Research Article

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High-sensitivity on-chip temperature sensor based on cascaded microring resonators

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Abstract: This article proposes an on-chip optical temperature sensor based on a cascaded microring resonator, which is composed of a reference ring and a sensing ring cascaded with different temperature sensitivities and free spectral ranges. By changing the temperature of the sensing window environment, the thermal optical effect of the waveguide causes a change in the refractive index of the waveguide, which affects the temperature sensitivity and free spectrum changes of the sensor. The output spectral response of the sensor shifts, achieving temperature sensing detection. The experimental results show that the temperature sensitivity of this microring cascaded temperature sensor is 303.6 pm/°C, which is 3.65 times the limit of a single microring temperature sensitivity of 83 pm/°C. The temperature-sensing range of the sensor is 100°C, which can well meet the temperature-monitoring requirements of ultra-large-scale integrated circuits.

Keywords: microring resonator, vernier effect, on-chip temperature sensor, refractive index sensing

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1 Introduction

In the current very-large-scale integration (VLSI) system, temperature monitoring of the integrated circuit (IC) is an important step to ensure the normal and stable operation of the circuit system [1]. How to monitor and control the temperature of ICs has become a hot spot in the design of ICs. In recent years, temperature sensors based on silicon photonics have received extensive attention. The application of silicon photonics temperature sensors to the temperature detection of ICs is an important direction of temperature measurement of ICs. Compared with traditional on-chip temperature sensors, silicon photonics temperature sensors have better anti-electromagnetic interference ability, higher compatibility, and lower energy consumption, and have excellent performance in many application scenarios [2,3]. Various integrated optical temperature sensors based on different structures and mechanisms have been developed, such as microring resonators [4–6], Bragg gratings [7], and Mach–Zehnder interferometer (MZI) [8,9]. However, because the thermo-optical coefficient of silicon is about 1.86×10^{-4}/°C, the sensitivity of most temperature sensors is limited to 83 pm/°C [10,11]. How to improve the sensitivity of the sensor is an important direction in the current research field of silicon photonics sensors, and it is also the main work of this article.

In order to obtain better sensor performance, many scholars have studied temperature sensors based on silicon-on-insulator (SOI) platform in different ways and structures and obtained good results. Kim and Yu used cascade ring resonators to improve the sensitivity of the sensor, and the sensitivity of the temperature sensor was increased to 293.9 pm/°C under the effect of the vernier [12]. Zhang *et al.* proposed a temperature sensor based on a cascade silicon photonic crystal (PhC) nanobeam cavity. Two PhC nanobeam cavities with superimposed width modulation structure and parabolic beam structure were used to improve the sensitivity. When the temperature increased, the wavelengths of the two cavities were red-shifted and blue-shifted, respectively. Thus, the sensitivity of the temperature sensor is increased to 162.9 pm/°C [13].

Zhang *et al.* used the MZI structure to study temperature sensors and cut the waveguides of the two MZI arms into a structure with different sensitivity widths but almost the same refractive index to obtain a sensing sensitivity of 438 pm/°C [14]. Although the aforementioned sensor structures have achieved relatively large sensitivity, compared with the single microring resonator, temperature sensor has a great improvement, but at the same time, these sensor structures also occupy relatively large chip space. For example, Kim's cascade microring resonator temperature sensor achieves 293.9 pm/°C, but the radii of the two microring waveguides reach 271.94 and 232.23 µm. Different from the research carried out by the aforementioned scholars, the reflective Fabry–Perot cavity and microring resonator cascaded temperature sensor studied by Xie *et al.* [15] increased the contrast of the spectrum through the fiber reflector and Fabry–Perot cascaded, increased the sensitivity of the sensor to 1.9434 dB/°C, and achieved a high sensitivity, while the sensor has a relatively small size.

According to the development trend of high integration and small size of ICs, this study proposed a new structure of double microring cascaded temperature sensor based on the vernier effect. The sensitivity of the traditional single microring resonator temperature sensor is limited to 83 pm/°C. The double-ring cascade resonator sensor structure that forms the vernier effect can greatly improve the sensitivity of the sensor. Different from the sensor structure designed by Kim, the reference ring and the sensing ring are set on the same side of the sensor structure designed in this study, which can greatly reduce the volume of the sensor waveguide structure while ensuring that the sensor has a good sensitivity (303.6 pm/°C). The radii of the two microring waveguides are only 38.17 and 39.52 µm. The novel sensor waveguide structure proposed in this study achieves the coexistence of small volume and high sensitivity to a certain extent, which has certain research significance and can provide reference for subsequent research.

