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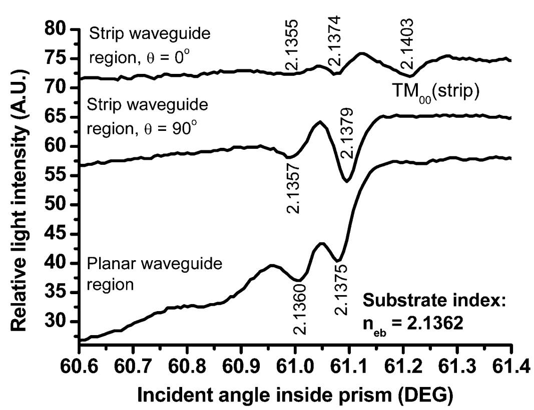

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Mode Indices Measurement of a Special Ti-Diffused $LiNbO_3$ Waveguide Structure: A Strip Waveguide Array Embedded in a Planar Waveguide

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Abstract: We demonstrate the feasibility of using a commercial Metricon 2010 prism coupler to characterize the mode indices (at 1.5-μm wavelength) of a special Ti-diffused $LiNbO_3$ waveguide structure where a single-mode strip waveguide is embedded in a multimode planar waveguide. To achieve it, a structure of a strip waveguide array embedded in a planar waveguide was fabricated. The characterization involves simultaneously coupling light from a prism into an array of identical strip waveguides and a planar waveguide. As a result, the modes of the strip waveguide and planar waveguides simultaneously appear on the light reflection pattern measured in the case where the strip waveguide axis is parallel to the prism axis. The mode belonging to the strip waveguide is assigned by comparing the pattern with that measured either from the clear planar waveguide area or also from the strip waveguide array area but in the case where the strip waveguide axis is perpendicular to the prism axis. The direct observation for the near-field mode pattern of the strip waveguide and the numerical results of both the strip and planar waveguides provide evidences for the mode assignment.

Index Terms: Ti-diffused $LiNbO_3$ waveguide, mode index, prism coupling.

