Simultaneous measurement of refractive index and temperature of seawater based on surface plasmon resonance in a dual D-type photonic crystal fiber

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Abstract

A dual D-type photonic crystal fiber (PCF) was proposed in this work to measure the refractive index and temperature of seawater. Two golden layers were designed to be coated on the two polished planes in the dual D-type PCF. Two confinement loss peaks in the transmission spectrum appeared due to the surface plasmon resonances which were inspired on the two golden layers. In order to achieve two-parameter sensing, one of the two polished planes was further coated with a polydimethylsiloxane (PDMS) layer which was temperature-sensitive. Seawater was assumed to be coated on the outer surface of the PCF. Numerical results by using the finite element method showed that the measurement sensitivity of the refractive index of seawater reached 1371 and 1228 nm/RIU, while the measurement sensitivity of temperature reached $-0.3$ and $-1.06$ nm/$^\circ$C, respectively. Finally, we obtained the transfer matrix expression which could be used to measure the refractive index and temperature of seawater simultaneously. The designed dual D-type PCF, which is simple in structure, highly sensitive and two-parameter measuring, could be a promising candidate for the monitoring of seawater.

1. Introduction

Compared with the traditional optical fiber, photonic crystal fiber (PCF) exhibits endless single-mode transmission, controllable dispersion, high birefringence, and high nonlinearity [1–4]. In recent decades, PCF has been widely used in the area of optical devices such as optical sensors, filters, and lasers [5–7]. PCF-based sensors were more attractive in terms of the humidity sensor, temperature sensor, and refractive index sensor [8–10]. Surface plasmon resonance (SPR), which is highly sensitive to the refractive index of the material in contact with metal, has been used in many sensing frameworks [11]. In recent years, owing to the characteristics of compact structure, highly integration and remote sensing function, optical fiber-based SPR sensors showed great potential in the field of chemical and biomedical sensing [12].

At present, the temperature and refractive index sensors were used to monitor the variation of seawater. Salinity and temperature of seawater were related to refractive index of seawater and were important factors for aquaculture and protection of marine biological resources [13]. Different marine organisms live in seawater with different refractive indices and temperatures. Seawater with abnormal salinity and temperature could affect the reproduction and growth of fish, coral, and algae. The salty of seawater depicts a linear relationship with refractive index [14]. Therefore, it is essential to monitor the refractive index and temperature of the seawater. With the development of ocean exploration, the requirements for the information extraction of seawater were getting higher and higher. Multi-parameter sensor could built a three-dimensional data network of seawater [15]. The current difficulty in the research of multi-parameter sensors lies in the decoupling of cross-sensitivity.
Some researchers began to be used the transfer matrix method to solve the cross-sensitivity problem \[16\]. Zhao et al designed a C-type micro-structured optical fiber for the simultaneous detection of temperature and salinity of seawater \[17\]. In recent years, many PCF-based temperature and refractive index sensors have been proposed. In 2017, Yang et al proposed a SPR sensor based on D-type micro-structured optical fiber. The polished surface was coated with a gold layer, and the air holes were filled with chloroform solution to achieve simultaneous measurement of refractive index and temperature. The sensitivity of refractive index was 2214 nm/RIU and the sensitivity of temperature was \(-1.81\) nm/°C \[18\]. However, the infiltration of medium into the air hole was difficult. In 2018, Wang et al proposed a SPR based PCF sensor by coating the fiber with gold-PDMS films. The measurement sensitivity of refractive index was 4613 nm/RIU and the sensitivity of temperature was 1551 pm/°C in the temperature range of 35 °C–100 °C \[19\]. But the resonant peak showed a nonlinear relationship with refractive index. In 2019, Alam et al designed a high-sensitivity dual-core PCF sensor with a maximum temperature sensitivity of 818 pm/°C and a maximum refractive index sensitivity of 25000 nm/RIU \[20\]. However, the sensitivity was not so good in term of temperature.

