Numerical Analyses of Liquid-Core Fiber Optic SPR Sensor with Nano-Porous SiO$_2$ as Inner Coating

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Abstract. In this paper, a novel type of liquid-core fiber optic SPR sensor with a nano-porous SiO$_2$ inner coating is proposed. The nano-porous SiO$_2$ is deposited on the inner wall of the quartz tube. Due to the flexible and adjustable refractive index of the deposited material, the RI detection range of the sensor is expanded. The simulation results show that the proposed sensor owns good responses in both low and high refractive index regions, with the corresponding RI sensitivities of 1043.71 nm/RIU and 1234.86 nm/RIU respectively, while the FWHM is only about 20 nm. There are some potential applications for the proposed sensor in environmental monitoring, biochemical detection, food safety etc.

1. Introduction

Surface plasmon resonance (SPR) sensors have been widely used as a fast, label-free and real-time sensing technology in life sciences, drug screening, food detection, clinical analysis and environmental monitoring, and other fields due to its high sensitivity to refractive index changes in recent years [1-4]. SPR is a kind of electron resonance phenomenon that occurs between the metal interface and the dielectric interface when the wave vector is balanced. Since SPR technology entered the field of vision of researchers in 1970s, it has developed four basic coupling types of prism type, fiber type, grating type and optical waveguide type, showing unique application value in many fields [5-7]. Optical fiber SPR sensor has attracted considerable attention because of its compact structure and low loss compared with prism type or grating type [8, 9].

The traditional solid-core optical fiber SPR sensor uses quartz as the optical waveguide medium, and the measured liquid and quartz are located on both sides of the metal layer. In this case, the sensor cannot detect liquid with a RI higher than 1.46 due to the refractive index limitation of the quartz material [10]. Even if the material with RI higher than 1.46 is used as the core, it will greatly increase the manufacturing cost and the manufacturing difficulty. To overcome this difficult, a liquid-core channel optical fiber SPR sensor was proposed [11, 12]. Different from the solid-core sensor, the liquid core sensor uses the internal liquid as the optical waveguide and the quartz or the polymer as the flow channel. In this case, the optical waveguide medium and the measured medium are unified. This kind of optical fiber SPR sensor has a good detection effect in a high refractive index range. However, they don't work in low refractive index ranges.
Nano-porous SiO$_2$ is a special optical material with high purity and stable optical properties [7]. It can be used in Cherenkov detector, optical waveguide and anti-reflection layer of photovoltaic cells and other fields [13, 14]. The nano-scale air holes are distributed in the material, the pore size and density can be regulated by adjusting the proportion of the material and the preparation process, so that the refractive index of the material can be adjusted flexibly. Nano-porous SiO$_2$ is deposited on the inner surface of the quartz tube as the cladding, and then silver is deposited as the excitation metal. A new three-layer membrane structure is formed after the liquid is passed through. By changing the refractive index of porous materials, the liquid with different refractive index ranges can be detected.

A liquid-core channel optical fiber SPR sensor model based on nano-porous SiO$_2$ film is proposed in this paper. This sensor can further expand the detection range and combine the advantages of the above two types of sensors. The sensor model is numerically simulated by using the three-layer membrane theory in this paper. The detection of low refractive index and high refractive index liquids by sensors under the new structure are simulated in the following sections.

2. Theoretical Model
Firstly, the material properties of each layer structure need to be clarified before analyzing the performance of the sensor. As shown in figure 1, the innermost layer is the "core layer" which composes of the liquid to be measured. To ensure that the light energy is confined in the liquid core, the total reflection condition needs to be satisfied. Therefore, the refractive index of the liquid to be measured should be higher than that of the porous layer. The diameter of the liquid core layer is initially set as 600 μm in this paper.

Then, the second layer is the metal layer used to generate the SPR effect. Since the liquid acts as the optical waveguide layer and it cannot support the metal, the metal is deposited on the inner surface of the porous layer. The previous study has reported that silver has a better excitation effect in SPR effect than gold [15], so silver is selected as the metal layer material in this study.

