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Spiral Photonic Crystal Fiber Temperature Sensor Based on Surface Plasmon Resonance

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Abstract: In this paper, we demonstrate and evaluate a high sensitivity spiral design photonic crystal fiber (PCF) temperature sensor based on surface plasmon resonance (SPR). Besides, the coupling phenomenon is studied. The selective air holes are filled by temperature sensitive liquid and coated with gold layer to enhance the sensitivity of the sensor. Variation of temperature leads different loss spectra that has been analyzed. The computer simulation result indicate that the obtained wavelength sensitivity of the proposed sensor is as high as 585 pm/°C and wide detection range of temperature 0°C to 80°C. In addition, the variation of structural parameter such as metal thickness and air holes are investigated on the performance of the sensor sensitivity. Considering high sensitivity and wide detection range of temperature, this spiral PCF temperature sensor can be potentially employed to monitor the temperature of manufacturing industry, medical environment, transformer oil, battery of electric vehicles etc.

Keywords: photonic crystal fibers (PCF), finite element method, temperature sensor, surface plasmon resonance (SPR).

I. INTRODUCTION

In medical, manufacturing industry, environmental monitoring, transformer oil, temperature has significant effects to consider. Over the last few years, sensors have offered some attractive features to monitor the temperature of a particular application. Compared to conventional sensor, optical fiber based sensor has some tremendous advantages such as high sensitivity, light weight, isolation with electrical signal, variable shape, low cost etc. [1,2]

Plasmonic has significant importance for designing PCF based temperature sensor. The sensitivity of the temperature sensor can be improved by combining PCF with surface plasmon resonance (SPR) technology. Normally, silver, gold, aluminum and copper are some of the plasmonic material. However, silver as a plasmonic material has oxidization problem that reduces the sensing range and performance. On the other hand, gold is chemically stable. The use of gold as plasmonic material for designing temperature sensor is preferable for better performance. Although there are different types of optical fiber sensor such as fiber Bragg grating (FBG) [1,2], Mach-Zehnder Interferometer (MZI) [3] but the recent trend indicates that researchers have shown significant interest to design SPR based temperature sensor. Because the wavelength based sensor has superior performance than intensity-based sensor.

In order to enhance the sensitivity Hassani et al. first reported PCF sensor based on SPR and obtained sensing resolution of 10-4 RIU (refractive index units) [4]. Y. Zhao et al. have proposed SPR based temperature sensor that has sensitivity of 1.575nm/°C [5]. However, they used silver as plasmonic material that has oxidization problem. Y.Chen et al. reported a liquid sealed temperature sensor with low sensitivity about -166 pm\°C [7]. N. Liu et al. have proposed a temperature sensor with Bragg gratings and have found sensitivity around 10 pm/°C [8]. Their temperature sensor has also low sensitivity. S.K.Srivastava et al. have shown a localized surface-plasmon-resonance-based fiber optic temperature sensor and found sensitivity 0.188 pm\°C [9].

In this paper, a spiral design optical fiber temperature sensor based on surface plasmon resonance is demonstrated and loss spectra and mode distribution is analyzed by using COMSOL Multiphasic software. The effect of variations of temperature and wavelength on the sensor performance is analyzed precisely. The obtained sensitivity of the proposed sensor is around 585 pm\C that is higher than that of exiting temperature sensor reported in [7-9].

II. DESIGN METHODOLOGY

The spiral design temperature sensor depicted in Fig. 1. To enhance the coupling between a plasmonic mode and a core guided mode, and to reduce the plasmonic to plasmonic mode coupling is the purpose of the design. The proposed designconsists of three rings with diameter d_1, d_2 and d_3 respectively from the inner ring. A (pitch) is the center to center distance between the air holes. The optimum value for the proposed design are d_1=0.582 μm,d_2=1.074 μm, d_3=0.746 μm and A =0.91 μm.The first and third rings are filled with air and known as air hole. On the other hand, the second ring is filled with chloroform (high temperature co- efficient material) and coated with plasmonic material (gold). The refractive index of the chloroform is calculated by [10]

$$\eta = \eta_{liquid} + (\frac{dn}{dT})(T - T_0) \qquad (1)$$

Wheredn/dt =-4 × 10^{-4}(°C^{-1}), $l_{iquid}$is the refractive index of the liquid at the reference temperatureT_0 =25°C . By neglecting the material dispersion of the liquid and let us assume η_{liquid} = 1.35from thespectral wavelength from 500 nm to 1000 nm at 25 °C.The optimum thickness for gold is 40 nm for better performance.The three rings of the design confirms the formation of the spiral photonic crystal fiber sensor.We assume that the background of PCF is made of fused silica and is characterized by the Sellmeier equation [11]. The plasmonic material goldischaracterized by the Drude-Lorentz model [12].

