

Characterization of 3×3 and 4×4 multimode interference couplers in InP generic photonic integration technology

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MMI couplers with multiple inputs are important building blocks for generic photonic integration technology. Previously we have developed a design approach for these components, which uses three key performance parameters, excess loss, imbalance, and phase error. The optimized MMI couplers were manufactured in a dedicated run with passive components only. Test results of these devices have been published. In the current work we characterize MMI couplers that were manufactured in the Smart Photonics generic active-passive integration process. Integrated PIN detectors are included in the test circuits and their output is read out electrically. We characterized the test circuits and compare the results with the measured in the passive run values.

Introduction

MMI couplers have a wide range of applications, such as power-splitting and combining [1], (de)multiplexing [2] and key elements in 90° and 120° hybrids [3, 4]. The performance of MMI couplers is rather sensitive to the waveguide width, which is a critical parameter in the design [5]. The measurements that we carried out for the devices that were fabricated in the dedicated passive run show low imbalance and good tolerance to the fabrication errors. In order to include those building blocks into the component library used for designing in the multi-project wafer runs, characterization of the MMI couplers fabricated in such a full MPW run was made. This paper focuses on the characterization results of those devices. The data analysis is described and the results for the properties of MMI couplers are evaluated.

MMI Design

Figure 1 shows the general geometry of an MMI coupler. Typical parameters are indicated in Figure 1a. There are two cross-sections available in the Smart Photonics MPW run layer stack: shallow and deeply etched waveguides with different index contrast. The MMI coupler and access waveguides are fabricated in the deep-etched cross-section. This allows to reduce the separation between the access waveguides and make them wider and them while keeping optical coupling between them low. It is the influence of W_{MMI} , indicated in Figure 1a, on the coupler performance that we want to analyze.

Performance parameters. According to the design approach, three parameters are used to measure the performance of an MMI coupler, the excess loss L_{ex} , the imbalance χ_{max} and the phase error $\Delta\phi_{\text{max}}$. The definition of these quantities is given in eqs. (1). The power which is not coupled out from the coupler is assessed by excess loss. Imbalance measures the deviation from the ideal coupling ratio. The phase error is the deviation from the ideal phase difference between two adjacent output ports, which equals $2\pi/N$

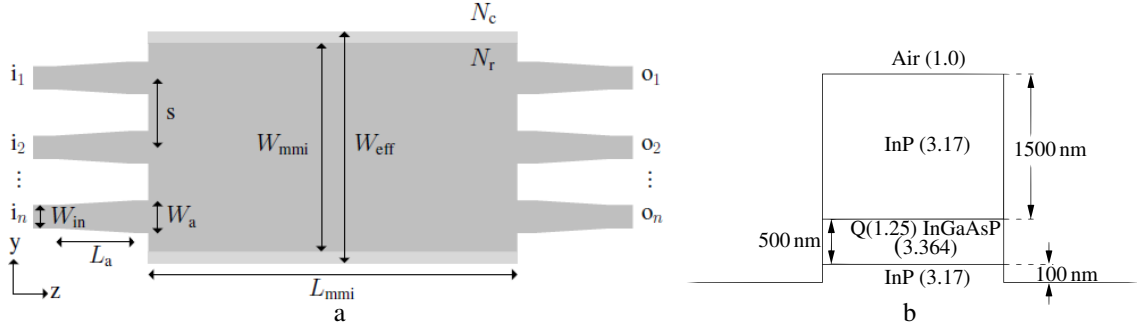


Figure 1: a – MMI coupler geometry. b – Cross-section of the deep etched waveguide in Smart Photonics technology

for a $N \times N$ MMI coupler.

$$\begin{aligned}
 L_{ex}[\text{dB}] &= -10 \log(P_{out}/P_{in}) \\
 \chi_{\max}[\text{dB}] &= \max|\chi_{ij}|, \quad i \neq j & \chi_{ij} &= -10 \log(P_{oi}/P_{oj}) \\
 \Delta\phi_{\max} &= \max|\Delta\phi_{ij}|, \quad i \neq j & \Delta\phi_{ij} &= \phi_{oi} - \phi_{oj} - 2\pi/N
 \end{aligned} \tag{1}$$

For imbalance and phase error, according to equation (1), there are $N(N-1)/2$ combinations of the output ports oi and oj . Analysing them individually is not necessary. We take the maximum value of these two parameters to measure coupler performance.

