C-Band Optical 90° Hybrids in Silicon Nanowaveguide Technology

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***Abstract*—We present a fully passive silicon nanowire-based optical 90° hybrid based on a 4×4 multimode interference (MMI) coupler for application in coherent receivers. Simulations show 4×4 MMI coupler performance regarding excess loss, imbalance, bandwidth, and phase accuracy. The 4×4 MMI couplers show stable performance over C-band with excess loss and imbalance < 0.5 dB and phase accuracy better than 5°. We obtain over C-band minimum extinction ratios of 20 dB.**

***Index Terms*—Coherent receiver, 4×4 multimode interference (MMI) coupler, nanowire, optical 90° hybrid, Si-photonic, silicon-on-insulator (SOI) technology.**

I. INTRODUCTION

A large body of research on coherent transmission systems was conducted during the 90's. Coherent transmission has now seen a strong revival due to progress in digital signal processing and increased demand on fiber capacity. If we consider the integrated optics required for coherent reception we identify the optical 90°-hybrid as the central building block. An optical 90°-hybrid is a 6-port device with 2 inputs and 4 outputs. At the outputs the hybrid provides a linear combination of the two input fields, with a phase offset relative to one of the fields of $\pi/2$, π, $3/2\pi$. Most integrated optical 90° hybrids are realized using multimode interference (MMI) devices, because MMI couplers have proven robust devices with respect to fabrication tolerances. Considerable effort has been invested in realizing MMI based integrated optical hybrids over a broad spectrum of technologies. There are two approaches to implementing such optical 90° hybrids. One approach realizes the 90° hybrid using 2×2 MMI couplers plus a phase shifting element, which is used to achieve the required phase relation at the output waveguides of the 2×2 couplers. This approach has been successfully pursued, e.g., in LiNbO3 [1] and in nanowire Silicon photonics [2]. The disadvantages are the need for an additional control circuit, extra power dissipation and an increased footprint. increased footprint. To overcome these drawbacks, the 90° hybrid can be realized in a fully passive way using a 4×4 MMI coupler that intrinsically provides the correct phase relations between the output ports.

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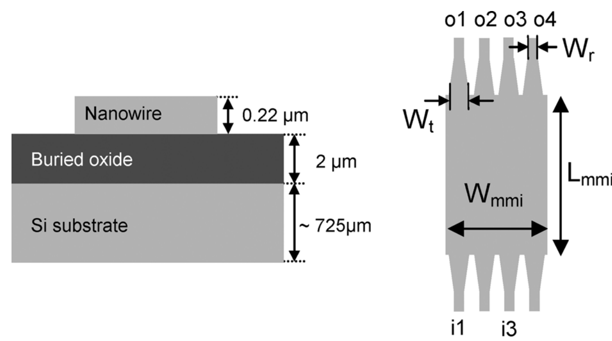

(a) (b)

Fig. 1. (a) Schematic of the nanowaveguide structure and (b) the labeling of the 4×4 MMI coupler. The terms nanowaveguide and nanowire have become common in recent years and are used synonymously for this kind of waveguide.

Such fully passive optical 90°-hybrids were realized in InP [3] and in 4 μm Silicon-on-Insulator (SOI) [4]. Fully passive devices can achieve high performance as shown by various system experiments [5]. A particularly interesting option for realizing coherent receivers is integration on a silicon photonic platform because that allows potentially for cointegration with high-speed electrical signal processing. A first passive optical 90° hybrid in Silicon nanowaveguide technology could was demonstrated by use of shallow-etched (70nm) MMI couplers [6]. Here we focus on optical 90° hybrids in Si-nanowaveguide technology based on deep-etched 4×4 MMI couplers. The realized devices demonstrate high-performance with respect to imbalance, excess loss and phase. Etching down to the buried oxide considerably eases process control and wafer-level uniformity because the oxide forms a highly-selective etch-stop layer.

II. SIMULATION RESULTS

A. Excess Loss and Imbalance of the 90° Optical Hybrid

The basic design of the 4×4 MMI coupler follows straight forward the guidelines of [7]. MMI couplers in nanowaveguide technology are intrinsically more compact than 4×4 MMI couplers realized in 4 μm SOI technology [4]. However, nanowaveguides show higher polarization dependence. In this letter, we use TE polarized light for investigation of the 90° hybrid performance. Fig. 1 shows a schematic of the nanowire waveguide material layers (a) and the 4×4 MMI coupler labeling (b) used in this letter for description of the coupler performance. First calculations consider MMI coupler geometry with respect to minimization of excess loss and imbalance.

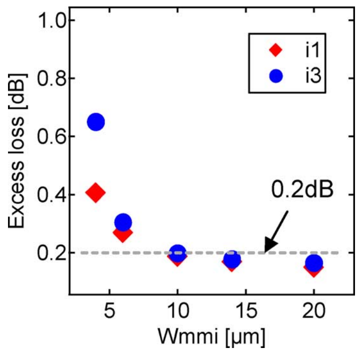

Fig. 2. The 4 × 4 MMI coupler excess loss by use of input 1 (i1) and input 3 (i3) as function of the MMI coupler width W_{mmi}.

