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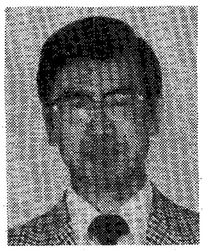

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GaAs/GaAlAs Curved Rib Waveguides

MICHAEL W. AUSTIN

Abstract—**Curved dielectric optical waveguides suffer from radiation loss due to bending. To minimize the bending loss and reduce the radius of curvature, it is necessary to fabricate guides which provide strong optical confinement. This paper gives a brief review of curved waveguide analysis and presents some experimentally measured loss values for GaAs/GaAlAs curved rib waveguides. The rib waveguides, fabricated using ion beam milling, have a large rib height and are tightly guided structures. When corrected for reflection losses and input coupling efficiency, a minimum loss of approximately 3 dB has been achieved for a multimode 90° curved guide with a radius of curvature of 300 μm, and 8.5 dB for a single-mode curved guide with a radius of curvature of 400 μm. It is believed that most of this residual loss is not radiation loss due to bending, but rather scattering loss due to rib wall imperfections.**

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INTRODUCTION

MANY devices likely to be incorporated in integrated optical circuits, such as directional couplers, Y-couplers, and switches may require sections of curved optical waveguide and it will also be necessary to use curved waveguides in order to increase the device packing density in these circuits. In addition to the loss mechanisms present in straight waveguides, such as absorption and scattering, curved dielectric guides suffer from radiation loss due to bending [1]. This bending loss may be very large if the guide is bent abruptly. Several authors [1]-[11] have investigated the problem of continuous radiation from curved dielectric waveguides, but very few curved guides have been fabricated [12]-[16]. The guides that have been made were in either sputtered glass films on glass substrates or in lithium niobate, and guiding was observed at a wavelength of 0.6328 μm. This paper reports preliminary results of an investigation into curved rib waveguides in III–V semiconductors.

Curved Waveguide Analysis

Curved dielectric waveguides have been analyzed by several authors using different techniques [1]-[11]. In most cases it was assumed that the refractive index difference between the waveguide core and the surrounding media was small. In other words, weak guiding was assumed. The analyses were further simplified by assuming that the power radiated from the waveguide per unit length was small compared with the total power carried by the mode in the guide. This requires that $\alpha R \ll 1$, where α is the attenuation coefficient of the curved guide due to radiation losses and R is the radius of curvature of the guide.

In general, the attenuation coefficient of the curved slab guide is found to be of the form

$$\alpha = C_1 \cdot \exp(-C_2 \cdot R) \tag{1}$$

where C_1 and C_2 are independent of R. They depend on the difference in refractive index between the waveguide core and the surrounding media, and hence the lateral confinement of the fields. The attenuation is most sensitive to the exponential and the more slowly varying multiplier reflects some of the geometrical details of the guide. Several authors [6]-[10] have looked at the bending loss of rectangular dielectric waveguides and have found an additional $R^{-1/2}$ dependence for the attenuation coefficient. This additional $R^{-1/2}$ dependence should occur in all finite cross section structures.

It must be stressed that these analyses are appropriate only to structures with relatively weak confinement in the lateral direction. For these guides, large radii curves are needed for low loss. The work reported in this paper is concerned with tightly guided structures, as these are necessary to obtain low loss for a small radius of curvature.

Curved Waveguide Design

The two main design criteria for these curved waveguides are that they be single moded and that they exhibit low radiation loss. Single-mode operation is essential because the guides are to be used in monomode devices such as directional couplers. For rib waveguides with a small lateral effective refractive index step (guides with small rib heights), the optical confinement is relatively weak and calculations show that a radius of curvature of the order of a few mm is needed for the guide to exhibit a tolerable, less than 1 dB/rad, bending loss. To minimize the bending loss and reduce the radius of curvature, it is necessary to fabricate guides which have a large rib height so that the rib is surrounded predominantly by air. This provides strong lateral confinement. Increasing the relative height of the rib by etching away more and more of the slab layer adjacent to the rib also tends to decrease the propagation constant of a guided mode and hence, reduce the number of allowable modes in the waveguide. In the present work a variational program [17] is being used to evaluate the propagation constants and the modal intensity distributions of the rib waveguides. The modal distributions show that the confinement becomes stronger and the number of modes decreases as the height of the slab adjacent to the rib is reduced. In Fig. 1 the modal distributions for two different waveguide geometries are shown. Because of symmetry, only half the rib guide is shown. Fig. 1(a) and (b) shows the two possible modes of the guide when the slab thickness t equals 0.5 μm, and Fig. 1(c) shows the only mode of the guide when $t = 0.2$ μm.

