Minimization of the Loss of Intersecting Waveguides in InP-Based Photonic Integrated Circuits

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***Abstract*— Waveguide intersections contribute significantly to the total loss of complex photonic integrated circuits. A systematic theoretical and experimental investigation into the loss of waveguide intersections in InP-based waveguides is presented, including an approach for minimizing intersection loss. Extremely low loss below 20 mdB per intersection is demonstrated experimentally.**

***Index Terms*—Integrated optics, loss reduction, semiconductor waveguides, tapers, waveguide intersections.**

I. Introduction

In complex photonic integrated circuits (PIC's), such as the integrated crossconnect reported previously by our group [1], the total number of waveguide intersections in some signal path is in the order of ten. With increasing complexity this number will become even larger, and the contribution of the intersection loss to the total insertion loss may become significant. In order to investigate and minimize this, we performed a series of systematic simulations and experiments that are reported in this article.

II. Description of the Experiments

Loss is highest for waveguides intersecting under a small angle. Measurements on Ti : $LiNbO_3$ show loss higher than 0.5 dB per waveguide intersection for intersection angles smaller than 10° [2]. A study by Van Dam *et al.* [3] found loss in InP-based waveguides to be higher than 0.3 dB per intersection for angles smaller than 30°.

We investigated both orthogonal and angled waveguide intersections by comparing BPM-simulation results with measurements for waveguide widths ranging from 2 to 8 μm. Further we included both linear and parabolic tapers that are required to connect waveguides of different width.

All experiments have been carried out in a waveguide structure as depicted in Fig. 1. The layer stack consists of an InP substrate with a 600-nm quaternary film layer and a 300-nm InP top layer. Both layers were grown by MOVPE. A 100-nm-thick PECVD-SiN layer served as etching mask for the waveguides. The pattern was defined using contact illumination with positive photo-resist and was transferred in the SiN-layer by CHF_3 reactive ion etching. The waveguides were etched employing an optimized CH_4/H_2 etching and O_2 descumming process [4]. The InP top layer and 50 nm of the quaternary material were removed in this process.

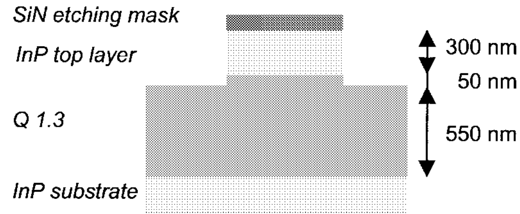

Fig. 1. Waveguide structure.

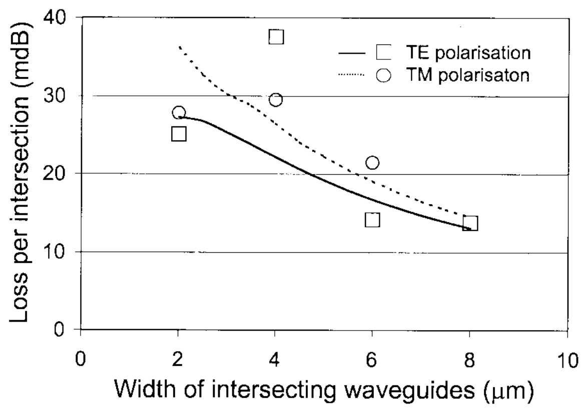

Fig. 2. Loss of an orthogonal intersection. Results of BPM-simulations (lines) and experimental results (symbols).

Measurements have been carried out with a Fabry–Perot measurement setup [5]. The experimental error of this method is estimated to be within ±0.3 dB, including variations in the input coupling conditions. Because of the low loss involved, large numbers of components (both intersections and tapers) have been cascaded. Due to nonuniformities resulting from the processing the actual spread measured on identical devices may be larger than the experimental error. To assure identical coupling conditions, all test structures were terminated with 2-μm-wide waveguides using appropriate tapers.

