Enhanced Nonlinear Thermo-optic Effect in Silicon Microring Resonators with p-i-p Microheaters for Non-reciprocal Transmission

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Abstract: We report the enhancement of nonlinear thermo-optic effect in silicon microring resonators integrated with p-i-p microheaters. Non-reciprocal transmission is achieved at low input power of 32.4 μW with a non-reciprocal transmission ratio of ~19 dB.

OCIS codes: (130.3120) Integrated optics devices; (230.3240) Isolators; (230.5750) Resonators.

1. Introduction

The nonlinear thermo-optic wavelength shift in optical resonators has attracted much interest as it can be employed in optical bistable devices [1-3] and non-reciprocal devices [4-6]. The relatively large thermo-optic coefficient of silicon, $\partial n/\partial T=1.86\times10^{-4}$ K^{-1}, permits a large resonance wavelength shift in silicon resonators. However, the operation of some devices based on the nonlinear thermo-optic effect still requires high input power, which limits their practical applications. For example, the input power has to be several milliwatts high in order to obtain useful non-reciprocal transmission [5, 6]. Several methods have been proposed to increase the nonlinear thermo-optic wavelength shift. One approach is to use ultra-high Q resonators to increase the stored optical energy in the cavities [3], but it simultaneously reduces the operation bandwidth. Another solution is to thermally isolate resonators from their substrates [2], but the temporal response becomes slower.

In this paper, we report the enhancement of nonlinear thermo-optic effect in silicon microring resonators by using p-i-p type microheaters. The p-i-p microheaters have recently been employed in tunable Vernier filters [7] and lattice filters [8], which shows higher tuning efficiency and faster temporal response than conventional metal heaters. Low-power non-reciprocal transmission is demonstrated based on two cascaded microrings. The non-reciprocal transmission ratio (NTR) is ~19 dB around 1557.45 nm with 32.4 μW input power.

2. Enhancement of nonlinear thermo-optic effect

Figure 1 shows the 3-D perspective view of the microring resonators with two bus waveguides. We embed p-i-p type microheaters into the microring waveguide to tune the microring resonators, as shown in the inset. The waveguide width is 500 nm and the waveguide height is 220 nm with a thin slab of 60 nm thick. The radius of the microring is 10 μm. The gap between the ring and the bus waveguide is 200 nm. The measured coupling loss is ~19.4 dB around 1560 nm wavelength. The details of the device fabrication can be found in Ref. [7].

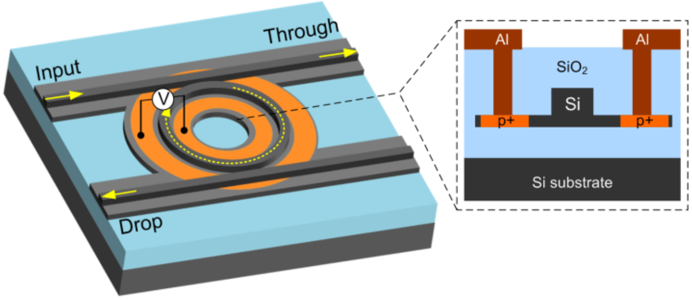

Fig. 1. Schematic illustration of the microring resonator integrated with a p-i-p type microheater. Inset: cross-sectional view of the p-i-p microheater.

We use the Agilent loss and dispersion analyzer (86038B) to characterize the device transmission performances. A continuous-wave tunable laser source with a 10 pm sweeping step is amplified by Erbium-doped fiber amplifier (EDFA) followed by a variable optical attenuator (VOA) to adjust the input optical power. An external voltage source is used for active tuning via a pair of metal probes.

Figure 2(a) shows the measured transverse-electric (TE) polarization transmission spectra of the through port with no voltage applied to the p-i-p microheater. The input optical power varies from 20.4 μW to 813 μW. At low optical powers, the resonance dip is symmetric with a full-width-half-maximum (FWHM) width of 0.158 nm, corresponding to a Q-factor of ~9800. The extinction ratio of the resonance is ~21 dB. As the input power increases, the resonance wavelength redshifts due to the optical power induced thermo-optic effect of silicon. The increase of input optical power from 20.4 μW to 813 μW makes the resonance shift ~0.185 nm. No pronounced asymmetric resonance dip is observed, indicating that the microring is working in the linear regime even when the input power is 813 μW. Fig. 2(b) and (c) show the measured spectra when the applied voltage is 5 V and 10 V, respectively. The resonance shifts more when the input power increases. The maximum redshift is 0.541 nm at 5V and 1.05 nm at 10 V. It suggests that the resonance thermo-optic shift is enlarged with the increasing voltage. It can also be seen that the resonance dips become asymmetric at both 5 V and 10 V when the input power increases to 813 μW. The FWHM width of the resonance is expanded to 0.243 nm at 10 V. Fig. 2(d), (e) and (f) show the corresponding spectral responses of the drop port. The excess loss of the drop port at the resonance wavelength is ~8.6 dB. The enhancement of nonlinear thermo-optic effect after tuning on the p-i-p microheater is also observed at the drop port.