$$\mathcal{E}(\omega) = \mathcal{E}_1 + i\mathcal{E}_2 = \mathcal{E}_\infty \frac{\omega_p^2}{\omega(\omega + i\omega_c)} \qquad (2)$$

Where ω_c is the collision frequency, ω_p is the plasma frequency, and $\mathcal{E}_\infty$is associated with the absorptionpeaks athigh frequency ($\omega \gg \omega_c$).For gold, we take $\mathcal{E}_\infty$=9.75,$\omega_0 = 1.3659 \times 10^{16}$, and $\omega_c = 1.45 \times 10^{14}$.Equating the propagation constants of the two modes, implying that the effective refractive indices of the two modes have to be shut is required by phase matching, theoretically.

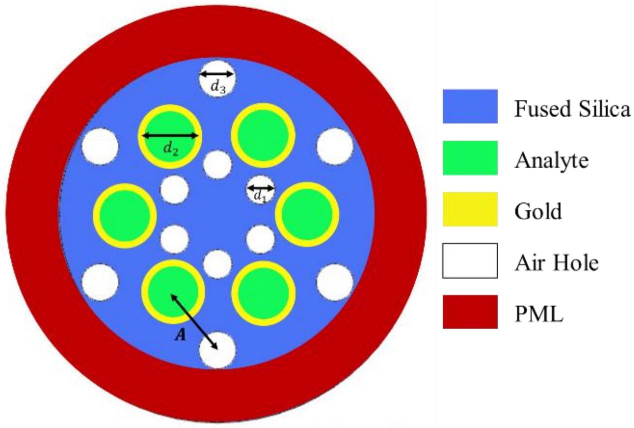

Fig.1. Cross section view of the proposed spiral designed PCF temperature sensor

When a metallic layer is used to coat the dielectric then there exist two plasmonic modes for each mode order. These two modes are known as silica-bounded plasmonic mode and sensing medium bounded plasmonic mode. The phase matching is occurred at a certain wavelength known as resonance wavelength. In this resonance wavelengththe energy of core-guided mode is transferred to a plasmonic mode. A significant loss will be observed at this resonance wavelength as plasmonic mode is highly lossy.When refractive indices of the sensors vary with temperature, the resonance wavelength between the core guided mode and plasmonic mode changes.Therefore, with the temperature change the absorption peak can be shifted.

