Practical design of Microstructured Optical Fibers for Surface Plasmon Resonance sensing.

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Abstract: Plasmons on the surface of large metallized holes containing analyte are excited by the fundamental mode of a microstructured fiber. Phase matching between plasmon and core modes is facilitated by the perforation of fiber core.

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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. Optical fibers offer 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 metalized fiber Bragg gratings have been studied [2, 3]. 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. 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 [2] (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. In principle, phase matching problem can be alleviated by coupling to a plasmon via the high order modes of a multimode waveguide [3]. Such modes can have significantly lower effective refractive indices than a waveguide core index. In such a set-up light has to be launched into a waveguide as to excite high order modes some of which will be phase matched with a plasmon mode. 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.

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 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 [4, 5] 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. It was also recently demonstrated [6] that plasmon mode can be excited by the core guided mode of a single mode holey fiber featuring a single ring of metallized holes. 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 [7] or wet chemistry deposition technique used in fabrication of metal covered hollow waveguides [8].

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. Fig. 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 (an array of even smaller holes in the core can equally be used). 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 $d_2 = 0.8\Lambda$, while diameter of a central hole is $d_c = 0.45\Lambda$. Pitch of the underlying hexagonal lattice is $\Lambda = 2\mu m$. 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). 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.

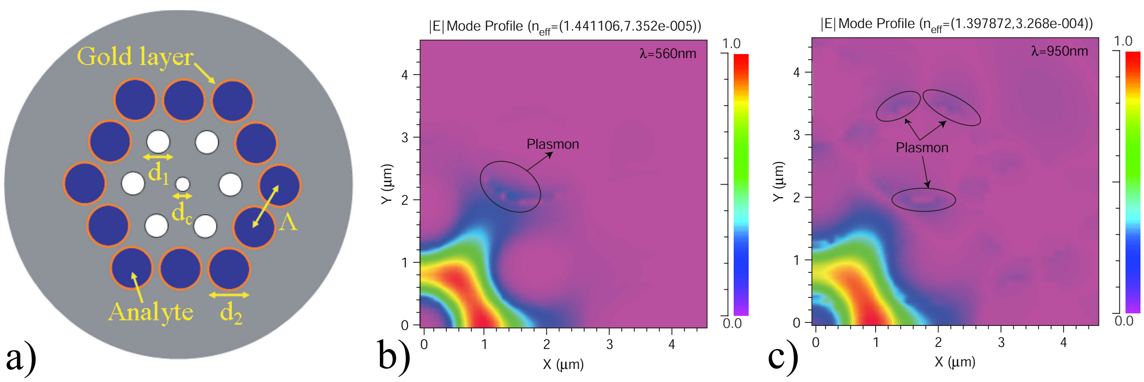

Fig. 1. a) Schematic of a MOF-based SPR sensor. Holes in the second layer are filled with analyte and metallized for plasmon excitation. Air filled holes in the first layer enable guiding in the higher refractive index fiber core, while at the same time controlling coupling strength between the core 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 resonance with a plasmon at $\lambda = 560nm$. c) Field distribution of a core mode at the second resonance with a plasmon at $\lambda = 950nm$.

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(a) we present loss of a 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(a) 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 present. 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 the 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. 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.

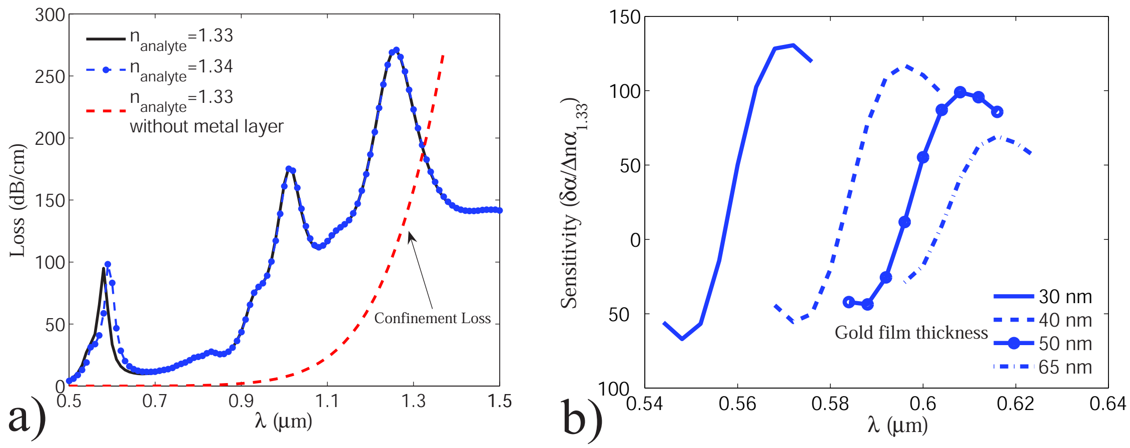

Fig. 2. a) Loss spectra of the MOF core guided mode. Loss peaks correspond to various plasmonic excitations in the metallized holes. Black solid line - $n_a = 1.33$, blue doted line - $n_a = 1.34$. For comparison, red dashed-line shows the confinement loss of a core guided mode in the absence of a metal coating. b) Sensitivity of the MOF-based SPR sensor for the 30nm, 40nm, 50nm and 65 nm thicknesses of a gold coating.

4 Characterization of sensitivity of a MOF-based SPR sensor

Typically, SPR sensor measures changes in the bulk refractive index of the analyte. 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 also 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 loss. Choosing sensor length as $L = 1/\alpha(\lambda, n_a)$, leads 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. 2(b) we present sensitivity of the proposed MOF- SPR sensor for various thicknesses of the metal layers. As seen from the figures 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.

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