# Low-Loss Ti:LiNbO$_3$ Waveguide Bends at $\lambda = 1.3\ \mu m$

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***Abstract*—Low-loss waveguide bends are necessary for many proposed integrated optical circuits. The bend loss associated with an *S*-shaped transition connecting offset 6 $\mu$m wide titanium-indiffused lithium niobate strip waveguides has been measured as a function of transition length and initial Ti metal thickness for 1.3 $\mu$m wavelength. Losses as low as 0.2 ± 0.2 dB have been achieved for a transition between offset parallel waveguides with a 0.1 mm lateral and 3.25 mm longitudinal separation. The bend loss is shown to be strongly dependent on the mode confinement and less sensitive to the shape of the transition curve.**

## I. Introduction

GUIDED-WAVE optical devices often require waveguide bends as an integral part of the design. This occurs, for example, in the transition region where the interguide separation characteristic of optical circuitry is enlarged to permit input/output coupling to fibers. The density of optical circuits which can ultimately be achieved depends, to a large extent, on the guide transition length that can be tolerated for acceptably low bend losses.

To date, several configurations for the transition path have been considered for titanium-indiffused lithium niobate (Ti:LiNbO$_3$) strip waveguides. Hutcheson *et al.* [1] have measured bending losses for offset parallel waveguides connected by straight sections and also sections having a constant radius of curvature. For a transition of 0.1/3.0 mm (lateral offset/longitudinal offset), for example, the joined circular segments ($R \approx 2.3$ cm) yielded an attenuation at $\lambda = 0.63\ \mu$m of approximately 2.5 dB, while the attenuation for a similar transition using a single straight section with two abrupt bends of $\approx 2^\circ$ was greater than 10 dB. Taylor and Shumacher [2] have reported an attenuation of approximately 4 dB for the same single straight section transition at $\lambda = 0.63\ \mu$m. The high losses in both of these cases were due, in part, to the weakly guiding waveguides used and to transition curves with discontinuities in the first and second derivative.

Johnson and Leonberger [3] have been able to reduce losses resulting from abrupt bends by increasing the optical confinement and by utilizing a coherent coupling effect first proposed by Taylor [4]. By choosing the optimal length between abrupt $1^\circ$ bends, they were able to take advantage of coherent coupling to obtain an attenuation of 1.5 dB at $\lambda = 0.63\ \mu$m for a transition of 0.15/4.4 mm. At $\lambda = 1.06\ \mu$m, the coherent coupling length measured is larger, requiring a longer transition for comparable losses.

A further improvement in bend transmission has been achieved by Ramaswamy and Divino [5] by removing most discontinuities and employing strongly guiding structures. The *S*-shaped curve used was a raised-cosine function, as considered by Marcuse [6], which avoids all discontinuities in the first and second derivatives, except for those at the matching points to the parallel guides. An attenuation of 0.3 ± 0.3 dB was obtained for a transition 0.1/3.0 mm at $\lambda = 0.63\ \mu$m.

In the works summarized here, efforts to reduce bending loss have focused on $\lambda = 0.63\ \mu$m and on the transition curve geometry. Comparison of the corresponding losses and extrapolation to the 1.2–1.6 $\mu$m wavelength regime, important for optical fiber communication systems, is made difficult because the degree of optical confinement in each case is unknown and no simple method for the scaling of bend loss with wavelength has been given.

Here we report the measurements of bending loss for single-mode strip waveguides at $\lambda = 1.3\ \mu$m using an *S*-shaped transition curve which has no discontinuities in the first and second spatial derivatives. This curve is designed to minimize losses due to curvature reversals and straight-curved transitions, which have recently been reported to contribute over 1 dB to the total loss of an *S*-shaped transition [3]. The effect of the longitudinal transition length on the bending loss was studied for a fixed lateral offset of 0.1 mm. A loss as low as 0.2 ± 0.2 dB was achieved for a transition length equal to 3.25 mm. We have also investigated the effect of mode confinement on the bending loss by varying the initial metal thickness for a fixed diffusion condition. An analysis of the data based on the bend loss model of Marcatili and Miller [7] is used to quantify the dependence of loss on mode confinement. The importance of the transition curve shape is addressed, and we show that it is less critical than the degree of mode confinement.