In this paper, we designed and numerically studied a dual D-type PCF sensor based on SPR. This sensor can be used to measure the temperature and refractive index of seawater. The PCF was polished on both sides, and the SPR material of gold layer which was coated on the polished surfaces to improve the sensing performance. PDMS layer which was coated on the bottom gold layer was selected as the temperature-sensitive material. The confinement loss spectrum before coating a PDMS layer showed only one resonance peak. After coating a PDMS layer, the confinement loss spectrum showed two heterogeneous resonance peaks. Contrast to coat metal films and fill temperature-sensitive materials in the inner air holes of PCF, the SPR based PCF in this paper was easier to implement. In simulation, the full-vector finite element method was used to study the sensing performance of the gold and PDMS coated dual D-type PCF. In order to optimized the sensing performance, we analyzed the influence of structural parameters on the sensing characteristics. By measuring the displacement of the two resonance peaks, the variations in temperature and refractive index of seawater were measured. We studied the sensitivity of the sensor with a refractive index range from 1.33 to 1.34 for seawater and a temperature range of 0 °C–40 °C. The calculated results showed that the resonance peak varied linearly with the refractive index and temperature. The purpose of this article was to demonstrate the idea of measuring the refractive index and temperature of seawater simultaneously based on the SPR-PCF sensor and to provide a theoretical basis for the involved experimental research.

2. Structural design and basic theory

The cross-section of the proposed SPR-based dual-sided polished PCF sensor is shown in figure 1. The PCF structure is composed of three layers of air holes and dual-sided polished. Polishing the PCF on both sides is one of the difficulties in manufacturing this optical fiber sensors. The arrangement of the air holes in PCF is simple, which can reduce the fabrication difficulty. The D-type PCF, which decreases the distance between fiber core and sensing medium, enhances the evanescent field intensity greatly. Motor-driven polishing wheel method has been used to fabricate the D-type PCF \[21\]. The two polished surfaces of the PCF are symmetrically arranged. By coating the gold layers with same thickness on the two polished surfaces and further coating a PDMS layer on the bottom gold layer, two heterogeneous resonance peaks are generated in the confinement loss spectrum which
show different temperature and refractive index sensing properties. Gold is chosen as the SPR layer to generate SPs, as it has a larger shift of resonance wavelength and is more stable than silver. The lattice pitch is denoted by \( \Lambda \) and its initial value is 2.5 \( \mu \text{m} \). The diameter of the air hole is represented by \( d \) which is initially set at 1.6 \( \mu \text{m} \). Gold is deposited on the polished surface, and its thickness is represented by \( t_g \). The initially value of \( t_g \) is set at 40 nm. PDMS layer is coated on the bottom gold layer, and its thickness is represented by \( t_{\text{PDMS}} \) and initially set at 100 nm. Seawater is placed on the outer surface of the PCF. Perfect matching layer (PML) boundary condition is adopted to fully absorb the radiant energy of the external area to prevent light reflection from interfering with the fiber mode. Since this fiber is a dual D-type PCF, it can be spliced by using core alignment method when splices it with other traditional optical fibers.

By using the commercial software of COMSOL multiphysics, the finite element method is used to study the sensor characteristics of the proposed PCF. Both the refractive index of seawater and PDMS vary with temperature. The refractive index of seawater depending on temperature at a concentration of 33.8% can be expressed as [14]:

\[
n(T) = 1.34482 - 0.0002T
\]

Considering that the refractive index of seawater changes with temperature, we introduced the formula that the refractive index of seawater changes with temperature in the simulation. As the temperature is a constant, the refractive index of seawater shows a linear relationship with the concentration of salt:

\[
n(S) = 0.00025 + 1.333043
\]

