Tunable Silicon Comb Filters Based on Fabry-Perot Resonators Formed by Sagnac Loop Mirrors

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Abstract: We experimentally demonstrate tunable silicon comb filters based on Fabry-Perot resonators composed of Sagnac loop mirrors using periodically-interleaved PN junctions. Forward and reverse biases blue- and red-shift the comb lines, respectively.

OCIS codes: (130.3120) Integrated optics devices; (230.2090) Electro-optical devices; (230.7408) Wavelength filtering devices

1. Introduction

Optical comb filters, making use of the constructive and destructive light interferences with periodic response to create regularly spaced multichannels, have been demonstrated to be useful in the development of wavelength division multiplexing (WDM) optical communication systems [1-3]. They can be used to simultaneously separate and compensate dispersion of multiple WDM channels. Recently, silicon photonics has received growing interests in producing highly-compact nano-photonic integrated chips for optical telecommunication and interconnect applications due to its compatibility with complementary-metal-oxide-semiconductor (CMOS) technology [4-6]. Fabry-Perot (FP) resonators consisting of a pair of mirrors formed by Bragg gratings is one of the most common structures for comb filters [7], which permits to achieve a high reflectivity over a very narrow bandwidth. However, due to the subwavelength period and shallow etch depth of Bragg grating, it makes the fabrication more complex and challenging to achieve the desired filtering characteristics.

Here, we experimentally demonstrate an electrically tunable FP comb filter formed by two Sagnac loop mirrors. Resonance tuning is enabled by changing the refractive index of the cavity waveguide with free-carrier plasma dispersion effect enabled by periodically-interleaved PN junctions [8, 9].

2. Device design and Fabrication

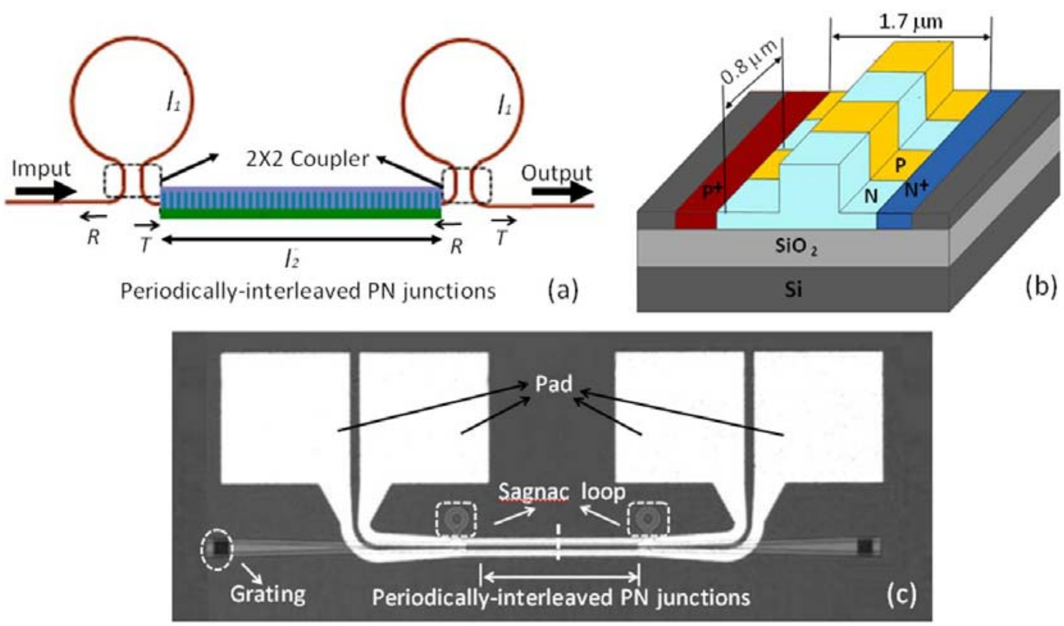

Fig. 1. (a) Schematic of the FP resonator with periodically-interleaved PN junctions. Light is launched from input port and collected from output port. (b) 3D perspective-view of the PN junctions. (c) Microscope photograph of the tunable FP comb filter formed by two Sagnac loop mirrors.

