2×2 Adiabatic 3-dB Coupler on Silicon-on-Insulator Rib Waveguides

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ABSTRACT

We demonstrated 2×2 broadband adiabatic 3-dB couplers based on silicon rib waveguides. Functioning as 50/50 optical power splitters, these devices can be used in optoelectronic applications. Fabricated using silicon-on-insulator technology, we demonstrated the performance of the adiabatic 3-dB couplers by integrating two couplers into an unbalanced Mach-Zehnder Interferometer (MZI). Measurements of the MZI were made over a 100 nm wavelength range. Extinction ratios in excess of 33.4 dB were obtained over the wavelength range from 1520 nm to 1600 nm, for light injected into Input Port1 and measured at Output Port2, i.e., the cross port response.

Keywords: Adiabatic 3-dB coupler, broadband, silicon-on-insulator, rib waveguide, Mach-Zehnder interferometer

1. INTRODUCTION

Optical couplers are essential components that are used in photonic integrated circuits to couple light between waveguides with desired coupling ratios.[1,2] Adiabatic 3-dB couplers are 2×2 couplers that are used for coupling/splitting light evenly. These couplers are essentially wavelength independent and less sensitive to fabrication variations, particularly as compared to other couplers such as symmetric directional couplers or multimode interference (MMI) couplers. The fundamental (even) and the first order (odd) modes in a conventional directional coupler, as shown in Fig. 1(a), are excited initially and interfere with each other as they propagate along the coupler which results in the power transferring back and forth between the two waveguides, whereas, in an adiabatic 3-dB coupler, only one mode, either the even or the odd mode, is excited (see Fig. 1(b)). When the even or odd mode is initially excited, all of the power stays in the excited mode, even in the presence of dimensional changes of the waveguide structure and the mode shape. As a result, no energy exchange or power coupling occurs between the modes in the coupler. Unlike Y-junctions, adiabatic 3-dB couplers, functioning as passive 2×2 couplers, can be used to construct active 2×2 switches. Functioning as 50/50 power splitters, adiabatic 3-dB couplers can be used to construct Mach-Zehnder Interferometer (MZI) based electro-optic modulators.

During the past two decades, adiabatic 3-dB couplers have been developed and fabricated using various types of waveguide materials, such as $LiNbO_3$,[3] SiO_2,[4] Polymers,[5] and Silicon-on-Insulator (SOI).[1] Among these materials, SOI waveguides provide a high refractive index contrast that enables extreme device miniaturization and, thus, allows for the large-scale integration of photonic circuits. In 2006, Solehmainen et al.[1] demonstrated the first SOI adiabatic 3-dB coupler on 3.5-μm-wide silicon rib waveguides with a coupling length of 250 μm and obtained an MZI extinction ratio (ER) of 15-20 dB. In 2008, Spector et al.[6] designed and integrated an SOI adiabatic 3-dB coupler, with a coupling length of 130 μm, into an MZI based electro-optic modulator and obtained a modulation depth of 22% (∼6.6 dB) at a wavelength of 1550 nm. In 2010, Cao et al.[2] optimized the 3-dB coupler with a coupling length of 200 μm and measured an ER of >10 dB over the wavelength range from 1555 nm to 1640 nm. Recently, Watts et al.[7] designed and integrated a SOI strip waveguide based adiabtic 3-dB coupler, with a coupling length of 100 μm, into an MZI based thermal-optic switch and observed an ER of 20-30 dB over a wavelength range of 70 nm. Here, we present design and experimental results for a broadband

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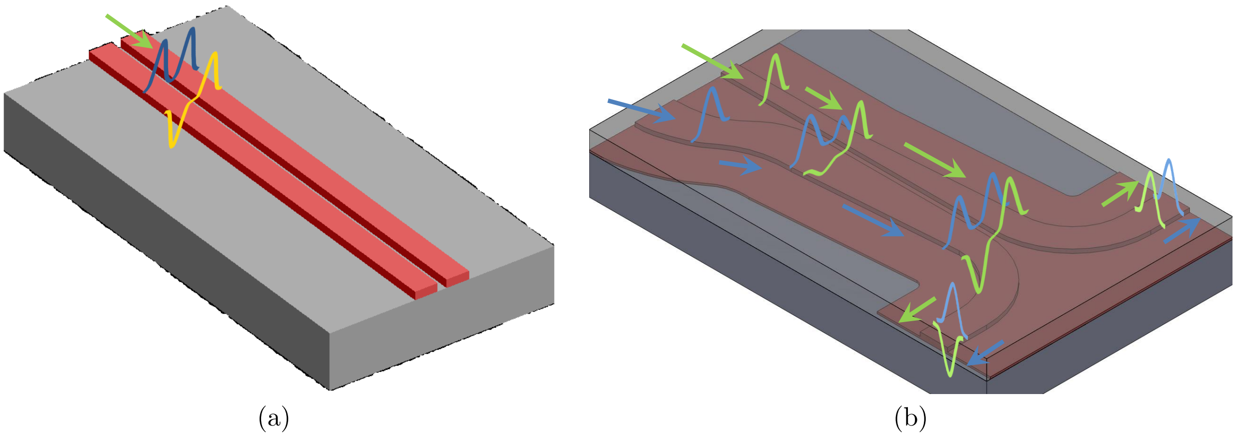