The enhancement of nonlinear thermo-optic wavelength shift can be explained as follow. As for the p-i-p microheaters, it is the waveguide itself that works as a resistive heater to generate heat. The stored optical energy in the microring cavity at the resonance wavelength is much higher than that at the non-resonance wavelength. As a consequence, the generated free-carries due to two-photon absorption and surface states absorption are much more at resonance wavelength, leading to reduced resistance of the p-i-p microheater. When a constant voltage source is used, the generated heat at the resonance wavelength is thus higher according to the ohm’s law, therefore resulting in a larger redshift and a more asymmetric resonance profile. Such an effect is more pronounced with the increase of input optical power and bias voltage, since more heat is generated on resonance either by reducing resistance or increasing driving voltage.

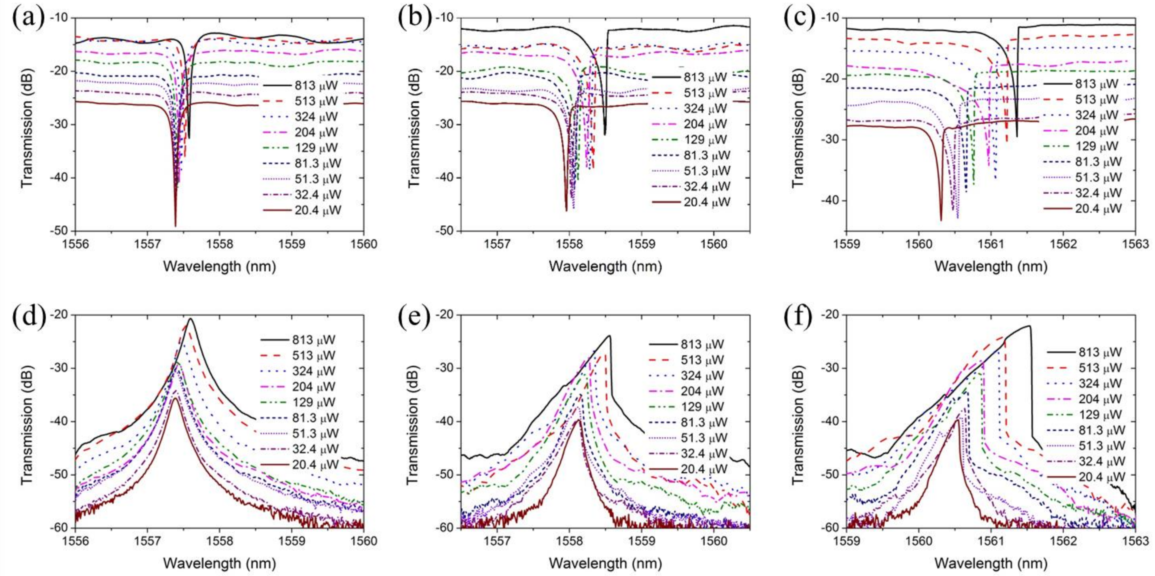

Fig. 2. Measured transmission spectra under multiple input optical powers for (a)-(c) through port and (d)-(f) drop port. The applied voltage on the p-i-p microheater is: (a) and (d) 0V, (b) and (e) 5V, and (c) and (f) 10 V.

