Efficient Single-Mode Fiber to Titanium Diffused Lithium Niobate Waveguide Coupling for $\lambda = 1.32\ \mu m$

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Abstract—We report detailed results on the achievement of very high optical throughput for titanium diffused lithium niobate waveguides coupled between input and output single-mode fibers. By determining appropriate diffusion parameters to obtain excellent dimensional match between the fiber and waveguide modes and simultaneously low propagation loss, we have achieved total measured fiber-waveguide-fiber insertion loss as low as 1 dB for a 1 cm long waveguide at $\lambda = 1.32\ \mu m$. The relative contributions of coupling and propagation loss are determined. Very good correlation is found between the coupling loss and the match between the fiber and waveguide mode dimensions. Design data for diffusion parameters to obtain good mode match for arbitrary fiber dimension are presented.

Introduction

EFFICIENT fiber-waveguide coupling as well as low waveguide propagation loss are essential if integrated optic devices such as modulators, switches, and filters [1] are to find practical application in single-mode lightwave systems. Here we report detailed results of an investigation of the coupling between a single-mode fiber and titanium diffused waveguides for $\lambda = 1.3\ \mu m$, an important wavelength for lightwave communications. By determining diffusion parameters to simultaneously achieve good waveguide-fiber mode match and low propagation loss, we have achieved a total measured fiber-waveguide-fiber insertion loss as low as 1 dB for 1.3 cm long titanium diffused waveguides. The contributions of propagation and coupling loss to the total insertion loss are determined. We have measured the fiber and waveguide mode profiles and we show the very good correlation between coupling loss and waveguide-fiber mode match. In addition, the results of a variational technique to calculate the expected mode size are used to provide design data for choosing diffusion parameters to achieve good mode match to other fibers. These results are used to assess the fabrication tolerances in the diffusion parameters required to assure optimum coupling. Furthermore, these design data were used to determine the appropriate diffusion time and metal thickness to reduce the diffusion temperature from that of our original results. The resulting diffusion conditions were used to fabricate a waveguide directional coupler modulator with total fiber-device-fiber insertion loss as low as 1.5 dB.

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Several studies of single-mode fiber to titanium diffused lithium niobate coupling have been previously reported [2]-[7]. The best results have been achieved for the Z-cut, Y-propagating orientation which is the orientation also used for this study. Fukuma and co-workers have measured fiber-waveguide coupling loss for $\lambda = 0.6328\ \mu m$ and $\lambda = 1.15\ \mu m$ under a variety of waveguide diffusion parameters [2], [3]. For a 1 cm long titanium diffused lithium niobate waveguide, they report a minimum fiber-waveguide-fiber insertion loss of 3.8 dB at $\lambda = 1.15\ \mu m$. This figure includes an assumed Fresnel reflection loss of ~1.3 dB for the two fiber-waveguide interfaces. Keil and Auracher have measured a fiber-waveguide coupling loss as low as 1 dB excluding reflection loss for $\lambda = 0.6328\ \mu m$. However, the propagation loss for their waveguides was very high so that typical fiber-waveguide-fiber insertion loss for a 1 cm waveguide was ~10 dB. Bulmer *et al.* have achieved a fiber-waveguide-fiber insertion loss as low as 3 dB for a 1 cm long Ti-diffused lithium niobate waveguide at $\lambda = 0.6328\ \mu m$ [6]. They use water as an index matching fluid.

Assuming perfect fiber-waveguide alignment, the two contributions to fiber-waveguide coupling loss are reflection loss and the mismatch between the fiber and waveguide modes. The former can be reduced if not completely eliminated by using either index matching fluid or antireflection coatings on the lithium niobate end faces. The loss, due to mismatch between the fiber and waveguide modes, is then the principal source of fiber-waveguide coupling. We seek to fabricate titanium diffused waveguides whose mode size is well-matched to that of our fiber. Because of the large index difference between lithium niobate and air, the waveguide depth mode is typically quite asymmetric while the fiber is circularly symmetric. Furthermore, for operation at $\lambda = 1.3\ \mu m$ and for fiber core sizes typical for lightwave communication applications, the fiber mode is relatively large. Thus, relatively deep diffusion of the titanium into the lithium niobate is required. Fortunately, a deep diffusion also helps to reduce propagation loss due to surface scattering. The diffusion depth D is determined by the diffusion time t, temperature T, and activation temperature, T_o, $D \propto (te^{-T_o/T})^{1/2}$. The titanium metal thickness τ should satisfy two requirements. First, for the diffusion parameters required to achieve the desired depth,

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the titanium metal must be thin enough to allow complete diffusion. However, it must be sufficiently thick to produce a waveguide substrate index difference $\Delta n = n_g - n_s$ to provide strong guiding. Within these general constraints we want to choose t, T, τ, and the waveguide strip width W to produce a waveguide mode which matches the fiber mode as closely as possible.

