New Design Approach to MMI-Couplers in Photonic Wire Substrates

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***Abstract*—In this paper we present a new design approach for multimode-interference devices exemplified by 2×2 couplers based on photonic wire substrates with excellent performance. We discuss the influence of guided modes in multimode section. Excess loss and imbalance values can be adjusted to better than 0.1 dB.**

***Keywords*—2×2, multimode-interference (MMI) coupler, silicon-on-insulator (SOI), rib waveguide, Si-wire, photonic wire**

I. Introduction

In the recent past, photonic wires have shown their high potential for innovations in the field of integrated optics. Based on the high-index contrast between core and cladding material, the pushed miniaturization of devices enables very high integration densities. Amongst others, this leads to a reduction of required footprint of interferometric devices due to the small waveguide-dimensions and minimal bend radii.

Advanced silicon technology now offers the possibility of considerable length-reduction of multimode-section of MMI couplers compared to low-index contrast devices. The question remains whether the high performance of low index-contrast MMIs (e.g. in 4µm SOI rib waveguide technology [1]) can be transferred to nanowire technology. We ought to keep in mind that high index-contrast MMI devices have to deal with phase deviations proportional to the order of modes differing considerably from low-index materials [2, 3].

So far, 1×2 MMI-couplers were most promising candidates for splitting and combining devices on photonic wire substrates. They offer high design flexibility due the symmetric layout of this type of MMI-coupler. Simulations show excess losses of better than 0.1 dB [4]. 2×2 MMI couplers would be more versatile devices due to input/output symmetry. However, 2×2 devices are also considerably more prone to performance degradation. We would therefore like to present our design approach using the example of 2×2 couplers. In this paper we argue that maximum length reduction of the MMI section will not lead to optimum performance. To this end, we shall provide simulation results as well as experimental evidence.

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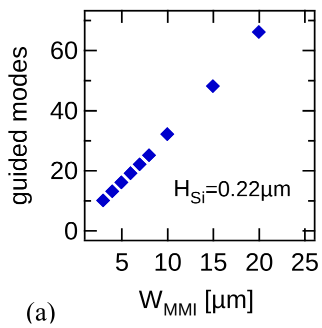
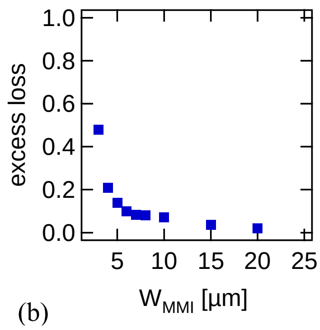
II. MMI-Coupler Simulation

Optimum performance of MMI-coupler devices will show low excess loss and imbalance. Therefore, simulations are used to obtain these performance characteristics while varying geometrical dimensions. Rough estimation of geometry can be done by extrapolation of the waveguides on chip defined by single-mode (SM) condition. Considering the 2×2 MMI-coupler with two input and output waveguides, we need obviously multiple widths of SM-waveguide. This sets a lower limit to the MMI-coupler width, minimizing the final dimensions. We also need to take into account the quadratic scaling between width and length of the multimode section. Additional optimization is required for positioning of the access waveguides, as well as width and shape. Here we will focus on the effect of changing the width of the multimode-section.

Generally, as predicted for symmetric slab waveguides, we can at the same waveguide width expect a higher number of modes for high-index guiding systems compared to low-index systems. This is in accordance with the value of normalized thickness of the guide $V = k_0 \cdot W_{MMI} \cdot (n_F^2 - n_{Cl}^2)^{1/2}$, which is higher for high-index case. Here k_0 is the free space wave number, W_{MMI} the effective width of multimode section, n_F and n_{Cl} the effective refractive indices of the guiding and the cladding layer, respectively. Therefore, by changing the width of multimode section (W_{MMI}), we also change the number of guided modes (see Fig. 1a) that should have influence on the imaging quality at output-side of the MMI-coupler.



(a)



(b)

Fig.1a Relation between guided modes and width of multimode-section in silicon-on-insulator material with Si-thickness H of 0.22µm. Fig. 1b shows the excess loss of 2×2 MMI-coupler realized in the same substrate for TE-mode.

