고분자 버퍼층을 갖는 $LiNbO_3$ 집적 광디바이스

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$LiNbO_3$ integrated optic devices with an UV-curable polymer buffer layer

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Abstract - A new lithium niobate optical modulator with a polymer buffer layer on *Ni* in-diffused optical waveguide is proposed for the fist time, successfully fabricated and examined at a wavelength of *1.3 μm*. The experimental results show that the measured half-wave voltage is of *~10 V* and the total measured fiber-to-fiber insertion loss is of *~6.4 dB* for a *40 mm* long waveguide at a wavelength of *1.3 μm*, respectively.

1. Introduction

The two mainly used techniques for the fabrication of $LiNbO_3$ optical waveguides are *Ti* in-diffusion and proton exchange [1,2]. *Ti* in-diffusion is a high temperature process that increases both ordinary and extraordinary indices ($\triangle_{no}$ and $\triangle_{ne}$), and gives waveguides both the ordinary and extraordinary polarizations in $LiNbO_3$ [3]. Proton exchange is a relatively low-temperature process that provides waveguides with supporting only the extraordinary polarizations ($\triangle_{no}<0$ and $\triangle_{ne}>0$). For some applications, a singly polarized waveguide can be desirable for better device performances so that the interaction between the *TM* and *TE* waves can be avoided. Recently, not only *TE* but also *TM* and both *TE/TM* polarized waveguides have been demonstrated by *Ni* in-diffusion, which can be obtained by varying the fabrication conditions of *Ni* in-diffusion [4]. Furthermore, one of important advantages in *Ni* in-diffused waveguides is relatively low-diffusion process in compare with *Ti* in-diffusion, so that there is no out-diffusion guiding layer by Li_2O and no changing electro-optic coefficient [5].

However, most of common $LiNbO_3$ modulators have been employed a buffer layer of SiO_2, because a metallic layer, such as gold-electrodes, induces high propagation loss in guided optical fields. The process of SiO_2 layer requires a high temperature of over *300 ℃* to form a reasonable quality of deposited SiO_2 layer on the top of $LiNbO_3$ waveguides, but in case of *Ni* in-diffused waveguides such a high temperature may induce un-expected index changes in *Ni* in-diffused waveguide because of rapid diffusion of *Ni* metal source into $LiNbO_3$ substrate[1,6]. On the other hand, a fabrication process with a polymer material to build the similar buffer layer on $LiNbO_3$ waveguides can be significantly simple as compared to the traditional process of $LiNbO_3$ waveguides due to the low temperature process and easy control of a polymer material. This polymer is originally used for making polymer waveguides in the integrated optic areas as seen in [9].

From the earlier reported papers [1-8], *Ni* in-diffusion method can be a good alternative in the $LiNbO_3$ integrated optic devices, but the optimum fabrication condition of the *Ni* in-diffused waveguides for the fiber-pigtail has not been established at this point.

Furthermore, there are several applications of *Ni* waveguides such as Mach-Zehnder interferometric modulators, directional couplers and splitters, but any competitive result against *Ti*: $LiNbO_3$ waveguides has not been reported till now.

Therefore, in this work, further investigations into *Ni* in-diffused waveguides regarding to the fabrication condition of optimum mode in *Ni* in-diffused waveguides and its optical confinement including the polymer buffer layer effect on the driving voltage have been carried out under several diffusion condition at a wavelength of *1.3 μm*.

2. Fabrication & Results

Several sets of waveguides were fabricated by diffusing *Ni* film evaporated onto a $LiNbO_3$ substrate in a tube furnace at a temperature of *900 ℃* for diffusion time ranging from 1 to 3 *h*. All channel waveguides before diffusion have a width of *8 mm*, and *Ni* thickness of *300 Å*. The *Z*-cut $LiNbO_3$ wafers were used for the fabrication of waveguide. After diffusing, a UV-curable epoxy (*UV-15*, Masterbond Co.) layer was spun on diffused waveguides to give a buffer layer between optical waveguides and metal electrodes. The gold electrodes of *1.5 μm* thickness were formed by electroplating and diced to each device. The device end-faces were cut without an angle to the waveguides and then polished to an optical finish.

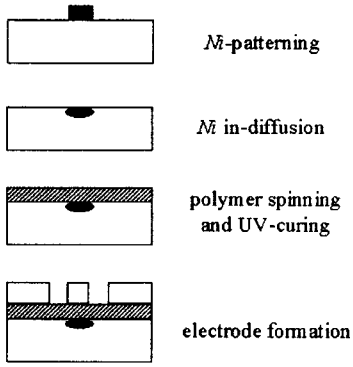

Fig. 1. Fabrication procedure of a $Ni:LiNbO_3$ integrated optic device with a polymer buffer layer.

