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EXTREMELY SMALL FABRICATION TOLERANT InP-BASED POWER-SPLITTING AND COMBINING STRUCTURES BY DEEP ETCHING.

L.H. Spiekman Y.S. Oei E.G. Metaal * F.H. Groen † I. Moerman ‡
M.K. Smit B.H. Verbeek

Dept. of Electrical Engineering
Delft University of Technology
P.O. Box 5031, 2600 GA Delft
The Netherlands

Abstract

Design and realization of extremely small InP-based coupling structures with high performance and good compatibility with other components is reported: 3 dB coupler (90μm long, 0.7 dB loss), 1×16 coupler (141×32μm), Mach-Zehnder interferometer (0.6 dB loss, −28 dB crosstalk.

1 Introduction

In photonic integrated circuits, optical couplers are key components for splitting and routing of the signal. Because of their large bandwidth, polarization independence, and fabrication tolerance [1, 2], Multimode Interference (MMI) couplers are extremely suited for this application.

MMI couplers have already been succesfully demonstrated in Mach-Zehnder interferometer switches [3, 4], an optical coherent receiver [5], and ring lasers [6].

In this paper we will show the operation of a number of different MMI configurations, which have been miniaturized applying maximum lateral index contrast by etching completely through the quaternary layer. This provides a large tolerance for the etch rate. The design of structures for avoiding increased scattering and field mismatch losses is discussed and experimentally demonstrated. The concepts treated are widely applicable for increasing integration scale.

2 Design

For its operation, the MMI coupler relies on the self-imaging properties of a multimode waveguide [7]. For low-loss imaging, a sufficient number of modes must participate in this process, and in miniaturizing the components, this is assured by increasing the lateral index contrast. In the limiting case, the device pattern is etched completely through the waveguiding layer. Although, strictly speaking, device behaviour can now no longer be simulated with the effective index method, substituting $n = 1$ in the slab regions (see fig. 1) gives results consistent with other methods.

In waveguides of this geometry, the number of modes is no longer limited by lateral cutoff, but by radiation into the substrate of modes having effective indices lower than the substrate index. Computations indicate that waveguides as shown in fig. 1 are cutoff for $W < 0.6\mu$m, and monomode for $0.6 < W < 1.3\mu$m.

The following design parameters have been optimized: A) MMI width/length, B) adjustment of mode profiles in input waveguides.

A) The optimal length of a MMI 3 dB coupler in *full resonance* operation [8] is very close to $\frac{3\pi}{2(\beta_0-\beta_1)}$, i.e. three times the beat length between the lowest two modes. A full modal propagation simulation provides a correction of less than 1μm. Thus, the design of deeply etched MMI couplers is exceedingly simple.

B) It has been shown that MMI coupers become more tolerant to lithographic width variations with increasing width of the incoming beam waist [2]. To verify this relationship, MMI couplers with different access waveguide widths have been designed.

Wide high contrast bends, however, show poor mode fit at straight/bend junctions. Therefore, a scheme as shown in fig. 2 has been used. The S-bends have a bending radius of 50μm (teststructures have revealed bend losses < 0.2 dB/90° for radii down to 30μm!), and are 1.5μm wide for low junction loss and monomode transmission. Because straight waveguides of this width have shown scattering losses of 7 dB/cm, we use a width of 3μm for the connecting waveguides, which yields

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* PTT Research, Leidschendam, The Netherlands

† Dept. of Applied Physics, Delft University of Technology, The Netherlands

‡ Dept. of Infomation Technology, University of Gent, Belgium

losses of only 0.6 dB/cm. These are connected to the S-bend via 30μm long tapers. A second taper provides the MMI with the desired access field distribution width for better tolerance.

Cross couplers, 3 dB couplers, and passive Mach-Zehnder interferometers consisting of two MMI 3 dB couplers and equal interferometer arms were designed this way, as well as a 32μm wide and 141μm long 1×16 splitter.

3 Fabrication

The devices were made on a SI-InP substrate with MOVPE-grown undoped epilayers [9]: 660 nm InGaAsP ($\lambda_g = 1.3\mu$m) and 320 nm InP. The devices were patterned in a 140 nm thick RF-sputtered SiO_2 masking layer and then etched 1μm with an optimized CH_4/H_2 RIE etching/descumming process [10].

4 Results

Figure 3 shows the performance of **cross couplers** of different access waveguide widths W for TE polarisation, as a function of coupler width. The dependence of the coupler performance on the MMI section width becomes less pronounced with larger width W of the input waveguides, indicating better tolerance for width variations. The shortest coupler (180μm) has an insertion loss of 1.2 dB and a crosstalk of -27 dB and the best coupler (L = 375μm) has an insertion loss of 0.14 dB and a crosstalk of -25 dB.

