

Mode/Polarization Manipulation in Silicon Photonics

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Abstract. Mode-division-multiplexing and polarization-division-multiplexing are becoming very important to enhance the capacity of single-wavelength carrier. One of the keys is the realization of efficient mode/polarization manipulation. Silicon photonics provides an excellent platform to achieve high-performance on-chip mode/polarization manipulation. This paper gives a review for our recent work on the high-performance silicon photonic devices for mode/polarization manipulation.

1. Introduction

The demand for data increases exponentially and further enhancement of the information capacity is a perennial goal from the access to data-centre interconnects and to long-haul transmissions [1]-[2]. One of the most cost-effective solution is utilizing some advanced multiplexing technologies. A straightforward way is using wavelength-division-multiplexing (WDM) technology, which has been developed very successfully for long-haul optical communication network. As it is well known, the cost for WDM systems is usually very high and the wavelength management is pretty complicated. Therefore, it is very desired to improve the capacity of a single-wavelength carrier. The polarization-division-multiplexing (PDM) utilizing dual polarizations and the mode-division-multiplexing (MDM) utilizing multiple guided-modes are become the most popular technologies [2]. In order to enable the MDM and PDM technologies, one of the keys is the realization of efficient mode/polarization manipulation. Silicon photonics provides an excellent platform to achieve high-performance on-chip mode/polarization manipulation. This paper gives a review for our recent work on the high-performance silicon photonic devices for mode/polarization manipulation.

The devices for on-chip polarization manipulation include polarizers, polarization beam splitters (PBSs), and polarization rotators (PRs). For an SOI (silicon-on-insulator) nanowire, which has an ultra-high birefringence, it possible to realize on-chip polarization-manipulation devices with ultra-compact footprints [3]-[4]. However, one should note that it is still a challenge to realize ultra-compact on-chip polarization-manipulation devices with excellent performances, e.g., low excess loss and high extinction ratio in a broad wavelength-band. In this paper, we give a review on the recent work of high-performance silicon-based on-chip polarization-manipulation devices.

The devices for on-chip mode manipulation include mode-division-multiplexers and mode converters, which work as the key component for the combination/separation/conversion of different mode-channels. Great progresses has been made on the development of on-chip mode (de)multiplexers by using multimode interferometers, adiabatic mode-evolution couplers, asymmetric Y-junctions, and asymmetric directional couplers. In this paper, we give a review recent progresses of multi-channel mode-division-multiplexer. Recent results for hybrid (de)multiplexers enabling the MDM, PDM, and WDM simultaneously are also reviewed.

2. Silicon photonic devices for on-chip polarization-manipulation

As discussed before, an SOI nanowire has the birefringence as high as 10^{-1} [3]-[4], which makes it possible to realize on-chip polarization-manipulation devices with ultra-compact footprints [3]. Various devices have been proposed theoretically and demonstrated experimentally for on-chip polarization-manipulation [3]-[4].



However, one should realize that it is still a challenge to obtain high-performance on-chip polarization-manipulation devices with ultra-compact footprints. In the following part, a review is given on the recent work of high-performance silicon-based on-chip polarization-manipulation devices, including polarizers, PBSs and PRs.

(1). Polarizers.

Fig. 1(a) shows the ultra-compact TM-pass polarizer realized with a subwavelength grating (SWG) structure based on a SOI nanowire [5]. Here this SWG waveguide is designed to work as a Bragg reflector for TE polarization, in which way the incident TE-polarized light is reflected efficiently. On the other hand, as TM polarization mode has a much lower effective index than TE polarization, a Bloch mode is supported for TM polarization. Consequently, the incident TM-polarized light goes through the structure with a low excess loss. Fig. 1(b) shows the measurement and calculation results for the transmissions of the polarizers as the period number N for the grating varies. It can be seen that the measured excess loss for the fabricated polarizers is <1 dB and is not sensitive to the period number N . For TE polarization, the transmission decreases almost linearly (in dB) as the period number N increases. When choosing $N=40$, the measured extinction ratio is as high as 40dB, while the polarizer is as short as $\sim 18 \mu\text{m}$.