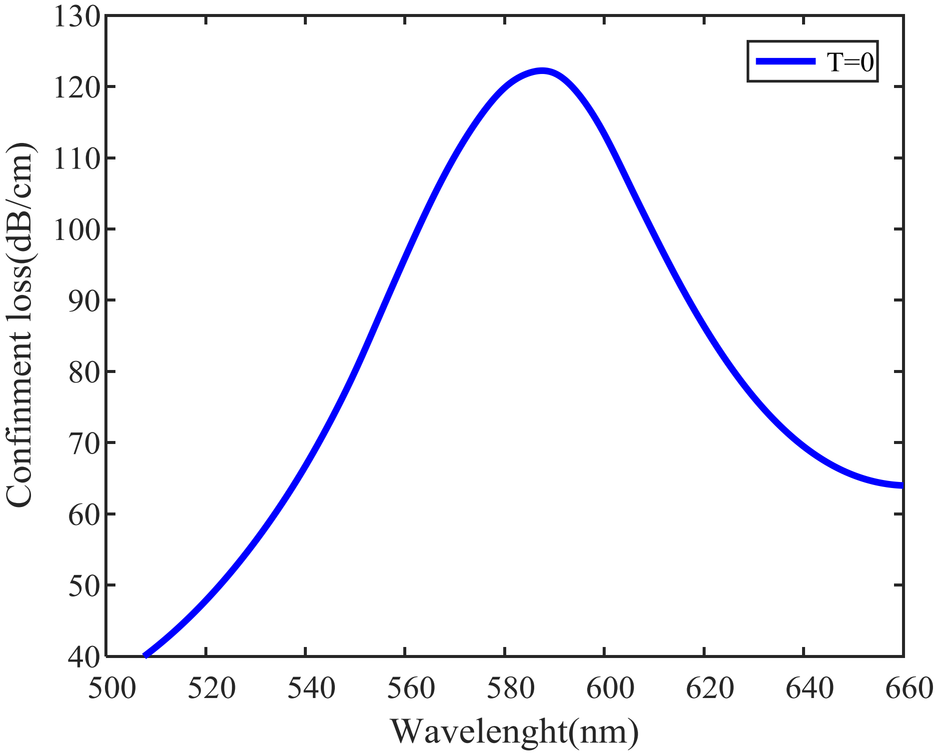

Fig.2 Confinement loss spectra as a function of wavelength at T=0°C for x-polarization

The Fig. 2 shows the dispersion profile where the blue line indicate the confinement loss. From the Fig. 2, it is seen that with the increasing wavelength, the loss also increases and at one particular wavelength, a sharp loss peak is observed. In this condition, the energy of core-guided mode is transferred to a plasmonic mode.

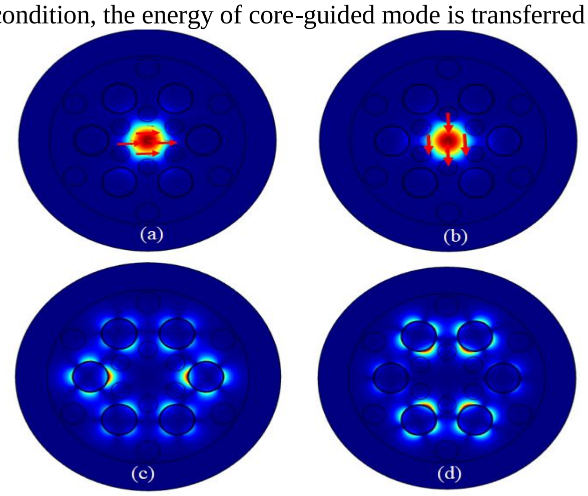

Fig. 3 The electric field distribution of the temperature sensor for fundamental mode (a) x-polarization (b) y-polarization and SPR modes (c) x-polarization (d) y-polarization

The fundamental optical field distribution for x and y- polarized modes is shown in Fig 3(a) and Fig 3(b) respectively. The SPP modes for x-polarization and y-polarization is represented in Fig 3(c) and Fig 3(d) respectively. In this paper, the performance of the proposed sensor is analyzed for x-polarization light only.

III. PERFORMANCE ANALYSIS:

A finite element method with PML boundary was used to investigate the performance of the proposed temperature sensor. In this paper, the performance is analyzed in the sensing ranges from 0 °C to 80 °C. Fir 4 shows the confinement loss curves as a function of wavelength for a range of temperature where gold layer thickness isselected at 40 nm. The confinement loss curve is obtained by the equation depicted in [13].

$$A = 40\pi.\frac{Im(neff)}{\ln(10)\,\lambda}$$
$$A \simeq 8.686 \times k_o.Im(neff) \times 10^4 dB/cm \qquad (3)$$

where, n_{eff} is the imaginary part of effective refractive index and k_o is the free space wave number. The simulation result for the optimum parameters is shown in Fig. 4.

