CMOS-compatible Athermal Tunable Silicon Optical Lattice Filters

Liangjun Lu, Linjie Zhou*, Xiaomeng, Sun, Jingya Xie, Zhi Zou, Xinwan Li, and Jianping Chen
State Key Laboratory of Advanced Optical Communication Systems and Networks,
Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
**ljzhou@sjtu.edu.cn*

Abstract: We present a CMOS-compatible temperature-independent tunable silicon lattice filter composed of 10 cascaded 2×2 asymmetric Mach-Zehnder interferometers. Experiments show the device has a wide wavelength tuning range and low temperature sensitivity of ~6.2 pm/^{o}C.
OCIS codes: (130.3120) Integrated optics devices; (130.7408) Wavelength filtering devices; (230.7408) Wavelength filtering devices.

1. Introduction

Silicon waveguide devices and circuits are one of the most promising waveguide platforms for optical communication and interconnect applications, because of their compact size and easy integration with microelectronic circuits. However, high temperature sensitivity is one of the fundamental limitations for silicon waveguide devices, such as ring resonators, Mach-Zehnder interferometers (MZIs), and arrayed waveguide gratings (AWGs), because silicon has a large thermo-optic coefficient of 1.86×10^{-4} K^{-1}. Indeed, silicon ring resonators have a temperature sensitivity of ~110 pm/K [1], and silicon MZIs and AWGs show the temperature dependent wavelength shifts of about 80 pm/K [2]. Several approaches have been proposed to reduce the temperature sensitivity; however, most of the approaches are either not compatible with CMOS process [3, 4] or power hungry [5]. One choice is to use an asymmetric Mach-Zehnder interferometer (MZI) structure, which has been theoretically analyzed and experimentally demonstrated [1, 2, 6]. However, to the best of our knowledge, there are no reports on reducing the temperature dependence of optical lattice filters, which are widely applied for (de)multiplexing and dispersion compensation with the advantages of design flexibility and large free spectral ranges (FSR) [7, 8].

In this paper, we present a CMOS-compatible temperature-independent tunable silicon optical lattice filter based on cascaded athermal MZIs, which shows a wide wavelength tuning range and low temperature sensitivity of ~6.2 pm/^{o}C near 1.55 μm wavelength.

2. Device structure and fabrication

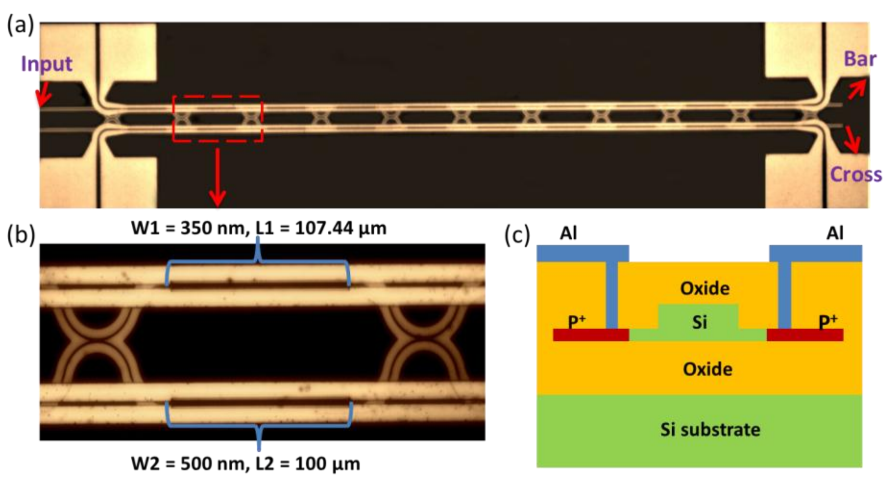

Fig. 1. (a) Microscope image of the proposed device. (b) Zoom-in view of one MZI stage. (c) Cross-sectional schematic of the p-i-p junction-based micro-heater.