III. Simulation and Experimental Results

A. Orthogonal Intersections

The loss of an intersection depends on the width of the intersecting waveguides. In Fig. 2, calculations with a scalar finite difference beam propagation method (FD-BPM) for an intersection angle of 90° are shown. Predicted intersection loss

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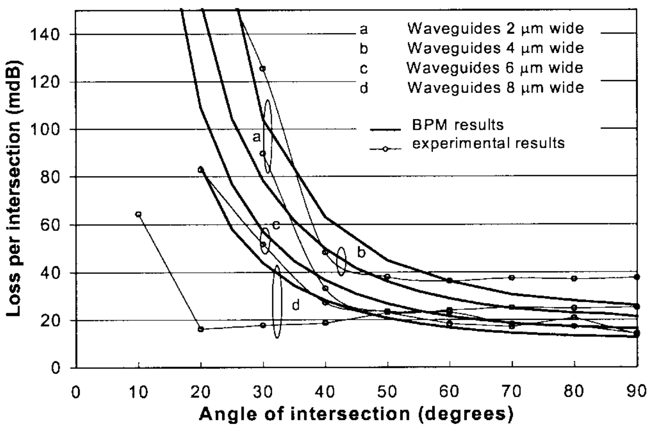

Fig. 3. Simulated (solid thick curves) and experimental (symbols connected by thin lines) results for intersections under varying angles. Waveguide widths at the intersections are 2, 4, 6, and 8 μm.

is seen to be in the order of 30 mdB (millidB) for 2-μm-wide waveguides and it becomes smaller than 20 mdB for waveguides wider than 6 μm. BPM also predicts a lower polarization dependence for wide waveguides. TE–TM coupling effects may play a role at these low loss levels; they will not show up in our results because we measure the total power coming out of our waveguides. Our experimental results compare well with the BPM calculations, as can be seen from Fig. 2.

B. Angled Intersections

In practical PIC's, intersection at angles less than 90° may save a lot of space. The dependence of loss on the intersection angle, as calculated by a BPM, is presented in Fig. 3 for TE polarization (widths of intersecting waveguides are 2, 4, 6, and 8 μm). In the range from 60° to 90° the loss is seen to be below 40 mdB, independent of the width of the waveguides. At lower angles the loss increases rapidly, it rises fastest for narrow waveguides. Results for TM polarization are similar. For intersection angles larger than 30° we find crosstalk values below −30 dB, both from simulations and experiments. This is in line with observations reported by van Dam *et al.* [3].

To check our BPM-results we have cascaded 100 similar intersections in waveguides of 2, 4, 6, and 8 μm width. We included intersection angles ranging from 10° to 90° in steps of 10°. In order to avoid beat effects due to mode conversion the distance between consecutive intersections was varied.

Intersection loss is calculated by comparing the loss of a waveguide with intersections to a straight waveguide of the same width, and dividing the difference by the number of intersections in the test structure.

The measured loss of waveguide intersections for different angles of intersection is displayed in Fig. 3 (by symbols connected by a thin line). Measured values for the loss are close to or even lower than calculated, in the range from 60–90° differences are within 5 mdB (except for the 4-μm-wide waveguides). In this range measured loss is well below 40 mdB, independent of the width of the waveguides, in accordance with BPM-predictions. At lower angles the loss increases rapidly. For 8 μm wide waveguides the loss remains below 20 mdB for angles down to 20°.

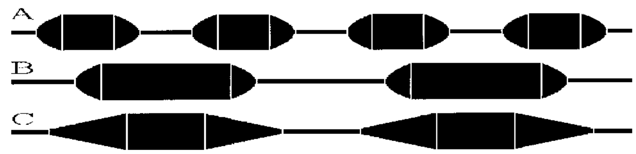

Fig. 4. Taper configuration. The length of the wide waveguide section is equal to the length of the narrow waveguide section. Straight tapers (C) are three times as long as parabolic tapers (A and B).

