

Reduced bending and scattering losses in new optical `double-ridge' waveguide

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up to two errors, since the length of the sliding block decoders is 8 bits for these $R = 1/4$ codes.

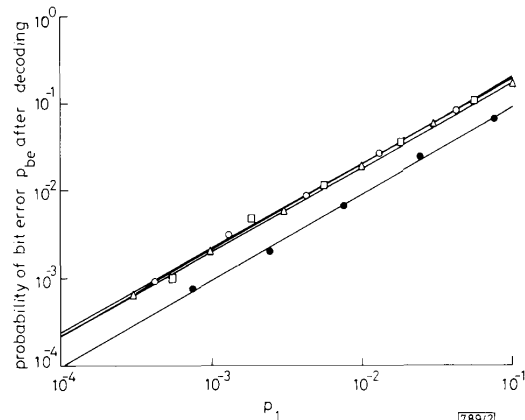


Fig. 2 BER after sliding block decoding on two-state bursty channel
 \triangle $(d, k) = (5, 9)$ \square $(d, k) = (4, 7)$ \circ $(d, k) = (4, 8)$
 \bullet $(d, k) = (1, 2)$

The error propagation due to isolated single bit errors was next investigated and it was obtained by randomly selecting a bit within a long sequence of code bits where an isolated single bit error was introduced. The number of decoding information bit errors, due to a single code bit error, were thus determined for a large number of randomly selected events. The average probabilities that an isolated channel

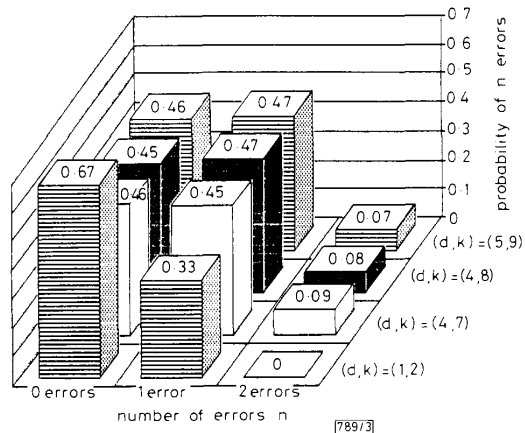


Fig. 3 Probability of propagated decoding errors following isolated single code bit error

REDUCED BENDING AND SCATTERING LOSSES IN NEW OPTICAL 'DOUBLE-RIDGE' WAVEGUIDE

Indexing terms: Waveguides, Optical waveguides, Optoelectronics, Integrated optics

A new type of waveguide is proposed combining a low and a high ridge. Experiments at $\lambda = 632.8$ nm show an excess loss of 0.6 dB for a 90° bend with $R = 50 \mu\text{m}$ in SiO_2 cladded Al_2O_3 , and showing reduced scattering losses compared with a conventional ridge waveguide.

Introduction: The successful development of optoelectronic integrated circuits depends largely on the ability to miniaturise components and to reduce their losses. A necessary ingredient of these circuits is the curved waveguide with small radius of curvature and low propagation losses. These bends not only provide directional changes, which can also be sup-

plied by corner mirrors,¹ but they also separate waveguides in directional couplers, are used in ring lasers and they enable the miniaturisation of long components such as phase modulators and external cavities by folding them onto a small area.

Attenuation of light in a waveguide bend is caused by radiation, which is due to roughness scattering, and by transition losses at the junction of the straight and curved sections. The radiation losses decrease with increasing difference in refractive index. In ridge waveguides the radiation losses can therefore be reduced by etching a high ridge, but this has two important drawbacks. First, a large refractive index difference causes the waveguide to become multimode, whereas most applications require monomode waveguides. Secondly imperfections in the mask and etching processes lead to edge roughness coupling the bound mode to the continuum of unguided modes.² These scattering losses increase with refractive-index difference and with ridge height.