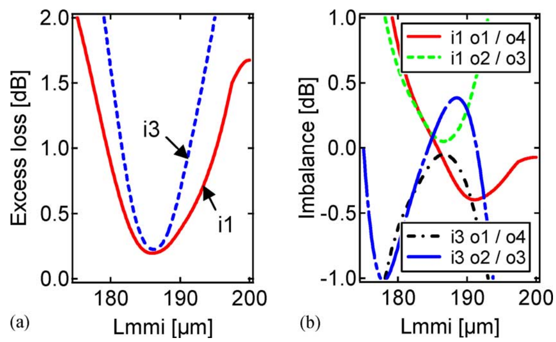

Fig. 3. (a) Calculated MMI coupler excess loss and (b) imbalance as a function of 4 × 4 MMI coupler length ($W_{\mathrm{mmi}} = 10\ \mu$m).

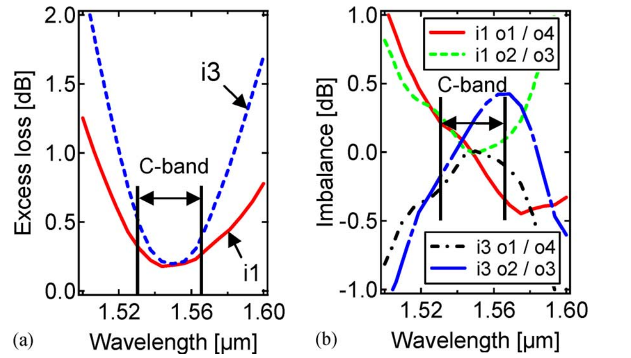

Fig. 4. (a) Calculated excess loss and (b) imbalance in the wavelength range from 1.5 to 1.6 μm. The C-band range is additionally marked.

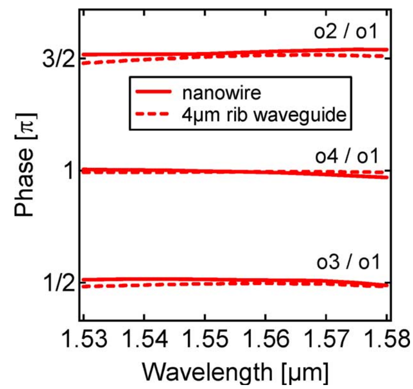

Fig. 5. Calculated phases of 4 × 4 MMI coupler outputs realized in nanowire technology (solid line) and 4-μm rib waveguide technology (dashed line). Phase reference of the plots is phase at output 1.

According to the influence of the coupler geometry on excess loss and imbalance, i.e., the coupler width (W_{mmi}) and width of the attached waveguides (W_t), the 4 × 4 MMI coupler width was varied from 4 to 20 μm. During the simulations, the width of the attached waveguides scale with the coupler width W_{mmi} by a factor of ~ 0.2. The regular waveguide width W_r is 0.48 μm. For this regular waveguide geometry we computed an effective refractive index of $N_{\mathrm{eff}} = 2.1809$ and a group index $N_g = 4.5335$.

The excess loss reduces with increasing width W_{mmi} (see Fig. 2). At $W_{\mathrm{mmi}} = 10\ \mu$m and $W_t = 2\ \mu$m, the excess loss is about 0.2 dB. Further simulations are focused on this MMI coupler width. Fig. 3(a, b) shows length dependent excess loss and imbalance by use of input 1 and 3. The optimum coupler length with respect to excess loss is about 186 μm. The excess loss dependence on length (Fig. 3(a)) is more pronounced for input 3 (i3). The imbalance (Fig. 3(b)) of the π-shifted output ports o1/o4 and o2/o3 by use of input ports i1 and i3 does not exceed the value of 0.1 dB at a coupler length $L_{\mathrm{mmi}} = 185\ \mu$m.

B. Bandwidth of the 90° Hybrid

The bandwidth of MMI couplers is another important characteristic. As described in [8], the bandwidth of MMI couplers decreases inversely proportional to the number N of coupler ports ($\sim 1/N$). Therefore, we can expect slightly worse performance than for 2 × 2 MMI couplers [9]. Over C-band, the excess loss of a 2 × 2 MMI coupler ($W_{\mathrm{mmi}} = 6\ \mu$m) is less than 0.16 dB.

The wavelength dependent excess loss and imbalance of the 4 × 4 MMI coupler is plotted in Fig. 4(a, b). In the C-band, the excess loss increases up to 0.46 dB, and the imbalance increases up to 0.42 dB.

C. Phase Dependence

Another important MMI characteristic is the accuracy of the phase offsets, which is shown in Fig. 5. The expected phase offsets of 90° remain in a 5° range between the MMI coupler outputs. Here, the differential phase at output 1 (o1) is used as phase reference. Corresponding to MMI coupler transfer matrix we obtain a π phase offset between output 1 and 4 as well as output 2 and 3. The phase variation over the C-band is less than 5°. The same figure shows for comparison the phase accuracy of a 4 × 4 MMI coupler in 4 μm SOI technology [4]. Obviously, the nanowire design is able to obtain comparable phase accuracy.

