Wavelength and bandwidth-tunable silicon comb filter based on Sagnac loop mirrors with Mach-Zehnder interferometer couplers

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Abstract: We propose and experimentally demonstrate a wavelength and bandwidth-tunable comb filter based on silicon Sagnac loop mirrors (SLMs) with Mach-Zehnder interferometer (MZI) couplers. By thermally tuning the MZI couplers in common and differential modes, the phase shift and reflectivity of the SLMs can be changed, respectively, leading to tunable wavelength and bandwidth of the comb filter. The fabricated comb filter has 93 comb lines in the wavelength range from 1535 nm to 1565 nm spaced by ~0.322 nm. The central wavelength can be red-shifted by ~0.462 nm with a tuning efficiency of ~0.019 nm/mW. A continuously tunable bandwidth from 5.88 GHz to 24.89 GHz is also achieved with a differential heating power ranging from 0.00 mW to 0.53 mW.

OCIS codes: (130.3120) Integrated optics devices; (130.7408) Wavelength filtering devices; (230.5750) Resonators.

References and links

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1. Introduction

Optical comb filters, which perform data filtering and blocking of multi-wavelength channels, are key components in wavelength-division multiplexed (WDM) optical networks [1–6]. In practical applications, dynamic tuning of central wavelengths and bandwidths of comb filters is desired to meet the requirements of flexible WDM optical networks. Comb filters based on silicon photonics can offer competitive advantages including compact device footprint, complementary metal oxide semiconductor (CMOS) compatible fabrication, and low power consumption [7]. Various schemes have been proposed to realize on-chip comb filters based on Bragg gratings [2–4], microring resonators [5,6], and cascaded Sagnac loop mirrors (SLMs) [8]. However, the bandwidths of the above comb filters cannot be tuned without changing the central wavelength. In our previous work [9], we proposed and experimentally demonstrated a variable bandwidth comb filter based on cascaded SLMs with Mach-Zehnder interferometer (MZI) couplers. The variable bandwidth is achieved by thermally tuning one arm of the MZIs, but not in a differential mode [10], which changes the central wavelength. Thus, independent bandwidth and wavelength tuning cannot be realized.

In this paper, we experimentally demonstrate a wavelength and bandwidth independently tunable comb filter based on cascaded SLMs with MZI couplers. The directional couplers of the SLMs are replaced by MZI couplers. By controlling the MZI couplers in common and differential modes with micro-heaters, the phase shift and reflectivity of the SLMs can be changed, leading to tunable wavelength and bandwidth of the comb filter. By thermally tuning the device, the central wavelength can be red-shifted by ~0.462 nm with a tuning efficiency of ~0.019 nm/mW. The bandwidth can be tuned from 5.88 GHz to 24.89 GHz with a differential heating power ranging from 0.00 mW to 0.53 mW. These experimental demonstrations of wavelength and bandwidth tuning verify the feasibility of the proposed tunable comb filter.

2. Device structure and operation principle

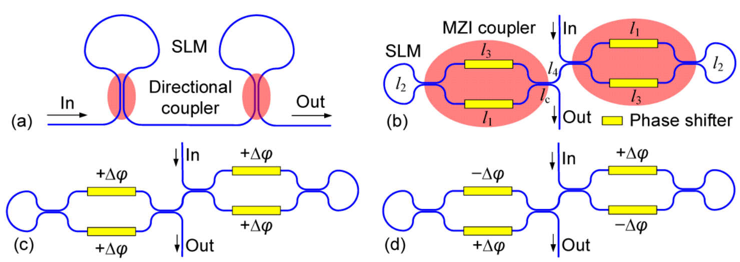

Fig. 1. (a) A FPI comb filter consists of two loop mirrors. (b) Schematic of the proposed comb filter based on SLMs with MZI couplers. (c) Common and (d) differential tuning of the MZI couplers for wavelength and bandwidth tuning of the comb filter, respectively. SLM: Sagnac loop mirror. MZI: Mach-Zehnder interferometer. FPI: Fabry-Perot interferometer.

