High-sensitivity temperature sensor based on photonic crystal fiber fully coated with gold and PDMS films.

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High-sensitivity temperature sensor based on photonic crystal fiber fully coated with gold and PDMS films

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Abstracts

This paper presented a high-sensitivity temperature sensor based on photonic crystal fiber fully coated with gold and PDMS films. For the convenience of production, gold film is coated outside the fiber cladding, and it is used to excite the surface plasmon resonance (SPR) effect. In addition, the temperature response has been effectively improved by depositing poly-dimethylsiloxane (PDMS) layer outside the gold film. This fully coated structure on the outside of PCF enables temperature-sensitive medium to be in direct contact with the environment, which reduces the difficulty of internal coating and filling. The influences of the parameters on the sensing characteristics are investigated by using the finite element method (FEM). Simulation results show that the average temperature sensitivity is up to 9.287nm/°C in the range of -20°C-40°C. Moreover, compared with other designs, the optimized process of structure in this study provides an effective method, which shows a wide application prospect to overcome the difficulty of filling liquid in the air holes.

Keywords : Photonic Crystal Fibers; Surface Plasmon Resonance; Temperature Sensing; High-sensitivity

Introduction

Photonic crystal fibers (PCFs), also known as microstructured fibers that have various air holes extending along the fiber in its cross section [1-3]. PCFs have been extensively applied to sensors [4], filters [5], lasers [6], and other optical devices due to the flexible structural design and many distinctive characteristics [2]. Since the distinguished performance of surface plasmon resonance (SPR) technology in the sensing domain, SPR technology has been combined with

PCFs to increase the function of this fiber [7]. Compared to conventional fiber sensors, SPR-PCF sensors are obviously optimized in terms of cross-sensitivity and coupling loss. In addition, it has qualities of wide operating wavelength range, high sensitivity, and multi-parameter measurement [8-10]. Owing to surface plasmon polaritons are sensitive to the external environment and easily changing transmission constants of sensor, SPR-PCF sensors have aroused tremendous interest in temperature measurement, medical diagnostics and more [10].

Temperature measurement plays an indispensable role in industrial production, environmental monitoring and other fields. At present, electrical temperature sensor has been developed and matured. But as technology advances, fiber temperature sensor based on combination of fiber and metal has attracted people's attention. Fiber temperature sensors have gradually substituted electrical temperature sensors because of its preponderance of long-distance transmission and design flexibility. In 2014, Yang et al. [11] proposed and experimentally demonstrated a PCF temperature sensor based on SPR, which achieves temperature sensing by filling PCF with silver nanowires and liquid. Experimental results show that the sensitivity was $-2.08\text{nm}/^\circ\text{C}$, whereas the operation procedure for filling in PCF was cumbersome. In 2015, Zhao et al. [12] presented a PCF-SPR sensor for temperature detection by using a temperature-sensitive liquid as an intermediate and combined with fiber SPR structure. The sensing element is fabricated by packaging a silver-coated fiber probe into a capillary filled with thermosensitive anhydrous ethanol. This proposed sensor achieves the sensitivity of $1.5745\text{nm}/^\circ\text{C}$ between $35\text{--}70^\circ\text{C}$. In 2016, Luan et al. [13] presented a SPR sensor, which can simultaneously realize refractive index (RI) and temperature sensing in an exposed-core microstructured fiber. Two orthogonal passageways coated with silver layers are designed in cladding air holes, one of which is filled with thermosensitive liquid to distinguish the variation of analyte RI and temperature. The corresponding sensitivity was $6.18\text{nm}/^\circ\text{C}$ as the temperature changed from 26 to 43°C . The same year, Lu et al. [14] accomplished sensing by filling liquid crystals into a hollow-core fiber which was coated with a gold film on the inner wall. The sensitivity was $4.72\text{nm}/^\circ\text{C}$ in the range of 20 to 34.5°C . Subsequently, Zhu et al. [15] proposed a novel PCF sensor by combining SPR principle with defect coupling mechanism. Two air holes are determined in cladding, metal films are deposited on one of inner surfaces while the diameter of the other air hole is changed. Magnetic fluid material is filled in these two air holes. By analyzing the relationship between RI of magnetic fluid with its temperature and magnetic field, simultaneous sensing of temperature and magnetic field are realized. Liu [16] presented a new core-cladding symmetrical structure PCF in 2019, which fills all air holes of a group of core-cladding with ethanol. Temperature measurement is achieved due to RI of ethanol changes with temperature. Simulation results show that the sensitivity of 1cm fiber meets

