SOI based 2×2 and 4×4 waveguide couplers - Evolution from DPSK to DQPSK

Karsten Voigt, Lars Zimmermann, Georg Winzer, Klaus Petermann
Technische Universität Berlin, FG Hochfrequenztechnik HFT4, Einsteinufer 25, 10587 Berlin, Germany

Abstract—We compare 2×2 and 4×4 multi-mode interference (MMI) couplers with respect to performance of D(Q)PSK-demodulators. We shall provide simulation and experimental data of MMI-devices realized in 4µm silicon-on-insulator (SOI) rib waveguide technology.

I. MMI-COUPLERS FOR PSK-DEMODULATION

Phase-shift-keying (PSK) has attracted considerable attention in previous years due to promising properties, e.g. increased optical signal-noise-ratio (OSNR) and relaxed dispersion requirements. PSK-formats require phase-sensitive demodulation, which is usually achieved by Mach-Zehnder (MZ) like add-and-delay structures ([1],[2],[3]). In integrated solutions the waveguide couplers are one of the key elements to realize MZ-interferometers.

The demodulation structure depends on the demodulation format. For example DPSK-demodulators require a delay interferometer consisting of two 2×2 waveguide couplers. DQPSK-demodulators require also interferometer structure, where one of the 2×2 couplers is replaced by a 4×4 coupler (see Fig. 1). The use of the coupler is determined by the modulation format. Therefore the switch from DPSK-format to DQPSK-format can be considered as an evolution from 2×2 to 4×4 imaging properties. The supported modes in the multi-mode region are limited to 9 for the 2×2 MMI-coupler and 12 in the case of 4×4 MMI-coupler.

For a first evaluation of the achievable BW of 2×2 and 4×4 rib waveguide couplers we conducted wavelength dependent simulations. The first criterion was the wavelength stability of the output phases. The corresponding plot is depicted in Fig. 2 (a) for the 2×2 coupler, in Fig. 2 (b) for the 4×4 coupler. The output phases remain stable within a 5% window across the C-band.

Also we investigated the excess loss of the MMI section as a function of wavelength. The input-port dependent loss is plotted in Fig. 3 for transverse electric (TE) and transverse magnetic (TM) polarization. The excess loss for the 2×2 coupler never exceeds 0.3 dB over the C-band, although the loss increases at borders of the band. The 4×4 coupler shows the same behavior at the boarder, but with higher losses in particular for input 3 of the order of 1dB.

II. DESIGN MMI-COUPLERS IN SOI-TECHNOLOGY

Amplitudes and phases at the outputs are related to the lengths and widths of the MMI-couplers. The position of input and output waveguides can also effect the resulting self-image. The device performance, i.e. phase relations, intensities, polarization dependent loss (PDL) and imbalance at outcoming waveguides, can be estimated by variation of these parameters. Concerning higher numbers (N) of input and output waveguides we have to keep in mind that optical bandwidth (BW) inversely scales with that number [7]. Therefore we might expect higher excess loss for the 4×4 MMI-coupler.

Our devices are realized in SOI rib waveguide technology with 4 µm top Silicon, and a rib height of approximately 2 µm. We used a numerical mode-solving tool (FimmWave) to determine parameters of the multi-mode waveguide to achieve 2×2 and 4×4 imaging properties. The supported modes in the multi-mode region are limited to 9 for the 2×2 MMI-coupler and 12 in the case of 4×4 MMI-coupler.

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Imbalance determines the achievable extinction ratio of interferometric devices. Simulated imbalance values between the π/2-shifted outputs of the 2×2 MMI-coupler and the quadrature outputs (o1/o4 and o2/o3) of the 4×4 coupler at different input waveguides have been plotted in Fig. 4.

Fig. 1. Mach-Zehnder interferometer (MZI) with 40 GHz free spectral range.