Experimental Results

To determine diffusion conditions required to mode match our single-mode fiber, we prepared a series of straight waveguides with titanium strip widths from 2 to 10 μm in 0.5 μm steps on a single crystal. Three Z-cut, Y-propagating crystals with metal thicknesses of 720, 900, and 1100 Å were tried. Each was diffused at 1100°C for 6 h. Diffusion was performed in a flowing argon atmosphere with cool down in flowing oxygen. Both flow gases were bubbled through water [8], [9]. The crystals were brought up to the diffusion temperature at a rate of ~3°/min and cooled down at ~8°/min. The crystal ends were cut and carefully polished using 1 and 0.25 μm diamond paste. The fiber ends were prepared by simple cutting.

To measure the waveguide and fiber modes, the near field patterns were imaged onto an infrared vidicon. The output from the vidicon was displayed on a signal averaging oscilloscope and waveguide mode intensity profiles were recorded in the width and depth directions. The source for the mode measurements as well as the fiber-coupling measurements was an Nd-Yag laser which oscillates at $\lambda = 1.32$ μm. Our fiber has a 10 μm core, a Δ of ~0.25 percent, and a measured mode $1/e$ intensity full width of 7.8 μm.

Waveguides fabricated with 720 Å metal thickness exhibited mode sizes most compatible with that of the fiber. An example of the width and depth mode profile for the waveguide with a 9 μm metal strip width is shown in Fig. 1. Also shown in Fig. 1(a) is the measured fiber mode profile. The waveguide mode in the crystal plane is essentially Gaussian and is an excellent match to the fiber. The mode profile in depth is asymmetric as expected. However, as shown in Fig. 1(b), although it is approximated by the Hermite-Gaussian function over most of the profile, the intensity rolloff, both of the surface and into the substrate, is slower than for the Hermite-Gaussian. The evanescent tail on the air side of the waveguide is especially significant because of its better compatibility with the symmetric fiber mode. The measured $1/e$, intensity full width w_x, and depth w_y for these waveguides, all of which were single-mode, versus metal strip width is shown in Fig. 2 for both the TE and TM polarizations. Also shown is the geometric-mean mode diameter $\sqrt{w_x w_y}$. The mode dimensions are relatively constant over the range of strip widths between ~6 and 10 μm which correspond to well-guided modes. The rapid increase in mode size for small strip width results from poor confinement as these waveguides approach cutoff. The ratio of the mode width to depth w_x/w_y is approximately 1.5 for the well-confined modes and approaches unity for waveguides near cutoff. As shown in Fig. 2, for these diffusion conditions, there is a very good match between the fiber mode diameter and the mean waveguide mode diameter for strip widths from approximately 7-10 μm. This good match occurs for a slightly greater range of strip widths for the TE than for the TM mode.

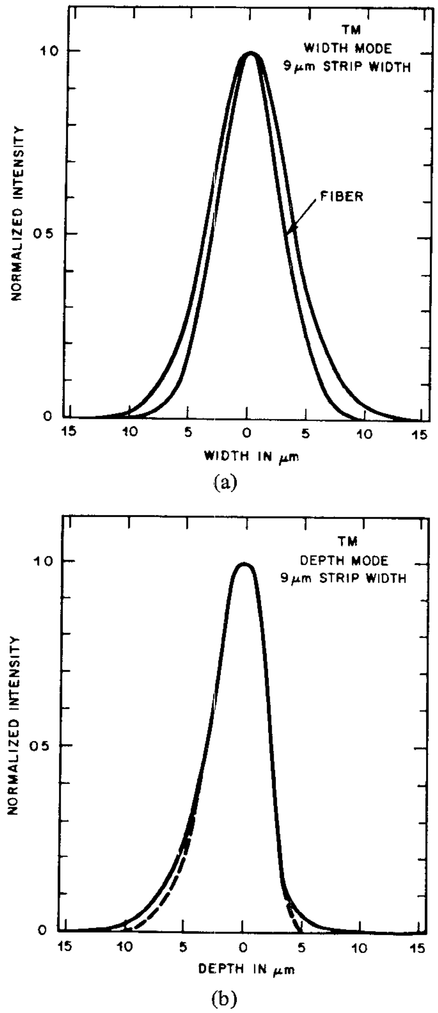

Fig. 1. (a) Measured mode width and (b) depth profile for waveguide with 9 μm strip width with diffusion parameters. $T = 1100$°C, $\tau = 720$ Å, and $t = 6$ h. The fiber mode profile is also shown in (a). The dashed curve in (b) is the best Hermite–Gaussian fit to the depth profile.