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Figure 1(a) shows a Fabry-Perot interferometer (FPI) comb filter [8] consisting of two cascaded SLMs. By replacing the directional couplers of the SLMs with MZI couplers in Fig. 1(b), the phase shift and reflectivity of the SLMs can be controlled by the phase shifters along the MZI arms. Consequently, the effective cavity length and reflectivity of the FPI can be tuned accordingly, leading to tunable central wavelength and bandwidth of the comb filter [11,12]. Note that comb filters do not generate new frequencies as comb generators [13].

As shown in Fig. 1(c), the central wavelength can be tuned in a common mode, which varies the phase shift of the MZI arms symmetrically. Therefore, a varied cavity length and a constant reflectivity of the FPI are achieved, resulting in a tunable central wavelength with an unchanged bandwidth. To obtain different bandwidths at the same central wavelength, the MZI arms are tuned in a differential mode, which changes the phase shifts of two MZI arms l_1 and l_3 asymmetrically, as depicted in Fig. 1(d). Based on transfer matrix method [10], the field transmission function of the structure can be given as follows:

$$t_{\mathrm{FP}} = t_{\mathrm{s}}^2 a_4 / (1 - r_{\mathrm{s}}^2 a_4^2), \tag{1}$$

$$t_{\mathrm{s}} = a_1 a_2 a_3 (k^4 + t^4) - 2a_2 (a_1^2 + a_1 a_3 + a_3^2) k^2 t^2, \tag{2}$$

$$r_{\mathrm{s}} = 2 j a_2 (a_1 + a_3)(a_1 k t^3 - a_3 k^3 t), \tag{3}$$

where t_{s} and r_{s} are the transmission and reflection functions of a SLM with MZI coupler, respectively. t and k ($t^2 + k^2 = 1$) are the transmission and coupling coefficients of the directional couplers, respectively. $a_i = \exp(-\alpha l_i - j2\pi n_{\mathrm{g}}/\lambda l_i)$ (i = 1, 2, 3, 4) are the transmission factors of the waveguides, with l_i (i = 1, 2, 3, 4) denoting the lengths of the waveguides depicted in Fig. 1(b). α and n_{g} are the loss factor and the group index of the silicon waveguides, respectively. The structural parameters are chosen as follows. The lengths of the waveguides $l_{1,3}$ = 287.965 μm, l_2 = 146.842 μm, and l_4 = 134.998 μm are used to achieve a narrow channel spacing. The cross sections of the waveguides are 450 nm × 220 nm. The coupling length and gap of the directional couplers are l_{c} = 20 μm and 300 nm, respectively. The directional couplers are designed to be 3-dB couplers (t = ~0.707) to realize independent tuning of central wavelength and bandwidth of the comb filter. Therefore, t_{s} and r_{s} can be simplified to $t_{\mathrm{s}} = -a_2(a_1^2 + a_3^2)/2$ and $r_{\mathrm{s}} = ja_2(a_1^2 - a_3^2)/2$, respectively.

3. Simulation results

Figure 2 shows the simulated results of central wavelength and bandwidth tuning of the proposed comb filter. In the simulations, the wavelength and bandwidth tuning are realized by changing the refractive indexes of the phase shifters along the MZI arms in common and differential modes, respectively. The simulation parameters are α = 10.16 dB/cm, t = 0.707, and n_{g} = 4.31. The length of the phase shifters along the MZI arms is 236.549 μm. The transmission function of the comb filter in Eq. (1) can be simplified to $t_{\mathrm{FP}} = a_2^2 a_1^4 a_4$ if the MZIs have equal arm lengths ($l_1 = l_3$), leading to a constant transmission amplitude. Thus, a small length difference of 0.1 μm is introduced to the two arms of the MZIs to avoid constant transmission amplitude.