Only input 1 & 3 of the 4×4 coupler are used.
Table 1 collects the waveguide coupler results. The phases across the C-band remains stable (5%-window) for both coupler types. Values for imbalance and excess loss are summarized across the C-band range. Again Fig. 3 (a) & (b) show that in the couplers. Imbalance values of 2×2 are smaller than 0.1dB size of the 4×4 MMI-coupler is to respect for integration of higher for 4×4 MMI-coupler compared to 2×2 coupler. Larger coupler types. Values for imbalance and excess loss are

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>2×2 MMI</th>
<th>4×4 MMI</th>
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<tbody>
<tr>
<td>Phase C-band (&lt;5%)</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Phase S &amp; L-band (&lt;5%)</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Imbalance C-band</td>
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<td>&lt; 0.7 dB</td>
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<td>&gt; 1 dB</td>
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<tr>
<td>Excess loss C-band</td>
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<td>&lt; 0.9 dB</td>
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<tr>
<td>Excess loss S &amp; L-band</td>
<td>&lt; 1 dB</td>
<td>&gt; 1 dB</td>
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<tr>
<td>PDL C-band</td>
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<td>0.2 dB</td>
</tr>
<tr>
<td>Device length</td>
<td>780 µm</td>
<td>2400 µm</td>
</tr>
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</table>

IV. EXPERIMENTAL RESULTS

To probe the phase behavior of 2×2 and 4×4 MMI-devices we implemented the devices into delay interferometers of 40 GHz free spectral range (see Fig. 1). Only inputs 1 & 3 of the 4×4 MMI were used. Devices were realized in 4 µm SOI rib waveguide technology. We used reactive-ion etching for rib definition on bonded and etch-back material (BESOI). Nominal rib etch was 2 µm deep, but SOI thickness & etch depth could vary due to non-uniformities by approximately 10% We fabricated devices with lengths: L=780 µm (2×2 MMI) & L=2400 µm (4×4 MMI).

Devices were characterized across the C-band. We characterized for a single polarization only, because samples were not subject to birefringence tuning. Birefringence tuning is necessary to decrease polarization dependence of extinction ratios, and has been demonstrated already in previous work [4]. It is, however, not required for the purpose of the present paper. Fig. 5 (a) & (b) show the transmission characteristic of a 40GHz 2×2 MZI & 4×4 MZI as depicted in Fig. 1. The signal was taken with respect to the fiber-to-fiber measurement.

Fig. 5 (a) reveals a uniform insertion loss of about 3 dB for the MZI based on 2×2MMI-couplers. The transmission curves for the MZI-constellation with 4×4 MMI-coupler shows, with respect to the intrinsic 3dB loss, slightly higher losses. The signals at port 2 and port 3 are about 0.7 dB lower.

Fig. 6 (a) and (b) collect the extinction ratio and relative phase data of the same MZI devices. On the left side are arranged the data with 2×2 MMI-coupler based MZI. The right side shows the constellation with introduced 4×4 MMI-coupler. Fig. 6 (b) shows that toward the edge of the C-band imbalance values tend to increase. The effect is more pronounced for the inner port 2 & 3 and consistent with the simulation data. They show that the extinction ratios at port 2 & 3 decrease toward the right edge of the band. Port 2 also has an overall slightly lower extinction ratio. The relative phases in Fig. 6 (b) for both MZI-constellations offers the wanted demodulation characteristic.
Fig. 5 Filter characteristics around 1550nm of 2×2 and 4×4 MZI, see Fig. 1. The port numbers are labeled with respect to the outgoing waveguide number.

Fig. 6. C-band transmission characteristics for MZI-devices. (a) Extinction ratios for 2×2 MZI and 4×4 MZI. (b) Phases at the output ports for both, 2×2 MZI and 4×4 MZI with respect to port 1 (O1).

III. CONCLUSION

From the above presented results we can identify the following tendency. Increased phase resolution comes at the price of decreasing bandwidth. Non-idealities of the couplers lead to increased inhomogeneity in case of N>2, even of adjacent ports. Therefore, filter-curves from different ports can differ considerably. Comparing 2×2 and 4×4 we can conclude that excess loss increases for 4×4 devices according to the theoretical prediction up to 1 dB. The imbalance of 4×4 coupler is increased due to device non-idealities up to 0.7 dB. The results show clearly the difficulty to switch to higher order modulation formats due to limitations of underlying waveguide couplers. As the experimental data shows, high C-band performance is possible up to 4×4 waveguide couplers.

IV. ACKNOWLEDGMENT

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VI. REFERENCES