Microstructured Optical Fiber Based on Surface Plasmon Resonance for Dual-Optofluidic-Channel Sensing

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Received: 25 January 2022 / Accepted: 31 May 2022 / Published online: 23 June 2022
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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 by 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 the mode-coupling theory between core and plasma modes. By filling the dual channel with different liquid analytes, 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 the 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]. These SPR-based devices possess the advantages of high performance, which makes them a promising tool for 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. For instance, Liu et al. reported a symmetrical dual D-shape MOF sensor with a silver sensing layer and the performance of this sensor could be enhanced by optimizing the structures to increase the mode-coupling efficiency [5]. Liu et al. proposed an Au-metallized SPR chemical sensor based on MOF for refractive index sensing, as well as environmental monitoring [14]. Wang et al. demonstrated a MOF-SPR sensor based on dual-gold nanowires series-wound structure and realized high-sensitivity detection for sample analytes with a low refractive index range [15]. These SPR sensors based on MOFs possess the features of flexible design, good compatibility, and excellent sensing properties. However, the traditional design of fiber-optic SPR sensor is mostly integrated with a 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.

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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 of 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 of integration, have been widely used in the fields of optofluidic sensing [19–22], mode-field/wavelength conversion [23, 24], and nanoparticle tracking analysis [25]. MOFs as the integration of optical waveguide and microfluid channels show their distinct advantages in constructing optofluidic devices. The micron-sized air holes of the MOFs are inherent microflow cells for holding liquid samples, which could simplify the experimental system design. The holey structure of the MOFs also greatly enhances the sensing surface area for microanalysis, while avoiding sample contamination. Moreover, the presence of a cross-sectional holey array in MOF can enhance the interaction ability between light and fluidic liquids with small sample consumption. Part of the modal field of the MOFs is located within the cladding holes. This allows the large overlap and direct interaction between the guided light and liquid samples over a long optical path. 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 analysis, etc.

**MOF Design and Principle**

Figure 1 shows the schematic diagram of the SPR-based MOF with Ag film attached to its dual-holes walls. Figure 1b 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 with 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 the evanescent wave, which could 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 $\theta$, 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:

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

$$k_{sp} = k \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$  \hspace{1cm} (2)

where $k = 2\pi/\lambda$ is the wave number and $\lambda$ is the free-space resonance wavelength. $\varepsilon_0$, $\varepsilon_1$, and $\varepsilon_2$ are the dielectric constants of the fiber core, Ag film, and liquid samples in the microfluidic channel, respectively.

When these two plasmon waveguides 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’s theory [30], the reflection coefficient $r$ of TM polarization wave could be expressed as:

$$r = \left| \frac{r_{01} + r_{12}e^{i(2k_i d)}}{1 + r_{01}r_{12}e^{i(2k_i d)}} \right|^2$$  \hspace{1cm} (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:

$$r_{01} = \frac{(\epsilon_1 k_{z1} - \epsilon_1 k_{z0})}{\epsilon_1 k_{z1} + \epsilon_1 k_{z0}}$$  \hspace{1cm} (4)

$$r_{12} = \frac{\epsilon_1 k_{z2} - \epsilon_2 k_{z1}}{\epsilon_1 k_{z2} + \epsilon_2 k_{z1}}$$  \hspace{1cm} (5)

$$k_{zi} = \sqrt{k_i^2 - k_z^2}$$  \hspace{1cm} (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:

$$s = \frac{\Delta\lambda}{\Delta n} = \frac{1}{\left(\frac{n_2}{n_0} \frac{dn_0}{dx} - \frac{n_2}{n_0} \frac{dn_2}{dx}\right)}$$  \hspace{1cm} (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**

The mode-coupling characteristics between the core guided mode and the plasmonic mode are investigated by the 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 the 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.

According to Eqs. (3)–(6), the transmission spectrum is calculated and the resonance wavelength curve is 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 is 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 degrees and 84.6 degrees to adjust different coupling conditions for channel 1 and channel 2 sensing. The parameters of the 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 frames are used to analyze the characteristics of the dual-optofluidic-channel sensing. In addition, external disturbance or inaccurate input polarization would cause the existence of undesired polarization, leading to the change of the resonance wavelength. Therefore, the structural parameters of the SPR-MOF are optimized to obtain a low birefringence effect to suppress the influence of polarization during the design process. By selecting appropriate parameters of Ag film thickness and distance between the fiber core and air holes, the polarization crosstalk could be effectively minimized and the stability of the SPR sensor could be improved.

To determine the dual-channel sensing characteristic of the SPR-based MOF to operate in self-referencing condition, 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 loner 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 redshift of SPR resonance dip for channel 1. In addition, the RI of the 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 sinisterly is 1439.29 nm/RIU in the RI range of 1.33–1.39.

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 keeps 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 the 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.

Figure 9 shows the relationship between sample RIs and SPR resonance dips. SPR dips in channel 1 shift from 413 to 499 nm, and SPR dips in channel 2 shift from 513 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 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 a nano-Ag film to excite surface plasma wave. When the phase of the core mode and plasmon mode are matched, 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.

Author Contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Jixuan Wu, Ye Li, Binbin Song, Cheng Zhang, Qian Wang, Xinliang Gao, and Kaixing Huang. The first draft of the manuscript was written by Jixuan Wu and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the Tianjin Education Commission Scientific Research Project (Grant NO. 2019KJ016).

Availability of Data and Materials The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval This study complied with the ethical standards.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Consent for Publication All authors give consent for the article to be published.

Conflict of Interest The authors declare no competing interests.

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