The ideal solution would be to use a local increase of the etched step, as several authors^{3,4} have suggested. For straight waveguides a low ridge could be used that leads to a low-loss

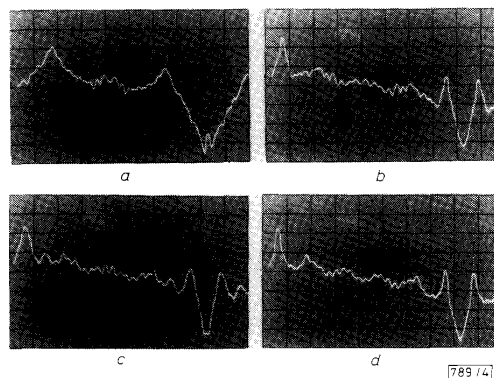


Fig. 4 Measured power spectral densities

Vertical scale: power spectral density, 10 dB/div; horizontal scale: frequency, 500 Hz/div; bit rate: 4166 bit/s
 a $R = 1/3, (d, k) = (1/2)$ b $R = 1/4, (d, k) = (4, 7)$
 c $R = 1/4, (d, k) = (4, 8)$ d $R = 1/4, (d, k) = (5, 9)$

The power spectral densities of the codes were measured with a spectrum analyser after programming a SDK-51 micro-processor kit to function as a finite-state machine encoder and these are shown in Fig. 4.

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4th April 1989

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References

- VAN RENSBURG, G., and FERREIRA, H. C.: 'Four new runlength constrained recording codes', *Electron. Lett.*, 1988, **24**, pp. 1110-1111
- FERREIRA, H. C., HOPE, J. F., NEL, A. L., and VAN WYK, M. A.: 'Jacoby and Kost's binary two-thirds rate modulation code', *Electron. Lett.*, 1986, **22**, pp. 1155-1157
- FERREIRA, H. C., STEGMANN, W. DE V., and WYMAN, C. R.: 'Comparison between the Jacoby-Kost and Horiguchi-Morita binary two-thirds rate modulation codes', *Electron. Lett.*, 1987, **23**, pp. 837-838
- FERREIRA, H. C., HOPE, J. F., NEL, A. L., and VAN WYK, M. A.: 'Viterbi decoding and the power spectral densities of some rate one half binary DC free modulation codes', *IEEE Trans.*, 1987, **MAG-23**, pp. 1928-1934

monomode waveguide, and a high ridge at the bends reduces the radiation losses. Such a scheme, however, needs two different masks and leads to problems with the required submicron alignment.

In this letter we propose a new type of waveguide called 'double ridge guide', as shown in Fig. 1, that combines a low inner and a high outer ridge in a self-aligned procedure. In straight waveguides the field is mainly confined by the inner ridge. The height of this ridge can be chosen to yield a monomode waveguide with low scattering losses. In a tight waveguide bend the field profile shifts outwards to the high ridge preventing radiation of light out of the waveguide.

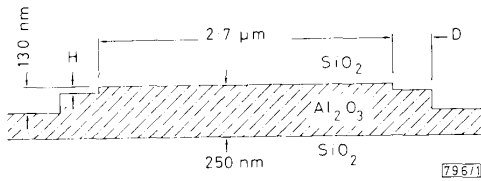


Fig. 1 Geometry of double-ridge guide

Modelling: Theoretical predictions for the radiation losses in curved waveguides have been made by applying the effective dielectric constant (EDC) method, after which a conformal transformation was used.⁵ The solution of the transformed scalar wave equation was then found by numerical integration.

The scattering losses in a planar slab waveguide^{2,6} are proportional to the square of the power-normalised electric field, to the square of the dielectric-constant difference and to λ^{-k} , where k varies from two to four depending on the statistical model of the roughness. These proportionalities and the EDC method have been used in a semiempirical formula for the scattering losses:

$$\alpha = \alpha_0 + \alpha_1 \sum [\Delta N_i^2]^2 |E(x_i)|^2 / \int |E(x)|^2 dx \quad (1)$$

in which α represents the total loss in dB/cm, α_0 is the attenuation for the planar waveguide, ΔN_i is the difference in effective refractive index at interface i , $E(x_i)$ is the electric field at interface i , x is the lateral co-ordinate and the contributions are summed over all interfaces, which is justified if the roughness in different ridges is not correlated. α_0 and α_1 have been fitted to experimental values yielding $\alpha_0 = 1$ dB/cm and $\alpha_1 = 0.14$ dB for our waveguides, presuming that the correlation length and the RMS value of the roughness are a constant of the process.

