Broadband High-Performance 2×2 MMI 3-dB Coupler Enabled by SWG Lateral Cladding for the Silicon-on-Insulator Platform

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Abstract: We demonstrate a high-performance silicon photonic 2×2 MMI 3-dB coupler enabled by SWG lateral cladding. Measured imbalance below 0.3 dB and phase error below 1.83° are achieved over a 130 nm bandwidth covering the C-band.

OCIS codes: (050.6624) Subwavelength structures; (230.1360) Beam splitters; (230.3120) Integrated optics devices.

1. Introduction

2×2 3-dB couplers are essential devices in photonic integrated circuits for coupling light between two waveguides. 2×2 multimode interference (MMI) 3-dB couplers, 2×2 adiabatic 3-dB couplers, and 2×2 directional 3-dB couplers are the three major types of 2×2 3-dB couplers. Among them, the 2×2 MMI 3-dB couplers have the advantages of relaxed fabrication tolerances and broad operating bandwidth. However, for 2×2 MMI 3-dB couplers based on the silicon-on-insulator (SOI) platform, the performance is limited by the high lateral refractive index contrast between the silicon core and the oxide cladding [1]. The high lateral refractive index contrast leads to the large modal phase errors of the higher-order modes of the MMI coupler, and thus lowers the level of imaging quality and deteriorates the device performance.

In the paper, we design and experimentally demonstrate a broadband and high-performance 2×2 MMI 3-dB coupler enabled by subwavelength-grating (SWG) lateral cladding. Our device is designed for the fundamental transverse electrical mode and has been fabricated on the 220-nm SOI platform with oxide cladding. We reduce the lateral refractive index contrast by introducing the SWG lateral cladding. The SWG effectively behaves as a uniform material whose refractive index is between those of silicon and oxide [2]. As a result, the SWG lateral cladding has a higher equivalent refractive index than that of oxide. Our fabricated 2×2 MMI 3-dB coupler achieves measured imbalance lower than 0.3 dB and phase error lower than 1.83° over a 130 nm bandwidth from 1500 nm to 1630 nm.

2. Design and Simulations

The schematic of our 2×2 MMI 3-dB coupler is shown in Fig. 1. The SWG lateral cladding with a width, W_{SWG}, a duty cycle, D, and a pitch, Λ, is introduced to the multimode waveguide of the MMI coupler. The widths of

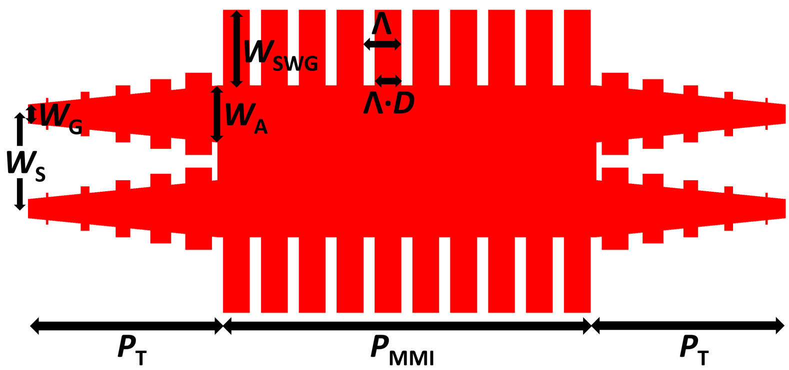
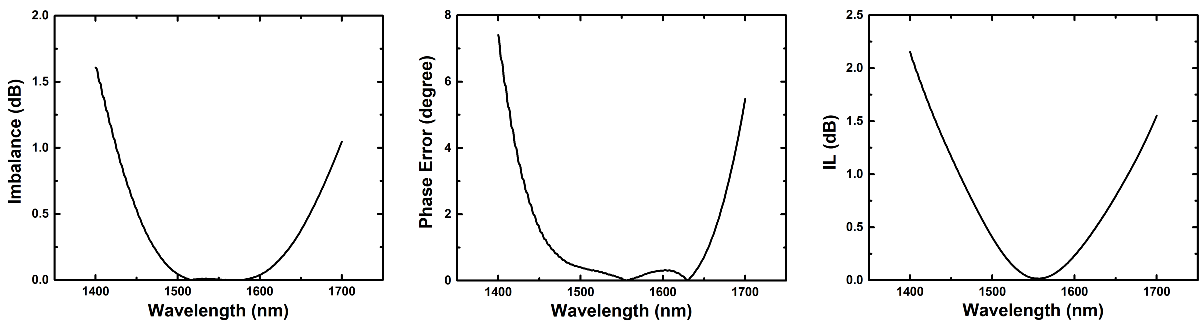


