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A Highly Sensitive Refractive Index Sensor Based on a V-Shaped Photonic Crystal Fiber with a High Refractive Index Range

Xin Yan *, Rao Fu, Tonglei Cheng and Shuguang Li

Abstract: This paper proposes a highly sensitive surface plasmon resonance (SPR) refractive index sensor based on the photonic crystal fiber (PCF). The optical properties of the PCF are investigated by modulating the refractive index of a liquid analyte. The finite element method (FEM) is used to calculate and analyze the PCF structure. After optimization, the fiber can achieve high linearity of 0.9931 and an average refractive index sensitivity of up to 14,771.4 nm/RIU over a refractive index range from 1.47 to 1.52, with the maximum wavelength sensitivity of 18,000.5 nm/RIU. The proposed structure can be used in various sensing applications, including biological monitoring, environmental monitoring, and chemical production with the modification and analysis of the proposed structure.

Keywords: surface plasmon resonance; photonic crystal fiber; refractive index sensor; sensitivity

1. Introduction

The waveguide characteristics and structural controllability of photonic crystal fibers (PCFs) [1] have led to the high popularity of the PCF-based surface plasmon resonance (SPR) devices. With the development of the SPR sensors, more of its peculiarity has been discovered and discussed. The SPR-based optical fiber sensor has the advantages of ultra-high sensitivity [2] and resolution [3], fast response speed [4], small size [5], and real-time detection capability [6], and they have been widely applied to the environmental monitoring, disease diagnosis, biological analysis [7], and many other fields [8–11]. Fiber SPR sensors generally have higher refractive index (RI) sensitivities than the RI sensors based on the fiber grating or interferometer, and thus have been widely applied to many fields [12]. Commonly, to increase the evanescent wave outside an optical fiber, a certain amount of or the entire optical fiber cladding is deployed on a traditional SPR optical fiber sensor [13].

In recent years, many studies on improving the sensors’ performances have been conducted. Liang et al. [14] proposed a D-shaped PCF-RI sensor with a different coating combination and added Graphene and Zinc Oxide above silver as a plasmonic exciton source material, thus achieving an average sensitivity of 6000 nm/RIU in the refractive index range of 1.37–1.41. This sensor has excellent stability and a good specialty for oxidation resistance, but its sensitivity is two times lower than the proposed sensor and its detection range is also small. Al Mahfuz et al. [15] designed a highly sensitive PCF-SPR biosensor having a maximum wavelength sensitivity of 12,000 nm/RIU in the measurement range from 1.33 to 1.40 for both gold and silver as plasmonic materials, this sensor has high sensitivity and the advantage of being easy to prepare. Wang et al. [16] proposed a refractive index sensor based on PCF with ultra-wide detection range from 1.29 to 1.49, which filled the central air holes with analyte and preformed the fiber with gold wires. This sensor has a wide detection range and stability, but to realize this fiber, the requirements of...
temperature, pressure and tension are very high. Yang et al. [17] presented a graphene-Au coated PCF sensor with a side-polish D-shaped plane, where graphene on gold helped to enhance the sensor’s sensitivity because it could stably adsorb biomolecules and increase the propagation constant of the surface plasmon polarization.

In this paper, a V-shaped highly-sensitive SPR-PCF refractive index sensor is proposed. The finite element method (FEM) is used to calculate and analyze the PCF structure [18]. A nano-level gold film is coated on the second layer of the proposed structure to excite the SPR, and an analyte liquid is infused in the second, third and fourth V-shaped layers. The simulation results show that the resonance wavelength of the loss curve follows a linear fitting rule [19] within the detecting range. After optimization, high sensitivity of up to 14,771.4 nm/RIU is obtained.

2. Proposed Structure Design and Working Principle

The two-dimension (2D) cross-sectional view of the proposed SPR-PCF refractive index sensor is shown in Figure 1a, where it can be seen that the proposed structure has four layers of air holes. In the $y$-axis lattice, two adjacent air-holes center-to-center distance, which is defined as a lattice constant $p_1$ is 1.7 $\mu$m, and in the $x$-axis lattice, the center-to-center distance is defined as a lattice constant $p_2$, and $p_2 = 2.0$ $\mu$m. The diameter $d_1$ is 1.4 $\mu$m, and the inner diameter of the hole having the metal layer $d_2$ is 1.6 $\mu$m. A thin gold layer is used as a plasmonic material, and its diameter $t_g$ is 30 nm. The dielectric constant of gold is characterized by the Drude-Lorentz model, and the middle diameter denoted as $d_3$ is 0.7 $\mu$m, while the diameter $d_4$ is 1.7 $\mu$m. A V-shaped structure is used to fill in an analyte liquid, and to minimize the air holes between the fiber core and metal layer.

