Ultra-high-efficiency Tunable Silicon Photonic Filter

Hongyuan Cao[a], Huan Li[a], Daoxin Dai*[a]

[a]State Key Laboratory for Modern Optical Instrumentation, College of Optical Science and Engineering, International Research Center for Advanced Photonics, Zhejiang University, Hangzhou, China, 310058

ABSTRACT

Optical tunable filters play a key role in silicon photonic integrated circuits. Highly energy-efficient tunability and a wide continuous tuning range are strongly desired for silicon photonics filters. All-optically thermo-optic (TO) tunable devices based on the light absorbers integrated close to the silicon structure as localized heaters have attracted increasing attention because optical heaters, compared with electrical ones, can greatly reduce thermal loads and heat leakage for the device. They provide a new approach to implementing high-efficiency TO tuning with a fast response. In this work, we propose and experimentally demonstrate an on-chip all-optically tunable filter based on a suspended silicon microdisk resonator with an ultra-compact optical heater, which is a platinum absorber deposited directly on the top of the ridge waveguide. Attributed to the novel optical pumping scheme, ultra-small device size, and suspended waveguide structure, an ultra-high tuning efficiency of 37.70 nm/mW is achieved. Only 1.405 mW pump power is required to tune the single-resonance filter over a wide spectral range of ∼54.5 nm. The demonstrated tunable optical filter has the advantages of high tuning efficiency, compact footprint, and simple fabrication processes, which has significant applications for on-chip all-optical systems.

Keywords: Silicon photonics, all-optical tuning, tunable filters, microdisk resonator, high tuning efficiency, wide tuning range, suspended structures, photothermal effect

1. INTRODUCTION

Optical tunable filters are one of the key elements in silicon photonic integrated circuits, which can be widely used in optical signal processing, wavelength division multiplexing (WDM), and infrared spectrometry systems due to their versatility in a variety of applications[1]. Highly energy-efficient tunability and a wide continuous tuning range are strongly desired for silicon photonics filters. Compared with electro-optic (EO) tuning based on carrier injection/depletion, thermo-optic (TO) tuning features significantly wider tuning ranges, lower insertion loss, and simpler fabrication processes. Therefore, TO tuning is indispensable for on-chip devices. Typical TO tuning is accomplished by using resistive micro-heaters on silicon waveguides[2]. However, metallic wires are required for the electrical power supply for the micro-heaters, which leads to extra thermal loads and heat leakage channels. In addition, a silica cladding layer between the silicon waveguides and the metallic micro-heaters is usually needed to avoid light absorption caused by the metal, which also limits the heating efficiency. As a result, numerous strategies to enhance heating efficiency have been proposed, including transparent graphene nano-heaters[3], suspended waveguide structures[4], and photothermal effects[5]. Among these schemes, all-optically TO tunable devices as an alternative have attracted increasing attention. All-optically TO switches with high tuning efficiency has been demonstrated with light absorbers integrated close to the silicon structure as localized heaters. The optical heaters can be powered by a pump beam through an optical waveguide[6] or free space[7], which can greatly reduce thermal loads and heat leakage for the device compared with electrical heaters. They provide a new approach to implementing high-efficiency on-chip TO tuning with a fast response.

In this paper, we propose and experimentally demonstrate an on-chip all-optically tunable filter based on a suspended silicon microdisk resonator (MDR) with an optical heater, which is a metal film deposited directly on the top of the ridge waveguide. Attributed to the novel optical pumping scheme, ultra-small device size, and suspended waveguide structure, an ultra-high tuning efficiency of 37.70 nm/mW is achieved, which is ~2 times as much as the best result reported previously[8]. The device shows a single resonance with a continuous tuning range, and only 1.405 mW pump power is required to tune the filter over a wide spectral range of ∼54.5 nm. Moreover, by integrating an ultra-compact optical heater directly on the silicon, the present filter features a compact footprint and simple fabrication processes. The demonstrated energy-efficient tunable device has wide applications in on-chip optical signal processing, WDM, and infrared spectrometry.