The dielectric constant of the metal layer is obtained by the Drude free electron model:

$$
\varepsilon_m(\lambda) = \varepsilon_{mr} + i\varepsilon_{mr} = 1 - \frac{\lambda_p^2 \lambda_c}{\lambda_p^2 (\lambda_c + i\lambda)}
$$

(1)

where, $\lambda_p$ and $\lambda_c$ are plasma constants and resonance wavelength constants of the metal layer, respectively. $\lambda_p$ = 1.4514 × 10$^{-7}$ m and $\lambda_c$ = 1.7614 × 10$^{-5}$ m.

Next, the third layer is the nano-porous SiO$_2$ layer. In the third layer, the size and density of the air holes determines the effective refractive index of the material [10]. This effective refractive index can be expressed as:

$$
n_{NPS} = (\phi_an_s^2 + (1-\phi_an_a^2)^{1/2}, d_a/\lambda \leq 1
$$

(2)

where $a$ is the volume fraction of the hollow porosity in the porous layer, while $n_a$ and $n_s$ are the refractive indices of air and silica respectively ($n_a$ = 1.0, $n_s$ = 1.46). The following restriction is to prevent the transmission loss caused by light scattering.

Nano-porous SiO$_2$ is a kind of mesoporous material with an average aperture of 2-50 nm, which is much smaller than the wavelength of incident light. Therefore, the influence of air hole density on the distribution uniformity of the metal sensing layer is very slight and can be ignored.

The variation range of the refractive index of the porous layer is written as:

$$
1.0 < n_{NPS} \leq 1.46
$$

(3)

In fact, this material has been prepared with an extremely low refractive index of 1.10 [6]. The porous layer with varying refractive index can be produced by controlling the proportion of precursor materials, preparation temperature, aging time and other factors.

Next, the transmission performance of the sensor model is analyzed by geometrical optics method. When the incident angle is small enough, the transmission loss of incident light in liquid-core fiber can be approximately equivalent to that of light passing through meridian. The light path propagation diagram is illustrated in figure 1.
As shown in Figure 1a, $\alpha$ is the incidence angle, and $\theta$ is the refraction angle. According to Snell’s law, the two satisfy the following relationship, namely:

$$\sin \alpha \cdot n_1 = \sin \theta \cdot n_c$$

(4)

where $n_1$ is the refractive index of the coupling fiber, which is generally 1.45, and $n_c$ is the refractive index of the liquid to be measured.

![Figure 1](image)

(a) Section view (b) Cross section view

**Figure 1.** The liquid-core fiber SPR sensor transmits optical path.

When light is injected into the liquid-core fiber, plasma waves will be excited in the sensing region when the total reflection condition is satisfied. The conditions for total reflection of light waves are shown as follows:

$$\theta > \theta_{cr} = \sin^{-1}(n_1/n_{NPS})$$

(5)

where, $\theta_{cr}$ is the total reflection angle between the liquid core layer and the porous layer, and $n_{NPS}$ is the refractive index of the porous layer mentioned above.

Generally, the light intensity $P_0$ incident into the liquid core fiber through the coupled fiber is approximately Gaussian distribution with the angle $\alpha$ [16], namely:

$$P_0(\alpha) \propto \exp(-\alpha^2/\alpha_0^2)$$

(6)

where, the angle $\alpha_0$ is related to the divergence angle of the incident light. Hence, the power of the output light is as follow:

$$P = \int_{\theta_{cr}}^{\pi/2} P_0(\theta)R(\theta)N(\theta) d\theta$$

(7)

where, $N(\theta)$ is the number of total reflections of light in the sensing region. Represented by [17]:

$$N(\theta) = L/(d \times \tan(\theta))$$

(8)