The proposed design uses the partial filling technology [20] to infuse refractive index sensitive liquid materials selectively into the second, third and fourth layers of air holes closest to the gold coated layer so that the surface plasmons can efficiently and effectively propagate through the metal-dielectric surface. First, the UV glue carried by the mental tip is aligned with the air holes of the target PCF. Second, a UV lamp is used to irradiate the end face of the PCF. Third, the end face of the PCF is inserted into the analyte, and a gas pump is used to pump it into the five air holes. Fourth, the first and second steps are reused to seal the five air holes filled with the analyte liquid. If all the air holes are filled with analyte liquid, then the fiber can’t have total reflection because of the high RI range of the analyte. The fused silica is selected in the proposed structure as the background material, and the diameter of the silica layer is 17 $\mu$m. To demonstrate the RI of fused silica, the well-known Sellmeier mathematical model is used, which is a distinct detail in the perfectly matched layer (PML) [21]; the thickness of PML is 1.0 $\mu$m, and the RI of the PML is set to be 0.03 higher than the RI of the substrate material—SiO$_2$; the scattering boundary condition (SBC) is applied to the external section of the sensing analyte to avoid reflected echoes, and to absorb the energy of outward radiation. In the simulation, finer meshing elements were used to map the smaller air holes accurately. The computational domain took total triangular elements of 8992, edge elements of 1016, and vertex elements of 180.

The peak loss caused by the core mode resonantly coupled to the metal defect mode is presented in Figure 1b, where the dispersion relation between the $y$-polarized core-guided mode and plasmonic mode for analyte RI of 1.50 are presented by the black-dot and blue-dot lines, respectively. The refractive index curves leap reversely when the loss curve reaches the peak. Therefore, the refractive index of a measured object can be obtained based on the position of the loss peak. Then, the sensitivity of the proposed structure under different peak shifts is analyzed using software the COMSOL Multiphysics 5.2a software on a computer.
To distinguish the different conduction modes of this fiber, the energy distribution of coupling mode was analyzed at the wavelength in the range of 1600–1900 nm when the refractive index was 1.50, and the results are shown in Figure 2. The optical field distributions of the \( y \)-polarized core-guided mode, metal defect mode, and coupling of the core mode with the SPP mode are shown in Figure 2a–c, respectively. As the wavelength increases from 1600 nm to 1900 nm, the electric field strength of the core mode field changed from strong to weak and then to strong again. When the core mode and the metal defect mode were resonantly coupled, the core mode field energy was largely transferred and formed the resonant coupling mode.

The proposed fiber consists of fused silica. In the simulation process, the Sellmeier dispersion equation was used to set the scattering boundary conditions and finite element network, which was defined as [22]:

\[
n(\lambda) = \sqrt{1 + \frac{B_1^2}{\lambda^2 - C_1} + \frac{B_2^2}{\lambda^2 - C_2} + \frac{B_3^2}{\lambda^2 - C_3}} \tag{1}
\]

where \( \lambda \) represented the wavelength of the free space in microns, and the other fitting constants were set as given in [23]. In this study, gold was used to excite the SPR.
The dispersion of gold can be described by the Drude-Lorentz model [24] as follows:

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega - j\gamma_D)} - \frac{\Delta\varepsilon \cdot \Omega_L^2}{(\omega^2 - \Omega_L^2) - j\Gamma_L \cdot \omega}$$  \hspace{1cm} (2)

where $\varepsilon_\infty = 5.9673$ denotes the permittivity at infinite frequency, $\Delta\varepsilon = 1.09$ is a weighting factor, and $\omega$ denotes the angular frequency of the guiding light, $\omega_D$ and $\gamma_D$ are the plasmon frequency and the damping frequency, and $\omega_D/2\pi = 2113.6$ THz and $\gamma_D/2\pi = 15.92$ THz, respectively; $\Omega_L$ and $\Gamma_L$ represent the frequency and the spectral width of the Lorentz oscillator, and $\Omega_L/2\pi = 650.07$ THz and $\Gamma_L/2\pi = 104.86$ THz, respectively. The parameters of gold are given in [25].

