Tunable silicon Fabry–Perot comb filters formed by Sagnac loop mirrors

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We experimentally demonstrate tunable silicon comb filters based on Fabry–Perot (FP) resonators composed of two Sagnac loop mirrors. The comb filter resolves up to 54 comb lines with a 115 GHz channel spacing over a spectral range from 1510 to 1560 nm. The comb line extinction ratio is ~26.3 dB and the quality factor is ~57,000 around 1550 nm wavelength. Electrical tuning is enabled via periodically interleaved PN junctions embedded inside the FP resonator. The comb lines are blue shifted by ~0.92 nm (one channel spacing) with a 5 mA forward-bias current and red-shifted by ~0.05 nm with a −10 V reverse-bias voltage.

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Silicon photonics have attracted a lot of research interest for photonic integrated circuits, benefiting from their high index contrast and noteworthy advances in nanoscale fabrication [1,2]. The compatibility of silicon photonics with microelectronics allows for many applications from long-haul telecommunications to short-reach on-chip optical interconnects. The wavelength division multiplexing (WDM) technology has been imposed as the preferred option to improve the capacity and spectral efficiency of optical communications by using multiple wavelengths capable of parallel data transmission [3,4]. Optical comb filters and switches, making use of the regularly spaced WDM channels, are useful for multichannel switching and routing [5–9]. There have been many implementations of silicon comb filters and switches reported in the literature, such as ring resonators [6–8] and Bragg gratings [5]. To generate narrow channel spacing, the ring circumference should be long. To make the ring more compact, an Archimedean spiral structure is proposed and demonstrated [8]. However, the complexity of the spiral structure lowers the fabrication tolerance. Sampled Bragg gratings can achieve a high reflectivity over a very narrow bandwidth, and yet it is difficult to generate multiple uniform channels [5]. Moreover, Bragg gratings are very sensitive to a grating profile. Grating period, chirp, and etch depth are all crucial parameters that need to be precisely controlled, making it quite challenging to obtain the desired filtering characteristics.

In this Letter, we propose and experimentally demonstrate an electrically tunable Fabry–Perot (FP) comb filter formed by a pair of Sagnac loop mirrors (SLMs). Compared to a ring resonator, which is a traveling wave resonator, the FP resonator is a standing wave resonator, and hence the cavity waveguide physical length is nearly half shorter. The refractive index of the cavity waveguide is tunable using the free-carrier plasma dispersion effect enabled by periodically interleaved PN junctions embedded in the cavity waveguide [10]. Our comb filter possesses the merits of narrow bandwidth, large extinction ratio (ER), and wide spectral tuning range covering one full-channel spacing. Because of the standing wave nature of the FP cavity, the comb-line tuning efficiency is twice higher than if using a travelling wave resonator.

Figure 1(a) shows the schematic drawing of the proposed FP comb filter. The Sagnac loops composed of 2×2 directional couplers work as reflective mirrors. The SLM circumference is l_1 and the active waveguide length in between the SLMs is l_2. To electrically tune the refractive index of the FP cavity waveguide, periodically interleaved PN junctions oriented perpendicular to the light propagation direction are embedded in the cavity waveguide, as depicted in the inset. The interleaved PN junctions allow for both free-carrier injection and depletion, and thus both blue shift and red shift of the FP resonances. The interleaved PN junction has a large tolerance to overlay misalignment and its period is not critical to the filter optical performance. The device is input- and output-coupled using a pair of grating couplers. Note that the comb filter itself is independent of the grating couplers.