The measured fiber-waveguide-fiber total insertion loss for these waveguides for both the TE and TM polarization is shown in Fig. 3 [10]. An index matching fluid with $n \simeq 1.65$ at $\lambda = 1.32$ μm was employed at each fiber waveguide interface. Each waveguide is ~1.3 cm long. As indicated in Fig. 3, total insertion loss as low as 1 dB has been achieved. Very low insertion loss is achieved for both TE and TM polarization for strip widths from 7 to 10 μm.

To determine the relative contribution of coupling and propagation to this total insertion loss, another set of waveguides was fabricated under the same diffusion conditions, the total insertion loss measured. The sample was then cut in half, repolished, and the fiber-waveguide-fiber insertion loss remeasured. By assuming identical coupling loss in the two cases, the propagation and coupling losses can be determined. The measured propagation and coupling loss versus the metal strip width for the TE mode is shown in Fig. 4. Comparable results apply for the TM mode. For the waveguides with mini-

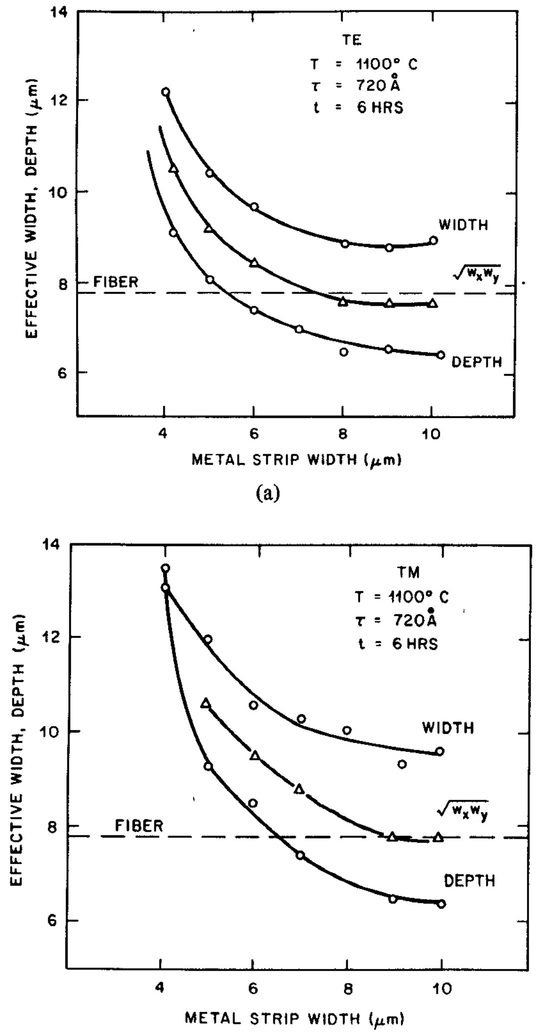

Fig. 2. Measured waveguide mode $1/e$, intensity full width, and depth versus metal strip width for the (a) TE and (b) TM polarizations. Also shown is the geometric mean. The fiber mode diameter 7.8 μm is indicated.

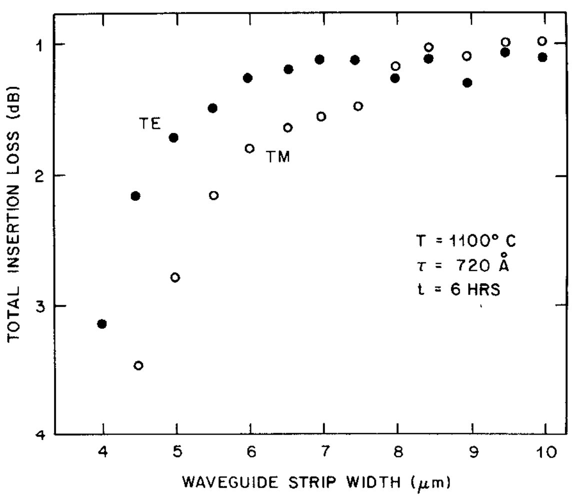

Fig. 3. Measured total fiber-waveguide-fiber insertion loss for 1.3 cm long waveguides versus titanium metal strip width for diffusion parameters indicated. Values include residual reflection loss with n = 1.65 index matching fluid.