1. Introduction

The special waveguide structure, where a strip waveguide is embedded in a planar waveguide, may find its use in developing some functional devices such as long-period waveguide grating (LPWG) [1]–[4] and photonic crystal waveguide device [5]. Of course, like the conventional strip waveguide, such special waveguide structure can also find its use in developing various passive and active devices. Obviously, the measurement of the effective indices of the modes guided in the strip and planar waveguides of such special structure is of crucial importance for the design and fabrication of related devices. The prism-coupling technique is a standard method for the measurement of the mode index of a thin film, a slab waveguide, or a planar waveguide [6], [7]. For a single-mode index-graded (such as ion-exchanged or metal-diffused) strip waveguide, the characterization for the mode index and hence the index profile is not an easy thing. As an alternative, one can do it from the measured near-field pattern of the guided mode [8], [9]. However, the near-field method requires highly accurate measurement data and a sophisticated data processing procedure. It is essential to explore other simple and practical methods. In principle, the prism-coupling method is also applicable to the strip waveguide. There is, however, a practical difficulty in getting accurate results with a commercial prism coupler system, which is designed for the thin films and slab waveguides rather than for the strip waveguide. Because the light spot from a commercial prism coupler system is $\sim$1 mm in diameter and the width of a strip waveguide is typically several micrometers only, very different from the planar waveguide case, the amount of light that can be coupled into a single strip waveguide is small. This leads to low contrast of dark lines (mode lines), which appear on the pattern of light reflected from the waveguide and correspond to the excitation angles of guided modes and, hence, gives rise to a poor resolution. The problem may be solved by employing an array of identical strip waveguides. When the waveguide separation is large enough, there is no interaction among the strip waveguides, and the reflection pattern generated from the prism coupler is the total contribution from all the strip waveguides. Thus, the contrasts of mode lines and hence the resolution can be improved considerably. By employing this method, the polymeric ion-exchanged glass [7] as well as proton-exchanged $LiNbO_3$ [1] channel waveguides have been successfully characterized. Among various types of waveguides, the Ti-diffused LN (Ti:LN) waveguide is the most attractive and most often employed. Besides the excellent electrooptic, acoustooptic, and nonlinear properties of the crystal itself, such waveguide is also of some other inherent merits such as lower waveguide loss, higher thermal, electric, and chemical stabilities, easily realizing rare-earth doping, retained crystalline phase and hence electrooptic property. Thus, the characterization for the Ti:LN strip waveguide is of more important significance. For the case of ion-exchanged glass or proton-exchanged $LiNbO_3$ channel waveguide, the waveguide is entirely defined underneath the glass or crystal surface, and there is no swelling of the waveguide surface. In this case, the waveguide surface and the base plane of the prism are tightly contacted, and hence, the prism-coupling measurement is readily realized. For the case of the polymeric channel waveguide, the waveguide is usually either ridge-type or rib-type. Nevertheless, the waveguide surface and the base plane of the prism are also tightly contacted because the polymer usually has lower hardness, and the prism-coupling measurement is also readily realized. For the Ti:LN strip waveguide, however, the situation is different. There is usually an apparent swelling (several tens of nanometers) of the waveguide surface due to the lattice expansion induced by the Ti in-diffusion. Moreover, the Ti:LN waveguide is obviously harder than the polymeric one. Due to these two factors and the imperfection of the waveguide surface, the contact between the prism base plane and the waveguide surface is not as tight as that between the prism base plane and the surface of the other waveguides mentioned above. It is unclear if the aforementioned prism-coupling method is also applicable to the Ti:LN strip waveguide. It is thus essential to carry out an additional study to clarify this point. Here, we exemplify a special Ti:LN waveguide structure, where an array of Ti:LN strip waveguides are embedded in a planar Ti:LN waveguide, and demonstrate the feasibility of using the prism-coupling technique to simultaneously measure the effective indices of the modes guided in the strip and planar Ti:LN waveguides of the special structure. To achieve that, we fabricated at first an array of single-mode (at 1.5-μm wavelength) Ti:LN strip waveguides (80 in total) embedded in a multimode planar Ti:LN waveguide. Then, the modes guided in the strip and planar waveguides of such a special structure were characterized by a commercial Metricon model 2010 prism coupler system. The assignment of the mode belonging to the strip waveguide is done by comparing the results measured from the clear planar waveguide area and from the strip waveguide array area in the two cases where the strip waveguide axis is aligned either parallel or perpendicular to the prism axis. To support the mode assignment, direct observation for the near-field mode pattern of the strip waveguide and theoretical analysis for the modes guided in both the strip and planar waveguides were carried out.

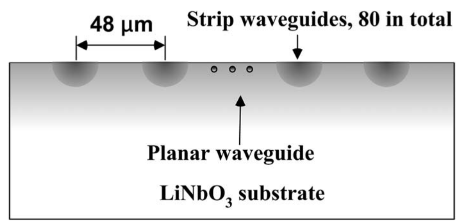

Fig. 1. Schematic of the cross section of an array of 80 8-μm-wide 48-μm-separated Ti:LN strip waveguides embedded in a Ti:LN planar waveguide.

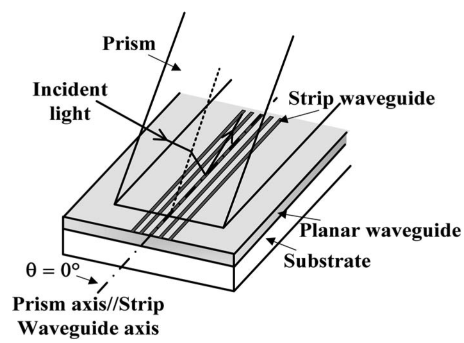

Fig. 2. Schematic of the characterization in the case where the strip waveguide axis is aligned parallel to the prism axis.