In the calculation, a perfectly matching layer is introduced to absorb the radiation energy incident from different angles. By using the imaginary parts of effective refractive indices of the core and SPP modes, their confinement losses ($L_C$) can be calculated by [26]:

$$L_C = \frac{20 \ln 10}{\lambda} \cdot 2\pi \cdot \text{Im}[n_{\text{eff}}] \times 10^6 \text{ (dB/cm)}$$  \hspace{1cm} (3)

where $\lambda$ denotes the wavelength expressed in $\mu$m which is proportional to the $\text{Im}[n_{\text{eff}}]$ that is the imaginary part of the effective refractive index. A large number of free electrons are present on the PCF coated metal surface and their free movements generate plasma waves near the metal surface. When the propagation constant of the incident light wave matches the propagation constant of the plasma wave on the metal surface, free-electron resonance in the metal film is caused. In the performance measurement, the focus was only on the $y$-polarized fundamental core mode since it had a sharper and higher loss peak in the propagation direction.

3. Simulation Result Analysis and Discussion

The sensing performance of the proposed structure was studied in the refractive index range from 1.470 to 1.520 with the step of 0.01. The relationship between the peak loss of the core mode versus the incident wavelength when the refractive index of the analyte increasing from 1.470 to 1.520 with the increment of 0.01 is displayed in Figure 3a. With the gradual increase in the refractive index, the resonance loss curve realized a significant red shift, and the loss value peak first gradually decreased at first and then increased. That was because the RI of SPP mode increased with the analyte’s RI, but the RI of the core mode remained unchanged, which caused the rise of the SPP mode RI curve and the red shift in the resonance wavelength. Since phase matching was satisfied between the core mode and the surface plasmon mode, the SPR was generated. The energy of the core mode was transferred to the metal surface to form a surface plasmon mode, so the core mode loss curve was generated. The increase in the refractive index of the liquid altered the phase-matching conditions. The loss matching wavelength gradually increased, and the resonance loss curve performed a significant red shift. As the refractive index of the liquid material had a high value, it was relatively prone to absorb the light. Therefore, the core loss of the fiber gradually increased with the RI of the analyte. The refractive index and peak wavelength of the linearly fitted analyte are presented in Figure 3b. Within the analyte RI range, the linear fitting result of the refractive index sensor could be expressed as $y = 14,771.43x - 20,458.29$, the linear fit was $R^2 = 0.99314$, and the average sensitivity was $14,771.43$ nm/RIU.

By analyzing the loss curve, the PCF sensor was reckoned that it had good refractive index sensing performance over such a high measurement range, and the lowest loss value was $2410.8$ dB/cm over the test range of 1.470–1.520. Large losses could shorten the fiber’s length, making the sensor small enough to be integrated into equipment for inspection.
The wavelength sensitivity $S_\lambda$ was calculated as follows [27]:

$$S_\lambda (\text{nm/RIU}) = \frac{\Delta \lambda_{\text{peak}}}{\Delta n_a} \quad (4)$$

where $\Delta \lambda_{\text{peak}}$ denoted the deviation between the adjacent peak wavelength shifts, and $\Delta n_a$ was the deviation of the analyte’s RI.

As a factor in this paper, the figure of merit (FOM) on which the sensing enactment is being influenced is discussed. The FOM was calculated as follows [28]:

$$\text{FOM} = \frac{S_\lambda}{\text{FWHM}} \quad (\text{RIU}) \quad (5)$$

where FWHM is the full width at half-maximum of the transmittance spectrum, and the FWHM of the loss curve are 41 nm, 79 nm, 135 nm, 242 nm, 252 nm and 263 nm corresponding to the RI range from 1.47 to 1.52.

An important factor of a wavelength filter is the capacity to give high wavelength selectivity, which represents a high-quality factor (Q) [29]:

$$Q = \frac{\lambda_{\text{res}}}{\text{FWHM}} \quad (6)$$

where the $\lambda_{\text{res}}$ is the resonance wavelength of the core mode and the SPP mode.
3.1. Discussion on Different Structural Parameter

3.1.1. Discussion on $d_1$ Optimal Value

As shown in Figure 4, with the increase in the analyte RI, the loss spectrum made a red shift. When $d_1 = 0.5 \, \mu m$, the loss curves corresponding to both $n_a = 1.48$ and $n_a = 1.49$ indicated wide bandwidth, and the loss curve had a lower peak value than $d_1 = 0.6 \, \mu m$ and $d_1 = 0.7 \, \mu m$, so it could be concluded that $0.5 \, \mu m$ was not a good choice for the size of $d_1$.

