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Microstructured Optical Fiber Based on Surface Plasmon Resonance for Dual-optofluidic-channel Sensing

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Abstract

A surface plasmon resonance (SPR) based microstructured optical fiber (MOF) is designed and theoretically investigated for dual-channel optofluidic sensing. The design of the MOF consists of a solid silica core surrounded with double air holes, and the hollow section is coated with thin Ag film to excite the surface plasmon waves on the dielectric interface. The optofluidic sensing characteristics of the individual channel have been analyzed based on mode-coupling theory between core and plasma modes. By filling the dual channel with different liquid analyte, the resonance wavelengths are adjusted away from each other to achieve dual-optofluidic-channel sensing. When the refractive index (RI) of liquid samples varies from 1.33 to 1.39 RIU, the optofluidic sensing sensitivities of channel 1 and channel 2 in MOF are 1439.29 nm/RIU and 4003.57 nm/RIU, respectively. The proposed SPR-based MOF is appropriate for multi-channel biological and chemical sensing fields.

Keywords: microstructured optical fiber, surface plasmon resonance, dual-channel, optofluidic sensing

Introduction

In recent years, surface plasmon resonance (SPR) technique has been extensively investigated and developed for a wide range of sensing applications, owing to its features of compact footprint and non-destructive label-free detection [1-5]. SPR is a phenomenon in which the evanescent wave and the plasma wave of the metal medium resonate on the light-transmitting surface of the waveguide, that resulting a sharply loss in the reflective spectrum. To excite SPR, there are few nanomaterials placed on a dielectric substrate to achieve the interaction of light and free electrons, such as gold and silver. Up to now, several SPR devices have been proposed including prism-coupled microfluidic systems [6-10], metal-coated fiber-optic sensors [11-13], gold-integrated MOF sensors [14,15], graphene-based plasmonic chip [16], and antimonene-based sensor [17], etc. These SPR-based devices possess the advantages of high performance, which makes them a promising tool for the optical detection. Among them, SPR-based fiber-optic devices are more versatile in investigations of light-matter interactions by assessing the refractive index (RI) variation of the liquid analyte on a fiber surface. However, traditional design of

fiber-optic SPR sensor is mostly integrated with single channel, which is difficult to meet the needs of multi-channel detection in the biomedical and biological fields. Therefore, dual-channel or multi-channel fiber-sensing technology remains a challenge.

Multi-channel optofluidic sensing is an important and effective method for biological multianalyte, medical diagnosis, and environmental monitoring. To perform biosensing of complex liquid samples, distributed fiber-optic arrays have been proposed by containing spatial multiplexing microchannels [18]. Nevertheless, the chip-scale arrayed design may increase the structure complexity, which would affect its applications. Due to the flexibility mechanical architecture and tunable optical property, microstructured optical fibers (MOFs) with special geometry have attracted significant attention over the past decades. Nowadays, MOF-based devices with several desirable merits such as compact size, and ease to integration, have been widely used in the fields of optofluidic sensing [19-22], mode-field/wavelength conversion [23,24], and nanoparticle tracking analysis [25]. Moreover, the presence of cross-sectional holey array in MOF can enhance the interaction ability between light and fluidic liquids. Therefore, MOF provides an effective platform for developing multi-channel optofluidic SPR devices.

In this work, a new SPR-based MOF is designed and demonstrated for dual-channel optofluidic sensing. The proposed MOF consists of two symmetrical air holes coated with thin Ag film as independent microfluidic channels. The spectral characteristics of the dual-channel optofluidic MOF have been analyzed and the resonance wavelength can be independently tuned by filling the microfluidic channel with different liquid samples. With the high integration, flexible design and less sample consumption, the proposed optofluidic MOF based on SPR is attractive for label-free multi-channel biological sensing in the fields of health monitoring, biological engineering, chemical analysing, etc.

MOF design and principle

Figure 1 shows the schematic diagram of the SPR-based MOF with Ag film attached on its dual-holes walls. Figure 1(b) and (c) show the cross-sections of the MOF before and after coated the air-hole walls with thin Ag film, respectively. The incident light propagates along the MOF core with total internal reflection. Due to the existence of the nano Ag film, the propagating light in the fiber core will leak out to excite evanescent wave, which could be interact with the free electrons on the surface of the Ag film to produce a TM or TE polarization wave. The SPR could only be excited by TM polarization wave [26-29].