$N$ is integer. $L$ and $d$ represent the length and inner diameter of the liquid core fiber, respectively. $R(\theta)$ is the cascade reflectivity of the three-layer model [6], specifically expressed as:

$$R(\theta) = \left| \frac{r_{cm} + r_{mnNPS} \cdot \exp(2ik_{mc}T)}{1 + r_{cm} \cdot r_{mnNPS} \cdot \exp(2ik_{mc}T)} \right|^2$$

(9)

where, $c$, $m$, $NPS$ and $z$ represent the liquid core layer, the metal layer, the porous layer, $r_{cm}$ and $r_{mnNPS}$ describe the reflection coefficients at the interface of liquid core/metal layer and metal/porous layer, respectively. $k_{mc}$ represents the wave vector component of light propagating along the $z$ axis in the metal layer, and $T$ is the thickness of the metal layer.

Furthermore, $r_{cm}$ and $r_{mnNPS}$ are defined by the following formulas:

$$r_{cm} = \frac{k_{cc}/(n_c^2) - k_{mc}/(\epsilon_m)}{k_{cc}/(n_c^2) + k_{mc}/(\epsilon_m)}$$

(10)

$$r_{mnNPS} = \frac{k_{mc}/(\epsilon_m) - k_{NPSNPS}/(n_{NPS}^2)}{k_{mc}/(\epsilon_m) + k_{NPSNPS}/(n_{NPS}^2)}$$

(11)

$$r'_{cm} = \frac{k_{cc} - k_{mc}}{k_{cc} + k_{mc}}$$

(12)
The superscripts $p$ and $s$ represent $p$-polarized light and $s$-polarized light, respectively. $k_c$ and $k_{NPS}$ represent the light wave vector components propagating along the $z$ axis in the liquid core layer and the porous layer, respectively.

The wave vector of all light waves is given by the same expression [18]:

$$k_i = \frac{2\pi}{\lambda} \left[ n_i^2 - (n_i \sin \theta)^2 \right]^{1/2}$$

In the above equation, $i$ represents liquid core layer ($c$), metal layer ($m$) and porous layer ($NPS$) respectively. And $n_{m}^2 = \varepsilon_m$.

The transmission light intensity is expressed as [15]:

$$I = \frac{\int_{\theta}^{\pi/2} P_0(\theta) R(\theta)^{N(\theta)} d\theta}{\int_{\theta}^{\pi/2} P_0(\theta) d\theta}$$

SPR resonance occurs when the incident light vector is equal to the surface plasma vector. As a result, an SPR resonance absorption peak appears in the normalized transmission spectrum.

When the wave vector in the liquid core layer and the wave vector of the surface plasmon propagating along the metal-medium interface are equal, the resonance condition is satisfied. The wave vector of surface plasma propagating along the interface between metal and medium can be expressed as:

$$k_{sp} = \frac{\omega}{c} \left[ \frac{\varepsilon_m \varepsilon_c}{\varepsilon_m + \varepsilon_c} \right]^{1/2}$$

In equation (16), $\omega$ is the angular frequency of light wave, and $c$ is the light speed. The resonance condition is shown as follows:

$$\frac{2\pi}{\lambda} n_i \sin \theta = \frac{\omega}{c} \left[ \frac{\varepsilon_m \varepsilon_c}{\varepsilon_m + \varepsilon_c} \right]^{1/2}$$

The thickness of the porous layer should not be too thin, because the evanescent wave stimulates the surface plasmon resonance, and the effective distance of evanescent wave field is about 100 nm. Otherwise evanescent field will not be stimulated effectively in the metal layer. Moreover, the thickness of the metal layer is about several tens of nanometer, so the porous layer of about 150 nm is suitable.

The sensitivity $S$ of the sensor is defined as [19]:

$$S = \frac{\delta \lambda_R}{\delta n_e}$$

The full width at half maxima (FWHM) is also an important parameter which describes the resolution of the SPR dip. That is, the larger the dip width is, the harder it is to locate the dip position. The dip strength represents the strength of SPR effect, which is an important sensor performance parameter.