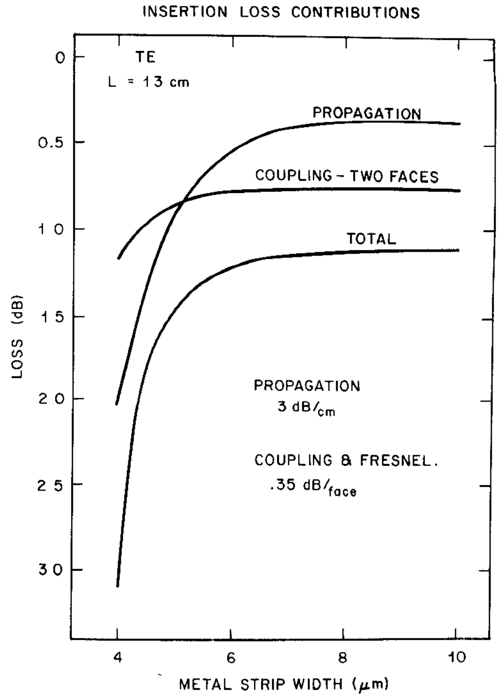

Fig. 4. Experimentally determined coupling and propagation loss contributions versus metal strip width. The diffusion conditions are the same as for Fig. 3. Best fit solid curves are shown although data correspond to 0.5 μm strip width increments.

mum total insertion loss, the coupling loss per face is ~0.35 dB and the propagation loss is ~0.3 dB/cm. This measured coupling loss includes a calculated residual Fresnel loss of ~0.12 and 0.09 dB per face for the TE and TM mode, respectively, assuming a matching index of 1.65. This loss component could presumably be reduced by better index matching or by antireflection coatings. As shown in Fig. 4, the rapid increase in total insertion loss for small metal strip widths is principally due to large propagation loss resulting from poor mode confinement as waveguide cutoff is approached.

The sensitivity of the fiber-waveguide coupling efficiency to lateral and vertical (depth) translational misalignment was measured by moving the output fiber. The results for $W = 10$ μm and the diffusion conditions of Fig. 3 are shown in Fig. 5. A slight asymmetry with respect to vertical offset is evident. Because of the relatively large mode size for $\lambda = 1.32$ μm, the coupling efficiency is not very sensitive to alignment errors. For both vertical and lateral translation an offset of ±2 μm increases the coupling loss by only ~0.25 dB relative to best alignment. This insensitivity to alignment accuracy should simplify the task of mechanical fiber-waveguide connectors.

Analysis

The expected coupling efficiency can be determined by calculating the overlap between the fiber and waveguide modes. By computing the overlap of the fiber to the calculated modes for diffused waveguides, Burns and Hocker have shown that the power coupling coefficient can be written as [11]

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

where a is the fiber mode $1/e$ intensity diameter. The constant

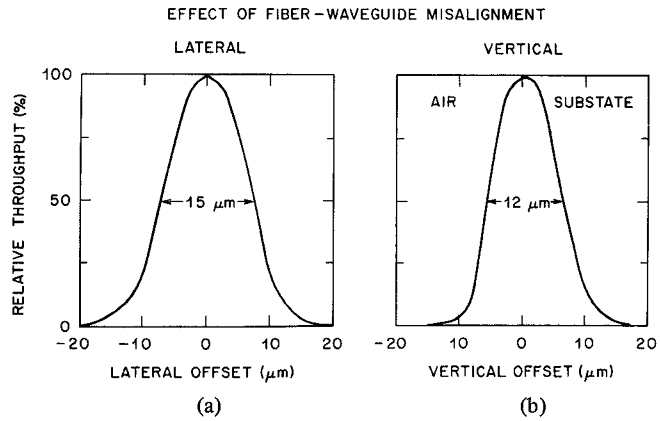

Fig. 5. Measured relative throughput versus output fiber translational misalignment in (a) the substrate plane and (b) perpendicular to the substrate plane.

factor of 0.93 accounts for the mismatch between the symmetric fiber mode and the diffused channel waveguide mode assuming identical $1/e$ dimensions for the two. The second factor then includes the further reduction in coupling efficiency due to any difference in the dimensions of the fiber and waveguide modes.