## II. Experiment

An *S*-shaped curve specified by

$$y(x) = \frac{h}{l}\, x - \frac{h}{2\pi} \sin\left(\frac{2\pi}{l}\, x\right) \tag{1}$$

was used for the transition connecting two offset parallel waveguides separated by a length $l$ in the longitudinal direction ($x$) and offset $h$ in the lateral direction ($y$). The curvature $\kappa$ along the transition curve is approximately given by

$$\kappa = \frac{2\pi h}{l^2} \sin\left(\frac{2\pi x}{l}\right). \tag{2}$$

With this curve, we seek to minimize phase front mismatch losses along the entire waveguide path by eliminating all discontinuities in curvature. An example of a mask used to generate the curved transition is shown in Fig. 1. This mask

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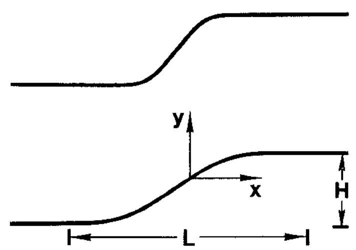



Fig. 1. Microphotograph of two *S*-shaped transitions from the EBES generated mask.

was produced by an electron beam exposure system (EBES) which wrote the curves as a series of discrete 0.25 $\mu$m steps of varying longitudinal length. On the mask, two straight waveguides were situated on either side of a set of three curved waveguides for relative loss measurements. The waveguides were separated by at least 0.20 mm to prevent coupling between them. The longitudinal transition length $l$ was varied from 1-4 mm, while the lateral offset $h$ was fixed at 0.10 mm, which represents the minimum separation necessary for coupling to an array of fibers.

The waveguides were fabricated on $Z$-cut, $Y$-propagating $LiNbO_3$ crystals. Waveguide patterns were delineated using standard photolithographic techniques. Titanium was evaporated on crystals to thicknesses of 740, 850, and 1110 ± 20 Å. The waveguide strip widths were 6 $\mu$m wide. All crystals were diffused at 1050°C for 6 h with flowing Ar replaced with $O_2$ during the cool-down process. Both gases were bubbled through heated $H_2O$ to prevent surface guiding [8]. The ends of the crystals were then cut and polished.

Using end-fire coupling, optical radiation of $\lambda = 1.318$ $\mu$m wavelength from an Nd-YAG laser was launched into the waveguides. All waveguides supported only a single TE and TM mode. Two Ge detectors with lock-in amplifiers were used to monitor both the laser intensity and the output of the waveguides at the polarization selected. Measurements of the waveguide output intensity were normalized to that of the laser. Each bend loss reported is the ratio of the normalized transmittance of one bent waveguide and the average of the four nearby straight waveguides on the substrate.

The bend losses for the TM and TE modes as a function of the transition length for 740, 850, and 1110 Å Ti thickness are shown in Fig. 2(a) and (b). The statistical range of measured losses is ±0.2 dB, which is essentially the limit of sensitivity for this experimental setup. As indicated in the figures, we have achieved low-loss (0.2 ± 0.2 dB) bends for transition lengths as short as 3.25 mm for the TM polarization and 4.10 mm for the TE polarization. The significantly lower losses observed for the TM mode are attributed to the larger change in refractive index experienced for this polarization [9]. This is advantageous for device design because the TM polarization in $Z$-cut $LiNbO_3$ can utilize the large $r_{33}$ electrooptic coefficient.