For rib waveguides which have a large rib height there is no analytical theory available for evaluating the bending loss. An estimate of the losses which may be expected can, however, be obtained by using an estimate of the field lateral penetration depth, obtained from the variational model, and by using an extension of existing theories which are valid for weak confinement. This procedure indicates that low-loss guides with small radii of curvature of the order of 200–300 μm are possible. However, for the type of rib structures being considered, a large fraction of the guided energy may impinge on the etched side walls of the guide and the limiting loss of this type of guide may not be radiation loss due to bending but rather scattering loss due to rib wall imperfections.

Experimental

Curved rib waveguides have been fabricated on $GaAs/Ga_{0.82}Al_{0.18}As$ and $GaAs/Ga_{0.92}Al_{0.08}As$ slices grown by MO-CVD. A dry etch technique, ion beam milling, was used to fabricate the waveguides. This is because most wet chemical etches are anisotropic and the resulting waveguide geometry depends on the guide orientation with respect to the semiconductor crystal axis. This is disadvantageous when 90° curved guides are being fabricated. Ion beam etching is done using 1 keV Ar^+ ions at a current density of 1.2 mA/cm^2 for which the etch rate of GaAs is approximately 1600 Å/min.

The mask used to define the guides was made using electron-beam lithography and consists of 90° curves of 75, 100, 125, 150, 200, 250, 300, and 400 μm radius with a 300 μm straight section at each end of the curves. The guides are 3 μm wide. After milling, the substrate is cleaved. This reduces the total length of the straight sections at the end of the curves and consistently produces waveguide ends with good surface quality. Fig. 2 is a photomicrograph of a set of guides with different radii of curvature. The apparent corrugations in the guides at the center left of the figure are an artifact of the SEM detection system. They moved as the sample was rotated.

Optical waveguiding is observed at a wavelength of 1.15 μm using a TE polarized He-Ne laser. The infrared radiation is "end-fire" coupled into the cleaved end of the waveguide via a $\times 45$ microscope objective. The output cleaved face is imaged by an infrared camera via a $\times 20$ microscope objective. Both the input and output faces of the sample may be imaged in white light in order to locate the waveguides and to check the quality of the cleaved edges. As well as observing the guiding on a TV monitor, measurements of the mode intensity profile can be made by selecting and displaying a single camera line on an oscilloscope. This can be plotted on an X–Y recorder via a boxcar integrator. Loss measurements are made by imaging the waveguide near field onto a GE photodetector and measuring the transmitted optical power. The input coupling is optimized and measurements are taken when the optical output is maximized.