Figure 4 shows the performance of **3 dB couplers** of different access waveguide widths W for TE polarisation. Here, also, better tolerance for width variations is observed for larger W. The shortest coupler (90μm) has an excess loss of 0.7 dB and an unbalance of 0.05 dB, and the most tolerant coupler (L = 249μm) has an excess loss of 0.3 dB and an unbalance of 0.05 dB, including S-bends and 4 tapers.

Figure 5 shows the performance of the most tolerant 3 dB couplers (with an access waveguide width W = 3μm), both for TE and TM. The component is polarization independent and performs well at the original design width.

Figure 6 shows the performance of a passive **Mach-Zehnder interferometer** with equal interferometer arms. In the optimum, the excess loss is only 0.6 dB (which is about twice the excess loss of the corresponding 3 dB coupler, as is expected), and the crosstalk is -28 dB.

In figure 7, the performance of an MMI **1×16 splitter** is shown. The MMI is 32μm wide and 141μm long. The insertion loss is between 1 and 3.5 dB above the expected splitting loss of 12 dB for all output branches, both for TE and TM.

5 Discussion

A generally applicable method has been described to fabricate extremely small components. Miniaturized MMI cross, 3 dB and 1×16 devices have been made this way, as well as a miniaturized Mach Zehnder Interferometer. Waveguide tapers are essential to meet the requirements of low propagation loss, small field mismatch losses and good fabrication tolerance, and small bend radius is important for size reduction. A trade-off, however, has to be made between coupler size and tolerance: 250μm long couplers can be produced with less than 1 dB insertion loss within a tolerance window of $\pm0.3\mu$m for the coupler width.

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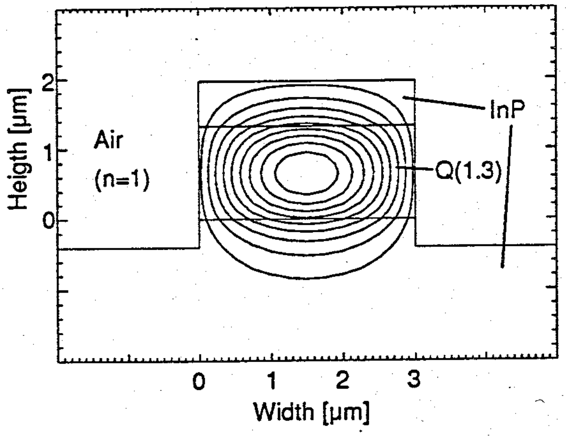


Figure 1: Waveguide structure: the thickness of the Q(1.3) layer is 660 nm, and of the InP top layer 320 nm. The etch depth is non-critical, and approximately 1μm.

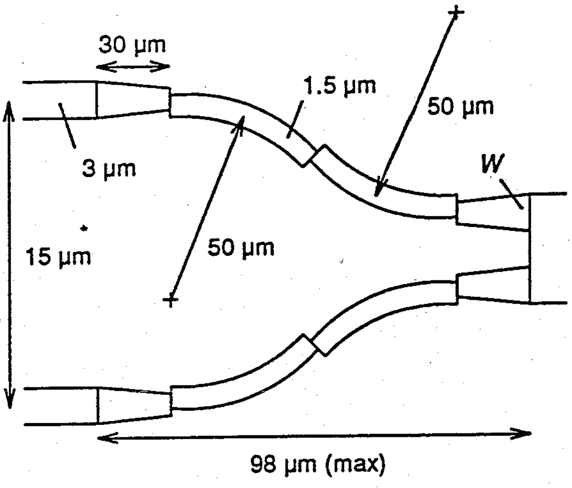


Figure 2: Input/output sections of the MMI couplers. The maximum length is 98μm for 15μm waveguide separation, including the tapers.

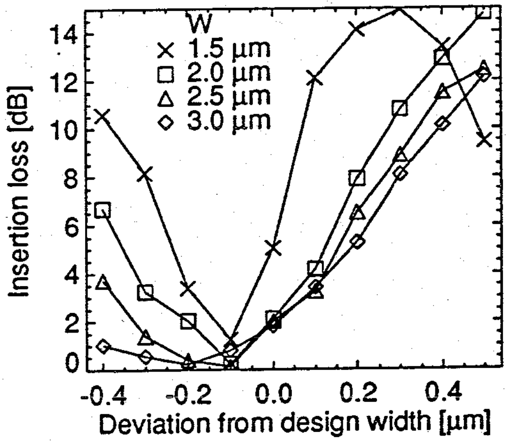
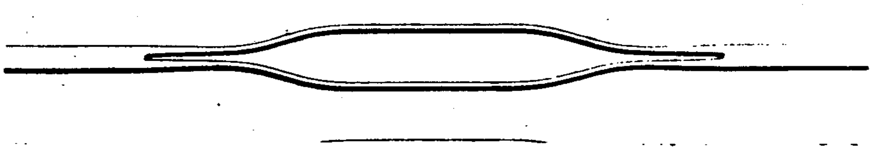


Figure 3: Insertion loss for MMI cross coupler as a function of coupler width for TE polarization, for a number of access waveguide widths W.