The refractive index of PDMS is given by Sellmeier equation [22] and its thermo-optical coefficient is \(-4.5 \times 10^{-4} / \text{°C}\) [23]. The background material of PCF is fused silica which refractive index is calculated by Sellmeier equation [24]:

\[
n(\lambda) = \sqrt{1 + \sum_{i=1}^{m} \frac{B_i \lambda_i^2}{\lambda^2 - \lambda_i^2}}
\]

where \( n \) is the refractive index, \( \lambda \) is the wavelength, and the unit is \( \mu \text{m} \). \( m = 3 \), \( B_1 = 0.6961663 \), \( B_2 = 0.407926 \), \( B_3 = 0.8974794 \), \( \lambda_1 = 4.67914826 \times 10^{-2} \mu \text{m} \), \( \lambda_2 = 1.35120631 \times 10^{-2} \mu \text{m} \), and \( \lambda_3 = 97.9340025 \mu \text{m} \).

Gold is used as the SPR material and its dielectric constant is expressed by the Drude-Lorentz model [25]:

\[
\varepsilon_m = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma_D)} - \frac{\Delta \varepsilon \cdot \Omega_I^2}{(\omega^2 - \Omega_I^2) + i\Gamma_I \omega}
\]

where \( \varepsilon_m \) is the dielectric constant, \( \varepsilon_\infty = 5.9673 \) is the high-frequency dielectric constant, \( \omega = 2\pi c/\lambda \) is the angular frequency of guiding light, \( \omega_D \) and \( \gamma_D \) represents the plasma frequency and the damping frequency, \( \omega_D/2\pi = 2113.6 \text{ THz} \), and \( \gamma_D/2\pi = 15.92 \text{ THz} \). Weight factor \( \Delta \varepsilon = 1.09 \). \( \Omega_I \) and \( \Gamma_I \) are the frequency and spectral width of the Lorentz oscillator, where \( \Omega_I/2\pi = 650.07 \text{ THz} \) and \( \Gamma_I/2\pi = 104.86 \text{ THz} \).

Confinement loss which is an important criterion for studying performances of SPR-fiber sensor can be defined as [26]:

\[
\alpha(x, y) = 8.686 \times \frac{2\pi}{\lambda} \text{Im}(n_{\text{eff}}) \times 10^6
\]

where \( \lambda \) represents the operating wavelength and \( \text{Im}(n_{\text{eff}}) \) represents the imaginary part of the effective refractive index. The units of \( \lambda \) and mode loss are nm and dB/ m, respectively.

We use the displacement of the resonance wavelength to calculate the measurement sensitivity of refractive index and temperature. The refractive index sensitivity \( S_n \) can be written as:

\[
S_n(\text{nm}/\text{RIU}) = \Delta \lambda / \Delta n
\]

The temperature sensitivity \( S_T \) can be written as:

\[
S_T(\text{nm}/\text{°C}) = \Delta \lambda / \Delta T
\]

where \( \Delta \lambda \) is the shift of the resonance wavelength, \( \Delta T \) represents the variation in temperature and \( \Delta n \) is the variation of refractive index of seawater [17].

In the SPR-based dual-sided polished PCF sensor, it is assumed that the resonance wavelength shift corresponding to the two resonance peaks are \( \Delta \lambda_{\text{I}} \) and \( \Delta \lambda_{\text{II}} \). The two resonance peaks change linearly with temperature and refractive index. The influence of temperature and refractive index on the resonance wavelength can be defined as:

\[
\begin{bmatrix}
\Delta \lambda_{\text{I}} \\
\Delta \lambda_{\text{II}}
\end{bmatrix} = \begin{bmatrix} K_{\text{T I}} & K_{\text{II}} \\ K_{\text{T II}} & K_{\text{III}} \end{bmatrix} \cdot \begin{bmatrix}
\Delta T \\
\Delta n
\end{bmatrix} = K \begin{bmatrix}
\Delta T \\
\Delta n
\end{bmatrix}
\]

where \( \Delta T \) and \( \Delta n \) are the variation in temperature and refractive index, \( K_{\text{T I}} \) and \( K_{\text{T II}} \) are the temperature fitting coefficients, while \( K_{\text{II}} \) and \( K_{\text{III}} \) are the refractive index fitting coefficients.
3. Results and discussion