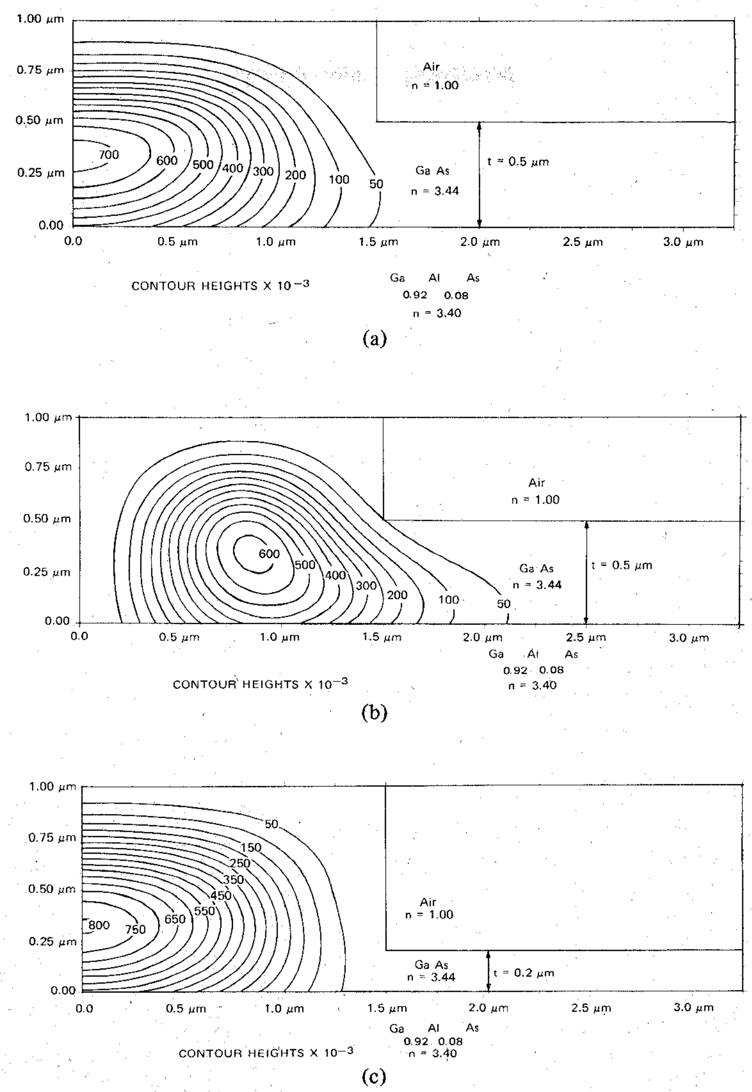

Fig. 1. The modal intensity distributions for two different waveguide geometries showing (a) the first symmetric, (b) the first antisymmetric modes when $t = 0.5$ μm, and (c) the single mode when $t = 0.2$ μm. The contours are normalized to unity.

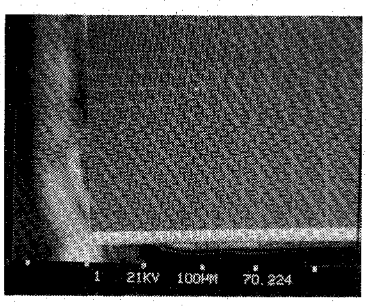

Fig. 2. SEM photomicrograph of a set of guides with different radii of curvature.

The first curved waveguides to be measured were multimode guides fabricated on GaAs/$Ga_{0.82}Al_{0.08}As$ slices. The GaAs layer was 0.8 μm thick. Results for two waveguide geometries, where the height of the layer adjacent to the rib t is 0.3 and 0.4 μm are shown in Fig. 3. Two modes were seen in these guides. As can be seen, the insertion loss, measured as the incident optical power divided by the output optical power and not corrected for reflection losses at the ends of the waveguide or input coupling efficiency, appears to increase exponentially for small radii and exhibits a minimum loss for radii of 250-300 μm. For radii of curvature larger than 300 μm it is believed that the increase in insertion loss is due to scattering loss. Assuming that the scattering per unit length is the same for all guides of similar cross-sectional geometry, the total scattering loss is proportional to the guide length and hence the radius of curvature. The carrier concentration of the GaAs layer is approximately 2.10^{16} cm^{-3} and hence free carrier absorption losses are assumed to be negligible.

The insertion loss consists of the reflection losses at the ends of the guide, the input coupling efficiency, the bending loss of the curved section of the guide, and the total scattering loss from both the curved and straight sections. At 1.15 μm, the wavelength of light being used in this work, the refractive indices of GaAs and $Ga_{0.82}Al_{0.18}As$ are approximately 3.44 and 3.35, respectively, [18] and therefore the reflection coefficient at each end of the guides is approximately 0.3 or −3.1 dB. The input coupling efficiency and attenuation coefficient due to scattering may be calculated by assuming that the bending loss is negligible for the 300 and 400 μm radii guides with $t = 0.3$ μm, as is suggested by using an extension of

