Variable bandwidth comb filter based on tunable silicon Sagnac-loop reflectors

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***Abstract* — We propose and experimentally demonstrate an on-chip comb filter implemented by tunable silicon Sagnac-loop reflectors. By using thermal-optic tuning, variable bandwidth from 4.0 GHz to 24.6 GHz is achieved.**
***Keywords* — silicon photonics, comb filter, tunable filter, Sagnac-loop reflector.**

I. Introduction

Silicon photonic devices have been proved to be promising candidates for realizing photonic integrated circuits (PICs) due to high index contrast and CMOS compatibility [1, 2]. Various silicon-based devices have been developed, such as filters, modulators, switches, routers, and detectors. Among these devices, optical comb filters, which perform data routing and blocking of multi-wavelength channels, are widely used in wavelength division multiplexing (WDM) systems [3–8]. Compared to optical comb filters based on fiber optics [3], silicon-based comb filters can offer advantages of large-scale integration, low power consumption, and improved stability.

Various schemes have been proposed to realize on-chip comb filters based on Bragg gratings [4], silicon microring resonators [5, 6], and Sagnac-loop reflectors (SLRs) [7]. But the bandwidths of the above comb filters cannot be dynamically tuned, making them difficult to satisfy flexible-grid requirements in WDM networks. A bandwidth-tunable comb filter based on microfiber SLRs was proposed in [8], however, it is not suitable for on-chip integration.

In this paper, an on-chip comb filter with tunable bandwidth is proposed and experimentally demonstrated, which consists of two SLRs with Mach-Zehnder-interferometer (MZI) couplers [9]. The reflectivities of the SLRs can be dynamically changed by thermal-optic phase shifters along the MZI arms, leading to tunable bandwidth of the comb filter. The measured spectra show that the fabricated device has 50 comb lines in the wavelength range from 1540 nm to 1560 nm and a tunable bandwidth from 4.0 GHz to 24.6 GHz.

II. Device Structure and Operation Principle

Figure 1 shows the schematic of the proposed comb filter consisting of two SLRs, which form a Fabry-Perot (FP) resonator. To adjust the reflectivities of the SLRs, MZI couplers are chosen instead of directional couplers. By applying DC voltages to the micro-heaters along one arm of each MZI, the phase shifts of the corresponding waveguides are changed. As a result, the coupling coefficients of the MZI couplers are tuned, which determine the reflectivities of the SLRs. For a FP resonator, the Q factor of the comb lines increases with the reflectivities. Therefore, the bandwidth of the proposed comb filter can be tuned. On the other hand, the effective cavity length of the FP resonator increases with the phase shifts of the waveguides, resulting in redshift of the resonances. By tuning the resonance wavelengths over several free spectral ranges (FSRs) or by employing push-pull scheme [10], variable bandwidth at the same central wavelength can be obtained.

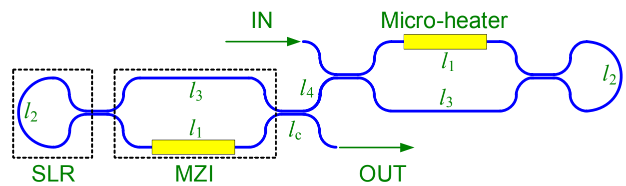

Fig. 1. Schematic of the proposed comb filter.

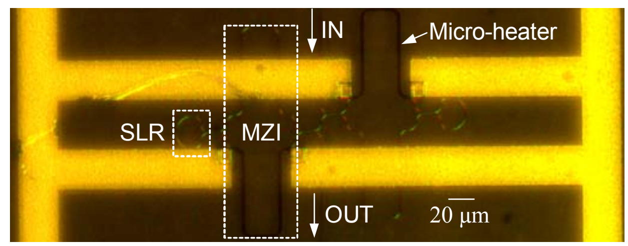

Fig. 2. Micrograph of the fabricated device.

Based on transfer matrix method, the field transmission function of the structure is given by [7]:

$$t_{\mathrm{FP}} = \frac{t_s^2 a_4}{1 - r_s^2 a_4^2} \tag{1}$$

$$t_s = a_1 a_2 a_3 (k^4 + t^4) - 2a_2 (a_1^2 + a_1 a_3 + a_3^2) k^2 t^2 \tag{2}$$

$$r_s = 2 j a_2 (a_1 + a_3)(a_1 k t^3 - a_3 k^3 t) \tag{3}$$

where t_s and r_s are the transmission and reflection functions of a SLR with a MZI coupler, respectively. t and k are the transmission and coupling coefficients of the directional couplers, respectively. $a_i = \exp(-\alpha l_i - j\beta l_i)$ (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 MZI arm with a micro-heater, the SLR, the other MZI arm, and the waveguide connecting two MZIs, respectively. α is the loss factor, and β is the propagation constant of the silicon waveguide. The structural parameters are chosen as follows: l_2 = 101.5 µm, $l_{1,3}$ = 260.5 µm, l_4 = 25.1 µm, coupling length l_c = 9 µm, and a coupling gap of 0.18 um. The directional couplers are designed to be 3-dB couplers.