$3.21\text{nm}/^\circ\text{C}$ in the area from 20 to 25°C . According to previous studies, most existing fiber temperature sensors selected to be filled with temperature-sensitive materials in PCF. Since infiltrating liquid into air holes or coating metal on the inner wall is comparatively inconvenient in practical approach, fabrication of sensors described above is rather complicated. In addition, filling media are mainly alcohol, benzene or liquid crystal. These materials respond significantly to changes in temperature but poisonous and volatility, which is not conducive to preservation and recycle of sensors. In order to surmount the above problems, this study chooses to wrap the double-layer membrane immediately outside PCF, which reduces complexity of the structure and is more sensitive to external surroundings.

This paper numerically reports a high-sensitivity temperature sensor by using commercial software COMSOL Multiphysics, finite element method (FEM), with anisotropic perfectly matched layers (PML). First of all, SPR material gold is deposited outside PCF cladding with chemical vapor deposition (CVD), owing to its chemical stability and is less likely to be oxidized in presence of temperature sensing medium. Then, PDMS is wrapped outside the gold film through the curing process, which makes it in direct contact with the environment to be measured and reduce the manufacturing difficulty. By optimizing the parameters, results show that the identification ability of sensor for temperature changes is improved effectively. It's found that the average sensitivity of sensor is $9.287\text{nm}/^\circ\text{C}$, and the maximum can reach $13\text{nm}/^\circ\text{C}$. Finally, the influences of diameters d_1 , Λ , t_1 and t_2 on resonance wavelength, loss value and sensitivity are analyzed. Owing to the simple structure and stable performance, the proposed sensor has a chance of actually being manufactured with current technology.

Structural design and theoretical analysis

Fig.1. (a) Cross-section of the proposed PCF; (b) the meshing of computational region for the optimized structure: $d_1=1.2\mu\text{m}$, $d_2=3\mu\text{m}$, $\Lambda=2.5\mu\text{m}$, $t_1=35\text{nm}$ and $t_2=1.1\mu\text{m}$.

The two-dimensional cross-sectional of the proposed PCF is depicted in Fig. 1(a). It consists of twelve air holes arranged in a hexagonal grid. In order to promote the surface plasmons propagate effectively on metal dielectric surface, air holes with two different diameters are designed. The large air holes are placed on both sides parallel to the fiber core while the small air holes are arranged on the upper and lower sides. Consequently, evanescent wave is transferred to gold film through passageways as shown by arrows in Fig. 1(a), which passageways radius is $r=7.5\mu\text{m}$. The diameters of air holes are represented by d_1 and d_2 , where $d_1=1.2\mu\text{m}$, $d_2=3\mu\text{m}$; Λ represents the horizontal distance between adjacent small air holes, which was determined to be $2.5\mu\text{m}$; A gold layer with diameter of $t_1=35\text{nm}$ is used as plasmonic material, which is deposited outside the PCF cladding by CVD method; Symbol t_2 expresses the thickness of sensing medium PDMS, which is wrapped on top of the gold surface and it is considered to be $t_2=1.1\mu\text{m}$; The proposed PCF is practically realizable through stack-and-draw fabrication means because of its simple structure. By commercial software COMSOL Multiphysics to investigate sensing properties of the proposed PCF. Fig. 1(b)

indicates the meshing of the calculation region for optimized structure. To guarantee the computational accuracy, PML and scattering boundary condition are increased.

Pure silica is the background material of PCF whose dispersion coefficient is calculated by the Sellmeier equation [17] :

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (1)$$

Here, n is the refractive index of fused silica, which is decided by incident light wavelength λ in vacuum. $B_1, C_1, B_2, C_2, B_3, C_3$ are known as Sellmeier constants.

