High-performance monomode planar couplers using a short multi-mode interference section

HIGH-PERFORMANCE MONOMODE PLANAR COUPLERS USING A SHORT MULTI-MODE INTERFERENCE SECTION

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***Abstract*— A new type of integrated optical coupler, based on Multi-Mode Interference (MMI) is analysed theoretically and experimentally at 1.52-µm. Results show high performance: low loss (typically less than 0.5 dB), low polarisation dependence, high reproducibility and small device dimensions.**

1. Introduction— Optical couplers are key components in photonic integrated circuits both for signal routing and signal processing. Two-Mode Interference (TMI) couplers were reported in 1977 [1] as a simpler alternative to weak synchronous couplers based on parallel waveguides. By comparison, TMI couplers are shorter, less sensitive to fabrication variations and less polarisation dependent. They consist of a two-moded central waveguide (TMI-section) coupled to two single-moded Y-junctions (Fig. 1.a). Requirements of proper mode excitation and high coupling efficiency from the monomoded access waveguides to the two-moded central section determine the use of access waveguides very close to each other. Due to the finite resolution of the lithographic process, part of the gaps between the access waveguides (shaded areas in Fig. 1.a) get filled in a non-reproducible way. This introduces considerable uncertainty in the actual length of the TMI-section, causing spread in coupler performance.

We show that replacement of the two-moded section by a (wider) Multi-Mode Interference (MMI) section (Fig. 1.b) leads to a natural separation of the single-moded access waveguides, eliminating the problem of the filling-in. Moreover, due to the high number of modes supported by the MMI-section, power coupling efficiencies between the single-moded access waveguides and the MMI-section are higher and consequently device insertion losses are lower compared to those of TMI couplers (which are typically 1 dB).

2. Theory and Modeling— The operation of the MMI coupler is based on the self-imaging property of a multi-moded waveguide, as suggested by Bryngdahl [2] and studied in some detail by Ulrich [3, 4]. The propagation constants $\beta_{0\nu}$ of the modes supported by a multi-moded slab waveguide (MMI-section) with effective index of refraction N and width W_{MMI} (Fig. 1.b) show a nearly quadratic dependence with the mode number ν:

$$\beta_{0\nu} \approx \frac{2\pi}{\lambda_0}N - \frac{\pi\lambda_0(\nu+1)^2}{4NW_{MMI}^2} = \frac{2\pi}{\lambda_0}N - \frac{\pi(\nu+1)^2}{3L_\pi} \quad (1)$$

where λ_0 is the free-space wavelength, and $L_\pi=\pi/(\beta_{00}-\beta_{01})$. Based on this dependence, it can be proven that when the length of the MMI-section L_{MMI} is an even multiple of $3L_\pi$ the field at the input of the MMI-section (z=0) is replicated at the output ($z=L_{MMI}$) and thus the coupler works in the *bar* state. When L_{MMI} is an odd multiple of $3L_\pi$ the field at the input appears at the output mirrored with respect to the xz-plane and thus the coupler works in the *cross* state. For L_{MMI} half way between the *bar* and the *cross* states, the field at the input appears at the output split in two and with a relative phase of $\pi/2$, thus the coupler works in the *3-dB* state. Furthermore, a similar behaviour can be predicted for shorter couplers with MMI-section lengths which are now a multiple of L_π instead of $3L_\pi$, provided that the modes 2, 5, 8,... are not excited. This is very interesting from a technological point of view, since it permits a considerable reduction in the coupler's length. The condition of selective excitation is easy to fulfil if one notes that the field profiles of the 2^{nd}, 5^{th}, 8^{th},... order modes have a zero (and odd symmetry) at almost the same y-positions (around 1/3 and 2/3 of W_{MMI}) for a multi-moded waveguide. Centering the (even symmetric) input field profile of the access waveguides around those y-positions ensures low excitation of these modes.

Coupler behaviour has been analysed by computing the excitation coefficients of the modes at the input of the MMI-section with a one-dimensional overlap integral, propagating them through the MMI-section, reconstructing the total field at the output, and computing the coupling efficiencies to both single-moded output access waveguides.

