Design of the Microstructured Optical Fiber-based Surface Plasmon Resonance sensors with enhanced microfluidics

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Abstract: The concept of a Microstructured Optical Fiber-based Surface Plasmon Resonance sensor with optimized microfluidics is proposed. In such a sensor plasmons on the inner surface of large metallized channels containing analyte can be excited by a fundamental mode of a single mode microstructured fiber. Phase matching between plasmon and a core mode can be enforced by introducing air filled microstructure into the fiber core, thus allowing tuning of the modal refractive index and its matching with that of a plasmon. Integration of large size microfluidic channels for efficient analyte flow together with a single mode waveguide of designable effective refractive index is attractive for the development of integrated highly sensitive MOF-SPR sensors operating at any designable wavelength.

OCIS codes: (130.6010) Sensors; (240.6680) Surface plasmons; (060.2370) Fiber optic sensors; (999.9999) Photonic crystal fiber.

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1. Introduction

Propagating at the metal/dielectric interface, surface plasmons [1] are extremely sensitive to changes in the refractive index of the dielectric. This feature constitutes the core of many Surface Plasmon Resonance (SPR) sensors. Typically, these sensors are implemented in the Kretschmann-Raether prism geometry to direct p-polarized light through a glass prism and reflect it from a thin metal (Au, Ag) film deposited on the prism facet [2]. The presence of a prism allows resonant phase matching of an incident electromagnetic wave with a high-loss plasmonic wave at the metal/analyte interface at a specific combination of the angle of incidence and wavelength. By detecting changes in the amplitude or phase of a reflected light due to its coupling with a plasmon wave one can detect minute changes in the refractive index of an analyte bordering the metal layer. Using optical fibers instead of a prism in plasmonic sensors offers miniaturization, high degree of integration and remote sensing capabilities. Over the past decade driven by the need of miniaturization of SPR sensors various compact configurations enabling coupling between optical waveguide modes and surface plasmonic waves have been investigated. Among others, metallized single-mode, polarization maintaining, and multi-mode waveguides, metallized tapered fibers, and metallized fiber Bragg gratings have been studied [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. Two principal difficulties hindering development of the integrated waveguide-based sensors have been identified.

One of the problems is phase matching of a waveguide core mode and a plasmonic wave. Mathematically, phase matching constitutes equating the effective refractive indexes of the two modes at a given wavelength of operation. In the case of a single mode waveguide effective refractive index of its core mode is close to that of a core material, which for most practical materials is higher than 1.45. Effective refractive index of a plasmon is typically close to that of a bordering analyte, which in the case of air is ~ 1.0, while in the case of water is ~ 1.33. Only at higher frequencies [5, 6] (which for the case of a gold metal film corresponds to $\lambda < 700nm$) plasmon refractive index becomes high enough as to match that of a waveguide core mode. High frequency of operation limits plasmon penetration depth into the analyte, thus reducing sensitivity. Moreover, since plasmon in a planar film covering the waveguide can only be excited with a p-polarized light this necessitates the use of polarization-maintaining fibers to improve coupling efficiency between the plasmon and core guided modes [11]. From a sensor design point of view it is quite unsatisfactory to be limited by the values of the material re-

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fractive indices without the ability of compensating material limitations with a judicious choice of a sensor geometry. In principle, phase matching problem can be alleviated by coupling to a plasmon via the high order modes of a multimode waveguide [16, 17, 18]. Such modes can have significantly lower effective refractive indices than a waveguide core index. In such a setup light has to be launched into a waveguide as to excite high order modes some of which will be phase matched with a plasmon. As only a fraction of higher order modes are phase matched to a plasmon, then only a fraction of total launched power will be coupled to a plasmon, thus reducing sensor sensitivity. Moreover, as power distribution in high order modes is sensitive to the launching conditions this adds additional noise due to variations in a coupling setup.

Second problem that limits development of waveguide based sensors is that of packaging of a microfluidics setup, waveguide and a metallic layer into a sensor. Thus, in traditional single mode fiber based sensors, to metallize fiber surface one has to first strip the fiber jacket and then polish fiber cladding almost to the core to enable evanescent coupling with a plasmon. This laborious procedure compromises fiber integrity making resulting sensor prone to mechanical failures. Integration of a metallized fiber piece into a microfluidics setup presents yet another additional step in sensor fabrication, thus increasing the overall fabrication cost.