By algebraic manipulation, the power coupling coefficient of (1) can be rewritten more conveniently as

$$\kappa = 0.93 \left\{ \frac{4(w/a)^2}{[(w/a)^2 + \epsilon]\,[(w/a)^2 + 1/\epsilon]} \right\} \tag{2}$$

where w is the geometric mean $w = \sqrt{w_x w_y}$ and ϵ is the ratio of the waveguide mode width and depth $\epsilon = w_x/w_y$. Equation (2) indicates that the coupling efficiency can be specified simply by w/a and the waveguide mode eccentricity. The dimensional dependence of the expected coupling loss [the bracketed term in (2)] is shown in Fig. 6. The total expected coupling loss (per interface) is the sum of the value given by Fig. 6 and 0.3 dB corresponding to the constant in (2). Most of this latter contribution (~0.2 dB) is due to depth mode mismatch for an assumed Hermite-Gaussian waveguide mode [11]. However, as shown in Fig. 1 our measured mode in depth is a better fit to a Gaussian than is the Hermite-Gaussian. Therefore, this constant factor of 0.3 dB is probably conservative [6].

The results in Fig. 6 indicate that, regardless of the mode eccentricity, the optimum coupling is achieved for $w = a$. The dependence of the coupling loss on mode mismatch is weak for w near a. A mismatch in mean mode size of 10 percent causes an increase in coupling loss of only ~0.04 dB relative to its value for $w/a = 1$ for each of the values of ϵ shown. The coupling loss is less sensitive to nonunity eccentricity. A 10 percent error from the optimum condition $\epsilon = 1$ increases the coupling loss by only ~0.01 dB for $w/a = 1$.

As indicated in Fig. 2, for waveguides with strip widths from ~7 to 10 μm for TE and 8 to 10 μm for TM, the condition $w/a = 1$ is well met. The condition $w = a$ is satisfied somewhat better for the TM mode, but the eccentricity is generally lower for the TE mode. The aspect ratio of ~1.5 contributes, according to Fig. 6, ~0.18 dB/face to the coupling loss. Thus, the theoretically expected coupling loss is ~0.5 dB per face.

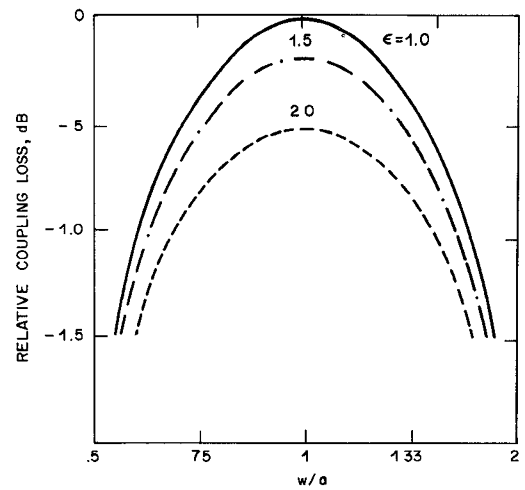

Fig. 6. Calculated coupling loss (per interface) due to dimensional mismatch between the fiber and waveguide modes versus the ratio of the waveguide mean diameter to the fiber diameter. ϵ is the waveguide mode eccentricity $\epsilon = w_x/w_y$. Note the horizontal scale.

The fact that we measure values substantially lower than this is further evidence that the waveguide mode in depth is probably less mismatched to that of the fiber than the typically assumed Hermite-Gaussian [6].

The measured coupling loss (Fig. 4) and the measured mode dimensions are very accurately correlated by the mode overlap of (2). The insensitivity of the mode overlap to small changes in w/a, together with the fact that for well-confined modes the mode width and depth are relatively constant over a large range of channel waveguide strip widths (Fig. 2), results in a coupling loss that is very insensitive to channel width (Fig. 4). Very good coupling efficiency has been achieved for both TE and TM modes because, for the diffusion conditions used, the mean mode sizes for well-guided modes are roughly equal for both polarizations. The latter results because the Δn for the extraordinary and ordinary indexes are not greatly different for diffusion parameters required for modest values of Δn. However, for large values of titanium concentration, Δn_o and Δn_e may be very different [12] and mode matching simultaneously for the TE and TM modes would be more difficult. Fortunately, for the typically large fiber mode sizes at $\lambda = 1.3$ μm only modest values of Δn are necessary.

