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dependence for the refractive index of oxides grown in an rf-induced oxygen plasma. No thickness dependence of the data is apparent for the anodic oxides listed in Table I. However annealing the anodic oxide at 250 °C for 1 h in N_2 lowered the refractive index and tightened the distribution as indicated above.

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We propose parabolic-shaped coupling horns to provide adiabatic transition regions between wide- and narrow-channel optical waveguides. The parabolic shape is shown to derive from a simple ray model of channel propagation and is consistent with diffraction theory in the wide-channel limit. An approximate mode dispersion theory is used to convert the criteria into a horn design for indiffused channel waveguides. Experimental horn transmission measurements of nearly 90% are reported for transitions from 25 μm to 8, 6, and 4 μm in Ti:$LiNbO_3$ waveguides at 0.6328 μm.

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Many devices in integrated optics require transitions between planar waveguides or wide-channel waveguides, which support many modes, and narrow-channel waveguides, which support only a single mode. For these horn-shaped transition regions to efficiently transfer optical power, the first-order mode should propagate adiabatically through the device without mode conversion to higher-order modes or to radiation modes. The problem of the design of tapered horn-shaped structures for minimum length has been considered theoretically by Winn and Harris[1] and by Nelson.[2] They give coupling efficiencies for various length linear tapers in glass waveguide systems and Winn and Harris showed that a given coupling efficiency could be achieved in a shorter length by using an exponential taper. Unfortunately these results are not conveniently adaptable to other waveguide systems, such as the metal-ion diffused ferroelectrics. To date no experimental coupling efficiencies have been published.

We propose a design for a shaped coupling horn based on considerations of adiabatic propagation in waveguides and a desire to minimize length. In the limit of well-confined modes far from cutoff, our criterion reduces to a design based on diffraction theory and the horn shape becomes parabolic. The design criteria can be easily applied to any waveguide system whose dispersion characteristics are known and to any wavelength, and is therefore completely general. We report preliminary experimental measurements of coupling efficiencies made with various sized channel waveguides in Ti-diffused $LiNbO_3$.

Consider a two-dimensional channel waveguide of width W as shown in Fig. 1. We desire to expand W but maintain nearly adiabatic propagation for the first-order mode. Using a ray model to describe the mode propagation, let θ_p be the projection of the ray angle of the lowest-order mode in the plane of the horn. The horn angle θ_h is defined as the local angle of the wall of the waveguide with the axis of the channel z. If θ_h exceeded θ_p, in the ray model the ray would not "see" the waveguide wall and the phase front of the wave would become distorted, resulting in mode conversion from the first-order local normal mode. Therefore, we take as our design criterion

$$\theta_h(z) = \alpha\theta_p(z), \tag{1}$$

where α is a constant less than or equal to unity. Equation (1) is to be interpreted locally so that as W increases with z, θ_p and θ_h decrease and the horn angle becomes shallower as it expands. The constant α is

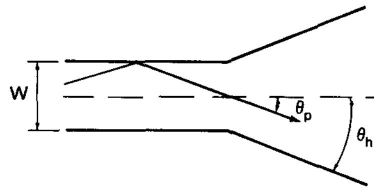

FIG. 1. Top view of a two-dimensional waveguide with expanding width W, showing the projection of the lowest-order-mode ray in the plane of the figure.

chosen smaller if a smaller amount of mode conversion is desired. Note that this criterion only gives a rationale for a specific horn shape while actual coupling efficiency for a given case must be calculated independently or measured experimentally.

Assume a diffused channel waveguide of width W. We define the parameter Δn to be the index difference between the surface index n_s, which would be obtained for a wide channel with $W \rightarrow \infty$, and the bulk index n_b. The effective index method[3,4] can be used to approximate the projection of the ray angle for the case of no sideways diffusion as

$$\cos\theta_p = (n_b + \Delta n b b')/(n_b + \Delta n b), \tag{2}$$

where the normalized mode effective indices[4,5] b and b' are defined by

$$b = (n_{\rm eff}^2 - n_b^2)/(n_s^2 - n_b^2), \tag{3a}$$

$$b' = (n_{\rm eff}'^2 - n_b^2)/(n_{\rm eff}^2 - n_b^2). \tag{3b}$$

Here $n'_{\rm eff}$ is the effective index of the first-order mode for finite W and $n_{\rm eff}$ would be its effective index for $W=\infty$. For small Δn, Eq. (2) can be reduced to give

