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Ultrasmall waveguide bends: the corner mirrors of the future?

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Abstract: Curved waveguides with strong lateral modal confinement have been fabricated on InGaAsP/InP by etching through the waveguide core. This has resulted in extremely sharp bends (radii as small as 30 μm) with negligible bend loss, enabling fabrication of very low loss 90° turns on a chip area as small as that of a corner mirror.

1 Introduction

Over the years, in optoelectronic component research many high quality components have been developed, both passive (3 dB couplers, wavelength demultiplexers, polarisation splitters and converters) and active (lasers, photodetectors, phase and intensity modulators, switches). One of the targets of integrated optics is to integrate a variety of these components on the same substrate. This must lead to low cost devices which are suitable for large bandwidth communications.

Optical waveguides will serve as interconnects between the components of such a circuit, requiring the ability to change the propagation direction of the guided light. This is not a trivial problem, and it has received due attention in the literature. The proposed solutions can be subdivided into two categories: those that employ curved waveguides which smoothly change the propagation direction [1-6], and those that use a corner mirror structure for abrupt directional change [7-11], originally proposed by Benson in 1984 [12].

Each of these approaches has its own specific advantages and disadvantages. Curved waveguides can be made with extremely low (radiation) loss, but only for large bending radii. (As far as we know, no bending radii smaller than 100 μm have been reported.) The mirror solution, on the other hand, results in extremely small components (±30 x 30 μm), at the cost of a higher loss (typically 1 dB/90°). The purpose of this paper is to present the fabrication of improved waveguide bends, which combine the low loss of previously known bends with the extremely small size of corner mirror structures.

For comparison, first some aspects of corner mirror and curved waveguide fabrication are discussed. Then, design and fabrication of the improved waveguide bends are treated, followed by the measurement results and a short conclusion.

2 Corner mirrors

Corner mirrors on semiconductor material are typically fabricated in a self-aligned two-step process with a geometry as shown in Fig. 1. The waveguides are patterned in the first masking step, which also defines the position of the mirror, and then etched to the desired depth. The second masking step protects the entire chip, except for an etching window left at the position where the mirror is to be formed by a deep etching step.

There are a number of critical parameters that make it difficult to attain low loss corner mirrors:

1. It is very important that the etched mirror facet is at right angles with the chip surface. A slight tilt, as shown in Fig. 1, will reflect part of the light into the substrate instead of into the output waveguide. Therefore, an etching process optimised for facet verticality must be used, and even then a deviation from verticality of only 2° will cause between 0.5 and 1 dB loss [10].

2. Misalignment of the mirror facet will cause an offset between the reflected beam and the output waveguide. Therefore, an etching process optimised for facet verticality must be used, and even then a deviation from verticality of only 2° will cause between 0.5 and 1 dB loss [10].

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tion process due to mask erosion during etching. Also, a tilt of the facet will influence the position of the mirror.

3. Finally, the facet roughness induced by imperfections in the mask or the etching process will introduce additional mirror loss, which can be in the order of 0.5 to 1 dB [11].

Thus, the mirror etch process must be optimised for high anisotropy (facet verticality), low mask erosion and low roughness etching — conditions which are difficult to combine.

3 Curved waveguides

Directional change by means of curved waveguides is relatively easy to accomplish. The bends are defined in the same masking step as the other waveguides, and only one etching step is needed. There are, however, some other aspects that need consideration:

1. Curved waveguides have radiation loss, the more so the smaller the radius of curvature. In Fig. 2, this effect is demonstrated. Typically, the radiation loss is negligible for larger radii R, while for smaller R it rises exponentially to unacceptable values. The transition between these regions can be shifted to lower radii by applying a larger refractive index contrast. In the case shown, 200 μm is a usable radius. This implies usage of a rather large chip area.

2. In a curved waveguide, the optical mode shifts outward. This shift is larger for smaller bending radii, as Fig. 3 shows, and leads to coupling loss at the connection between a straight waveguide and a bend. The solution to this problem is the application of a well optimised inward offset at a straight-to-bend junction, which can reduce this loss to 0.01–0.1 dB.