Figure 1. Perspective view of (a) a conventional, directional coupler with its even (blue line) and odd mode (yellow line) excited at the input and (b) an adiabatic 3-dB coupler with only either the even (blue line) or the odd (green line) mode excited.

SOI rib waveguide based adiabatic 3-dB coupler. As compared to SOI strip waveguides, SOI rib waveguides are less sensitive to sidewall roughness, which enable more compact design and are more tolerant to fabrication variations.[8] In comparison with previous work, our rib waveguide geometry is as compact as for SOI strip waveguides,[7] having a coupling length of 100 μm, and achieves broadband even splitting with an ER of >33.4 dB and an average normalized power splitting ratio of 50.4%/49.6% over a wavelength range of 80 nm. We integrated two adiabatic 3-dB couplers into an MZI to experimentally verify the performance of the couplers.

2. DESIGN AND SIMULATION

2.1 Design

We designed our adiabatic 3-dB coupler based on SOI rib waveguides. The adiabatic 3-dB coupler, as shown in Fig. 2, consists of four parts. In Region I, two parallel strip waveguides with 500 nm waveguide widths and a 3 um gap distance are used as the two inputs and are tapered to 400 nm and 600 nm wide strip waveguides, respectively. They are then converted to corresponding rib waveguides with 1-μm-wide slabs on each side of the waveguides by using adiabatic linear tapers. In Region II, the two rib waveguides are brought together using an S-shape waveguide bend in one of the waveguides to reduce the gap distance from 3 μm to 200 nm. The S-shape waveguide bend in Region II is designed using Bezier curves to minimize the mode mismatch and thus reduce the waveguide bending loss.[9] In region III, linear tapers are used to gradually convert the dissimilar input waveguides into two identical waveguides with a constant coupler gap of 200 nm. The widths of the two waveguides at the end of Region III are both 500 nm. In Region IV, the light in the two output waveguides is separated using two waveguide bends, to avoid further coupling.

2.2 Simulation

We use the 3-D finite-difference time-domain (FDTD) method to simulate the layout shown in Fig. 2. When the light is injected into one of the input waveguides, the large asymmetry between the 400 nm and 600 nm wide rib waveguides in Regions I and II avoids coupling between the two waveguides (see Fig. 2). As shown in Fig. 2, the input light in the 600-nm-wide waveguide, which has the larger effective refractive index, excites the fundamental mode of the coupler in Region III while the input light in the 400-nm-wide waveguide excites the first order mode of the two waveguides due to its smaller effective refractive index. The length of the linear tapers in Region III are designed to be sufficiently long to have a gradual taper so that the excited modes at the interface between Regions II and III can be adiabatically transmitted into the even or odd mode of the symmetric 500-nm-wide waveguides at the end of Region III. The excited even or odd mode automatically has half of the power in each waveguide which is then guided to one of the output waveguides by the two bending waveguides in Region IV. The simulated transmission responses of the adiabatic coupler, given in Fig. 3, show

