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Analyte-filled core self-calibration microstructured optical fiber based plasmonic sensor for detecting high refractive index aqueous analyte

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ABSTRACT

This paper presents a theoretical investigation on an analyte-filled core self-calibration microstructured optical fiber plasmonic refractive index sensor. The proposed microstructured optical fiber sensor introduces the concept of simultaneous detection in different ranges of wavelength because the sensing performance of the sensor in different wavelength ranges is relatively high, which will be useful for high accuracy measurement. The resonant peak 1 and peak 2 are stronger and more sensitive to the variation of analyte refractive index than any other peaks in this kind of microstructured optical fiber. An average refractive index sensitivity of −4354.3 nm/RIU (refractive index unit) and 2280 nm/RIU in the dynamic index range from 1.46 to 1.485 as well as −2660 nm/RIU and −4240 nm/RIU from 1.50 to 1.52 corresponding to the peak 1 and peak 2 can be obtained, respectively. The self-calibration sensor demonstrates high linearity and accuracy. The influence of the structural parameters on the plasmonic excitations is also studied, with a view of turning and optimizing the resonant spectrum.

1. Introduction

Surface plasmon resonance (SPR) refers to the excitation of surface plasmon polaritons (SPPs), which are electromagnetic waves coupled with free electron density oscillations on the surface between the metal and the dielectric material [1]. The SPRs have many potential applications, such as optical sensing [2,3] optical filtering [4,5] and near-field tips for sub-wavelength-scale imaging [6,7]. Recently, surface plasmon resonance sensors have attracted much attention, especially in the field of label-free and real-time biochemical sensing. SPR biochemical sensors have gathered continuous research interests in detecting the bulk refractive index changes of analyte, as well as monitoring the formation of nanometer-thin biolayers on top of a metalized sensor surface. The detection and analysis of biochemical materials are widely needed on many important frontiers of industrial and daily life applications, such as medicine, biochemical technology, environment protection, food safety and medical diagnostics. Consequently, the SPR sensor has become a powerful tool for biochemical analysis without molecule labeling.

The commonly used methods for surface plasmon excitation typically employ prism coupling, planar waveguide coupling, fiber optic coupling, and grating coupling. Microstructured optical fiber (MOF) with a regular hexagonal array of air holes running along the propagation direction can provide a flexible platform for sensing [8,9]. The flexibility of design and ease of fabrication make it easy to equate the effective index of the core mode to that of the material under test, phase matching condition between the core mode and the plasmon is thus easily achieved at the required wavelength for resonance. Moreover, their holes can be controllably filled with ultrasmall volumes of analytes [10,11]. Simply to say, it has promoted the development of MOF-SPR sensors. In recent years, many scholars have put forward a multitude of surface plasmon resonance sensor designs based on MOFs and a large number of simulations and calculations have been made that show great advantages and favorable applications of these new sensors [12–17]. Among these extensively investigated MOF-SPR refractive index sensors, the majority of the reported MOF-SPR sensors have an upper detection limit of index of refraction lower than that of the silica glass. This makes the high refractive index analyte under examination inconvenient to be detected. In a latest report, Shuai et al. presented and numerically characterized a closed-form multi-core holey fiber based plasmonic sensor with only one metalized analyte channel [17]. The dynamic range of detected refractive index is from 1.33 to 1.53. However, it only has one analyte channel, which make it lack of compensating ability and prone to suffer from noises in real world applications, such as instrumental instability, temperature fluctuation and non-specific molecular interactions. In this paper, we report and numerically characterize an analyte-filled core self-calibration MOF plasmonic

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refractive index sensor by using the finite element method (FEM). It is found that the novel sensor can detect analyte with a refractive index higher than that of the host material. In addition, the sensor demonstrates high linearity and accuracy. The detection method is that measuring the resonant wavelength and transmission intensity of peak 1 and peak 2 for distinct aqueous analytes simultaneously. This method not only can operate at simultaneous sensing of positive and negative refractive index sensitivity, but is able to work at both negative refractive index sensitivity as well in different refractive index ranges. The sensor can be used for calibration with high linearity and accuracy using this detecting method. This paper is organized as follows: the structure design and theoretical modeling are given in detail in the next section. Then, the sensing performance is analyzed. Furthermore, the tuning of plasmonic excitations are also studied for the structure optimization. Finally, the conclusions are summarized in the last section.

