A Compact Silicon-on-Insulator Optical Hybrid for Low Loss Integration with Balanced Photodetectors

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Abstract An optical hybrid design based on paired multimode interference couplers in silicon-on-insulator process is investigated. The device exhibits greater than 20 dB CMRR and low phase deviation (<10°) over 30 nm in the C-band. The design eliminates the use of optical cross waveguides for integration with balanced photodetectors.

Introduction Coherent detection scheme provides high spectral efficiency and high sensitivity for dense wavelength division multiplexing (WDM) systems. One of the reasons that coherent detection became popular in the last few years is the possibility of low-cost post-processing electronic compensation on the detected impaired signal. However to get those benefits and reduce the component operation complexity, the key building blocks of a coherent receiver such as polarization beam splitter, 90° optical hybrid, and balanced photodetectors, should be integrated on the same substrate. Recently, InP and silicon-on-insulator (SOI) based integrated coherent receiver have been demonstrated. SOI-based coherent receivers are a cost-effective approach taking advantage of CMOS compatible fabrication processes. Optical hybrid designed using 2×2 and 2×4 general interference (GI) multimode interference (MMI) has been demonstrated in SOI. A four 2×2 GI MMI coupler based optical hybrid with integrated Ge-SOI photodetectors (PD) has been demonstrated whereas the PDs were flip-chip onto a passive optical hybrid device. Conventionally, balanced detection requires optical waveguide crossings because the in-phase output (ports 1-3) of the MMI is interleaved with the quadrature-phase output (ports 2-4). This situation increases the optical loss and footprint leading to a more complex solution for integrating the PDs.

MMI-based optical hybrids making use of paired interference (PI) do not require optical crossings as the in-phase and quadrature-phase components of the output signal are available at output ports 1 and 3, respectively. Additionally for the same width, PI-based MMIs are three times shorter in length compared to the GI-based MMIs. With PI-based MMIs, however, a 45° phase shifter and a 2×2 MMI coupler are required at output ports 3 and 4 to maintain the same common mode rejection ratio (CMRR) for both the in-phase and quadrature components. While low-loss InP MMI couplers have already been demonstrated, a more compact low-loss PI-based MMI couplers has not been investigated yet in an SOI substrate. An analysis is presented for the design of a low-loss 1×2 MMI coupler with small footprint (192 μm² core MMI waveguide area) in a 220 nm SOI process. In this work, a compact optical hybrid using PI-based MMI couplers is demonstrated for the first time in a SOI process. The compact device (0.39 mm²) integrates a 2×4 PI-based MMI, a 45° phase shifter and a 2×2 GI-based MMI coupler (fig. 1). Experimental result shows that the device maintains greater than 20 dB CMRR and minimum phase error between the output ports over the C-band. The footprint of the fabricated optical hybrid is three times smaller compared to recent demonstration of SOI-based optical hybrids. Furthermore, lower cost coherent receiver solutions become possible by eliminating the optical waveguide crossings leading to more practical integration with on-chip balanced PD.

Fig. 1: Schematic of the SOI 90° optical hybrid.

Design and simulation results First, an analytical equation is used to determine the required length for PI-based and GI-based MMI couplers in SOI. A beam propagation method (BPM) simulation is then performed to determine more precisely the length of the device and resulting phase relation at the optical hybrid output ports for an assumed MMI width. However due to the high refractive index contrast of the structure, the accurate MMI and phase shifter lengths need to be found.
using tools based on finite difference time domain (FDTD) simulation. Table 1 outlines the feature size of different sections of the 90° optical hybrid found through simulation and used for fabricating the device. A parabolic waveguide structure is designed to achieve the 45° phase difference between the two SOI input waveguide of the 2×2 MMI coupler. As pointed out in2 without the 45° phase shifter, maxima of the transmission response at output channels 3 and 4 will be around 0.65 dB less than at output channels 1 and 2. The absence of the phase shifter will also theoretically limit the extinction ratio of channel 3-4 to 7.89 dB, considerably increasing crosstalk. Through FDTD simulation, a 45° phase difference between two waveguides can be achieved if one of the waveguide is of parabolic taper shape (fig. 1). Simulation result shows a robust design approach with a phase offset variation under 3° over 5 nm variation in the smallest taper width at the center. Waveguide width variation in standard CMOS process can be controlled within 2 nm7.