Figure 2(a) shows the transmission spectra of wavelength tuning if the device operates in a common mode. The refractive indexes of the phase shifters are set to be $n_{\mathrm{g}} + \Delta n$ with Δn denoting the refractive index change. The central wavelength is tuned from 1548.713 nm to 1548.871 nm with Δn ranging from 3.6×10^{-3} to 4.4×10^{-3}, which can be achieved by the thermo-optic effect in silicon. Figure 2(b) depicts the resonance shift in central wavelength for various Δn. One can see that the resonance shift increases linearly with Δn.

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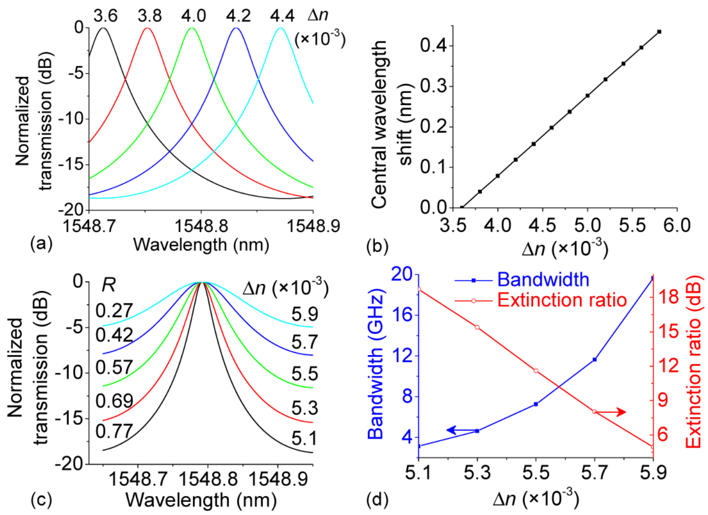

Fig. 2. (a), (c) Simulated transmission spectra of (a) central wavelength and (c) bandwidth tuning by changing the refractive indexes of the phase shifters along the MZI arms according to Figs. 1(c) and 1(d), respectively. (b) Central wavelength shift versus Δ*n*. (d) Bandwidth and extinction ratio versus Δ*n*. Δ*n*: refractive index change. *R*: reflectivity.

Figure 2(c) shows the bandwidth tuning effect obtained by operating the device in a differential mode. The refractive indexes of the phase shifters along the two MZI arms are set to be $n_g + \Delta n/2$ and $n_g - \Delta n/2$, respectively. The 3-dB bandwidth of the resonance at 1548.792 nm can be tuned from 3.13 GHz to 19.64 GHz by varying Δn from 5.1×10^{-3} to 5.9×10^{-3}. The reflectivity *R* of the SLM with MZI coupler is also shown in Fig. 2(c). The bandwidth and maximum transmission increase as *R* decreases. As shown in Fig. 2(d), for an increased Δn, the bandwidth and extinction ratio (ER) increases and decreases, respectively.

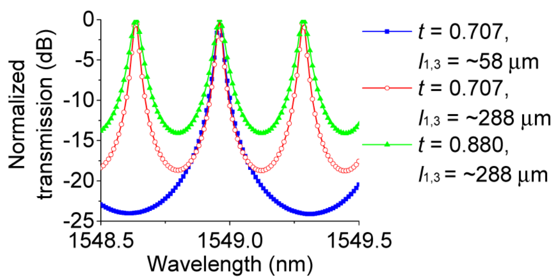

Fig. 3. Simulated transmission spectra of the comb filter with different t and $l_{1,3}$.

We also investigated the dependence of the ER on the transmission coefficients of the directional couplers and the cavity length. The cavity length can be controlled by varying the lengths $l_{1,3}$ of the MZI arms. As shown in Fig. 3, the ER decreases from 18.43 dB to 14.08 dB by changing t from 0.707 to 0.880. The ER decreases from 23.01 dB to 18.43 dB with $l_{1,3}$ increasing from 57.965 μm to 287.782 μm.