Final design. The geometry of MMI couplers was optimized numerically for the best performance in the wavelength interrogator device. This requires the lowest imbalance between the output channels. Although the phase error is important, the effect can be reduced significantly by using a compensation algorithm [6]. Compared to passive run, we expect a slight degradation of the MMI coupler performance due to a larger number of fabrication steps in the full MPW run.

Performance measurement

An unbalanced Mach–Zehnder interferometer (MZI) is used as a test structure for the designed MMI coupler. Figure 2 shows the components and layout of the test structure. The design arm difference of $\Delta L = 1121.21 \mu\text{m}$ corresponds to a free spectral range of $\Delta\lambda_{\text{FSR}} \approx 580 \text{ pm}$. Given the wavelength setting accuracy of the tunable laser of 1 pm and temperature stabilization of 0.004°C , this gives an accuracy of phase measurement of 0.7° . The outputs of the MZI are terminated with PIN photodetectors, measured photocurrent is proportional to the intensity of light at the corresponding output of the MMI coupler.

The manufacturing of the test structure was carried out as a part of Multi-Project Wafer (MPW) run, following a generic integration methodology. Besides our custom-designed 3×3 and 4×4 MMI couplers, the test structure contains a set of standard building blocks such as waveguides, 3-dB MMI coupler and PIN detectors was used. The characteristics of the building blocks are provided by the foundry in the design manual, and no detailed knowledge on the manufacturing process is required by the designer [7].

The measurement setup consists of a tunable laser source and a polarization maintaining lensed fiber to couple TE-polarized light to the chip into the input of the MZI. The electrical signal from the PIN photodetectors is transferred through a probe card to the current meter module. For a better responsivity at longer wavelength a reverse bias $V = -2 \text{ V}$

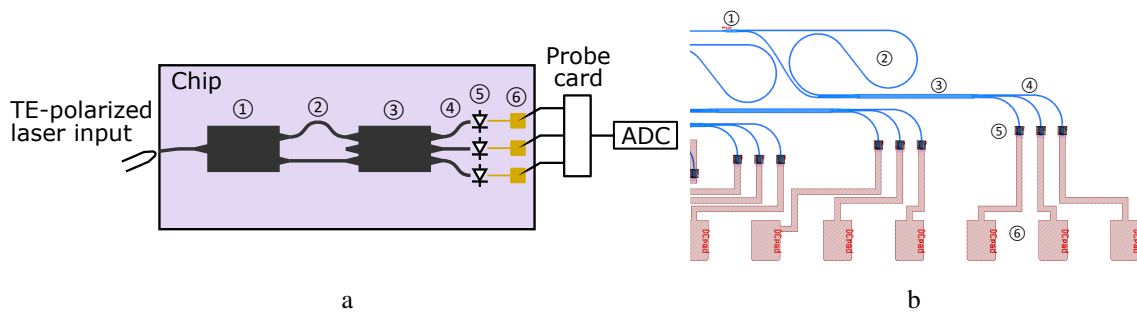


Figure 2: Schematic (a) and mask layout (b) of the MZI test structure for 3×3 coupler: (1) 3-dB MMI coupler; (2) asymmetric arms of the interferometer; (3) 3×3 MMI coupler; (4) output waveguides; (5) PIN detectors; (6) metal probe pads

is applied to the photodetectors. The corresponding dark current for each photodetector is measured separately before the wavelength sweep and is later subtracted from the measured spectral response. During the measurement the tunable laser is swept in the 1520–1580 nm range, and the photocurrent from all output detectors is recorded at each wavelength. The acquired spectral responses are then each fitted to the expected signals to extract optical power P_{oi} and the phase φ_{oi} from equation (1). The details of fitting procedure could be found in [5].

The use of the photodetectors in the test structure makes it possible to obtain the wavelength response from all coupler outputs in one sweep, contrary to the passive run, where light from the output should be coupled out from the chip and therefore separate sweeps are required. This may reduce the measurement error associated with coupling or temperature variations from sweep to sweep.