Fig. 1. Schematic of our 2×2 MMI 3-dB coupler (not to scale).



(a) (b) (c)

Fig. 2. Simulated (a) imbalance, (b) phase error, and (c) IL of the designed 2×2 MMI 3-dB coupler from 1400 nm to 1700 nm.

the interconnecting strip waveguides and the access ports of the MMI coupler are W_{G} and W_{A}, respectively. The center-to-center spacing of the interconnecting strip waveguides is W_{S}. The interconnecting strip waveguides and the access ports of the MMI coupler are connected by linear tapers. The linearly-tapered SWG lateral cladding is introduced to the linear tapers for a smooth transition of the lateral refractive index. The number of SWG pitches for the linear tapers and the multimode waveguide are P_{T} and P_{MMI}, respectively.

For our 2×2 MMI 3-dB coupler, D is chosen to be 0.7 for an optimal equivalent refractive index of the SWG lateral cladding. Λ is chosen to be 200 nm, short enough to avoid Bragg reflection. W_{SWG} is chosen to be 2 μm, wide enough so that almost all the evanescent field of the multimode waveguide is within the SWG lateral cladding region. W_{G} is chosen to be 500 nm for the C-band operation. W_{A} is chosen to be 1.5 μm, wide enough to assure that only the lower order modes of the multimode waveguide are excited [3]. W_{S} is chosen to be 2.5 μm, wide enough to avoid crosstalk between the two input or the two output waveguides. P_{T} is chosen to be 50, large enough to ensure adiabatic transition of the linear tapers. P_{MMI} is chosen to be 314 according to the beat length of the MMI coupler [4].

The three-dimensional (3D) finite-difference time-domain (FDTD) simulation is performed to characterize the performance of the designed 2×2 MMI 3-dB coupler. The simulated imbalance, defined as $\left|10\cdot\log(P_{\mathrm{Through}}/P_{\mathrm{Cross}})\right|$, phase error, defined as $\left||\phi_{\mathrm{Through}}\text{-}\phi_{\mathrm{Cross}}|\text{-}90^{\mathrm{o}}\right|$, and insertion loss (IL), defined as $-10\cdot\log(P_{\mathrm{Through}}+P_{\mathrm{Cross}})$, are shown in Fig. 2(a), 2(b), and 2(c), respectively. The simulated imbalance is lower than 0.3 dB and phase error is lower than 1$^{\mathrm{o}}$ over a 175 nm bandwidth from 1467 nm to 1642 nm, while the IL is below 0.89 dB.

3. Fabrication and Experimental Results

Our designed 2×2 MMI 3-dB coupler has been fabricated by electron beam lithography at Applied Nanotools Inc. Only one etching step is required for the fabrication of our device. Two of the designed 2×2 MMI 3-dB couplers are integrated to form an imbalanced Mach-Zehnder interferometer (MZI) test structure. Light is coupled to the chip through the grating couplers (GCs). The measured MZI transmission spectra, after calibrating out the ILs from the GCs, are shown in Fig. 3(a). The imbalance of the fabricated 2×2 MMI 3-dB coupler is extracted from the extinction ratio of the measured straight-through transmission spectrum [5], and is shown in Fig. 3(b). The phase error is extracted from the relative position of the transmission minima of the measured straight-through and cross-over transmission spectra [6], and is shown in Fig. 3(c). Over a 130 nm bandwidth from 1500 nm to 1630 nm, the measured imbalance is lower than 0.3 dB and phase error is lower than 1.83$^{\mathrm{o}}$. The IL of the fabricated 2×2 MMI 3-dB coupler could be estimated as the half of the MZI excess loss. The estimated IL is lower than 0.58 dB over the measured 130 nm bandwidth. Table 1 compares our device with other 2×2 MMI 3-dB couplers that have been experimentally demonstrated on the SOI platform.