As the TM polarization wave is incident to the Ag film interface with the resonance angle θ , the wave vector component k_x of the excited SPR waveguide in the horizontal direction and the surface plasma waves k_{sp} propagating along the interface between the Ag film and the filling samples can be expressed as:

$$k_x = k\sqrt{\varepsilon_0} \sin \theta \quad (1)$$

$$k_{sp} = k\sqrt{\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1 + \varepsilon_2}} \quad (2)$$

Fig. 1 (a) Schematic diagram of SPR-based dual-channel MOF, (b) original cross-sectional geometry of dual-channel MOF, (c) cross-sectional geometry of the MOF with Ag film

where $k=2\pi/\lambda$ is the wave number and λ is the free-space resonance wavelength. ε_0 , ε_1 , and ε_2 are the dielectric constants of the fiber core, Ag film, and liquid samples in the microfluidic channel, respectively.

When these two plasmon waveguide satisfy the resonance condition, the SPR effect will occur at the interface between the Ag film and liquid samples, and the resonance wavelength could appear in the transmission spectrum. According to Kretschmann theory [30], the reflection coefficient r of TM polarization wave could be expressed as:

$$r = \left| \frac{r_{01} + r_{12}e^{(i2k_{z1}d)}}{1 + r_{01}r_{12}e^{(i2k_{z1}d)}} \right|^2 \quad (3)$$

where d is the thickness of the nano Ag film; r_{01} is the reflection coefficient between the fiber core and Ag layer; r_{12} is the reflection coefficient between the Ag layer and liquids samples in the microchannel. The reflection coefficient r_{01} , r_{12} and the wave vector component k_{zi} of medium i ($i = 0, 1, 2$) perpendicular to the interface can be expressed as:

$$r_{01} = \frac{(\varepsilon_1 k_{z1} - \varepsilon_0 k_{z0})}{(\varepsilon_1 k_{z1} + \varepsilon_0 k_{z0})} \quad (4)$$

$$r_{12} = \frac{(\varepsilon_1 k_{z2} - \varepsilon_2 k_{z1})}{(\varepsilon_1 k_{z2} + \varepsilon_2 k_{z1})} \quad (5)$$

$$k_{zi} = \sqrt{k^2 \varepsilon_i - k_x^2} \quad (6)$$

For the sensing length L of the SPR-based MOF, several reflections of propagating waveguide will occur and the light energy will be attenuated simultaneously, leading to an attenuated transmission spectrum. By solving the reflection coefficient equation, the total transmission spectrum of surface plasma waves could be obtained. From the transmission spectrum, the resonance dips could be determined, and the sensing sensitivity could be expressed as:

$$s = \frac{\Delta\lambda}{\Delta n} = \frac{1}{\left(\frac{n_2}{n_0} \frac{dn_0}{d\lambda} - \frac{dn_2}{d\lambda} \right)} \quad (7)$$

where, n_0 and n_2 are the effective refractive indexes of silica fiber and liquid samples in the microchannel, respectively. From Eqs. (1-2) and (7), the resonance wavelength could be tuned away from each other by changing the resonance angle, and filling the dual-air-holes with different RI fluidic liquid. Thus dual-optofluidic-channel sensing could be achieved by utilizing SPR-based MOF.

Results and discussion

Fig. 2 (a) Three-dimensional field distribution of a core guided mode in the SPR-based MOF, (b) and (c) Three-dimensional field distribution of a core mode at the plasmon resonance in channel 1 and channel 2, respectively, (d)-(f) cross-sectional view of the mode field distributions of core guided mode and plasmon modes excited in the Ag-coated holes of the dual-channel MOF, respectively

The mode coupling characteristics between the core guided mode and the plasmonic mode are investigated by finite element method. Figure 2 shows the mode field distributions of core guided mode and plasmon modes excited in the MOF when the wave vector of the propagation constant of evanescent wave exactly matches with that of the surface plasmon waveguide. It could be found that part of the energy of the core mode couple to the surface plasmon mode at the interface of Ag film and liquid sample. The excited plasmon waveguide could be interacted with the liquid samples in the channel, and enhance the synergistic capability between light and fluidic liquids.

Fig. 3 Transmission spectrum of the SPR-based dual-channel MOF

According to Eqs. (3)-(6), the transmission spectrum is calculated and the resonance wavelength curve are shown in Fig. 3. The parameters used in Fig. 3 include: the fiber core is solid silica doping with other materials with the RI of 1.45; the background material is solid silica with the RI of 1.445; the thickness

of the Ag film is 50 nm; the RI of the samples in the dual channel are 1.33; the sensing length is 15 mm; the diameters of MOF core, air hole, and cladding are 9 μm , 43 μm and 125 μm , respectively; the resonance angles are set as 70.2 degree and 84.6 degree to adjust different coupling conditions for channel 1 and channel 2 sensing. The parameters of fiber core, air-hole, and cladding are unified with the commercial single mode fiber (SMF), and perform low insertion loss in the actual optical connection. In addition, the small fiber core is conducive to confine the light in the core area, and improve the coupling efficiency of the core mode and the SPP mode, thereby increasing the light-matter interaction strength on the inner surface of the air-hole. The design of the large air-holes makes it easy for liquid to flow in and out, and the large air-hole has a large surface ratio, which further improves the degree of interaction between light and matter. As shown in the transmission spectrum, there are two obvious resonance dips corresponding to channel 1 and channel 2, respectively. Then these two-sensing frame are used to analyze the characteristics of the dual-optofluidic-channel sensing.