4. Device fabrication and measured transmission spectra

The device was fabricated on an 8-inch silicon-on-insulator (SOI) wafer. 248-nm deep ultraviolet (DUV) photolithography was used to define the pattern and an inductively coupled plasma (ICP) etching process was used to etch the top silicon layer. Grating couplers for TE polarization were employed at the two ends of the device to couple light into and out of the chip with single mode fibers. Four TiN micro-heaters [14] were fabricated along the MZI

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arms to tune the phase shifts of the SLMs. A micrograph of the fabricated device is shown in Fig. 4(a). Finally, the device was wire-bonded to a printed circuit board (PCB) for electrical connections, as shown in Fig. 4(b).

The transmission spectrum of the fabricated device is measured using a tunable laser (Keysight 81960A) scanning from 1535 nm to 1565 nm with a step size of 1 pm. The measured transmission spectrum is shown in Fig. 4(c). The total insertion loss of the chip is ~25 dB, including a ~19-dB coupling loss introduced by a fiber coupling system. There are 93 comb lines in the wavelength range from 1535 nm to 1565 nm with a channel spacing of ~0.322 nm. The channel spacing can be designed to fit the International Telecommunications Union (ITU) grids by varying the waveguide lengths. The peak-transmission variation of the comb lines can be attributed to the wavelength-dependent coupling coefficients of the directional couplers and the ripples in the transmission spectrum of the grating couplers. The measured transmission spectrum in a 2-nm spectral range is shown in Fig. 4(d), which is fitted by the theoretically calculated transmission spectrum (red-dot curve) obtained from Eq. (1). The fitting parameters are $\alpha = 10.16$ dB/cm, $t = 0.88$, and $n_g = 4.31$.

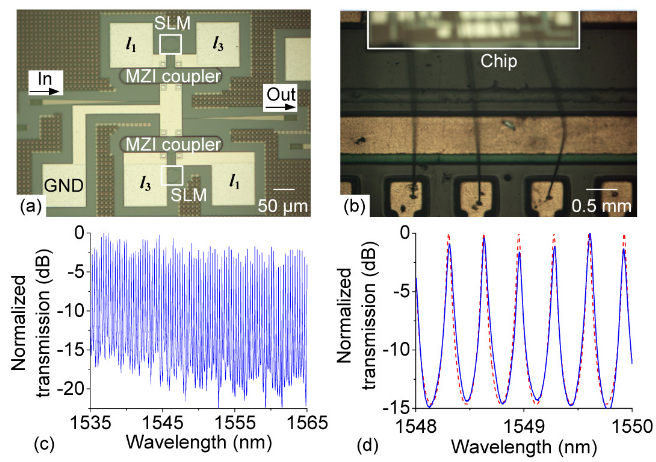

Fig. 4. (a), (b) Micrograph of (a) the fabricated device and (b) the device after wire-bonding to a PCB. (c) Measured transmission spectrum of the comb filter in the wavelength range from 1535 nm to 1565 nm. (d) Measured (blue-solid curve) and fitted (red-dot curve) transmission spectra in the wavelength range from 1548 nm to 1550 nm. SLM: Sagnac loop mirror. MZI: Mach-Zehnder interferometer. PCB: printed circuit board.

5. Experimental demonstration of central wavelength and bandwidth tuning

To realize wavelength tuning, the MZI arms are tuned in a common mode. The resonance redshifts as the cavity length increases. Figure 5(a) shows the measured transmission spectra of central wavelength tuning. The resonance redshifts from 1548.628 nm to 1548.803 nm with the heating power P of each micro-heater tuned from 4.97 mW to 7.53 mW. The bandwidth also changes from 6.13 GHz to 4.38 GHz, which can be attributed to the small change of the transmission coefficients of the MZI couplers arising from the small difference of heating powers applied to the two MZI arms.

