Distributed optical fiber surface plasmon resonance sensors

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The relationships of the resonant wavelength of optical fiber surface plasmon resonance (SPR) sensors to the modulation layer refractive index, thickness and the refractive index of the bulk medium are obtained by using theoretical calculation model of optical fiber SPR sensors under certain conditions, which indicates that resonant wavelength of the sensors is approximately linear with modulation layer thickness. Based on the linear relationship, multiple SPR sensors with different resonant wavelengths can be fabricated in a single optical fiber named as distributed optical fiber surface plasmon resonance sensors (DOFSPRSs). Experimental results are presented, showing that it is practical to fabricate more than one SPR sensors in a single optical fiber.

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As a new kind of sensors, optical fiber surface plasmon resonance (SPR) sensors[1−3] have been widely applied to bio-chemical detection, environmental monitoring and physical test etc.[4−6]. Compared with prism SPR sensors[7], optical fiber SPR sensors are more portable and more convenient to use but for little lower sensibility. In addition, optical fiber SPR sensors can make real-time and on-line detection of the refractive index variation of the bulk medium because wavelength spectrum integration is adopted. Resonant wavelength is the most important parameter for an optical fiber SPR sensor and closely relative to many factors such as metal type[8], metal film thickness[9], fiber core[10], modulation layer refractive index, modulation layer thickness[1], environment temperature[11−13] and bulk medium.

In this paper, the dependences of the resonant wavelength on the modulation layer refractive index and thickness are discussed theoretically in detail. The results show that it is more convenient and practical to control the resonant wavelength of optical fiber SPR sensors by changing the thickness of modulation layer. Moreover, wavelength spectrum analysis is adopted in optical fiber SPR sensors and the used light source is broadband lamp with a wavelength range from 400 to 900 nm, which provides conditions to design and fabricate multiple SPR sensors with different resonant wavelengths in a single optical fiber referred to as distributed optical fiber surface plasmon resonance sensors (DOFSPRSs).

Environment temperature weakens the performance of traditional optical fiber SPR sensors and it is difficult to eliminate the effect. DOFSPRS can be considered as an ideal alternative to overcome the problem if one of the sensors is used as a reference. Additionally, the sensor is particularly usable for multi-position detection in certain bulk medium with different refractive indices at different positions at the same time.

A given optical fiber SPR sensor is shown in Fig. 1, where the symbol n_0 denotes the refractive index of out material connected with the optical fiber core, n_1, n_2, n_3, and n_4 are the refractive indices of the optical fiber core, the metal film, the modulation layer, and the bulk medium, respectively, Ψ_{i} is the reflecting angle in the core, d is the diameter of the fiber core, l is the sensing length, and $n_0 \sin\alpha_i = n_1 \cos\Psi_{\mathrm{i}}$. According to Fresnel equations, the theory calculation equation of the optical fiber SPR sensors is[14]

$$R_{\mathrm{p}}(d, l, d_2, d_3, n_1(\lambda), n_2(\lambda), n_3(\lambda), n_4(\lambda)) =$$

$$\frac{1}{M}\sum_{i=1}^{M} r_{\mathrm{p}}(\alpha_i, d_2, d_3, n_1(\lambda), n_2(\lambda), n_3(\lambda), n_4(\lambda))^{N(l,d,\alpha_i)} I(\alpha_i), \tag{1}$$

where $N(l, d, \alpha_i)$ denotes the number of total reflections of the ray in the sensing area, $I(\alpha_i)$ the power distributed function for all propagation angles[15], M the number of propagating angles, d_2 and d_3 the thicknesses of the metal film and the modulation layer respectively, and r_{p} the reflection coefficient at a single point of the interface between the fiber core and the metal film.