In order to investigate the optical intensity distribution of the *Ni* in-diffused waveguide output power that is required to get a mode match to a single mode fiber, Near-field patterns of a series of fabricated channel waveguides were observed. Figure 2 shows the variation of mode sizes of fabricated *Ni* in-diffused waveguides with several diffusion time along the width and depth direction of the channel waveguide, respectively. The mode diameters in width and depth directions were evaluated at the 1/e point of each near field pattern for comparison. From the figure 2, it is found that the mode sizes in depth and width of waveguides were slightly dependent on the diffusion time for the fundamental *TM* mode. As diffusion time increases, the mode size in depth increases rapidly. On the other hand, the mode size in width was not changed too much along the diffusion time. However, making the diffusion time shorter, the optical confinement of the guided mode becomes much stronger [12]. The sample at a diffusion time of *1 h* has mode size of *4.54* μm in depth and *7.52* μm in width, that is, the shorter diffusion time can make the mode size a short. It is considered that the best diffusion time at this point which has more desirable mode size comparable to a single mode fiber was turned out to be a diffusion time of *3 h*. In other words, among the examined conditions, even though waveguides fabricated by diffusion time of *1 h* with a diffusion temperature of *900* ℃ looks like having an excellent optical confinement, the waveguides fabricated under *900* ℃ for *3 h* has more appropriate mode sizes in depth of *8.86* μm and width of *7.68* μm to that of a single mode optical fiber which usually has *8~10* μm of core size.

In the case of the diffusion condition of *900*℃ for diffusion time of *3 h*, the near field optical contour profile and the mode profile in depth and width direction are shown in Figure 3. It is also believed that it has excellent optical confinement and less substrate radiation. The waveguide mode profile in the depth direction is a little asymmetric as expected and the mode shape in width was essentially Gaussian mode.

Also the mode profile of the fiber was measured and mode diameter at the 1/e intensity was turned out to be *7.58* μm.

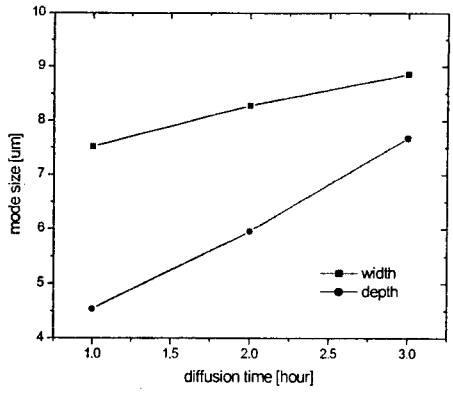

Fig. 2. Optical output distribution of *Ni* in-diffused channel waveguides in depth and width for the fundamental *TM* mode at a wavelength of *1.3* μm under a diffusion temperature of *900* ℃.

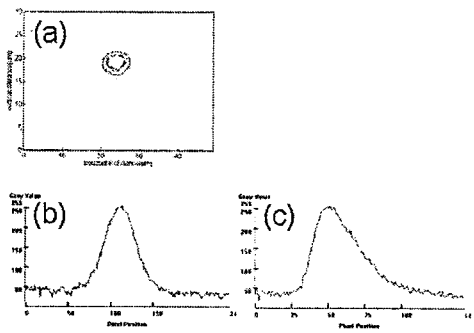

Fig. 3. Optical contour profile (a) and mode size in width (b) and depth (c) of the fundamental *TM* mode of the *Ni* in-diffused channel waveguide at a wavelength of *1.3* μm. The fabrication condition was diffusion time of *3 h*, temperature of *900* ℃, and *Ni* thickness of *300* Å.

The expected coupling efficiency can be evaluated by computing the overlap integral between the fiber and the measured modes for *Ni* in-diffused channel waveguide. A power coupling coefficient can be written as [15]

$$\kappa = 0.93\left[\frac{4}{(w_x/a+a/w_x)(w_y/a+a/w_y)}\right] \quad - - - \quad (1)$$

Where a is the fiber mode diameter at 1/e optical intensity, and ω_x is the measured 1/e intensity full width and ω_y is full depth, respectively. More conveniently [16], to investigate the dimensional dependence of the expected coupling loss, the power coupling coefficient can be written as

$$\kappa = 0.93\left[\frac{4(w/a)^2}{((w/a)^2+\varepsilon)((w/a)^2+1/\varepsilon)}\right] \quad --- \quad (2)$$

Where ω is the geometric mean, $\omega = 1/(\omega_x\ \omega_y)$, and is the ratio of the waveguide mode width to depth $\varepsilon = \omega_x/\omega_y$. The fabrication condition of *Ni* thickness of *300 Å* and diffusion time of *3 h* gives the aspect ratio, of *1.53* which contributes *0.085 dB* per interface to the coupling loss, thus according to the equation (2), the total expected coupling loss will *be 0.526 dB* per interface.