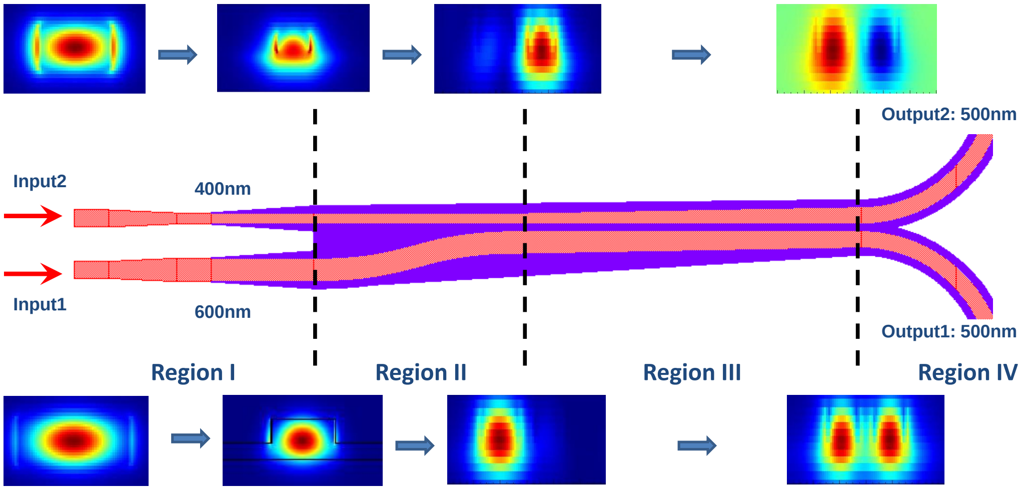


Figure 2. Schematic of adiabatic 3-dB coupler with simulation results.

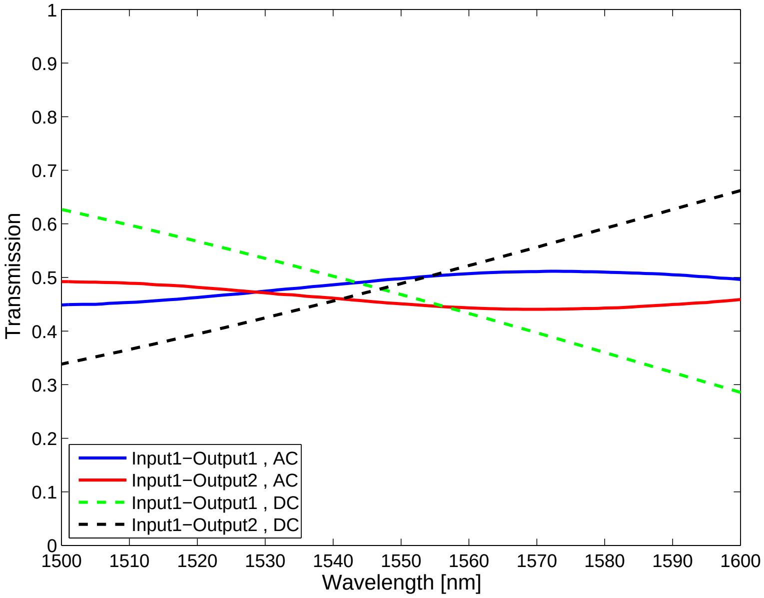


Figure 3. Simulated transmission responses of an adiabatic 3-dB coupler (AC) and a conventioanl, directional coupler (DC).

that the device has much smaller wavelength dependence and more robust 3-dB coupling over a wide spectral range, as compared to conventional, directional couplers.

3. FABRICATION AND EXPERIMENT

3.1 Fabrication

The couplers were fabricated using electron-beam lithography, with plasma etching, on the SOI platform. The input strip waveguides were 500-nm-wide by 220-nm-high silicon nanowires. The rib waveguides had 220-nm-high ribs with 90-nm-high slabs. Figure 4(a) and (b) show optical images of a fabricated 3-dB coupler. The linear tapers that converted the strip waveguides to rib waveguides were 15 μm long. The S-bend in Region II was 30