3. Experiments and Discussion— Two series of devices (3-dB and cross couplers) were designed and fabricated for operation at 1.52-µm wavelength in a dielectric ridge-type $SiO_2/Al_2O_3/SiO_2$ waveguide structure on silicon substrate [5], as shown in Fig. 2. All curved access waveguides have 300-µm radii and a width of 2 µm, thus being strictly single-moded.

The 3-dB couplers have W_{MMI}=14µm (supporting a total of 9 modes). The optimum designed length for the MMI-section is 155 µm. Couplers were fabricated with L_{MMI} ranging from 120 to 190 µm in steps of 5 µm in order to test coupler behaviour versus MMI-section length.

The cross couplers have W_{MMI}=12µm (supporting a total of 7 modes). The optimum designed length for the MMI-section is 235 µm. Couplers were fabricated with L_{MMI} ranging from 200 to 270 µm in steps of 5 µm.

Measurements were carried out by coupling in light with the prism-coupling technique [6] to one of the single-moded input access waveguides and recording the light intensities of both output access waveguides. Each coupler was repeated 3 times in the lay-out; and each lay-out was repeated 3 times on the silicon wafer. In this way each measured value is an average from 9 devices, which allows to test in-wafer repeatibility.

Figure 3 presents the results for the 3-dB couplers. The measured power splitting ratio for the optimum designed MMI-section length (L_{MMI}=155µm) was 0.18 dB and simultaneously the insertion loss reaches a minimum (measured to be below 0.2 dB). Both power splitting ratio and insertion loss show flat curves with respect to the MMI-section length, providing an indication of the very low sensitivity to this process parameter.

Figures 4 presents the results for the cross couplers. Solid lines are simulation results for the sharp ridge profile shown in Fig. 2. Markers are average measured values. The obtained ridge profile was somewhat smoother, which results in more modes being supported by the MMI-section. This can be accounted for by simulating wider waveguides. Dashed lines show the results of these last simulations, which are seen to predict a general "flattening" of the curves, and improving the fitting between expected and observed behaviour. It must be noticed, however, that coupler behaviour is almost not degraded, which gives an idea of the low sensitivity of coupler behaviour to this process parameter.

4. Conclusions— The self-imaging property of multi-moded waveguides has been applied for the design of passive integrated optical couplers. Simulations were carried out which indicated high performance and low sensitivity to process parameters. Cross couplers and 3-dB couplers were fabricated in a dielectric waveguide structure and tested at 1.52-μm wavelength. Experimental agreement with computer-simulated behaviour is very good. Cross couplers showed insertion loss better than 0.5 dB and cross-talk better than 16 dB (best observed was above 18 dB) for the optimum designed MMI-section length. 3-dB couplers showed power splitting ratios within ±0.2 dB and insertion loss better than 0.4 dB (best observed was 0.1 dB) for the optimum designed MMI-section length. Both kinds of couplers performed rather independently of light polarisation, with 0.2 dB extra insertion loss for *TM*-polarisation.

Due to its remarkable tolerance to process parameters, this new coupler is suitable for application in critical components such as an integrated coherent receiver and phase diversity networks.

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6. References—

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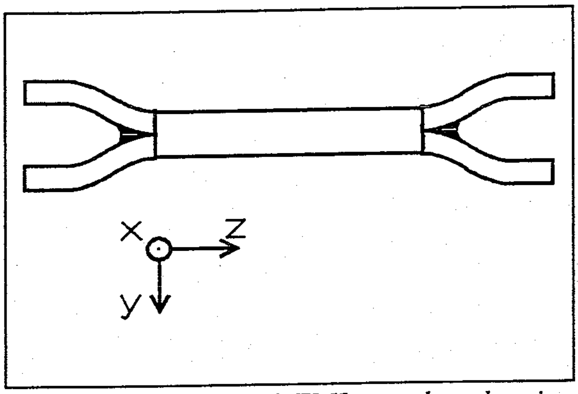

