illustrate variations of the line capacitance in terms of the conductor voltage, normalised to the thermal potential $V_t$, where the parameters are respectively, the active layer doping rate $N_A$, and conductor half-length $W$.

Conclusion: The two-dimensional approach developed in this study has allowed us to take into account exact boundary conditions on the ground planes of a microcoplanar MES transmission line by using a conformal mapping technique. An accurate calculation of the depletion layer is carried out which leads to the establishment of a rigorous localised model, including edge effects. As far as slow-wave propagation is concerned, this model is preferable to the conventional layered model used for full-wave analyses since it reflects much better the physical behaviour of the microstructure. The structure seems particularly interesting to be used in variable phase-shifters, attenuators and coupled lines.

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References

LOW-LOSS BENDS IN PLANAR OPTICAL RIDGE WAVEGUIDES

Indexing terms: Optical waveguides, Optical waveguide components, Integrated optics, Losses

Bending losses lower than 0.7 dB for 90° bend sections with radii of curvature as small as 75 μm were measured on silicon-based Al₂O₃ ridge waveguides with SiO₂ cladding layers at a wavelength of 632.8 nm. These values, which are close to the calculated values, are the lowest thus far reported.

Introduction: In optoelectronic integrated circuits waveguide bends play an important role in connecting components. The size of these bends essentially determines the maximum density with which components can be integrated on a single chip. Waveguide bends may also enable long components such as external cavities and phase modulators to be folded and miniaturised.

The only previous results on millimetre bends in ridge waveguides seem to be those of Austin, where 1 dB/90° loss has been reported for GaAs/AlGaAs bends with $R = 300$ μm. Realisation of directional changes with totally reflecting corner mirrors has not yet yielded losses below 1.5 dB per mirror.

We investigated bending losses in very short bends with radii of curvature from 50 to 200 μm in 3 μm wide ridge waveguides, etched in SiO₂ clad Al₂O₃ films on silicon substrates. Measurements and calculations were performed at a wavelength of 632.8 nm.

Bending loss mechanisms: The total loss of a waveguide bend of finite length is due to radiation loss, field mismatch at the transition between the straight and curved waveguide and increased scattering by roughness of the outer edge. We will discuss these mechanisms.

(i) Every curved structure exhibits losses in the form of radiation, because of the finite speed of light in the cladding material. The radiation losses can be reduced either by increasing the radius of curvature or by introducing a large refractive-index contrast. In our case, we created a large contrast by etching a high ridge, the price of which is paid by increased propagation losses of the straight sections due to scattering by edge roughness. The calculation of the radiation losses involved the effective-index method. The resulting two-dimensional bend is transformed into an equivalent straight structure by means of a conformal transformation, which is then solved by means of the staircase approximation.

(ii) In a curved waveguide the intensity distribution shows a shift of its maximum towards the outer edge. For small radii of curvature the mode is guided by the outer edge alone (like a whispering gallery mode). The shape of this mode profile is therefore not determined by the width of the waveguide bend but mainly by the refractive-index contrast and the radius of curvature, whereas the shape of the straight-waveguide mode profile strongly depends on the width of the waveguide. At the transition between the straight and curved waveguide conversion losses will occur because of the mismatch between the two field distributions. These conversion losses can be minimised by introducing a lateral offset between the straight and curved waveguide to align the field maxima, and by optimising the width of the straight waveguide to match the widths of both field distributions, as exemplified in Fig. 2. The conversion losses have been estimated by applying overlap integrals. The improvement in coupling efficiency can be substantial as can be seen in Fig. 1. For a 3 μm-wide straight

![Fig. 1 Coupling losses for H₈₀₀ mode as function of lateral offset for different widths of straight waveguide](image)
ELECTRONICS LETTERS

Fig. 3

(iii) The scattering losses depend on the edge roughness of the ridge waveguide. We found that an optical pattern generator (ASET COMBO 250) with rotating head in combination with a 4 x reduction camera gives an edge quality superior to electron-beam generated patterns, which often exhibit a step-like pattern due to electron-beam quantisation. This may be solved by choosing a very small spot size, but at the price of excessive writing time. Fig. 2 demonstrates the edge quality of the optically generated pattern.

Fig. 2 SEM photograph of ridge waveguide bend with R = 50 μm defined in photoresist.

Experiments and results: We designed and fabricated two wafers with five identical sets, each set containing five different S-bends and several straight reference waveguides. Each S-bend starts with a 200 μm 90° bend and is followed by a second 90° bend with R = 50, 75, 100, 150 and 200 μm respectively. Waveguides were formed by atom-beam milling a 100 nm step in a 250 nm thick sputtered Al₂O₃ layer (n = 1.69) through a photoresist mask and by covering the circuit with a sputtered SiO₂ layer (n = 1.457). The 100 nm step creates a lateral effective-index contrast of Δn/Δn ≈ 3.4%. Light from a He-Ne laser (λ = 632.8 nm) was coupled into the S-bend and several straight reference waveguides. Each wafer contained five identical sets, each set containing five different S-bends and several straight reference waveguides. Each S-bend starts with a 200 μm 90° bend and is followed by a second 90° bend with R = 50, 75, 100, 150 and 200 μm respectively. Waveguides were formed by atom-beam milling a 100 nm step in a 250 nm thick sputtered Al₂O₃ layer (n = 1.69) through a photoresist mask and by covering the circuit with a sputtered SiO₂ layer (n = 1.457). The 100 nm step creates a lateral effective-index contrast of Δn/Δn ≈ 3.4%. Light from a He-Ne laser (λ = 632.8 nm) was coupled into the S-bend and several straight reference waveguides. Each wafer contained five identical sets, each set containing five different S-bends and several straight reference waveguides.

Because of the selective excitation we could measure bending losses for the HE₀₀ and HE₁₁ modes as well. The offsets between straight and curved waveguides have not been optimised for these modes and consequently there is considerable intermodal conversion at the transitions. Despite the increased contribution of coherent interference effects the qualitative agreement between measured and predicted results remains quite good. The crossing of the HE₀₀ and HE₁₁ attenuation curves as predicted by theory is indeed measured.

Conclusions: We have fabricated ridge waveguide S-bends with radii of curvature as small as 75 μm and measured a total loss of 0.75 dB, which is very close to the calculated value. These low losses were obtained by introducing a large lateral effective-index contrast and a lateral offset at the transition and by optimising the width of the straight waveguide. The low losses made it possible to cascade a considerable number of bends with negligible bending losses, thus demonstrating the feasibility of folding and miniaturising long components such as external cavities and phase modulators.

Fig. 4 Four loops with R = 200 μm

References