Silicon photonic devices for optical signal processing in wavelength, polarization and mode domains

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Abstract: We review recent progress on silicon photonic devices for optical signal processing, including nanobeam devices for wavelength filtering and switching, directional couplers for polarization/mode processing, and subwavelength grating devices for multi-dimensional processing.

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1. Introduction

Silicon photonic devices have attracted considerable attention due to the advantages of compact footprint, low power consumption, and compatibility with complementary metal-oxide-semiconductor (CMOS) process [1]. On-chip wavelength, polarization and mode multiplexing techniques can increase the data transmission capacity and reduce the cost. Various device structures such as Mach-Zehnder interferometer (MZI) [2], microring [3], photonic crystal cavity [4], and grating-assisted coupler [5], can be used to achieve on-chip wavelength filtering, multiplexing, and switching functions. Recently some impressive results have been reported. A GHz-bandwidth optical filter was implemented based on high-order silicon microrings [6]. A 512×512 silicon AWG was demonstrated with a channel spacing of 25 GHz [7]. Large port-count (≥16) switch fabrics with built-in monitors and automated wavelength alignment was reported [8]. In the polarization domain, polarization beam splitters (PBSs), polarization rotators (PRs) and polarization splitters and rotators (PSRs), are widely used in the polarization diversity scheme and optical coherent transceivers. Multimode interference (MMI) [9], directional coupler [10], and topological photonics [11] were used to realize on-chip polarization processing. A directional-coupler-based PBS was demonstrated with dimensions of 7 μm×16 μm and an extinction ratio of 15 dB [12]. To achieve higher extinction ratios, a silicon PBS employing cascaded bent directional couplers was demonstrated with extinction ratios of > 25 dB [13]. As a new dimension, mode or space has been explored to increase the data-carrying capacity. Various building blocks for on-chip mode processing have been demonstrated, including mode (de)multiplexer [14], high-order mode filter [15], two-mode power splitter [16], and multimode switch [17]. Recently, a dual-polarization 10-channel mode (de)multiplexer was proposed and realized with cascaded dual-core adiabatic tapers [18]. A thermo-optic tunable multimode switch was demonstrated based on microrings [19]. A high-speed two-mode switch was also reported based on MZI [20]. Due to the space limitation, the above brief review cannot cover all the state-of-the-art work in this topic, and readers should be aware of many other good demonstrations. In the following, we will review our recent progress on silicon photonic devices for wavelength, polarization and mode processing.

2. Photonic crystal nanobeam devices for wavelength processing

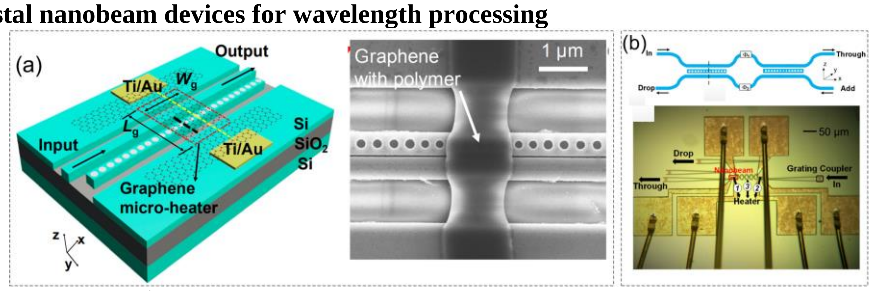

Fig. 1 (a) A silicon filter based on PhC nanobeam cavity [21]; (b) a 2 × 2 thermo-optic crossbar switch [22].

The photonic crystal (PhC) nanobeam cavity can be utilized to achieve wavelength processing. As shown in Fig. 1(a), a silicon bandpass filter based on a PhC nanobeam cavity was demonstrated with an energy-efficient grapheme micro-heater [21]. The thermo-optic tuning efficiency was 1.5 nm/mW. Furthermore, recently we experimentally demonstrated a 2×2 thermo-optic crossbar switch implemented by dual silicon PhC nanobeam cavities [22], as shown in Fig. 1(b). Attributed to the ultra-small mode volume of the nanobeam cavity, only ~0.16 mW power was needed to change the switching state.