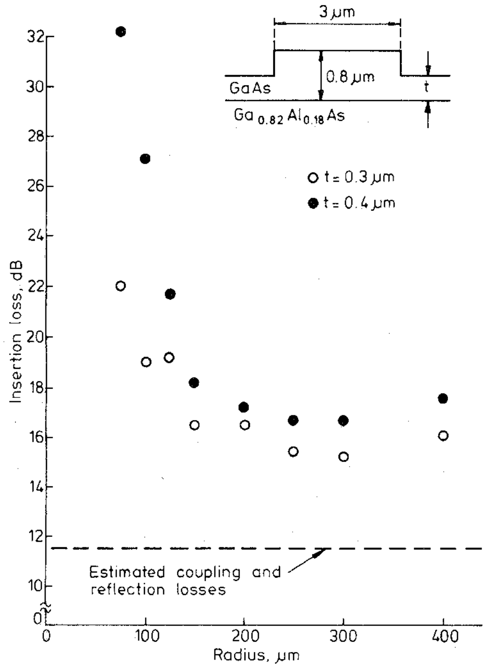

Fig. 3. Plot of measured insertion loss as a function of radius of curvature for the guide geometries shown.

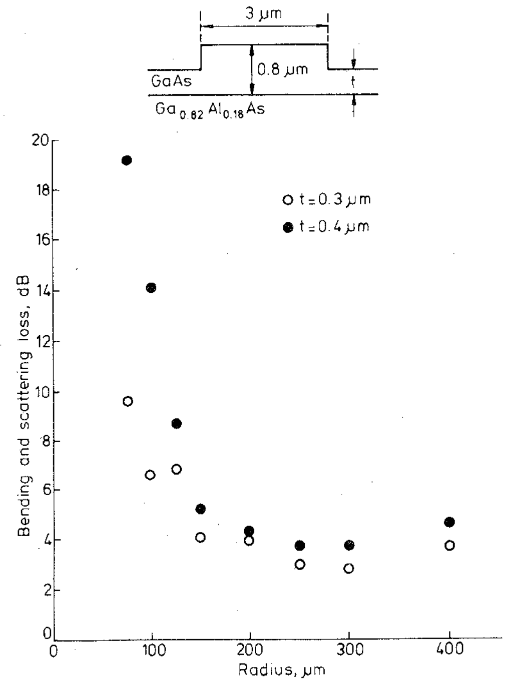

Fig. 4. Plot of measured insertion loss, corrected for estimated coupling losses and scattering from the straight sections of guide, as a function of radius of curvature.

the existing bending loss theories. The coupling efficiency is calculated to be approximately 14.5 percent, or -8.4 dB. This low value for the coupling efficiency is because the minimum focused laser spot size is approximately 2.5-3 μm in diameter whereas the GaAs layer is only 0.8 μm thick. This restricts the amount of light which can be coupled into the guide. A similar coupling efficiency is expected for the guides with $t = 0.4$ μm. The attenuation coefficient due to scattering was calculated to be approximately 6.9 cm^{-1}. When corrected for reflection losses (-3.1 dB), input coupling efficiency (-8.4 dB), and scattering from the straight sections, a minimum loss of approximately 2.8 dB has been achieved for a 90° curved guide with a radius of curvature of 300 μm as shown in Fig. 4. The lengths of the straight sections are 150 μm for the guides with $t = 0.3$ μm, and 255 μm for the guides with $t = 0.4$ μm and it has been assumed that the scattering attenuation coefficient is the same for both waveguide geometries. Most of the residual loss is due to scattering from the rib wall imperfections. The rib profiles were studied with a SEM and the edge roughness appears to be of the order of 100 nm, as seen in Fig. 5.