2. MOF structure and the theoretical modeling

The schematic diagram of the MOF-SPR refractive index sensor with the analyte-filled core is shown in Fig. 1(a). The index-guiding MOF consists of five layer of air holes arranged in a regular hexagonal way. The analyte-filled core and six metallic analyte channel are formed by selectively filling the larger-sized air holes with an analyte of refractive index higher than the silica substrate. The hole to hole pitch Λ is 2.0 μm. The outer diameter of the metallic analyte channel, diameters of cladding air holes and analyte-filled core are $d_2=0.8\Lambda$, $d_1=0.5\Lambda$, $d_c=0.8\Lambda$, respectively. The thickness of the gold layer is fixed to $t=40$ nm. The background material is pure silica, and the Sellmeier equation is used for calculating the chromatic dispersion of silica, thus the material dispersion of the MOF has been taken into account [18]. The cladding holes are filled with air $n_{air}=1.0$. The analyte refractive index n_a varies from 1.46 to 1.485 and from 1.50 to 1.52. The dielectric constant of gold is defined by the Drude–Lorentz model [19], and the equation can be written as follows:

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

where ε_m is the permittivity of gold, ε_∞ is the permittivity in the high frequency, $\Delta\varepsilon = 1.09$ is interpreted as a weighting factor, ω is the angular frequency of the guided light, ω_D and γ_D are the plasma frequency and damping frequency, respectively. $\omega_D/2\pi = 2113.6$ THz, $\gamma_D/2\pi = 15.92$ THz, Ω_L and Γ_L are the frequency and spectral width of the Lorentz oscillator, $\Omega_L/2\pi = 650.07$ THz, $\Gamma_L/2\pi = 104.86$ THz. The FEM is used for investigating the mode characteristics and finding the complex propagation constants of the plasmonic and the core-guided modes. Only a quarter of the structure is considered thanks to its symmetry. As the FEM mesh in Fig. 1(b) shows, the two orthogonal sides of the computational region are assigned with two artificial boundary conditions: Perfect Electric Conductor (PEC) and Perfect Magnetic Conductor (PMC). A Perfectly Matched Layer (PML) with several micrometers thickness is added to the outmost layer, which is used for absorbing the radiation energy. Moreover, a scattering boundary condition outside the PML region is used to reduce the reflections. The meshed computational region consists of 12 264 elements, and the number of degree of freedom equals 94 056. In this paper, coupled mode theory has been deployed to investigate the coupling between surface plasmon and core modes [20]. The intersection point of the dispersion curves for the plasmonic mode and core mode, which corresponds to the largest energy transmission from the core-guided mode to the plasmonic mode, is used for locating the resonance wavelength [12]. The confinement loss can be obtained through the following equation:

$$L = 8.686 \times \frac{2\pi}{\lambda} \mathrm{Im}(n_{\mathrm{eff}}) \times 10^4 \qquad (2)$$

which is in proportion to the imaginary part of the mode effective refractive index. The units of the leakage loss and the wavelength are dB/cm and μm, respectively.

With regard to fabrication, the proposed structure should be relatively easy to fabricate due to the regular hexagonal array of the air holes design. In addition, the coating and infiltration techniques are gradually mature. In previous studies, a selective coating technique for MOF has been successfully demonstrated in the experiment reported [21]. And a selective filling skill has been previously illustrated both theoretically and experimentally, where the aqueous samples were introduced into the MOF either by utilizing capillary forces or by applying pressure, even in holes with diameters of 1 μm [11,12,22]. We believe that our MOF-SPR sensor can be successfully implemented with a precise fabricating process.

3. Numerical results

To investigate the coupling properties of the novel sensor, the resonant curves for analyte refractive index $n_a=1.46$ are depicted in Fig. 2. The phase-matching wavelength is the one at which the

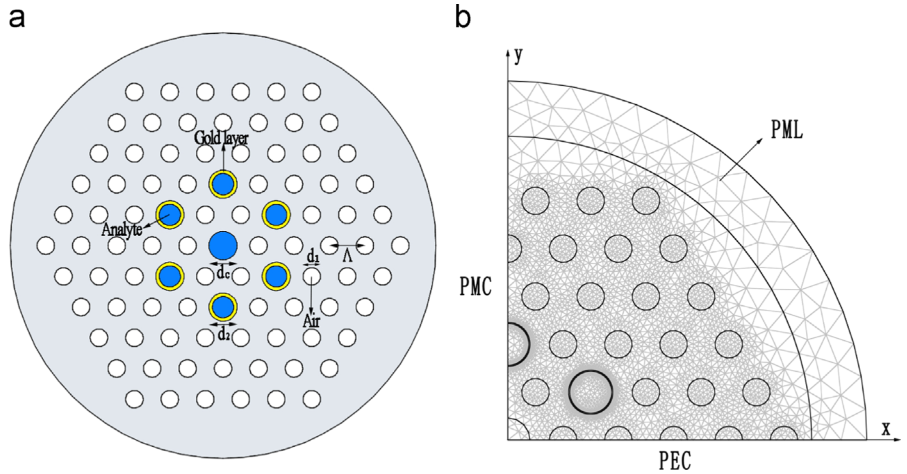

Fig. 1. (a) Cross section of the MOF-SPR sensor with the central analyte-filled core and six metalized analyte channel. (b) FEM mesh and boundary conditions for computation.