Abstract—We demonstrate 4 × 4 multimode interference couplers in a silicon-on-insulator rib waveguide technology that enable compact integrated fully passive optical 90°-hybrid devices with operation across the C-band.

Index Terms—Multimode interference, optical hybrid, rib waveguide, silicon-on-insulator (SOI) technology.

I. INTRODUCTION

The functionality of 90° optical hybrids or quadrature optical hybrids is central to many advanced applications in optical communications, such as coherent transmission systems, phase sensitive detection, or linear optical sampling [1], [2]. Quadrature optical hybrids realized in LiNbO₃ have been well-established for some time already ([3]), while optical hybrids based on free-space optics are more recent. Both technologies are commercially available. However, there are drawbacks related to these technologies, e.g., relatively large bias voltages, additional bias control loops, and general incompatibility with integrated optics. A more compact and fully passive solution to the problem of quadrature detection is the use of 4 × 4 coupler devices that rely on self-imaging or multimode interference (MMI). First, work on such integrated optics devices by Niemeier et al. [4] was based on glass stripe waveguides. Later, 4 × 4 MMI couplers were realized in InP technology [5]. Both works focused on demonstration of the self-imaging principle and single wavelength performance.

Despite these early studies, optical hybrids based on integrated 4 × 4 couplers are presently much less known to the community than LiNbO₃ or free-space optics devices. Part of the reluctance in recognizing integrated solutions could be related to the stringent specifications concerning polarization dependence, which is usually difficult to achieve in waveguide-based technologies. However, recently we demonstrated a differential phase-shift keying demodulator chip (based on a delay interferometer (DI) using 2 × 2 MMI couplers) realized in 4-μm silicon-on-insulator (SOI) technology showing state-of-the-art performance, and, in particular, very low polarization dependence [6]. In this letter, we shall show that SOI-based optical hybrids are an attractive alternative to nonintegrated solutions.

We shall start with an outline of ideal 4 × 4 coupler properties, for readers less familiar with the MMI concept. We shall then proceed with simulation data of 4 × 4 MMI coupler devices in SOI rib waveguide technology, predicting C-band performance of such devices. Following, we shall present experimental results demonstrating C-band quadrature behavior of 4 × 4 MMI couplers realized in the aforementioned SOI technology, to prove the potential of SOI waveguide based optical 90°-hybrids.

II. IDEAL 4 × 4 MMI COUPLER

An optical 90°-hybrid is a six-port device with two inputs and four outputs. At the outputs the hybrid provides a linear combination of two input fields $E_1$ and $E_3$, with a relative phase shift of one of the fields of $\pi/2$, $\pi$, $3\pi/2$, and $0$. If we assume perfect balance and omit any constant phase offset, the output fields are proportional to $E_1 + jE_3$, $E_1 - E_3$, $E_1 - jE_3$, and $E_1 + E_3$, respectively.

Such a relation is exactly valid at the output ports of an ideal 4 × 4 MMI coupler, when signals are present only at input ports 1 and 3 (see Fig. 1). Following [7], we may calculate the phase increment $\varphi_n$ of $E_3$ with respect to $E_1$ at each output port ($n = 1 \ldots 4$). The corresponding phase values are $\varphi_1 = -45°$, $\varphi_2 = 225°$, $\varphi_3 = 45°$, and $\varphi_4 = 135°$. Obviously, the ideal 4 × 4 coupler satisfies the desired hybrid characteristics. Most important for phase quadrature demodulation are the differential signals between outputs 1 and 4, and 2 and 3 ($\Delta\varphi = 180°$).

MMI couplers rely on the self-imaging effect [8], which is intrinsic to all highly multimode waveguide structures. Self-imaging is the result of interference between a large number of supported modes at well defined lengths of the multimode waveguide. In general, the quality of the self-images depends on the number of supported modes, the confinement of the waveguide, and the waveguide birefringence. Real MMI couplers, therefore, show polarization dependence, imbalance, and excess loss that depend on the underlying technology.
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III. COUPLER DESIGN

Our devices are realized in SOI rib waveguide technology with 4-μm top silicon, and a rib height of approximately 2 μm. A four-fold image of a single input appears approximately at L = n_{eff} W_{eff} / \lambda, where n_{eff} is the effective slab index, W_{eff} the effective width of the multimode waveguide, and \lambda the center wavelength. We used a numerical mode-solving tool to determine parameters of the multimode waveguide to achieve 4 × 4 imaging properties [FimmWave, Fig. 2(a)]. The simulated phase increments at 1550 nm [Fig. 2(b)] deviate from the ideal only within 5° although the number of supported modes in the multimode region is limited to 12.