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2. PRINCIPLE AND DESIGN

Fig. 1 (a) shows the three-dimensional (3D) view of the proposed all-optically tunable filter based on a suspended silicon MDR, whose cross-section is illustrated in Fig. 1 (b). This device consists of a side-coupled MDR, a near-infrared probe waveguide, and a pump waveguide with a metal film directly deposited on the top. When the pump beam is coupled to the pump waveguide and reaches the metal film, it is absorbed and then converted to heat. Then, the heat quickly transfers into the MDR through the silicon slab between the two waveguides. As a result, the increase in temperature causes a change in the refractive index of silicon. Because silicon has a positive TO coefficient of ~1.8×10^{-4}/K, the resonant wavelength redshifts proportionally to the pump power. Therefore, the all-optically tunable filter can be implemented on the chip.

The silicon-on-insulator (SOI) platform with 220-nm-thick top silicon is chosen to design our device. The waveguides and MDR are shallowly etched with a depth of 170 nm, which are suspended between air trenches. The air trenches can provide excellent thermal insulation and the heat generated by an optical heater can be localized around the MDR due to the lower thermal conductivity and limited convection of the air. The radius of the MDR is only 1.5 μm. To achieve critical coupling, the gap between the MDR and probe waveguide is set to 80 nm, and the ridge width of the probe waveguide is 400 nm. The pump waveguide has a ridge width of 500 nm to enhance the light absorption of the metal. We choose platinum (Pt) as the metal absorber due to its excellent chemical and thermal stability and broadband absorption. The width, thickness, and length of the Pt film are 900 nm, 100 nm, and 2.5 μm, respectively. To prevent excessive absorption loss from the metal, the distance between the metal absorber and MDR is adjusted to 400 nm.

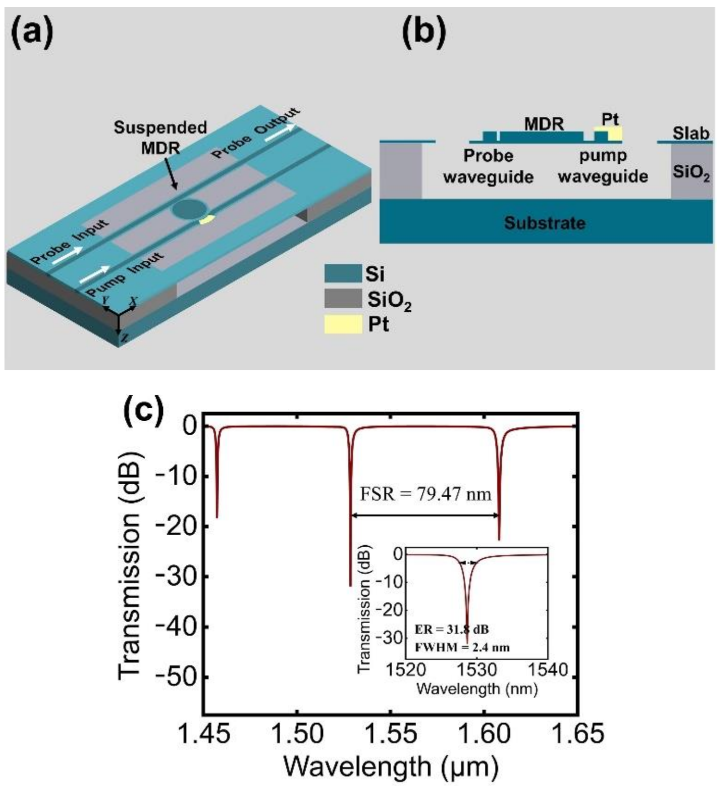
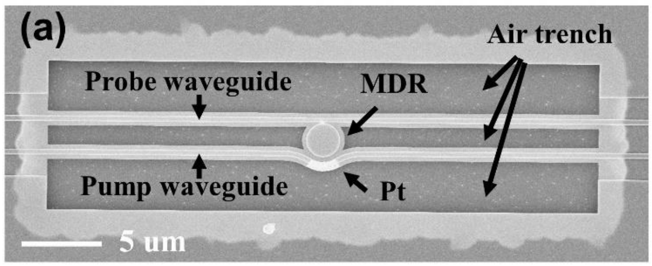


Figure 1. (a) 3D view and (b) yz cross-section of the all-optically tunable filter based on a suspended silicon MDR. (c) Simulated transmission spectrum of the suspended MDR. Inset: the transmission spectrum around the resonance of 1528.66 nm.