2 Design principle and structure

The sensor detection of microring resonator sensors is mainly divided into light intensity detection and spectral detection [16,17]. Light intensity detection refers to the detection power within the same wavelength range. Spectral detection is to detect the offset of the resonant peak of the output projection spectrum. In this study, the temperature sensor of the cascade microring resonator based on the vernier effect is designed to measure the environmental temperature change by means of spectral detection, *i.e.*, the temperature in the environment is obtained by detecting the resonance wavelength drift caused by the temperature change of the output spectrum at a fixed wavelength.

Microring resonator working principle of temperature sensor is due to the waveguide surface evanescent field [18], when the environment temperature changes, because the thermo-optic effect of polymer waveguide effective refractive index changes, leading to model the spread of the annular resonator in phase change and influence the resonant condition of the sensor, changing the microring resonator output spectrum. The change of ambient temperature is transformed into the drift of resonant wavelength, and the ambient temperature can be detected by detecting the change of output spectral line at the output end. The temperature detection of the temperature sensor of the microring resonator is mainly affected by the thermo-optical effect and thermal expansion effect. When the temperature changes, the refractive index of the waveguide is affected by the thermo-optical effect, and the perimeter of the microring waveguide is changed by the thermal expansion effect [19]. Therefore, the overall shift of the microring resonant wavelength caused by temperature is as follows:

$$\Delta\lambda = \Delta\lambda_{\mathrm{L}} + \Delta\lambda_{\mathrm{T}}, \tag{1}$$

where $\Delta\lambda_{\mathrm{T}}$ is the wavelength shift caused by thermal–optical effect, and $\Delta\lambda_{\mathrm{L}}$ is the wavelength shift caused by the thermal expansion effect.

$$\Delta\lambda_{\mathrm{T}} = \frac{\partial n_{\mathrm{eff}}}{\partial T}\lambda\Delta T, \tag{2}$$

$$\Delta\lambda_{\mathrm{L}} = \alpha_{\mathrm{W}}\frac{n_{\mathrm{eff}}}{n_{\mathrm{g}}}\lambda\Delta T. \tag{3}$$

Where λ is the wavelength of light, ΔT is the change in temperature, that is, the change between the current temperature and the initial temperature, the variation between the α_{W} is thermal expansion coefficient, this study designed based on cascade microring resonator waveguide materials for temperature sensor; therefore, in this study, the thermal expansion coefficient of silicon waveguide 2.5×10^{-6}/°C, n_{eff} is an effective refractive index of waveguide, and n_{g} is the group refractive index of the microring resonator waveguide. Under the influence of the thermo-optical effect, the effective refractive index of the microring resonator waveguide will change, which is the main influencing factor for the temperature sensing of the microring resonator temperature sensor. The effective refractive index of the waveguide changes is as follows:

$$n_{\mathrm{eff}} = n(\lambda, T)\left[1 + \frac{1}{n(\lambda, T_0)}\frac{\partial n}{\partial \varepsilon}\varepsilon + \frac{1}{n(\lambda, T_0)}\frac{\partial n}{\partial T}(T - T_0)\right], \tag{4}$$

where $n(\lambda, T)$ is the refractive index of the waveguide material. In this study, the microring resonator waveguide structure uses silicon material, then $n(\lambda, T) = 3.48$, and $C_T = \frac{1}{n(\lambda, T_0)} \frac{\partial n}{\partial T}$ is the thermal and optical coefficient of the microring resonator waveguide. In this study, the C_T of waveguide silicon material is 1.86×10^{-4}/°C [20,21]. $C_\varepsilon = \frac{1}{n(\lambda, T_0)} \frac{\partial n}{\partial \varepsilon}$ is the strain coefficient of the microring waveguide, ε is the strain state, T is the current temperature, and T_0 is the temperature value at room temperature. The microring resonator temperature sensor designed in this study is not affected by external forces, so it ignores strain changes and only considers the influence of temperature changes. From the effective refractive index of the microring resonator waveguide, the group refractive index of the waveguide can be obtained as follows:

$$n_g = n_{\mathrm{eff}} - \lambda\left(\frac{\partial n_{\mathrm{eff}}}{\partial \lambda}\right). \tag{5}$$

