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An Optical Passive 3-dB TMI-Coupler with Reduced Fabrication Tolerance Sensitivity

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Abstract—Two-mode-interference (TMI) couplers are shorter than weakly coupled waveguides, and less sensitive to production tolerances. Modifications for further reduction of the sensitivity of the coupler to production tolerances are presented and experimentally demonstrated. 3-dB couplers with dimensions of \(40 \times 700 \, \mu m\) were realized with 0.5-dB insertion loss.

I. INTRODUCTION

The most frequently applied coupler type, the directional coupler, consists of two parallel waveguides with a small gap in between (Fig. 1(a)). Fabrication tolerance requirements are extremely tight because the coupling strength depends exponentially on this gap width \[1\]. For components requiring good control of the coupling between different ports, the only practical way to meet these requirements is by including a tuning or trimming capability. This complicates component design and restricts the choice of materials.

A more process-tolerant alternative to the directional coupler is the two-mode-interference (TMI) coupler. It can be regarded as a directional coupler in which the gap is reduced to zero, as shown in Fig. 1(b). TMI couplers have been applied in electrically controlled switches \[2\], \[3\], polarization splitters \[4\], and wavelength demultiplexers \[5\]–\[8\]. A zero interwaveguide gap introduces three advantages. The length of the coupler is shorter due to the stronger mode dispersion, the coupler is less polarization dependent due to the fact that the relative mode dispersion is less polarization dependent in strongly coupled waveguides, and the coupler is less sensitive to fluctuations in the fabrication process. If, for example, the width of the waveguides of a directional coupler, realized in the waveguide structure which is discussed in the sequel, with an interwaveguide distance of 1 \(\mu m\) changes from 2.0 \(\mu m\) to 2.2 \(\mu m\) (thus reducing the interwaveguide distance to 0.8 \(\mu m\)), the coupling length changes by 11%. If the width of the TMI section of a TMI coupler changes from 4.0 to 4.2 \(\mu m\), the coupling length changes by only 6%. Hence the tolerance sensitivity is reduced by a factor of 2. Experiments carried out previously in our laboratory confirmed that the TMI coupler performs better than the directional coupler with respect to fabrication tolerances. However, for application in a passive phase diversity network based on the principle described by Hoffman et al. \[9\], employing at least four 3-dB couplers, the sensitivity to production tolerances must be further reduced.

When the coupler shown in Fig. 1(b) is fabricated, part of the gap between the flares of the Y-junction will be filled (the hatched areas of Fig. 1(b)). This is due to the finite resolution of the photolithographic process. Since it is difficult to control the length of the filled part of the Y-junction, it affects the coupling contribution of the Y-junction in a poorly reproducible manner. Experimentally we found that it is difficult to keep gaps narrower than 1 \(\mu m\) open. For the coupler of Fig. 1(b) with an angle of 1\(^\circ\) between the Y-junction flares, the gap will be filled over several tens of microns with a spread in the order of 10 \(\mu m\). This filling increases the phase contribution of the Y-junctions by a factor of two, relative to the unfilled situation.

To reduce this problem we applied strongly curved input and output flares (Fig. 1(c)). In a curved waveguide the modes tend to shift toward the outer edge of the bend. Therefore, in order to get optimal transmission from a straight waveguide...
to a curved waveguide an offset must be applied: the center of the straight waveguide should not be connected to the center of the curved waveguide, but must be shifted toward the outer edge of the bend [10], [11]. For this reason we have used an offset between the input waveguide and the first bend of the flare and between the flare and the TMI section (Fig. 2(a)). The first two offsets are used only to reduce the transmission loss in the flares, the last offset provides a gap (equaling twice the offset) between the flares at the beginning and at the end of the TMI section. If the gap is larger than the resolution of the photolithographic process no filling will occur. Furthermore, the coupling effects in the Y-junctions are reduced.

As a further improvement we replaced the TMI section with a wider multimode section, while the input and output flares remained single mode. If we position the bent input waveguides such that the profile of their fundamental mode is centered around a zero of the second-order mode profile of the multimode section, this second-order mode will not be excited and the coupler will operate in a TMI regime. We will, therefore, continue to denote it as a TMI coupler. Since the distance between the zeroes of the second-order mode increases with increasing waveguide width, wide TMI sections allow for a greater separation of the input waveguides. In this article numerical simulation data and experimental results of thus modified 3-dB TMI couplers, realized in a silicon-based aluminum oxide ridge-type waveguide structure [12], are presented. We note that the results are dependent on this specific waveguide structure.

