To calculate T^N we use $T_o^N = UD_T^N U^{-1}$ and the following expansion, valid for finite $(N\kappa)$ and $N \gg 1$.

$$(1 \pm i\kappa)^N = [1 + N\kappa^2/2] \exp(\pm iN\kappa) + O(1/N). \tag{25}$$

Combining these equations we obtain (6), and with a lengthy summation procedure

$$S_N(\kappa) = (N^2\kappa^2/2)[R_N - R_{N-1} + i(\sin 2\mu \sin N\kappa/N \sin \kappa)J]. \tag{26}$$

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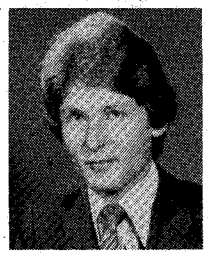

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Crosstalk Characteristics of Ti-LiNbO$_3$ Intersecting Waveguides and Their Application as TE/TM Mode Splitters

HIROCHIKA NAKAJIMA, TETSUO HORIMATSU, MEMBER, IEEE, MINORU SEINO, AND IPPEI SAWAKI

***Abstract*—Crosstalk characteristics of an intersecting waveguide are presented. Two straight channel waveguides which intersect at an angle of a few degrees on *y*-cut LiNbO$_3$ were fabricated by in-diffusion of Ti. Experimental results show that the crosstalk characteristics are determined by the refractive index change profile and the geometry of intersection associated with guided wave modes. In a special case, a TE/TM mode splitter was obtained by using the intersecting waveguide which provides adequate anisotropy by the change in refractive indices. Splitting ratio was 17 and 14 dB for the TE and TM modes, respectively.**

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I. INTRODUCTION

RECENT growth in research concerning planar optical devices has spread to cover a wide range of applications. For example, functional optical devices, such as optical modulators/switches based on directional coupling between two adjacent strip waveguides have been theoretically designed and demonstrated [1]-[3]. On the other hand, experimental results and theoretical analysis on functional devices using *Y*-branch waveguides have also been reported [4], [5]. We have focused our attention on an intersecting waveguide [6], [7] as another useful planar device for functional applications. This

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type of waveguide is indispensable not only for realization of functional devices, but for integration of large scale optical planar circuits. However, there have been few reports on the basic properties of intersecting waveguides [8]. We fabricated our waveguide on a y-cut $LiNbO_3$ substrate by in-diffusion of Ti and measured basic properties, such as the near-field pattern of the waveguide and crosstalk between its channels. This paper reports experimentally measured crosstalk in this intersecting waveguide and its application as a TE/TM mode splitter.

II. Crosstalk Characteristics of the Intersecting Waveguide

A. Fabrication and Measurement

Two straight channel waveguides which intersect at an angle of a few degrees on y-cut $LiNbO_3$ were fabricated by in-diffusion of Ti (Fig. 1). Deposited and lift-off patterned Ti strips on a wafer were diffused at 960° C for 5 h in air, and the Ti thickness at the intersection was the same as for the input and output straight channel waveguide. Ti thickness, pattern width, and angle of intersection of the waveguide fabricated are listed in Table I. No special methods were taken to suppress the out-diffusion of Li_2O, but no surface guiding was observed. After polishing the end faces, guiding properties of the $LiNbO_3$ chips fabricated were measured by a conventional method. The waveguide was excited by end fire using a 0.633 µm He-Ne laser. The near-field pattern of the output end face was magnified with a microscope objective and viewed on a screen. One example of the results is shown in Fig. 2. Throughput light power $P_{\ominus}$ and crossover leakage $P_{\otimes}$ were calculated from recorded near-field patterns. The waveguide acts as a multimode one for light originated by a 0.633 µm He-Ne laser. As is shown in Fig. 2, $P_{\ominus}$ dominates support of the fundamental mode, but $P_{\otimes}$ supports higher modes in this case.