The goal of this paper is to build upon a great body of ideas developed by the waveguide-based SPR sensing community and to illustrate that the phase matching and packaging issues can be facilitated using Photonic Crystal Fibers (PCFs) or Microstructured Optical Fibers (MOFs) operating in the effectively single mode regime. Recently, we have demonstrated that effective refractive index of a Gaussian-like core mode propagating in the ati-guiding Bragg waveguide [20, 21] can be designed to take any value from 0 to that of a refractive index of a core material. This allows phase matching and plasmon excitation by the Gaussian-like waveguide core mode at any desirable wavelength. Microfluidics in microstructured fibers is enabled by passing the analyte though the porous cladding, thus solving one of the packaging problems. Deposition of metal layers inside of the MOF can be performed ether with high pressure CVD technique [22] or wet chemistry deposition technique used in fabrication of metal covered hollow waveguides [23].

2. Geometry of a MOF-based SPR sensor

In this paper we develop general principles of a Microstructured Optical Fiber design for applications in plasmonic sensing for which phase matching with a plasmon wave and optimized microfluidics are the two key requirements. Figure 1(a) shows schematic of a proposed hexagonal solid-core MOF based SPR sensor. Fiber core is surrounded by the two layers of holes. Metallized holes of the second layer are considerably larger than these of the first layer, thus simplifying the flow of the analyte through them. To lower the refractive index of the core guided mode (in order to facilitate phase matching with a plasmon) we introduce a small hole in the core center, which, in principle, can be substituted by an array of even smaller holes. Holes in the core and a first layer are filled with air $n_{air} = 1.0$, while metal covered holes of the second layer are filled with analyte (water) $n_a = 1.33$. Diameters of the holes in the first and second layers are $d_1 = 0.6\Lambda$ and $d_2 = 0.8\Lambda$, respectively. Pitch of the underlying hexagonal lattice is $\Lambda = 2\mu m$. The core of a MOF features a central air hole of diameter $d_c = 0.45\Lambda$. By changing the size of this hole, one can tune the effective-index of a fundamental mode. The first layer of holes works as a low index cladding enabling guidance in the fiber core. Size of the holes in the first layer influences strongly coupling strength between the core mode and a plasmon (larger hole size results in weaker coupling, thus longer sensors). Holes in the second layer are metallized with a 40nm layer of gold and feature large diameters to facilitate the flow of analyte. Here, we assume that the MOF is a glass made with refractive index given by the Sellmeier formula. Dielectric constant of the gold layer is given by the Drude model. We note

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in passing that many other designs that feature large microfluidic channels to simplify analyte flow can be readily envisioned. For example, Fig. 1(d) shows a fiber crossection where instead of a second layer of holes two large semi circular channels covered with metal are used instead. In the rest of the paper we discuss in details sensor design with crossection shown in Fig. 1(a).

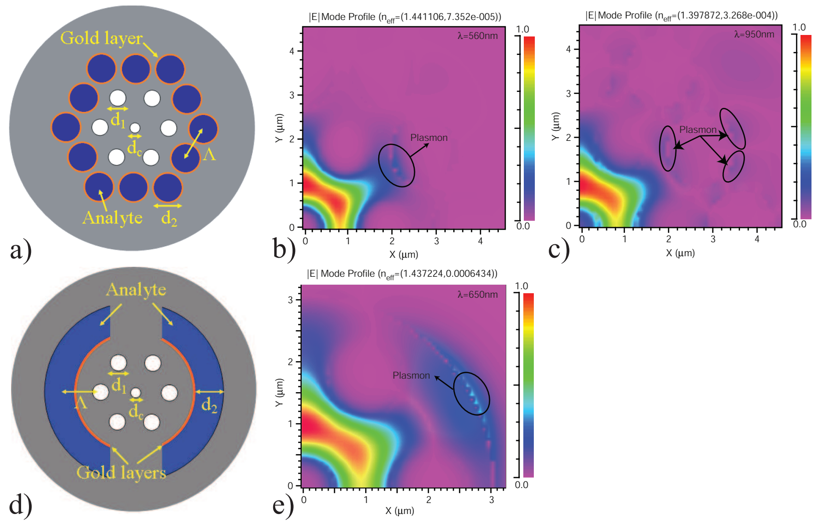

Fig. 1. a) Schematic of a MOF-based SPR sensor. Holes in the second layer are filled with analyte and metallized for plasmon excitation. Air filled holes in the first layer enable guiding in the higher refractive index fiber core, while at the same time controlling coupling strengths between the core mode and a plasmon. Small air filled hole in the fiber core is used to lower the refractive index of a core guided mode to facilitate phase matching with a plasmon. b) Field distribution of a core mode at the first plasmon resonance at $\lambda = 560nm$. c) Field distribution of a core mode at the second plasmon resonance at $\lambda = 950nm$. d) Alternative schematic featuring larger microfluidic channel. e) Field distribution of a core mode at the plasmon resonance at $\lambda = 650nm$ for crossection d).

