Silicon-on-Insulator All-Pass Microring Resonators Using a Polarization Rotating Coupling Section

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***Abstract*— We propose a novel microring resonator concept that uses a polarization rotating asymmetrical directional coupler. The quasi-transverse electric polarized mode in the bus waveguide is used to excite the quasi-transverse magnetic (TM) polarized mode in the microring. This enables the realization of microrings with a high quality factor due to the lower scattering loss of the quasi-TM polarized mode. We demonstrate the operation principle with two all-pass microrings with radius 30 μm, working in the critically coupled regime with a quality factor of 31 000 and in the under-coupled regime with a quality factor of 125 000.**

***Index Terms*— Microring resonators, polarization rotator, silicon-on-insulator (SOI).**

I. Introduction

MICRORING resonators are considered to become key components in integrated photonic circuits, especially for high-index-contrast platforms such as Silicon-on-Insulator (SOI). Due to the high-index contrast, one can achieve a very high density of resonators on a chip with a vast amount of functionalities and steadily increasing performance [1]. Silicon photonic wires have a large waveguide birefringence which causes polarization-dependent behaviour. Since fiber communication applications require polarization-independent behaviour, one typically chooses for a polarization-diversity scheme either based on polarization rotators [2] or polarization splitting grating couplers [3]. The quasi-TE polarized mode is typically the preferred mode of operation due to its high confinement and small bending loss. However, for some applications one prefers the less confined quasi-TM polarized mode because of its smaller scattering loss and lower back-reflections when propagating in a 220 nm high SOI waveguide [4]. This can be explained by the fact that the quasi-TM polarized mode has a smaller overlap with the sidewall roughness on the vertical edges of the waveguide, created during the dry etch process. TM-based microring resonators have been shown to have a higher quality factor compared to TE-based resonators. They do not show resonance splitting and have lower back-reflections in the input port, especially in the under-coupled regime where back-scattering can add up coherently resulting in a bad uniformity and an unpredictable behavior [5]. Therefore, we aim to combine the advantages of both polarizations: use quasi-TE polarized light for compact guiding of the light towards the microring and quasi-TM polarized light in the microring to take advantage of the lower propagation loss and back-scattering for e.g. large and accurate sensor arrays or ultra-dense wavelength-division multiplexing (WDM) filters. To make this polarization change possible one could use a separate polarization rotator in front of a microring resonator. However, this usually requires complicated fabrication steps and increases the footprint of the device. An elegant and simple solution for a polarization rotator is using an asymmetrical directional coupler similar as the one presented in [2] and [6], which is based on the existence of hybrid supermodes [7]. In this letter we go one step further and use this polarization rotating directional coupler in the coupling section of the microring resonator to excite the fundamental quasi-TM mode in the ring. The design rules on how a small transition loss and thus a microring with a high quality (Q) factor can be achieved are explained. Experimental verification of the concept is provided.

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II. Theory

To achieve a high Q-factor microring resonator using TM-polarized light, two conditions need to be fulfilled. The first condition is achieving efficient coupling from the fundamental quasi-TE mode (TE_{11}) in the bus waveguide to the fundamental quasi-TM mode (TM_{11}) in the ring waveguide and avoiding coupling to other modes. The second condition is that there should be a low loss of the excited TM_{11} mode of the ring waveguide at the coupler. In order to analyze the polarization conversion in a microring resonator, an all-pass microring resonator (radius = 30 μm) with an asymmetrical directional coupler such as presented in Fig. 1 is used. There are two required levels of asymmetry in this directional coupler: 1) a different waveguide width for the bus and the ring and 2) an asymmetrical cladding. In such a vertically asymmetrical waveguide the second and the third eigenmode are hybrid [7] and are anti-crossing around 0.65 μm (Fig. 2a). By narrowing the bus waveguide, the TE_{11} bus mode is almost phase matched with both hybrid modes and thus coupling is expected. This behaviour is visible in Fig. 2b, where the supermodes of the asymmetrical directional coupler are shown (gap = 100 nm). Since the mode overlap between two quasi-phase matched modes with the same polarization