III. Device Fabrication and Measured Spectra

The micrograph of the fabricated device is shown in Fig. 2. The proposed device is fabricated on an 8-inch silicon-on-insulator (SOI) wafer with a 220-nm-thick top silicon layer and a 2-µm-thick buried dioxide layer. The cross section of the silicon waveguide is 450 nm × 220 nm. Micro-heaters are fabricated along the MZI arms to tune the phase shifts based on thermal-optic effect in silicon. Grating couplers for transverse electric (TE) polarization are employed to couple light with single-mode fibers.

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Figure 3(a) shows the measured transmission spectrum of the fabricated comb filter. There are 50 comb lines with a channel spacing of ~0.4 nm in the wavelength range from 1540 nm to 1560 nm. The amplitude variation of the comb lines can be attributed to the wavelength dependence of the coupling coefficients of the directional couplers [11]. The measured transmission spectrum is fitted by the red-dot curve calculated using Eq. (1). From Fig. 3(b), one can see that the measured spectrum fits well with the simulated one. The fitting parameters are loss factor $\alpha \approx 160\ \mathrm{m}^{-1}$, coupling coefficient of the directional couplers $k \approx 0.650$, and the waveguide group index of the TE mode $n_g \approx 4.550$.

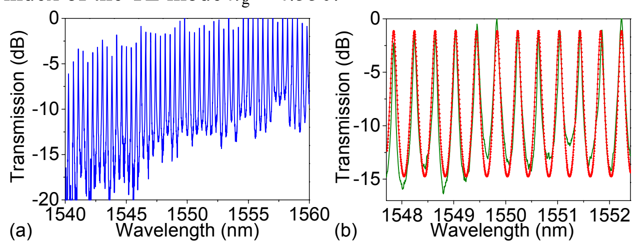

Fig. 3. (a) Measured transmission spectrum of the comb filter. (b) Measured (green-solid curve) and fitted (red-dot curve) transmission spectra in the wavelength range from 1547.5 nm to 1552.5 nm.

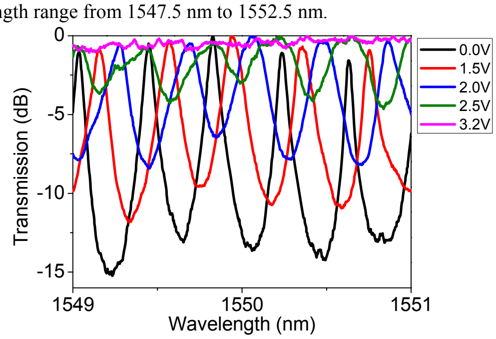

Fig. 4. Measured transmission spectra of the comb filter by applying 0–3.2 V DC voltages.

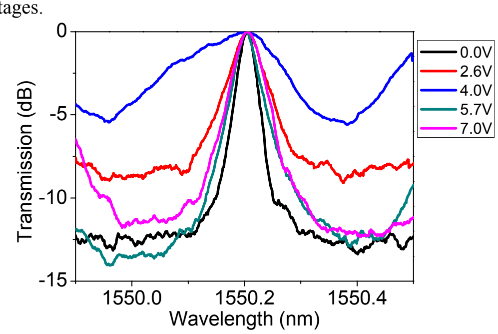

Fig. 5. Measured transmission spectra with various bandwidths at the same central wavelength by applying 0–7 V DC voltages.

Tab. 1. 3-dB bandwidths of the resonance versus applied DC voltages.

Voltage (V)	0.0	2.6	4.0	5.7	7.0
Bandwidth (GHz)	4.0	7.5	24.6	5.6	6.5

By applying DC voltages to the micro-heaters along the MZI arms, the spectrum redshifts since the effective cavity length of the FP resonator increases with the phase shifts of the MZI arms. Figure 4 shows the measured transmission spectra by applying various voltages from 0 V to 3.2 V. The resonances redshift with increased bandwidth and decreased extinction ratio. If the voltage is higher than 3.2 V, the resonances continue to redshift, whereas the bandwidth decreases and the extinction ratio increases. This process periodically repeats with increased voltage, due to the periodical change of the reflectivities of the SLRs with MZI couplers. To obtain various bandwidths at the same central wavelength, the resonance wavelengths are tuned over several FSRs, as shown in Fig. 5. The bandwidths of the comb lines range from 4.0 GHz to 24.6 GHz by applying 0–7 V DC voltages. Tab. 1 presents the applied DC voltages and corresponding 3-dB bandwidths of the resonance at 1550.204 nm. In practical applications, the redshift of the resonances can be avoided by employing push-pull phase shifters [10] along the MZI arms.

IV. Conclusion

We have proposed and experimentally demonstrated a comb filter with variable bandwidth on a SOI platform. The integrated comb filter consists of two SLRs. Owing to the adjustable reflectivities enabled by MZI couplers, the bandwidth of the comb lines can be tuned. The measured spectra of the fabricated device show 50 comb lines with a channel spacing of ~0.4 nm in the wavelength range from 1540 nm to 1560 nm. Bandwidth tuning from 4.0 GHz to 24.6 GHz by applying 0–7 V DC voltages is demonstrated.

V. Acknowledgement

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