As the phase matching condition core mode and SPP mode in PCF match, the core-guided light couples to the SPPs on the gold film surfaces. Figures 2(a) and (b) shows the electric field distributions of two core modes when the refractive index of seawater is 1.334 and \( T = 36 ^\circ C \). One core mode is called the x-polarized (x-pol) mode and the other one is the y-polarized (y-pol) mode. Figures 2(c) and (d) shows the electric field distributions of two y-pol SPP modes when the refractive index of seawater is 1.334 and \( T = 36 ^\circ C \). Figure 3(a) depicts the confinement loss spectrum of the core mode and the dispersion relationship when the refractive index of seawater is 1.334 and \( T = 36 ^\circ C \), with no coating a PDMS layer on the bottom gold layer. The figure clearly shows that the refractive indices of the y-pol mode and the y-SPP modes overlap, which means that there is only one sharp confinement loss peak, corresponding to a resonance wavelength. This is because when PDMS is not added, the upper and bottom metal interfaces have a homogeneous structure, and the resonance for the core mode and the SPP modes of the upper and bottom metal interfaces occurs to the same wavelength. Figure 3(b) shows the dispersion relationships and confinement loss spectra when the refractive index of seawater is 1.334 and \( T = 36 ^\circ C \). When the refractive index of the y-pol mode and the y-SPP modes coincides, a sharp confinement loss peak is generated. At this resonance wavelength, a maximum energy is transferred from the core guided mode to the SPP modes. The figure clearly shows that the refractive indices of the y-pol mode and the y-SPP modes overlap twice, which means that there are two sharp confinement loss peaks (namely peak I and peak II), corresponding to two resonance wavelengths. One is the y-pol SPP mode of peak I at 600 nm and the other one is the y-pol SPP mode of peak II at 686 nm. Peak I is generated by the coupling of the core mode and the plasma mode on the upper surface, and peak II is generated by the coupling of the core mode and the plasma mode on the bottom surface. This is because after adding PDMS to the bottom surface, the metal film on the upper surface does not change, and the resonance wavelength of the core mode and the metal film on the upper surface does not change. However, since the core mode only resonates with the upper surface metal at this
wavelength at this time, the resonance intensity is lower than when PDMS is not added. The SPP mode on the bottom surface is modulated by PDMS, so the phase changes and the resonance wavelength are red shifted. Since the confinement loss of the x-polarized mode is very small, only the y-polarized mode is considered here to study the propagation confinement loss. It can be clearly seen that after coating PDMS, the loss peak has changed from one to two. In this way, after PDMS is added, the upper and bottom metal surfaces are heterogeneous structures, and two confinement loss peaks with different response characteristics are realized, which can be used for dual-parameter sensing.

Then, we optimized the performances of the sensors by changing the structural parameters in PCF including the diameter of air holes, the lattice pitch, the thickness of the gold layers, and the thickness of the PDMS. Figure 4 shows the confinement loss spectra under different diameters of air holes. The refractive index of seawater is 1.33, $T = 36^\circ C$, $d = 1.6 \mu m$, $\Lambda = 2.5 \mu m$, $t_g = 40 \text{ nm}$, and $t_{\text{PDMS}} = 100 \text{ nm}$.

Next, we studied the sensing performance under different lattice pitches. The confinement loss spectra under different $\Lambda$ is shown in figure 5. When the $\Lambda$ changes from 4 to 4.2 $\mu m$, the resonance wavelength of peak I has not change, and peak II shows a slight shift. Obviously, the lattice pitch $\Lambda$ has a limited impact on the sensitivity of the sensor. By changing the air holes and lattice pitch, it can be seen that this sensor has the characteristics of stable structure.

