Tolerant and high performance 3×3 and 4×4 multimode interference couplers

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We designed, fabricated and characterized a set of 3×3 and 4×4 MMI couplers with minimum imbalance and high tolerance for fabrication errors in InP. They were designed using a generic design approach for N×N MMI couplers, which uses three key performance parameters, excess loss, imbalance, and phase error. The design procedure includes the use of an analytical model followed by a numerical optimization. The effect of various design parameters on the performance of the MMI is discussed. Experimentally found results correspond very well to simulations. 3×3 MMI couplers with excess loss of 1 dB, imbalance of 0.3 dB and phase errors below 3° are realized.

Introduction

Multimode interference (MMI) couplers have proven to be versatile building blocks for integrated optical circuits. All-optical switches and quadrature phase-shift keying (QPSK) demodulators are among many of the applications of MMI couplers. In this paper we present the design and realization of 3×3 and 4×4 MMI couplers that achieve a very low imbalance and high tolerance to fabrication errors, making them very suitable as photonic building blocks. The MMI couplers are designed for the InP platform of the COBRA institute at the Eindhoven University of Technology.

Fig. 1 shows a schematic top-view of a 3×3 MMI coupler, which is fabricated in a deeply etched cross section as shown in Fig. 2. This cross section provides a high tolerance to fabrication errors and a reduced footprint and polarization sensitivity. For the access waveguides the high confinement reduces the coupling between adjacent access ports, making it possible to reduce the waveguide separation s.

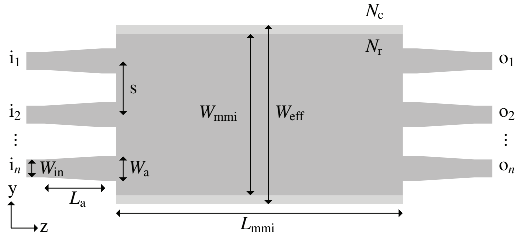

Figure 1: Schematic drawing of the MMI coupler geometry.

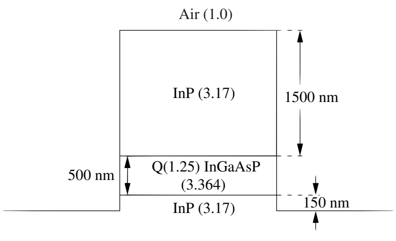

Figure 2: Cross section of waveguide in the COBRA deep layer stack.

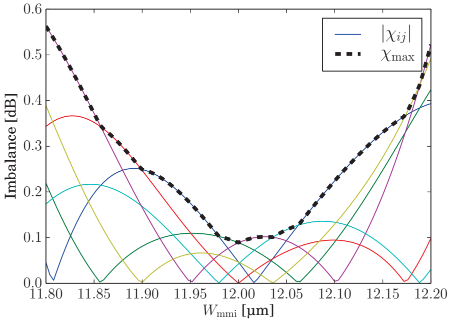

Figure 3: Illustration of the worst-case imbalance in a 4×4 MMI coupler.

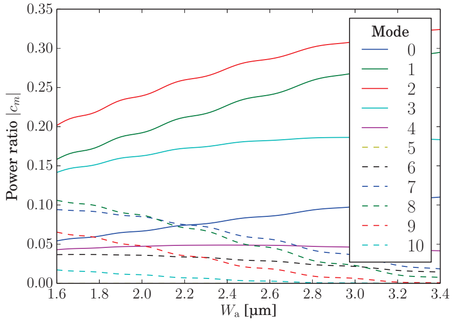

Figure 4: Excitation of guided modes in a 3×3 MMI coupler as a function of access waveguide width W_{a}.

Design procedure

We define the performance parameters excess loss L_{ex}, imbalance $\chi_{\max}$, and phase error $\Delta\varphi_{\max}$ to determine the performance of the device. Where i and j indicate the port numbers and S_m the scatter matrix element for mode m. For the access waveguides, $m_{\max} = 2$.