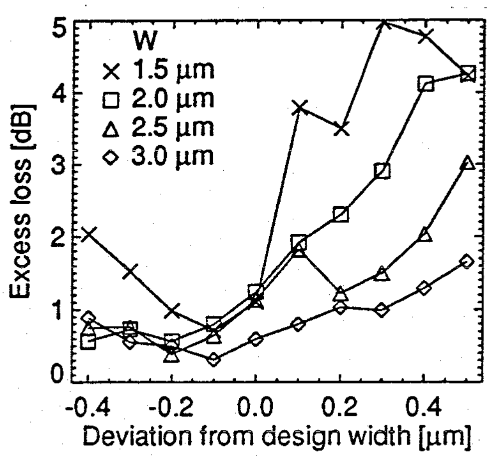


Figure 4: Excess loss for MMI 3 dB coupler as a function of coupler width for TE polarization, for a number of access waveguide widths *W*.

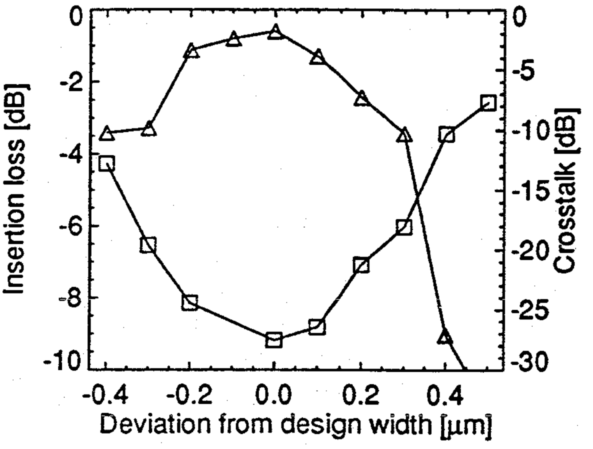


Figure 6: Mach-Zehnder interferometer performance (TE) as a function of coupler width. The triangles indicate the insertion loss, and the squares represent the crosstalk. The interferometer arms, shown by the photograph, have an equal length of 150μm. The 3 dB couplers are 249μm long. The total length of the device, including access waveguides, is 844μm.

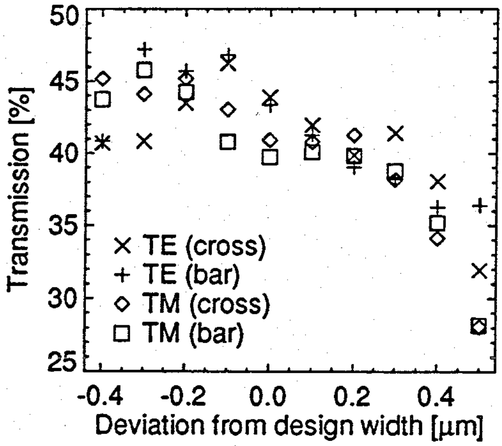


Figure 5: Transmission to cross and bar outputs of 249μm long MMI 3 dB coupler as a function of coupler width for an access waveguide width $W = 3\mu$m.

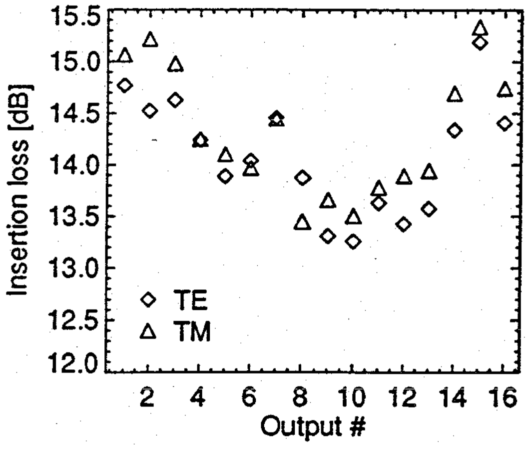


Figure 7: Insertion loss for 1×16 MMI splitter. The expected splitting loss is 12 dB. The insertion losses are 1–3.5 dB above this value. The device size is only 141×32μm.