The calculated radiation and scattering losses for Al_2O_3 ($n = 1.690$) and SiO_2 ($n = 1.457$) at $\lambda = 632.8$ nm are given in Fig. 2, while the relevant parameters of the double ridge wave-

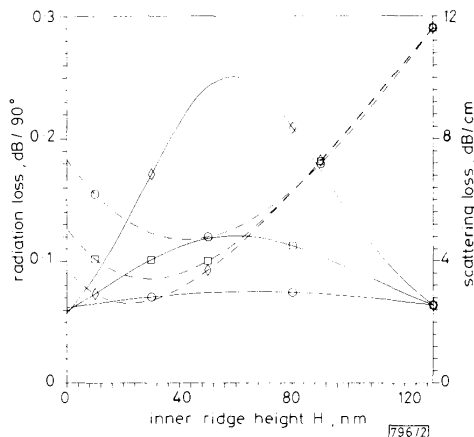


Fig. 2 Radiation loss for $R = 50 \mu\text{m}$, $2.7 \mu\text{m}$ -wide curved waveguide (solid lines) and scattering losses for $1.7 \mu\text{m}$ -wide straight waveguide (broken lines)

Sum of both ridge heights is constant, i.e. 130 nm
 $\circ D = 0.2 \mu\text{m}$ $\square D = 0.4 \mu\text{m}$ $\diamond D = 0.6 \mu\text{m}$

guide are explained in Fig. 1. For $D = 0.2 \mu\text{m}$ the radiation curve is nearly flat, indicating that for small ridge separations the radiation loss depends on the sum of both ridge heights and not on the individual ridge heights. The scattering loss in the straight waveguide on the other hand strongly depends on the way the total ridge height is divided and it shows a minimum between $H = 20 \text{ nm}$ and $H = 40 \text{ nm}$. For $H = 0$ and for $H = 130 \text{ nm}$ the waveguide is single-ridge and asymmetry in the scattering curves stems from the fact that at $H = 0 \text{ nm}$ the waveguide has become wider by an amount $2D$. The inner ridge will be single mode for ridge heights H smaller than 25 nm .

Experiments: Waveguides have been fabricated in 250 nm thick sputtered Al_2O_3 films on oxidised silicon wafers. We reported⁷ previously on conventional ridge waveguides in the same material system, which allows a comparison with present results. The double-ridge waveguide was dimensioned so as to keep the scattering loss in the straight waveguides approximately equal to those of the single-ridge case and to reduce the radiation losses. This led to a total ridge height of 130 nm , an inner ridge height of 40 nm and a distance D of $0.4 \mu\text{m}$. To create the double-ridge guide we used a self-aligned process that creates both ridges in one photolithographic step. On top of the Al_2O_3 film we sputtered 400 nm SiO_2 , on which photoresist was applied, patterned and developed. Buffered HF was then used to etch the SiO_2 film. Owing to the isotropic nature of this etch a large underetch developed (see Fig. 3), the amount of which could be controlled by varying the etching time. The photoresist defined the 90 nm high outer ridge that was etched by atom beam milling, and after stripping the photoresist the remaining SiO_2 served to mask the inner ridge of 40 nm height. The SiO_2 mask was then etched away and a cladding layer of 650 nm SiO_2 was sputtered as a cover.

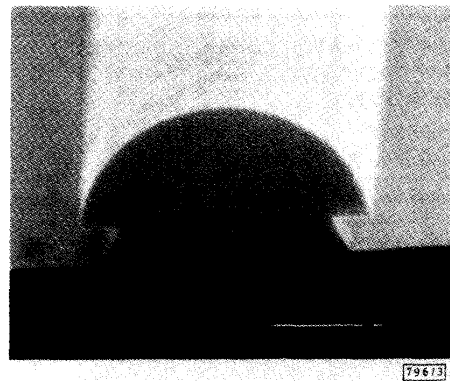


Fig. 3 SEM photograph showing controlled underetch in photoresist-covered SiO_2 on Al_2O_3

Bar represents $1 \mu\text{m}$

The same mask was used to pattern both the single and the double-ridge waveguide. Since the straight single-ridge waveguides were $2.5 \mu\text{m}$ wide, the inner ridge of the straight double-ridge waveguides was $1.7 \mu\text{m}$ wide.

