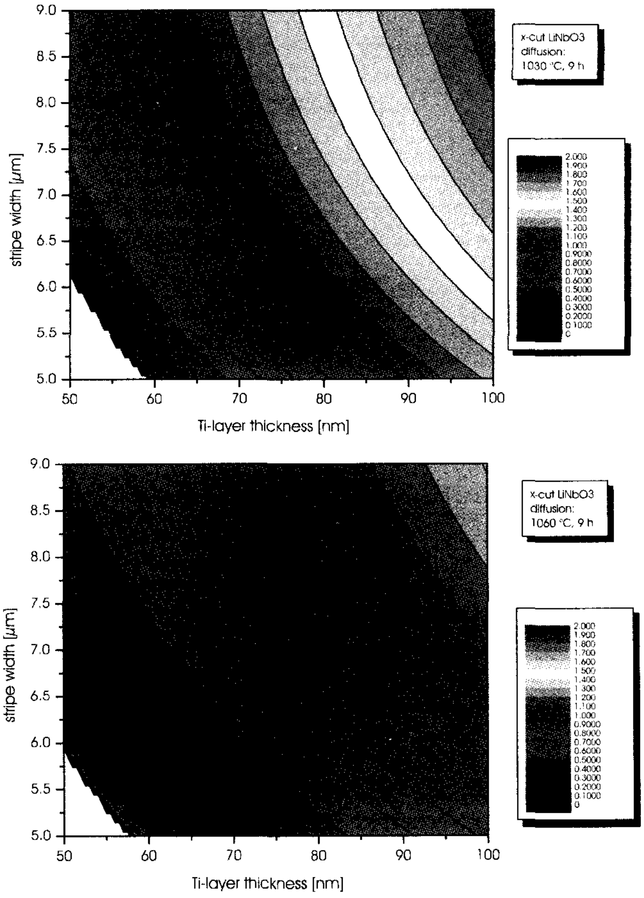

FIG. 4. Calculated coupling loss in dB due to mode size mismatch for coupling between Corning SMF-28 fiber and Ti-diffused waveguides in x-cut $LiNbO_3$ as function of Ti-stripes width and layer thickness. Upper diagram: diffusion at 1030℃, 9 hours; lower diagram: diffusion at 1060℃, 9 hours.

larger. When using a stripe width around 7 μm and Ti layers of about 700Å thickness, it should be possible to limit the coupling losses due to field mismatch to less than 0.7 dB.

To verify that the GHG approximations yield sufficiently precise results, some further calculations were performed by using the FEM for mode field calculation and a numerical evaluation of the overlap integral. In Fig. 5 the coupling loss as a function of the stripe width is shown. The calculations were performed for the case of TM polarized waves in z-cut $LiNbO_3$ waveguides, which were fabricated by indiffusing 700A thick Ti stripes for 9 hours at 1060℃. This comparison reveals that the losses calculated by the FEM are slightly smaller for wider stripes. However, the differences between the results obtained by the two calculation methods are in an acceptable range.

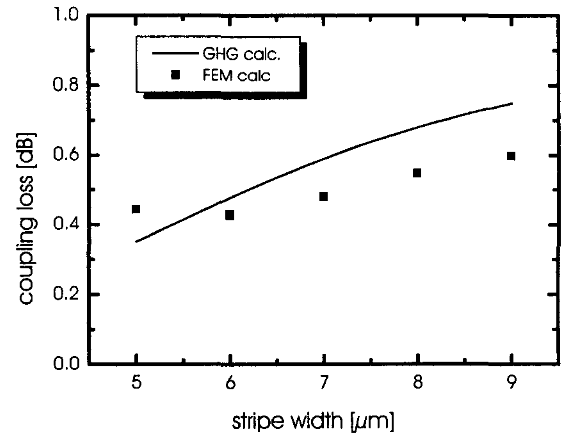

FIG. 5. Calculated coupling loss in dB due to mode size mismatch for coupling between Corning SMF-28 fiber and TM polarized waveguide mode in z-cut $LiNbO_3$ as function of Ti-stripes width (layer thickness: 70 nm, : diffusion at 1060℃, 9 hours). The solid lime was obtained using the GHG-approximation, and the symbols mark FEM results.

IV. FABRICATION AND CHARACTERIZATION OF TAPERED WAVEGUIDES

Based on the modeling results described in the preceding section, test structures have been developed for the fabrication of optical waveguides. A mask has been designed with a series of waveguides with different widths and tapering of the widths at one end of the structure. Two groups of waveguides, one of straight structure and the other of tapered structure, were fabricated. The straight waveguide group consists of 9 stripes with width varying from 4.5 μm to 8.5 μm in steps of 0.5 μm. The stripes are laterally 100 μm separated to avoid optical interaction between neighboring waveguides. The tapered structures are single-side tapered with a starting width W_s and an end width W_e. The length of the taper section is 2000 μm. There are three different tapered structure groups with parameters, which are listed in Table 1.

A set of samples was fabricated in the fabrication conditions as follows (substrate material: z-cut $LiNbO_3$, evaporated Ti-layer thickness: 960Å, diffusion temperature: 1060℃, diffusion time: 8.5 hours, diffusion ambient conditions: Ar during the first 7.5 hours and O_2 during the last hour).

