International Journal of
Sensor Networks and Data Communications

San-min et al., Int J Sens Netw Data Commun 2018, 7:2
DOI: 10.4172/2090-4886.1000155

Research Article Open Access

Optical Multi-ring Cascade Cavity Temperature Sensor with Ultra-High Sensitivity

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Abstract

An ultra-small integrated photonic ten-order resonators temperature sensor has been proposed and demonstrated and fabrication using well-developed MEMS technologies incorporates a silicon ring resonator. The temperature variation is measured by monitoring the shift in the ten-order resonant wavelength of the silicon resonator, which was induced by the thermo-optic effect and the thermal expansion effect. The best achieved sensitivity is about 130 pm/°C for a waveguide width of 450 nm, and the radius of the micro ring is about 5 μm. Meanwhile, the two-channel sensor based on double racetrack rings is also reported.

Keywords: Ten-order resonators; Temperature sensor; Thermo-optic effect; Thermal expansion effect

Introduction

Recently silicon photonics technology has received much attention for application in optical communications, temperature sensor, high speed optical modulators, circuit integrated and detectors integrated with silicon waveguides [1-6]. Therefore, high-Q optical waveguide cavity has been widespread concern due to its high integration, small volume mode and high sensitivity. Recently, a lot of articles on the temperature characteristics of the silicon micro-ring resonator or fiber-optic temperature sensors based on Bragg gratings were mainly attempted featuring a high sensitivity and easy fabrication [7,8]. But integrate electrical/optical cascade resonators temperature characteristics have not been reported. The high index contrast waveguides are very sensitive to small variations in dimension, refractive index, and especial temperature [9,10]. Meanwhile, the ultra-small dimension of the silicon resonator is expected to help extend the sensing temperature range due to its broad free spectral range (FSR) [11].

In the paper, we fabricated a high performance temperature sensing based on SOI ten-order micro ring resonators. The radius of the micro ring is about 5 μm, after thermal tuning, we achieved a high-efficiency temperature sensing function in the broadband range. Meanwhile, we fabricated a 2-channel temperature sensing based on a double ring, and obtain some meaningful testing results from these devices.

Design and Fabrication

As it all know that smaller dimensions are needed to keep waveguides single mode, and smaller gaps between waveguides are needed to allow weakly coupled structures with a limited length. High-index contrast structures are more sensitive to geometrical and refractive index deviations. The devices were fabricated with SOI material, with a top Si layer of 220 nm thicknesses, an isolation SiO_2 layer of 3 μm thickness and a cover SiO_2 layer of 2 μm thickness. The fabrication procedure was demonstrated as follows: SOI wafer pre-processing, photo resist coating, exposed in PMMA with the 50 kV EBL system, photography development, ICP etching around the Si waveguide core area, photo resist stripping, covering layer SiO_2 produced via plasma enhanced chemical vapor deposition (PECVD).

The structure of the device is illustrated in Figure 1. It shows the cross section of the waveguide, with a Si core area of 450 nm width and 220 nm height, a SiO_2 area of 2 μm cladding layer and a 3 μm isolation layer. The structure of the filters is illustrated in Figure 2. Figure 2a shows a scanning-electron micrographs (SEM) photograph of the micro ring resonator temperature sensor, including the bus line waveguide, drop line waveguide and a tenth-order micro ring resonator. From Figure 2a, we can figure out that the radius of the micro ring is about 5 μm and the gap between the micro ring and the straight waveguide is about 150 nm.

In addition, we fabricated high-order temperature sensor based on a single ring and a racetrack ring. Figure 2b shows a two channel temperature sensor based on double racetrack micro-ring. Figure 2c shows the sidewall of the waveguide about the gap areas.

Results

The optical measurement setup for the temperature sensor micro ring resonator is shown in Figure 3. In experiments, a tunable laser (1550 nm band) is used as the optical source to characterize responses of micro-ring resonators. Before the laser is coupled into the bus waveguide through a lensed single mode fiber tip, it will be enlarge through an erbium-doped fiber amplifier. To obtain a

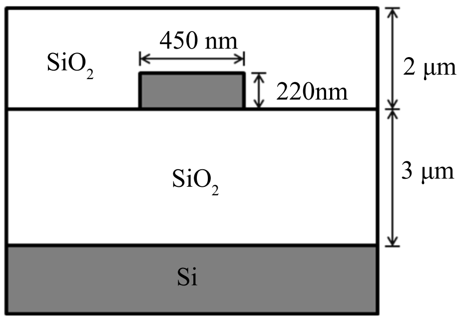

Figure 1: Crosssection of waveguides.