In optical fiber SPR sensors, the factors related to the resonant wavelength include metal type, metal film thickness, refractive index of fiber core, refractive index and thickness of modulation layer, refractive index of bulk medium, and environment temperature. We can use the dependence on any above factor to design multiple SPR sensors having different resonant wavelengths theoretically. Although the resonant wavelength can be modulated by different metals and different metal film thicknesses theoretically, it is not feasible to implement the idea because the metals used in SPR sensors are very limited and metal film thickness is restricted in a very narrow range from 40 to 80 nm[9]. Moreover, it is impossible to do so by adopting different fiber cores since the

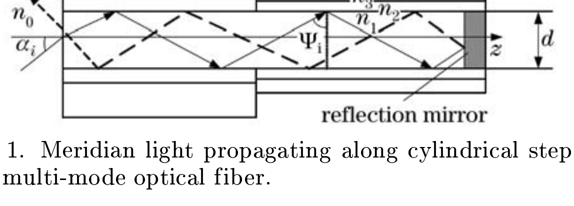

Fig. 1. Meridian light propagating along cylindrical step index multi-mode optical fiber.

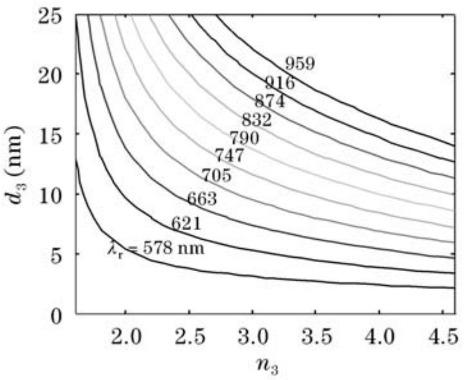

Fig. 2. Theoretical contour plots of the resonant wavelength $\lambda_{\rm r}$ varying with the thickness d_3 and refractive index n_3 of modulation layer.

types of fiber core used here are very limited too. On the other hand, the bulk medium is the measurement object and the shift of spectrum dip introduced by environment temperature must be eliminated. Thus the best scheme to implement the idea is to control the modulation layer's parameters including refractive index and thickness.

Assuming that the length of the sensing element is 15 mm, the diameter of the fused quartz fiber core is 600 μm, the thickness of the silver film is 50 nm, the thickness of the modulation layer varies from 0 to 25 nm with the refractive index varying from 1.5 to 4.5, the parameters n_1, n_2 and $I(\alpha_i)$ are obtained from Refs. [15,17], and the refractive index of the bulk medium is 1.33303. With the above assumption, the relationships between the resonant wavelength and the parameters of the modulation layer consisting of the thickness and the refractive index can be obtained from Eq. (1), as shown in Fig. 2. It is easy to observe that varying the refractive index of modulation layer will result in shift of the resonant wavelength in case of a fixed modulation layer thickness. Although we can design multiple SPR sensors with different resonant wavelengths theoretically based on the above relationship, it is not a good idea to do so because it is difficult to obtain the materials with the refractive indices covering the range from 1.5 to 4.5 completely. However, it can be helpful to choose an appropriate material as the modulation layer. For instance, the materials with indices from 2.0 to 2.5 are available and can be selected among ZrO_2, TiO_2, Ta_2O_5 and so on. On the other hand, we find that varying the thickness of the modulation layer will result in the same effect while fixing the refractive index of modulation layer[1,10]. The corresponding relationship which could be deduced from Eq. (1) is almost linear while fixing the refractive index of the modulation layer at 2.2 and the corresponding approximate relation expression is

$$\lambda_{\rm r} = 13.74 d_3 + 532.96\ \text{nm}, \tag{2}$$

where 0 nm $\leq d_3 \leq$ 25 nm, $\lambda_{\rm r}$ denotes the resonant wavelength and 532.96 nm $< \lambda_{\rm r} <$ 876.46 nm.

Obviously, such an approximately linear relationship is highly advantageous to design multiple SPR sensors with different resonant wavelengths because it is easy and feasible to control the thickness of the modulation layer accurately in industrial process.

Suppose that all the conditions are the same as above except that the thickness of modulation layer is fixed as 5 nm. The theoretical relationship between the resonant wavelength and the refractive index of the bulk medium can be obtained from Eq. (1) and the corresponding approximate relation expression is

$$\lambda_{\rm r} = 10^8 \cdot (0.108605 n_4^5 - 0.707768 n_4^4 + 1.845201 n_4^3 \\ -2.405472 n_4^2 + 1.568006 n_4 - 0.408848)\ \text{nm}, \tag{3}$$

where $1.25 \leq n_4 \leq 1.4$ is assumed. It is easy to find the corresponding resonant wavelength while certain bulk medium is given according to Eq. (3).