The dielectric constant of gold is described by the Drude-Lorentz formula [18] :

$$\epsilon_m = \epsilon_\infty - \frac{\omega_D^2}{\omega(\omega + i\gamma_D)} - \frac{\Delta\epsilon \cdot \Omega_L^2}{(\omega^2 - \Omega_L^2) + i\Gamma_L\omega} \quad (2)$$

where ϵ_m expresses the permittivity of gold, and $\epsilon_\infty=5.9673$ is the permittivity at high frequency. $\omega=2\pi c/\lambda$ indicates angular frequency of guided light where c is the velocity of light, $\omega_D=2\pi \times 2113.6$ THz refers to plasmon frequency, and $\gamma_D=2\pi \times 15.92$ THz represents the damping frequency. $\Delta\epsilon=1.09$ can be interpreted as a weighting factor, $\Omega_L=2\pi \times 650.07$ THz and $\Gamma_L=2\pi \times 104.86$ THz are frequency and spectral width of the Lorentz oscillator, respectively.

PDMS is silicone material with unique optical properties extensively applied to optical field, which has excellent qualities of wide operating range, non-toxic and chemically stable [19]. It has high thermo-optic coefficients and is sensitive to temperature change. At the same time, the extraordinary optical characteristics of PDMS are not affected after curing. Its effective refractive index varies with temperature as determined by the equation [20-22] :

$$n_{PDMS} = n_0 - \gamma\Delta T \quad (3)$$

In this expression, $n_0=1.421332$ is the effective refractive index of PDMS at 20°C , $\gamma=-4.66 \times 10^{-4}/^\circ\text{C}$ is thermo-optical coefficient, ΔT refers to temperature variation.

Confinement loss is an indispensable parameter while investigating PCF, which can be defined by the following equation [23] :

$$\alpha = 8.868 \times \frac{2\pi}{\lambda} \text{Im}(n_{\text{eff}}) \times 10^{-4} \quad (4)$$

where the units of α are dB/cm. λ is wavelength in vacuum and $\text{Im}(n_{\text{eff}})$ represents virtual part of the effective refractive index.

The capability of sensor can also be reflected by sensitivity, which can be calculated by wavelength interrogation method as follows [24] :

$$S(\lambda) = \frac{\Delta\lambda_{\text{peak}}}{\Delta T} (\text{nm}/^\circ\text{C}) \quad (5)$$

Here, $\Delta\lambda_{\text{peak}}$ represents the distance of resonance peak shift and ΔT indicates the amount of temperature change.

As shown in Fig. 2, experimental setup for realize temperature sensing mainly includes the following three parts: broadband light source (BBS), temperature control chamber and optical spectral analyzer (OSA). BBS is used to transmit light into single mode fiber (SMF) and couple with PCF-SPR sensor. Then the sensor responds to temperature by changing the temperature of surroundings with temperature control chamber. Finally, transmission spectrum is tracked and displayed by OSA. Temperature changes will lead to variations in RIs of PDMS. Since different RIs will change the phase matching condition of fundamental mode and SPR mode result in loss peak shift. Therefore, temperature measurement is achieved by analyzing the relationship between temperature variation and resonance wavelengths drift.

Fig.2. Schematic diagram of the experimental setup for the proposed PCF temperature sensor.

Results and discussions

A. Influences of different parameters on sensing characteristics

In this segment, the influences of structural parameters d_1 , Λ , t_1 , and t_2 on loss values, sensitivity and resonance wavelengths are discussed.

Fig.3. (a) Variation of loss spectrum at 20°C with different d_1 ; (b) Variation of the resonance wavelengths with different d_1 in the range -20~40°C.