In order to determine the relative contribution of coupling and propagation loss to the total insertion loss, the devices were aligned with fibers, a PMF for input endface and a SMF for output endface of a channel waveguide. The coupling loss of *~0.43 dB* and propagation loss of *1.39 dB/cm* evaluated from cut-back method have been achieved. The total measured fiber-to-waveguide-to-fiber insertion loss for *4.0 cm* long waveguide was as low as *~ 6.42 dB*. It is noticed that the estimated value of the coupling loss of *0.43 dB* was lower than the calculated one of *0.526 dB*, so that the waveguide mode in depth is probably less mismatched to that of the fiber.

For evaluating the thickness effect of polymer buffer layer on the driving voltage of the fabricated devices, a simple closed-form solution was used to calculate the optical-electrical field overlap as a function of the thickness of the polymer buffer layer [8, 11, 18]. The transverse field profile $E_{op}(x,y)$ of the optical waveguide can be expressed by a Hermite-gaussian function. And also an overlap integral of the optical field profile with the electric field profile is quantitatively evaluated

$$\Gamma = \frac{V}{S}\frac{\int\int E_{op}(x,y)^2 E_{el}(x,y)dxdy}{\int\int E_{op}(x,y)^2 dxdy} \quad --- \quad (3)$$

The driving voltage V can be expressed as

$$V_\pi = \lambda\frac{S}{2(n^3 r_{33} L\Gamma)} \quad --- \quad (4)$$

Where λ is the optical wavelength, n is the optical refractive index, L is the length of the electrode, r_{33} is the electro-optic coefficient that produces a phase change for light polarized in z-direction for a z-directed applied electric field, and is the overlap integral. As an example of the calculated results, a buffer layer of *1 μm* with silicon oxide gives a driving voltage of *5.8V* : on the contrary, a polymer buffer layer of *1 μm* gives a driving voltage of *9.5 V* which value is over *59* percent higher than that of silicon oxide buffer layer according to the same calculation with the relativity permittivity of *4.0* for silicon oxide [21]. In order to realize an acceptable performance with a driving voltage, the buffer layer thickness should be determined by ~ 0.5 *μm* to keep the driving voltage less than *7 V*.

Fig.4 (a) shows the modulation output of the fabricated Ni in-diffused lithium niobate modulator operating at a wavelength *1.3 μm* wavelength that is corresponding to the diffusion condition of *900 °C* for *3 h*. The thickness of polymer buffer layer and electrode thickness was *0.75 μm* and *1.5 μm*, respectively. The measured half-wave voltage was about *~ 10 V*. The measured value was much worse than the simulation result. A possible reason showing a worse driving voltage would be the fabrication error which could be caused by a misalignment between waveguide and electrodes. Another reason is that the simulation method may lead to inaccurate result at this point. The measured electro-optical modulation shows that the extinction ratio is high of *13.0 dB* enough for practical applications. The picture in Fig.5 (b) shows one of devices aligned with fibers in both sides of waveguide.

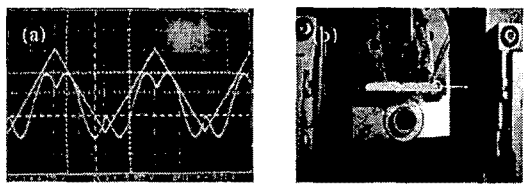

Fig. 4. (a) The modulation performance of a *Ni* in-diffused modulator at a *1.3 mm* wavelength under diffusion condition of temperature of *900 °C* for time of *3 h*. Upper trace is the modulating voltage (5V/*div*), lower trace is the optical signal (200m*V/div*). The buffer layer was defined by *0.75 mm* thickness of *UV-15* polymer. (b) a photo of one of waveguide devices aligned with fibers.

3. Conclusion

A *Ni* in-diffused lithium niobate modulator with a polymer buffer layer was experimentally fabricated and characterized. By studying the mode size variations along the diffusion time, the optimum fabrication condition was extracted. The measured coupling loss of *~0.43dB* and propagation loss of *1.39 dB/cm* have been achieved. The fabricated device shows a driving voltage of *~10 V* and extinction ratio of over *13.0 dB* and the fiber to fiber insertion loss was found to be less than *6.4 dB*. Moreover, It is found that the fabrication process of the *Ni* in-diffused optical modulator can be significantly simplified by using the polymer buffer layer because of easy fabrication-process compared with that of silicon oxide buffer layer.

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