Results: We fabricated five different S-bends, where every S-bend started with a $90^\circ R = 200 \mu\text{m}$ bend and the second 90° bend had $R = 50, 75, 100, 150$ and $200 \mu\text{m}$, respectively. All S-bends had optimised offsets at the junctions between straight and curved sections to reduce the transition losses.⁷ Light from a He-Ne laser was coupled into and out of the waveguides by means of a prism.⁸ The attenuation for the straight waveguides was measured by sliding the output prism along the waveguide, and was found to be $3.8 \pm 0.5 \text{ dB/cm}$ for a 100 nm -wide single-ridge guide and $4.4 \pm 0.4 \text{ dB/cm}$ for a 110 nm -wide single-ridge guide. The 130 nm double-ridge guide had only $4.7 \pm 0.3 \text{ dB/cm}$ attenuation. This value of 4.7 dB/cm is slightly higher than the predicted reduction from 11.6 dB/cm to 3.6 dB/cm as can be seen from Fig. 2. This deviation may be due to extra roughening of the SiO_2 mask during the buffered HF etch. The total attenuation of these

S-bends was compared with four straight reference waveguides. Fig. 4 shows the results for 100 nm and 110 nm single-ridge guides and a double-ridge guide with 130 nm total ridge height. The double-ridge guide showed a total excess loss of 0.6 dB for the $R = 50 \mu\text{m}$ 90° S-bend, which is the lowest value for bending losses reported thus far.

Conclusions: The double-ridge waveguide offers a solution to the conflicting requirements for short bends and for low scattering losses. A self-aligned procedure has been used to create

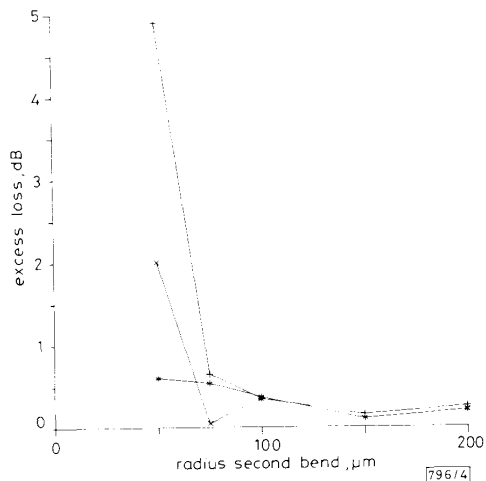


Fig. 4 Measured S-bend losses for HE_{00} mode

* double ridge, 90/40 nm × single ridge, 110 nm
+ single ridge, 100 nm

EFFECT OF ELEVATED TROPOSPHERIC LAYER ON RADIO WAVE PROPAGATION IN SURFACE DUCT

Indexing terms: Radiowave propagation, Antennas

A confinement factor is defined for the purpose of providing a quantitative measure of ducted radiation. It is shown that a five-fold increase in the confinement factor can result from the presence of an elevated m -inversion for an antenna situated above the surface duct and below the m -inversion.

Introduction: One of the important mechanisms of electromagnetic wave propagation beyond the radio horizon is that of transmission in a tropospheric duct close to the surface of the earth. This situation can occur if the negative refractivity gradient near the earth's surface is sufficiently strong that a surface duct is formed. The simultaneous existence of an elevated tropospheric layer above the surface duct (as illustrated by the modified refractive index profiles on the right of Fig. 2c) can modify the field distribution both within the duct and outside it. We study this modification and introduce a quantitative measure of it in terms of a 'confinement factor' in analogy with similar situations in dielectric waveguides. The effect of an elevated layer on ducted transmission has been investigated by Kukushkin and Sinitsyn¹ in a mixed and rather involved procedure that rests on describing the field within the duct in terms of modal expansion and the field contributed by the elevated layer in terms of geometrical optics. The one numerical example given in this reference presumes the impressed field to emanate from a point within the surface duct without making reference to the field that would exist in the absence of the elevated layer. Clearly, an appreciable contribution from the elevated layer in this case is obtained only if the duct is weak.