Fig. 1(a) shows the optical microscope image of the proposed device which consists of 10 cascaded 2×2 MZIs. Fig. 1(b) shows one stage of the asymmetric MZI structure with the waveguide width and length labeled in the figure. The width and length of the MZI arms are designed carefully to cancel the temperature-induced phase shifts in the two arms [2]. The narrow waveguide (350 nm width) in the up arm is connected with 4-μm-long tapers to regular waveguides (500 nm width). The 2×2 couplers in the MZIs are based on directional couplers. The phase shifters are embedded in both up and bottom arms which are composed of lateral p-i-p junctions as schematically shown in Fig. 1(c). The rib waveguide slab height is 60 nm. The two highly doped P^+ regions are separated by 600 nm away from the edges of the rib waveguide. The intrinsic region has a high resistivity and works as a micro-heater. Heat will be generated there when an electric current flows through the resistor. It should be noted that it is the waveguide itself that make up the thermal resistor, and therefore, the generated heat directly interacts with the optical mode.

We used a SOI wafer with a top silicon layer thickness of 220 nm and a buried oxide layer thickness of 2 μm for the device fabrication. The top silicon layer was p-type lightly doped with a resistivity of 10 to 15 Ohm·cm (corresponding to a hole concentration of ~10^{15} cm^{-3}). We employed 248-nm deep ultra-violet (DUV) photolithography to define the device patterns and plasma dry etch with an etched depth of ~160 nm to transfer the patterns onto the silicon device layer. We implanted boron (~10^{20} cm^{-3}) dopants to form the P^+ doped regions for ohmic contact. After depositing a 1 μm thick silicon dioxide layer using plasma-enhanced chemical vapor deposition (PECVD) as the device upper-cladding, contact holes were etched through. Finally, we sputtered and patterned aluminum to form electrical connection.

3. Experimental results

We used the Agilent loss and dispersion analyzer (86038B) to characterize the device transmission performances. Light is coupled into and out of the device through on-chip inverse tapers with a tip width of 180 nm. The active tuning of the device was performed by applying an external current to the thermal resistor via a pair of metal probes. In order to characterize the device thermal sensitivity, we positioned a thermoelectric cooler (TEC) and a temperature sensor beneath the chip so that the device temperature can be accurately tuned and monitored.