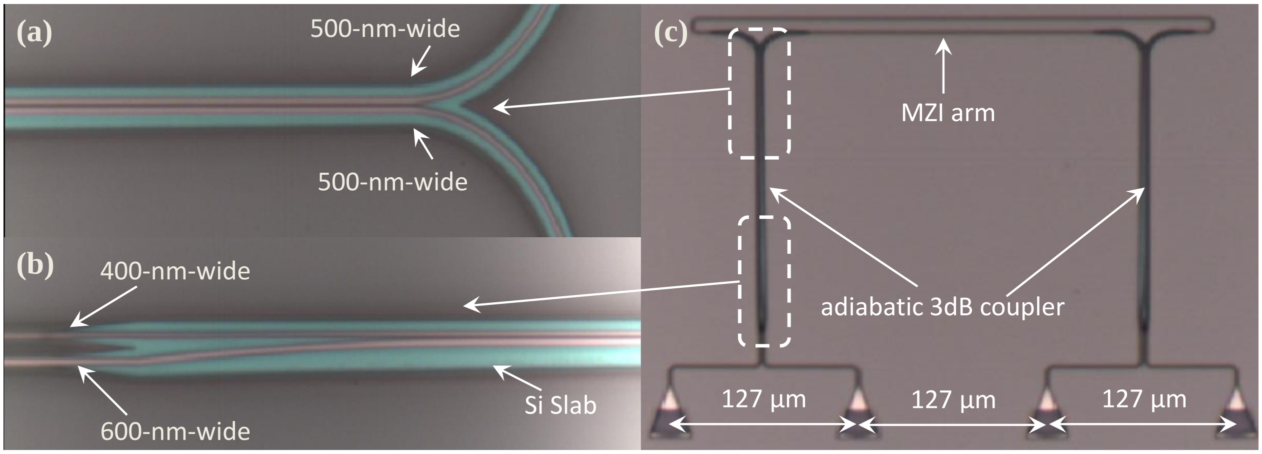
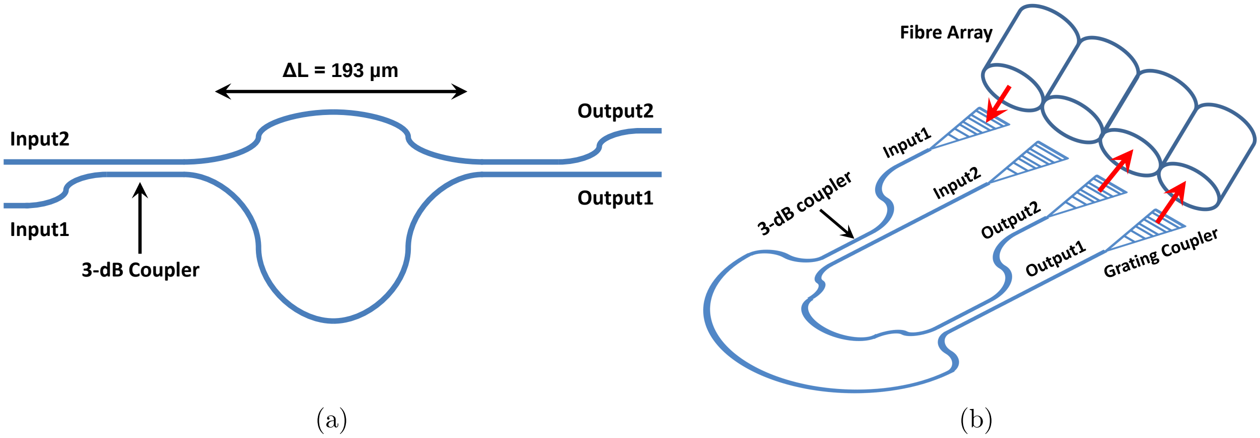


Figure 4. Optical images of a fabricated, unbalanced MZI with two adiabatic 3-dB couplers.

μm long and the linear tapers in Region III were 100 μm long. The radii of the waveguide bends in Region IV were 20 μm.

3.2 Measurement

To demonstrate the performance of our adiabatic 3-dB couplers, we integrated two couplers into an unbalanced MZI with a length difference of 193 μm, where the output coupler was a 180-degree-rotated image of the input coupler (see Fig. 5(a)). We designed the layout of the MZI, as shown in Fig. 5(b), for measurements using an optical fiber array. A fiber array containing four single-mode, TE-polarization-maintaining fibers, with 127 μm pitch, was used to simultaneously inject the input signal and to collect the two output signals. We integrated four TE-mode grating couplers onto the input and output ports to couple the light into and out of the 2×2 MZI circuit. The grating couplers were parallel to each other and were placed on the chip with 127 μm spacing (see Fig. 4(c)), which enables us to align the fiber array to the two output ports at the same time and measure the two output responses simultaneously. The incident angle of the fiber array was adjusted to maximize the coupling efficiency at $\lambda_0 = 1550$ nm.



(a)

(b)

Figure 5. Schematics of (a) a 2×2 unbalanced MZI with two adiabatic 3-dB couplers and (b) the MZI circuit used to make the measurements.

Measurements were taken at the two output ports of the 2×2 MZI when light was injected into one of the input ports. The MZI spectrum, after calibrating out the insertion loss introduced by the grating couplers, shows that extinction ratios from both output ports were greater than 18 dB over a 100 nm wavelength range (see