![Figure 4. The loss spectrum ($n_a = 1.48, n_a = 1.49$) when $d_1$ varied from 0.5 $\mu m$ to 0.7 $\mu m$.](image)

The analysis results showed that $d_1 = 0.7 \, \mu m$ represented a better option than the other two parameter values since it provided a higher peak value and a lower bandwidth. The reason for this result could be the increase in the value of $d_1$, which increased the power transmitted between the gold layer and the analyte. Under a larger value of $d_1$, the light energy could easily penetrate into the analyte liquid, so the loss peak value was higher. When $d_1 > 0.7 \, \mu m$, the power of light would propagate more into the second layer of analyte-filled holes, and the core mode could not resonate with the SPP mode. After optimization, $d_1 = 0.7 \, \mu m$ was selected as an optimal value of $d_1$.

3.1.2. Discussion on $d_2$ Optimal Value

The loss spectrum when the value of $d_2$ varied from 0.7 $\mu m$ to 0.9 $\mu m$ is presented in Figure 5, where it can be seen that the loss curve showed a red shift when the refractive index of the analyte increased.

As $d_2$ increased, the loss peak value also increased, and the loss was in direct proportion to $d_2$. When $d_2 = 0.9 \, \mu m$ ($n_a = 1.48$), the peak value reached 3200 dB/cm, but at $n_a = 1.49$, the loss curve showed certain distortions. Using the mode field distribution map in the COMSOL software, two different plasmon modes that realized the power transmission with the core mode were observed, but these two plasmon modes' phase matching points did not overlap. Thus, $d_2 = 0.9 \, \mu m$ did not represent an optimal solution, and $d_2 = 0.8 \, \mu m$ denoted a better option than $d_2 = 0.7 \, \mu m$. When $d_2 = 0.8 \, \mu m$, the loss peak value was as high as 1400 dB/cm and the bandwidth was low. Based on the analysis results comparison, $d_2 = 0.8 \, \mu m$ was selected as an optimal value for $d_2$. 
194 Figure 5. The loss spectrum ($n_a = 1.48, n_a = 1.49$) when $d_2$ varied from 0.7 $\mu$m to 0.9 $\mu$m. As $d_2$ increased, the loss peak value also increased, and the loss was in direct proportion to $d_2$. When $d_2 = 0.9 \mu$m ($n_a = 1.48$), the peak value reached 3200 dB/cm, but at $n_a = 1.49$, the loss curve showed certain distortions. Using the mode field distribution map in the COMSOL software, two different plasmon modes that realized the power transmission with the core mode were observed, but these two plasmon modes’ phase matching points did not overlap. Thus, $d_2 = 0.9 \mu$m did not represent an optimal solution, and $d_2 = 0.8 \mu$m denoted a better option than $d_2 = 0.7 \mu$m. When $d_2 = 0.8 \mu$m, the loss peak value was as high as 1400 dB/cm and the bandwidth was low. Based on the analysis results comparison, $d_2 = 0.8 \mu$m was selected as an optimal value for $d_2$.

3.1.3. Discussion on $d_3$ Optimal Value

The loss curve was also analyzed when $d_3$ varied from 0.35 $\mu$m to 0.55 $\mu$m under $n_a$ of 1.47–1.52, and the obtained results are presented in Figure 6.

When $n_a = 1.47$ and $d_3 = 0.55 \mu$m, the core mode had incomplete coupling with the plasmon mode, so the loss curve had a low peak value. Besides, when $d_3 = 0.55 \mu$m and $d_3 = 0.45 \mu$m, the loss spectrum tended to have a higher loss peak and a lower bandwidth, but as $d_3$ increased, the loss curve showed a red shift. The results given in Table 1, indicate that at $d_3 = 0.35 \mu$m, the loss curve had a wider range ($n_a = 1.47$–1.52) than $d_3 = 0.45 \mu$m and $d_3 = 0.55 \mu$m.

![Figure 5: Loss spectrum with varying $d_2$.](image1)

![Figure 6: Loss spectrum with varying $d_3$.](image2)
3.1.4. Discussion on \( d_4 \) Optimal Value

The loss spectrum under \( n_a \) of 1.47–1.52 when \( d_4 \) varied from 0.65 \( \mu \)m to 0.95 \( \mu \)m is presented in Figure 7, and the numerical results are given in Table 2, the loss curve showed a red shift when the analyte RI increased.

![Figure 7](image-url)  
Figure 7. The loss spectrum \((n_a = 1.47–1.52)\) when \(d_4\) varied from 0.65 \(\mu\)m to 0.95 \(\mu\)m.