$$\theta_p \simeq [(2\Delta n b/n_b)(1-b')]^{1/2}. \tag{4}$$

If we assume no sideways diffusion in the channel, the dispersion equation relating b' and W is[4,5]

$$V'(1-b')^{1/2} = 2\tan^{-1}[\,b'/(1-b')]^{1/2}, \tag{5a}$$

where

$$V' = kW(n_{\rm eff}^2 - n_b^2)^{1/2}. \tag{5b}$$

Here V' is the normalized guide width and $k = 2\pi/\lambda_0$ is the free-space wave vector. Substituting Eq. (5) into Eq. (4) yields

$$2\theta_p = \frac{\lambda_0}{n_b W}\left(\frac{\tan^{-1}[b'/(1-b')]^{1/2}}{\frac{1}{2}\pi}\right). \tag{6}$$

Equation (6) now shows the explicit dependence of θ_p on W. As W becomes large and $b' \rightarrow 1$, the term in brackets in Eq. (6) approaches unity. We can then write Eq. (1) for well-confined modes far from cutoff as

$$\theta_h \simeq \alpha\lambda_0/2n_b W, \tag{7}$$

which suggests a horn which diverges more slowly than diffraction from an aperture of width W. The rate of change of waveguide width W is given by

$$\frac{dW}{dz} = \alpha\lambda_0/n_b W, \tag{8}$$

which after integration yields

$$W^2 = (2\alpha\lambda_0/n_b)z + W_0^2. \tag{9}$$

Here W_0 is the initial guide width for $z=0$. In this limit the horn shape is parabolic. In the more general case of arbitrary $b'(W)$ the integration cannot be explicitly performed and the horn shape will not be strictly parabolic.

Coupling horns were designed using Eqs. (1), (4), and (5) for channels of initial width of 2, 4, 6, and 8 μm increasing to 30 μm. For our design we assumed values of $\alpha=1$, $n_b=2.2$, $\Delta n b = 5\times10^{-4}$, and calculated b' from Eq. (5) which neglects sideways diffusion. The resulting horns were between 2.5 and 2.7 mm long. The theoretical curved shapes were approximated by three or four linear segments to facilitate the photolithographic mask fabrication on a computer-controlled pattern generator.[6] A portion of the final mask showing the 4-μm channel with identical input and output horns is shown in Fig. 2. The other channels had similar coupling horns and the 2-μm channel had an additional 1.8° section. A 100-μm-wide strip was also included on the mask to provide an essentially planar waveguide for relative transmission measurements.

The pattern of four channels with input and output coupling horns was photolithographically delineated on a Y-cut sample of $LiNbO_3$ coated with 175 Å of Ti. The channels ran parallel to the X axis. After etching to remove the field the Ti was diffused at 1000 °C for 6 h in Ar. Such a procedure had previously been determined to

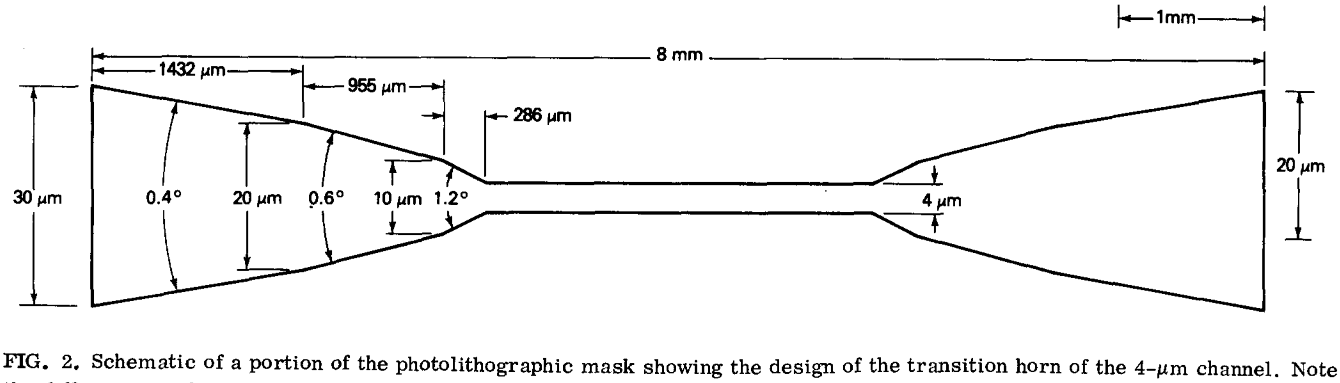

FIG. 2. Schematic of a portion of the photolithographic mask showing the design of the transition horn of the 4-μm channel. Note the difference in the horizontal and the vertical scales.