III. Experimental Results

The 90° hybrids were inserted into a 2 × 4 Mach-Zehnder delay interferometer (MZ-DI) structure for testing purposes (see Fig. 6(a)). The Mach-Zehnder delay length ΔL and the propagation constant of the interferometer arms β_{arm} provide a phase shift according to $\Delta\varphi = \beta_{\mathrm{arm}} \cdot \Delta L$ between the two inputs of the 4 × 4 MMI coupler. This phase shift results in the characteristic filter curve of a delay interferometer.

The free spectral range (FSR) is a typical characteristic of a MZ-DI. The FSR is defined by a phase difference of 2π. A

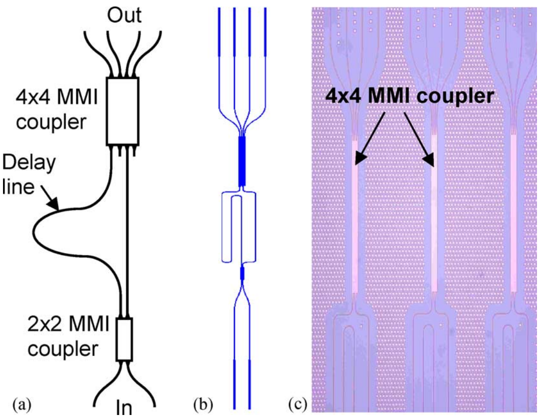

Fig. 6. (a) Scheme and (b) layout of the used 2×4 MZ-DI. (c) Microscope picture of realized 4×4 MMI couplers in nanowaveguide technology.

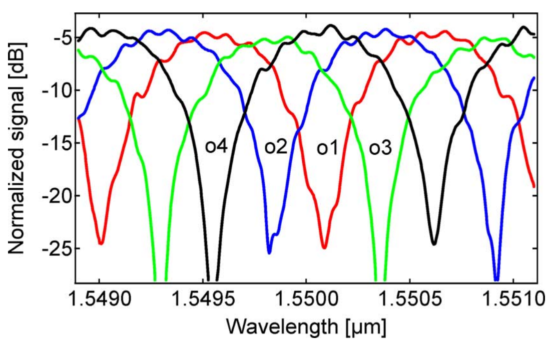

Fig. 7. Transfer function of the 2×4 MZ-DI around 1550 nm. The signals are normalized with respect to a reference waveguide.

wavelength sweep allows therefore determination of the relative phase offsets of the 4×4 MMI coupler at the output ports of the 2×4 MZ-DI. The phase offsets $\Delta\varphi$ can be calculated by use of the following relation $\Delta\varphi/\Delta\lambda = 2\pi/\mathrm{FSR}$. Here, $\Delta\lambda$ denotes the distance of MZ-DI transmission curve minima at the different ports. The FSR can be determined numerically by using the group index ($N_g = 4.5335$) and the following relation: $\lambda^2/(N_g \cdot \Delta L)$. The layout of the used MZ-DI structure is shown in Fig. 6(b). Here, the MZI delay line length ΔL is 500 μm corresponding to a FSR of about 1.1 nm. Bends with bending radii of 8 μm were used. The footprint of the MZ-DI device is 75 μm× 1460 μm. The major part of this area is due to input and output waveguides.

For fabrication of 90° hybrids we used 200 mm SOI wafers with silicon thickness of 0.22 μm and a 2 μm buried oxide layer. We used 248 nm Deep-ultraviolet (DUV) lithography and decoupled plasma source etching (Applied Materials) for structuring. Typical loss values of the nanowires (480 nm $\times$ 220 nm) are 2 dB/cm. Fig. 6(c) shows a microscope picture of realized 4×4 MMI couplers.

One dimensional gratings were used for optical chip coupling, which allow only the use of TE polarized light in measurements. Fig. 7 shows the measured transfer function of the 2×4 MZ-DI around the wavelength of 1.55 μm. The signals are normalized to straight reference waveguides on the same chip. With regard to intrinsic loss of 3 dB and the loss of the 2×2

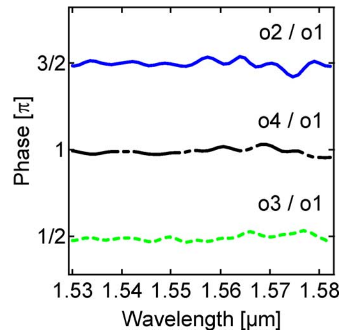

Fig. 8. Measured phase distances of the 4×4 MMI coupler.

MMI coupler, the 4×4 coupler shows an excess loss < 0.5 dB. Over the C-band we obtain minimum extinction ratios of 20 dB. A slight oscillation of the signal is probably due to reflections in the measurement setup. The phase accuracy is in good agreement to the calculated phases (see Fig. 8).

IV. Conclusion

We realized a fully passive 90° optical hybrid in Si-nanowire technology. Measurements show an excess loss of < 0.5 dB and phase accuracy better than 5° over C-band. The minimum extinction ratio of 2×4 MZ-DI test drives is 20 dB. Our results show that 4×4 MMI coupler devices can be realized using a deep Silicon etch to the buried oxide without compromising device performance.

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