Mode Matching Design Procedure

The above experimental results demonstrate that by properly choosing the waveguide diffusion parameters excellent fiber-waveguide coupling efficiency can be achieved. To allow waveguide fabrication to match fibers with other mode dimensions, a theoretical model to calculate the expected mode size directly from the diffusion parameters would be very convenient. Indeed, even for a given fiber it is useful to know what other combinations of diffusion parameters result in the same mode size. This is particularly true in the present case because, although we have used a high temperature to ensure a sufficiently deep depth mode, 1100°C is approaching the Curie temperature for lithium niobate and, for active devices like modulators, a lower value would be preferable to ensure no loss of the electrooptic effect due to depoling [3].

Korotky *et al.* have recently reported a variational analysis which allows calculation of mode size and effective index directly from diffusion parameters, known diffusion coefficients, and the refractive index dependence upon titanium concentration [13]. This model has provided results which are in good agreement with the mode size measurements of Fig. 2 and thus offers potential as an excellent design tool. In Fig. 7 we show calculated geometric-mean mode diameter results for 8 μm wide waveguides diffused for 6 h as a function of diffusion temperature with titanium metal thickness as a parameter. In Fig. 8 the calculated mean mode diameter is plotted as a function of metal thickness with diffusion time as a parameter for an 8 μm wide waveguide diffused at 1050°C. In both cases we assume that $\lambda = 1.32$ μm and the results are appropriate for the index change to the extraordinary index (TM for Z-cut crystals). The calculated results are not very sensitive to the strip width, provided that, for the diffusion parameters, it corresponds to a well-confined mode. Note that the calculations do not indicate when the waveguide becomes multimode and assume that the titanium diffusion is complete. The results of Figs. 7 and 8 cover a rather wide range of mean mode sizes and should facilitate the design of diffusion parameters for particular fibers with mode sizes different than that used in this study. These results should be considered as a guide to choosing diffusion parameters. Effective diffusion parameters may vary somewhat from laboratory to laboratory and depend upon the method of titanium disposition, crystal stoichiometry, etc.

The calculated mode size results of Figs. 7 and 8 can be used for estimating the increase in coupling loss due to waveguide fabricated errors. For example, a temperature error of 25°C for the fabrication parameters described above changes the mean mode size by nearly 1 μm (Fig. 7) resulting in an expected increase in the coupling loss of 0.1 dB/face (Fig. 6). On the other hand, for $T = 1050$°C and $t = 12$ h, according to Fig. 8, a variation of ±40 Å in the titanium metal thickness results in a change of ~∓0.3 μm in the mean mode size. Assuming a mode width to depth ratio of 1.5, the resulting increase in coupling loss is less than 0.01 dB/face. Typical metal thickness accuracy is ~±15 Å and the diffusion temperature reproducibility is ~±2°C. Thus, once the proper diffusion parameters are determined, the required fabrication tolerances to ensure reproducibly good fiber-waveguide coupling should be readily obtainable.

To demonstrate the usefulness of the results in Figs. 7 and 8 in designing diffusion parameters for good mode match, we consider the question of reducing the diffusion temperature from the value of 1100°C used for the above experimental results to ensure no degradation in electrooptic effect. First, we note from Fig. 7 by interpolation that, for the diffusion parameters for the data in Fig. 3, the calculated mean mode size is ~8.2 μm in good agreement with the experimental data of Fig. 3 (~7.7 μm). Now, according to Fig. 8, to reduce the diffusion temperature from 1100 to 1050°C the geometric-mean mode size can be maintained at ~7.8 μm for a diffusion time of 12 h and a titanium metal thickness of ~740 Å. Of course other combinations of T, t, and τ are possible. Indeed, the best choice is that which simultaneously provides $w = a$,

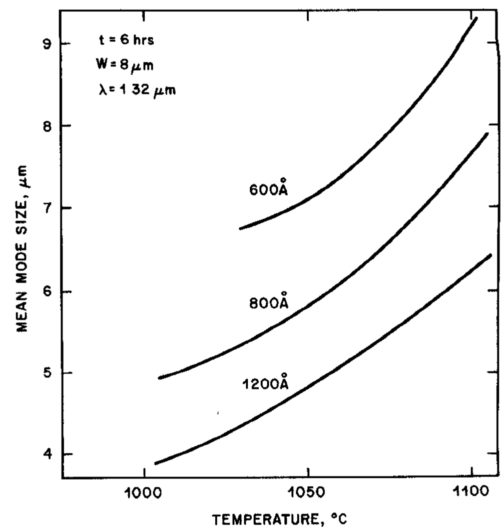

Fig. 7. Calculated waveguide mode geometric-mean diameter $w = \sqrt{w_x w_y}$ versus titanium metal thickness and diffusion temperature. The results are calculated for $\lambda = 1.32$ μm, strip width $W = 8$ μm, and diffusion time $t = 6$ h.