Fig. 1(c) shows the simulated transmission spectra of the suspended MDR by using FDTD Solutions. The simulated insertion loss is as low as 0.02 dB. Due to the very small size of the MDR, only the fundamental whispering gallery modes are supported here and the free spectral range (FSR) near 1550 nm is as large as 79.47 nm. The transmission spectra around the resonance of 1528.66 nm are also shown in the inset. The corresponding extinction ratio (ER) and full width at half maximum (FWHM) are 31.8 dB and 2.4 nm, respectively. As a result, the wavelength shifts of the resonance of 1528.66 nm are utilized in our experiment.

3. FABRICATION AND CHARACTERIZATION

The fabrication processes were started on an SOI wafer with a 220 nm-thick silicon top layer on a 2 μm-thick buried silica layer. The ridge waveguides, MDR, air trenches, and grating couplers were fabricated with E-beam lithography (EBL) followed by an inductively coupled plasma (ICP) etching process. Then, a 100-nm-thick Pt heater was sputtered on the pump waveguide. The heater was fabricated by an EBL lift-off process with an extremely small footprint of ~0.9 μm × 2.5 μm. Finally, the silica layer beneath the MDR and waveguides was removed with a dilute hydrofluoric acid solution to form the suspended structure. The length and width of the air trenches for thermal insulation are approximately 50 and 13 μm, respectively. The scanning electron microscope (SEM) image of the fabricated device is shown in Fig. 2(a). The suspended MDR is supported by the silicon ridge waveguide.



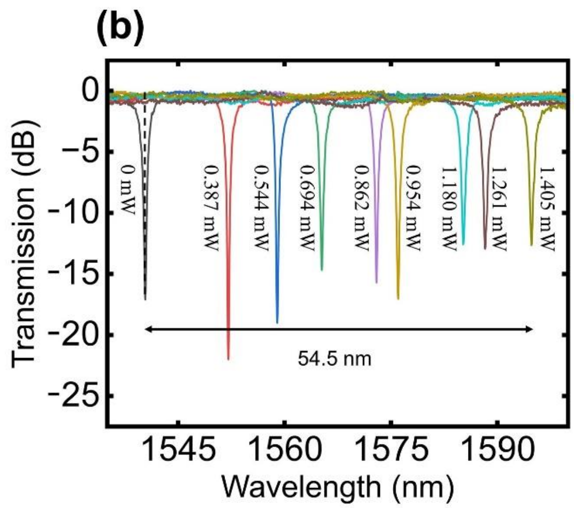


Figure 2. (a) Top-view SEM image of the fabricated device. (b) Measured transmission spectra of the all-optically tunable filter with different pump powers. The ER is shown by the dashed line at the first resonant peak.

To measure the static characteristics of the device, a continuous-wave (CW) laser was used as the pump light source with a central wavelength of 1957 nm. The transmission spectra of the filter were measured with an amplified spontaneous emission (ASE) light source and an optical spectrum analyzer at the input and output of the probe waveguide, respectively. Fig. 2(b) shows the transmission spectra of the fabricated all-optically tunable filter with different pump powers. When no pump power is applied, the center wavelength and the FWHM are 1540.36 nm and 1.30 nm, respectively. With the pump power increasing to 1.405 mW, the center wavelength and the FWHM of the redshifted resonance are 1594.82 nm and 1.28 nm, respectively. Experimental results show that the filter achieves a wide single-resonance tuning range of greater than 54.5 nm, while the ER is consistently greater than 13 dB. The tuning efficiency is ~37.70 nm/mW according to the linear fit of the center wavelength shifts versus the pump powers. The pump power for full-FSR (~76.64 nm) tuning is estimated to be ~2.033 mW.

4. CONCLUSION

In conclusion, we have proposed and experimentally demonstrated an on-chip all-optically tunable filter based on a suspended silicon MDR with an ultra-compact optical heater. The measured tuning efficiency is as high as 37.70 nm/mW. Only 1.405 mW pump power is required to tune the single-resonance filter over a wide spectral range of ~54.5 nm. To the best of our knowledge, the demonstrated all-optically filter has the highest tuning efficiency and widest tuning range in TO tunable silicon photonic filters. In addition, by integrating an ultra-compact optical heater directly on the silicon, the present filter features a compact footprint and simple fabrication processes, which has potential applications in an all-optical network-on-chip.

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