B. Crosstalk Characteristics

One of the most important properties of an intersecting waveguide is the crosstalk between the throughput power $P_{\ominus}$ and crossover leakage $P_{\otimes}$. We defined it as follows:

$$\text{crosstalk} = 10 \log \{P_{\otimes}/(P_{\ominus} + P_{\otimes})\} \text{ dB}. \quad (1)$$

As the first step, we studied the relationship between crosstalk and the angle of intersection when the fundamental TE mode rather than a higher order mode was excited in the dominant (larger) output power port. Fig. 3 shows the experimental results for guide patterns of 3, 5, and 10 µm widths with a Ti thickness of 420 Å. When the intersection angle ϕ was greater than 4°, crosstalk was less than -25 dB for all pattern widths. However, crosstalk increased rapidly as ϕ was reduced below 4° and the characteristics displayed by the 10 µm pattern were different from those of the others. For widths of 3 and 5 µm, the crosstalk values normally increased with smaller ϕ and converged to a value of -3 dB. However, for the 10 µm width, the relationship between crosstalk and intersection angle ϕ was somewhat strange. Namely, at an angle of 2°, crosstalk was less than -0.1 dB. This means that almost all light power was guided into the crossover branching waveguide, as if the incident power were reflected at the intersection by a virtual mirror. Such intersections, which showed crosstalk values from 0 to -3 dB, will hereafter be referred to as M-type (mirror-type) intersections. On the other hand, crosstalk at 1° decreased to -13 dB, as did that at angles greater than 3°. When we measured the crosstalk characteristics using a guide pattern of 10 µm width with a Ti thickness of 200 Å, these strange phenomena did not occur. (See Fig. 4.)

To study M-type intersections, the ray paths at the intersection were observed by scattered light from the waveguide.

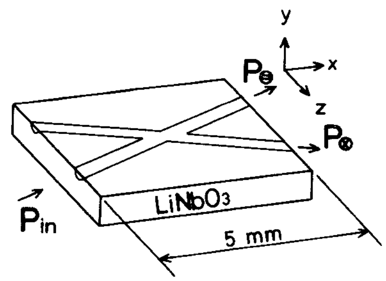

Fig. 1. An intersecting waveguide fabricated on a y-cut $LiNbO_3$ substrate by in-diffusion of Ti. The two straight channel waveguides intersect at an angle of a few degrees, and their length is 5 mm.

TABLE I
Waveguide Parameters and Diffusion Conditions

Diffusion condition	Ti pattern		
	Thickness	Width	Intersecting angle
960°C 5 h in air	200 Å 420	3 5 µm 10	1° 2° 3° 4°

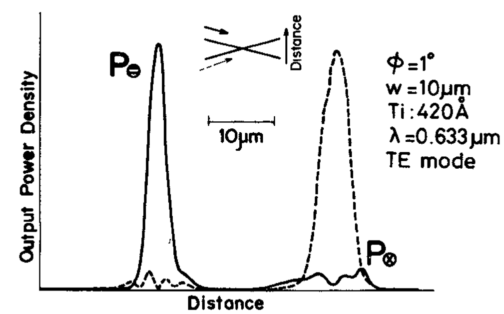

Fig. 2. Near-field pattern of the output end face. Guide pattern width is 10 µm and the intersecting angle is 1°. Throughput light dominates support of the fundamental mode, but crossover leakage supports higher modes.

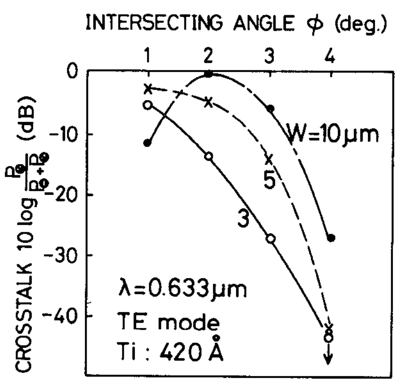

Fig. 3. Crosstalk versus intersecting angle ϕ for guide pattern widths of 3, 5, and 10 µm with Ti thicknesses of 420 Å. Light source is a 0.633 µm He–Ne laser and the TE mode is excited in the input channel.

