Оптический журнал

Оптическое приборостроение и метрология
Optical materials and technology

DOI: 10.17586/1023-5086-2023-90-08-87-95

UDC 535.3

Design of high sensitivity on-chip temperature waveguide sensor based on sensitive cladding

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Abstract

Subject of study. This paper introduces a high-sensitivity on-chip temperature waveguide sensor based on sensitive cladding. **Purpose of the work.** The operating temperature of integrated circuit has an important influence on the efficient and stable operation of the circuit system. Therefore, on-chip temperature sensor plays an important role in the normal use of the integrated circuit chip. **Method.** By coating the sensor waveguide structure with temperature-sensitive materials a new hybrid sensor waveguide is formed to increase the sensitivity of the waveguide to temperature changes. The waveguide structure of the sensor adopts a typical all-pass microring resonator as the basic structure of the sensor. The surface of the waveguide is coated with ethanol, which is more sensitive to temperature, to increase the temperature sensitivity of the waveguide structure and realize the improvement of the sensitivity of the temperature sensor. **Main results.** When the designed radius of the sensor is 3.34 μm and the coating thickness of the temperature-sensitive material cladding is 0.12 μm, the experimental results show that the sensitivity of the sensor reaches 105 pm/°, and it has good linearity. **Practical significance.** Compared with the currently reported studies on cladding sensors, there are certain improvements and enhancements in terms of sensitivity and sensor size. At the same time, it provides a solution for the research and design of on-chip temperature sensor.

Keywords: microring resonator, temperature sensor, sensitive cladding, micro-nanodevices, system on chip

Acknowledgment: we are thankful to the reviewers for the valuable suggestion.

Funding: This work is supported by National Natural Science Foundation of China (61861012,2161008), Guangxi Key Laboratory of Automatic Detecting Technology and Instruments (YQ21105), Science Foundation of Guilin University of Aerospace Technology (XJ20KT09) and Research Basic Ability Improvement Project for Young and Middle-aged Teachers of Guangxi Universities (2021KY0800).

For citation: Hu Cong, Shi Yunying, Zhou Tian, Wan Chunting, Xu Chuanpei, Zhu Aijun. Design of high sensitivity on-chip temperature waveguide sensor based on sensitive cladding (Высокочувствительный встроенный волноводный датчик температуры на основе чувствительного покрытия) [In English] // Opticheskii Zhurnal. 2023. V. 90. № 8. P. 87–95. http://doi.org/10.17586/1023-5086-2023-90-08-87-95

OCIS code: 120.678.

Высокочувствительный встроенный волноводный датчик температуры на основе чувствительного покрытия

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Аннотация

Предмет исследования. Особенности проектирования высокочувствительного встроенного волноводного датчика температуры. **Цель работы.** Разработка высокочувствительного волноводного датчика для контроля рабочей температуры интегральных микросхем. **Метод.** Повышение чувствительности к изменениям температуры типичного датчика на основе сквозного микрокольцевого резонатора посредством нанесения на волновод специально подобранного термочувствительного материала. Выбор покрытия на основе этанола по критерию увеличения чувствительности. **Основные результаты.** Подтверждено увеличение чувствительности датчика до 105 pm/° при радиусе датчика 3,34 мкм, и толщине термочувствительного покрытия 0,12 мкм с достаточной для практического использования линейностью статической характеристики. **Практическая значимость.** Доказана возможность проектирования датчика с увеличенной чувствительностью и уменьшенными габаритами, предложенное проектное решение определяет новое направление в исследовании и проектировании встроенных волноводных датчиков изменения температуры.

Ключевые слова: микрокольцевой резонатор, датчик температуры, термочувствительное покрытие, микро-наноустройства, система для чипов

Благодарность: мы благодарны рецензентам за их ценное предложение.

Эта работа поддержана Национальным фондом естественных наук Китая (61861012,2161008), Гуансийской ключевой лабораторией технологий и приборов автоматического обнаружения (YQ21105), Научным фондом Гуйлиньского университета аэрокосмических технологий (XJ20KT09) и Проектом по повышению базовых способностей преподавателей университетов Гуанси молодого и среднего возраста (2021KY0800).