$$P_{\mathrm{out}} = \sum_{i=1}^{N} P_{\mathrm{o}i} \qquad P_{\mathrm{in}} = \sum_{i=1}^{N} P_{\mathrm{i}i} \qquad P_{\mathrm{o}i} = \sum_{m=0}^{m_{\max}} |S_m|^2 \tag{1}$$

$$\begin{aligned} &L_{\mathrm{ex}}\,[\mathrm{dB}] = -10\log\left(P_{\mathrm{out}}/P_{\mathrm{in}}\right) \\ &\chi_{ij}\,[\mathrm{dB}] = -10\log\left(P_{\mathrm{o}i}/P_{\mathrm{o}j}\right) \qquad \chi_{\max}\,[\mathrm{dB}] = \max|\chi_{ij}| \quad \text{for } i \neq j \\ &\Delta\varphi_{ij} = \varphi_{\mathrm{o}i} - \varphi_{\mathrm{o}j} - 2\pi/N \qquad \Delta\varphi_{\max} = \max|\Delta\varphi_{ij}| \quad \text{for } i \neq j \end{aligned} \tag{2}$$

For a $N\times N$ MMI coupler, $2(N-1)$ combinations for imbalances are possible. A worst-case variable for the imbalance is introduced, which is found by taking the maximum absolute value of all possible individual imbalances at any point in the parameter sweep. An illustration of the definition of $\chi_{\max}$ for a 12 µm wide 4×4 MMI coupler is shown in Fig. 3. An identical approach is used for the phase error.

The use of these variables results in a reduced set of parameters to control during the design, and can be implemented for any MMI coupler. To match the simulations with a real device these parameters are checked for varying wavelength and MMI coupler width. Variation of W_{mmi} due to the limited fabrication accuracy is the most critical parameter regarding the performance of the device.

A better imaging in the MMI coupler is achieved if most of the power is in the lower order modes, which will reduce power loss (L_{ex}) and phase error ($\Delta\varphi_{\max}$) [1]. This is achieved by increasing the access waveguide width W_{a} as presented in Fig. 4. The maximum width is limited by W_{mmi} and the minimum waveguide separation s.

Numerical analysis

The MMI couplers are optimized numerically to achieve optimum performance for use in a wavelength interrogation device. This requires the imbalance to be as low as possible, while the phase error is also important. To ensure the best performance the devices are optimized for TE polarization.

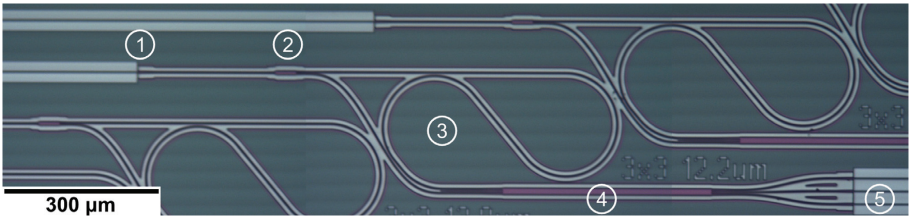

Figure 5: Test structure implemented on chip with indicated components: (1) shallow-deep transition; (2) 3-dB MMI coupler; (3) MZI with asymmetrical arms; (4) 3×3 MMI coupler; (5) Fan-out of output waveguides and deep-shallow transition.

Four MMI couplers are selected for experimental verification, 12 and 14 µm wide 3×3 MMI couplers and 16 and 20 µm wide 4×4 MMI couplers. For the final design of the MMI coupler angled back-walls are used to suppress reflections [2]. This optimization can be done without having to compromise the performance.

Measuring performance

A Mach-Zehnder Interferometer (MZI) is used to test the MMI coupler, Fig. 5. The path length difference $\Delta L = 1120\,\mu\text{m}$ corresponds to a phase difference $\Delta\varphi$ and a free spectral range of $\approx$580 pm, required to measure phase errors in the order of degrees. A transfer matrix system is used to model the behaviour of the test structure and derive the expected output expressions [3]. The measured MMI spectral responses require fitting to the expected signals after which the performance variables can be derived.

$$\begin{aligned}
\overline{P_{o1}} &= c_0{}^2 + c_1{}^2 + 2c_0c_1\cos(\Delta\varphi + c_2) \\
\overline{P_{o2}} &= c_3{}^2 + c_4{}^2 + 2c_3c_4\cos(\Delta\varphi + c_5) \\
\overline{P_{o3}} &= \underbrace{c_6{}^2 + c_7{}^2}_{P_{oi}} + 2c_6c_7\cos(\Delta\varphi + \underbrace{c_8}_{\varphi_{oi}})
\end{aligned} \tag{3}$$

The characterization setup consists of a tunable laser in combination with a lensed polarization maintaining fiber to couple TE polarized light into the chip. The output is also coupled into a lensed fiber and measured using an optical power meter. A wavelength sweep from 1520 to 1580 nm provides the data for analysis, after which the fitting procedure is used to extract the performance parameters.