Here we implement a paired interference device. We change the width of 2×2 MMI-coupler (H = 220 nm) and estimate the overall excess loss of the device. The width of in- and outgoing sections scales in both cases with the width of the multimode-section with factor of ~ 0.3. Figure 1b shows the calculated excess loss at the two 3 dB-points for 2×2 MMI-coupler depending on W_{MMI} at wavelength of 1550 nm. We can observe the convergence of the excess loss adapted to a given width of the MMI-coupler. From $W_{MMI} > 4$µm we keep the excess loss below 0.2 dB. Moreover, from mode number of about 50 ($W_{MMI} \sim 15$ µm), we can reduce the loss to about 0.05 dB. Here, the imbalance is better than 0.01 dB. Another important design parameter is the optical bandwidth of the MMI-coupler. In Fig. 2 is plotted the excess loss around the C-band for three different widths of multimode-section, i.e. 4 µm, 6 µm and 10 µm. As shown before, the excess loss at 1550 nm increases for reduced W_{MMI}. The same trend is observed towards the boarders of C-band and beyond.

III. Experiment

For a first fabrication of selected MMI-coupler with $W_{mmi} < 5$ µm we prepared an SOI wafer with a BOX-layer of 2 µm thickness and a silicon layer of 0.22 µm. To determine the basic performance characteristics of the 2×2 MMI-coupler we put them into a MZI-interferometer consisting of a delay line with 25 ps. For the delay line we used additional bends with stretched radius of 20 µm as shown in Fig. 3a. The corresponding free spectral range (FSR) can be calculated with $\lambda / (n_g \Delta L)$. Here λ is the free space wavelength, n_g the group index and ΔL the length difference between the two interferometer arms (~ 2 mm, corresponding to delay time). We used 248nm Deep-UV-lithography and decoupled plasma source etching (Applied Materials) for structuring. The samples were furthermore separated per dicing and polished at the facets. Finally anti-reflection coating was applied. The footprint of the device is about 200 × 1000 µm^2 with potential for further reduction by use of smaller bending radii. A typical measured filter curve of a 2×2 MZI around 1550 nm is shown in Fig. 3b. We achieve, as expected for precise phase correlations at the outputs of the MMI-coupler, π - shifted transfer curves between bar and cross port.

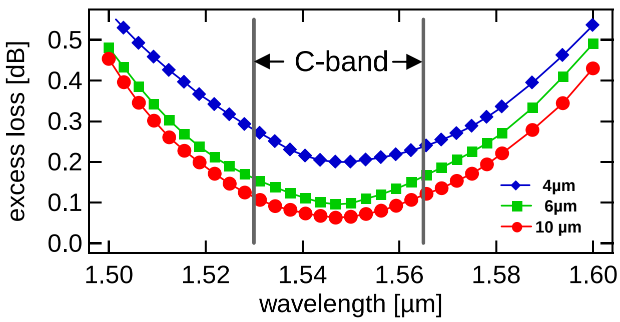
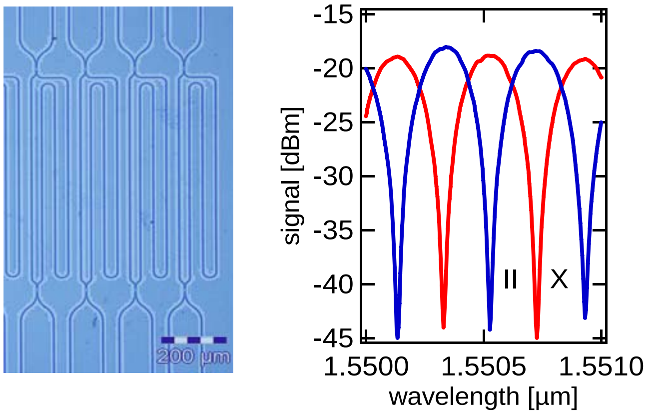


Fig.2 Excess Loss of 2×2 MMI-coupler over wavelength around 1550nm and as function of W_{MMI}.



(a) (b)

Fig.3 Realized 2×2 Mach-Zehnder Interferometers with delay line of 25 ps (3 a) and measured transfer curve at 1550nm for TE-mode (3 b). Extinction ratios for bar and cross port exceed 20 dB.

The extinction ratio over C-band never goes below 20 dB. Because of degrading effects, induced by noticeable different loss in the interferometer arms, the ratio is certainly higher for devices with bigger FSR. The excess loss of MMI-coupler was estimated by employing a 1×1 delayless MZI realized in the same wafer run. We measured excess loss of < 0.5 dB per MMI-coupler, which is in accordance with the simulations above.

IV. Conclusions

We presented a promising approach for the design of MMI-couplers in thin silicon. The approach based on consideration of the number of guided modes conditions in the multimode section. For SOI-wafer with thickness of 0.22 µm, excess loss can be minimized depending on the number of guided modes to be less than 0.1 dB and better. We have also shown high bandwidth operation with slightly increasing losses to the borders of C-band. The experimental data show the applicability of this design method for practical use. Finally, we also see potential for applicability of the presented approach in other substrate types.

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