Table 1. Comparison of 2×2 MMI 3-dB Couplers Experimentally Demonstrated on the SOI Platform

Reference	Bandwidth (nm)	Imbalance (dB)	Phase Error (degree)	IL (dB)	Length (μm)
[3]	1530 - 1570	~ 1.3	~ 5	N/A	42.85
[7]	1375 - 1700	< 1	< 5	< 1	25.4
[8]	1530 - 1565	N/A	N/A	$\leq 0.15\pm0.01$	152
This work	1500 - 1630	< 0.3	< 1.83	< 0.58	82.8

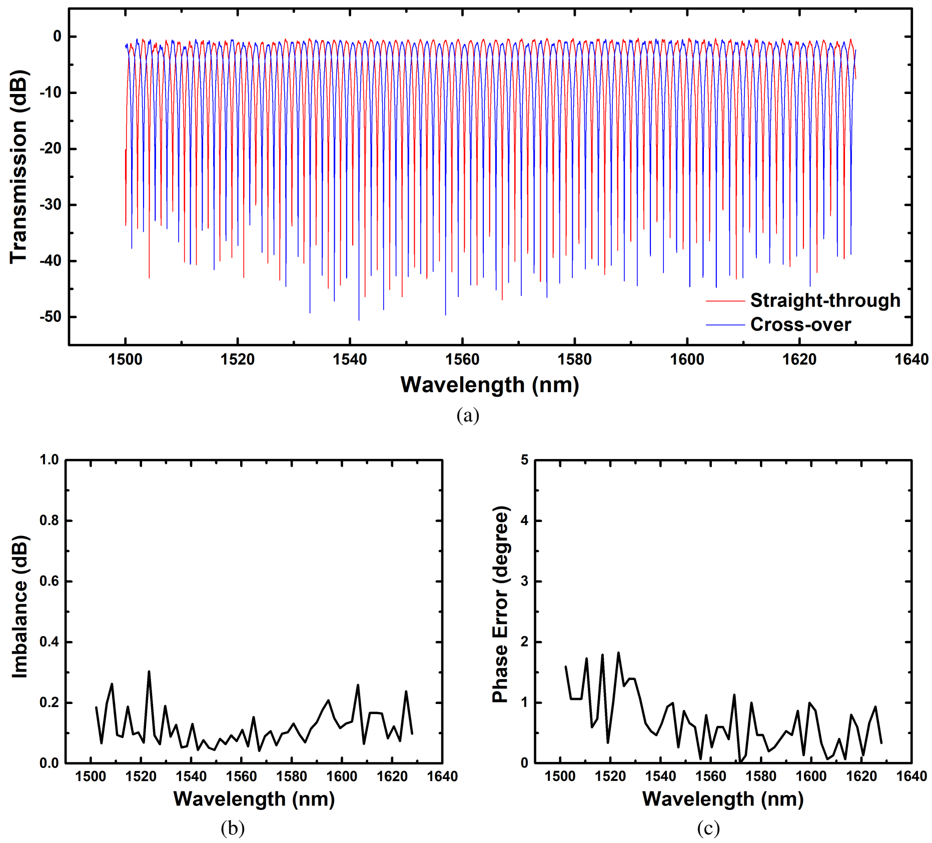


Fig. 3. (a) Measured MZI transmission spectra, (b) extracted imbalance, and (c) extracted phase error of the fabricated 2×2 MMI 3-dB coupler from 1500 nm to 1630 nm.

4. Conclusion

We have designed and experimentally demonstrated a broadband and high-performance 2×2 MMI 3-dB coupler enabled by SWG lateral cladding for the 220-nm SOI platform. The SWG lateral cladding is employed to reduce the lateral refractive index contrast of the MMI coupler, leading to high-performance operation over a broad operating bandwidth. Our fabricated device achieves measured imbalance lower than 0.3 dB and phase error lower than 1.83^{o} over a 130 nm bandwidth that covers the C-band and the L-band.

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