Fig. 1(a) shows the schematic drawing of the FP resonator with periodically-interleaved PN junctions. The Sagnac loops working as reflective mirrors are composed of 2×2 directional couplers with a coupling length of 7.5 μm and a gap size of 0.2 μm (around 50:50 split ratio). The Sagnac loop circumference is $l_1 \approx 119$ μm. The active waveguide length in between the Sagnac loop mirrors is $l_2 = 200$ μm. The transmission spectrum of the comb filter can be tuned by changing the refractive index of the active waveguide. In order to increase the overlap of the optical waveguide mode with the free-carrier variation, a linear array of periodically-interleaved PN junctions that are oriented perpendicular to the light propagation direction is designed across the cavity waveguide, as shown in Fig. 1(b). Each interleaved lightly doped region (either P- or N-type doped) is 0.4 μm long and 1.7 μm wide. Fig. 1(c) shows the microscope photograph of the tunable FP comb filter.

The device was fabricated on a silicon-on-insulator (SOI) substrate with a 220 nm thick top silicon layer and a 2 μm thick buried oxide (BOX) layer. The cross-sectional dimension of the silicon waveguide is 500 nm × 220 nm with a 0.06 μm slab. The top cladding silicon dioxide thickness is 1 μm. Gratings are used for input and output coupling. The grating period is 0.63 μm with a 50% duty ratio and the etch depth is 0.07 μm. Interleaved PN junction has a period of 0.8 μm. Both P and N regions have a low doping level of ~10^{17} cm^{-3} to minimize the optical loss. The highly doped N^+ and P^+ regions have a doping level of ~10^{20} cm^{-3} for good ohmic contact.

3. Measurement results and discussion

We used an Agilent loss and dispersion analyzer (86038B) to characterize the device performance. 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.

Fig. 2(a) shows the measured transmission spectrum of the FP comb filter. Over the spectral range from 1.51 μm to 1.56 μm, the FP resonance has a free spectral range (FSR) of ~1 nm with an extinction ratio of >19 dB. Figs. 2(b)-(e) show the magnified FP resonance peaks at various wavelengths. We can see that the resonance full-width-half-maximum (FWHM) bandwidth changes from 0.054 nm (corresponding to a Q-factor of 28,000) at 1.515 μm to 0.02 nm (Q-factor of 78,000) at 1.5591 μm. Meanwhile, the extinction ratio is increased from 22 to 30 dB. In particular, at 1.5506 μm, the resonance Q-factor is ~52,000 with an extinction ratio of ~28 dB. The variation in comb lines is resulted because the coupling coefficient of the directional couplers and hence the reflectivity of the Sagnac loop mirrors are wavelength dependent. At the longer wavelength side, the reflectivity is high, which means the cavity external decay rate is low, resulting in a higher Q-factor and an enhanced extinction ratio (since the adjacent channels are less overlapped and their cross-talk reduced).

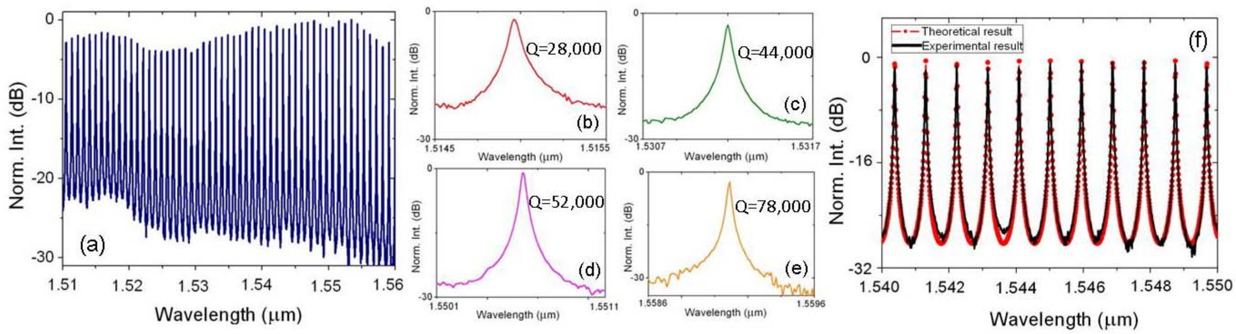

Fig. 2. (a) Measured transmission spectrum of the FP comb filter. (b)-(e) show the magnified resonance peaks at (b) 1.515 μm, (c) 1.5312 μm, (d) 1.5506 μm, and (e) 1.5591 μm. (f) Theoretical fitting of the transmission spectrum in the wavelength range from 1.54 to 1.55 μm. The spectra are all normalized to a reference waveguide.