The relative refractive index difference $\Delta$ is a structural parameter describing the light transmission characteristics of the optical fiber, which is given by the following formula:

$$\Delta = \frac{n_e^2 - n_{NPS}^2}{2n_e^2} \approx \frac{n_e - n_{NPS}}{n_e}$$

In the following results, two types of liquids with different RIs are used to evaluate the proposed, and their RIs are 1.35 and 1.45, respectively.
3. Result and Discussion

In this study, the length of the sensing region, the thickness of the metal layer, the unevenness of the metal layer and the refractive index of the porous layer on the sensor performance are analyzed respectively. The following results are applicable to both low and high refractive index segments.

3.1. Length

In this part, the metal layer thickness is set at 45 nm, and the effect of sensing region length on the sensor performance is discussed.

It can be seen from figure 2a, figure 2b and table 1 that with the increase of length of the sensing region, the SPR dip depth increases gradually, while the resonant wavelength shift is insignificant. At the same time, the FWHM increases and therefore the resolution worsens. In general, the increase of dip depth becomes less significant as the sensing region length increases. Therefore, it is appropriate to choose the length of the sensing area between 15 mm and 20 mm.

![Figure 2](image)

**Figure 2.** a and b are normalized spectra of different sensing zone lengths under low and high refractive index, respectively. (n(a)=1.35, n(b)=1.45)

| L(mm) | \( \lambda_R \) (nm)-low | Dip depth-low | FWHM (nm)-low | \( \lambda_R \) (nm)-high | Dip depth-high | FWHM (nm)-high |
|-------|--------------------------|---------------|---------------|--------------------------|---------------|---------------|
| 5     | 404.3                    | 0.817         | 12.2          | 400.5                    | 0.8394        | 11.4          |
| 10    | 404.3                    | 0.701         | 13.6          | 400.5                    | 0.7304        | 12.6          |
| 15    | 404.3                    | 0.5808        | 16.8          | 400.5                    | 0.6062        | 15            |
| 20    | 404.3                    | 0.5512        | 18.4          | 400.5                    | 0.5721        | 16.3          |
| 25    | 404.3                    | 0.5206        | 21.6          | 400.5                    | 0.5332        | 18.9          |
| 30    | 404.3                    | 0.5131        | 23.2          | 400.5                    | 0.5225        | 20.2          |

3.2. Thickness

Then, the influence of the same length and different thickness of the metal layer on the performance of the sensor is discussed. In the experiment, the common coating method of quartz tube is liquid deposition. In this process, the metal film deposition in the capillary will be uneven. The distribution of this unevenness is affected by some factors such as the deposition time, the proportion of deposition materials, the deposition environment, and the deposition substrate and so on. Therefore, a metal layer model with nonuniform distribution of sensing layers along the axial direction is proposed in this paper, as the figure 3 shows. In this model, the distribution and unevenness of the sensing layer are set to adapt to different coating conditions. The coating material enters from one end of the capillary. Obviously, the thickness of the coating decreases gradually from the inlet to the outlet. Empirically, the unevenness of the thickness of the metal layer with the length is close to the e-index decreasing situation.
When the end point is set as the origin O the distribution of the metal layer thickness along the z-axis is as follows:

\[ T = T_m - z \cdot (e^k - 1) \]  \hspace{1cm} (20)

Where, \( T_m \) is the metal layer thickness at the end point, and \( k \) is the decline rate.

Firstly, the influence of the metal layer on the sensor performance is discussed under the same length, different thickness and no unevenness. The length of the metal layer is set to 15 mm.

It can be seen from figure 4a, figure 4b, table 2 that with the increase of thickness, the position of the dip shifts towards the longer wavelength. The depth of the dip first increases and then decreases. At the same time, the FWHM increases and therefore the resolution worsens. Therefore, it is appropriate to choose the length of the sensing area between 35 nm and 45 nm.