3. Coupling of a MOF core guided mode with plasmonic waves

We use finite element method with PML boundaries to find complex propagation constants of the guided modes. In Fig. 2 we plot in dB/cm losses of the core guided mode in a $0.5\mu m$-$1.5\mu m$ wavelength range for the two values of the analyte refractive index $n_a = 1.33$ and $n_a = 1.34$. Loss curves in Fig. 2 feature three plasmonic peaks located at 560nm, 950nm and 1290nm. For comparison, in red dotted line we present confinement loss of a core guided mode for the case when no metal layers are presented. Resonant frequency of the first plasmonic peak near 560nm is the most sensitive of the three to the changes in the refractive index of the analyte. Modal field distribution of a core guided mode at the first plasmonic resonance is shown in Fig. 1(b), where plasmon excitation on a boundary of a metallized hole closest to the fiber core is clearly visible. It is interesting to note that the shape of a metalized surface modifies plasmonic excitation spectrum. Thus, planar metallized surface supports only one plasmonic peak, while cylindrical metal layer can support several different plasmonic peaks [10, 12, 13, 19]. In Fig. 1(c) modal field distribution of a core guided mode at the second plasmonic resonance is shown. Again, plasmon excitation at the boundary of a metallized hole is clearly visible, however, most of the plasmon intensity is concentrated away from the fiber core leading to a decreased sensitivity of the core mode losses at the second plasmonic peak to the changes in the analyte. In principle,

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by monitoring changes in excitation of several SPR resonances in cylindrical metallic layers, one can improve sensor sensitivity. With this method refractive-index resolution of about 10^{-6} has been demonstrated [13]. For completeness, in Fig. 1(e) modal field distribution of a core guided mode of the fiber shown in Fig. 1(d) at the plasmonic resonance is presented where plasmon excitation is again clearly identifiable.

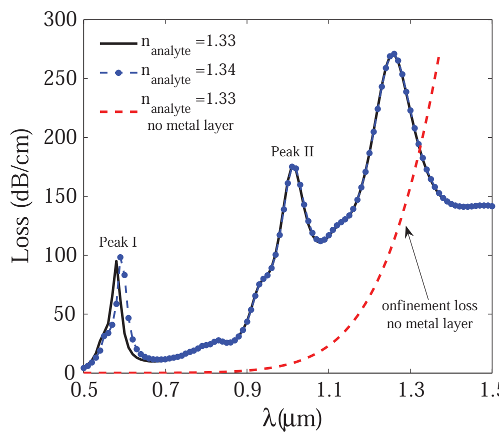

Fig. 2. Calculated loss spectra of the MOF core guided mode exhibiting three loss peaks corresponding to the excitation of various plasmonic modes in the metallized holes. Black solid line - $n_a = 1.33$, blue doted line - $n_a = 1.34$. For comparison, red dashed-line shows the confinement loss of a core guided mode in the absence of a metal coating.

In what follows we focus on the first peak around 560nm which is the most sensitive to the changes in the refractive index of the analyte. Figure 3(a) shows changes in the position of a plasmonic peak when thickness of the gold layer is varied between 30nm and 50nm. Modal loss at resonance decreases when thickness of the gold layer increases, and simultaneously the peak shifts towards longer wavelength. For example, plasmonic peak corresponding to the 30nm thick gold film shifts 24nm towards longer wavelengths when layer thickness is changed to 40nm. Such changes in the peak position due to nanometer variations in the metal layer thickness can be easily detected. This transduction mechanism can be used to study metal nanoparticle binding events to the walls of the metallized holes. This mode of sensor operation can be of interest to the monitoring of the concentration of nanoparticles used as carriers of the photosensitive drugs in the photodynamic cancer therapy [24].