Measurement results

There are three chips measured in total, each containing 12 3×3 and 12 4×4 MMI couplers. For 3×3 couplers, the nominal widths of 12 and 14 μm are chosen. For 4×4 MMI couplers, the widths of 16 and 20 μm are chosen. Variations of ± 100 and ± 200 nm from the design width were also included to simulate the fabrication error.

Figure 3a shows the width dependency of 4 types of couplers close to the central design wavelength $\lambda = 1550$ nm. In general, minimum of the curves is shifted towards smaller nominal design. This is most probably due to increase of an actual waveguide width with respect to the designed. Also noticeable is that the 14- μm -wide 3×3 coupler performs worse than the 12- μm -wide, while 4-output couplers of both width perform similarly. In further result discussion we refer only to the narrow 3×3 coupler variation. In figure 3b wavelength dependency of MMI couplers of selected width is shown. Similar to the passive run, the values are constant over the C-band.

Compared to the passive run, all devices have additional excess loss of 1 to 2 dB, imbalance is similar and is approximately 0.4 dB, and the phase error is increased by 4° .

Conclusions

We presented a 3×3 and 4×4 MMI coupler characterization in a complete MPW run with active-passive integration. For 12 μm -wide 3×3 MMI coupler experimental results at the central wavelength $\lambda = 1550$ nm show worst-case imbalance of less than 0.4 dB, phase error of 6° and excess loss of 4 dB. Performance in the measured wavelength span of 1520–1580 nm is very constant. Using the correction algorithm [6] the phase error can

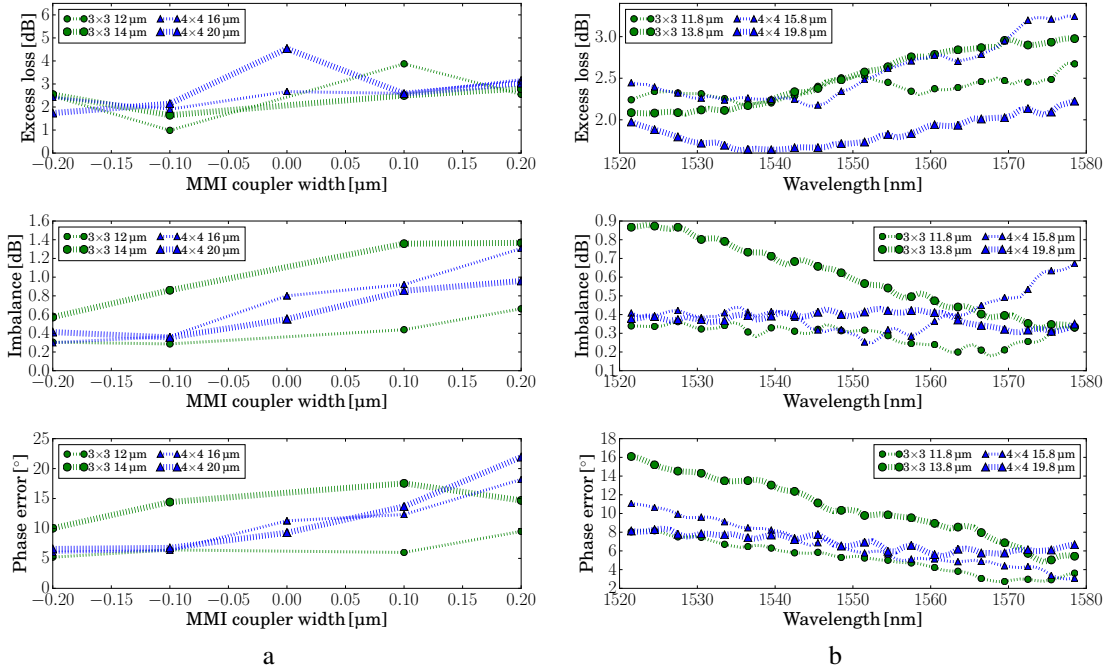


Figure 3: Measured performance of the 3×3 (●) and 4×4 (▲) MMI couplers. a – design MMI width dependency. The values are average over 1545–1555 nm interval. b – wavelength dependency.

be reduced to 2° , which for the given FSR gives a wavelength measurement sensitivity of less than 4 pm.

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