Measurement results

A total of four chips, each containing 12 3×3 and 12 4×4 MMI couplers were fabricated and characterized. The performance is measured over varying wavelength, as shown in Fig. 6, and measured for varying W_{mmi} as shown in Fig. 7. The average values in the range of 1545-1555 nm are taken to exclude any local variations. The dotted lines with markers represent the measured devices.
The measurement results are in good agreement with the simulations. The MMI couplers with nominal width show the best performance. A notable result is that $\Delta\varphi_{\text{max}}$ is not as dependent on wavelength and width as the simulation suggests. Furthermore the quality is very constant over different devices. Apart from broken structures all measured structures are taken into account.

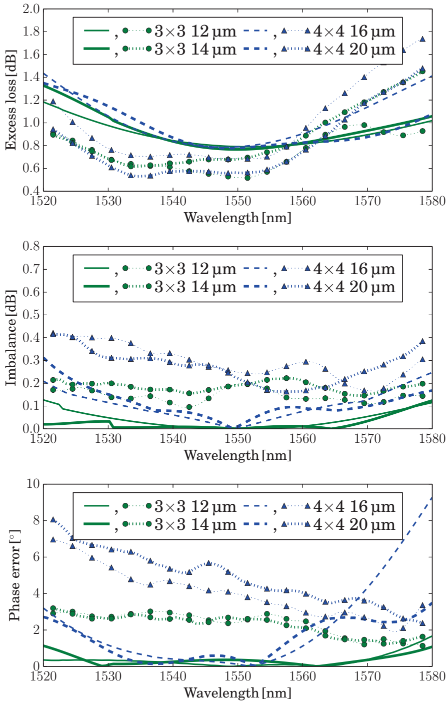

Figure 6: Performance of selected MMI couplers over wavelength.

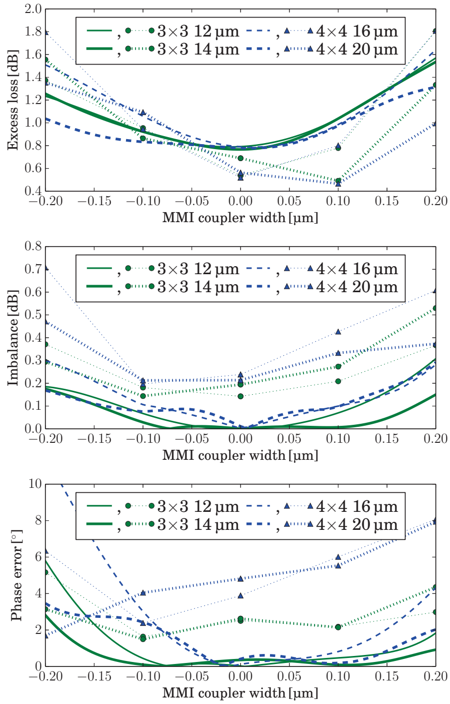

Figure 7: Performance of selected MMI couplers over MMI coupler width.

Conclusion

We presented a design for 3×3 and 4×4 MMI couplers optimized for imbalance. The generic design procedure for $N \times N$ MMI couplers is used to identify the most critical design parameters and provides an accurate simulation model. This procedure can also be used to optimize MMI couplers with respect to phase errors or excess loss.

Experimental results show worst-case imbalances below 0.3 dB and phase errors below 3°. Performance over the measured wavelength span, which exceeds the C band of 1530-1565nm, is very constant and the high tolerance to fabrication errors is verified as was intended by design. This enables the use of these MMI couplers as building blocks in a generic integration platform.

References

[1] Hill, M. T. and Leijtens, X. J. M. and Khoe, G-D and Smit, M. K. Optimizing imbalance and loss in 2×2 3-dB multimode interference couplers via access waveguide width. *Lightwave Technology, Journal of*, 21(10):2305–2313, Oct 2003.

[2] Kleijn, E. and Melati, D. and Melloni, A. and de Vries, T. and Smit, M. K. and Leijtens, X. J. M. Multimode interference couplers with reduced parasitic reflections. *Photonics Technology Letters, IEEE*, 26(4):408–410, Feb 2014.

[3] Bachmann, M. and Besse, P. A. and Melchior, H. General self-imaging properties in N×N multimode interference couplers including phase relations. *Applied Optics*, 33(18):3905–3911, Jun 1994.