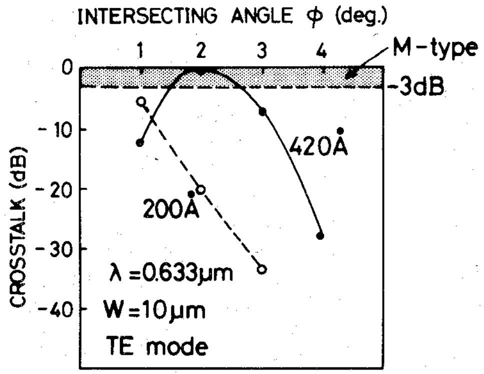

Fig. 4. Crosstalk versus intersecting angle ϕ for Ti thicknesses of 200 and 420 Å with guide pattern width of 10 μm. The *M*-type effect occurs with the Ti thickness of 420 Å, but not with a thickness of 200 Å.

Fig. 5 shows a photograph of the scattered light, and Fig. 6 shows models of the ray path at the intersection for different angles of waveguide intersection. The angles of intersection are 4°, 2°, and 1°, and the stripe pattern widths are 10 μm. The figure in the center shows the difference in the ray path for 420 and 200 Å strips with an intersection angle of 2°. When the optical wave from the straight channel waveguide enters the intersection, the ray path begins to oscillate. This is because the intersection acts as a multimode waveguide even if a fundamental mode is excited in the input channel. This phenomenon can be referred to as "single-multi-single" mode conversion. It assumes that the curvature, or oscillation period, depends on the difference in refractive indices inside and outside the waveguide. For example, the curvature for 200 Å Ti strips is smaller than that for 420 Å strips because the lower concentration of Ti in the waveguide makes the change in refractive index smaller. A similar explanation can be made for Fig. 3. Because of Ti diffusion in the in-plane direction, the concentration of Ti is lower for 3 or 5 μm stripe widths than it is for 10 μm stripe widths. The direction of the outgoing optical wave is determined by the curvature of the ray path and the length of the intersection. When the angle of intersection is 1°, the ray path oscillates twice because the intersection is of sufficient length. The length of intersection L is determined as

$$L = w / \sin(\phi/2) \tag{2}$$

where w indicates the pattern width. The larger the value of L, the more frequently the *M*-type effect occurs. Thus, the *M*-type effect can hardly occur in guides with widths of 3 or 5 μm.

III. TE/TM Mode Splitter Using Intersecting Waveguide

All previous experiments were carried out using light excited in the TE mode. We also studied the properties with the TM mode and discovered that, under certain conditions, the intersection acts differently for the TM mode. In this case, the fundamental mode, rather than a higher order mode, was excited in the dominant output power port. Fig. 7 shows the difference in crosstalk characteristics between the TE and TM modes for a sample with a Ti stripe width of 10 μm and a thickness of 420 Å. The difference was dramatic for guides with intersection angles of 1° and 2°. When $\phi = 2°$, TM mode power is guided into the throughput channel, but TE mode power is guided into the crossover channel. On the other hand, when $\phi = 1°$, TE mode power goes straight through, but TM mode power is reflected. Thus, TE and TM mode optical power can be removed at different output ports. This means that the intersection acts as a TE/TM mode splitter [9]. To confirm mode splitting performance, the following experiments were carried out.

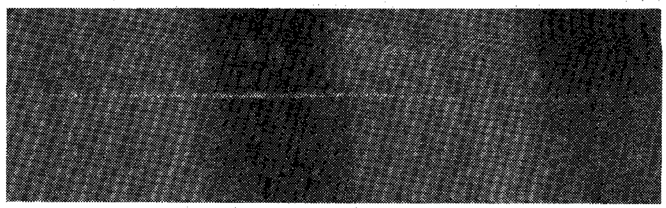

Fig. 5. A photograph of scattered light from the waveguide. $\phi = 1°$, $w = 10$ μm, Ti thickness: 420 Å, $\lambda = 0.633$ μm, TE mode.