A central performance figure of optical hybrids is available bandwidth (BW), which refers to the wavelength range wherein device performance deviates from specs only within a certain margin (e.g., of excess loss or of phase). Since MMI devices rely on interference, BW limits could be a serious drawback for the application of such devices. It is known that the BW of N × N MMI couplers follows a ∼ 1/N law [9]. We have recently shown that 2 × 2 MMI-based SOI devices cover well the C-band [6] wavelength range. For a first evaluation of the achievable BW of 4 × 4 rib waveguide couplers, we conducted simulations in which the wavelength was varied. We studied the wavelength dependence of the output phases. The corresponding plot is depicted in Fig. 3(a). Across the C-band the output phases remain stable within a 5% margin. Excess loss of the MMI section as a function of wavelength and input port is plotted in Fig. 3(b) for both polarizations. Excess loss refers to the total loss in intensity, i.e., the sum of all output intensities in relation to the input intensity.

If we allow for a penalty of 1 dB, the entire C-band is covered by the coupler. A permitted penalty of 0.5 dB would reduce the available wavelength window by 20 nm. Polarization-dependent excess loss remains <0.1 dB.

Imbalance determines the achievable extinction ratio of interferometric devices. Simulated imbalance values between quadrature outputs (o1/o4 and o2/o3) have been plotted in Fig. 4. Similar to excess loss, input 3 suffers from slightly higher imbalance. An imbalance of up to 0.5 dB results in extinction ratios of not less than 20 dB. The simulations, therefore, indicate satisfactory C-band performance of 4 × 4 rib waveguide couplers. Although not included here, transverse-magnetic (TM) performance is comparable according to simulations.

IV. EXPERIMENTAL RESULTS

To probe the phase behavior of 4 × 4 MMI devices we implemented 4 × 4 DIs (4 × 4 DI) of 40-GHz free spectral range. In the 4 × 4 DI, a 2 × 2 coupler was replaced by a 4 × 4 coupler (see Fig. 5). Only inputs 1 and 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). The nominal rib etch was 2 μm deep, but SOI thickness and etch depth could vary due to nonuniformities by approximately 10%. We fabricated devices of two different lengths: L = 1600 μm and L = 2400 μm. Devices were characterized across the C-band. Polarization dependence is an important issue for 90°-hybrids, with two major elements visible in MZI devices: Polarization-dependent frequency shift ([PDFS] also responsible for the polarization dependence of the extinction ratio), and polarization-dependent loss (PDL). PDFS can be minimized by birefringence tuning, which has been demonstrated in SOI MZI devices already in previous work [6]. On the other hand, birefringence tuning has little impact on PDL. According to Fig. 3(b), the intrinsic PDL of the couplers is smaller than 0.4 dB over the C-band.

Samples were not subject to birefringence tuning. We therefore characterized only for a single polarization. Birefringence
tuning is not required to prove optical hybrid behavior. However, birefringence tuning can be applied to integrated waveguide circuits with $4 \times 4$ MMI couplers in a similar fashion to [6]. Transmission values are provided with respect to the fiber-to-fiber value, i.e., coupling loss was included. A zoom in around 1550 nm of the filter curves at the four outputs of the interferometer is shown in Fig. 6.

The filter characteristics of $4 \times 4$ DIs were measured over a range from 1530 to 1580 nm. Since temperature dependence is an important property of passive devices, filter curves were recorded at 35 °C and 70 °C. Fig. 7(a) and (b) collect the extinction ratio data of $4 \times 4$ devices (short and long) at 35 °C and 70 °C, respectively.

The simulation data in Fig. 5 show that toward the edge of the $C$-band imbalance values tend to increase. The effect is more pronounced for the inner ports 2 and 3. Fig. 7(a) and (b) both exhibit this effect and are consistent with the simulation data.

They show that the extinction ratios at ports 2 and 3 decrease toward the right edge of the band. Port 2 also has an overall slightly lower extinction ratio. Relative output phases are shown in Fig. 7(c). The phase variations on the traces in Fig. 7(c) are mainly due variations of the wavelength output of our tunable laser source (estimated phase error $\approx 2.5^\circ$). Phases remain stable across the $C$-band and for temperatures up to 70 °C. Temperature dependence of excess loss was not observed.

Short devices show slightly lower performance than longer devices. This might be attributed to narrower waveguide spacing in the first case, and therefore increased sensitivity to process variations. It had already been pointed out [5] that the single wavelength behavior of $4 \times 4$ MMI couplers is rather insensitive to temperature variations. We can confirm this statement for the entire $C$-band.

V. SUMMARY AND CONCLUSION

Fully passive $C$-band optical quadrature behavior has been demonstrated for the first time using $4 \times 4$ MMI couplers. We could verify that the devices exhibit phase stability across the band and are insensitive to temperature variations. The devices were realized in SOI rib waveguide technology. SOI $4 \times 4$ MMI couplers are therefore an attractive alternative to nonintegrated or actively controlled $90^\circ$-hybrids.

REFERENCES