2. Fabrication and Characterization

The special Ti:LN waveguide structure, where an array of single-mode strip waveguides are embedded in a multimode planar waveguide, was fabricated in the following way. A 1-mm-thick Z-cut pure congruent LN plate with the optical grade surfaces was used as the substrate. At first, the planar waveguide was fabricated by in-diffusion of a 70-nm-thick homogeneously coated Ti film at 1050 °C for 10 h in an environment of flowing O_2 bubbled through 20 °C water at a rate of 1.5 L/min. Next, a 74-nm-thick Ti film was coated onto a part of the planar waveguide surface. The remaining part of the planar waveguide surface was not coated with a Ti film for the convenience of mode index characterization of the planar waveguide. By using the standard photolithographic technique and the method of wet Ti-metal etching in a mixed solution of hydrofluoric acid and nitric acid, an array of identical Ti strips, 80 in total, were patterned on the planar waveguide surface. Each strip has an initial width of 8 μm, and the period is 48 μm. Finally, the sample was further annealed at the same temperature for an additional 6 h under the same wet O_2 atmosphere. Accordingly, a special structure, where an array of 8-μm-wide 48-μm-separated Ti:LN strip waveguides are embedded in a Ti:LN planar waveguide, is formed on the crystal surface. Fig. 1 shows the schematic of the cross section of the special structure.

After the fabrication, the modes guided in the strip and planar waveguides of the special structure were characterized at the wavelength of 1553 nm by a commercial Metricon model 2010 prism coupler system with an index accuracy better than 0.0005. The characterization focuses on the transverse magnetic (TM) modes guided in the strip waveguide array area. The modes belonging to the strip waveguide and the planar waveguide may simultaneously appear on the measured light reflection pattern. To facilitate the assignment of the mode guided in the strip waveguide, the characterization was carried out in two different cases regarding the relative orientations between the strip waveguide axis and the prism axis. One case is that the strip waveguide axis was aligned parallel to the prism axis, as shown in Fig. 2. The other case is that the angle θ between the prism axis and the strip waveguide axis was 90°, i.e., the strip waveguide axis was aligned perpendicular to the prism axis, as shown in Fig. 3. For the same purpose of facilitating the mode assignment, the

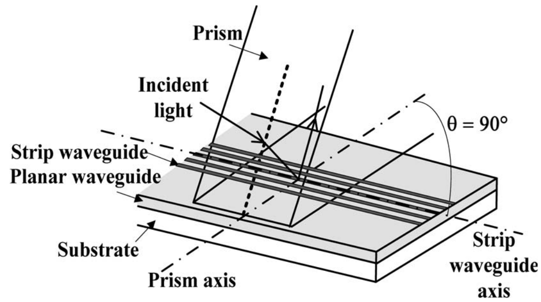

Fig. 3. Schematic of the characterization in the case where the strip waveguide axis is aligned perpendicular to the prism axis.

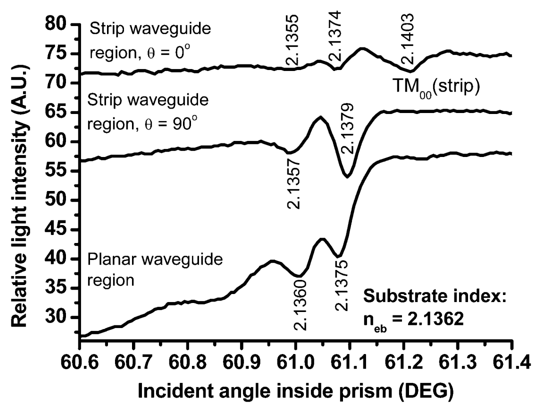

Fig. 4. Patterns of relative intensity of TM-polarized 1553-nm light (reflected from the surface of the strip waveguide array or the planar waveguide area) measured as a function of the incident angle inside the prism.

characterization was also carried out on the area where there is only the planar waveguide and no strip waveguide. All of the measurements were carried out under the room temperature of 20°.