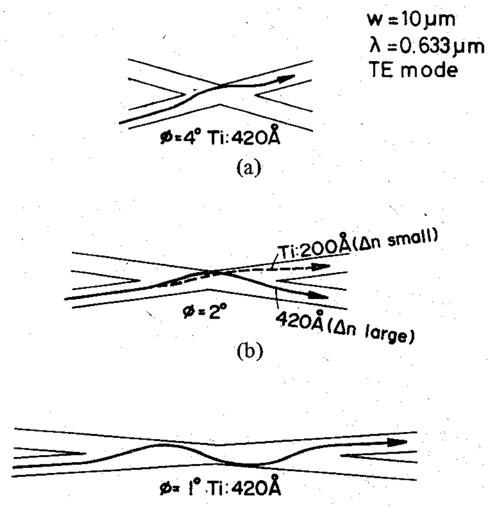

Fig. 6. Ray paths at the intersection for different angles of waveguide intersection. The angles of intersection are 4°, 2°, and 1°.

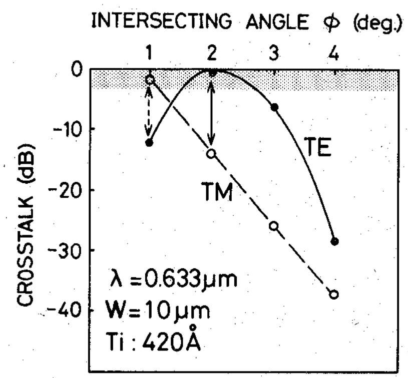

Fig. 7. The difference in crosstalk characteristics between the TE and TM modes for a sample with a Ti stripe which is 10 μm wide and 420 Å thick.

To measure splitting performance, we chose a $\phi = 2°$ guide as the appropriate sample and studied the dependence of output power on polarization of input power. When polarization of the optical input wave was changed from the TE to the TM mode by rotating the polarizer in front of the input port, the

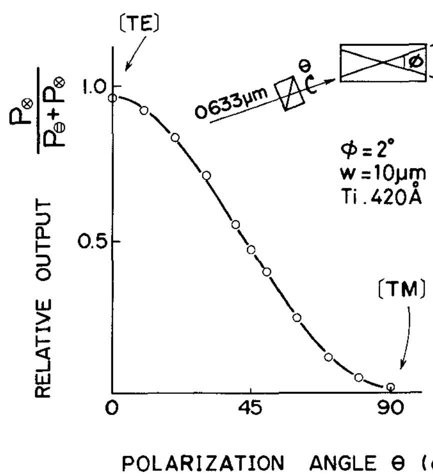

Fig. 8. Splitting performance of the intersecting waveguide. When polarization of the optical input wave was changed from the TE to the TM mode by rotating the polarizer in front of the input port, the reflected power output decreased. This means that the TE mode is guided almost entirely into the crossover channel and that the TM mode is guided into the throughput channel.

reflected power output decreased as shown in Fig. 8. Here, the vertical axis shows relative branching power $P_{\otimes}/(P_{\ominus} + P_{\otimes})$. The splitting ratio of this mode splitter for the TE mode was 17 dB and that for the TM mode was 14 dB, where the splitting ratio was defined as follows:

$$\text{splitting ratio (TE)} = -10 \log \{P_{\ominus}/(P_{\ominus} + P_{\otimes})\} \quad (3)$$

$$\text{splitting ratio (TM)} = -10 \log \{P_{\otimes}/(P_{\ominus} + P_{\otimes})\}. \quad (4)$$

The mechanism of mode splitting is the same as that described in the previous section, namely, the refractive index change Δn_e for the TE mode wave traveling along the x-axis of the crystal is larger than Δn_o for the TM mode [10]. Thus (as is shown in Fig. 9), M-type guidance of the TE mode at the intersection occurs because of the large refractive index change, but the TM mode is guided straight through because of the small Δn_o. So, if appropriate anisotropy is provided by the change in refractive indices in the intersecting waveguide, we can obtain TE/TM mode splitter characteristics by means of the M-type properties of intersection. This type of TE/TM mode splitter is very simple because it does not use any electrodes or complicated mechanisms.

IV. Discussion

In the previous sections, measured crosstalk characteristics of Ti in-diffused $LiNbO_3$ intersecting waveguides and their application as TE/TM mode splitters were reported. In this section, some discussions on the experimental results are presented.