The thickness of the gold layer also plays a vital role in the performance of the PCF sensor. Figure 6 shows the confinement loss spectra when the $t_g$ changes from 30 to 50 nm. The refractive index of seawater is set at 1.33. When the thickness of the gold film increases, the resonance peak shows a red shift and the value of confinement loss peak becomes smaller. In figure 6, at the resonance wavelength of 566 nm, the confinement loss peak at
$t_g = 30 \text{ nm}$ is the largest, and at the resonance wavelength of 702 nm, the confinement loss peak at $t_g = 50 \text{ nm}$ is the smallest. It is found that a relatively thin gold film layer would reduce the signal-to-noise ratio of the sensor. On the other side, when the gold film is thicker, the SPR effect is weakened due to less evanescent field reaching the analyte interface, which is not conducive to high-sensitivity sensing. Therefore, we chose a gold layer thickness with $t_g = 40 \text{ nm}$ to ensure high-sensitivity sensing and appropriate signal-to-noise ratio.

The sensing properties at different thickness of PDMS has also been studied. Figure 7(a) shows the confinement loss spectra of the proposed sensor as the $t_{\text{PDMS}}$ increases from 80 to 100 nm. As the $t_{\text{PDMS}}$ increases, the resonance wavelength of peak I do not change, while the resonance wavelength of peak II experiences a red shift. This is because the peak I is generated by the surface plasmon resonance on the upper gold layer. The PDMS which is coated on the bottom surface exhibits influence on peak II but no effect on peak I. Figure 7(b) shows the confinement loss spectra when the $t_{\text{PDMS}} = 80, 90$ and 100 nm. The refractive index of seawater is 1.33 and the temperature increase from 0 to 30 °C. The resonant wavelength of peak I varies with temperature to the same degree, moving from 616 to 606 nm. As temperature increase from 0 to 30 °C, the resonance wavelength of peak II decreases from 710 to 682 nm at $t_{\text{PDMS}} = 80$ nm, from 720 to 682 nm at $t_{\text{PDMS}} = 90$ nm and from 728 to 696 nm at $t_{\text{PDMS}} = 100$ nm, respectively. The shift of resonance wavelength of peak II becomes larger as $t_{\text{PDMS}}$ increases from 80 to 100 nm. The same is true for the confinement loss value at resonance wavelength. Figure 7(c) shows the confinement loss spectra at the refractive index of seawater increases from 1.33 to 1.34 at the $t_{\text{PDMS}}$ of 100, 90, and 80 nm. The temperature is 36 °C. The resonance wavelength of peak I maintains the same as $t_{\text{PDMS}}$ increases from 80 to 100 nm. As the refractive index increases from 1.33 to 1.34, the resonance wavelength of peak II increases from 668 to 680 nm at $t_{\text{PDMS}} = 80$ nm, from 676 to 686 nm at $t_{\text{PDMS}} = 90$ nm and from 682 to 694 nm at $t_{\text{PDMS}} = 100$ nm, respectively. Among them, temperature and refractive index have a better influence on the resonance wavelength when $t_{\text{PDMS}} = 100$ nm, while only temperature changes have a greater influence on the resonance wavelength when $t_{\text{PDMS}} = 80$ nm. Therefore, we finally set the thickness of PDMS at 100 nm.
Through the above analysis, the optimized PCF structure parameters are $d = 1.6 \, \mu m$, $\Lambda = 2.5 \, \mu m$, and $t_g = 40 \, nm$. Then, we begin to study the seawater sensing performance based on the optimized PCF. The refractive index of seawater is 1.33, 1.332, 1.334, 1.336, 1.338, and 1.34 corresponding to the salt concentration of 0%, 10%, 20%, 30%, 40% and 50%. Figure 8(a) shows the confinement loss spectra under different seawater refractive indices when the temperature is at $36 ^\circ C$, and two confinement loss peaks in the spectra are observed. As the refractive index of seawater increases, the resonance wavelength of peak I increases from 594 to 608 nm, while the resonance wavelength of peak II increases from 682 to 694 nm. Both confinement loss peaks undergo red shift.