It is assumed that all the conditions are satisfied, the performance of DOFSPRS is only related to the initial refractive index n_{4b}, the maximum refractive index n_{4e} of the bulk medium, and the difference of different points at a same time in the bulk medium. First, the resonant wavelength of each sensing element is determined from the initial refractive index of the bulk medium by Eq. (3), and then the resonant wavelength differences between different sensing elements are determined based on both the maximum difference of refractive indices in the bulk medium and the maximum resolution of the used optical fiber spectrographs. Meanwhile, assume the refractive index varies from n_{4b} to n_{4e}, $\delta n_{4\,\max}$ denotes the maximum difference of refractive index of the bulk medium at a given time because the refractive index of the bulk medium is not absolutely even and the DOFSPRS has n sensors. By taking the derivative of both sides of Eq. (3), the corresponding curve of $\frac{{\rm d}\lambda_{\rm r}}{{\rm d}n_4}$ upon n_4 is illustrated in Fig. 3 and the resonant wavelength will get longer when increasing the refractive index of the bulk medium n_4, i.e., optical fiber SPR sensors can attain higher sensitivity if operating at longer wavelengths[8,16]. Thus the highest resonant wavelength $\lambda_{\rm r1\,max}$ of sensor 1 should be firstly determined according to the maximum refractive index n_{4e} of the bulk medium, and then the initial resonant wavelength $\lambda_{\rm r1}$ of sensor 1 determined according to n_{4b} in terms of Eq. (3). Then the initial resonant wavelength $\lambda_{\rm r2}$ of sensor 2 with the shorter resonant wavelength can be determined by the difference of $\lambda_{\rm r1\,max}$ and $\lambda_{\rm r1}$, i.e., $\lambda_{\rm r2} = 2\lambda_{\rm r1} - \lambda_{\rm r1\,max}$. Similarly, the initial resonant wavelengths $\lambda_{\rm r3}, \cdots, \lambda_{{\rm r}n}$ of all other sensors can be determined by $\lambda_{\rm r3} = 3\lambda_{\rm r1} - 2\lambda_{\rm r1\,max}, \cdots, \lambda_{{\rm r}n} = n\lambda_{\rm r1} - (n-1)\lambda_{\rm r1\,max}$ respectively. Finally, all the thicknesses d_{31}, d_{32}, d_{33}, $\cdots$, d_{3n} of the modulation layers deposited

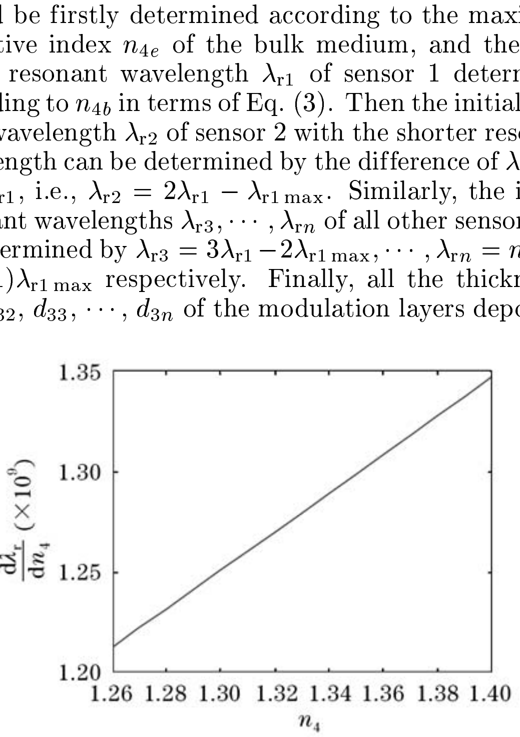

Fig. 3. Illustration of the theoretical dependence of $\frac{{\rm d}\lambda_{\rm r}}{{\rm d}n_4}$ upon n_4.

on each sensing element can be determined based on the corresponding initial resonant wavelength by Eq. (2).