Waveguide bends thus allow directional change with extremely low loss, at the cost of using a larger chip area.

4 Design of deeply etched curved waveguides

The radiation loss suffered at a certain bending radius can be reduced by increasing the mode confinement in the bend, i.e. by increasing the refractive index contrast. For ridge waveguides, this means increasing the etching depth. As Fig. 4 indicates, the result is that curved waveguides with smaller radii of curvature can be used.

![Fig. 4 An increased etching depth decreases radiation loss, and thus allows sharper bends](image)

Our approach in this work is to increase the index contrast by etching through the guiding layer, resulting in a waveguide structure as shown in Fig. 5. As the limiting case of maximum optical confinement in a ridge waveguide, that is expected to enable minimal bending radii with low radiation loss. This has already been established theoretically by Benson, Kendall and co-workers, who have derived exact formulae for the curvature loss from any solution known on a cylinder of reference in a layered medium [13, 14]. They have applied these results to the rib waveguide and predicted that the curvature loss would drop dramatically when the outer slab waveguide of the layered structure is cut off. This theoretical prediction has been confirmed by microwave simulation [15]. In our work, the outer slab of the curved waveguides is indeed cut off, and the qualitative aspects of this theory are shown to be strongly supported by our results.

In view of the complicated formulas involved, we here use only the effective index method (EIM), and make no attempt to calculate numerical values for the bending loss. Because the EIM is based on a separation of the modal fields in the x- and y-directions (first treating the lateral regions of the waveguide as slab waveguides, and

![Fig. 5 Deeply etched waveguide structure used throughout this work](image)
then solving the two-dimensional problem with the thus obtained effective indices, the cut off nature of the slabs next to the waveguide poses some problems. However, directly inserting $N_{eff}^c = 1$ in the second step of the EIM seems to give reasonable results. A comparison with the results of a finite element straight waveguide mode solver (Fig. 6) indicates good agreement for widths $\geq 2 \mu m$.

![Fig. 6 Comparison of effective index of deeply etched straight waveguides, as calculated with EIM (line) and with a finite element method 2-D mode solver (points)](image)

For modelling curved waveguides with the EIM, a conformal transformation technique is used as described by Reference 16. According to the EIM, for bending radii in the order of the waveguide width, radiation loss is still negligible. The modal effective index decreases with decreasing radius. As soon as it becomes lower than the substrate refractive index, substrate leakage will occur. This effect helps to maintain monomodality, but it also imposes a lower bound to the range of possible bending radii [17]. In our waveguide structure, substrate leakage for the fundamental mode will occur at $R = 26 \mu m$ for $W = 1 \mu m$, and at smaller radii for larger $W$.

Another factor influencing the range of usable bending radii is the mode profile (Fig. 3), which is not only shifted, but also changed in shape. The latter effect cannot be cured with an offset. Fig. 7 shows the straight-to-bend coupling loss (with optimal offset) for different radii and waveguide widths. Clearly, very wide bends are not a good choice. The light will then propagate as a 'whispering gallery mode', i.e. a mode that is only guided by the outer waveguide ridge and is not influenced by the inner ridge. Apparently, the mode shape then changes more than with narrower waveguides (in which the inner ridge contributes to the modal confinement), leading to increased coupling loss.

On the other hand, small waveguides are not desirable from the perspective of scattering loss. We therefore applied 3 $\mu m$-wide straight waveguides in the straight sections. They were connected to narrower bends using tapers. The bend width was chosen as $W = 1.4 \mu m$, for at this width the fundamental mode does not suffer substrate leakage, while the first-order mode is cut off.

With these parameters, for radii of curvature of 100, 70, 50 and 30 $\mu m$, a set of U-bend structures was designed with different curved waveguide path lengths, to assess bend loss per 90°. No offsets were used in the straight-to-bend junctions, because these would be smaller than 0.1 $\mu m$ even for the 30 $\mu m$ bends (Fig. 8).