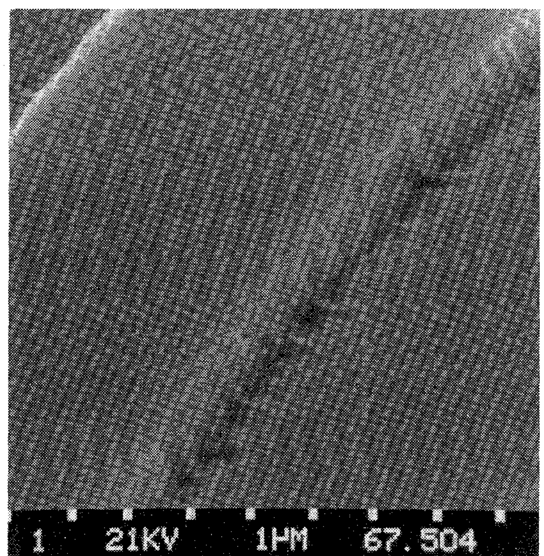

Fig. 5. SEM photograph showing edge roughness of a curved rib waveguide.

Guides with $t = 0.15$ μm have also been fabricated on this material. Although the insertion loss for the 75 μm radius guides, -20.4 dB, was smaller than for the guides with $t = 0.3$ μm due to tighter lateral field confinement, the decrease of insertion loss with increasing radius was not as fast and there was a minimum in the insertion loss at a radius of approximately 200 μm. For radii of curvature larger than 200 μm, the loss increased rapidly. It seems most likely that scattering loss per unit length is larger in these guides because of greater interaction of the optical field with the rough edges.

Although multimode guides may be useful in some applications, single-mode guides will be needed for most integrated optics requirements. Single-mode operation may be obtained by reducing the guide width, decreasing the height of the GaAs layer adjacent to the rib, and/or decreasing the aluminium content in the GaAlAs. Two batches of curved rib waveguides have been fabricated on GaAs/$Ga_{0.92}Al_{0.08}As$ material where the GaAs layer is approximately 1 μm thick. At 1.15 μm, the refractive index of $Ga_{0.92}Al_{0.08}As$ is approximately 3.40 and theoretical studies using the variational program show that for 3 μm wide guides, single-mode operation can be obtained for $t < 0.45$ μm. The first batch of guides had $t \simeq 0.5$ μm. These guides supported two modes and were very lossy, as seen in Fig. 6. Insertion loss decreased exponentially with increasing radius of curvature and showed no sign of a minimum loss for radii less than 400 μm. The second batch had $t \simeq 0.35$

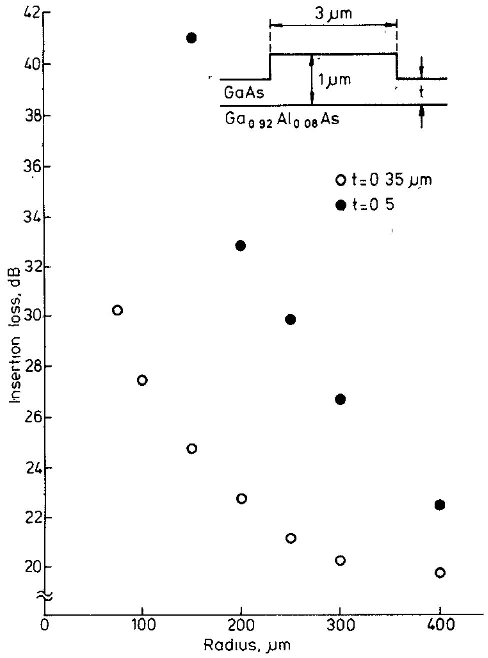

Fig. 6. Plot of measured insertion loss as a function of radius of curvature for the guide geometries shown.

μm. These guides were single moded as predicted. Insertion losses, as seen in Fig. 6, were smaller than for $t = 0.5$ μm and appear to be approaching a minimum loss, determined by scattering, at a radius of 400 μm. No figure for the coupling efficiency or scattering coefficient has been measured, however if a value for the coupling efficiency similar to that obtained for the multimode case is assumed, then a minimum loss of approximately 8.5 dB has been achieved for a 90° curved guide with a radius of curvature of 400 μm. It should be noted that guides fabricated in $GaAs/Ga_{0.92}Al_{0.08}As$ have higher loss than guides fabricated in $GaAs/Ga_{0.82}Al_{0.18}As$, since the overall optical confinement is not as tight.