yield a planar waveguide with a Gaussian diffusion depth of about 2 μm. Measurements of the input prism coupling angle on the 100-μm-wide strip showed that the strip supported a single TM mode with parameters $\Delta n = 0.005$ and $b = 0.2$.[7] The effect of achieving an experimental value of $\Delta n\, b$ larger than the design value is equivalent to choosing α slightly less than unity at the narrow end of the horn and increasing α to unity at the wide end. Electron microprobe results on similar samples indicate that the sideways diffusion for this orientation is quite large, approximately 4.5 times diffusion down, so that the diffused channel width was larger than the width defined by the mask. In this case Eq. (5a) is no longer valid and Eq. (2) must be generalized as discussed in Ref. 4. Qualitatively we find that for small values of W the normalized effective index b' is reduced and the ray angle θ_p increases. For large values of W the opposite occurs and θ_p decreases slightly.

Transmission measurements at 0.6328 μm were made by prism coupling a TM mode into each input horn and coupling out at various points along each channel and output horn. Relative measurements were obtained by making identical measurements on the 100-μm-wide strip. Geometrical matching at the input horn was obtained by focusing the input laser with a combination of a 1-m-focal-length circular lens and a 50-mm-focal-length cylindrical lens. This resulted in a rectangular focal spot on the prism base roughly 1 mm by 50 μm. To correct for input prism coupling efficiency differences between the horns and the 100-μm-wide strip, the back-reflected power from the input prism was monitored and the prism coupling efficiency was calculated for each case. Typical prism coupling efficiencies were 69% and 47% of the incident power in the prism for the 100-μm-wide strip and the horns, respectively. With the edge of the input prism placed at a position corresponding to a horn width of 23 μm, horn transmission data were taken for prism separations of 5.5, 4.5, and 4.0 mm. In evaluating the data we ignore differences in transmission loss between the 100-μm-wide strip and the channels. Since any power mode converted to higher-order modes in the output horn is still coupled out by the output prism and detected, we take the transmission of the output horn to be 100%. The resulting average value of the input horn transmission for the three largest channels is shown in Table I and is close to 90% in each case. Reliable data for the 2-μm channel could not be obtained either because of a break in the channel or because the mode in the channel was so close to cutoff that very little power was transmitted. These data were taken at low incident power levels (< 1 μW) to avoid effects of optical damage in the channels. TM (ordinary) polarization was used to avoid additional extraordinary planar modes that arise from Li outdiffusion.[8] Experimental observations of the input azimuthal coupling angle about the axis of the horn indicated that the 4-μm channel was single mode, while the 6- and 8-μm channels supported two transverse modes.

TABLE I. Measured average values of input horn transmission.

Channel width (μm)	Transmission (%)
8	92 ± 7
6	92 ± 10
4	87 ± 5

We have developed an analytical approach for estimating the power lost through mode conversion in horn-shaped structures which suggests that an upper bound on the power converted from the lowest-order mode in a parabolic horn can be given by

$$(P_{\text{conv}}/P_0)_{\max} = \tfrac{1}{16}\alpha^2. \tag{10}$$

For our structures which have $\alpha \simeq 1$ we would therefore not expect losses due to mode conversion from the transition to be greater than 6%. This is consistent with our experimental results, considering that we have ignored increased transmission loss in the channels. Details of the mode conversion calculation will be published elsewhere.[9]

The theory presented here indicates that the widest part of a transition horn is the critical section, and that with proper design horn length should be nearly independent of the width of the channel at the narrow end. Our experimental results are consistent with this in that high transmission efficiencies have been measured for three horns of essentially the same length but with narrow channel widths differing by a factor of 2. We conclude that very high transmission efficiencies can be achieved with parabolic-shaped horns, and that this shape is likely to provide maximum transmission in a minimum length. A consequence of the parabolic shape is that transitions to very wide waveguides will require very long structures.

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