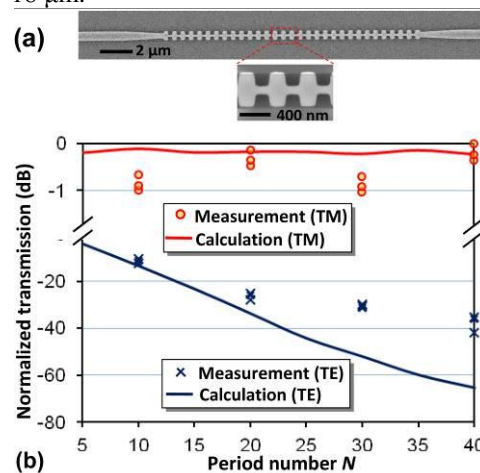


Fig. 1. (a) SEM pictures of a fabricated polarizer. (b) Measured transmissions of the SWG-based polarizers. [5]

(2). Polarization beam splitters (PBSs).

In the past years, the concept of using an ADC to realize ultra-broadband and ultra-short PBSs is becoming one of the most popular options [3], because of the design convenience and structural simplicity. An ADC can be formed by combining different types of optical waveguides. For example, when choosing a regular SOI nanowire as one of the coupling waveguides, one can introduce a special optical waveguide for the other waveguide in the coupling region, e.g., silicon HPWGs [9]-[10], silicon nano-slot waveguides [11]-[12], etc. It is also possible to form an ADC by choosing two or three non-identical waveguides, like a three-waveguide ADC [6], as well as a bent DC [7]-[8]. For a bent DC, one can make the TM-polarized light cross-coupled completely by choosing the waveguide widths and the length of the coupling region appropriately [7]-[8]. In contrast, for TE polarization, the cross-coupling is weak due to the intrinsic phase-mismatch.

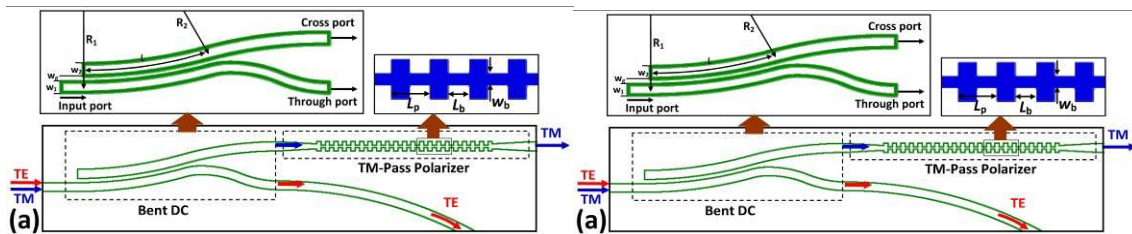


Fig. 2 A PBS consisting of a bent DC and a SWG polarizer. (a) Schematic configuration; (b) SEM pictures. [13]

One might note that the extinction ratio for those compact PBSs demonstrated previously is usually not high (e.g., <15 dB). It is still a challenge to achieve a broadband high-performance PBS with a compact footprint. In [13], a compact PBS consisting of a bent DC cascaded with a SWG TM-passed polarizer was realized for the first time, as shown in Fig. 2(a)-(b). For TE polarization, there exists some weak cross-coupling, which is filtered out with the SWG-based TM-pass polarizer cascaded at the cross port, as shown in Fig. 3(a)-(b). From the measurement results shown in Fig. 4(a)-(b), it can be seen that the extinction ratio for TE polarization is

improved to be >20dB within a 70nm wavelength band when choosing $N=20$. For TM polarization, the extinction ratio is >20dB over a 60nm band (very similar to that of a single bent DC).