4. Characterization of sensitivity of a MOF-based SPR sensor

A more traditional mode of operation of the proposed sensor would be detection of changes in the refractive index of the analyte in the immediate vicinity of the metal surface. Since the real part of a plasmon effective refractive index is strongly influenced by the value of the dielectric constant of the analyte, the wavelength of phase matching between the waveguide and plasmon modes is very sensitive to the changes in the analyte refractive index. We define transmission loss of a core mode as a function of the wavelength and the refractive index of analyte as $\alpha(\lambda, n_a)$. Considering P_0 to be the power launched into the core mode of the waveguide, the detected power after propagation along the sensor of length L will be $P(L,\lambda,n_a) = P_0 exp(-\alpha(\lambda,n_a)L)$. Relative sensitivity to the dn_a changes in the analyte refractive index can then be defined as $S(\lambda) = [P(L,\lambda,n_a+dn_a) - P(L,\lambda,n_a)]/P(L,\lambda,n_a)/dn_a$. Here, the length L of an optimally designed sensor is determined by the modal transmission

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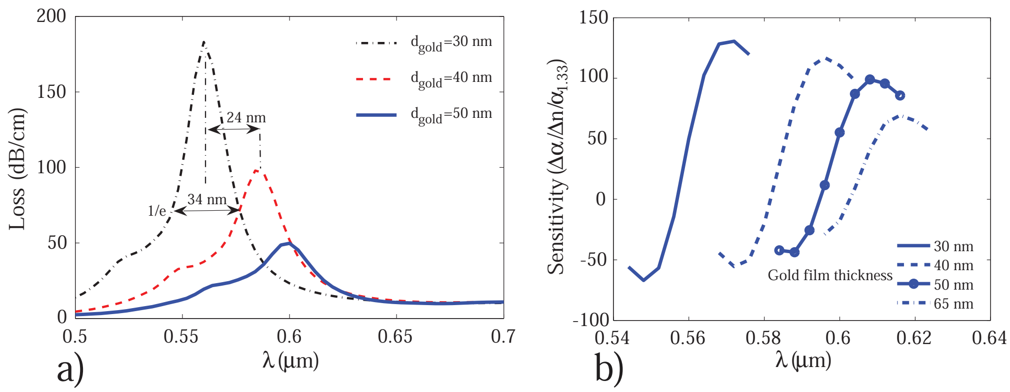

Fig. 3. a) Calculated loss spectra of the first plasmonic peak for 30nm, 40nm and 50nm thicknesses of a gold coating. b) Sensitivity of the MOF-based SPR sensor for the 30nm, 40nm, 50nm and 65 nm thicknesses of a gold coating.

loss. A reasonable choice for a sensor length is $L = 1/\alpha(\lambda, n_a)$, leading to a simple definition of sensitivity for small changes in the analyte refractive index

$$S(\lambda) = -(\partial\alpha(\lambda, n_a)/\partial n_a)/\alpha(\lambda, n_a).$$

In Fig. 3(b) we present sensitivity of the proposed MOF-SPR sensor for various thicknesses of the metal layers. As seen from the Fig. 3(b) sensitivity depends weakly on the gold layer thickness. The maximum of sensitivity shifts to shorter wavelengths for thinner metal films. For all the curves, at the wavelengths of maximal sensitivity the 10^{-4} change in the analyte refractive index results in at least 1% change in the transmitted intensity, which is well comparable to what is obtained in conventional fiber-based SPR sensors.

Note that due to very high loss of a MOF based plasmonic sensor its length is limited to several centimeters. Therefore, such a sensor should be rather considered as an integrated photonics element than a fiber. To rigorously evaluate performance of such a sensor [20] one first has to calculate modal excitation pattern generated by the external laser beam at the coupling end, and then propagate all the excited modes along the sensor length. In such an arrangement sensor performance will be also influenced by the parameters of an excitation laser beam.

5. Conclusions

We have introduced the design principles of a MOF based Surface Plasmon Resonance sensor. The two main design challenges were identified as phase matching of the effective refractive indices of the core guided and plasmonic modes, and optimizing microfluidics for efficient analyte flow. Phase matching was facilitated by introducing hollow microstructure into the fiber core to lower the modal refractive index, while improved microfluidics was realized by employing large size analyte containing channels. Sensor sensitivity studies show that refractive index change of 10^{-4} leads to the easily detectable 1% change in the intensity of a transmitted light.

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