The sensitivity of the temperature sensor designed by the traditional single microring resonator is limited to 83 pm/°C. In order to break through the sensitivity limit of the single microring temperature sensor, the vernier effect is adopted to cascade multiple microring resonators to expand the sensitivity of the sensor [22]. As mentioned earlier, a novel cascade microring sensor structure is designed in this study. The waveguide plane of the sensor is shown in Figure 1(a), and the waveguide structure diagram of the sensor is shown in Figure 1(b). The cascaded microring temperature sensor designed in this study is composed of input and output waveguides, cascaded transmission waveguides, and two ring resonators. The reference ring and sensing ring are arranged on the left side of the cascaded transmission waveguide in an upper and lower structure. The sensor structure is designed with SOI material. In order to prevent thermal crosstalk in the sensor waveguide, a TiO_2 coating with negative thermal and optical coefficient is covered on the waveguide except the sensing ring 2. The exposed ring 2 is used as the sensing window, and the temperature change of the sensing window affects the waveguide mode characteristics through the evanescent field and then affects the characteristics of the whole sensor.

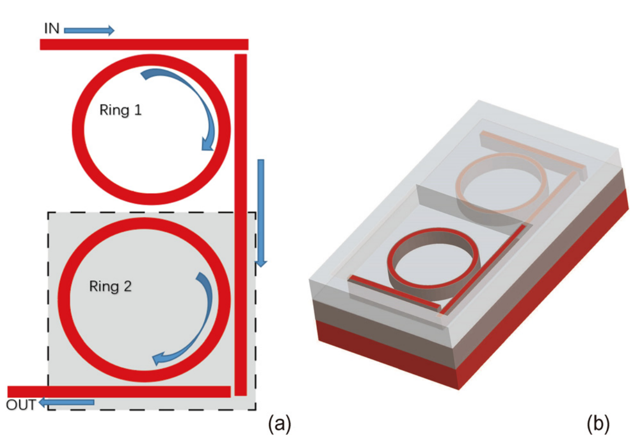

Figure 1: Structure diagram of sensor: (a) sensor waveguide plan and (b) structure diagram of sensor waveguide.

The light source is projected into the sensor structure from the input port of the waveguide structure and is coupled with ring 1 in the middle of the incident waveguide. The light beam is coupled into ring 1 from the incident waveguide and transmitted in the ring. When the beam propagates in ring 1, the optical path around the ring is equal to an integer multiple of the wavelength, i.e., when it satisfies:

$$2\pi R n_{\mathrm{eff}} = m\lambda. \tag{6}$$

The interference enhancement will occur with the light newly coupled into the microring, and the beam will output a spike in the transmission waveguide when it is coupled to the transmission waveguide. In the aforementioned equation, R is the radius of the microring, n_{eff} is the effective refractive index of the waveguide, m is the resonant order, and λ is the wavelength. After coupling from ring 1 to the transmission waveguide, the beam continues to propagate forward in the waveguide, and coupling occurs again at the closest distance to ring 2, entering ring 2. Similar to ring 1, when the beam enters ring 2, it will generate interference enhancement when satisfying Eq. (6), and output the corresponding spectrum when coupled to the output waveguide. The temperature sensor based on cascade microring resonator designed in this study, under different temperature environments, the output spectrum of the output port will shift to different degrees, so as to show the change of temperature.

According to the microring resonator theory, it can be deduced that the output spectrum of a single microring resonator of this temperature sensor at the output end is as follows:

$$T_{\mathrm{out}} = 10 \times \log_{10}\left|\frac{k_1 k_2 \exp(-j(\beta - j\alpha_R)\pi R)}{1 - t_1 t_2 \exp(-j(\beta - j\alpha_R)2\pi R)}\right|^2, \tag{7}$$

where k_1 and k_2 are the amplitude coupling coefficients of the two coupling regions of the microring resonator, t_1 and t_2 are the amplitude transmission coefficients, respectively, in the coupled-mode equations for $k = \sin[\int_{-L}^{L} K(z)\mathrm{d}z]$, and $t = \cos[\int_{-L}^{L} K(z)\mathrm{d}z]$, where $K(z)$ is the coupling coefficient varying along the direction of light propagation, and $k^2 + t^2 = 1$ according to the law of energy conservation. α_R is the transmission loss of the microring, β is the propagation constant of the microring, and R is the radius of the microring.