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Received May 21, 2018; **Accepted** May 26, 2018; **Published** June 05, 2018

Citation: San-min S, Jia-hao D, Shu-bin Y (2018) Optical Multi-ring Cascade Cavity Temperature Sensor with Ultra-High Sensitivity. Int J Sens Netw Data Commun 7: 155. doi: 10.4172/2090-4886.1000155

Citation: San-min S, Jia-hao D, Shu-bin Y (2018) Optical Multi-ring Cascade Cavity Temperature Sensor with Ultra-High Sensitivity. Int J Sens Netw Data Commun 7: 155. doi: 10.4172/2090-4886.1000155

power transmission spectrum, the laser wavelength is swept at a step continuously while the output power of each wavelength is recorded sequentially. The tunable range of laser wavelengths is 1520 –1570 nm. The output is collected by another lensed single mode fiber tip and then fed into a photodetector. Finally, the power transmission spectrum can be recorded via an oscilloscope or power meter connected with photodetector. The completed temperature sensor is evaluated by mounting it on a holder placed on a precision stage, whose temperature is adjusted by a built-in thermoelectric cooler and monitored in situ by a k-type thermocouple.

The normalized measured responses of the micro ring temperature sensor shown as Figure 4. It shows three peak responses at the length from 1528 nm to 1570 nm and the free spectral range (FSR) reaching ~18 nm, and the bandwidth ~0.14 nm. The corresponding quality factor (Q-factor) was ~11,000, which is high enough to allow for a high sensing resolution.

The thermo-optic (TO) coefficient of silicon is ~1.86 × 10^{-4}/°C. When the temperature varies, the refractive index of the silicon is altered by the TO effect and the response point of the ring is changed by the thermal expansion effect. The overall shift in the resonant wavelength Δλ is shown as [11,12]:

$$\Delta\lambda = \Delta\lambda_L + \Delta\lambda_T = m\alpha \frac{n_{eff}}{n_g}\lambda\Delta T + \frac{\sigma_T}{n_g}\lambda\Delta T \qquad (1)$$

where ΔλL and ΔλT are the shift of wavelength because of thermal expansion effect and TO effect respectively; neff is the effective index of the waveguide, ng is the group index of the waveguide, m is the number of the resonant, α is the coefficient of thermal expansion (CTE), ΔT is the temperature change, and σT is the rate of change of the effective index with the current temperature T, and it depends on the thermo-optic coefficient of the core material and cladding material. σT is calculated as follows:

$$\sigma_T = \frac{dn_{eff}}{dT} \qquad (2)$$

Some of the crucial parameters used for the analysis are: the TO coefficients of the SiO2 is ~ 1.0 × 10^{-5}/°C, and silicon is used substrate and the CTE α is ~2.6 × 10^{-6}/°C while that of the oxide layer is ignored due to the thickness of the silicon substrate is much larger than the oxide layer [11-13]. In this paper, the observed effective index and group index are neff = ~2.85 and ng = ~3.89, therefore, when the sensor wavelength changes 5.2 nm around 1550 nm, it can be calculated that the temperature variation of the waveguides is about 40°C shown as Figure 5.

From this theoretical result, we can draw this conclusion: when the temperature rises by 1°C, the resonant wavelength results in 110 nm. The relationship between wavelength and temperatures is shown as Figure 6. Compared with testing result of 130 nm/°C, we can see that the experiment coincides fairly well with theoretical calculation.

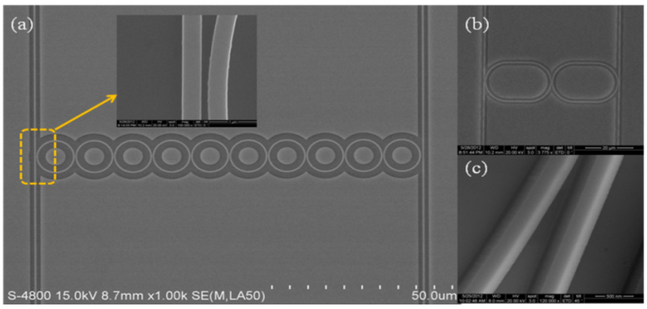

Figure 2: Structures of filters. (a) SEM of tenth-order temperature sensor. (b) SEM of a two-channel temperature sensor based on double racetrack ring. (c) SEM of the sidewall waveguide.

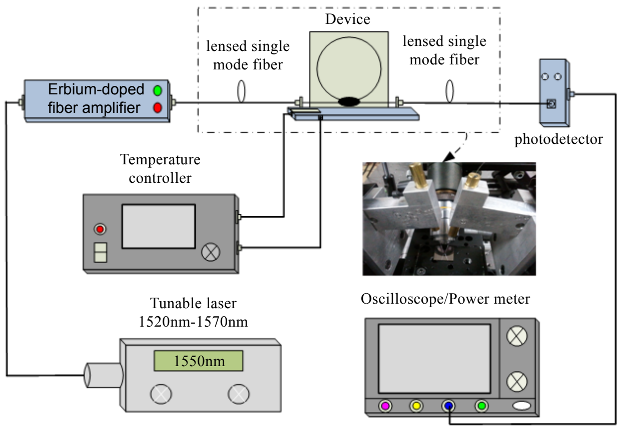

Figure 3: Schematic diagram of the measurement system.