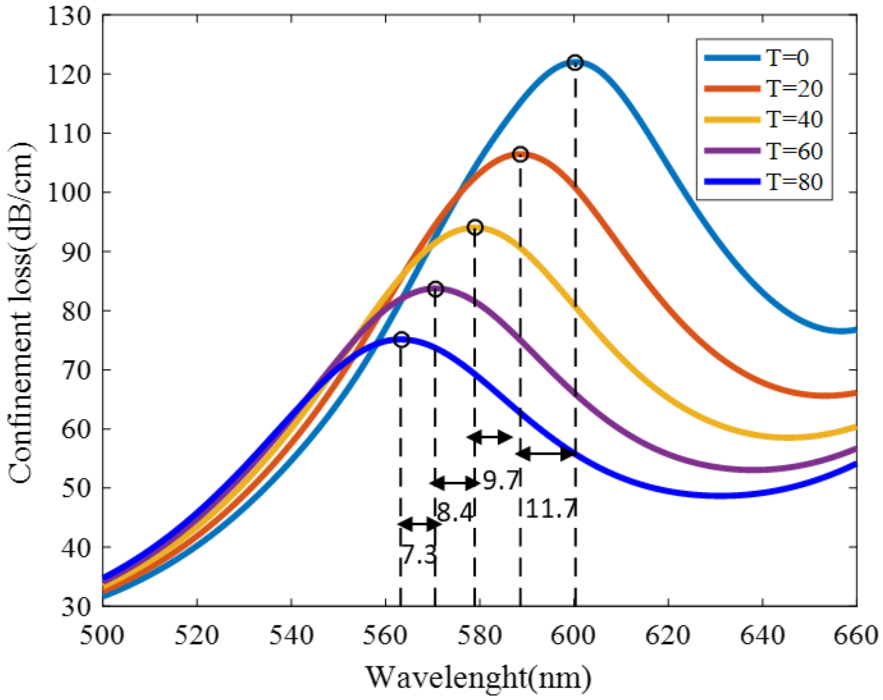

Fig. 4 Confinement loss spectra as a function of wavelength of the proposed temperature sensor for a range of temperature

It shows that sharp loss peak is obtained at 600.3 nm, 588.6 nm,578.9 nm,570.5 nm and 563.2 nmfor the temperature of 0°C, 20°C, 40°C, 60°C, and 80°C respectively. The wavelength difference between two adjacent loss curves is 11.7 nm, 9.7 nm, 8.7 nm, 7.3 nm at resonance condition. The wavelength sensitivity is measured by wavelength interrogation method

$$S_\lambda\left[\frac{nm}{°C}\right] = \frac{d\lambda_{peak}\ (T)}{dT} \qquad (4)$$

Where, $d\lambda_{peak}$ is the wavelength difference between two adjacent loss curve at resonance condition and dT is the difference of two temperature. The predictable maximum resonance peakshift in this work is about 585 nm according to Fig. 4 for the detection range 0°C to 80°C. The sensor shows lower sensitivity for high temperature and high sensitivity for low temperature detection range.

Now we will observe what will be the result of sensitivity of the temperature sensor if the parameter fluctuates from its optimum value during fabrication process.First the effect of variation of diameter d_1 is considered in Fig 5(a) while other parameters are kept constant. One can observe from Fig. 5(a) that with the increasing the diameter d_1 of air hole in the first ring of the PCF the resonance wavelength increases linearly. The larger air hole in the first ring reduces the chance of light confinement in the core region. Therefore, there be an optimal value. The optimum value for diameterd$_1$ is kept at 0.582 µm for this particular design.