Because the cascade microring resonator temperature sensor designed in this study is realized by cascade of two microring resonators, and the transmission spectrum form of the microring resonator is the same, according to the output spectrum of a single microring resonator, the output spectrum of the sensor is as follows:

$$T = T_{\text{ref}} \times T_{\text{sen}}, \tag{8}$$

where T is the total output spectrum of the sensor, T_{ref} is the output spectrum of the reference ring, and T_{sen} is the output spectrum of the sensing ring. The reference ring, sensing ring, and total output spectrum of the sensor designed in this study are shown in Figure 2. As can be seen from the figure, when the reference ring resonant peak coincides with the sensing ring resonant peak, the resonant peak in the output spectrum is enhanced, while when the reference ring resonant peak and the sensing ring resonant peak are staggered, the resonant peak of the output spectrum is weakened, and an envelope spectral peak appears in the output spectrum.

Since the reference ring is covered with TiO_2 cladding with negative thermo-optical coefficient, the reference ring is almost not affected by the external temperature. In contrast, a bare window is designed on the sensing ring to fully feel the temperature change and serve as the sensing window of the sensor. When the temperature in the window changes, it can be seen from Eqs. (4) and (5) that the refractive index of the waveguide changes, and the free spectral range formula is as follows:

$$\text{FSR} = \frac{\lambda^2}{n_g \times 2\pi R}, \tag{9}$$

which shows that the free spectral range of the sensing ring changes with the temperature in the sensing window. Because the sensor is composed of two ring resonators in cascade, and the output spectrum of the sensor is the product of the output spectrum of the reference ring and the sensing ring, when the free spectral range of the sensing ring changes, the resonant peak of the output spectrum of the sensing ring will also change. Under this change, the total output spectrum of the sensor will be separated to form two spectral peaks, and the range between the two spectral peaks is the free spectral range of the cascaded double-ring sensor. When the temperature of the sensing window changes, the transmission spectrum of the sensing ring produces a small change $|\text{FSR}_{\text{sen}} - \text{FSR}_{\text{ref}}|$. Therefore, the resonant peaks of the reference ring and the sensing ring that originally overlapped on the output spectrum are separated, and overlap with the next resonant peak in the output spectrum, so that the total output spectrum of the sensor is shifted by a distance of FSR_{ref}, the output spectral offset equivalent to the sensing ring is amplified over the total output spectrum of the sensor, and the amplification factor of the sensor is as follows:

$$F = \frac{\text{FSR}_{\text{ref}}}{|\text{FSR}_{\text{sen}} - \text{FSR}_{\text{ref}}|}. \tag{10}$$

3 Experimental results and analysis

The temperature sensor of the cascade microring resonator is realized on the silicon material of SOI. The sensor

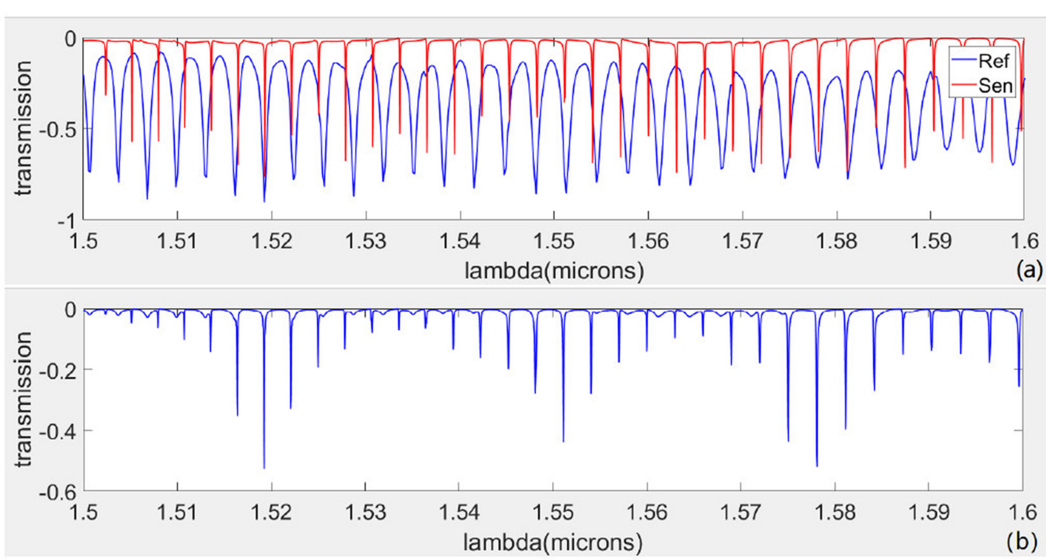

Figure 2: Output spectra of the microring resonator: (a) output spectra of the reference ring and the sensing ring and (b) total output spectrum of the sensor.