To support the mode assignment, direct observation for the near-field mode pattern of the strip waveguide was carried out using the endface coupling technique. To facilitate the end-fire coupling, the two endfaces of the sample were optically polished. The final length of the waveguides is about 1.2 cm. The end-fire experiment was carried out by launching into the waveguides the polarized 1.5-μm light emitted from an AEDFA-23-B-FA erbium-doped fiber amplifier (Amonics Ltd.) with a bandwidth of 1530–1563 nm via endface butt-coupling between a section of polarization-maintaining fiber and one strip waveguide. A polarization controller (Optics for Research Inc.) was used to control the state of polarization of the light launched into the waveguide. The magnified near-field image of the guided TM mode was projected onto an LBA-USB-L130-1550 infrared CCD camera (OPHIR-Spiricon Inc.) through a Melles Griot microscope objective lens with a magnification of 40$\times$ and a numerical aperture (NA) of 0.65. The camera has a spectral response range of 1440–1605 nm and an effective pixel number of 1392 $\times$ 1040 with a pixel pitch of 3.2 μm in the lateral direction and 4.3 μm in the vertical direction. To increase the spatial resolution, a microscope objective lens with a large NA was employed. The mode pattern was captured with the aid of a computer.

3. Results and Discussion

Fig. 4 shows the patterns of relative intensity of TM-polarized 1553-nm light (reflected from the waveguide surface) measured as a function of the incident angle inside the prism. The three patterns were measured from the clear planar waveguide area and the strip waveguide array area

TABLE 1

A summary of measured and calculated effective indices of TM modes guided in the strip and planar waveguide of the special waveguide structure at the 1553-nm wavelength

1553 nm wavelength, substrate index n_{eb} = 2.1360, d_x = 3.5 μm, d_y = 7.0 μm, d_y'= 4.2 μm, Δn_1 = 0.004, Δn_2 = 0.0095.				
Measured			Calculated	Assignment
Strip waveguide array area (θ=0°)	Strip waveguide array area (θ=90°)	Planar waveguide array area		
2.1403	-	-	2.1408	Strip TM_{00}
2.1374	2.1379	2.1375	2.1376	Planar TM_0
2.1355	2.1357	2.1360	2.1360	Planar TM_1

in the two cases where the strip waveguide axis was aligned either parallel or perpendicular to the prism axis. First, we give a brief explanation for the measured reflection pattern. The light is coupled into a waveguide through a high-index prism placed against the surface of the waveguide. When the phase velocity of the incident light along the base of the prism matches with that of a guided mode of the waveguide, the mode is excited, and the incident light leaks into the waveguide. By changing the incident angle of the input light, the guided modes of the waveguide can be excited individually. As a result, the pattern of the light reflected from the waveguide shows some dark lines (i.e., the mode lines) or dips (see Fig. 4) that correspond to the incident angles of the excited modes. By measuring the excitation angles (inside the prism) of these dark lines from the reflected pattern, one can determine the effective indices of the guided modes. The data indicated on each pattern in Fig. 4 are the effective refractive index (i.e., mode index) values of the guided modes. For convenience of comparison, these mode index data are also collected in Table 1.