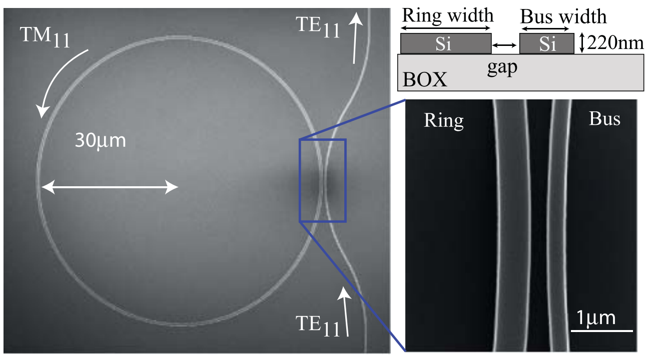

Fig. 1. All-pass microring resonator on SOI using a polarization rotating asymmetrical directional coupler. The fundamental quasi-TE mode in the bus is used to excite the fundamental quasi-TM mode using hybrid coupling.

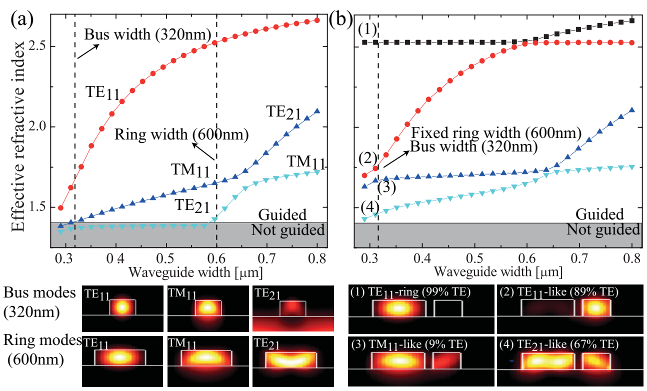

Fig. 2. Effective refractive index (n_{eff}) of (a) eigenmodes of an isolated silicon wire as a function of waveguide width and (b) supermodes of two coupled asymmetrical silicon wires with gap 100 nm as a function of the bus width and fixed ring width (600 nm). The waveguide height is 220 nm and operation wavelength is 1550 nm. The intensity mode profiles are plotted for both configurations with bus width 320 nm and ring width 600 nm.

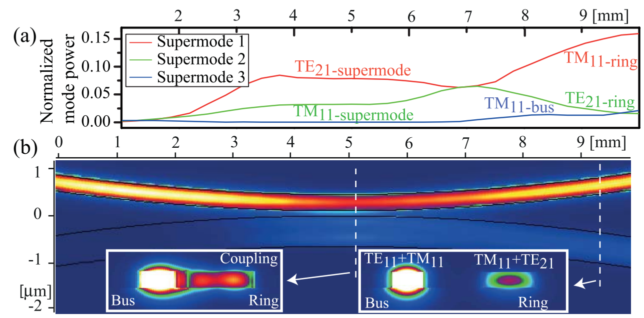

Fig. 3. (a) Supermode evolution and (b) intensity plot of the fields in an asymmetrical directional coupler for a bus and ring waveguide width of, respectively, 0.32 and 0.6 μm (100 nm gap and 30 μm radius). The TE_{11} bus mode is excited.

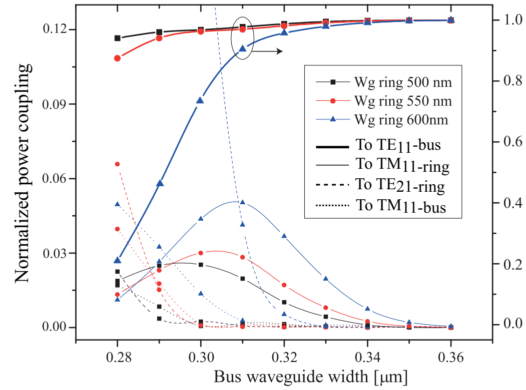

Fig. 4. Power coupling from the TE_{11} bus mode toward the TM_{11} and TE_{21} ring mode, and the TM_{11} and the TE_{11} bus mode as a function of varying bus width (300 nm gap and 30 μm radius). Legend: the color and symbol of the curves explain the ring waveguide (wg) width and the line type explains to which mode the coupling occurs.