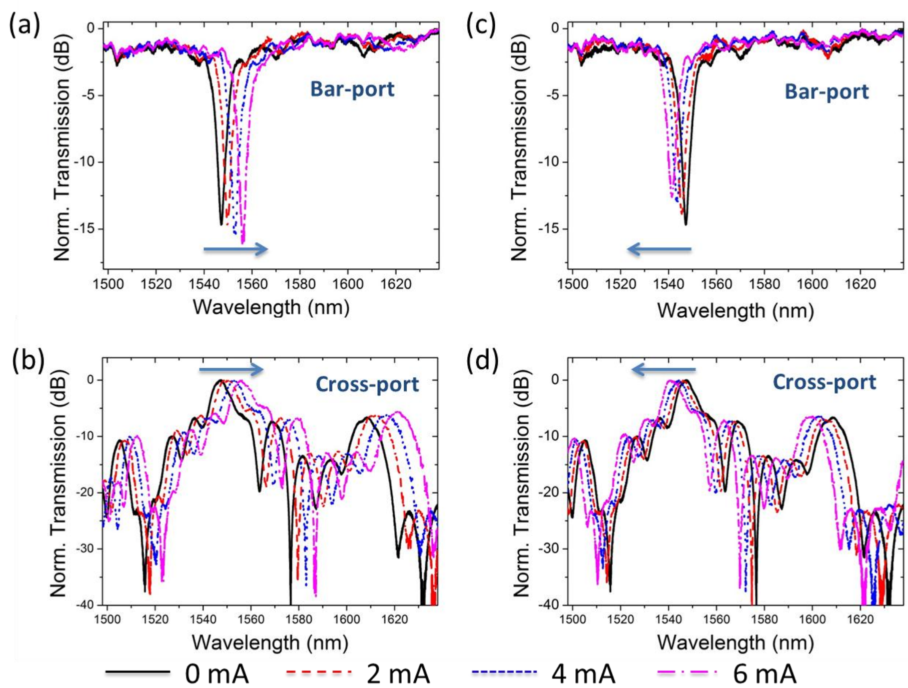

Fig. 2. Tuning of transmission spectrum under various electric currents from 0 to 6 mA with a step of 2 mA. (a) and (b): current is applied to the up arms. (c) and (d): current is applied to the bottom arms.

Fig. 2 shows the measured transmission spectra of the bar- and cross-ports of the proposed device with thermal tuning in the up and bottom arms of the MZIs. The extinction ratio of the bar-port is ~13 dB. The extinction ratio of the cross-port, defined as the intensity difference between the main peak and the first sidelobe, is ~7 dB. The 3-dB bandwidth of the lattice filter is ~7.8 nm. There is only one filtering band observed over the measured spectral range from 1495 nm to 1640 nm. The filter central wavelength shifts to a longer/shorter wavelength when the up/bottom arms are tuned. The overall wavelength shift is ~15 nm within power consumption of ~140 mW. The thermal tuning efficiency is ~0.107 nm/mW. The extinction ratio slightly changes upon tuning in that the coupling coefficient of the 2×2 couplers is wavelength dependent.

Figs. 3(a) and (b) show the measured transmission spectra of the optical lattice filter at various temperatures. It can be seen that temperature-induced spectrum shift is wavelength dependent. The spectrum redshifts with the rising of temperature at the longer wavelength side (~1.6 μm), while it slightly blueshifts at the shorter wavelength side (~1.5 μm). The temperature insensitive operation window is around 1.55 μm wavelength as seen from the insets of Figs. 3(a) and (b). By linear fitting the filter central wavelength shift with temperature, the thermal sensitivity dλ/dT of the lattice filter can be extracted as shown in Figs. 3(c) and (d). The thermal sensitivity is around -6.2 pm/^{o}C in the temperature range of 30 ^{o}C to 80 ^{o}C, which is more than one order smaller than that of regular silicon optical filters. It should be noted that, although the filter central wavelength is almost temperature independent, it can still be thermally tuned by locally heating the up or bottom arms of the lattice filter as shown in Fig. 2.

