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Compact 2×2 Multi-Mode Interference Couplers with Uneven Splitting-Ratios Based on Silicon Nanowires *

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Two types of uneven splitting-ratio 2×2 multi-mode interference (MMI) couplers based on silicon nanowires are designed, fabricated and characterized. The splitting ratios are 85:15 and 72:28, respectively. The devices have compact sizes and low excess losses. The footprints of the rectangular MMI region are only about 3 μm×18 μm and 3 μm×14 μm, and the minimum excess losses (ELs) are 1.30 dB and 0.82 dB. The measured splitting-ratios are consistent with the designed values. Based on their performance, these 2×2 MMI couplers are suitable candidates for the coupling section of microring resonators where a large resonance bandwidth is required for high speed signal processing. The uneven splitting capability also provides a convenient way to further optimize the Q factor and the bandwidth of the resonator.

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As the building blocks in applications of photonic integration circuits (PICs), microring resonators have been widely investigated.[1−5] They have been applied in add-drop filters[6] for wavelength division multiplexing (WDM), nonlinear optics, optical delay lines[7] and optical sensing.[8] High Q factors are usually indispensable in these applications. In order to achieve high Q factors, only very weak coupling between the ring cavity and the access bus waveguide is required. However, a high Q factor is undesirable for high speed signal processing since it would limit the bandwidth of the system. When ring resonators are used for the processing of data signals, their bandwidth must be wide enough so that all the signals can be transmitted through the ring with negligible distortion.

In general, directional couplers are used as the coupling section in the ring resonators. To achieve a broader bandwidth, one of the effective methods is to increase the coupling ratio between the ring cavity and the access bus waveguide. A narrow gap is favorable for a high coupling ratio. However, it is difficult to make a narrow gap less than 100 nm with precise gap control. Recent studies have shown that a non-adiabatic mode transition between the ring and the coupler sections would cause large excess mode conversion losses.[7] Besides directional couplers, 2×2 MMI couplers could also be used in microring resonators for signal coupling. Based on silicon nanowire technology, the footprint of MMI devices could be as small as 3 μm × 9 μm.[9] Their compact sizes make them more favorable for signal coupling in microring resonators to achieve ultra compact PICs. Compared with a directional coupler with a very narrow gap, using a 2 × 2 MMI coupler as the coupling section in a microring resonator has many advantages, as follows. First, the 2 × 2 MMI coupler has relaxed fabrication tolerance. The tiny deviations in the size would only cause small influences on the characterizations of the microring resonators, while for a directional coupler with a narrow gap, only a few nanometer deviations may result in tens of nanometer of resonant peak offset. Second, the 2 × 2 MMI couplers are more suitable for high efficiency coupling applications because MMI couplers can easily realize a 50:50 coupling ratio with relatively small footprint. The last advantage is that the 2 × 2 MMI coupler is insensitive to polarization and the wavelength of the lights transmits in the resonator. According to its excellent performance, the 2 × 2 MMI coupler is a more suitable candidate for microring resonator applications where a large resonance bandwidth is required for high speed signal processing.

For MMI based microring resonators, the Q factor and the bandwidth can be further adjusted by varying the splitting-ratios of the MMI. In this letter, two types of uneven splitting-ratio 2 × 2 MMI couplers based on silicon nanowires are designed and fabricated. The splitting ratios are 85:15 and 72:28, respectively, with footprints of 3 μm × 18 μm and 3 μm × 14 μm. The minima of the ELs are measured to be 1.30 dB and 0.82 dB. Compared with the reported SOI based MMI coupler,[10,11] the MMI coupler reported here has a more compact size and lower excess loss. Furthermore, The uneven splitting capabil-

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ity also provides a convenient way to further optimize the Q factor and the bandwidth of the resonator.

The operation of an MMI device is based on the so-called self-imaging principle. An analytical theory giving the positions, amplitudes and phases of the self-images in $N \times N$ MMI couplers have been reported.[12] N self-images of equal intensities $1/N$ are formed at the output of the MMI couplers of length L,

$$L = \frac{3M}{N} L_c, \tag{1}$$

where $L_c = 4n_r W_{eq}^2/(3\lambda)$ is the coupling length between the two lowest order modes, M and N are any positive integers without common divisor, n_r is the effective index of the MMI region and W_{eq} is the equivalent MMI width. With strongly guided eigenmodes in the MMI section, W_{eq} can be substituted by the MMI width W.

In order to obtain a compact size, $M = 1$ is required for short MMI couplers. An additional free parameter a limited to $0 \le a \le W/N$ has been defined to describe the position of input and output ports. However, if free parameter a approaches one of its limits ($a = 0$ or $a = W/N$), previously separated self-images overlap and cause interference. Thus, an overlapping image MMI coupler is formed. Because previously separated images merge in pairs, a reduced number of images can be obtained. Figure 1 shows the overlapping-image MMI coupler with reduced $N-1$ possible access waveguides. Overlapping-image MMI couplers produce non-uniform power distributions.