![Fig. 8 Junction loss with (---) and without (- - -) offset, for straight-to-bend junctions of 1.4 $\mu m$-wide waveguides](image)

In our design, we use deep etching on the entire chip. This is not at all a prerequisite for using deeply etched bends: they can be made with the same process as corner mirrors, as shown in Fig. 9. The etching depth of the
waveguide outside the etching window is freely choos-
able. The field mismatch at the discontinuities can be
reduced below 0.1 dB by adapting the waveguide width
at both sides of the junction.

5 Fabrication

The devices were made on an SI-InP substrate with
MOVPE-grown undoped epitaxial layers [18], the thick-
ess of which slightly deviated from the design values:
660 nm InGaAsP (\(n = 3.3\mu\)) and 320 nm InP. The
devices were defined in photoresist with projection litho-
ography, and transferred into a 140 nm-thick RF-
sputtered SiO, masking layer with CHF, reactive ion
etching. Device dimensions turned out to be 0.3 \(\mu\)m
smaller than the design values.

Subsequently, the chip was etched with CHF, RIE,
employing an alternate etching/O, -descumming process
to reduce polymer deposition induced roughness. This
process produces extremely smooth sidewalls and corre-
spondingly low propagation losses [19], which is a
matter of major concern for high index contrast wave-
guides.

6 Measurement results

Straight waveguide propagation loss was measured both
with Fabry-Perot (FP) contrast measurements and
cutback transmission measurements. Other losses were
measured with transmission measurements as excess
losses relative to the straight waveguide loss.

For the FP measurements, the wavelength was swept
between 1533 and 1535 nm using a temperature tuned
DFB laser. The transmission measurements were per-
formed with a 1508 nm Fabry-Perot laser. Light was
coupled in and out of the chip with AR coated micro-
scope objectives (\(NA = 0.65\)) and projected onto a Ge-
detector through a pinhole. All measurements were
performed with the chip uncoated.

Cutback measurements revealed a propagation loss
through the 1.1 \(\mu\)m straight waveguides of 0.06 dB/cm for
TE and 5.0 dB/cm for TM (the TE/TM difference reflects
the better lateral confinement of the TM mode), in good
agreement with the FP results. For the (multimode)
2.7 \(\mu\)m straight waveguides, losses of 0.6 dB/cm were
measured, both for TE and TM polarisation. FP mea-
surements gave a higher value of 0.2 dB/cm, but are not
very reliable for multimode waveguides.

Waveguides incorporating series of tapers with lengths
varying from 10 to 50 \(\mu\)m were measured, and showed an
excess loss, in the order of the statistical measurement
error of the set-up, of about 0.2 dB. This indicates that
the loss introduced by individual tapers was negligible for
all taper lengths.

Fig. 10 shows the excess loss of the U-bend structures
for TE polarisation (the TM results are comparable). For
each of four bending radii, four U-bends with different
total curvatures were measured. The points missing from
the Figure are due to provable defects in the correspond-
ing waveguides.

It is seen that there is no significant increase in loss
with increasing total bend angle, indicating that radiation
loss and substrate leakage are negligible. Mainly, the loss
due to the constant contribution at the straight-to-
bend and bend-to-bend junctions. It is seen, for example,
that the loss of the \(R = 30 \mu\) U-bends of around 0.6 dB
can be explained by this junction contribution (indicated
by the horizontal lines on the left of Fig. 10) of 0.52 dB,
as predicted by modal overlap calculations. Even for the
anomalous value of 1.1 dB for a 270° bend (which we
believe to be due to a defect so small as not to be found
with a microscope), the radiation loss must still be below
0.2 dB/90°.

7 Conclusion

It has been shown that, with deeply etched ridge wave-
guides, extremely sharp waveguide bends with negligible
bend loss can be made. In experiments, the main loss
contribution came from the junctions. Radiation losses
are smaller than 0.2 dB/90° even for bending radii as
small as 30 \(\mu\)m.

With the configuration proposed in Fig. 9, a 90°
change of direction can be made on an area with a size
comparable to that of a corner mirror, with an identical
two-step masking/etching process, but without the need
to carefully control the etching process for sidewall verti-
cality, and with considerably lower loss.

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