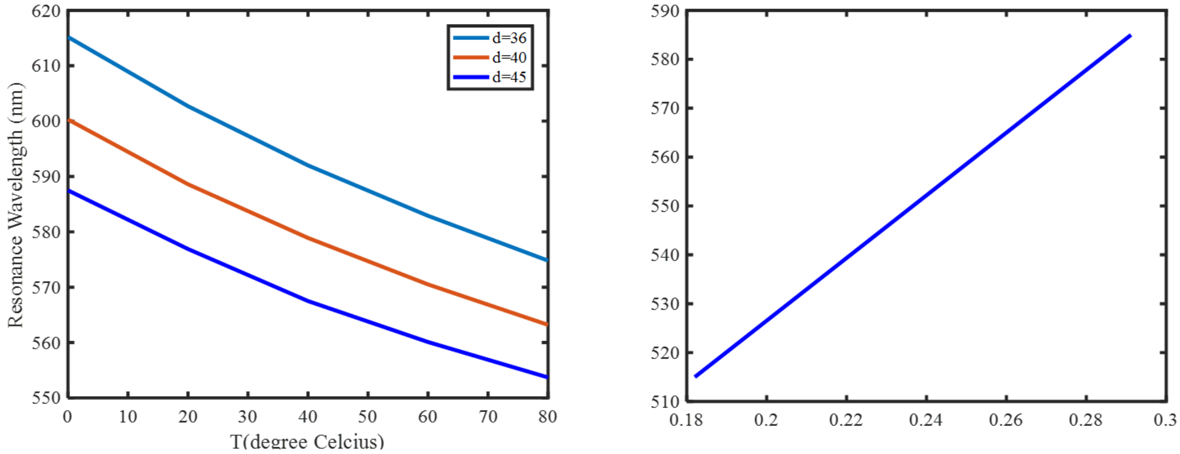

Fig. 5 (a) Stability test of gold as a function of T°C(b) Resonance wavelength as a function of radius r_1

Now, variation of thickness of gold layer is carefully investigated while other parameters are kept constant at the optimum value as shown in Fig. 5(b).The variationof plasmonic peak due to the variation of temperature for the sensor is relatively stable even with other goldlayer thickness, as depicted in Fig. 5(b).The figure shows that temperature–resonance wavelength curves are nearly linear. However, surface plasmonic waves are very sensitive to gold layer. When temperature is kept at 20°C and gold thickness are kept at 36 nm, 40 nm, and 45 nm, then the variation of the resonance peak of the proposed sensor are shown in Fig. 6.

The resonance peak shifts to a larger wavelength with the increasing of the thickness of the gold. When the gold thickness is thicker than 40 nm then lower resonance peak is observed with an increasing curve width. On the other hand, if the thickness is thinner than 40 nm then higher resonance peak is obtained with narrower curve width as shown in Fig. 6. There is a problem of penetration for electric field if the gold thickness is too much thicker. Moreover, the loss of the sensor is very high if the thickness is too low. Therefore, the optimal thickness of gold for better performance of the sensor is chosen at 40 nm.

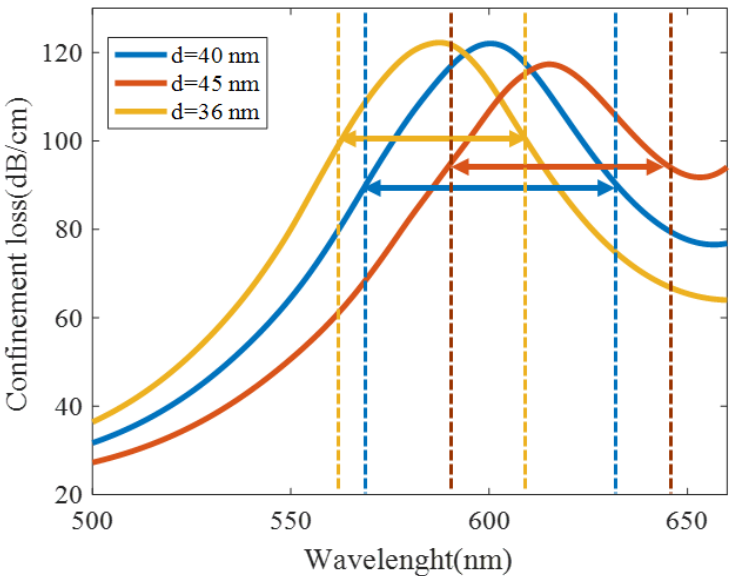

Fig. 6: Effect of gold thickness on the proposed sensor performance

IV. CONCLUSION

In essence, a spiral structured with gold-coatedphotonic crystal fiber using surface plasmon resonance temperature sensor has been proposed. A mode solver software with perfectlymatched layer boundary condition is used to demonstrate theperformance of the proposed temperature sensor.Numerical results indicate that the obtained wavelength sensitivity of the proposed sensor is as high as 585 pm/C and wide detection range of temperature **0**°C **to 80**°C that is much higher than many formerly demonstrated designs**.** Moreover, the air holes in the design are circular type that reduces the fabrication complexity.Considering high sensitivity and wide detection range of temperature, this spiral PCF temperature sensor can be potentially employed to monitor the temperature of variation applications.

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