is larger than when they are of opposite polarization, the coupling from the TE_{11} bus mode to the TE_{21}-like supermode is stronger than the coupling to the TM_{11}-like supermode. As the excited TE_{21}-like supermode travels further in the directional coupler and the gap becomes larger, it couples due to its hybrid nature rapidly to the fundamental TM_{11} ring mode and only a small part evolves to the leaky TE_{21} ring mode. The initially less excited TM_{11}-like supermode evolves to the TM_{11} ring mode and slightly to the TM_{11} bus mode. The supermode evolution of this non-adiabatic supermode taper is shown in Fig. 3a and the corresponding field intensity is plotted in Fig. 3b, calculated using a rigorous fully-vectorial eigenmode expansion and propagation tool FIMMPROP (Photon Design).

To exploit this polarization rotating behaviour, the power coupling to the different modes for different combinations of bus and ring waveguide widths is simulated for a 300 nm gap, shown in Fig. 4, where the power coupling from the TE_{11} bus mode to the TM_{11} and TE_{21} ring mode and the TM_{11} and TE_{11} bus mode is shown. Note that for each combination the power coupling to the TE_{11} ring mode is negligible due to a huge phase mismatch. From this figure, one can draw two intermediate conclusions for efficient polarization conversion. First, one can see that for each width of the ring waveguide maximum power coupling to the TM_{11} ring mode is achieved for another bus waveguide width which confirms the corresponding phase matching condition extracted from the eigenmodes of an isolated waveguide (Fig. 2). Although the maximum power coupling occurs for a ring width of 0.6 μm, this configuration also leads to the strong excitation of the leaky TE_{21} ring mode and the leaky TM_{11} bus mode. This can be prevented by selecting a wider bus waveguide width ($\geq$0.32 μm) or a narrower ring waveguide width ($\leq$0.6 μm).

The second condition to obtain a high Q-factor microring resonator is a low transition loss when the resonating TM_{11} ring mode passes the directional coupler. Besides the expected (reciprocal) coupling from the TM_{11} ring mode to the TE_{11} bus mode, there is also coupling to the TM_{11} bus mode and to the TE_{21} ring mode which results in a transition loss. This is visualized in Fig. 5a, where the power coupling to all these modes is plotted for an input TM_{11} ring mode with a bus waveguide width of 320 nm, 300 nm gap and a varying ring waveguide width between 0.5 μm and 0.6 μm. From this figure one can deduce that the coupling towards the TM_{11} bus mode becomes smaller using a wider ring waveguide, because of a higher phase mismatch with the 0.32 μm wide bus. On the other hand the coupling towards the TE_{21} ring mode becomes larger when using a wider ring waveguide because of larger hybrid coupling as explained in Fig. 2. The total transition loss, defined as all the power that goes to another mode than

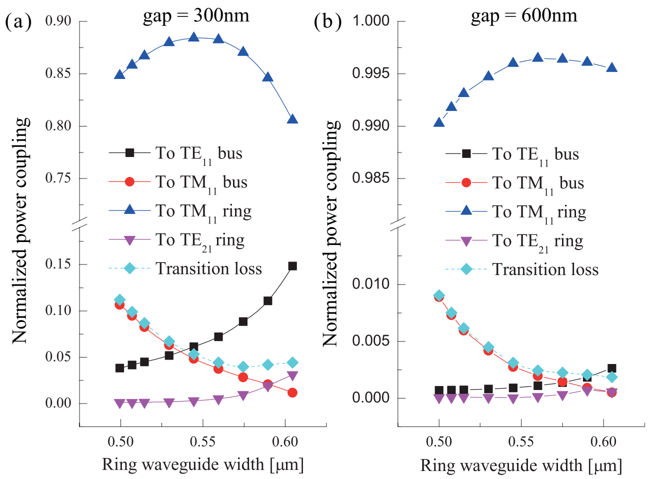

Fig. 5. Power coupling in an asymmetric directional coupler from the TM_{11} ring mode (320 nm bus width and 30 μm radius) for (a) gap 300 nm and (b) gap 600 nm. For (a) minimum transition loss occurs at a ring waveguide width of 0.575 μm, which is a tradeoff between the loss induced by phase mismatched coupling toward the TM_{11} bus mode and the losses due to hybrid coupling toward the TE_{21} ring mode.