Figure 7. (a) Confinement loss spectra under different $t_{\text{PDMS}}$. The refractive index of seawater is 1.33, $T = 36 ^\circ C$, $d = 1.6 \, \mu m$, $\Lambda = 2.5 \, \mu m$, and $t_g = 40 \, nm$. (b) Confinement loss spectra as temperature increase from 0 to $30 ^\circ C$ at different $t_{\text{PDMS}}$. The refractive index of seawater is 1.33, $d = 1.6 \, \mu m$, $\Lambda = 2.5 \, \mu m$ and $t_g = 40 \, nm$. (c) Confinement loss spectra as the refractive index of seawater increases from 1.33 to 1.34. The parameters are: $T = 36 ^\circ C$, $d = 1.6 \, \mu m$, $\Lambda = 2.5 \, \mu m$ and $t_g = 40 \, nm$.

Figure 8. (a) Confinement loss spectra at different concentrations of seawater and (b) resonance wavelength variation with refractive index of seawater. The $T = 36 ^\circ C$, $d = 1.6 \, \mu m$, $\Lambda = 2.5 \, \mu m$, and $t_g = 40 \, nm$. 
The matrix expression of temperature and refractive index of seawater can be both the refractive index and temperature of seawater, the two con... respectively. The sensitivity in the vertical and horizontal directions are 1371 nm RIU and 0.98429 for peak I, while those are 1228 nm RIU and 0.98048 for peak II.

Table 1. Comparison of sensitivity in fiber optic based two-parameter (refractive index and temperature) sensors.

| References       | Temperature | Sensitivity | Refractive Index | Sensitivity | References |
|------------------|-------------|-------------|------------------|-------------|------------|
| Alam et al (2019)| 30 °C–70 °C| 818 nm/°C   | 1.3328–1.3375    | 25000 nm/RIU (maximum) | [19]       |
| Weng et al (2016)| 10 °C–70 °C| 0.1371 nm/°C| 1.20–1.40        | 561.4286 nm/RIU | [27]       |
| Liu et al (2019) | 25 °C–80 °C| 42.7 pm/°C  | 1.33–1.376       | 141 nm/RIU | [28]       |
| Akter et al (2020)| 0 °C–60 °C| 1000 pm/°C  | 1.3209–1.3288    | 20000 nm/RIU (maximum) | [29]       |
| In this paper    | 0 °C–40 °C | 1.06 nm/°C | 1.33–1.34        | 1371 nm/RIU |            |

Figure 8(b) shows the relationship between resonance wavelength and refractive index of seawater. The linear fitting expression is \( y = 1371x + 77 \) for peak I and \( y = 1228x + 77 \) for peak II, where \( y \) and \( x \) represent the resonance wavelength and refractive index of seawater respectively. The sensitivity of refractive index and \( R^2 \) are 1371 nm/RIU and 0.98429 for peak I, while those are 1228 nm/RIU and 0.98048 for peak II.

Figure 9(a) shows the confinement loss spectra at different temperatures. The temperature increase from 0 to 40 °C and the concentration is at 33.8%. Two confinement loss peaks in the spectra are observed. As the temperature increases, the resonance wavelength of peak I experiences a blue shift from 616 to 604 nm, while the resonance wavelength of peak II undergoes a blue shift from 728 to 686 nm.

Figure 9(b) shows the relationship between resonance wavelength and temperature. The linear fitting equation for peak I is \( y = -0.3x + 615.6 \) and \( y = -1.06x + 728 \) for peak II. The sensitivity of temperature and \( R^2 \) for peak I are \( -0.3 \text{ nm/°C} \) and 0.98246, while those are \( -1.06 \text{ nm/°C} \) and 0.99858 for peak II.