3. Directional coupler devices for polarization and mode processing

Directional coupler can be employed to realize on-chip polarization and mode processing. As shown in Fig. 2(a), an ultra-compact silicon PBS was demonstrated based on a sharp bent directional coupler with a footprint of

1.5 μm×1.35 μm [23]. To the best of our knowledge, the PBS achieved the smallest footprint. Fig. 2(b) showes a highly-efficient PSR based on a bent directional coupler with a coupling length of 8.77 μm [24]. The TM-to-TE conversion loss was <1 dB. We also experimentally demonstrated an on-chip silicon 2×2 mode- and polarization-selective switch (MPSS) that can route four data channels on two modes and two polarizations simultaneously [25], as provided in Fig. 2(c). The proposed 2 × 2 MPSS chip consisted of 4 mode (de)multiplexers, 12 PBSs, 8 thermo-optic MZI switches, 8 1 ×2 multi-mode interferometer (MMI) couplers, and 40 waveguide crossings.

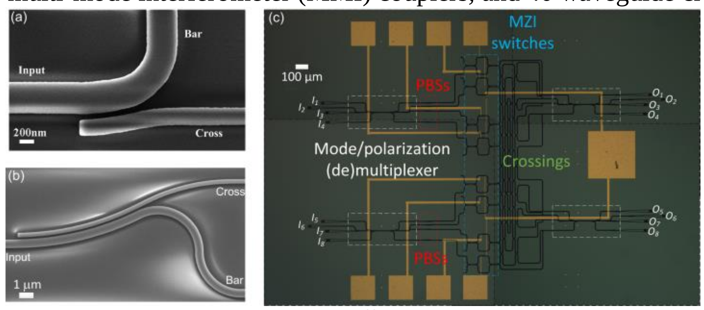

Fig. 2 (a) An ultra-compact silicon PBS [23]; (b) a highly-efficient silicon PSR [24]; (c) 2 ×2 MPSS chip [25].

4. Sub-wavelength grating devices for wavelength, polarization and mode processing

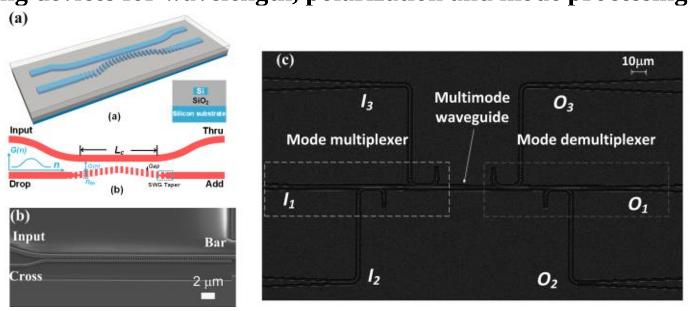

Fig. 3 (a) A SWG-based silicon filter [26]; (b) a high-extinction-ratio silicon PBS [27]; (c) SWG-based silicon three-mode (de)multiplexers [28].

Subwavelength grating (SWG) is a periodic structure functioning as a homogenous medium, which allows for flexible controlling of the effective refractive index (n_{eff}). This freedom in waveguide designs enables many possibilities in wavelength, polarization and mode processing. Fig. 3(a) showes a compact silicon bandpass filter with high sidelobe suppression ratio (>27 dB) employing an apodized SWG coupler [26]. A compact silicon PBS was experimentally demonstrated using grating-assisted contradirectional couplers (GACCs) [27], as shown in Fig. 3(b). Over 30-dB extinction ratios and less than 1-dB insertion losses were achieved for both polarizations. For mode processing, we experimentally demonstrated a silicon three-mode (de)multiplexer using SWG structure [28], as plotted in Fig. 3(c). The three channels showed < -16.3 dB crosstalk and <3.8 dB insertion losses.

5. Conclusion

Significant progress has been made recently towards the realization of silicon photonic devices for wavelength, polarization and mode processing. On-chip multi-dimension multiplexing and processing can further increase the capacity and introduce additional functionalities.

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