Fig. 2(a) and (b) also shows the large effect of the Ti thickness on the bend losses for the TM and TE polarizations. These measurements demonstrate that the effective index difference $\Delta N$, or mode confinement, is an important parameter determining bend loss. This fact must be included in establishing a device design if overall performance is to be optimized because

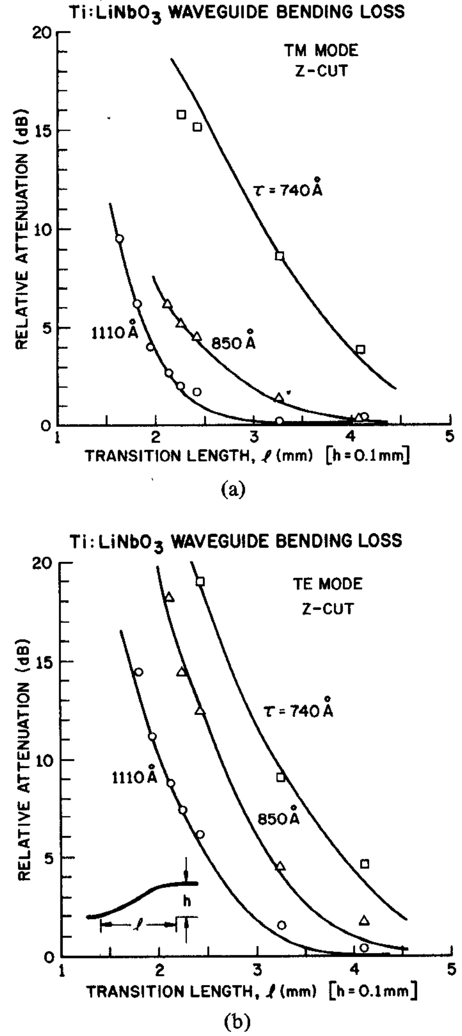



Fig. 2. Bend losses versus transition length $l (h = 0.1$ mm), for 740, 850, and 1110 Å Ti thickness and (a) TM and (b) TE polarizations.

the diffusion conditions required to maximize fiber-waveguide coupling [10] or device performance may not be compatible with those necessary to minimize bending loss.

## III. Analysis

To control bending losses it is necessary to assess the relative importance of the mode confinement and transition curve shape. Also, if design rules are to be established, a quantitative method of characterizing the bend loss associated with given diffusion conditions is required. To address these problems, we show that the loss model developed by Marcatili and Miller [7] for single-mode slab waveguides can be applied to the present experimental results with Ti diffused waveguides.

Marcatili and Miller have shown, under the assumption that the radius of curvature $R$ of the bend guide is large and mode conversion can be ignored, that the form of the attenuation coefficient $\alpha$ for single-mode slab waveguides with step index is

$$\alpha(R) = C_1 e^{-C_2 R}. \tag{3}$$

The parameters $C_1$ and $C_2$ are independent of $R$, but are functions of the guiding characteristics of the straight waveguide. Using differing theoretical approaches, White [11] and Heilblum and Harris [12] have shown that this expression is valid for more general waveguide structures.

When the effective index $N$ varies only slightly from the bulk index $n_b$ the expression for $C_2$ can be put into the form

$$C_2 = \frac{2\pi}{\lambda} \frac{(2\Delta N)^{3/2}}{\sqrt{n_b}} \tag{4}$$

where $\Delta N = N - n_b$ and $\lambda$ is the free space wavelength [7].

The expression for $C_1$ is not a simple function of $\Delta N$, but for completeness, we state it here.

$$C_1 = \frac{1}{2Z_c} \frac{\epsilon_l'}{\epsilon_t} \tag{5}$$

where

$$Z_c = \frac{n_b}{2\lambda} \left[t + 2\xi \cos\left[\frac{k_x t}{2}\right]\right]^2, \tag{6a}$$

$$\epsilon_t = \frac{t}{2} + \frac{1}{2k_x} \sin(k_x t) + \xi \cos^2\left[\frac{k_x t}{2}\right], \tag{6b}$$

and

$$\epsilon_l' = \frac{\xi}{2} \cos^2\left[\frac{k_x t}{2}\right] e^{t/\xi}. \tag{7}$$

In these expressions, $t$ is the width of the slab waveguide, $\xi$ is given by

$$\frac{1}{\xi} = \frac{2\pi}{\lambda} \sqrt{N^2 - n_b^2} \tag{8}$$

and

$$k_x = \frac{2\pi}{\lambda} \sqrt{n_e^2 - N^2} \tag{9}$$

with $n_e$ the index within the slab waveguide.