We employ the beam propagation method^{2,3} to solve the parabolic electromagnetic wave equation in the space above the ground enclosing the surface duct and the elevated layer. We consider situations where the radiating source is both

this waveguide. Experiments show a simultaneous reduction of bending and scattering losses. A total bending loss as low as 0.6 dB has been measured for a 90° S-bend with a radius of curvature of 50 μm .

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References

- ALBRECHT, P., DÖLDISSEN, W., NIGGEBRÜGGE, U., NOLTING, H.-P., and SCHMID, H.: 'Waveguide-mirror components in InGaAsP/InP'. Proc. 14th European conference on optical communication, Brighton, 1988, pp. 235-238
- MARCUSE, D.: 'Mode conversion caused by surface imperfections of a dielectric slab waveguide', *Bell System Techn. J.*, 1969, **48**, pp. 3187-3215
- MARCUSE, D.: 'Bending losses of the asymmetric slab waveguide', *Bell System Techn. J.*, 1971, **50**, pp. 2551-2563
- NEUMANN, E.-G., and RICHTER, W.: 'Sharp bends with low losses in dielectric optical waveguides', *Appl. Optics*, **22**, pp. 1016-1022
- HEIBLUM, M., and HARRIS, J. H.: 'Analysis of curved optical waveguides by conformal transformation', *IEEE J. Quantum Electron.*, 1975, **QE-11**, pp. 75-83, plus correction, *ibid.*, 1976, **QE-12**, p. 313
- HINKEN, J. H.: 'Film mode attenuation due to random surface irregularities'. Proc. 6th European microwave conference, Rome, 1976, pp. 513-517
- PENNINGS, E. C. M., MAHOUDT, G. H., and SMIT, M. K.: 'Low-loss bends in planar optical waveguides', *Electron. Lett.*, 1988, **24**, pp. 998-999 and references therein
- PASMOOIJ, W. A., MANDERSLOOT, P. A., and SMIT, M. K.: 'Prism-coupling of light into narrow planar optical waveguides', *J. Light-wave Technol.*, 1989, **7**, pp. 175-180

within the surface duct and outside it, and calculate the ducted field in the presence of the elevated layer and in its absence.

Theory: If we designate by ψ any field component, it can be shown that Maxwell's equations result in the wave equation

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} + k^2 n^2 \psi = 0 \quad (1)$$

where x and z designate the range and height above the ground, respectively, k is the free space wave number and n is refractive index of the air. We extract a carrier and solve the parabolic equation in terms of the 'attenuation function' u which is given by

$$\psi \sim \frac{e^{-ikx}}{\sqrt{(x)}} u \quad (2)$$

Substituting eqn. 2 into eqn. 1 and neglecting small contributions, the parabolic equation is obtained as

$$2ik \frac{\partial u}{\partial x} = \frac{\partial^2 u}{\partial z^2} + k^2 (m^2 - 1) u \quad (3)$$

where $m(z)$ is the modified refractive index given by $m(z) = n(z) + (z/a)$ and a is the radius of the earth. The modified refractive index of eqn. 3 accounts for the curvature of the earth. Eqn. 3, which closely resembles the Helmholtz equation, assumes that the variation of the attenuation function in the x -direction over a wavelength is small. The solution of eqn. 3 can be expressed formally as²

$$u(z, \Delta x) = e^{-i \Delta x / (4k) (\partial^2 / \partial z^2)} e^{-i \Delta x k / 2 (m^2 - 1)} \times e^{-i \Delta x / (4k) (\partial^2 / \partial z^2)} u(z, 0) \quad (4)$$

and is achieved by the application of the fast Fourier algorithm which in the present problem is implemented on a grid of 1024 points in the z -direction. The marching method