After the diffusion process, the wafer was diced and optically end-polished to characterize with respect to propagation loss and mode size. For the loss measurements the resonance method [12], which was slightly modified in KETI, was used. The typical results obtained from one sample are shown in Fig. 6. The measured loss is plotted versus the stripe width, i.e. the width of the titanium stripe before indiffusion. Although there are some variations of the loss, it can be seen clearly that for most of the structures the losses are in the range of 0.2 dB/cm. Even for quite narrow structures with widths around 5 μm the losses are reasonable low. Besides the straight waveguides, the tapered structures have been investigated as well. It has been found that there is no significant increase of the losses due to the tapering. The measured mode sizes are

Table 1. The waveguide dimension parameters to optimize the fiber-waveguide coupling.

Group T1		Group T2		Group T3	
L = 1100μm		L = 1300μm		L = 900μm	
W_s [μm]	W_e [μm]	W_s [μm]	W_e [μm]	W_s [μm]	W_e [μm]
8.0	8.0	8.0	8.0	7.0	7.0
7.5	8.0	7.5	8.0	6.5	7.0
7.0	8.0	7.0	8.0	6.0	7.0
6.5	8.0	6.5	8.0	5.5	7.0
6.0	8.0	6.0	8.0	5.0	7.0
5.5	8.0	5.5	8.0	6.0	6.0
5.0	8.0	5.0	8.0	5.5	6.0
6.0	6.0	7.0	7.0	5.0	6.0
5.5	6.0	6.5	7.0		
5.0	6.0	6.0	7.0		
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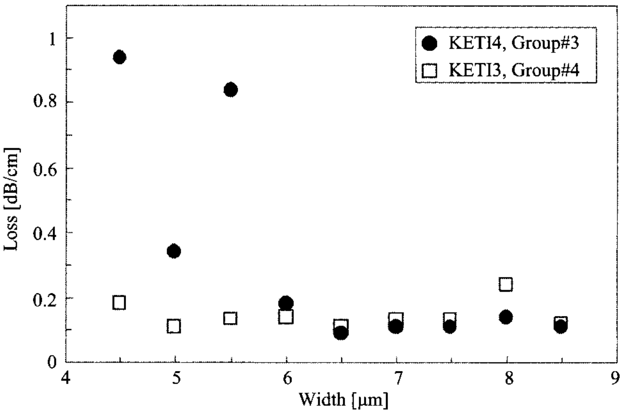

FIG. 6. Measured propagation loss of waveguides versus titanium stripe width for 1550 nm TM polarized mode.

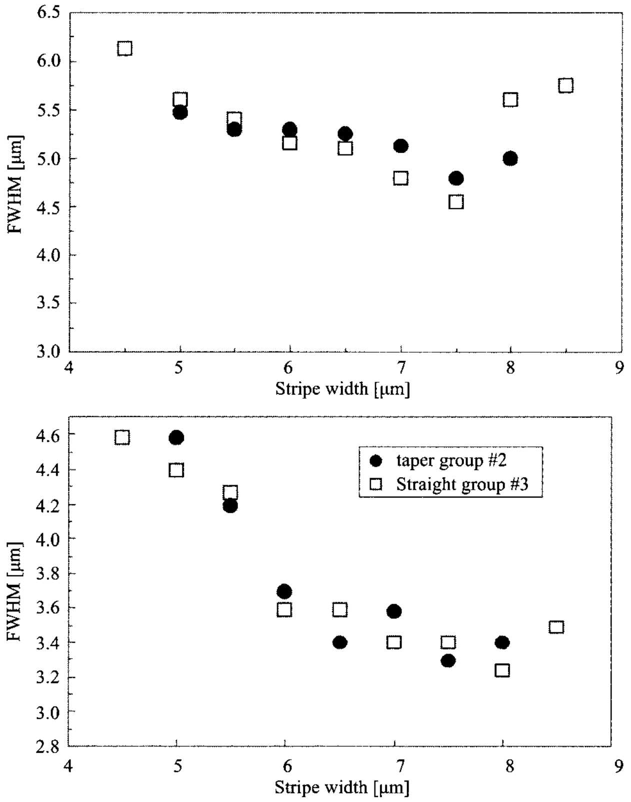

FIG. 7. Measured mode sizes of waveguides versus titanium stripe width for 1550 nm TM polarized mode (left: lateral mode width, right: vertical mode width).

shown in Fig. 7. In the left diagram the full width at half maximum (FWHM) of the lateral mode intensity distribution is shown, the corresponding results for the vertical direction are given in the right diagram. The stripe width has a relatively small effect on the lateral widths. However, the vertical mode sizes increase significantly with decreasing stripe width. Such an increase is required for an efficient fiber-waveguide coupling. Therefore, it can be expected that the coupling loss is smaller for narrower waveguides.

IV. CONCLUSIONS

We have demonstrated the simulation and experiments concerning an optimization of fabrication conditions of Ti-indiffused optical waveguides in z- and x-cut $LiNbO_3$. In a first step a parameter range for single mode guiding was determined. The modeling revealed that there should be a relatively broad range of parameters in which the waveguide supports only a single guided mode. Furthermore, the coupling efficiency at the transition between a single mode fiber (Corning SMF-28) and a Ti-diffused optical waveguide has been calculated. It was found that a rather deep diffusion is necessary to minimize the coupling losses. With a 9 hour long diffusion at 1060℃ coupling losses can be kept below about 0.5-0.7 dB using stripe width in the range of 7 μm. Additionally, loss of about 0.2 dB is due to reflection at the interface. Approaching close to cut-off, for instance by using narrower waveguides, may further reduce the coupling losses. On the other side, this may result in increasing propagation losses and, hence, in increasing overall losses. It is concluded that the coupling loss can be reduced by tapering the waveguide with a smaller width in the coupling regions and by keeping a wider width in the middle of the device.

*Corresponding author : hylee@keti.re.kr

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