the TE_{11} bus mode and the TM_{11} ring mode, is plotted in Fig. 5 as well, resulting in one optimum ring waveguide width around 0.575 μm for this configuration. For this width and gap the transition loss is 4.1% which can be converted to a distributed loss of 9.6 dB/cm in a ring with 30 μm radius. Together with the waveguide propagation loss of 1.95 dB/cm [5], this microring resonator will have an intrinsic Q-factor of around 54300 or a critically coupled Q-factor of 27000. As it is clear from Fig. 5a, the transition losses are relatively insensitive to a deviation in the ring width. The transition loss depends on the exact coupling from the bus to ring waveguide and can be improved by using a more adiabatic coupling section, e.g. a larger radius or a larger gap such as in Fig. 5b where the transition loss is only 0.21% for a gap of 600 nm.

III. Experiments

Ring resonators were fabricated in a complementary metal oxide semiconductor (CMOS) pilot line on an SOI platform using a 220 nm thick Si waveguide layer on top of a 2 μm buried oxide layer (BOX). The vertical asymmetry to create the hybrid coupling of the TM_{11} and TE_{21} mode is achieved using an air top-cladding. Both bus and ring waveguides were defined by a deep etch of 220 nm. To facilitate the characterization of the device, grating couplers were added to the design using a 70 nm shallow etch step. These grating couplers are highly polarization dependent, with an extinction ratio of 50dB and ensure only TE-polarized light is coupled in and out the microring. Light is guided with single-mode waveguides (width = 0.45 μm) and tapered down to a width of 0.32 μm at the coupler of the all-pass microring resonator (radius of 30 μm). Using scanning electron microscope, the width of the ring waveguide is measured to be 0.56 μm, which is slightly off the ideal waveguide width. A wavelength scan with 1 pm resolution is used to characterize the resonances between 1520 nm and 1540 nm. The measured free spectral range (FSR) is 3.45 nm and corresponds to the resonating

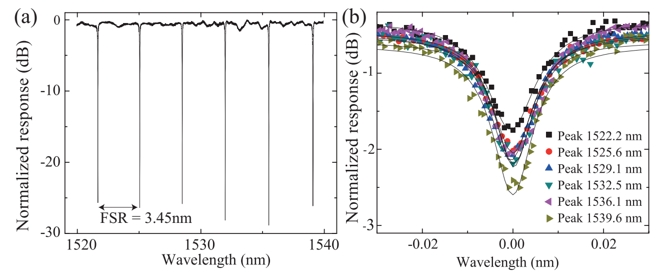

Fig. 6. TM_{11} resonating all-pass microring (a) in the critically coupled regime with 300 nm gap (mean extinction ratio of −27 dB and a mean Q-factor of 31 000) and (b) under coupled regime with 600 nm gap (mean Q-factor of 125 000 and a finesse of 335).

TM_{11} mode which has a lower group index ($n_g = 3.58$) than the TE_{11} mode ($n_g = 4.1$). Since all the resonances are very similar, their performance is reported as a mean value of the measured resonances. A critically coupled all-pass ring resonator with a mean extinction ratio of -26.8 ± 1.2 dB, a mean Q-factor of 30858 ± 1836 and a mean finesse of 83 ± 5 is achieved using a 300 nm gap, which is plotted in Fig. 6a. This agrees well with the simulations. When the gap is increased to 600 nm, the under coupled resonance shows a mean extinction ratio of -2.1 ± 0.2 dB, a mean Q-factor of 124988 ± 9698 and a finesse of 335 ± 25.2 over the measured wavelength scan. This shows that the resonating mode has a lower effective propagation loss corresponding to a 1.32% power transition loss as defined earlier (assumption of 1.95 dB/cm propagation loss). In Fig. 6b, an overlap of the resonances are plotted demonstrating the good uniformity.

IV. Conclusion

A novel class of microring resonators is proposed which makes use of a polarization rotating asymmetrical directional coupling section. A critically coupled all-pass filter showing good performance was demonstrated. This microring resonator is expected to also be useful for a whole class of compact and high Q-factor applications, e.g. in large and accurate sensor arrays or ultra-dense WDM filters.

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