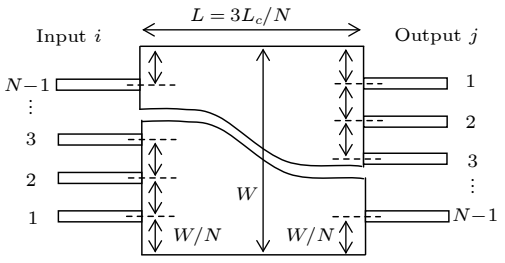


Fig. 1. Overlapping-image MMI coupler with $N-1$ possible access waveguides.

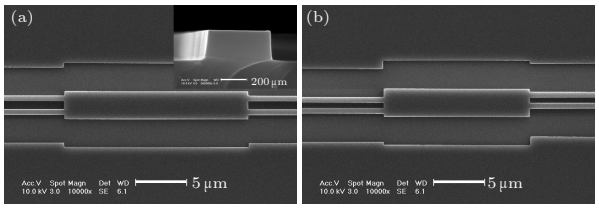


Fig. 2. The SEM image of the 2×2 MMI couplers with 85:15 (a) and 72:28 (b) splitting-ratios. The inset in (a) is the cross section of the silicon photonics nanowire.

All the intensities and phases of the overlapping-images can be obtained by calculation based on the self-imaging principle. For $N \le 12$, all possible input and output positions in overlapping-image MMI couplers have been listed in Ref. [12]. Among all the overlapping-image MMI couplers, we are mostly concerned with the 2×2 MMI couplers because they are the only candidates that can be used in microring resonators. There are four possible splitting ratios (100:0, 85:15, 72:28, 50:50) for the 2×2 overlapping-image MMI couplers. Since the splitting ratio of 50:50 has been widely investigated and the splitting ratio of 100:0 is not suitable for applications in microrings, we have focused on the 2×2 MMI coupler with splitting ratios of 85:15 and 72:28. The input and output positions and length of the MMI are given in Table 1.

Table 1. Overlapping-image MMI couplers with nonuniform splitting ratios 85:15 and 72:28, length L, input position x^{in} and output position x^{out}.

Ratio	$L = 3L_c/N$	$x^{\text{in}} = iW/N$	$x^{\text{out}} = jW/N$
85:15	$3L_c/4$	$i = 1, 3$	$j = 1, 3$
72:28	$3L_c/5$	$i = 2, 4$	$j = 1, 3$

All the MMI couplers are based on an SOI wafer with a silicon core thickness of 0.26 μm and a buried oxide (BOX) of 1 μm. Thus the height of waveguides is chosen to be 0.26 μm. As mentioned above, the length of MMI regions is in direct proportion to W^2. When the width of the MMI is reduced, the length of a rectangular MMI region L can be greatly decreased. Thus, the miniaturization of the MMI devices can be realized. On the other hand, W cannot be reduced too much because the multimode waveguide must be designed to support a large number of transverse modes (typically >3).[13] Although the device may be more compact, the narrow gap between the input and output waveguides may cause signal crosstalk and even make the fabrication difficult. We have certified that the MMI is not only compact in size but also supports enough transverse modes when the width is chosen to be 3 μm.[9] The footprint enables the MMI to act as the coupler region of the microring resonators with a radius of only 10 μm. The effective index n_r of the MMI waveguide can be calculated to be 2.968. We assume that the MMI works at $\lambda = 1.55$ μm. When we substitute all the factors into Eq. (1), the length of the MMI couplers L can be calculated, e.g. $L_1 = 17.3$ μm (for 85:15), $L_2 = 13.8$ μm (for 72:28).

For applications of compact microring resonators, there are three prerequisites to the 2×2 MMI couplers. First, to achieve an ultra compact microring resonator, the size of the MMI coupler must be small enough to match the footprint of the microring. Secondly, the excess loss of the coupling section should be as low as possible, because the optical coupling between the resonator and the bus waveguide may occur with many cycles when the lightwave resonance appears in the ring. Finally, since the splitting ratio affects the Q factor and bandwidth of the resonator, it is significant to obtain the desired splitting ratio.