The measured and fitted central wavelength shift from 1548.402 nm is shown in Fig. 5(b). The central wavelength shifts ~0.462 nm with the heating powers of the four micro-heaters tuned from 2.38 mW to 8.50 mW, which covers a channel spacing of ~0.322 nm. Thus, the wavelength tuning efficiency is ~0.019 nm/mW, which can be doubled by tuning the phase shift of the waveguide connecting the two SLMs [8]. Multi-wire structure micro-heaters [15] can also be used to improve the tuning efficiency.

To obtain tunable bandwidths without changing the central wavelength, the MZI couplers are tuned in a differential mode. Firstly, the four micro-heaters are biased at a heating power

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P of 4.60 mW. Then heating powers are changed according to Fig. 1(c) with a differential heating power ΔP, i.e. heating powers $P + \Delta P/2$ and $P - \Delta P/2$ are applied to the MZI arms l_1 and l_3, respectively. The bandwidth of the comb line at 1548.633 nm ranges from 5.88 GHz to 13.63 GHz with ΔP tuned from 0.00 mW to 0.24 mW, as shown in Fig. 5(c). Due to the imperfect 3-dB directional coupler, the central wavelength also shows a slight change, which can be reduced by fine-tuning the heating powers.

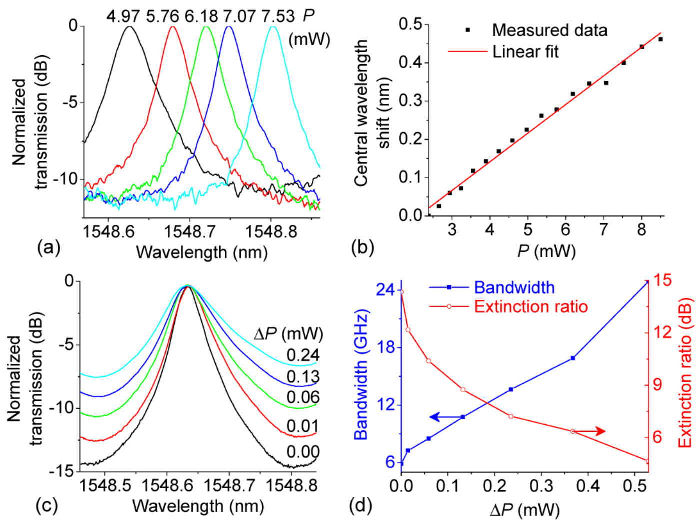

Fig. 5. (a), (c) Measured transmission spectra of (a) central wavelength and (c) bandwidth tuning versus heating power P of each micro-heater and differential heating power ΔP, respectively. (b) Central wavelength shift versus heating power P of each micro-heater. (d) Bandwidth and extinction ratio versus differential heating power ΔP.

Figure 5(d) shows the bandwidth and extinction ratio in bandwidth tuning. The 3-dB bandwidth changes from 5.88 GHz to 24.89 GHz with ΔP tuned from 0.00 mW to 0.53 mW. Meanwhile, the ER decreases from 14.34 dB to 4.66 dB due to the changed transmission coefficients of the MZI couplers, which determine the reflectivity of the SLMs. The ER can be improved by using more precise 3-dB couplers and shorter cavity length, as discussed in Section 3. Improved ER and flat-top passband can also be realized by cascading more SLMs [16]. Then the change of ER would have a smaller impact on the filtering performance.

6. Conclusion

In conclusion, a silicon comb filter implemented by Sagnac loop mirrors with MZI couplers has been proposed and experimentally demonstrated. The central wavelength and bandwidth of the comb lines can be tuned by controlling the MZI arms in common and differential modes, respectively. By thermally tuning the device, the central wavelength can be red-shifted by ~0.462 nm with a tuning efficiency of ~0.019 nm/mW. The bandwidth ranges from 5.88 GHz to 24.89 GHz with a differential heating power changing from 0.00 mW to 0.53 mW. The proposed device can be used for flexible filtering to suppress out-of-band noises or define the lasing wavelengths of multi-wavelength lasers [17,18] in WDM optical communication systems.

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