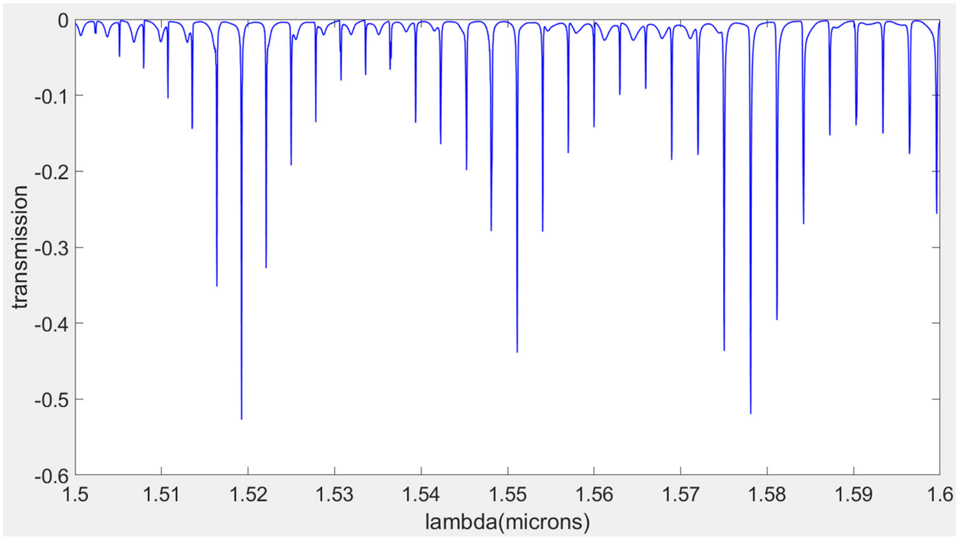

Figure 3: Sensor output spectrum at 300 K temperature.

waveguide structure with a height of 0.22 μm and a width of 0.5 μm is designed on the buried oxide layer. The radius of the reference ring waveguide structure is 38.17 μm, and the radius of the sensing ring waveguide structure is 39.52 μm. The distance between the reference ring and the sensing ring is 12 μm. In the experiment, the refractive index of Si material is 3.48 and that of SiO_2 material is 1.44. When the temperature is 300 K, a light source with a wavelength of 1.5–1.6 μm is radiated from the input end of the sensor waveguide. After transmission and coupling by the sensor, the output spectrum detected at the output end of the sensor is shown in Figure 3. After passing through the sensing ring, the output spectrum of the reference ring forms a new sensing spectrum, and a new spectral peak appears on the spectrum. Due to the change of the effective refractive index of the sensing ring waveguide at different temperatures, the peak value of the output spectrum will drift along with the change of temperature.

The traditional cascaded double-ring sensor will have a large spectral peak shift when detecting small refractive index changes, but it does not actually enlarge the measurement range of the sensor, i.e., the phenomenon that the free spectrum range does not enlarge. This study referred to the solution of Su *et al.* [23] in the research of cascaded double-ring sensor and adopted the envelope-fitting method to improve the sensing sensitivity and sensing