Two types of MMI coupler with different splitting-ratios were fabricated based on silicon nanowire technology in this work, which is compatible with CMOS technology. The SEM image of the 2×2 MMI couplers with 85:15 and 72:28 splitting-ratios are shown in Fig. 2. The adoption of silicon nanowires with a width of 500 nm in connection with the input and output ports of the MMI have greatly reduced the footprint of the MMI couplers. The footprints of the rectangular MMI region are only about 3 μm × 18 μm and 3 μm × 14 μm, respectively. The inlet in Fig. 2(a) is the cross section of the silicon photonics nanowire. The cross section is nearly a rectangle of 0.5μm × 0.26μm, which is satisfied under the mono-mode transmission condition. The waveguide has smooth and nearly vertical sidewalls. The bottom angle of the sidewall is measured to be 87°.

The light coupling between the nanowire and the fiber passes through the grating couplers, which are integrated at both ends of each silicon nanowire with a connecting taper that matches the size difference between the nanowire and the grating coupler. The devices are characterized through a vertical coupling configuration, as shown in Fig. 3. The light is fed into/out of the input/output fiber, which is mounted just above the grating couplers at an angle of 10° with respect to the normal plane. The input fiber is connected to a tunable laser and the output fiber is connected to a detector to measure the transmitted power and the total loss of the MMI coupler. In order to estimate the excess loss of the MMI coupler, a reference nanowire waveguide similar to the MMI coupler but without the MMI section is also fabricated on the same chip, so that the excess loss of the MMI coupler could be obtained by subtracting the loss of the reference waveguide from the total loss.

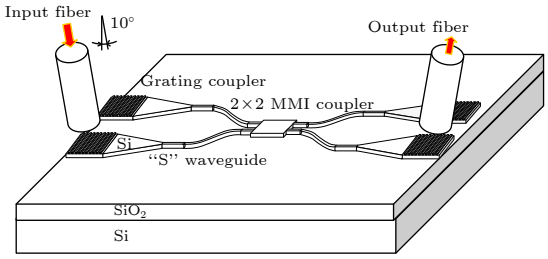


Fig. 3. A schematic diagram of the vertical coupling configuration.

Figure 4 shows the measured excess losses and splitting ratios of the 2×2 MMI couplers with designed splitting-ratios of 85:15 and 72:28 in the wavelength range of 1550–1560 nm. They are all calibrated with a reference nanowire waveguide nearby. In Fig. 4(a), the average excess loss of the 2 × 2 MMI coupler with splitting ratios of 85:15 is 1.62 dB. The minimum excess loss is 1.30 dB at the wavelength of 1555.6 nm. For convenience of analysis, here the splitting ratio is defined as the percentage of the optical power from the main output port to the total input light power. The splitting ratio varies in the range from 81.5% to 87.6% at different wavelengths, and the average splitting ratio is 83.6%. In Fig. 4(b), the average excess loss of the 2 × 2 MMI coupler with the designed splitting ratio of 72:28 is measured to be 1.34 dB. The minimum excess loss is 0.82 dB at a wavelength of 1548.6 nm. The splitting ratio varies from 67.8% to 75.2% with an average value of 70.5%. All the measured values are consistent with the designed values, and the slight differences might come from the process variations and the measurement errors.

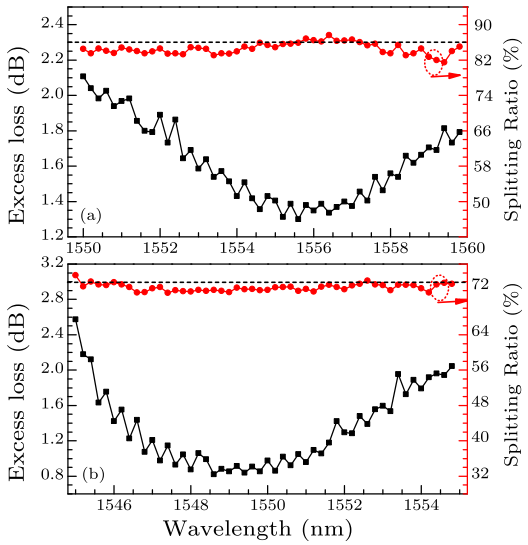


Fig. 4. The measured excess losses and splitting ratios of the 2 × 2 MMI couplers with splitting-ratios of (a) 85:15 and (b) 72:28.

In summary, two uneven splitting-ratio MMI couplers based on silicon photonic nanowires are designed, fabricated and characterized. The footprints of the rectangular MMI section are only about 3 μm × 18 μm and 3 μm × 14 μm, respectively, with the minimum excess losses of 1.30 dB and 0.82 dB. The splitting ratios show slight uniformities in the entire measuring spectrum. The deviations of the splitting ratios are less than 5%. The properties of compact size, low excess loss and precise control of the splitting ratios make the 2 × 2 MMI couplers preferable for use in microring resonators for high speed signal processing. Strict controls over fabrication processes may further improve the performance and are favorable for applications of ultra-compact PICs.

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