From (4) it is clear that $C_2$ is an increasing function of $\Delta N$. Physically, the bend radius, at which a certain loss occurs, moves to smaller radii when the confinement is increased. Less obvious is that $C_1$ is also an increasing function of $\Delta N$. From the viewpoint of the bend loss model of Marcatili and Miller, $C_1$ increases with $\Delta N$ because the difference between the propagation constant within the guide and the bulk medium increases, making it more difficult for the wavefront outside the guide to remain coherent with the wavefront within the guide. We note too that both $C$ coefficients are found to scale inversely with wavelength for fixed $N$.

Because $C_2$ depends only on $\Delta N$ and is not an explicit function of the slab waveguide parameters $n_e$ and $t$, it is not unreasonable to assume that the expression for $C_2$ is directly applicable to strip waveguides. The coefficient $C_1$, however, is strongly model-dependent. To calculate this coefficient for strip waveguides, it is necessary to translate the characteristics of the two-dimensional diffused waveguide to an equivalent slab waveguide with step index [13]. This is accomplished using the effective index method as applied to Ti:$LiNbO_3$ strip waveguides by Hocker and Burns [14], [15]. Values of the $C$ coefficients calculated in this manner show that $C_1$ is not a strong function of the strip waveguide parameters (width, depth, and $\Delta N$) and typically changes by a factor of four when going from single-mode cutoff to multimode operation. The $C_2$ coefficient, on the other hand, is very dependent on the waveguide parameters, changing about a factor of 40 across the single-mode region. Thus, because $C_2$ appears in the exponential of the expression for the attenuation coefficient, we expect the bending loss to decrease rapidly with increasing $\Delta N$, i.e., mode confinement. Similarly, for comparable confinement, the loss at longer wavelengths will be greater.

Because $C_2$ is directly related to $\Delta N$, the empirical determination of $C_2$ provides a method of characterizing and comparing waveguides in efforts to reduce bending loss. Also, once accurate values for $C_1$ and $C_2$ are known, the optimum-shaped curve can be determined for given boundary conditions. To demonstrate the usefulness of these ideas, we have extracted values for $C_1$, $C_2$, and $\Delta N$ from the present bend loss data for the various metal thicknesses and TE and TM polarizations. This was done, as described below, by effectively deconvoluting the $R$-dependence of the attenuation coefficient specified by (3) from the measured transition length dependence (Fig. 2).

The experimental data in Fig. 2 do not display oscillations characteristic of strong coherent coupling of the type considered by Taylor [4]. Nor is there evidence for loss arising from step-size quantization [6] on the fabrication mask. It is assumed, therefore, that the coupling to nonguided modes is a single-step process. Thus, if $P$ is the power at a given point along the waveguide, the power lost as radiation per unit length is given by

$$\frac{dP}{ds} = -\alpha P \tag{10}$$

where $\alpha \geqslant 0$ is the attenuation coefficient and $ds$ is the element of arc length. The attenuation coefficient is a parametric function of the position $s$ for the transition curve considered here. As a result, if power $P_0$ is launched into the transition curve, the power remaining at a given point is

$$P(s) = P_0 \exp - \int_0^s \alpha(s')\, ds' \tag{11}$$

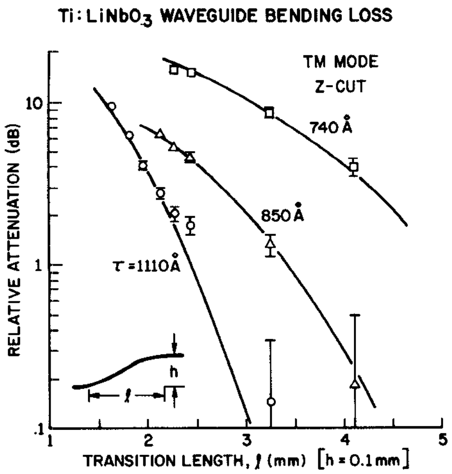
and the total attenuation in decibels $a$ for a curve of total arc length $S_l$ is