## II. COUPLER ANALYSIS

The basic TMI coupler (Fig. 1(b)) consists of a Y-junction to bring the flares together, the actual TMI section and a second Y-junction. The field launched into channel 1 can be decomposed into the even and the odd system mode of the coupled system which propagate through the coupler. As the interwaveguide gap reduces to zero, these modes degenerate into the fundamental and first-order mode of the bimodal section. Since these modes have different propagation constants ($\beta_{even}$ and $\beta_{odd}$), their phase difference will increase while propagating through the coupler. After the guides are well separated, the power in the output channels is described by the accumulated phase difference $\phi$ [1]

$$P_3 = P_1 \cos^2 (\phi/2)$$
$$P_4 = P_1 \sin^2 (\phi/2)$$

where $\phi$ is given by $\phi = \int \Delta \beta(z) \, dz$ and the integration is over the whole length of the coupler including the Y-junctions.

The coupler has three important states: the cross state ($P_3 = 0$, $P_4 = P_1$, and $\phi = 180^\circ$, $540^\circ$, ...), the bar state ($P_3 = P_1$, $P_4 = 0$ and $\phi = 0^\circ$, $360^\circ$, ...), and the 3-dB splitting state ($P_3 = P_1/2$, $P_4 = P_1/2$ and $\phi = 90^\circ$, $270^\circ$, ...).

The analysis presented above applies as long as the system modes can adapt their mode profile adiabatically to the changing waveguide geometry. If we apply offsets as described in the previous paragraph, this condition no longer holds. To include the effect of discontinuities we adopted the following approach. Coupler response was analyzed by removing one branch at both sides of the coupler. The waveguide track thus remaining was analyzed by representing the waveguides by their $n \times n$ propagation matrix and the junctions between them by their $n \times m$ coupling (overlap) matrix, where $m$ and $n$ are the numbers of guided modes on both sides of the discontinuity. The power $P_3$ that will be coupled into channel 3 was calculated with the waveguide track of Fig. 2(b), and $P_4$ was calculated with the track of Fig. 2(c), both on excitation of port 1 with power $P_1$. Since the difference between the effective indexes of the modes in the flares and in the TMI section in our waveguide structure is very small (1.5699 and 1.5728, respectively, for the fundamental mode), the reflection coefficient can be estimated from the Fresnel formula. Substitution of the effective indexes yields a reflection coefficient of $-60$ dB, which indicates that reflections can be neglected. TE/TM mode conversion is expected to be negligible because of the small effective index difference mentioned above and was experimentally determined to be below $-30$ dB. The analysis is valid as long as coupling between flares 3 and 4 (and between flares 1 and 2) is small. This is the optimal situation for eliminating the poorly reproducible contribution of the Y-junctions to the coupler response. For the long-wavelength coupler of Fig. 6 this condition is not fully satisfied: the prediction for the total power is slightly optimistic (greater than 100%).

Fig. 3 shows the calculated transmission loss through the structure of Fig. 2(c) with the coupler in cross state for 4 different widths of the TMI section. The tracks with $w_{TM1} = 4$ $\mu$m and with $w_{TM2} = 5$ $\mu$m guide three modes, the other four modes. The figure clearly shows that for a given gap width the transmission loss decreases with increasing TMI section width. For a sufficiently large gap ($\geq 1$ $\mu$m) and a
transmission loss lower than 1 dB the TMI section must be at least 5 \( \mu m \) wide and will guide at least three modes. Therefore we replaced the TMI section with a broader multimode section.

Figs. 4 and 5 show the calculated coupler response as a function of the TMI section length for two different configurations operating at 633-nm wavelength: one with a gap of 0.8 \( \mu m \) and a width of the TMI section \( w_{TM} = 4 \mu m \) (3 guided modes) and the other with a gap of 1.6 \( \mu m \) and \( w_{TM} = 7 \mu m \) (4 guided modes). Fig. 6 shows the calculated response of a configuration operating at 1550-nm wavelength with a gap of 1.6 \( \mu m \) and \( w_{TM} = 12 \mu m \). The TMI section guides four modes.