**Table 2.** Performance parameters at different thicknesses.

| T(nm) | \( \lambda R \)(nm)-low | Dip depth-low | FWHM(nm)-low | \( \lambda R \)(nm)-high | Dip depth-high | FWHM(nm)-high |
|-------|------------------------|--------------|--------------|-------------------------|---------------|--------------|
| 30    | 392.9                  | 0.5546       | 41.3         | 377.4                   | 0.5986        | 49.3         |
| 35    | 399.2                  | 0.5314       | 30.1         | 389.4                   | 0.5427        | 36           |
| 40    | 402.6                  | 0.5397       | 22.2         | 395.6                   | 0.5311        | 26.4         |
| 45    | 404.3                  | 0.5808       | 16.8         | 398.8                   | 0.55          | 19.5         |
| 50    | 405.3                  | 0.6582       | 13.5         | 400.5                   | 0.6062        | 15           |
| 55    | 405.8                  | 0.7515       | 11.7         | 401.4                   | 0.6948        | 12.4         |

3.3. Unevenness

Next, the influence of the metal layer on the sensor performance is discussed in the case of the same length and thickness with the initial value and considering the effect of unevenness. Among them, the
discussion of unevenness can be divided into two aspects: the situation of the metal layer at different positions at the same decline rate and the situation of the metal layer at the same position at different decline rates. The first case is discussed firstly. The initial value of the metal layer thickness is set as \( T_m=45 \) nm, the length is 15 mm, and the decline rate \( k \) is set as 0.8.

According to figure 5a and 5b, as well as table 3, at the same decline rate, with the increase of the distance from the endpoint, the SPR dips move to the left gradually, while the depth of the dip first increases and then decreases. With the increase of FWHM, the resolution decreases. In fact, the decline rate affects the performance of the sensor by affecting the thickness. The change of amplitude is consistent with the e-index model. Due to the existence of unevenness, the spectrum displayed on the spectrometer is essentially the superposition of spectra at various locations. It is further explained that the length of the sensing region should not be too long, otherwise, the influence brought by the unevenness will be magnified.

![Figure 5](image_url)

**Figure 5.** a and b are normalized spectra at different positions of the metal layer at the same decline rate under low and high refractive index, respectively. The inset shows a locally enlarged view of the dip. (\( n(a)=1.35, n(b)=1.45 \))

| \( z(\text{mm}) \) | \( \lambda R(\text{nm}) \)-low | Dip depth-\( \lambda R(\text{nm}) \)-low | FWHM (nm)-low | \( \lambda R(\text{nm}) \)-high | Dip depth-\( \lambda R(\text{nm}) \)-high | FWHM (nm)-high |
|-----------------|-----------------|-----------------|----------------|-----------------|-----------------|----------------|
| 0               | 404.3           | 0.5808          | 16.8           | 400.5           | 0.6062          | 15             |
| 3               | 403.1           | 0.5469          | 20.5           | 399.3           | 0.561           | 18.1           |
| 6               | 401.2           | 0.5323          | 25.6           | 397.5           | 0.5371          | 22.4           |
| 9               | 398.2           | 0.5332          | 32.1           | 394.6           | 0.5309          | 28.2           |
| 12              | 393.4           | 0.5521          | 40.4           | 389.9           | 0.541           | 35.4           |
| 15              | 385.5           | 0.5979          | 51.6           | 382.2           | 0.5743          | 44.6           |

The next step is to discuss the metal layer at the same position and at different decline rates. The initial thickness of the metal layer is set as \( T_m=45 \) nm, the initial length is set as 15 mm, and the position is set at the midpoint \( z=7.5 \). It can be seen from figure 6a, figure 6b, table 4 that, at the same location, with the increase of the decline rate, the position of the dip gradually shifts towards the lower wavelength while the depth of dip first increases and then decreases. The FWHM increases gradually, and the resolution decreases. This is consistent with the conclusion obtained in the part of uniform thickness variation.
Figure 6. a and b are the normalized spectra of the metal layer at the same position at different decline rates under low and high refractive indices, respectively. The inset shows a locally enlarged view of the dip. (n(a)=1.35, n(b)=1.45)