Ссылка для цитирования: Hu Cong, Shi Yunying, Zhou Tian, Wan Chunting, Xu Chuanpei, Zhu Aijun. Design of high sensitivity on-chip temperature waveguide sensor based on sensitive cladding (Высокочувствительный встроенный волноводный датчик температуры на основе чувствительного покрытия) [на англ. языке] // Оптический журнал. 2023. Т. 90. № 8. С. 87–95. http://doi.org/10.17586/1023-5086-2023-90-08-87-95

Код OCIS: 120.678.

1. INTRODUCTION

In recent years in the research of optical devices, optical sensors has become an important direction in the field of optical device research [1–5]. Optical devices of various structures have been studied and developed for sensing and detection applications, including photonic crystals [6, 7], Mach–Zehnder interferometers [8], Bragg gratings [9], microring resonators[10, 11], etc. The optical microring resonator temperature sensor studied in this paper is a typical application of optical devices in sensing and detection, especially the application of optical sensors in traditional integrated circuit systems, which is an important direction for the development of the integrated circuits in the future. The advantages of optical sensors, such as low power consumption, strong anti-interference, small size, and fast speed, are in line with the current development direction of integrated circuits [12–14]. To obtain higher performance a special structure design is usually adopted in the study of optical microring resonator temperature sensors [15]. Vernier effect is used to amplify the amount of spectral drift to obtain higher sensing performance, but at the same time, a large sensor structure size will be brought. Compared with special structures, it is a good solution to use sensitive materials as cladding to improve the sensing performance. In 2016, Chun-Ta Wang [16] of National Sun Yat-Sen University in Taiwan proposed an optical temperature sensor using a liquid crystal cladding microring resonator. Silicon nitride (SiN) is used as the sensor waveguide, and the waveguide is coated with a layer of Nematic Liquid Crystal (NLC). When the ambient temperature changes, the refractive index of the temperature-sensitive material NLC with large thermo-optic coefficient changes sharply, which affects the effective refractive index of the microring, and the sensing sensitivity is improved accordingly. The temperature sensitivity of TM polarized light devices with 5CB cladding is as high as 1 nm/°C between 25 °C and 33 °C and exceeds 2 nm/°C at temperatures close to the 5CB cladding clearing temperature, at least 55 times that of air-cladding microring resonators, the temperature-dependent wavelength shift of the air-clad microring resonator for TM polarized light is 18 pm/°C. In addition, Fu Xing-Hu of Yanshan University [17] and others also conducted research on sensitive cladding fiber sensors in 2015 and obtained a sensing sensitivity of 73.74 pm/°C in the temperature range of 35–95 °C. It can be seen from the above that the research of optical sensors based on sensitive cladding has great feasibility. In this paper we will use sensitive material as the waveguide cladding to study an microring resonator (MRR) temperature sensor suitable for on-chip systems.

2. SENSING PRINCIPLE AND STRUCTURE DESIGN

The design of the microring temperature sensor based on temperature-sensitive material cladding is mainly to coat a layer of material with higher sensitivity outside the waveguide structure during the design of the microring resonator structure to form a new hybrid sensing waveguide. In the design of this paper the material of the waveguide structure used is mainly a silicon-on-insulator (SOI). The refractive index of Si material in the waveguide structure is 3.475, the refractive index of SiO_2 material is 1.44, and the thermo-optic coefficient of silicon is $1.86{\times}10^{-4}$ /°C [18, 19]. In the design of the sensor the working environment is mainly considered in the integrated circuits, and the temperature range to be detected is not large, so ethanol with a higher thermo-optic coefficient is selected as the sensitive material to coat the waveguide core layer. The cladding temperature-sensitive material ethanol has the refractive index of 1.36 and the thermo-optic coefficient of $3.94{\times}10^{-4}$ /°C [20]. The cross-section of the sensor waveguide material is shown in Fig. 1, Fig. 2a is the electric field distribution diagram of the sensor waveguide during the experiment, and Fig. 2 is the energy cross-section distribution diagram.