As mentioned above, the modes belonging to the strip waveguide and the planar waveguide may simultaneously appear on the pattern measured from the strip waveguide array area. This takes place in the case where the strip waveguide axis is parallel to the prism axis. Thus, the key task is to distinguish the modes belonging to the strip waveguide from the pattern measured from the strip waveguide array area in the case where the strip waveguide axis was aligned parallel to the prism axis. Here, we try to do it by comparing these mode index values with those measured from the clear planar waveguide area and also from the strip waveguide array area but in the case where the strip waveguide axis was aligned perpendicular to the prism axis. The reasons for so doing include the following three aspects. First, the relative orientation between the strip waveguide axis and the prism axis does not affect the excitation of the planar waveguide modes. Second, the strip waveguide mode should not appear on the pattern measured from the planar waveguide area. Third, when an arbitrary angle θ exists between the prism axis and the strip waveguide axis, the apparent effective index $N_{eff}(\theta)$ obtained from the measured pattern is related to the actual effective index N_{eff} by $N_{eff} = N_{eff}(\theta) \times \cos\theta$ [7]. The equation implies that, in the case $\theta = 0°$, not only the planar waveguide modes but also the strip waveguide modes are excited, and the apparent effective index $N_{eff}(\theta = 0°)$ is the actual effective index N_{eff}. In the case $\theta = 90°$, which leads to $N_{eff} = 0$, the strip waveguide mode cannot be excited, and only the planar waveguide modes are excited. Therefore, the pattern measured from the strip waveguide array area in the case $\theta = 90°$ is similar to that measured from the planar waveguide area (as shown in Fig. 4), and the modes concerned all belong to the planar waveguide. Next, we assign the modes on the basis of these considerations. For a TM mode guided in a Z-cut LN substrate, the extraordinary index is concerned. The extraordinary index of the congruent substrate n_{eb} was measured to be 2.1360 ± 0.0005 at the wavelength of 1553 nm. According to the criterion for the waveguiding (i.e., the effective index of a guided mode must be larger than the substrate index), one can judge that all of the dips resolved on the three patterns in Fig. 4 result from the guided modes. One can see from Fig. 4 that three dips corresponding to the mode index values around 2.1360 ± 0.0005, 2.1375 ± 0.0005, and 2.1403 ± 0.0005 could be resolved on the top pattern. The former two dips also appear on the other two patterns, while the third dip could not be resolved at all. This means that the third dip, which corresponds to an effective index of 2.1403 ± 0.0005, results from the mode guided in the strip

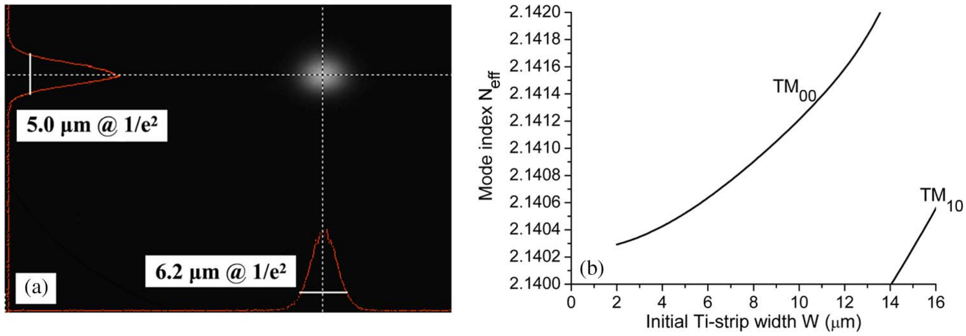

Fig. 5. (a) Near-field pattern of TM-polarized single-mode guided in the strip waveguide of the special waveguide structure at 1.5-μm wavelength. (b) Calculated mode index (at 1.5-μm wavelength) versus initial Ti-strip width W.

waveguide while the other two dips from the modes guided in the planar waveguide. The mode assignment is summarized in the last column of Table 1.

The aforementioned mode assignment implies that the strip waveguide supports only the fundamental mode at the 1.5-μm wavelength. This is confirmed by the direct observation for the near-field mode pattern of the strip waveguide. Fig. 5(a) shows the near-field pattern of the TM mode guided in the strip waveguide of the special waveguide structure. Note that the mode pattern shows clean and high-resolution width and depth profiles. These profiles are as-measured; we did not do any image processing. Indeed, the 8-μm-wide strip waveguide supports only the single-mode propagation. The mode has a full width 6.2/5.0 μm in the lateral/depth direction of the strip waveguide at the $1/e^2$ light intensity.

The mode assignment given above and the mode characteristics of the strip waveguide are further supported by the simulation results. For convenience, we consider an x–y Cartesian reference frame fixed at the center of the waveguide surface with the x axis along the surface direction and the y axis pointing to the depth direction. The extraordinary index increment $\Delta n_e\ (x, y)$ in the planar and strip waveguides can be respectively expressed as

$$\Delta n_e(x,y) = \Delta n_1 \exp\left[-(y/d_y)\right]^2 \quad \text{for} \quad y > 0 \tag{1}$$