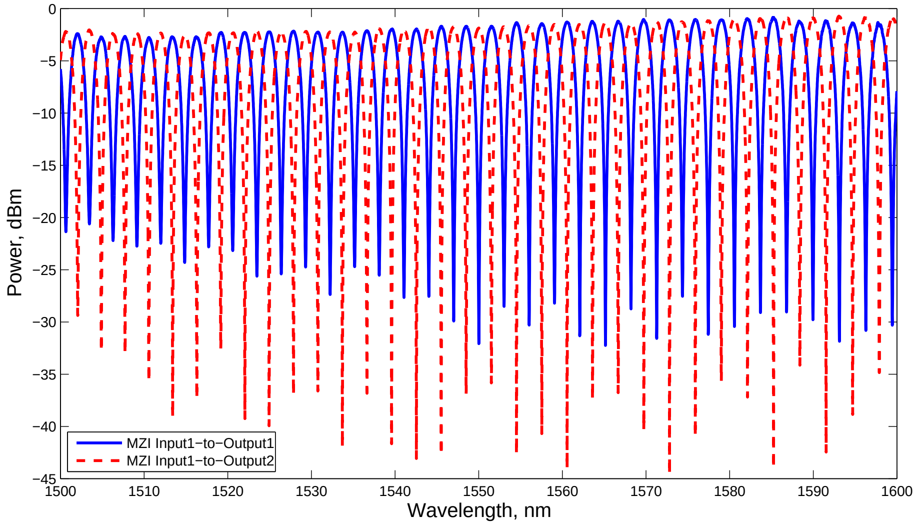


Figure 6. Measured MZI spectral responses after calibrating out the insertion loss from the grating couplers.

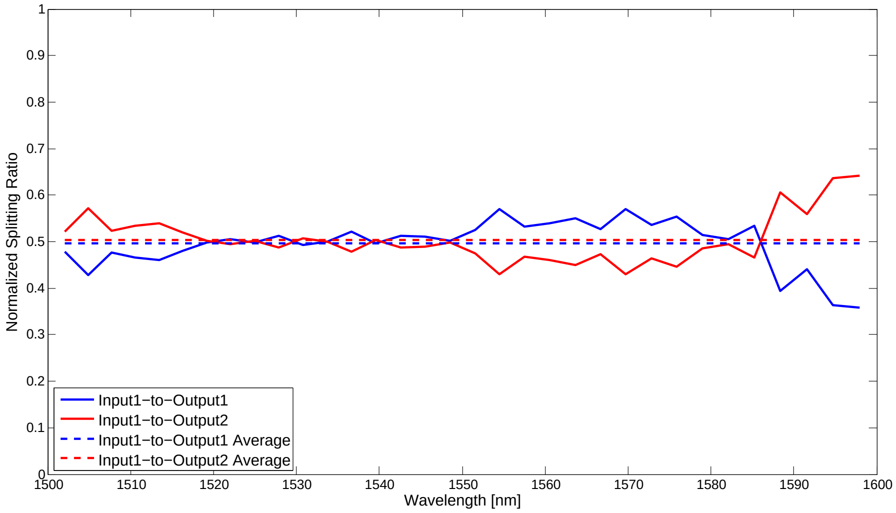


Figure 7. Calculated normalized power splitting ratio of the adiabatic 3-dB coupler and showing the average normalized power splitting ratio.

Fig. 6). The Input1-to-Output2 MZI responses, which were obtained between the 600-nm-wide rib waveguide of the input coupler and the 600-nm-wide rib waveguide of the output coupler, are given by the red line in Fig. 6 and show that a minimum ER of 27.2 dB was achieved over the 100 nm wavelength range, whereas a minimum ER of 33.4 dB was obtained over the wavelength range from 1520 nm to 1600 nm which covers the entire C-band and a portion of the L-band. A maximum ER of 42.5 dB was achieved at $\lambda_o = 1572.8$ nm. The measured spectrum also shows that the excess loss of the MZI is less than 2 dB, which indicates that the excess loss from each 3-dB coupler is less than 1 dB over the 100 nm wavelength range. The normalized splitting ratios of the device, which were extracted from the extinction ratios of the measured MZI response, are shown in Fig. 7. The average normalized splitting ratio, for the 100 nm wavelength range, was 50.4%/49.6%.

4. CONCLUSION

A 2×2 broadband adiabatic 3-dB coupler was fabricated using SOI rib waveguides. We experimentally demonstrated the performance of the coupler by integrating two couplers into an unbalanced MZI. Measurement results showed an ER of >18 dB over a 100 nm wavelength range at both output ports, whereas an ER of >33.4 dB was obtained over an 80 nm wavelength range for one of the output ports with a maximum ER of 42.5 dB from that port at $\lambda_o = 1572.8$ nm. The average normalized power splitting ratio, for the 100 wavelength range, was 50.4%/49.6%. This 2×2 adiabatic 3-dB coupler geometry can be used as a 50/50 power splitter and has the potential to be used in active 2×2 switches, MZI electro-optic modulators, etc.

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