### Table 2. The resonant wavelength of different RI \((n_a = 1.47–1.52)\) when \(d_4\) varied from 0.65 \(\mu\)m to 0.95 \(\mu\)m.

| \(d_4\) (\(\mu\)m) | \(n_a\) (RIU) | 1.47 | 1.48 | 1.49 | 1.50 | 1.51 | 1.52 | Average Sensitivity (nm/RIU) |
|-----------------|---------------|------|------|------|------|------|------|-----------------------------|
| 0.65            |               | 1230.1 | 1370.2 | 1520.8 | 1660.7 | 1790.1 | 1900.0 | 13,571.4                   |
| 0.75            |               | 1230.2 | 1400.7 | 1570.1 | 1710.4 | 1840.4 | 1950.1 | 14,457.1                   |
| 0.85            |               | 1230.1 | 1410.9 | 1570.5 | 1720.6 | 1850.5 | 1970.5 | 14,771.4                   |
| 0.95            |               | 1380.8 | 1550.4 | 1700.1 | 1850.5 | 1960.6 | 14,600.0 |                          |

In contrast, when the value of \(d_4\) increased, there was no apparent shift in the loss curve. When \(d_4 = 0.95 \mu \text{m}\), the loss peak value reached a high value. Based on the results in
Table 2, \( n_a = 1.47 \) was not in the sensing range, and after calculating an average sensitivity, it was found that the RI sensor had the best sensing performance when \( d_4 = 0.85 \) \( \mu \text{m} \). Therefore, \( d_4 = 0.85 \) \( \mu \text{m} \) was selected as an optimal value of \( d_4 \).

3.1.5. Discussion on \( p_2 \) Optimal Value

The loss spectrum under \( n_a \) of 1.48–1.49 when \( p_2 \) varied from 2.0 \( \mu \text{m} \) to 2.4 \( \mu \text{m} \) is presented in Figure 8.

As shown in Figure 8, the increase in both the analyte RI and the value of \( p_2 \) caused the loss curve to make a red shift. When \( p_2 = 2 \) \( \mu \text{m} \), the loss value was higher than at \( p_2 = 2.2 \) \( \mu \text{m} \) or \( p_2 = 2.4 \) \( \mu \text{m} \). Moreover, the loss curve had a lower bandwidth at \( p_2 = 2 \) \( \mu \text{m} \) than at the other \( p_2 \) values. The reason for this phenomenon was that an increase in \( p_2 \) value reduced the power transmission between the gold layer and the analyte hole. As \( p_2 \) increased, there was more space for the background material, fused silica, so a larger pitch reduced the surface plasmon resonance (SPR) effect.

3.1.6. Discussion on \( t_g \) optimal value

The optimal value of \( t_g \) was also analyzed. First, all possible values of \( t_g \) from the range of 20 nm–60 nm were analyzed under \( n_a \) of 1.49–1.50, and the obtained results are presented in Figure 9. As shown in Figure 9, the loss curve had the highest loss peak value at \( t_g = 50 \) nm, but the bandwidth was relatively large, so \( t_g = 50 \) nm was discarded as a possible optimal value. Then, the loss curve was analyzed when \( t_g \) value was 20 nm, 30 nm, 40 nm, and 60 nm under \( n_a \) of 1.48–1.53, and the obtained results are presented in Table 3. As shown in Table 4, when \( t_g \) was 20 nm or 60 nm, the wavelength sensitivity was relatively low, i.e., about 12,000 nm/RIU, so only \( t_g \) values of 30 nm and 40 nm were left as possible optimal values; at both of these values, the average sensitivity was at the 15,000 nm/RIU-level. Therefore, the loss corresponding to \( t_g \) values of 30 nm and 40 nm were compared, and it was concluded that the loss curve corresponding to \( t_g \) value of 30 nm had lower bandwidth and higher peak value than that of \( t_g \) value of 40 nm, which was flatter. Consequently, a value of 30 nm was selected as an optimal \( t_g \) value.
Figure 9. The loss spectrum ($n_a = 1.49$–$1.50$) when $t_g$ varied from $30$ nm to $50$ nm.