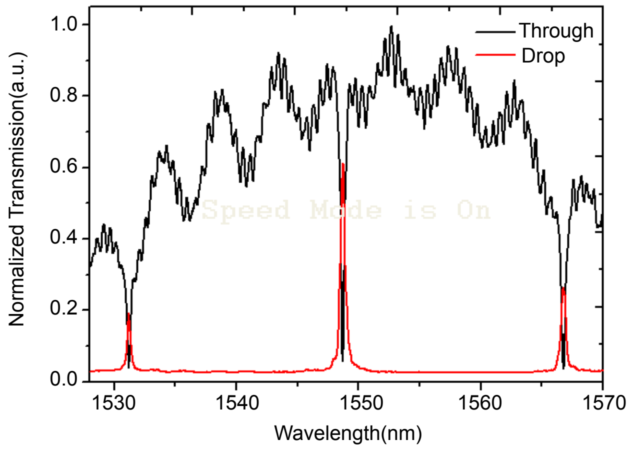

Figure 4: the response of the single micro ring temperature sensor.

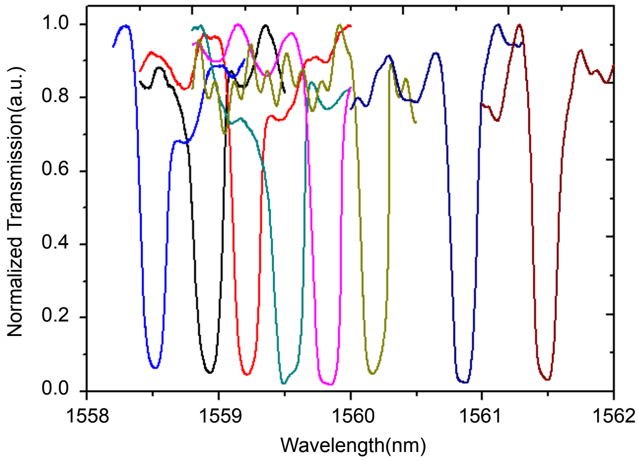

Figure 5: Normalized wavelength responses at different temperatures.

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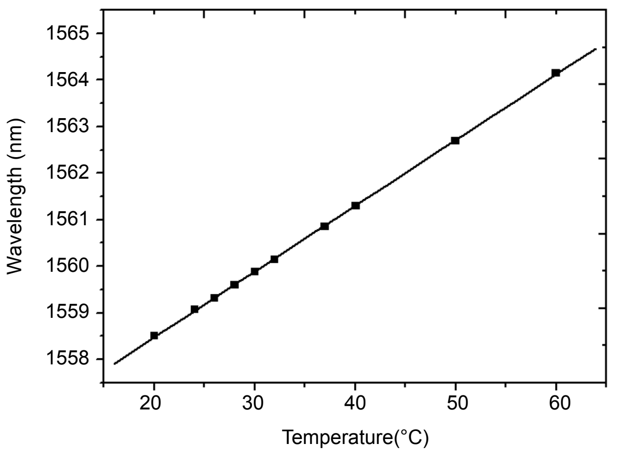

Figure 6: The relationship between wavelength and temperatures.

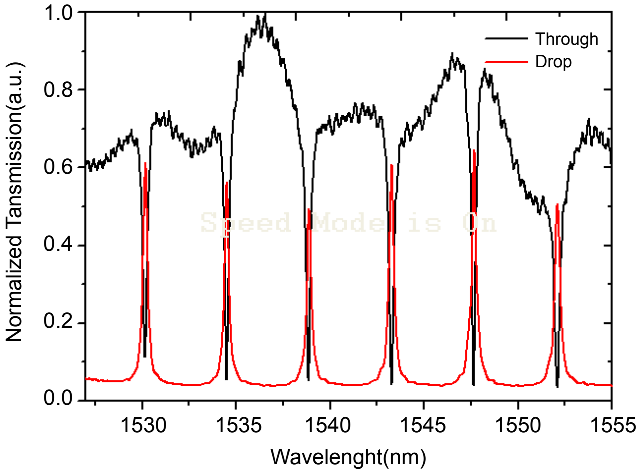

Figure 7: Normalized wavelength of two-channel sensor based on double racetrack rings.

The normalized measured responses of the double racetrack rings temperature sensor shown as Figure 7. It shows three peak responses at the length from 1529 nm to 1554 nm and the free spectral range (FSR) reaching ~4.4 nm.

Conclusion

In summary, a substantially miniaturized multi-ring photonic temperature sensor incorporating a silicon resonator was presented. A standard MEMS process was used to create the device. The influence of temperature upon the sensitivity was experimentally and theoretically examined. This device has 450 × 220 nm^2, large FSR (18 nm), and good linear thermo-optic effect (130 nm/°C). It is worth mentioning that the thermo-optic tuning bandwidth reaches 5.2 nm when temperature varies from 20 to 60.0°C. And the temperature-sensitive characteristics can be used for distributed temperature sensors, filter sensors, high-speed modulators, precision optical waveguide sensors. The demonstrated sensor affords to offer salient benefits like a low-cost, homogeneous integration into other electrical/optical devices in silicon.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant No.61675185), the National Natural Science Foundation of Shanxi Province (Grant No.201601D011008), the Fund Program for the Scientific Activities of Selected Returned Overseas Professionals in Shanxi Province, the Program for the Top Youngand Middle-aged Innovative Talents of Higher Learning Institutions of Shanxi, and the North University of China Science Fund for Distinguished Young Scholars.

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