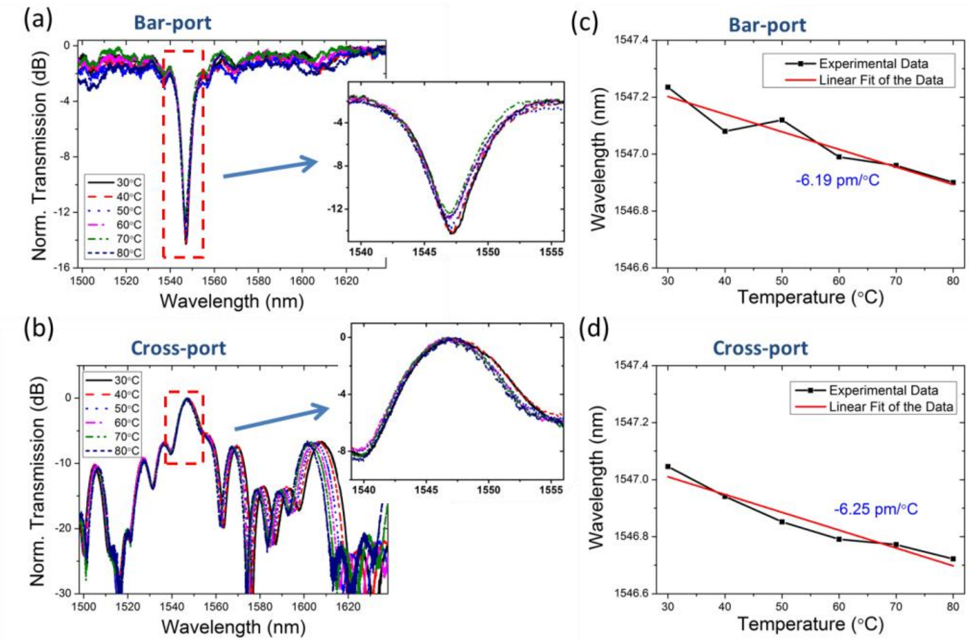

Fig. 3. (a) and (b) Transmission spectrum shift of the (a) bar-port and (b) cross-port at various temperatures. The insets show the zoom-in at 1.55 μm wavelength. (c) and (d) Extracted central wavelength change with temperature for the (c) bar-port and (d) cross-port.

4. Conclusion

CMOS-compatible athermal tunable silicon optical lattice filters were proposed, fabricated and experimentally demonstrated. Experiment results show the filter central wavelength can be tuned by ~15 nm within power consumption of ~140 mW. Temperature sensitivity measurements show that the temperature dependent wavelength shift is ~6.2 pm/^{o}C, improved by more than one order compared to regular designs. The extinction ratio and cross-talk of the lattice filter can be further improved by optimizing (apodizing) the coupling ratio in each MZI.

Acknowledgements

This work was supported in part by 973 program (ID2011CB301700), the National Natural Science Foundation of China (NSFC) (61007039, 61001074), the Science and Technology Commission of Shanghai Municipality (STCSM) Project (10DJ1400402). We also acknowledge IME Singapore for device fabrication.

References

[1] B. Guha, B. B. C. Kyotoku, and M. Lipson, "CMOS-compatible athermal silicon microring resonators," Opt. Express **18**, 3487-3493 (2010).
[2] M. Uenuma and T. Moooka, "Temperature-independent silicon waveguide optical filter," Opt. Lett. **34**, 599-601 (2009).
[3] J. Teng, P. Dumon, W. Bogaerts, H. Zhang, X. Jian, X. Han, M. Zhao, G. Morthier, and R. Baets, "Athermal Silicon-on-insulator ring resonators by overlaying a polymer cladding on narrowed waveguides, " Opt. Express **17**, 14627-14633 (2009).
[4] L. Zhou, K. Okamoto, and S. J. B. Yoo, "Athermalizing and trimming of slotted silicon microring resonators with UV-sensitive PMMA upper-cladding," IEEE Photonics Technol. Lett. **21**, 1175-1177 (2009).
[5] M. R. Watts, W. A. Zortman, D. C. Trotter, G. N. Nielson, D. L. Luck, and R. W. Young, "Adiabatic resonant microrings (ARMs) with directly integrated thermal microphotonics," in *Conference on Lasers and Electro-Optics (CLEO)* (Baltimore, MD, 2009).
[6] B. Guha, A. Gondarenko, and M. Lipson, "Minimizing temperature sensitivity of silicon Mach-Zehnder interferometers," Opt. Express **18**, 1879-1887 (2010).
[7] K. Yamada, T. Shoji, T. Tsuchizawa, T. Watanabe, J. Takahashi, and S. Itabashi, "Silicon-wire-based ultrasmall lattice filters with wide free spectral ranges," Opt. Lett. **28**, 1663-1664 (2003).
[8] S. Ibrahim, N. K. Fontaine, S. S. Djordjevic, B. Guan, T. Su, S. Cheung, R. P. Scott, A. T. Pomerene, L. L. Seaford, C. M. Hill, S. Danziger, Z. Ding, K. Okamoto, and S. J. B. Yoo, "Demonstration of a fast-reconfigurable silicon CMOS optical lattice filter," Opt. Express **19**, 13245-13256 (2011).