One further remark is that the difference of $\lambda_{\mathrm{r1\,max}}$ and λ_{r1} must be larger than the difference $\delta\lambda_{\min}$ referred to as the minimum resolution of the system which is related to the noise of system, the resolution of used charge-coupled device (CCD) and the initial resonant wavelengths of all sensing elements. In fact, less noise, higher resolution of CCD and longer resonant wavelength will produce less $\delta\lambda_{\min}$. In practical design, the larger the difference of the resonant wavelengths of two adjacent sensing elements, the better the performance of the DOFSPRS.

If the above conditions are satisfied, any number of sensors could be manufactured in a single optical fiber theoretically. Based on the present techniques it is not difficult to make 2 to 4 sensors in a same fiber. The DOFSPRS realized in our system only has 2 sensors because of the cost and manufacturing techniques, but it is enough for proving the above opinion. Figure 4 shows the photograph of the DOFSPRS we designed. It has 2 sensors with the Ta_2O_5 modulation layer, the optical fiber is made of fused silica, the metal film is gold, and all parameters are listed in Table 1.

The corresponding measurement system of the DOFSPRS in Fig. 5 is composed of a computer, an optical fiber, a light source, an optical splitter, and an optical fiber spectrometer, and the detected material is pure water. The theoretical and experimental curves in Fig. 6 show that the theoretical resonant wavelengths of two sensors in the DOFSPRS are approximately equal to the experimental results, but the theoretical and experimental intensities are different from each other, this is because that some extra intensity losses induced by the splitter, coupler and water absorption etc. have not been considered in the theoretical model.

Fig. 4. Photograph of the DOFSPRS with 2 sensors.

Table 1. Parameters of the Designed DOFSPRS

	Parameter	Value
Sensor 1	d (μm)	600
	l (mm)	10.0
	d_2 (nm)	51.0
	d_3 (nm)	0.0
Sensor 2	d (μm)	600
	l (mm)	10.0
	d_2 (nm)	51.0
	d_3 (nm)	18.8

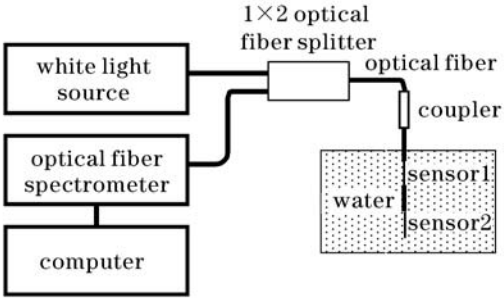

Fig. 5. Measurement system of the DOFSPRS with two sensors.

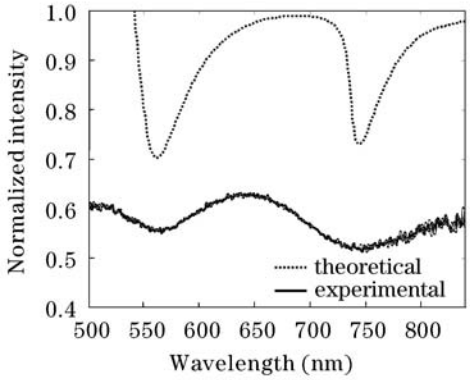

Fig. 6. Theoretical and experimental curves for detection of pure water.

This paper presents the relationships between the resonant wavelength and the parameters of the modulation layer including its refractive index and thickness and the relationship between the resonant wavelength and the bulk medium. The results show that resonant wavelength of optical fiber SPR sensors is almost linear with the thickness of modulation layer under certain conditions and thus multiple SPR sensors with different initial wavelengths can be designed by controlling the thickness of modulation layer. Multiple SPR sensors can be manufactured in a single optical fiber, resulting the sensor named as DOFSPRS which has been proved practical by the experiment. Compared with the traditional optical fiber SPR sensors, DOFSPRS has three important advantages: multi-position detection at the same time, automatic temperature compensation, and lower manufacturing cost.

Of course, the design of DOFSPRS still needs improvement. We have not yet given a general approach to the design and will perfect it in the future work. On the other hand, we should resort to signal processing to eliminate various noises existing in the detection system and further enhance its resolution.

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