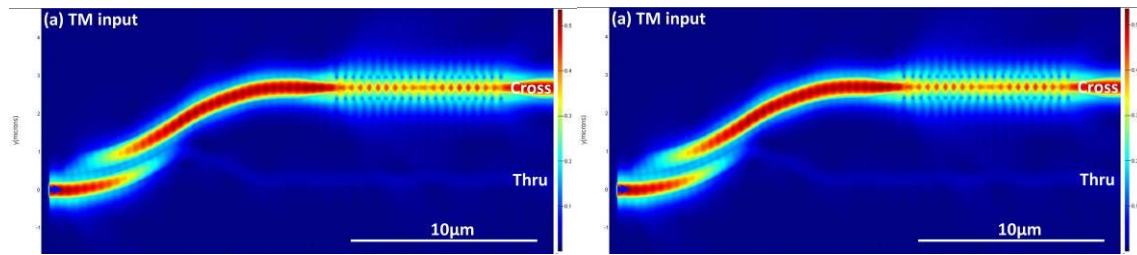


Fig. 3 Simulated light propagation in the designed PBS consisting of a bent DC and a SWG polarizer. (a) TM polarization; (b) TE polarization. [13]

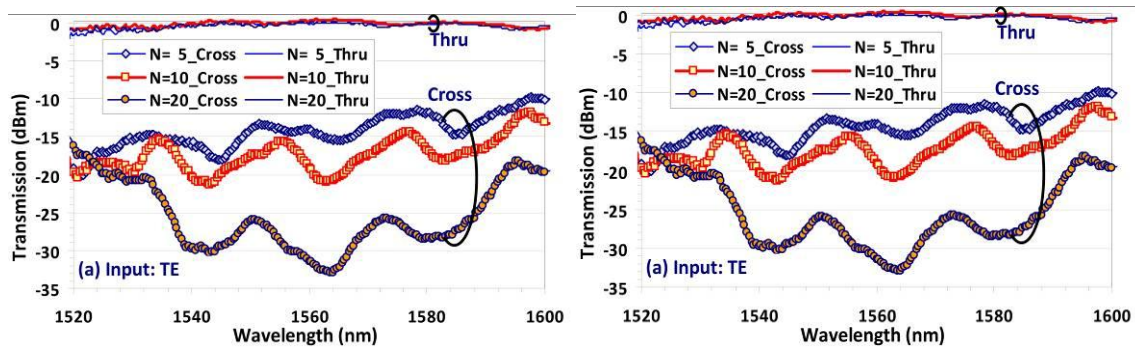


Fig. 4 Measured transmission at the cross- and through-ports for the PBS consisting of a SWG polarizer; (a) TE; (b) TM. Here the period number of the SWG structure is chosen as $N=5, 10$, and 20 . [13]

More recently we realized a near-perfect PBS by using a cascaded structure of bent DCs [14], which has a compact footprint as small as $\sim 6.9 \times 20 \mu\text{m}^2$, as shown in Fig. 5(a). Fig. 5(b) shows the measured transmissions at the through- and cross-ports when TE and TM polarization modes are launched at the input port, respectively. This PBS has a world-record bandwidth for a high ER and a low EL. For example, the measured bandwidths are as large as $\sim 126\text{nm}$, $\sim 97\text{nm}$ and $\sim 70\text{nm}$ for an ER of >20dB, >25dB and >30dB, respectively, while the measured ELs are <1dB and <0.5dB over a bandwidth of $\sim 137\text{nm}$ and $\sim 91\text{nm}$, respectively. Meanwhile, the PBS has a large fabrication tolerance ($\pm 20\text{nm}$) of the core-width variation. It can be seen that the present PBS has significant improvement compared to those best silicon-based PBSs reported previously, as shown in Table 1.

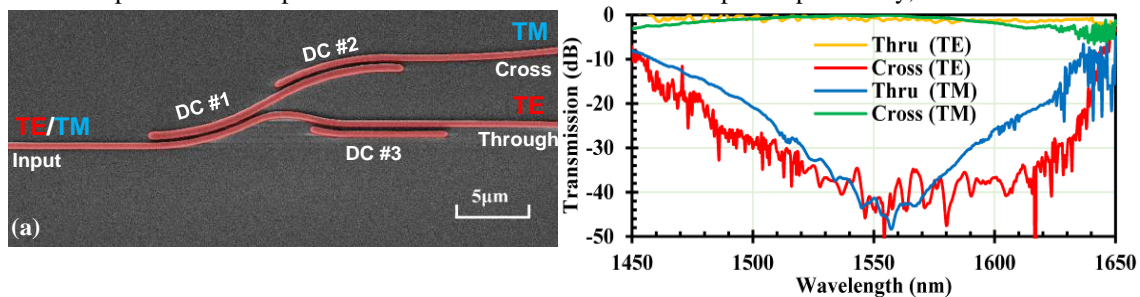


Fig. 5. (a) Structure of the present PBS; (b) measured transmission at the through- and cross-ports of the fabricated PBS.