$$a(\mathrm{dB}) = \frac{10}{\ln 10} \int_0^{S_l} \alpha(s)\, ds. \tag{12}$$

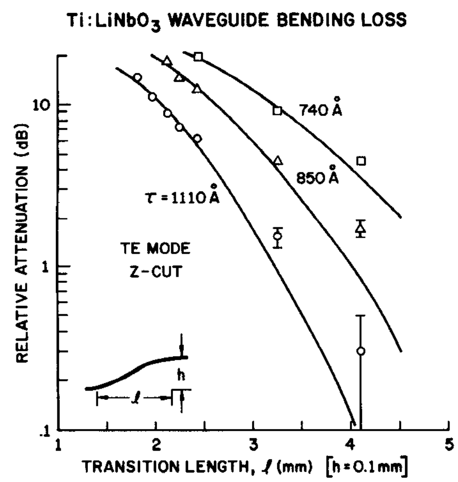
Using the expression for the curvature $\kappa = 1/R$ in the Cartesian coordinate system, the total bend attenuation for the transition curve specified by (1) can be integrated approximately. The result, ignoring propagation loss, is

$$a(\mathrm{dB}) \approx \frac{10}{\ln 10} 2\sqrt{2\pi} \frac{h}{l} \frac{C_1}{C_2} e^{-\gamma} [1 - e^{-\gamma/2}] \tag{13}$$

where $\gamma = C_2 l^2/(2\pi h)$. Curves calculated using this expression were fit to the experimental data to extract values for $C_1$ and $C_2$. The fitted curves are compared to the data in Fig. 3(a) and (b).




(a)




(b)

Fig. 3. Bend losses versus transition length $l(h = 0.1$ mm), for 740, 850, and 1110 A Ti thickness and (a) TM and (b) TE polarizations. The solid lines are the best fit of Marcatili and Miller's model to the data.

We conclude from the good fit to the data, that the form of the attenuation coefficient in (3) is valid for the bending radii encountered. We also note that the nearly exponential dependence displayed in the figures and present in (13) indicates that the geometry for a fixed attenuation does not scale simply as the aspect ratio $l/h$ or alternately, the bend angle, but is better described by an $l^2/h$ dependence. Thus, if the offset $h$ need be increased by a factor of two, then the transition length need only increase by $\sqrt{2}$ times the original length. Again, coherent coupling and mask-size quantization effects are apparently negligible in the present situation.

The fitted values of $C_1$ and $C_2$ are listed in Table I, together with the extracted values of $\Delta N$ (4) and measured values for the geometric mean of the mode size [16]. The effective index difference $\Delta N$ is also plotted in Fig. 4 as a function of initial metal thickness for both polarizations. The values are in good agreement with those obtained using a variational technique for the propagation constant [16]. It is clear from the above discussion that the mode confinement specified by $\Delta N$ is a useful quantity for comparing and projecting bend loss performance.

TABLE I

| Polarization | Titanium thickness $\tau$ (Å) | Empirical Loss Parameters $C_1$ (mm$^{-1}$) | $C_2$ (mm$^{-1}$) | $\Delta N$ ($10^{-3}$) | Mode Size $\sqrt{dw}$ ($\mu$m) |
|---|---|---|---|---|---|
| TM ($\eta_e$) | 740 | 7.07 | 0.100 | 0.49 | 6.6 |
| | 850 | 4.30 | 0.171 | 0.61 | 6.0 |
| | 1110 | 16 68 | 0.418 | 1.30 | 5.3 |
| TE ($\eta_o$) | 740 | 8.64 | 0.105 | 0.51 | 6.9 |
| | 850 | 11.05 | 0.159 | 0.67 | 5.8 |
| | 1110 | 10.83 | 0.231 | 0.86 | 6.2 |

* d and w refer to the depth and width of the mode measured at the 1/e value.

