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Published in:
IEEE Photonics Technology Letters

Published: 01/01/1992

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

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Fig. 4. AM noise spectra of the FRASL operating in (a) Non-SSFS-suppression state at 0.4 W pump level and (b) SSFS-free state at 0.18 W pump level at the fixed oscillation wavelength of 1.418 μm. Trace (c) is the noise spectrum of Nd:YAG pump laser.

A Long InGaAsP/InP Waveguide Section with Small Dimensions

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Abstract—We realized a spirally folded InGaAsP/InP ridge-type waveguide with 12.4 mm length on a device area of 1 × 1 mm². Insertion loss was measured to be 4 dB for TE-polarization and 4.5 dB for TM polarization (at 1.55 μm wavelength).

INTRODUCTION

LONG waveguide sections find applications in extended cavities and Mach–Zehnder interferometer structures. Raybon et al. [1] recently reported a mode-locked laser with a monolithically integrated 4.2 mm long straight passive waveguide section with a loss of 3–4 dB/cm. Beaumont et al. [2] reported at the same conference a single-turn folded arsenic-doped silica waveguide with a length of 2 cm and device dimensions 8 × 13 mm², with a potential to integrate 240 mm on the same surface. The device measured 2.2 dB insertion loss. In this letter we present a 12.4 mm long InGaAsP/InP waveguide spirally folded on a device area of 1 × 1 mm², with an insertion loss of 4 dB for TE-polarization and 4.5 dB for TM-polarization, measured at 1.55 μm wavelength.

DESIGN

Fig. 1 shows an optical micrograph of the device. The diameter of the outer loop is 1 mm. The spacing between the concentric waveguides in the spiral is 10 μm. The waveguide structure is shown in Fig. 2. It consists of a 0.5 μm Q1.3 layer and a 0.4 μm InP top layer, in which a ridge is etched with CH₄/He reactive ion etching. An important design parameter is the lateral effective index

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IEEE Log Number 9202927.
contrast, which is controlled by the etch depth. Radiation loss in bent waveguides decreases with increasing index contrast whereas scattering loss due to waveguide edge roughness increases. Further, the bending loss increases rapidly with decreasing bending radius, the curves with the smallest radius dominate the total radiation loss. If at the center of the spiral the waveguide is folded back by 180° in order to leave the spiral into the opposite rotation direction without crossing other waveguides we need two 180° bend sections with \( R = 200 \mu m \) at the center of the spiral. Based on calculations made by Agrawal [3] we expect the crosstalk at waveguide crossings with a crossing angle of 70° to be negligible. Therefore, we decided to apply the structure as shown in Fig. 1, which allows for a much greater bending radius inside the spiral. If a crossing angle of 70° is applied the bending radius of the inner bends can be increased from 200 to 320 \( \mu m \). With this radius the etch depth required in order to keep radiation loss sufficiently small is considerably reduced and the scattering losses will decrease correspondingly.

We applied a conformal transformation [4] in order to transform the problem of the curved slab waveguide into that of an equivalent straight waveguide with a transformed refractive index profile. The equivalent problem is then solved by approximating the smoothly varying transformed index distribution by a series of piecewise uniform regions (staircase approximation) and using a transfer matrix method to determine the complex propagation constant in the transformed domain. The angular propagation constant of the curved waveguide is directly inferred from the latter, the radiation loss follows from its imaginary part. Fig. 3 (solid curve) shows the computed radiation loss for TE-polarization, as a function of the etch depth. Results are presented for the waveguide structure shown in Fig. 2, with 2.2 \( \mu m \) width and a bending radius of 320 \( \mu m \). This is the smallest radius occurring in our design. Predicted TM-polarized losses are lower due to the higher lateral effective index contrast for this polarization.

The additional scattering loss due to edge roughness was calculated based on the assumption [5] that it is proportional to the normalized field intensity at the waveguide edge \( \frac{E_{edge}^2}{\int E^2 \ dx} \), and to the square of the effective dielectric contrast \( (N_1^2 - N_2^2)^2 \). Fig. 3 (dashed curve) shows the predicted dependence of the scattering loss on the etch depth, with an (etch-depth independent) film-loss contribution of 0.5 dB/cm. We calibrated the curve on experimental loss data obtained for straight waveguides as shown in Fig. 2. From Fig. 3 we see that the radiation losses should be negligible if the ridge is etched slightly into the quaternary layer. The corresponding straight-guide scattering loss is expected to be between 2 and 3 dB/cm.