Table 1 Comparison of demonstrated best-performed PBSs on silicon.

Structures	ER_{TE}/ER_{TM}	EL	$BW_{ER>20dB}$	$BW_{ER>25dB}$	$BW_{ER>30dB}$	Tolerance Δw	Length
Symmetric DC [16]	25/34 dB	0.5 dB	125 nm	NA	NA	NA	97.4 μm
Grating [17]	30/30 dB	1 dB	29 nm	25 nm	21 nm	$< \pm 10$ nm	27.5 μm
Bent DC [20]	26/33 dB	1 dB	60 nm	12 nm	NA	NA	22.5 μm
Bent DC [21]	33/36 dB	<1 dB	57 nm	32 nm	15 nm	± 20 nm	15 μm
This work	44/42 dB	0.35 dB	126 nm	97 nm	70 nm	± 20 nm	20 μm

*NA: Not available. * $BW_{ER>20dB}$, $BW_{ER>25dB}$ and $BW_{ER>30dB}$: Bandwidth for a >20dB, >25dB and >30dB ER.

(3). Polarization splitter-rotators (PSRs)

In 2011, a novel concept was proposed for realizing a PSR by using a simple structure consisting of an adiabatic taper and an ADC [15]. For this design, the fabrication is very simple and convenient because one-step etching is only required. An improved PSR with an MMI mode filter cascaded at the through port was proposed and demonstrated recently [22]. This MMI section is designed as a mode filter which is helpful to filter out the

residual power of the TE_1 mode originated from the launched TM_0 mode. The measured results have shown that the launched TE_0 mode outputs from the thru-port with a low transmission loss (~ 0.5 dB) and the extinction ratio is >20 dB in the band from 1520 nm to 1610 nm. For the TM_0 mode, light outputs from the cross port with a loss of ~ 1.5 dB in a broad band from 1520 nm to 1610 nm. For this PSR, the bandwidth for an extinction ratio of >20 dB is ~ 50 nm and the bandwidth for an extinction ratio of >15 dB is ~ 80 nm.

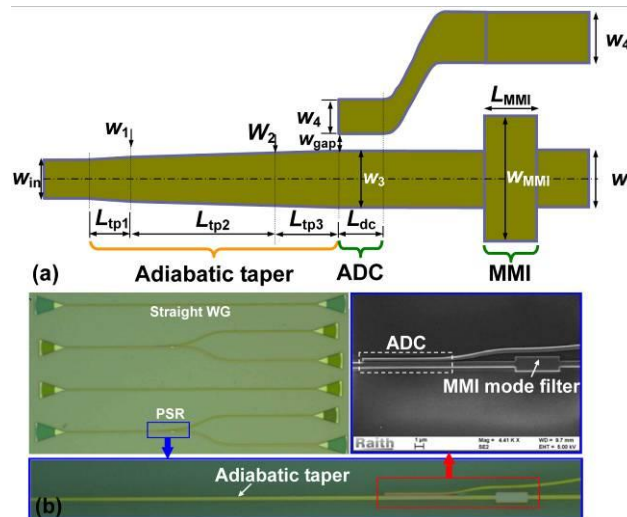


Fig. 6. An improved PSR with an MMI mode filter. (a) Schematic configuration; (b) Microscopy / SEM pictures. [22]

3. Silicon photonic devices for on-chip mode-manipulation

As the key component to combine/separate the signals carried by different mode-channels, various structures have been developed for realizing mode (de)multiplexers, including MMI couplers [24]-[25], adiabatic mode-evolution couplers [26], asymmetric Y-junctions [27]-[29], and ADCs [30]-[34]. In 2012, a $1 \times N$ mode-(de)multiplexer was proposed with cascaded ADCs, as shown in Fig. 7(a) [31]-[32]. The ADC is designed with an optimal width w_i for the i -th straight section according to the phase matching condition. Fig. 7(b) show the measured transmission responses for all output ports O_1 , O_2 , O_3 , and O_4 when light is input from port I_1 , I_2 , I_3 , and I_4 respectively. The (de)multiplexer shows low on-chip excess loss (<0.5 dB) and low crosstalk of <-20 dB in a wide wavelength-band. Because of this WDM-compatibility, it is possible to realize a kind of hybrid multiplexing technology for improving the capacity further. By using the ADC structure, it is also possible to realize a mode (de)multiplexer with dual polarizations [35]-[36].