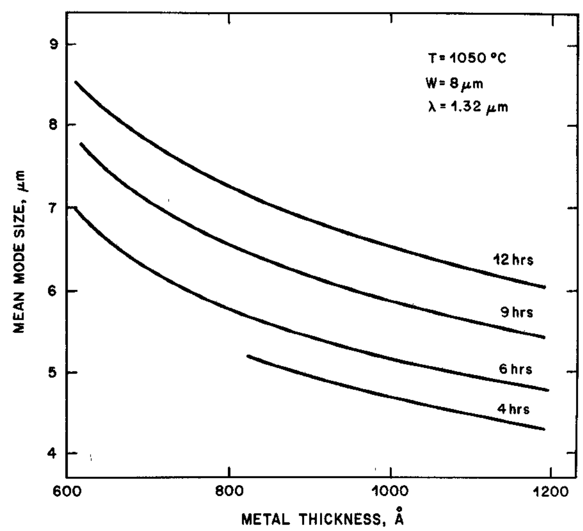

Fig. 8. Calculated waveguide mode geometric-mean diameter versus titanium metal thickness and diffusion time for $\lambda = 1.32$ μm, $T = 1050$°C, and $W = 8$ μm.

gives a near unity mode aspect ratio, and yields low-propagation loss. However, the latter two requirements are generally contradictory. It is typically true that the propagation loss minimizes as the mode becomes well confined. Unfortunately, theoretical considerations [11] and our experimental evidence for a variety of diffusion parameters indicate that a unity aspect ratio is not readily achievable for well-guided modes.

To test the effectiveness of the above design procedure, waveguides were fabricated with 760 Å (fabrication tolerance approximation to 740 Å) of titanium and diffused for 12 h at 1050°C. The measured total fiber-waveguide-fiber insertion loss versus metal strip width for waveguides 1.3 cm long is shown in Fig. 9. Very low insertion loss, comparable to that obtained with the 1100°C diffusion temperature, was achieved. The lowest loss is in fact achieved for narrower strip widths than for the 1100°C results. This fact, which

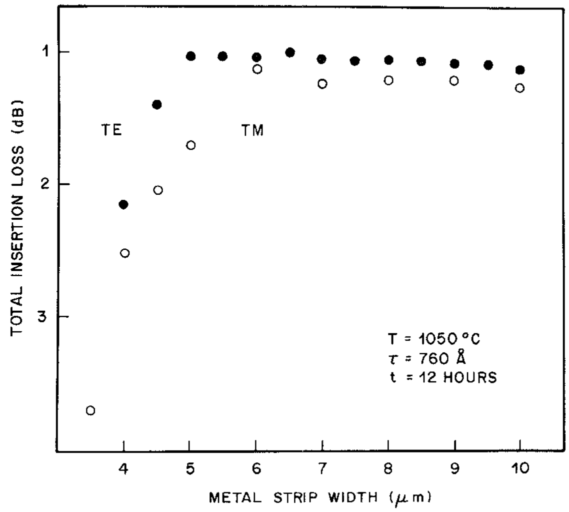

Fig. 9. Measured total fiber-waveguide-fiber insertion loss for 1.3 cm long waveguide versus metal strip width for diffusion parameters indicated.

results from a slightly larger Δn, is advantageous for modulator design.

For the design of waveguide electrooptic devices, such as modulators, a small mode is desirable to reduce the required drive voltage [14]. For a typical fiber with relatively large mode size as used in this study there is thus a tradeoff between fiber-waveguide coupling loss and drive voltage. Fortunately, as shown above, relatively large differences between the fiber and waveguide mode dimensions can be tolerated without introducing large excess coupling loss. As an example we have fabricated a directional coupler modulator with $\tau = 750$ Å, $T = 1050°$C, and a diffusion time of only 9 h. This shorter diffusion time reduces the mean mode size to ~6.9 μm, according to Fig. 7, which should increase the coupling loss by less than 0.1 dB/face relative to that for $w = a$. Indeed, for a 2 cm long modulator, the measured total fiber-modulator-fiber insertion loss was only 1.5 and 1.75 dB for the TE and TM modes, respectively [15]. This value includes any residual loading loss due to electrodes placed over the waveguides with an intermediate SiO_2 buffer layer.