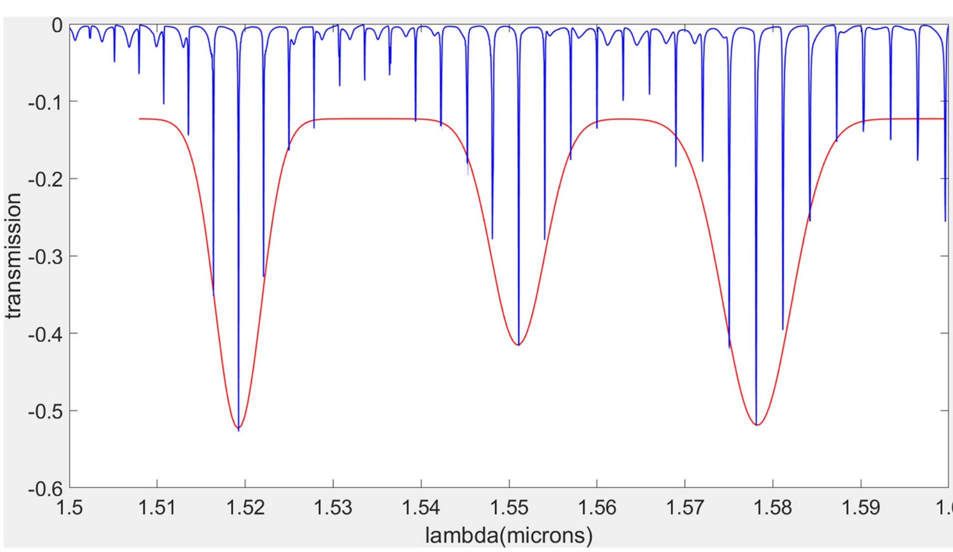

Figure 4: Spectrum waveform after envelope fitting.

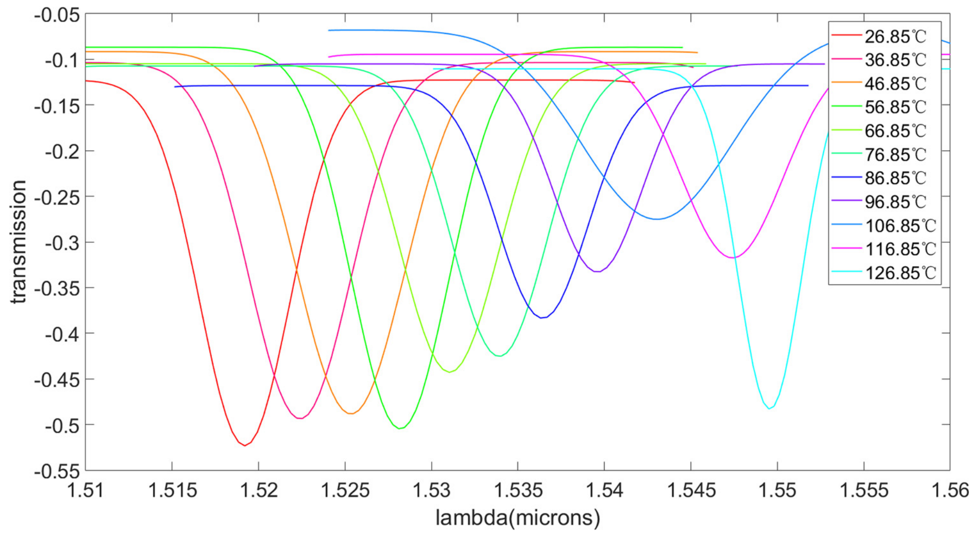

Figure 5: Spectral envelope curve of sensor output at 26.85–126.85°C.

measurement range of the temperature sensor. The output spectrum of the sensor in an environment of 26.85°C after envelope fitting is shown in Figure 4. After envelope fitting, the fitted curve can be used to measure the perceived variation of the sensor, which can significantly enlarge the measuring range of the sensor and optimize the sensing performance of the temperature sensor.

In order to verify the sensing performance of the cascaded microring resonator temperature sensor, including the sensitivity, measurement range, and other performance parameters, this study conducted simulation experiments on the temperature sensor under different temperature conditions. Experimental results show that the cascaded microring resonator temperature sensor designed in this study has good performance parameters and can measure the temperature parameters well. The curve shown in Figure 5 is the output spectrum-fitting curve of the sensor when the wavelength range is from 1.515 to 1.555 μm and the temperature is from 26.85 to 126.85°C. Figure 6 shows the spectral offset of the sensor in sensor output. As can be seen from the figure, this sensor has good sensing sensitivity and measurement range and has good linearity within the measurement range, and the linear relationship follows the formula $y = 0.000304x + 1.510945$, which has greatly improved the performance of temperature sensor compared with a single microring. Through the analysis of the experimental results, it can be found that the sensor has a high sensitivity at 86.85–116.85°C temperature, up to 437 pm/°C, in the measuring range of 26.85–126.85°C, and the sensor's average sensitivity reaches 303.6 pm/°C, which is