In this paper a typical all-pass microring resonator is used as the basic structure of the sensitive cladding sensor, and a sensitive material – ethanol – is coated on the structural waveguide to form a sensitive material cladding sensor. The structure of the sensitive cladding microring temperature sensor is shown in Fig. 3,where (a) is the side view and (b) is the front view. The microring radius is designed to be 3.34 μm, and the simulation design area of the entire sensor is 120 μm^2. After the optical signal enters the sensor waveguide from the incident port,

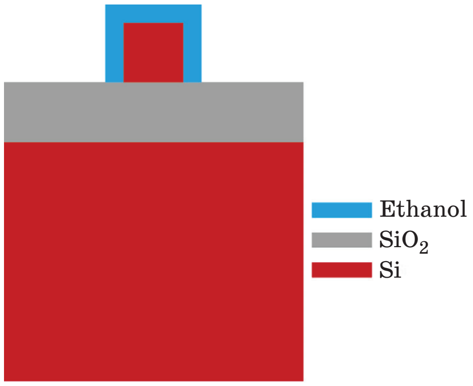

Fig. 1. Sectional view of the sensor waveguide material

Рис. 1. Вид в разрезе структуры слоёв материалов волноводного датчика

it is coupled and transmitted in the microring. When the microring resonator equation is satisfied

$$2\pi R n_{eff} = m\lambda \quad (1)$$

it produces resonance, and in the transmission to the sensor output port in the port sensor detection spectrum output, where R is the radius of the microring, n_{eff} is the effective refractive index of the waveguide, m is the resonance series of the microring, m is greater than 0 and m is an integer, and λ is the wavelength of optical signal at resonance. Due to the special properties of the structure of the cladding material, the optical signal transmitted in the

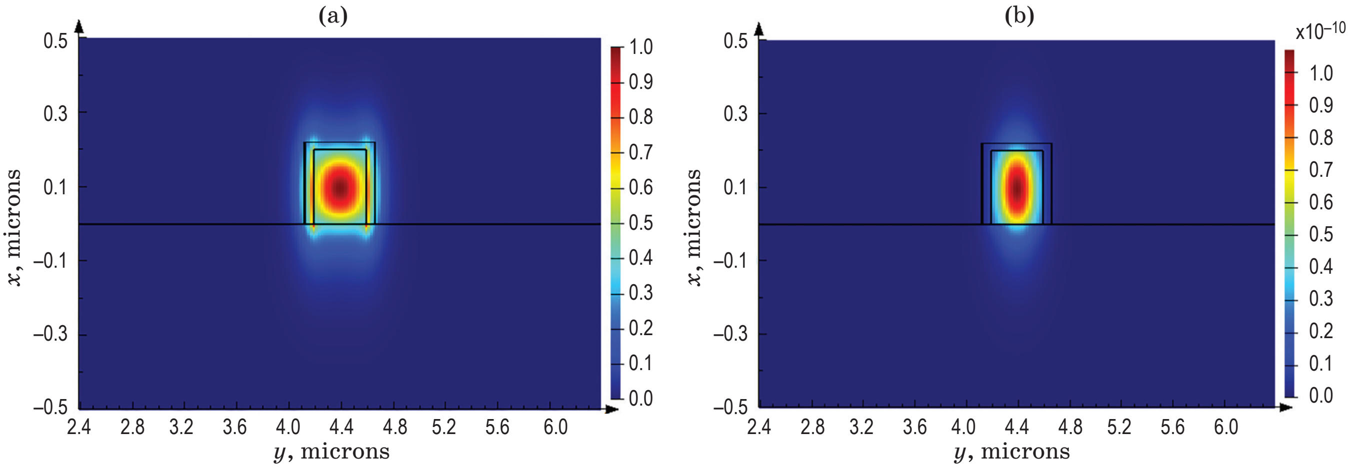

Fig. 2. Electric field and energy distribution of sensing waveguide. (a) Electric field distribution diagram and (b) energy cross-section distribution diagram of sensing waveguide during the experiment

Рис. 2. Диаграмма распределения электрического поля (a) и диаграмма распределения энергии в поперечном сечении чувствительного слоя волноводного датчика во время эксперимента (б)