To simplify interpretation we normalized the TMI section length \( L_{TM} \) by multiplying it with the difference \( \Delta \phi_{TM} \) in propagation constant between the fundamental and first-order mode. This normalized coupler length (NCL) equals the accumulated phase difference between the first two modes along the TMI section and is therefore given in degrees. The figures show the computed output power in channel 3 and channel 4 and their sum, which is indicative of the insertion loss. From the figures it is seen that the insertion loss of the wider coupler is less for all coupler lengths, which is consistent with our observation from Fig. 3. Further, the 3-dB point at \( \phi = 270^\circ \) exhibits much lower loss than the one at \( \phi = 90^\circ \). This phenomenon was observed for all wide couplers. The nonsinusoidal shape of the curves in Figs. 4 and 5 indicates the occurrence of higher order modes. These higher order modes have little effect on the location of the second 3-dB point (\( \phi = 270^\circ \)): according to the simulations shown in Fig. 5 the 3-dB point is at NCL = 276.6\(^\circ \). Their occurrence causes the total output power \( P_3 + P_4 \) to vary with the TMI section length: the power carried by the second and higher order modes will interfere constructively or destructively with the power carried by the fundamental and first-order mode, depending on the TMI section length. This length-dependent interference is responsible for the fact that the total power coupled to both output channels is optimal for NCL = 270\(^\circ \).

Simulation results indicate that application of a wide multimode section reduces the sensitivity to the tolerance in most parameters, except for the multimode section width, which is the most tolerance sensitive parameter of the coupler (\( \Delta \phi = \pm 14^\circ /0.2 \mu m \) width increment, with \( w_{TM} = 7 \mu m \) and a gap of 1.6 \( \mu m \)). The reproducibility is thus mainly determined by the precision of the lithography, which is \( \pm 0.2 \mu m \) for...
the fabrication process employed in the present experiments. Fig. 3 shows that the sensitivity of the loss to tolerance in the TMI section width decreases with increasing TMI section width (from 0.26 dB on reducing the width from 5 to 4 μm (with gap of 0.8 μm), to 0.08 dB on reducing it from 7 to 6 μm (with a gap of 1.6 μm)).

III. ANALYSIS OF THE Y-JUNCTION

The presented analysis neglects the coupling effect in the Y-junctions. Therefore we analyzed this effect separately. Since the distance between the flares varies with z, the Y-junction is divided into a number of small intervals, each of length Δz. Within each interval the distance between both flares is considered to be constant. The total accumulated phase shift at the end of the Y-junction is then given by

$$\phi_y = \Delta z \sum_{i=1}^{M} \Delta \beta_i$$

where M is the number of intervals (typically less than 50) and Δβ is the difference between the propagation constants of the even and the odd system mode in the ith interval. We designed the Y-junction in such a way that the waveguides are well separated before the second curve of the S-bend starts. Therefore, for analyzing the coupling, the Y-junction may be considered as consisting of two diverging single bends. As mentioned in the introduction, the modes in a strongly curved waveguide shift toward the outer edge of the bend. Therefore we can not simply approximate the Y-junction as piecewise parallel. Heiblum and Harris [13] developed a conformal transformation that transforms a curved waveguide into an equivalent straight waveguide with a transformed index profile of which the propagation constants can be computed with the transfer matrix method [14]. To obtain the index profile of the coupled Y-junction system, we calculated the transformed index profile of the equivalent straight waveguide of one bend, removed the part on the opposite side of the symmetry axis and mirrored this profile around the symmetry axis (Fig. 7). With this approach the modes in the coupled Y-junction system will no longer be leaky. As we are interested in bend modes with low radiation loss, differences will be small. This approach is a simple approximation to the more complex conformal transformation as proposed by Pennings [15]. Once we have found the index profile for the ith interval, we can calculate the effective indexes of the fundamental and first-order system mode and the mode dispersion Δβ for this interval.

For the 4-μm configuration we calculated $\phi_y = 12^\circ$, for the 7-μm configuration we calculated $\phi_y = 5^\circ$ and for the 12-μm configuration (1550-nm wavelength) we calculated $\phi_y = 12^\circ$. We checked some of our results by applying the beam propagation method to a coupler structure with zero TMI section length. The BPM predicts greater phase contributions, but the difference is less than a factor of 2. This indicates that our method gives a good estimate of the magnitude of the phase contribution of the Y-junctions.