A 0.633 μm He-Ne laser was used as a light source because this was convenient for the experiments. In the experiments, 10 μm width guides acted as multimode waveguides for the light. Thus, end fire coupling conditions had to be carefully controlled for the dominant waveguide output to support the fundamental mode, rather than a higher order mode, and to obtain larger output power. With this condition, a TE/TM mode splitter of high performance (with a high splitting ratio) could be realized. End fire coupling to smaller width waveguides was relatively stable, and M-type guiding was observed even in intersecting waveguides with 3 μm width and 560 Å thickness of deposited Ti.

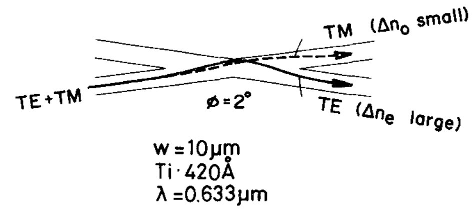

Fig. 9. The difference in ray paths between the TE and TM modes. M-type guiding occurs at the intersection for the TE mode because of the large change in refractive index, but the TM mode is guided through because of the small value of Δn.

When the higher order mode was excited, crosstalk characteristics changed. We measured the splitting performance and the output near-field patterns of a sample showing TE/TM mode splitter characteristics for various excitation modes. The results are shown in Fig. 10. When we moved the excitation point on the end face of the waveguide, the splitting ratio changed from 14 to 6 dB, and the best splitting ratio was obtained when output measured at the output channel was near the fundamental mode.

M-type intersections which can be realized under the special conditions of the waveguide width, the intersecting angle, and the Ti thickness occur in waveguides which have relatively large refractive index changes. As reported by Minakata *et al.* [10], high concentration of Ti in $LiNbO_3$ induces anisotropic refractive index changes. In the case of the experiment with y-cut $LiNbO_3$, the effective index of the TE mode traveling along the x-axis is controlled by both the extraordinary refractive index n_e and its change Δn_e. Also, the TM mode is controlled by both the ordinary refractive index n_o and its change Δn_o. Δn_e was larger than Δn_o for Ti concentrations of more than about 1 percent [10]. In our experiments, 420 Å thick Ti stripes diffused at 960°C for 5 h were used in recognition of this situation. On the other hand, 200 Å thick Ti stripes were not enough to change refractive indices sufficiently, so no strange guide phenomena were observed. Similar experiments were carried out using z-cut crystals and M-type intersections were observed more frequently for the TM mode than for the TE mode. This result is consistent with the above discussion because the TE mode optical wave in z-cut $LiNbO_3$ is controlled by n_o and Δn_o, and that of the TM mode is controlled by n_e and Δn_e.

In the present work, we have studied crosstalk characteristics. The other important characteristic is insertion loss. Insertion losses at the intersection are shown in Table II. The sample was the same as that used in Fig. 10. Measurement was performed under the condition in which the dominant output port supported the fundamental mode, e.g., the intersecting waveguide presented the lowest crosstalk when a single-mode fiber of 5 μm core diameter was used. The losses were less than 1 dB, but the difference between the TE and TM modes should be clarified by numerical analysis. Fiber-to-waveguide coupling loss was about 2 dB at one point for the single-mode fiber, but this loss will be lowered by optimizing the design of the waveguide [11].

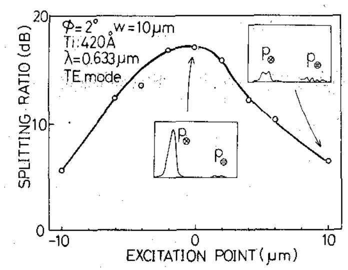

Fig. 10. Measured splitting ratio and the output near-field patterns for various excitation mode. The best splitting ratio was obtained when output measured at the crossover channel was near the fundamental mode.