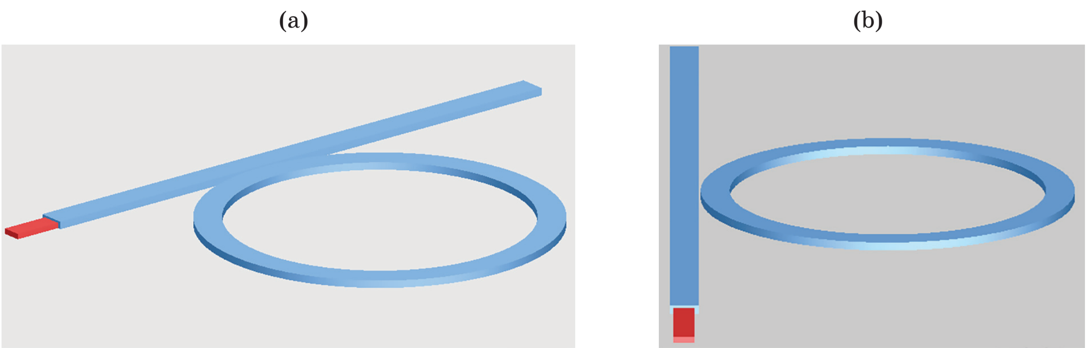

Fig. 3. 3D structure diagram of the temperature sensor of sensitive cladding microring. (a) Side view down and (b) front looking down

Рис. 3. Структура чувствительного элемента датчика температуры на основе сквозного микрокольцевого резонатора: а) вид сбоку, б) вид спереди waveguide core layer can be coupled to the cladding waveguide material for transmission under the condition that the coupling conditions are satisfied. Since the thermo-optic coefficient of the sensitive cladding layer is positive and higher than that of the waveguide core layer, as the ambient temperature increases, the sensing waveguide core layer is affected by the cladding layer, and the refractive index changes significantly. As the effective refractive index of the sensor waveguide increases, the transmission peak shift of the output spectrum increases. From the formula of the effective refractive index under the thermo-optic effect

$$n_{eff} = n(\lambda, T)\left[1 + C(T - T_0)\right]. \quad (2)$$

In the above formula $n(\lambda, T)$ is the refractive index of the waveguide material, C is the thermo-optic coefficient of the waveguide material, T is the ambient temperature during monitoring, and T_0 is the room temperature. It can be obtained that the effective refractive index of the waveguide core layer changes with temperature as

$$n_1 = n_1\left[1 + C_1(T - T_0)\right], \quad (3)$$

where n_1 and C_1 are the refractive index and thermo-optic coefficient of the sensor waveguide. The relationship of the effective refractive index of sensitive material cladding with temperature can be expressed as

$$n_2 = n_2\left[1 + C_2(T - T_0)\right], \quad (4)$$

where n_2 and C_2 are the refractive index and thermo-optic coefficient of the temperature-sensitive material cladding.

3. SENSOR EXPERIMENT AND ANALYSIS

The microring resonator temperature sensor based on temperature-sensitive material cladding uses SOI as the main material of the sensor. In this design the radius of the microring waveguide is set to 3.34 μm, and the experimental structure size of the entire sensor is only 120 μm^2. The microring temperature sensor characterizes the temperature change by the shift of the resonant wavelength of the transmission peak of the output spectrum. Therefore, when the light energy is injected from the signal input end of the sensor, the output spectrum can be detected from the output end of the sensor. Figure 4 is the output spectrum detected from the sensor output, when the temperature is 25 °C. It can be seen from the figure that the sensor has a large free spectral range, and from this angle it can be seen that the sensor has a large sensing measurement range. Figure 5 is an energy transfer diagram of light energy, when the sensor is working. It can be seen from the figure that after the light energy is incident on the sensor, most of the energy is coupled into the microring for resonance, and part of the