Table 4. Performance parameters at different decline rates.

| k   | λR(nm) - low | Dip depth - low | FWHM (nm) - low | λR(nm) - high | Dip depth - high | FWHM (nm) - high |
|-----|--------------|----------------|-----------------|---------------|-----------------|-----------------|
| 0   | 404.3        | 0.5808         | 16.8            | 400.5         | 0.6062          | 15              |
| 0.2 | 403.9        | 0.5629         | 18.3            | 400           | 0.5831          | 16.3            |
| 0.4 | 403.1        | 0.5468         | 20.5            | 399.3         | 0.5609          | 18.1            |
| 0.6 | 402          | 0.5352         | 23.8            | 398.2         | 0.5427          | 20.9            |
| 0.8 | 399.9        | 0.5308         | 28.6            | 396.2         | 0.532           | 25.1            |
| 1   | 396.1        | 0.54           | 36.1            | 392.5         | 0.5337          | 31.5            |

3.4. RI of Porous Layer
The influence of the refractive index of the porous layer on the performance of the sensor is finally discussed. For the convenience of discussion, the influence of the unevenness is ignored. It can be seen from figure 7a, figure 7b, table 5 that with the increase of the refractive index nNPS of the porous layer, the relative refractive index difference will decrease, and the position of the SPR dip will shift towards the longer wavelength. The depth of the dip decreases gradually. The dip shape widens gradually, and the resolution decreases. The decreasing range is reduced, but the difference is not obvious. The larger the relative refractive index difference is, the deeper and narrower the resonance curve will be.

Figure 7. a and b are normalized spectra of refractive index of different porous layers at low and high refractive index respectively. (n(a)=1.35, n(b)=1.45)
Table 5. Performance parameters at different refractive indexes of nano-porous layer.

| nNPS | Δ-low | λR(nm)-low | Dip depth-low | FWHM (nm)-low | Δ-high | λR(nm)-high | Dip depth-high | FWHM (nm)-high |
|------|-------|-------------|---------------|---------------|--------|-------------|---------------|---------------|
| 1.10 | 0.154 | 340.6       | 0.5396        | 15.5          | 0.172 | 349.8       | 0.5607        | 13.7          |
| 1.11 | 0.146 | 351.1       | 0.5435        | 15.9          | 0.166 | 358.6       | 0.5665        | 14            |
| 1.12 | 0.138 | 362.6       | 0.5488        | 16.2          | 0.159 | 368         | 0.5736        | 14.3          |
| 1.13 | 0.131 | 375.1       | 0.5562        | 16.4          | 0.152 | 378         | 0.5823        | 14.5          |
| 1.14 | 0.123 | 389         | 0.5665        | 16.6          | 0.145 | 388.8       | 0.593         | 14.8          |
| 1.15 | 0.115 | 404.3       | 0.5808        | 16.8          | 0.138 | 400.5       | 0.6062        | 15            |

After analyzing the performance of the sensor with liquid core porous layer structure, the performance of the sensor under the conventional structure is compared. The refractive index of the porous layer under the structure of liquid core porous layer is 1.15 (low refractive index section) and 1.25 (high refractive index section), respectively. It can be seen from figure 8a and table 6-8 that in the low refractive index region, with the increase of the refractive index of the liquid to be measured, the dip moves towards the lower wavelength, which is opposite to the phenomenon of the dip in the conventional structure. This means, under the conventional structure, the liquid to be measured and the light conducting layer are separated, while the two are unified under the liquid core porous layer structure. For the high refractive index region, the sensor under the conventional structure cannot work. The main reason is that in the high refractive index region, the sensor no longer meets wave vector equilibrium condition. Based on the dip type, the sensor with liquid core porous layer structure has significant advantages in dip depth and FWHM, but slightly inferior to the sensor with conventional structure in sensitivity. In fact, this conclusion is not absolute. By adjusting the refractive index of the porous layer, higher sensitivity can be obtained.