TABLE II
INTERSECTING LOSSES OF THE WAVEGUIDE. THE WAVEGUIDE IS EXCITED USING A SINGLE-MODE FIBER AND THE SPLITTING RATIO DIFFERS FROM THAT WITH EXCITATION USING MICROSCOPE OBJECTIVES BECAUSE THE EXCITED MODE IS SLIGHTLY DIFFERENT

Mode	Loss	Splitting Ratio
TE	0.9 dB	15 dB
TM	0.3 dB	19 dB

$\Phi = 2°$, $w = 10 \mu m$, Ti:420Å
$\lambda = 0.633 \mu m$

V. CONCLUSION

In summary, experimental results concerning characteristics of intersecting waveguides on Ti in-diffused $LiNbO_3$ have been reported. Crosstalk between the two channels of the intersecting waveguide was determined by the refractive index change profiles associated with the guided wave modes and the geometry of the intersections. The *M*-type intersection, which shows crosstalk of 0-3 dB, acts as if the incident power were reflected at the intersection by a virtual mirror; this was observed under the appropriate conditions. TE/TM mode splitters were obtained by using *M*-type intersections. The mode splitting mechanism is based on anisotropy in the change in refractive indices in high Ti concentration regions. With *M*-type intersections occurring for higher values of Δn_e than that of Δn_o, splitting ratios were 17 and 14 dB for the TE and TM modes, respectively. This type of TE/TM mode splitter is very simple and has potential for use in advanced planar optical circuits.

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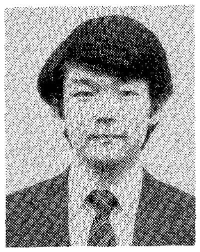

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Multimode Deposited Silica Waveguide and Its Application to an Optical Branching Circuit

HIDEFUMI MORI AND NOBUO SHIMIZU

Abstract—**A fabrication procedure has been developed for multimode deposited silica waveguide (DS guide), consisting of uniform and thick glass layer formation for core and cladding, and amorphous Si mask film for reactive sputter etching. The embedded multimode DS guide with a square core cross section has a transmission loss of 1.3 dB/cm at 633 nm wavelength. Waveguide parameters, such as core dimension, refractive index, and index difference, are similar to those of a multimode silica fiber. A multimode optical branching circuit with eight output ports was demonstrated by the above fabrication procedure. Excess insertion loss was 2 dB.**

I. Introduction

MULTIMODE optical circuit components, such as an optical branch, a tap, a coupler, a filter, and a branching filter, will increase the usefulness of multimode optical fiber systems. In order to fabricate these components precisely and reproducibly, an ion exchange waveguide [1] and a polymer waveguide [2] have been demonstrated with a planar configuration by making use of a photolighographic process. To meet the low coupling loss requirement between these components and multimode fibers, it is preferable for the waveguides to have numerical aperture and core cross section similar to multimode fibers.

A new embedded silica waveguide, called deposited silica (DS) waveguide, has been demonstrated recently for single and multimode waveguide devices [3]. The DS guide is fabricated by planar processing of doped silica deposition followed by reactive sputter etching and has a rectangular cross-sectional core with a unity aspect ratio. It can have almost the same guide parameters as silica fibers because it is made of the same material. A single-mode directional coupler has been fabricated by utilizing this procedure [4].

For the multimode device application of this procedure, high rate and homogeneous glass deposition and sufficiently thick etching mask are essential. This paper reports results of studies on the DS guide fabrication method optimized for multimode waveguides, and a multimode optical branching circuit is demonstrated.

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II. DS Guide Fabrication

The DS guide fabrication method consists of two kinds of processes: silica deposition process to form core and cladding layers and core glass etching process according to a waveguide pattern. The glass particle deposition and glazing is similar to an optical fiber fabrication process, such as the VAD method [5]. This method enables making sufficiently thick glass layers. In the planar configuration presently considered, it is important to deposit glass particles uniformly in contrast with a silica fiber preform where radial uniformity is a main concern.

The waveguide pattern is defined by a reactive sputter etching process. This etching process is suitable for waveguide core fabrication with a rectangular cross section because of high etching selectivity between SiO_2 and a metal mask. A perpendicular core side wall can be obtained without undercutting. To make use of these preferable etching characteristics, sputtered amorphous Si was studied as etching mask material.

Fig. 1 shows the waveguide fabrication process.

(a) Doped silica glass particles are deposited as a core material on a fused quartz substrate.

(b) The glass particle layer is glazed transparent by exposing to high temperature.

(c) An amorphous Si film is deposited by RF bias sputtering

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