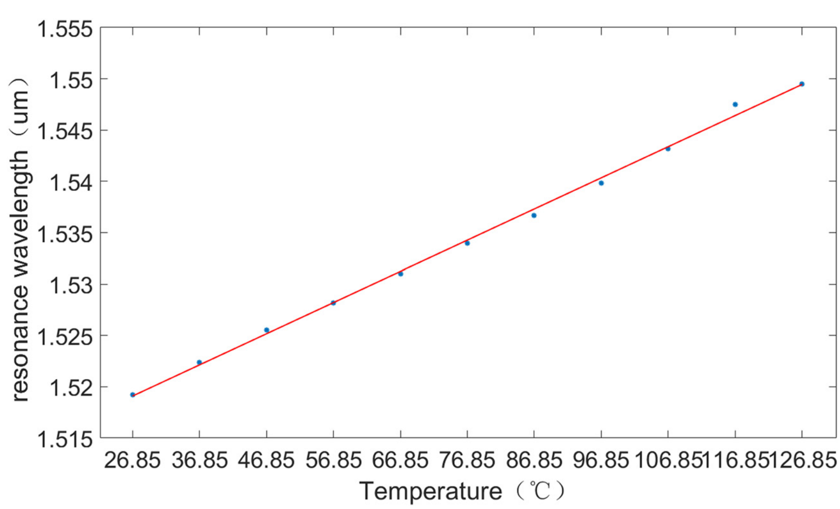

Figure 6: Sensor output spectrum offset at 26.85–126.85°C.

3.65 times the 83 pm/°C limit of a single microring temperature sensor. The sensor also has a temperature measuring range of 100°C, which can meet the needs of the general on-chip ambient temperature-monitoring work.

Compared with the sensors reported in other studies, this study has obvious advantages in terms of temperature-sensing sensitivity and sensor structure size. The temperature sensor designed by Kim and Yu [12] also adopted a double-ring cascade to design the sensor structure, but the size of their reference ring and sensing ring was much larger than that of our designed structure. And it is slightly less sensitive than our sensors in terms of temperature sensing. Although the temperature sensor designed by Zhang *et al.* [14] has achieved relatively high sensing sensitivity – up to 438 pm/°C, in terms of the sensor structure, they adopted the MZI structure, which has a large size. This study is different from the research of Xie *et al.* [15]: they detect the temperature change by the method of light intensity detection, while this study detects the temperature by the way of spectral migration. Both methods have their own advantages. Under the background of high-speed, low power consumption, and small size, VLSI design is obviously not suitable for use on ICs. The sensor designed in this study not only has a high sensing sensitivity, but also greatly reduces the size of the sensor structure, in line with the current development direction of IC design.

4 Conclusion

In this study, an on-chip temperature sensor based on a cascade microring resonator is presented, which is composed of two reference rings and sensing rings with different temperature sensitivities and free spectral ranges. The sensing sensitivity of the temperature sensor is improved, and the structure size of the sensor is reduced. The temperature sensitivity of the microring cascade temperature sensor reaches 303.6 pm/°C, which well breaks through the limit of 83 pm/°C of the single microring temperature sensitivity, and reaches 3.65 times of the single microring sensitivity. At the same time, the temperature sensing range of the sensor is 100°C, which can well meet the demand of VLSI temperature monitoring. In addition, the structure size of the temperature sensor designed in this study has been well improved. The radius of the reference ring and the sensing ring is only 38.17 and 39.52 μm, which is greatly reduced compared with the cascade microring temperature sensor designed and reported by other researchers. The size of the sensing ring is only 15% of the 271.94 μm radius of the sensing ring designed by Kim and Yu [12]. In summary, the cascade microring temperature sensor designed in this study has high sensing sensitivity, compact structure and size, and easy integration, and is suitable for VLSI, which has good research value and application potential in the field of system-on-chip temperature monitoring.

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References

[1] Islam AKMM, Shiomi J, Ishihara T, Onodera H. Wide-supply-range all-digital leakage variation sensor for on-chip process and temperature monitoring. IEEE J Solid-State Circuits. 2015;50(11):2475–90.

[2] Zhang L, Jie L, Zhang M, Wang Y, Xie Y, Shi Y, et al. Ultrahigh-Q silicon racetrack resonators. Photonics Res (Washington, DC). 2020;8(5):684.