Insertion losses are smaller for the guides with larger relative rib heights. For small radii of curvature, this is due to a difference in the bending loss resulting from tighter lateral field confinement. For larger radii, the losses asymptote to a value determined by scattering loss. More work with guides of different geometries and material composition is needed to determine whether radiation loss, scattering loss, or input coupling efficiency is limiting the guide performance and to minimize these losses.

Conclusion

This paper has given a brief review of curved waveguide analysis and has presented some experimentally measured loss values for GaAs/GaAlAs curved rib waveguides. Results look encouraging. When corrected for reflection losses and input coupling efficiency, a minimum loss of approximately 3 dB has been achieved for a multimode 90° curved guide with a radius of curvature of 300 μm, and 8.5 dB for a single-mode curved guide with a radius of curvature of 400 μm. In cases where the input coupling can be optimized, for example when a semiconductor laser and curved waveguide are integrated on the same substrate, the insertion loss of the guides may be reduced significantly. More work is needed with guides of different geometries and material composition to determine the limiting loss mechanisms.

The optimum material composition for tolerable radiation loss and single-mode operation is still being investigated. For efficient coupling to single-mode fibers a large guide width, of the order of 5-7 μm, is required, and to be compatible with directional coupler structures currently being investigated, GaAlAs with a low aluminium content of 2-5 percent is desirable. It is believed that single-mode curved rib waveguides with low radiation losses and radii of 200-300 μm may be achieved. The limiting loss may not be radiation loss due to bending, but rather scattering loss due to waveguide wall imperfections. Finally, the experience gained from investigating GaAs/GaAlAs curved rib waveguides is to be carried on to InGaAsP/InP structures.

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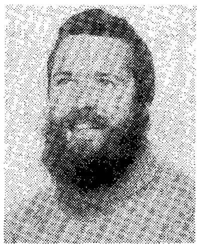

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CO_2 Laser Annealing of Si_3N_4, Nb_2O_5, and Ta_2O_5 Thin-Film Optical Waveguides to Achieve Scattering Loss Reduction

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Abstract—**Significant reductions in the optical scattering losses of Si_3N_4, Nb_2O_5, and Ta_2O_5 waveguides fabricated on SiO_2/Si substrates have been measured following CO_2 laser annealing. The largest improvements were observed for Si_3N_4 waveguides, where waveguide attenuation values of about 6.0 dB/cm before laser annealing were reduced to as low as 0.1 dB/cm afterwards. An improvement of more than an order of magnitude was obtained for a Nb_2O_5 waveguide upon laser annealing, the attenuation coefficient decreasing from 7.4 to 0.6 dB/cm. In the case of one Nb_2O_5 waveguide no improvement was obtained upon laser annealing. The attenuation coefficient of a reactively sputtered Ta_2O_5 waveguide was found to decrease from 1.3 dB/cm before laser annealing to 0.4 dB/cm afterwards. In the case of a thermally oxidized Ta_2O_5 waveguide a small initial improvement in waveguide attenuation was followed by degradation upon further laser annealing.**

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I. Introduction

SCATTERING of light propagating in thin-film optical waveguides represents a loss mechanism and, concommittantly, a limitation on the dynamic range obtainable in integrated optical signal processing devices [1]. An order of magnitude reduction in waveguide scattering loss, for instance, leads to an approximately 10 dB increase in dynamic range [1]. In addition, a lower loss waveguide requires a lower power light source, an advantage in some applications. Reduction of scattering in thin-film optical waveguides is thus desirable, as it would make integrated optical signal processing devices more competitive with other approaches.

We have previously reported CO_2 laser annealing that dramatically reduces scattering losses in Corning 7059 glass [2], [3] and ZnO [4] thin-film waveguides fabricated on thermally oxidized silicon substrates. Losses as low as 0.05 dB/cm for Corning 7059 glass waveguides and 0.01 dB/cm for ZnO waveguides have been achieved by this technique, a factor of 50–100 times lower than the best results previously reported for these two waveguide materials [5]–[10]. In this paper we wish to report the success of CO_2 laser annealing in reducing scattering losses in Si_3N_4, Nb_2O_5, and Ta_2O_5 waveguides, all fabricated on thermally oxidized silicon substrates.

The lowest loss reported for any thin-film optical waveguide

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