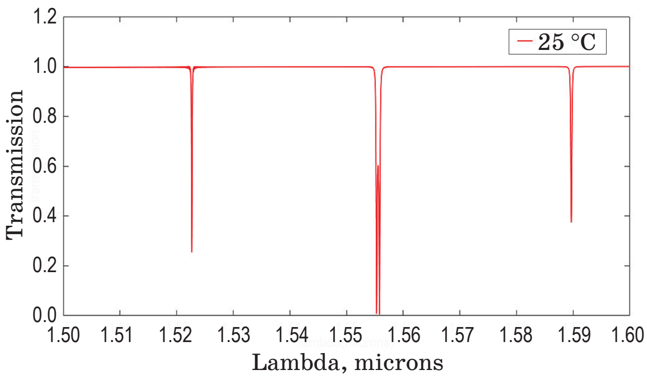

Fig. 4. Spectra detected at the output when the temperature is 25 °C

Рис. 4. Спектр выходного сигнала при температуре 25 °C

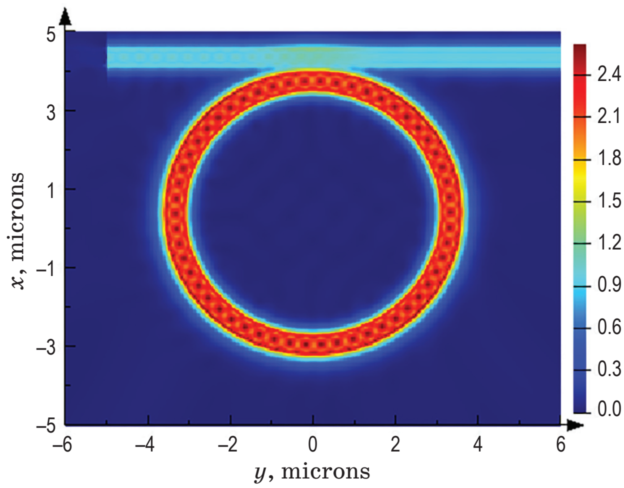

Fig. 5. Energy transfer diagram of sensitive cladding MRR temperature sensor when working

Рис. 5. Диаграмма распределения энергии при работе датчика температуры на основе сквозного микрокольцевого резонатора light energy after the resonance is output from the output port. From the energy distribution it can be seen that the sensor has a large coupling matching degree and less energy loss.

In order to enable the sensor to obtain greater sensing sensitivity, the thickness of the temperature-sensitive material cladding was experimentally tested in the experimental design. In the experiment the coating thickness of the temperature-sensitive material cladding was set to five different values, 0.05 μm, 0.08 μm, 0.1 μm, 0.12 μm, and 0.15 μm, respectively, for experimental comparison and data analysis, so that the sensor could obtain higher sensitivity. The experimental data of the sensor under different coating thicknesses are shown in Fig. 6.

From the Fig. 6 we can clearly see that the sensitive material cladding under different thicknesses has different promoting effects on the sensing of the optical waveguide. When the thickness of the cladding is relatively small (0.05 μm), the sensitivity of the sensor is only 99 pm/ °C, and the sensing sensitivity is greatly improved, when the thickness of the cladding is increased, and the sensitivity is increased to 103.5 pm/°C, when the thickness is 0.08 μm. When the thickness is 0.1 μm, the sensitivity is improved to 104 pm/°C, and the sensitivity is 105 pm/°C, when the cladding thickness is 0.12 μm and 0.15 μm. The same and higher sensitivity is obtained under the two cladding thicknesses. To make the performance of the sensor superior the structure of the sensor under these two thicknesses is further analyzed in this paper. Figure 7 is a graph showing the sensitivity of the optical waveguide sensor at the temperature of 25 °C to 75 °C for each segment with cladding thickness of 0.15 μm and 0.12 μm. It can be seen from the figure that when the thickness of the sensor is 0.12 μm, the sensitivity of the sensor does not fluctuate much, and it is more stable than the sensor with a thickness of 0.15 μm. That is, the linearity of the detection sensitivity of the sensor is better, when the thickness is 0.12 μm, while the linearity of the sensor is relatively poor, when the thickness is 0.15 μm. Therefore, in this paper the thickness of the sensitive cladding is set to 0.12 μm in the research of the sensitive material cladding-coated microring sensor.

Figure 8 shows the output spectrum, when the thickness of the sensitive material cladding is 0.12 μm and the temperature is from 25 °C to 75 °C. It can be clearly seen from the figure that there are three obvious resonance peaks in the detection band of the 1.5–1.6 μm spectral region. The resonant peak interval in the output spectrum at the same temperature is larger, that is, the free spectral range of the sensor with this structure is larger, reflecting that the sensor has a larger detection range. Figure 9 and Figure 10 are the spectrograms at wavelengths of 1.52–1.53 μm and 155–1.56 μm, respectively. It can be clearly seen from the two output