Based on the transfer matrix method, the output intensity is given by [10]:

$$I_{out} = \frac{T^2 \exp(-\alpha l_2)}{\left[1 - R\exp(-\alpha l_2)\right]^2 + 4R\exp(-\alpha l_2)\sin^2\left(\beta L_{eff}\right)} I_{in} \qquad (1)$$

where I_{in} and I_{out} are the input and output intensities, respectively, T and R are the transmissivity and reflectivity of the Sagnac loop mirrors, respectively, α and β are the average loss factor and propagation constant of the silicon waveguide, respectively, and $L_{eff} \approx 319$ μm is the effective length of the FP cavity accounting for the two Sagnac loops and the straight waveguide in between. From the equation, it can be seen that the output spectrum is determined by the Sagnac loop reflectivity and the waveguide loss. Using R and α as the fitting parameters, we get the theoretical spectrum as shown by the dashed red line in Fig. 2(f), which agrees well with the experimental result. Upon fitting, the Sagnac reflectivity *R* is deduced to be ~0.93 and waveguide propagation loss is ~2 dB/cm around 1.55 μm.

The transmission spectrum of the FP comb filter can be tuned by forward- or reverse-bias of the interleaved PN diode. Figs. 3(a) and (b) show the shift of transmission spectrum upon forward- and reverse-biases, respectively. With forward bias, free-carriers are injected across the junction, resulting in a blue-shift of the resonance. At 5 mA, the resonance is blue-shifted by ~1 nm (one FSR) while the extinction ratio is reduced by 17 dB due to the free-carrier induced optical loss, and the associated power consumption is ~6 mW. In contrast, with reverse bias, free carriers are depleted near the junction, inducing a red-shift instead. At -10 V, the resonance is red-shifted by ~0.05 nm without significant change in extinction ratio.

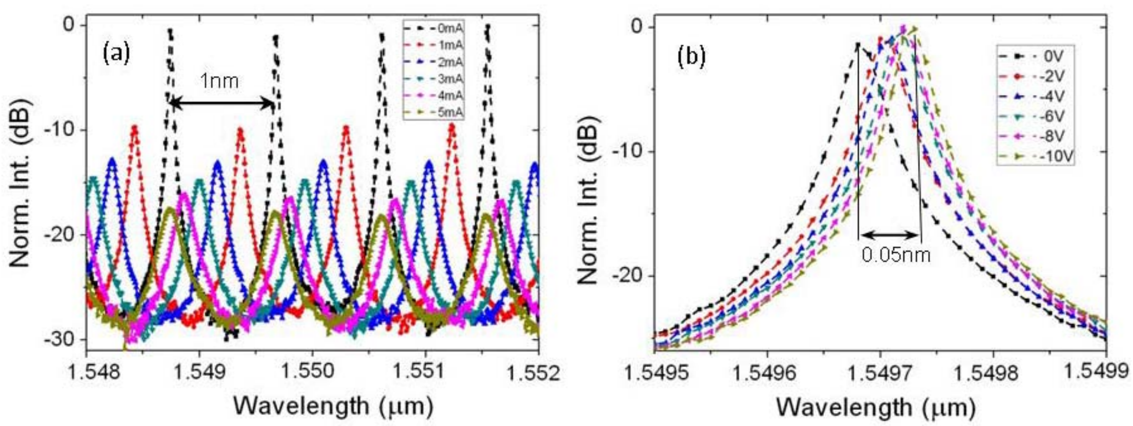

Fig. 3. Transmission spectra tuning under (a) forward and (b) reverse biases.

4. Conclusion

Tunable silicon comb filters based on FP resonators formed by Sagnac loop mirrors have been experimentally demonstrated. Electrical tuning is enabled by periodically-interleaved PN junctions inside the FP resonators. The resonances around 1.55 μm wavelength show a Q-factor of ~52,000, FSR of ~1 nm, and an extinction ratio of ~28 dB. The comb lines are blue-shifted by ~1 nm (one FSR) with 5 mA forward current and red-shifted by ~0.05 nm with -10V reverse bias voltage.

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