The field transmission and reflection functions of the SLMs can be expressed as

$$t_s = (t^2 - \kappa^2) a_1 e^{-j\beta l_1}, \tag{1}$$

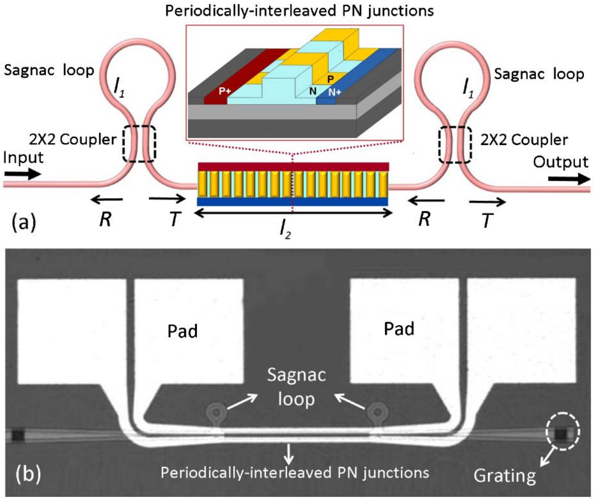

Fig. 1. (Color online) (a) Schematic of the FP comb filter with periodically interleaved PN junctions. The inset shows the schematic 3D view of the PN junctions. (b) Microscope photograph of the fabricated FP comb filter.

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$$r_s = -2jt\kappa a_1 e^{-j\beta l_1}, \tag{2}$$

where t and κ are the transmission and coupling coefficients of the directional couplers of the SLMs, a_1 is the loss factor, and β is the propagation constant of silicon waveguide. Total reflection is reached when the couplers are ideal 3 dB couplers ($t^2 = \kappa^2 = 0.5$). With t_s and r_s, the field transmission function of the FP resonator can be expressed as

$$t_{\mathrm{FP}} = \frac{t_s^2 a_2 e^{-j\beta l_2}}{1 - r_s^2 a_2^2 e^{-2j\beta l_2}}, \tag{3}$$

where a_2 is the loss factor associated with the active waveguide. The normalized intensity response of the FP resonator is then given by

$$\frac{I_{\mathrm{out}}}{I_{\mathrm{in}}} = |t_{\mathrm{FP}}|^2 = \frac{(t^2 - \kappa^2)^4 a a_1^2}{1 + 16t^4\kappa^4 a^2 + 8t^2\kappa^2 a \cos(\beta L)}, \tag{4}$$

where $L = 2(l_1 + l_2)$ and $a = (a_1 a_2)^2$ are the round-trip length and loss factor of the FP resonator, respectively.

The devices were fabricated on a silicon-on-insulator substrate with a 220 nm thick top silicon layer and a 2 μm thick buried oxide layer. The cross-sectional dimension of the silicon ridge waveguide is 500 nm × 220 nm with a 60 nm pedestal. The top cladding silicon dioxide thickness is 1.5 μm. The grating coupler has a period of 630 nm with a 50% duty cycle and the etch depth is 70 nm. The interleaved PN junctions have a finger pitch of 0.8 μm and a width of 1.7 μm. Both P and N regions have a low doping concentration of $\sim 10^{17}\ \mathrm{cm}^{-3}$ to minimize the optical loss. The highly doped N^+ and P^+ regions have a doping level of $\sim 10^{20}\ \mathrm{cm}^{-3}$ for good Ohmic contact. Figure 1(b) shows the optical microscope photograph of one of the FP comb filters.

The transmission of the FP comb filters were characterized using a tunable laser source scanning from 1510 to 1560 nm with a step size of 10 pm. Light is coupled into and out of the devices through grating couplers with the fibers tilted 8° from normal. A polarization controller is used to adjust the polarization to transverse electric (TE) mode. The measured transmission spectra are all normalized to a reference straight waveguide to eliminate the influence of the grating couplers.

Figures 2(a) and 2(b) show the measured transmission spectra of the FP comb filters with coupling lengths of $l_c = 5.5$ μm ($l_1 \approx 115$ μm) and $l_c = 7.5$ μm ($l_1 \approx 119$ μm), respectively. The coupling gaps are both 0.2 μm. The active waveguide lengths in both devices are $l_2 = 200$ μm. Over the measured spectral range, 54 comb lines are obtained. The comb lines have a channel spacing of ~0.92 nm (115 GHz).