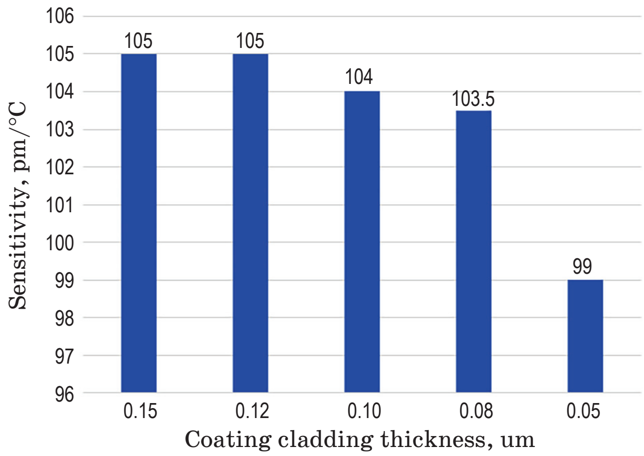

Fig. 6. Sensitivity comparison of sensitive cladding with different thicknesses

Рис. 6. Сравнение чувствительности датчика при различных толщинах термочувствительного покрытия

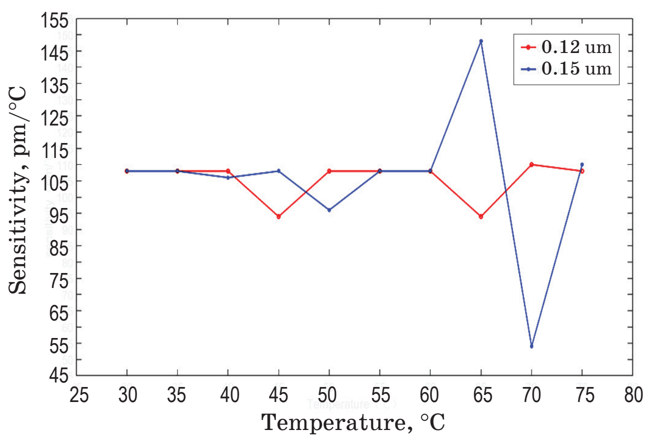

Fig. 7. Comparison of sensor linearity when the cladding thickness is 0.12 μm and 0.15 μm

Рис. 7. Сравнение линейности статической характеристики датчика для толщины покрытия 0,12 и 0,15 мкм spectrum graphs that the sensor has better output spectrum in these two different wavelength bands. The output spectral shift is obvious, when the temperature changes, and the spectral shift reaches 105 pm, when the temperature changes by 1 °C, which is a great improvement compared with the classic all-pass type microring resonator temperature sensor.

Compare this sensor with the two sensitive cladding-based sensors mentioned above, as shown in Table 1. The sensing sensitivity of the microring temperature sensor based on liquid crystal cladding designed by Chun-Ta Wang [16] of National Sun Yat-Sen University is relatively high. But it sacrifices the structure size of the sensor, which is more than ten times the size of the sensor structure designed in this chapter. The sensing sensitivity of the clad silica

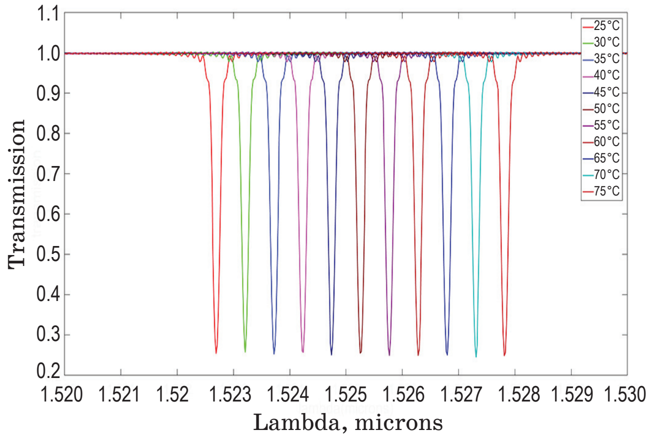

Fig. 9. The output spectrum when the wavelength is 1.52–1.53 μm

Рис. 9. Спектр выходного сигнала в дапазоне от 1,52 до 1,53 мкм при различных рабочих температурах