[3] Bogaerts W, De Heyn P, Van Vaerenbergh T, De Vos K, Kumar Selvaraja S, Claes T, et al. Silicon microring resonators. Laser Photonics Rev. 2012;6(1):47–73.

[4] Chen X, Huang K, Zeng Z, Zeng M, Shen C, Bai N. A temperature sensor using cascaded microring resonators. IOP Conf Ser Mater Sci Eng. 2019;490(7):72030.

[5] Hu C, Shi Y, Zhou T, Xu C, Zhu A. A small size on-chip temperature sensor based on a microring resonator. Silicon. 2022;14(11):5847–54.

[6] Amiri IS, Ariannejad MM, Daud S, Yupapin P. High sensitive temperature sensor silicon-based microring resonator using the broadband input spectrum. Results Phys. 2018;9:1578–84.

[7] Zhao CY, Zhang L, Zhang CM. Compact SOI optimized slot microring coupled phase-shifted Bragg grating resonator for sensing. Opt Commun. 2018;414:212–6.

[8] Tang T, Luo L. Refractive index sensor of Mach–Zehnder interferometer based on thermo-optic effect of SOI waveguide. Optik. 2016;127(16):6366–70.

[9] Guan X, Wang X, Frandsen LH. Optical temperature sensor with enhanced sensitivity by employing hybrid waveguides in a silicon Mach-Zehnder interferometer. Opt Express. 2016;24(15):16349–56.

[10] Kim GD, Lee HS, Park CH, Lee SS, Lim BT, Bae HK, et al. Silicon photonic temperature sensor employing a ring resonator manufactured using a standard CMOS process. Opt Express. 2010;18(21):22215–21.

[11] Xu H, Hafezi M, Fan J, Taylor JM, Strouse GF, Ahmed Z. Ultra-sensitive chip-based photonic temperature sensor using ring resonator structures. Opt Express. 2014;22(3):3098–104.

[12] Kim H, Yu M. Cascaded ring resonator-based temperature sensor with simultaneously enhanced sensitivity and range. Opt Express. 2016;24(9):9501.

[13] Zhang Y, Liu P, Zhang S, Liu W, Chen J, Shi Y. High sensitivity temperature sensor based on cascaded silicon photonic crystal nanobeam cavities. Opt Express. 2016;24(20):23037.

[14] Zhang Y, Zou J, He J. Temperature sensor with enhanced sensitivity based on silicon Mach-Zehnder interferometer with waveguide group index engineering. Opt Express. 2018;26(20):26057.

[15] Xie JY, Su GS, Li MY, He JJ. Temperature sensor cascading reflective Fabry-Perot cavity with microring resonator. Acta Opt Sin. 2022;42(23):226–31.

[16] Jin L, Li M, He J. Optical waveguide double-ring sensor using intensity interrogation with a low-cost broadband source. Opt Lett. 2011;36(7):1128–30.

[17] Tian C, Zhang H, Li W, Huang X, Liu J, Huang A, et al. Temperature sensor of high-sensitivity based on nested ring resonator by Vernier effect. Optik. 2020;204:164118.

[18] Biswas U, Rakshit JK, Das J, Bharti GK, Suthar B, Amphawan A, et al. Design of an ultra-compact and highly-sensitive temperature sensor using photonic crystal based single micro-ring resonator and cascaded micro-ring resonator. Silicon. 2021;13(3):885–92.

[19] Xin X, Wang L, Guo S. Doubled temperature measurement range for a single micro-ring sensor. Acta Phys Sin. 2014;63(15):197–202.

[20] Singha S, Bhowmik BB. On-chip photonic temperature sensor using micro ring resonator. 2018 Fifteenth International Conference on Wireless and Optical Communications Networks (WOCN); 2018. p. 1–4.

[21] Komma J, Schwarz C, Hofmann G, Heinert D, Nawrodt R. Thermo-optic coefficient of silicon at 1550 nm and cryogenic temperatures. Appl Phys Lett. 2012;101(4):41905.

[22] Dai D. Highly sensitive digital optical sensor based on cascaded high-Q ring-resonators. Opt Express. 2009;17(26):23817–22.

[23] Su C, Zhu H, Cao Z, He J. Fitting methods of transmission spectrum envelope in cascaded double-ring resonator sensors. Acta Photonica Sin. 2018;47(10):101–8.