For higher lateral confinement the intersection loss increases. Increasing the lateral confinement by a factor of two (i.e., increasing the etch depth to 150 nm) increases the intersection loss by a factor of 2–1.5 for waveguides with a width ranging from 2 to 8 μm. For low-loss design it is thus important to keep the lateral confinement low in the intersection region.

Both simulations and experimental results show a clear advantage in using wide waveguides at the intersections. In addition, propagation loss for wide waveguides is lower. In our structure we measured propagation loss of 1.1, 0.6, 0.5, and 0.4 dB/cm for waveguides of 2, 4, 6, and 8 μm width, respectively. Both effects favor the use of wide waveguides at intersections.

For a low-loss transition from narrow to wide waveguides, and vice versa, compact and low loss waveguide tapers are necessary and will be discussed below.

C. Tapers

An intersection with wide waveguides can be connected to the surrounding circuit by tapers. Parabolic tapers follow the expansion of the mode profile and are therefore shorter than straight tapers with similar loss. We have chosen the taper length such that the predicted loss is lower than 10 mdB per taper. For tapering from a 2-μm-wide waveguide to a 4, 6, or 8 μm wide waveguide, parabolic tapers have a length of 95, 195, and 340 μm, respectively, according to the BPM. For a straight taper these lengths are 300, 600, and 888 μm. Propagation loss of the tapers has not been taken into account. It is however lower than the propagation loss of a 2 μm wide waveguide.

Different numbers of tapers have been cascaded in our test structures. Tapers are placed in pairs to taper up to a wide waveguide and down again to a 2-μm-wide waveguide. In every test structure the length of the wide and the narrow (2 μm) waveguide sections between the tapers has been chosen equal (Fig. 4). Taper loss has been calculated by comparing test structures with different numbers of tapers and dividing the loss difference by the additional number of tapers. Test structures including 50 tapers showed no significant additional loss. Considering the accuracy of the measurement (±0.3 dB) we conclude that taper loss is well below 10 mdB in accordance with BPM predictions. This applies to both parabolic and straight tapers.

D. Loss Minimization

When comparing an intersection with 2 μm wide waveguides to one with 8 μm wide waveguides, both under an angle of 90°, the wide waveguide intersection has a 10 mdB lower loss. With the cost of tapering being about 20 mdB for tapering from 2 to 8 μm and back, tapering becomes advantageous if at least two intersections are cascaded. The use of an 8-μm-wide waveguide between the tapers instead of a 2-μm-wide waveguide adds an extra loss benefit of approximately 0.7 dB/cm in propagation loss.

In practical PIC's, such as the crossconnects reported earlier by our group, a waveguide is intersected with waveguides under different angles. As an example we consider a 1-mm-long by 2-μm-wide waveguide that is intersected by nine waveguides at an average angle of 50°. TE-polarized loss for such a structure is 0.5 dB (110-mdB propagation loss, 9 $\times$ 45 mdB loss per intersection). When we increase the width to 8 μm using two tapers the loss would be 0.25 dB (40 mdB propagation loss, 9 $\times$ 21 mdB loss per intersection, 20-mdB taper loss). This approach thus halves the loss contribution due to intersections. With increasing complexity of PIC's the number of intersections that can be placed between tapers increases, leading to an even greater advantage.

IV. Conclusion

BPM simulations and measurements show that the loss of waveguide intersections for waveguides wider than 6 μm are lower than 40 mdB for intersection angles in the range of 40°–90°. For 8-μm-wide waveguide intersections we found a loss below 20 mdB in the range of 60°–90°, both from BPM simulations and experimental results. For the tapers, which are required to connect the wide-waveguide intersections to the normal 2-μm-wide waveguides, we found a loss lower than 20 mdB per taper pair. By increasing the number of intersections cascaded between a taper pair the total intersection loss can be more than halved.

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