Fig. 3(a) shows that the confinement loss relies on the operable wavelength by changing diameter of d_1 . It can be seen that with increases of d_1 , the confinement loss decreases and resonance wavelength red-shifts, which is owing to the enhanced limitation of light. The energy transferred to gold surface decreases due to the enhancement of the bound light ability, which weakens the SPR phenomenon and reduces the loss value. Variations of the resonance wavelengths with different d_1 over the temperature ranges from -20°C to 40°C as depicted in Fig. 3(b). It can be seen from Fig. 3(b) that when d_1 is fixed, resonance wavelength blue-shifts with increase of temperature. Average sensitivity is obtained about 8.291nm/°C, 8.807nm/°C, 9.568nm/°C, 10.354nm/°C, 11.507nm/°C, respectively, with the d_1 increased from 0.8μm to 1.6μm. Increasing d_1 is instrumental in improving sensitivity, while

half-peak width tends to wider and the shape of spectrum is too smooth. Therefore, $d_1=1.2\mu\text{m}$ is the optimal value by considering the confinement loss and wavelength sensitivity.

Fig.4. (a)Variation of loss spectrum at 20°C with different Λ ; (b)Variation of the resonance wavelengths with different Λ in the range -20~40°C.

Fig. 4(a) describes the variation of confinement loss spectrum for different Λ at 20°C. From Fig. 4(a), it can be concluded that the resonance wavelength blue-shifts when Λ changes from $2.3\mu\text{m}$ to $2.4\mu\text{m}$ while peak loss decreases. The large Λ narrows the transmission route of energy to the metal layer, which results in a weakened coupling between fundamental mode and SPP mode. Variations of the resonance wavelengths with different Λ over the sensing range are shown in Fig. 4(b). The maximum wavelength sensitivity of $10.781\text{nm}/^\circ\text{C}$ is obtained at $\Lambda=2.3\mu\text{m}$, while the corresponding confinement loss is not conducive to practical application. All in all, by considering the peak loss and sensitivity Λ is determined to be $2.5\mu\text{m}$.

Fig.5. (a)Variation of loss spectrum at 20°C with different t_1 ; (b)Variation of the resonance wavelengths with different t_1 in the range -20~40°C.

As observed in Fig. 5(a), the confinement loss depends on operable wavelength by changing t_1 . The confinement loss decreases and the resonance wavelength red-shifts as t_1 increases. Since the effective refractive index of fiber core remains invariant, while the effective refractive index of SPP mode varies with t_1 , which results in the shift of coupling position between two modes. The thickness of metal film will influence the decay rate of evanescent wave and spp mode. Thicker gold layer is responsible for loss value decreases and half-peak width increases. With the increase of gold layer, the energy of evanescent field decreases and confinement loss increases. The thickness of the gold layer also affects sensitivity of sensor, as depicted in Fig. 5(b). As seen in Fig. 5(b), sensitivity increases from 10.452 to $11.093\text{nm}/^\circ\text{C}$ with the gold layer increases from 32nm to 38nm . Taking into account sensitivity and confinement loss, $t_1=35\text{nm}$ is determined as the optimum gold layer thickness of the sensor.

Fig.6. (a)Variation of loss spectrum at 20°C with different Λ ; (b)Variation of the resonance wavelengths with different Λ in the range -20~40°C.

The effect of varying sensor parameter t_2 on loss spectrum and sensitivity is illustrated in Fig. 6. Fig. 6(a) indicates that confinement loss increases significantly and blue-shifts as t_2 increases. In addition, the half-peak width greatly decreases and the spectral appears sharper. That is because the RIs of PDMS decreases with increase of temperature, which leads to the variation of phase matching wavelength. According to Fig. 6(b), sensitivities decreased from 11.094 to 10.116nm/°C, when the t_2 increased from 1.0μm to 1.4μm. In order to improve the sensing performance and meet practical applications, $t_2 = 1.1\mu\text{m}$ was chosen as the optimum PDMS layer thickness. Finally the influence of each parameter on sensor performance is summarized, which is illustrated in Table 1.

Table.1 The effects of different parameters on spectra and sensitivity.