**Experiment setup and method**

Figure 2 illustrates the experimental setup used to measure the transmission response, CMRR and phase relation between the output channels for the fabricated optical hybrid. A broadband optical source is used covering 30 nm (1535-1565 nm). A 50-50 fiber coupler and one pair of slightly mismatch (~4.5 mm) single mode fiber patchcord are used to make a Mach-Zehnder interferometer (MZI) structure at the input ports of the optical hybrid. The MZI allows to measure the two signal pairs with 180° phase difference: 1) the in-phase signal (port 1-2), and 2) the quadrature-phase (port 3-4). The transmission response is normalized to the output response of the hybrid with an optical signal at only one of the input ports. Similarly, the CMRR of the hybrid is measured using the procedure described in3. The phase relation between different output channels is measured from the wavelength response obtained with the off-chip MZI structure using the Hilbert transform.

**Tab. 1: Device dimension of the optical hybrid (to be completed)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOI waveguide(wg) width</td>
<td>0.5 μm</td>
</tr>
<tr>
<td>MMI i/o wg width, Wstr</td>
<td>2 μm</td>
</tr>
<tr>
<td>MMI core wg width, W2×4</td>
<td>18 μm</td>
</tr>
<tr>
<td>MMI core wg length, L2×4</td>
<td>187.5 μm</td>
</tr>
<tr>
<td>MMI core wg width, W2×2</td>
<td>6 μm</td>
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<tr>
<td>MMI core wg length, L2×2</td>
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<td>75 μm</td>
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<tr>
<td>Taper wg length, WPS</td>
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</tr>
</tbody>
</table>

**Experiment results**

A coupling loss of approximately 8 dB/facet is measured using a reference 5-mm long straight SOI waveguide. Edge couplers can be used for reduced coupling losses. The optical hybrid induces a 6 dB loss from its 2×4 coupling structure. The launched power of the input signal is 2.5 dBm giving an output signal of -21.5 dBm at one of the ports. Thus, the hybrid exhibits an insertion loss of around 2 dB. This can be attributed to the loss of the MMI input/output waveguides, tapers, and radiative loss in the core MMI waveguide.

Figure 3 shows the transmission response of the hybrid at the four output ports with the 180° phase difference between the two in-phase and quadrature-phase output channels. An extinction ratio of 16 dB is achieved for all four channels. We can conclude that the 45° extra phase shift is successfully achieved at the input of the 2×2 MMI coupler as extinction ratios are equal, and greater than 7.89 dB.

**Fig. 2: Experimental setup for the optical hybrid to measure relative phase difference at output ports (OSA: Optical Spectrum Analyzer)**

**Fig. 3: Transmission spectra of the optical hybrid using the off-chip MZ delay interferometer (inset shows the zoomed view).**

Figure 4 shows the relative phase difference of the output channels with respect to the phase response of output port 1 over 30 nm. The
in-phase and quadrature-phase components have a relative phase difference of 90° or a multiple of 90°. The relative phase deviation of each output port is below ±5°.

To calculate the CMRR, the transmission response at all output ports is first measured (Fig. 5). Firstly, a maximum transmission variation between the output ports of 0.6 dB is observed. The general spectral shape is attributed to the broadband source. Fig. 6 shows the calculated CMRR, \(-20\log[\frac{(P_1-P_2)}{(P_1+P_2)}]\), (where, \(P_1, P_2\) is the power of output channels 1, 2 respectively while giving optical input to channel 1 or 2 at a time). The same CMRR relation holds for output channels 3-4. Over the 30 nm wavelength range, CMRR remains greater than 20 dB, which is a good performance metric for integration with balanced PD\(^2,8\).

Conclusions
A CMOS compatible SOI 90° optical hybrid is demonstrated eliminating the need of any optical waveguide crossings for better on-chip integration with on-chip balanced PD. To the best of our knowledge, these are the first performance results presented for a PI MMI based SOI optical hybrid. The good performance results suggest that integration with on-chip Ge-SOI balanced PDs can be less complex leading the path for a lower cost implementation of coherent receiver.

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References