There remain several potential areas for further reducing the fiber-waveguide-fiber insertion loss. First, the optimum index matching fluid or antireflection coatings could reduce the Fresnel loss by ~0.1 dB/face. Although by using a deep diffusion we have somewhat reduced the asymmetry of the depth mode, further symmetrization could reduce the coupling loss by ~0.1 dB/face. This could be achieved by, for example, a high index overlay. Reducing the waveguide mode aspect ratio from that obtained here to unity offers the potential of ~0.15 dB/face reduction in coupling loss, but that may not be easily achievable. To our knowledge there are no published reports of the bulk propagation loss in lithium niobate for $\lambda = 1.32$ μm. At $\lambda = 1.15$, the bulk loss has been measured as ~0.1 dB/cm [16]. Thus, there is potential for reducing propagation loss from our present value.

Summary

We have shown that by using appropriate diffusion parameters, low fiber-waveguide coupling loss and propagation loss can be obtained for $\lambda = 1.32$ μm for Ti:$LiNbO_3$ waveguides. Fiber-waveguide coupling loss of 0.35 dB, which includes residual Fresnel loss of ~0.1 dB, and propagation loss of 0.3 dB/cm have been achieved. The total measured fiber-waveguide-fiber insertion loss for a 1.3 cm long waveguide is as low as 1 dB. We show that the coupling loss is very well correlated to the match between the fiber mode diameter and the waveguide geometric-mean diameter. Using appropriate diffusion parameters, we have achieved this match to within ~3 percent. Design data are presented which provide a guide for the appropriate diffusion parameters to achieve mode matching with a fiber of arbitrary diameter. The results presented here demonstrate that excellent optical throughput can be achieved with titanium diffused waveguide devices coupled to single-mode fibers.

Acknowledgment

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Manuel D. Divino, for a photograph and biography, see this issue, p. 1789.

Lawrence L. Buhl, for a photograph and biography, see this issue, p. 1789.

Analysis of Integrated-Optics Near 3 dB Coupler and Mach–Zehnder Interferometric Modulator Using Four-Port Scattering Matrix

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Abstract—The scattering matrix formalism for a lossless four-port device is used to describe the interferometric performance of the integrated-optics near 3 dB coupler and, consequently, the Mach–Zehnder interferometric modulator as a function of coupler and/or power imbalance. For the case of a coupler consisting of three single-mode dielectric guides forming a Y junction, a fourth port is incorporated which takes all the power radiated out of the guided-wave system in the vicinity of the junction. The interferometric properties of the coupler are shown to be relatively insensitive to fabrication and/or design errors of a magnitude which would make the use of this junction in the reverse direction as a 3 dB divider very marginal. A coupler with an extinction ratio as an interferometer better than −26 dB corresponds to a power divider which couples 22 percent more power into one arm than the other. It is also shown that the near 3 dB coupler used as the output of an interferometric modulator is similarly insensitive to the inequality of the powers in the two arms.

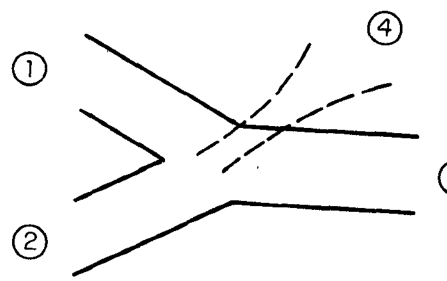

Fig. 1. Four-port representation of the 3 dB coupler. The coupler is exemplified by a Y junction of single-mode dielectric waveguides. The fourth port takes all the power radiated out of the guided-wave system in the vicinity of the Y junction for input power at port 1 and/or port 2.

I. Introduction

In this paper the scattering matrix formalism for a lossless four-port device which has been used successfully in the analysis of microwave circuits [1] is used to describe the interferometric performance of the integrated-optics near 3 dB coupler. A near 3 dB coupler is defined here as a real achievement of an ideal 3 dB coupler for which there is an imbalance in the power splitting. The near 3 dB coupler in integrated optics could be formed as a directional coupler or as a Y junction. Here we will take an example, a Y junction that consists in the forward direction of two single-mode dielectric waveguides coming together into a third single-mode guide, as shown in Fig. 1. Also, as shown in the figure, we include at the junction a fourth port which takes all the power radiated out of the guided-wave system in the vicinity of the coupler. Inclusion of this fourth port allows us to analyze this coupler as a lossless four-port network. The properties of the scattering matrix of the lossless four-port network—the matrix is

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