Parameters	Variation range(μm)	Loss value	Spectrum shift	Sensitivity
d_1	0.8~1.6	Decrease	Red-shift	Increase
Λ	2.3~2.7	Decrease	Blue-shift	Decrease
t_1	0.032~0.038	Decrease	Red-shift	Increase
t_2	1.0~1.4	Increase	Blue-shift	Decrease

B. Sensing Performances of the Proposed Temperature Sensor

From the above discussion, optimal parameters for this sensor were determined, which are observed in Table 2. Fig. 7(a) shows the confinement loss dependence on operable wavelength as temperature varies from -20°C to 40°C and the temperature interval is 10°C. At the resonance wavelength of 1380, 1280, 1150, 1030, 950, 890, and 840nm, the corresponding losses are 405.45, 328.57, 267.46, 229.97, 201.7, 175.35, and 152.77 dB/cm. The changes of resonance wavelength at different temperatures and fit curves are depicted in Fig. 7(b). The equation of the linear fitting is determined as $y=1168.28-9.287x$, where y and x represent the resonance wavelength and temperature, respectively. The slope K represents the average sensitivity of the sensor from -20°C to 40°C, which is 9.287nm/°C. Linearity R^2 is equal to 0.99114. The maximum sensitivity of the sensor reaches 13nm/°C in the range of -10°C ~ 0°C.

Fig.7. (a) Variation of loss spectrum; (b) Resonance wavelengths and its fit curve.

Table.2 The value of the optimized parameters.

Parameters	d_1	Λ	t_1	t_2
value(μm)	1.2	2.5	0.035	1.1

In addition to the criterion of sensitivity, measurement accuracy can also be regarded as intuitive reflection of sensor performance. The measurement accuracy determines the minimum temperature change sensed by sensor, which can be defined by the following expression [25] :

$$R = \frac{\Delta T \Delta \lambda_{\min}}{\Delta \lambda_{\text{peak}}} (^\circ\text{C}) \quad (6)$$

where ΔT refers to the temperature variation. The minimum detection accuracy of the spectrometer is $\Delta \lambda_{\min}$, which is generally taken as 0.1nm. $\Delta \lambda_{\text{peak}}$ expresses the wavelength shift. The proposed sensor is capable of detecting extremely small temperature changes with an accuracy of 0.01077°C. A detailed comparison of the performance of our work with previous studies based on sensing range and wavelength sensitivity, which is illustrated in Table 3.

Table 3. Comparison of the proposed temperature sensor with previous studies.

Reference	Sensing Type	Detection range(°C)	ΔT (°C)	Sensitivity(nm/°C)
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[26]	SPR	0~50	50	0.72
[27]	Sagnac	25~33	8	1.65
[13]	SPR	26~43	17	6.18
[28]	Mach-Zehnder	23.2~58.2	35	1.83
[29]	WGM	25~45	20	0.377
This work	SPR	-20~40	60	9.287

Conclusion

A high-sensitivity PCF temperature sensor is proposed in this paper. Both the gold and PDMS are deposited outer surface of PCF to minimize the fabrication complexity and achieve more efficient sensing. The FEM method is used to investigate sensing characteristics of the temperature sensor. At optimized sensor parameters, simulation results show that average sensitivity of the proposed sensor is 9.287 nm/°C as temperature changes from -20°C to 40°C, and the maximum sensitivity reaching 13nm/°C. Owing to its high sensitivity and wide sensing range, the proposed sensor supports temperature detection in intelligent monitoring and industrial production. Meanwhile, the design of forming an annular sensing channel outside the PCF effectively overcomes the problem, which is the difficulty of filling air holes in the PCF.

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Disclosures The authors declare no conflicts of interest.

Ethical Approval Approval was obtained from the ethics committee of YanShan University. The procedures used in this

study adhere to the tenets of the Declaration of Helsinki.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The participant has consented to the submission of the case report to the journal.

Availability of data and materials Data are available on request to the authors.

Code availability Not applicable

Authors Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Yuhui Feng, Shuguang Li, Hongyu Li, Xiaojian Meng, and Mengqiang Li. The first draft of the manuscript was written by Yuhui Feng and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Compliance with Ethical Standards

Conflict of Interests The authors declare that they have no conflicts of interest.

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