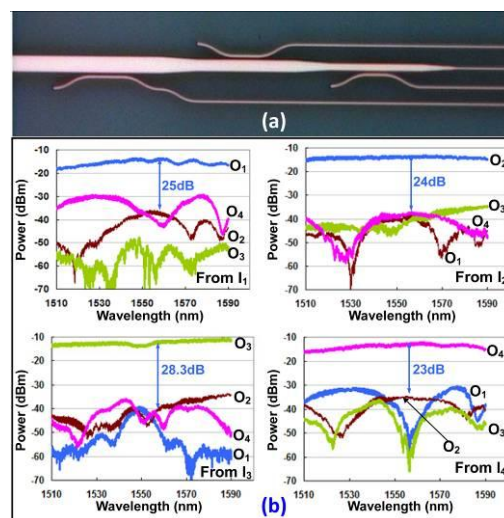


Fig. 7. (a) A four-channel mode demultiplexers based on ADCs' (b) Measured responses at output ports (O_1 , O_2 , O_3 , and O_4) when light is input from port $I_1 \sim I_4$, respectively. [32]

As demonstrated before, the mode (de)multiplexer based on cascaded ADCs works well in a broad wavelength-band. Thus it is promising to develop hybrid (de)multiplexer enabling MDM and WDM simultaneously by integrating an ADC mode (de)multiplexer [32] and wavelength-selective devices (e.g.,

AWGs). In [37], a hybrid multiplexer was realized with a four-channel mode demultiplexer and four identical AWG demultiplexers integrated on the same chip. A simplified hybrid MDM-WDM (de)multiplexer was then demonstrated by introducing bi-directional AWGs [38]. As shown in Fig. 8, the hybrid WDM-MDM multiplexer consists of a ADC-based mode demultiplexer with four channels and two bi-directional 17×17 AWG demultiplexers. It is expecting to develop high-performance hybrid WDM-MDM (de)multiplexer enabling more mode-/wavelength-channels in the near future.

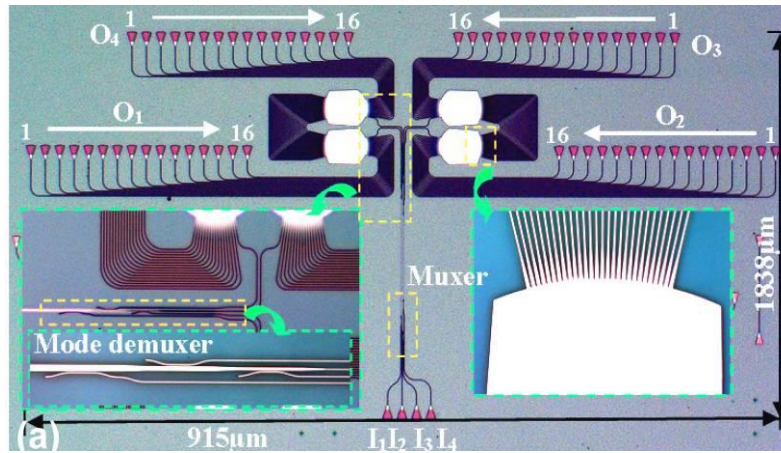


Fig. 8. A 64-channel hybrid MDM-WDM multiplexer with two bi-directional AWGs and a four-channel mode (de)multiplexer. [38]

4. Conclusion.

As a summary, we have given a brief review for the recent work on the high-performance silicon photonic devices for mode/polarization-manipulation, including PBSs, PRs, and mode converters/(de)multiplexers. It is expected to develop excellent hybrid (de)multiplexers enabling more than one (de)multiplexing technologies simultaneously, which is important for keeping the increase of the capacity of photonic networks in the future.

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