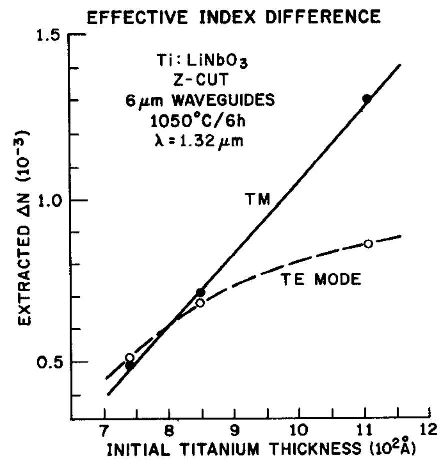



Fig. 4. Effective index difference versus Ti metal thickness for TE and TM polarizations as extracted from empirical bend loss parameter $C_2$.

As a final aspect of the present analysis, we have considered the relative importance of the curve shape in determining bending losses. To do this we fix the boundary condition of the transition geometry to be identical to that used for the measurements (1), i.e., the first and second derivatives of the function describing the transition shape should be zero at the matching points to the offset parallel waveguides. With this boundary condition fixed, we consider the shape of the curve as variable. Because the functional form of the attenuation coefficient and the values of its parameters ($C$-coefficients) are known, the shape of the transition curve which minimizes bending loss for fixed $h$ and $l$ can be determined using the calculus of variations [17]. In Fig. 5 we compare the attenuation that can be achieved using the optimum-shaped curve, as specified by the variational technique, to that of the analytic function used for the experiments. The values of the loss parameters $C_1$ and $C_2$ correspond to the lowest attenuation achieved at $\lambda = 1.3$ $\mu$m. We find that the curve given by (1) has a loss which closely approaches the theoretical lower limit. The calculations predict, however, that the attenuation of 0.9 dB for the analytic function with $h = 0.1$ mm and $l = 2.5$ mm can be reduced to about 0.3 dB by optimizing the shape of the curve. By extrapolating the curves shown in Fig. 4, we estimate that a similar reduction can be achieved by increasing the metal thickness by about 80 Å, or roughly 7 percent. Thus, although the reduction in loss that

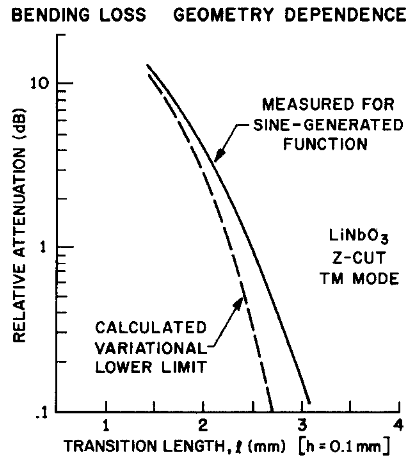



Fig. 5. Bend loss curves for analytical function measured and variational lower limit calculated for identical boundary conditions.

can be obtained by optimizing the curve shape may be important in some situations, the attenuation is less sensitive to changes in the shape than to changes in the waveguide parameters determining mode confinement.

## Summary

Measurements for the bending loss for $S$-shaped curves having no discontinuities in the first and second derivative have been presented for Ti:$LiNbO_3$ waveguides which are single mode at $\lambda = 1.3\ \mu m$.

For the most strongly confining waveguide, a loss as low as $0.2 \pm 0.2$ dB was achieved for a 3.25 mm longitudinal transition length and 0.10 mm lateral offset. The losses for waveguides fabricated using differing Ti metal thickness show that the mode confinement is a critical factor determining bending loss. The relationship was made clear by analyzing the data within the framework of the bend loss model of Marcatili and Miller. Using the results of the semiempirical analysis of the bend loss measurements, we have shown that the exact form of the transition curve is less important than the degree of mode confinement.

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**William J. Minford**, for a photograph and biography, see this issue, p. 1789.

**Steven K. Korotky**, for a photograph and biography, see this issue, p. 1789.

**Rod C. Alferness**, for a photograph and biography, see this issue, p. 1789.