In the curved waveguides the field pattern shifts to the outer edge, and becomes narrower than in an equivalent straight waveguide. In order to reduce field mismatch losses and excitation of higher-order modes, we adapted the straight-waveguide width (2.0 \( \mu m \) instead of 2.2 \( \mu m \) for the curved waveguides), and applied a lateral offset between the waveguide axes in order to compensate for the outward shift of the mode profile in the curved waveguides. At the junctions between (a) straight/\( R = 320 \mu m \), (b) Straight/\( R = 500 \mu m \), and (c) \( R = 320 \mu m / R = 450 \mu m \) waveguides we applied offsets of (a) 0.4 \( \mu m \), (b) 0.2 \( \mu m \), and (c) 0.1 \( \mu m \). Predicted conversion losses at the junctions are negligible.

**Fabrication**

The waveguide structure (InP buffer 1.2 \( \mu m \), Q1.3-layer 0.5 \( \mu m \), InP top layer 0.4 \( \mu m \)) was grown on a semi-insulating InP substrate with LP-MOCVD. TE-propagation loss, as measured with the FP-method on waveguides with a very shallow ridge, amounts to 0.5 dB/cm, which is indicative for the quality of the grown layers. Details are described by Moerman et al. [6]. The waveguide mask was produced with an optical pattern generator, and transferred into image-reversal photoresist with a 4 \( \times \) reduction mask aligner. The ridge was formed by reactive ion etching with 4 sccm \( CH_4 \) in 50 sccm He at a pressure of 60 mtorr and 0.4 W/cm² RF power. It was etched approximately 20 nm into the Q1.3 layer (etch depth 0.42 \( \mu m \)). The low CH₄ contents of the gas mixture employed is chosen in order to reduce polymerization and, consequently, waveguide edge roughness. This im-
were computed according to Buus [7]. For TE-polarization a reflection coefficient of 0.35 was calculated and for TM-polarization 0.21. In order to verify these data experimentally for our waveguide structure, we included a series of U-shaped waveguides "chicanes," as described earlier by Verbeek et al. [8], with in-line input and output guides in our mask design. All U's had the same bending radii, but different lengths of the straight sections. The total length within a series varied from 9 to 15 mm in steps of 1 mm. Further, a series of straight waveguides were included.

Waveguide attenuation was measured to be approximately 2 dB/cm both for TE- and TM-polarized light, in good agreement with results obtained previously. From the measurement results of the U-bends we inferred the reflection loss by extrapolating the regression line through the measured loss data to zero waveguide length. For TE-polarized light we found a reflection value of 0.34, for TM-polarized light we found a reflection value of 0.46. These results are close to the predicted values. The reproducibility of the loss measurement data is ±0.1 dB. The accuracy of the optical attenuation data as inferred from the FP measurement results is estimated to be ±0.3 dB.

Based on the computed reflection coefficients we found a spiral loss of 5.5 dB for TE-polarization, and 6 dB for TM-polarization. High loss values measured on defect spirals indicate negligible direct transmission from input to output waveguides. After subtraction of 1.5 dB loss occurring in the 7 mm long input and output leads, we obtain the following loss figures: 4 dB for TE-polarization and 4.5 dB for TM-polarization. From this loss approximately 2.5 dB may be contributed to scattering loss (1.24 cm × 2 dB/cm). The additional 1.5 dB for TE- and 2 dB for TM-polarization are due to additional bending losses. The radiation loss due to bending is expected to be largest for the TE-polarized mode, because the lateral effective index-contrast is smaller for TE-polarized modes than for TM-polarized ones. The fact that we did not find this dependence in our measurement results indicates that the contribution of the radiation loss to the total loss is small, and that most of the excess loss is due to scattering at the bend edge.

CONCLUSIONS

We realized a spirally folded InGaAsP/InP ridge-type waveguide with 12.4 mm length, corresponding to 4 cm free-space length, on a device area of 1 × 1 mm². Insertion loss was measured to be 4 dB for TE-polarization and 4.5 dB for TM-polarization, most of which is caused by normal propagation loss (2 dB/cm for straight waveguides). Excess bending loss is estimated to be 1.5 dB for TE and 2 dB for TM-polarization.

ACKNOWLEDGMENT

The authors wish to thank Prof. R. Baets and Prof. B. Verbeek for coordinating and stimulating cooperation.

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