Table 3. The resonant wavelength of different RI values ($n_a = 1.47$–$1.53$) under $t_g$ of $20$ nm, $30$ nm, $40$ nm, and $60$ nm.

| $d_4$ ($\mu$m) | $n_a$ (RIU) | Average Sensitivity (nm/RIU) | $t_g$=30 nm, $n_a$=1.49 | $t_g$=30 nm, $n_a$=1.50 | $t_g$=40 nm, $n_a$=1.49 | $t_g$=40 nm, $n_a$=1.50 | $t_g$=50 nm, $n_a$=1.49 | $t_g$=50 nm, $n_a$=1.50 |
|---------------|-------------|-------------------------------|--------------------------|-------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 20            | 1420.4      | 1560.4                        | 1690.3                   | 1810.6                  | 1910.9                   | 2010.1                   | 11,771.42                |                          |
| 30            | 1230.1      | 1410.1                        | 1570.2                   | 1720.5                  | 1850.4                   | 1970.7                   | 14,771.43                |                          |
| 40            | 1205.3      | 1400.1                        | 1570.1                   | 1720.2                  | 1850.3                   | 1970.1                   | 15,214.29                |                          |
| 60            | 1350.5      | 1520.7                        | 1660.4                   | 1780.7                  | 1890.0                   | 1990.1                   | 12,657.14                |                          |

Table 4. Performance comparison of fiber optic sensors based on SPR.

| Feature                                              | RI Range (RIU) | Average Sensitivity (nm/RIU) | Maximum Sensitivity (nm/RIU) | Reference |
|------------------------------------------------------|----------------|-----------------------------|-----------------------------|-----------|
| D-Shaped coated with Graphene and Zinc Oxide         | 1.36–1.47      | 4485.7                      | 6000                        | [11]      |
| Graphene-Enhanced Liquid Refractive Index Sensor     | 1.3330–1.3688  | 2290                        | -                           | [5]       |
| Wide-Range of Refractive Index Sensor                | 1.35–1.46      | 1931.03                     | -                           | [1]       |
| Graphene-Au Coated Plasmon Resonance PCF Sensor      | 1.32–1.41      | 3900                        | 4200                        | [14]      |
| Highly sensitive photonic crystal fiber plasmonic biosensor | 1.33–1.40    | -                           | 12,000                      | [12]      |
| Proposed Sensor                                     | 1.47–1.52      | 14,771.4                    | 18,000.5                    |           |

3.2. Fabrication Tolerance

During the fabrication process, it is relatively unlikely to maintain the value of the proposed structure’s parameters. Usually, the variation of ±1% in the structural parameter value during the fabrication process has been considered acceptable. However, the proposed sensor had a fabrication tolerance of ±2%, as depicted in Figure 10. The proposed optimized sensor’s parameters were $d_1 = 0.7 \mu$m, $d_2 = 0.8 \mu$m, $d_3 = 0.35 \mu$m, $d_4 = 0.85 \mu$m, $t_g = 30$ nm, and $p_2 = 2 \mu$m.
Figure 10. The loss spectrum when $t_g$ varied by $\pm 2\%$ ($n_a = 1.48, n_b = 1.49$) (a). The loss spectrum when $d_1$ varied by $\pm 2\%$ ($n_a = 1.48, n_b = 1.49$) (b). The loss spectrum when $d_2$ varied by $\pm 2\%$ ($n_a = 1.48, n_b = 1.49$) (c). The loss spectrum when $d_3$ varied by $\pm 2\%$ ($n_a = 1.48, n_b = 1.49$) (d). The loss spectrum when $d_4$ varied by $\pm 2\%$ ($n_a = 1.48, n_b = 1.49$) (e).
In Figure 10a,b,d, there are no obvious shifts in the loss curve, so changes in the values of $t_g$, $d_1$, and $d_4$ did not have an evident effect on the loss value. As shown in Figure 10c, when the value of $d_2$ increased, the loss curve had a tendency to perform a red shift, and the peak value also increased. Figure 10e shows that the change in the value of diameter $d_4$ did not result in an obvious loss curve shift but affected and increased the peak value. In conclusion, the proposed sensor has an excellent fabrication tolerance ability.

4. Conclusions

In this paper, a simple PCF-based SPR sensor, which has a high sensitivity, is proposed and optimized. The analyte is deposited in a V-shape adjacent to the gold layer to minimize the fabrication complexity and improve the sensing performance. Under the optimized sensor parameters, the proposed sensor shows a maximum wavelength sensitivity of 18,005.2 nm/RIU and an average sensitivity of 14,771.42 nm/RIU in the analytes measurement range of 1.47 and 1.52. The fabrication tolerance investigation has shown that the sensor parameters vary by ±2%, but these variations have no evident impacts on the sensing performance. Due to its simple structure and outstanding sensing characteristics, the proposed biosensor can be deployed in the liquid refractive index detection field.

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