From the above analysis, we can conclude that the two confinement loss peak wavelengths are affected by both the refractive index and temperature of seawater, the two confinement loss peaks change linearly with the temperature and refractive index. The matrix expression of temperature and refractive index of seawater can be deduced below based on equation (8):

\[
\begin{bmatrix}
\Delta T \\
\Delta n
\end{bmatrix} = K^{-1} \cdot \begin{bmatrix}
\Delta \lambda_I \\
\Delta \lambda_{II}
\end{bmatrix} = \begin{bmatrix}
K_{TI} & K_{TII} \\
K_{III} & K_{IIII}
\end{bmatrix}^{-1} \cdot \begin{bmatrix}
\Delta \lambda_I \\
\Delta \lambda_{II}
\end{bmatrix}
\]

By substituting the four coefficients \( K_{TI}, K_{TII}, K_{III} \) and \( K_{IIII} \) into the formula (9), and \( K_{TII} = -0.3 \text{ nm/°C} \), \( K_{III} = -1.06 \text{ nm/°C} \), \( K_{IIII} = 1371 \text{ nm/RIU} \) and \( K_{IIII} = 1228 \text{ nm/RIU} \), we can obtain the matrix expression of temperature and refractive index of seawater:

\[
\begin{bmatrix}
\Delta T \\
\Delta n
\end{bmatrix} = \begin{bmatrix}
-0.3 \text{ nm/°C} & 1371 \text{ nm/RIU} \\
-1.06 \text{ nm/°C} & 1228 \text{ nm/RIU}
\end{bmatrix}^{-1} \cdot \begin{bmatrix}
\Delta \lambda_I \\
\Delta \lambda_{II}
\end{bmatrix}
\]

According to equation (10), the temperature and refractive index of seawater can be determined by monitoring the two resonance wavelengths of peak I and peak II.

Some fiber optic based two-parameter (refractive index and temperature) sensors has been reported in literature as shown in table 1. Weng et al proposed a SPR-based optical fiber sensor with double-sided polishing in the vertical and horizontal directions [27]. Due to the polished surface was only coated with a metal layer, the measurement sensitivities of refractive index and temperature were only 0.1371 nm/°C and 561.4286 nm/RIU, respectively. The sensitivity in [28] were also not very high because of the sensor was not based on the SPR. Alam proposed a SPR-based optical sensor with double-sided polishing in the vertical and horizontal directions [27]. Due to the polished surface was only coated with a metal layer, the measurement sensitivities of refractive index and temperature were only 0.1371 nm/°C and 561.4286 nm/RIU, respectively. The sensitivity in [28] were also not very high because of the sensor was not based on the SPR. Alam
et al [19] and Akter et al [29] improved the sensitivity greatly by filled the liquid in the air hole. However, the relationship between wavelength with refractive index was not linear. Furthermore, the detection range of refractive index were a little narrow. In our designed sensor, moderate sensitivities of refractive index of 1371 nm/RIU and temperature of 1.06 nm/°C were achieved with a good linear relationship.

4. Conclusion

In this paper, a dual D-type PCF sensor based on SPR was proposed. Finite element method was used to study the temperature and refractive index sensing performances of seawater. By constructing two heterogeneous layers on the surface of PCF, two confinement loss peaks with different response characteristics appeared in the transmission spectrum. Therefore, simultaneous dual-parameter measurement of refractive index and temperature of seawater was realized. The PCF structural parameters were optimized to achieve better sensing performances. Numerical results showed that the average refractive index sensitivity and $R^2$ for peak I were 1371 nm/RIU and 0.98429, while 1228 nm/RIU and 0.98048 for peak II, respectively. The temperature sensitivity and $R^2$ for peak I were $-0.3$ nm/°C and 0.98246, while $-1.06$ nm/°C and 0.99858 for peak II, respectively. Finally, we obtained the matrix expression of the refractive index and temperature of seawater. The temperature and refractive index of seawater could be measured by monitoring the resonance wavelength of peak I and peak II in the confinement loss spectrum. The method of constructing heterogeneous layers on the surface of optical fiber is of important reference value for multi-parameter sensing.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

The authors declare that they have no competitive economic interests or personal relationships that may affect the work reported in this article.

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