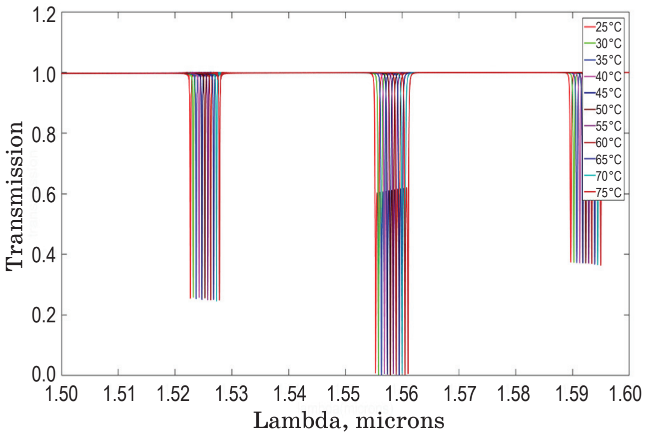

Fig. 8. Output spectrum from 25 °C to 125 °C when the cladding thickness is 0.12 μm

Рис. 8. Спектр выходного сигнала при температуре от 25 °C до 125 °C и толщине покрытия 0,12 мкм

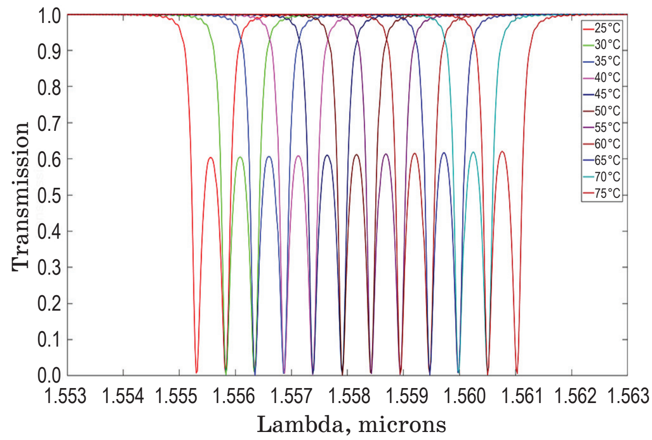

Fig. 10. Output spectrum at 1.55–1.56 μm

Рис. 10. Спектр выходного сигнала в диапазоне от 1,55 до 1,56 мкм при различных рабочих температурах

Results comparison

Сравнение полученных результатов с данными других авторов

	Chun-Ta Wang [16]	Fu Xing-Hu [17]	This work
Sensitivity	Up to 1nm/°C between 25 and 33°C	73.74 pm/°C	105pm/°C
Sensor waveguide and cladding materials	Based on SiNMRR and NLC cladding, the NLC material used in this reference is a commonly used commercial liquid crystal (5CB, Merck)	Special fiber, 10mm three-layer quartz special fiber is prepared by dissolving ordinary single-mode fiber at both ends	Microring waveguide structure and ethanol cladding of silicon-on-insulator material
Microring radius	40 μm	The fiber length of the sensing part is 10mm, and the fiber radius is 62.50μm	3.34 μm

special fiber designed by Fu Xinghu of Yanshan University [17] and others is only 73.74 pm/°C and the size of the sensor formed is relatively large, and the outer cladding radius reaches 62.50 μm. Compared with them, the sensor designed in this paper has certain advantages in terms of sensing sensitivity and size.

4. CONCLUSION

In this paper a temperature sensor based on the temperature-sensitive material cladding of the microring resonator is introduced. A typical all-pass microring resonator is used as the basic structure of the sensor, and the surface of the waveguide is coated with a layer of more temperature-sensitive cladding material to improve the sensitivity of the temperature sensor. To obtain higher sensitivity and better performance better sensing performance was explored by cladding of different thicknesses at the design time. Experimental simulation and analysis show that when the sensor radius is 3.34 μm and the coating thickness of temperature-sensitive material is 0.12 μm, the sensitivity and linearity of the sensor are better, and the sensor sensitivity reaches 105 pm/°C. Compared with the current reported research on the coating sensor, there are certain improvements and breakthroughs in the sensitivity and sensor size.

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The article was submitted to the editorial office 30.05.2022
Approved after review 31.10.2022
Accepted for publication 26.06.2023

Статья поступила в редакцию 30.05.2022
Одобрена после рецензирования 31.10.2022
Принята к печати 26.06.2023