Fig. 4 Transmission spectral responses to the different liquid samples in channel 1 of the SPR-based dual-channel MOF

Fig. 5 Wavelength shift as functions of liquid RI for SPR resonance dips in channel 1 and channel 2, respectively

To determine the dual-channel sensing characteristic of the SPR-based MOF to operate in self-referencing condition, the channel 1 is filled with liquid samples with the RI ranging from 1.33 to 1.39 while channel 2 is filled with water. Figure 4 shows the spectra response for microfluidic sensing in

channel 1. It could be seen that the SPR resonance dip for channel 1 shifts linearly to longer wavelengths with the RI increment of liquid samples, while the resonance dip for channel 2 keeps stable. Since the real part of the effective RI of plasmon mode is related to the dielectric constant of the liquid samples in the microfluidic channel, the increase of liquid sample RI in the channel 1 could affect the dielectric constant of the liquid analyte and correspondingly change the phase matching condition between the core guiding mode and plasmon mode, leading to the red-shift of SPR resonance dip for channel 1. In addition, the RI of liquid sample in channel 2 remains unchanged and has no impact on the plasmon condition in channel 2. Therefore, no wavelength shifts are observed for Channel 2 containing the fixed liquid sample. As shown in Fig. 5, the linear fitting of the SPR resonance dip as a function of the liquid RI in channel 1 indicates that the obtained sensing sensitivity is 1439.29 nm/RIU in the RI range of 1.33-1.39.

Fig. 6 Transmission spectral responses to the different liquid samples in channel 2 of the SPR-based dual-channel MOF

Fig. 7 Wavelength shift as functions of liquid RI for SPR resonance dips in channel 1 and channel 2, respectively

Next, the sensing characteristic in channel 2 is also analyzed by adjusting the resonance angle to change the plasmon condition in the SPR-based MOF. When channel 1 is filled with water, and channel 2 is filled with the liquid samples with the RI ranging from 1.33 to 1.39. As shown in Fig. 6, the RI increase of the liquid samples in Channel 2 causes the resonance dip to shift gradually towards longer

wavelengths while the SPR resonance dip in channel 1 keep unchanged. For SPR resonance dip in channel 2, the calculated sensing sensitivity is 4003.57 nm/RIU, as shown in Fig. 7. The obtained results have demonstrated that the designed SPR-based MOF can achieve independently dual-optofluidic-channel sensing.

Based on mode-coupling theory between the core and plasma modes, dual-optofluidic-channel sensing is investigated as the liquid sample RIs vary in two channels simultaneously. When the sample RIs in two channels increase from 1.33 to 1.39, the transmission spectra of the optofluidic MOF are shown in Fig. 8. It could be found that the wavelengths of the SPR dips in channel 1 and channel 2 exhibit redshift behavior as the dual-optofluidic channels are filled with liquid samples with the RI ranging from 1.33 to 1.39.

Fig. 8 Transmission spectral responses to the different liquid samples in two channels simultaneously

Fig. 9 Spectral shifts of the SPR resonance dips versus the liquid RIs in two channels simultaneously

Figure 9 shows the relationship between sample RIs and SPR resonance dips. SPR dips in channel 1 shifts from 413 nm to 499 nm, and SPR dips in channel 2 shifts from 513 nm to 758 nm with the increment of liquid RI. The transmission spectra responses demonstrate that both the SPR resonance dips

could discriminate the liquid samples in their respective channels at the same time. Thus, the dual-channel MOF based on SPR possesses the simultaneous sensing performance.

Conclusion

In this paper, a SPR-based MOF is proposed and theoretical investigated for dual-channel optofluidic sensing. The MOF adopts a symmetrical side-hole design and its air holes are coated with nano Ag film to excite surface plasma wave. When the phase of the core mode and plasmon mode are match, the SPR resonance will occur and the resonant dips can be observed in the transmission spectrum. The dual-channel sensing spectral characteristics are analyzed under different liquid sample RI, and the results indicate that dual-optofluidic-sensing could be achieved independently by utilizing the SPR-based MOF. The sensing sensitivities of the dual-channel MOF are 1439.29 nm/RIU and 4003.57 nm/RIU in the RI range of 1.33 to 1.39, respectively. With the flexible design and no crosstalk between these dual-sensing channels, the proposed SPR-based MOF is appropriate for multi-channel biological and chemical sensing fields.

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Author Contribution

All the authors have significant contribution in this paper.

Availability of Data and Materials

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Conflict Interests

The authors declare no competing interests.

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