Figure 8. a and b are normalized spectra of the liquid core porous layer structure sensor with different refractive indices for the liquid to be measured in the low and high refractive index interval, c and d are normalized spectra of the conventional...
structure sensor with different refractive indices for the liquid to be measured in the low and high refractive index interval, respectively.

Table 6. Performance parameters of low refractive index region with liquid core porous layer structure.

| ne  | λR(nm) | Dip depth | FWHM (nm) |
|-----|--------|-----------|-----------|
| 1.3 | 424.8  | 0.5198    | 24.2      |
| 1.31| 411.7  | 0.515     | 24.2      |
| 1.32| 400.2  | 0.5119    | 24.2      |
| 1.33| 389.9  | 0.5098    | 24        |
| 1.34| 380.7  | 0.5084    | 23.7      |
| 1.35| 372.4  | 0.5074    | 23.5      |

Table 7. Performance parameters of high refractive index region with liquid core porous layer structure.

| ne  | λR(nm) | Dip depth | FWHM (nm) |
|-----|--------|-----------|-----------|
| 1.4 | 478    | 0.5808    | 22        |
| 1.41| 462.5  | 0.5624    | 21.9      |
| 1.42| 448.8  | 0.5489    | 21.9      |
| 1.43| 436.7  | 0.5392    | 21.8      |
| 1.44| 425.8  | 0.5321    | 21.7      |
| 1.45| 416    | 0.5268    | 21.6      |

Table 8. Performance parameters of low refractive index region with conventional structure.

| ne  | λR(nm) | Dip depth | FWHM (nm) |
|-----|--------|-----------|-----------|
| 1.3 | 477.2  | 0.6826    | 18        |
| 1.31| 498    | 0.7188    | 18.8      |
| 1.32| 521.4  | 0.7589    | 20        |
| 1.33| 548.3  | 0.801     | 21.9      |
| 1.34| 579.5  | 0.842     | 25.1      |
| 1.35| 616.4  | 0.8787    | 31.6      |

Taking the low refractive index range as an example, the normalized spectrum shown in figure 9a is obtained at \(n_{NPS} = 1.20\). At this point, the sensor with liquid core nano-porous layer structure can also achieve the same degree of sensitivity as the conventional sensor. At the same time, the dip depth become shallower and the FWHM is significantly broadened. Figure 9b shows the scatter plot of the sensitivity varying with the refractive index of the porous layer in the detection range of 1.30-1.35. It can be seen that there is a positive correlation between them.
Figure 9. a is the normalized spectrum of the liquid core porous layer structure sensor with different refractive index in the low refractive index range, b is the S-n diagram when the detection interval is 1.30-1.35.

Compared with the conventional structure, the sensor with liquid core porous layer structure has considerable sensitivity in both low and high refractive index regions, respectively. Due to the existence of porous layer, the detection range is flexible and adjustable. At the same time, the sensitivity and the quality of dip curve (i.e. FWHM and dip depth) can be adjusted, so that the application range is wider.

4. Conclusion
In this paper, a theoretical model of the liquid-core optical fiber SPR sensor based on nano-porous SiO$_2$ thin film is proposed. The sensor under this model has good detection performance in both low and high refractive index regions, compared with the conventional fiber optic SPR sensor model. The corresponding detection sensitivity can reach 1043.71 nm/RIU and 1234.86 nm/RIU respectively, while the FWHM is only about 20 nm. The results show that with the increase of sensor length, the formant drops gradually, while the resonance curve is broadened. The increase of metal layer thickness makes the resonance intensity first increase and then decrease, while the FWHM decreases monotonically. By changing the thickness, the unevenness affects the sensor performance indirectly. At the same time, the effect of unevenness will be further amplified with the increase of length. The introduction of porous layer makes sensor detection more flexible and adjustable. It is hoped that this paper can provide some ideas for other researchers in expanding the detection range of the sensor and the performance of the sensor under the composite film and other fields.

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