Figure 1.a *Classical TMI coupler showing filled-in areas.*

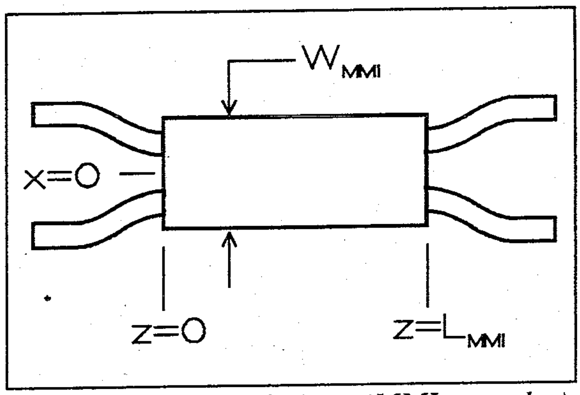

Figure 1.b *New design (MMI coupler). Single-moded curved access waveguides are well apart from each other.*

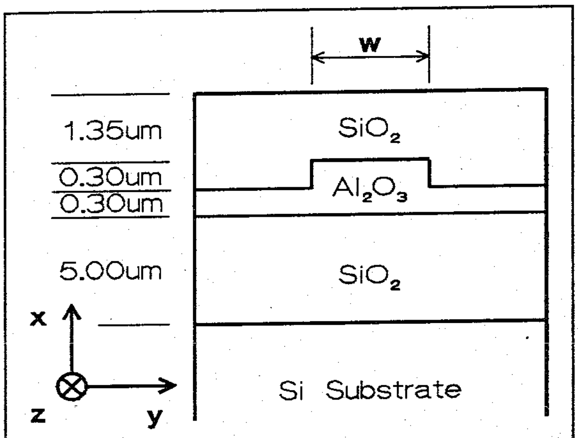

Figure 2 *Cross-section view of the dielectric ridge-type waveguide structure.*

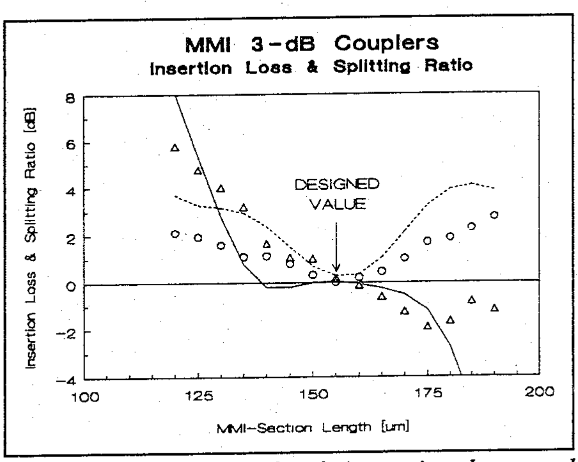

Figure 3 *3-dB couplers' insertion loss and splitting ratio. Solid line is simulated and (Δ) are measured splitting ratio values. Dashed line is simulated and (○) are measured insertion loss values.*

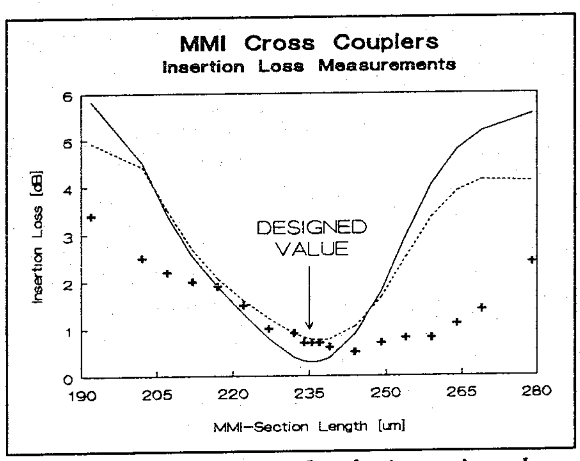

Figure 4 *Cross couplers' insertion loss. Solid and dashed lines are simulated results (see text), and markers are measured values.*