IV. EXPERIMENTAL DESIGN AND FABRICATION

We fabricated series of couplers with 4 and 7-μm TMI section width for operation at 633 nm, and 12-μm width for operation at 1550 nm, as simulated in Figs. 5–7, respectively. Fig. 8 shows a microscope photograph of part of the experimental devices. Each series consists of a number of couplers with increasing TMI section length. Each coupler has two reference channels parallel to the coupler, one on each side of the coupler. For each TMI section length we included three identical couplers in the design. The couplers were realized in a silicon-based sputtered SiO₂/Al₂O₃/SiO₂ ridge-type waveguide structure (n = 1.46/1.69/1.46 at 633 nm, n = 1.44/1.67/1.44 at 1550 nm) as described by Smit et al. [12]. The ridge was etched by atom-beam milling with Argon. The fabricated waveguides have a length and width tolerance of ±0.2 μm and a film thickness and etch depth tolerance of ±5%. The optical properties of this waveguide system at 633 nm closely resemble those of InGaAsP waveguides at 1300-nm wavelength, since the wavelengths within the guides is approximately the same ($\approx 0.4$ μm).

V. EXPERIMENTAL RESULTS

The couplers were excited at port 1 with a prism coupler as described by Pasmooij et al. [16]. The intensities at the output channels were recorded at the cleaved endface with a microscope objective and a video camera (CCD for 633, IR-
vidicon for 1550). The signal from the camera was digitized and processed by a computer. The average intensity of the two reference channels was used as reference intensity. The power transmission coefficients $T_3$ and $T_4$ of both output channels were determined by dividing the output intensity of the channel by the reference intensity. Insertion losses were determined from the total transmission ($\text{Loss} = -10 \log(T_3 + T_4)$).

The results are shown as markers in Figs. 4-6. Each marker represents the average of the output power of three identical couplers. In order to arrive at a good fit of the measured values to the calculated curves, we had to shift the measured values to the right (42° in Fig. 4, 25° in Fig. 5, and 35° in Fig. 6). Since the shifted measured values fit rather well to the calculated curves, this shift appears to be independent of the coupler length. It is therefore interpreted as a larger contribution $2\delta Y$ of the $Y$ branches than was predicted by (2).

From measurements on several series of straight and bent waveguides we found the accuracy of the applied method of measuring at 633 nm to be ±0.5 dB. The accuracy of the measurements at 1550 nm is estimated to be ±1 dB. For the couplers of Fig. 4 the transmission loss fluctuates between 1.5 dB and 0.1 dB and is approximately 1.3 dB at the second 3-dB point. For Fig. 5 the loss fluctuates between 1.3 and 0.3 dB and is approximately 0.5 dB at the second 3-dB point. When we compare the measurements of Figs. 4 and 5 we conclude that the couplers with the widest TMI section perform best.

We analyzed the spread in the results by calculating an equivalent accumulated phase difference or coupling phase $\phi$ of the single couplers according to (see (1)):

$$\phi = 2\arctan \sqrt{\frac{I_1}{I_3}}$$

where $I_3$ and $I_4$ represent the measured intensities of channel 3 and 4. The coupling phases of all couplers of Fig. 5 ($\lambda = 633$ nm, gap = 1.6 μm and $w_{TM1} = 7$ μm) are represented in Fig. 9(a) as a function of the normalized coupler length. As Fig. 9(a) shows, the spread in the results is broader for the bent waveguides than for the straight waveguides. The most important improvement is in the reduction of the phase contribution of the Y-junctions (i.e., the intersection of the regression line with the vertical axis) to the total accumulated phase, which is the main source of irreproducibility. As a result we see that the spread in the measurements is reduced and the regression lines through the measured values are more parallel to each other.

VI. DISCUSSION AND CONCLUSIONS

The shift of the mode profile toward the outer edge of bent waveguides has been successfully applied in order to improve the reproducibility of TMI couplers. It is shown that replacing the TMI section with a wider multimode section leads to a further improvement of the reproducibility. Simulation results indicate that employing a wider multimode section reduces the sensitivity of the coupler performance to tolerance in most parameters, except to tolerance in the width of the multimode section. Coupler performance is thus, to a large extent, determined by the geometric precision of the lithographic process, which amounts to ±0.2 μm for the fabrication process employed here.

We have described a numerical method to analyze the effects of the proposed modifications. Predicted results are in good agreement with experimentally measured data. Insertion losses as low as 0.5 dB were realized for 3-dB couplers. The experimental results reveal that the couplers with the widest multimode sections and corresponding gaps perform best. Because the required multimode section length increases with its width, the increase in performance leads to a larger device length and a corresponding increase in propagation loss. Simulations and experiments on the performance of wider multimode sections are presently being conducted.

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