Figures 2(c) and 2(d) show the comb-line Q factor and ER as functions of wavelength. For $l_c = 5.5$ μm, the comb-line resonance Q factor changes from 10,600 (corresponding to a FWHM channel bandwidth of 17.8 GHz) at 1510 nm to 20,500 (bandwidth of 9.5 GHz) at 1557 nm. The ER is increased from 12.5 to 18 dB. In contrast, for $l_c = 7.5$ μm, the comb-line resonance Q factor changes from 22,600 (bandwidth of 8.4 GHz) at 1510 nm to 61,000 (bandwidth of 3.2 GHz) at 1557 nm. The ER is increased from 19.3 to 29 dB. In particular, around 1550 nm, the resonance Q factor is 15,900 (bandwidth of 12.2 GHz) and the ER is ~18.4 dB for $l_c = 5.5$ μm, and the Q factor is 57,000 (bandwidth of 3.4 GHz) and the ER is ~26.3 dB for $l_c = 7.5$ μm. It can be seen that the latter possesses a higher Q factor and a larger ER. The higher Q factor of the latter is due to the larger reflectivity of the SLMs, since a higher reflectivity means a lower external decay rate. The SLM reflectivity is determined by the coupling length l_c. When $l_c = 7.5$ μm, the coupler is closer to a 3 dB coupler, resulting in a larger reflectivity. A higher Q factor means less overlap between adjacent channels, and therefore, the cross-talk is lowered, leading to a larger ER.

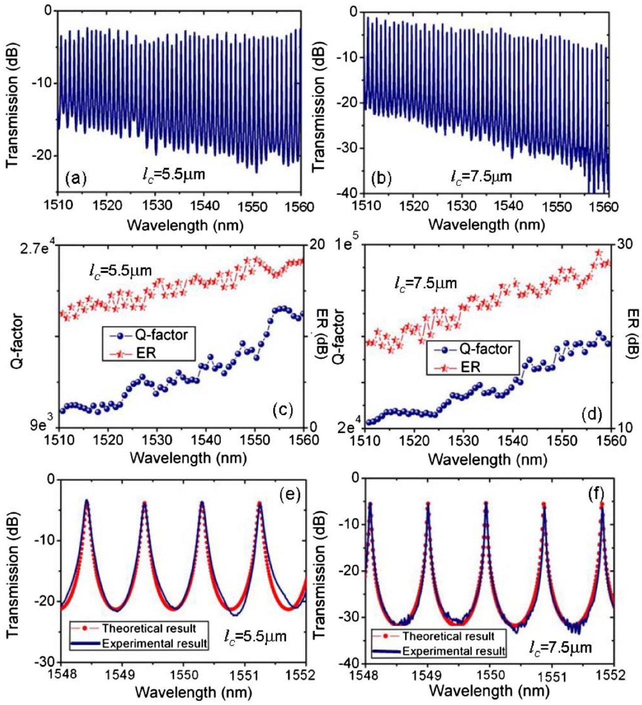

Fig. 2. (Color online) (a), (b) Measured transmission spectra of the FP comb filters. (c), (d) Comb line Q factor and ER variation with wavelength. (e), (f) Zoomed-in spectra showing both measurement and simulation results.

The wavelength dependence of the Q factor and ER is due to the fact that the splitting ratio of the directional couplers, and thus the reflectivity of the SLMs, change with wavelength. At the longer wavelength side, the reflectivity is high, resulting in a higher Q factor (narrower bandwidth) and thus an enhanced ER.

To better understand the experimental results, we also conducted theoretical analyses using Eq. (4). Using a, κ, and β as fitting parameters, we get the theoretical transmission spectra as shown in Figs. 2(e) and 2(f). The theoretical results are in good agreement with the experimental results. By fitting, we get $a \approx 0.978$, $\beta \approx 11.2\ \mu\mathrm{m}^{-1}$ (effective refractive index $n_{\mathrm{eff}} = 2.755$), and $\kappa \approx 0.515$ (SLM reflectivity $R \approx 0.773$) and 0.794 ($R \approx 0.925$) around 1550 nm for $l_c = 5.5$ and 7.5 μm, respectively.