3. Non-reciprocal optical transmission

Based on the above enhanced nonlinear thermo-optic effect, we configure a non-reciprocal transmission device by cascading two tunable microring resonators as shown in Fig. 3(a). The radii of the two microrings are 11 μm and 10 μm for the 1st and 2nd microrings, respectively. The other parameters are the same as described in the previous section. Note that through-port transmission is used for the 1st ring while drop-port transmission is used for the 2nd ring. We only tune the 1st microring for convenience in our experiment, although in principle the two microrings can be simultaneously tuned to freely set the operation wavelength. Forward and backward transmissions are obtained by switching the input and output fibers. We apply a voltage of 9.1 V to the 1st microring, so that the two microrings both resonate at 1557.45 nm. The other resonances are misaligned due to the Vernier effect. The working principle of the non-reciprocal transmission is similar to the previous work [4, 5]. In the forward direction, input light at 1557.45 nm wavelength passes the 1st microring with low insertion loss due to the strong nonlinear thermo-optic shift, and is then dropped by the 2nd microring, leading to a high transmission. In the backward direction, input light reaches the 1st microring at a lower power level as it first suffers the drop-port transmission loss (8.6 dB) of the 2nd microring. Therefore, the 1st microring resonance has less redshift, with the light residing in the resonance notch and hence suffering a high attenuation.

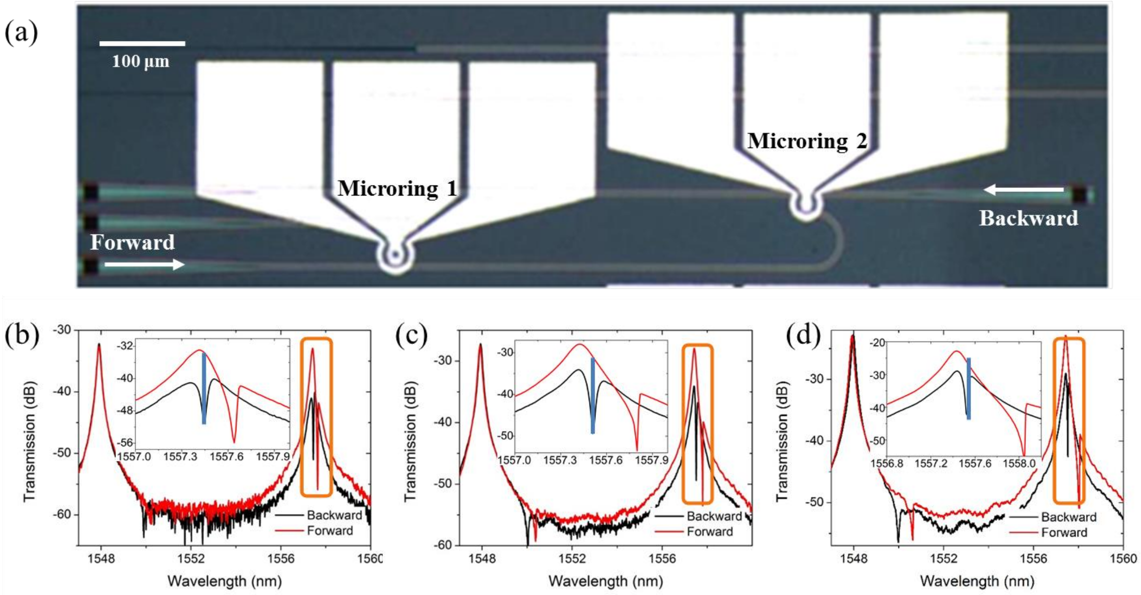

Fig. 3. (a) Microscope image of our fabricated non-reciprocal device composed of two cascaded microring resonators each integrated with a p-i-p microheater. (b)-(d) Measured forward and backward transmission spectra at input powers of (b) 32.4 μW, (c) 81.3 μW, and (d) 204 μW. Insets show the zoom-in view around the non-reciprocal transmission wavelengths.

Fig. 3(b), (c), and (d) show the measured forward and backward transmission spectra at three input power levels. Around 1547.9 nm resonance, forward and backward spectra are almost the same. When the input power is 32.4 μW, the non-reciprocal transmission is achieved at 1557.45 nm wavelength with an NTR of ~19 dB. The input power is almost two-orders smaller than that in Ref. [5, 6]. As the input power increases, the maximum NRT is still larger than 18 dB. However, the operation wavelength redshifts with the input power as seen from the insets in Fig. 3(c) and (d). A larger NTR can be realized by further increasing the resonance extinction ratio of the 1st microring and/or designing asymmetric coupling for the 2nd microring [5].

4. Conclusion

We experimentally demonstrated that the nonlinear thermo-optic effect in silicon microring resonators can be greatly enhanced with p-i-p microheaters. The nonlinear thermo-optic resonance shift is 1.05 nm when the input power increases from 20.4 μW to 813 μW at 10 V, which is nearly 6.7 times larger than without tuning. Non-reciprocal optical transmission was also demonstrated with NRT of ~19 dB at 32.4 μW input power.

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