$$\Delta n_e(x,y) = \Delta n_1 \exp\left[-(y/d_y)\right]^2 + 0.5\Delta n_2[\text{erf}[(W+2x)/(2d_x)] + \text{erf}((W-2x)/(2d_x))] \times \exp\left[-(y/d'_y)^2\right]/\text{erf}[W/(2d_x)] \quad \text{for} \quad -\infty < x < +\infty \quad \text{and} \quad y > 0 \tag{2}$$

where W is the initial Ti-strip width; d_y is the $1/e$ index change depth of the planar waveguide; d_x and d'_y are the $1/e$ index change width and depth of the strip waveguide, respectively; and Δn_1 and Δn_2 are the Ti-induced surface index increments corresponding to 70- and 74-nm-thick Ti films, respectively. In (2), the first term is the contribution due to the 16-h diffusion of the 70-nm-thick homogeneous Ti film, and the second term is the contribution due to the 6-h diffusion of the 74-nm-thick Ti strip. Note that the 1/e index change depth d'_y in (2), which corresponds to a shorter diffusion time of 6 h, is different from that in the planar waveguide d_y, which corresponds to a longer diffusion time of 16 h. Table 1 brings together the input parameter values used for the simulation. These parameters were evaluated from Refs. [10] and [11].

With the known index profile (1), we simulated at first the planar waveguide using the ray approximation method. The calculated mode indices are summarized in Table 1. The calculated effective index is 2.1376 for the TM_0 mode and 2.1360 for the TM_1 mode, which are in excellent agreement with the measured ones, 2.1375 ± 0.0005 and 2.1360 ± 0.0005, respectively.

Based upon the refractive index increment model described by (2), we further analyzed the TM mode guided in the strip waveguide using the variational method [12]. Fig. 5(b) shows the calculated mode index at 1.5-μm wavelength of the two lower order modes TM_{00} and TM_{10} versus initial Ti-strip width W. At first, we pay attention to the single-mode condition. For the planar waveguide, the substrate index is the index of the bulk material n_{eb}. For the strip waveguide, however, the substrate index is no longer the n_{eb} but the sum of n_{eb} and the index increment of the planar waveguide. This means that for the strip waveguide, the substrate index varies along the depth direction, and at the strip waveguide surface, the substrate index has a maximum of $n_{eb} + \Delta n_1 = 2.1400$. For the strip waveguide, the criterion for the waveguiding is thus that the mode index N_{eff} must be larger than 2.1400. It is evident from Fig. 5(b) that the strip waveguide with an initial Ti-strip width of 8 μm supports the single-mode TM_{00} propagation, consistent with the experimental observation. Moreover, the calculated effective index 2.1408 is in excellent agreement with the measured 2.1403. In addition, the numerical results show that the TM_{00} mode has a full width 6.0/4.8 μm in the lateral/depth direction of the waveguide at the $1/e^2$ light intensity, which is again in excellent agreement with the measured 6.2/5.0 μm. The good agreement between the theory and the experiment provides the evidence for the mode assignment.

Finally, we would like to point out that the TE modes guided in the special waveguide structure can be characterized and attributed in a similar way. Because the present work aims mainly at demonstrating the feasibility of using a commercial Metricon 2010 prism coupler to simultaneously characterize the planar and strip Ti:$LiNbO_3$ waveguides while not at studying the waveguide properties, the characterization results for the TE modes are no longer presented and discussed here.

4. Conclusion

We have demonstrated the feasibility of using a commercial Metricon 2010 prism coupler to characterize the special Ti:$LiNbO_3$ waveguide structure: a strip waveguide array embedded in a planar waveguide. The mode belonging to the strip waveguide is assigned by comparing the patterns measured from the clear planar waveguide area and from the strip waveguide array area in the two cases where the strip waveguide axis is aligned either parallel or perpendicular to the prism axis. Further direct observation for the near-field mode pattern of the strip waveguide and theoretical analysis for the strip and planar waveguides provide evidences for the mode assignment. It is concluded that the method is feasible for the characterization of this special Ti:$LiNbO_3$ waveguide structure and hence facilitates the design and fabrication of relevant waveguide devices.

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