Upon a forward- or reverse-bias of the interleaved PN junctions, the transmission spectrum of the FP comb filter can be easily tuned using the free-carrier plasma dispersion effect. We perform the tuning experiment on the FP comb filter with a coupling length of

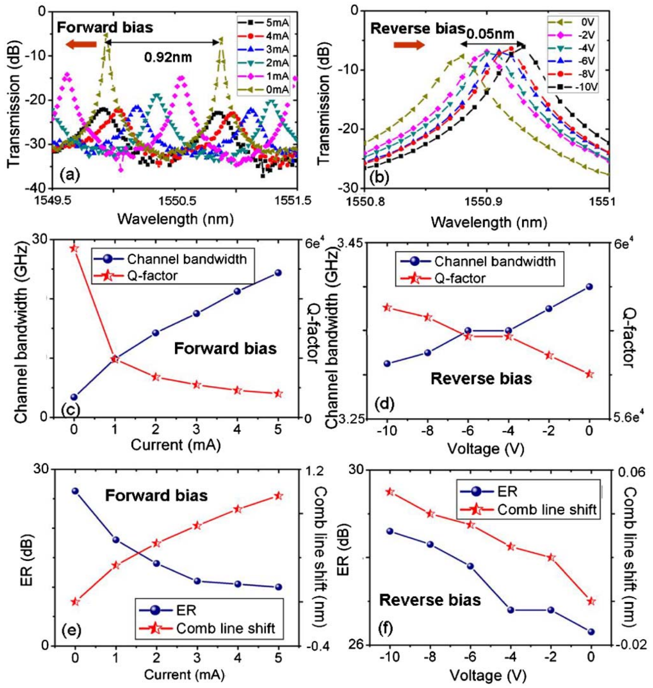

Fig. 3. (Color online) (a), (b) Transmission spectra tuning under various (a) forward and (b) reverse biases. (c), (d) Comb-line FWHM bandwidth and Q-factor variation with bias current or voltage. (e), (f) ER and comb-line shift with bias current or voltage.

7.5 μm. Figure 3(a) shows the blue shift of transmission spectrum upon forward-biases when free carriers are injected across the junction. Figures 3(c) and 3(e) show the comb-line bandwidth, Q factor, ER, and blue shift value versus bias current. The resonance bandwidth increases from 3.4 GHz (Q factor of 57,000) at 0 mA to 24.4 GHz (Q factor of 8000) at 5 mA, while the ER is reduced from 26.3 to 10 dB due to the free-carrier absorption loss. At the 5 mA bias current, the resonance is blue shifted by ~0.92 nm, covering one channel spacing. The associated power consumption is ~6 mW. In contrast, with a reverse bias, free carriers are depleted near the junction, resulting in a red shift of the resonance as shown in Fig. 3(b). With a bias voltage of −10 V, the resonance is red shifted by ~0.05 nm. Since the red-shift range is relatively small compared to the forward bias case, the bandwidth, Q factor and ER are only slightly changed as illustrated in Figs. 3(d) and 3(f). It should be noted that our comb filter can be designed to have a narrower channel spacing by using a longer cavity size, and then the deterioration of comb lines upon tuning is less severe and might be tolerated in practical use. Thermo-optic effect can also be used for comb-line tuning where no extra loss is incurred.

In conclusion, we experimentally demonstrated tunable silicon comb filters based on FP resonators formed by two SLMs. The optical comb spectrum of our device shows 54 nearly equally spaced comb lines with a 115 GHz channel spacing over the spectral range from 1510 to 1560 nm. The comb lines around 1550 nm wavelength show a FWHM bandwidth of 3.4 GHz, corresponding to a Q factor of 57,000 with an ER of ~26.3 dB for the FP comb filter with a coupling length of 7.5 μm. The comb lines were blue shifted by 0.92 nm covering one channel spacing with a 5 mA forward current and red shifted by ~0.05 nm with −10 V reverse voltage. The demonstrated tunable silicon FP comb filters can be used for dense WDM optical signal filtering or simultaneously switch/routing of multiple optical channels.

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