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

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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 SPR sensor miniaturization many compact configurations have been investigated. 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 is typically higher than 1.45. Effective refractive index of a plasmon is close to that of an analyte (~1.33 for water). Only at higher frequencies [2] (λ<700nm for a gold film) 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] as such modes have significantly lower effective refractive indices than that of a core. However, excitation of a limited number of high order modes is typically non-trivial. 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. In traditional single mode fiber based sensors, to metallize fiber surface one strips the fiber jacket and then polishes the fiber cladding to the core to enable evanescent coupling with a plasmon. This laborious procedure compromises fiber integrity making resulting sensor prone to mechanical failures.

In this paper we illustrate that phase matching with plasmon and packaging issues can be facilitated using Microstructured Optical Fibers (MOFs) [4]. Thus, refractive index of a core mode can be tuned by introducing microstructure in the MOF core. As microfluidics in microstructured fibers is enabled by passing analyte though the porous cladding, this naturally solves packaging problem. Finally, deposition of metal layers inside of the MOFs can be performed ether with CVD technique [5] or wet chemistry deposition technique [6].

2. Geometry of a MOF-based SPR sensor

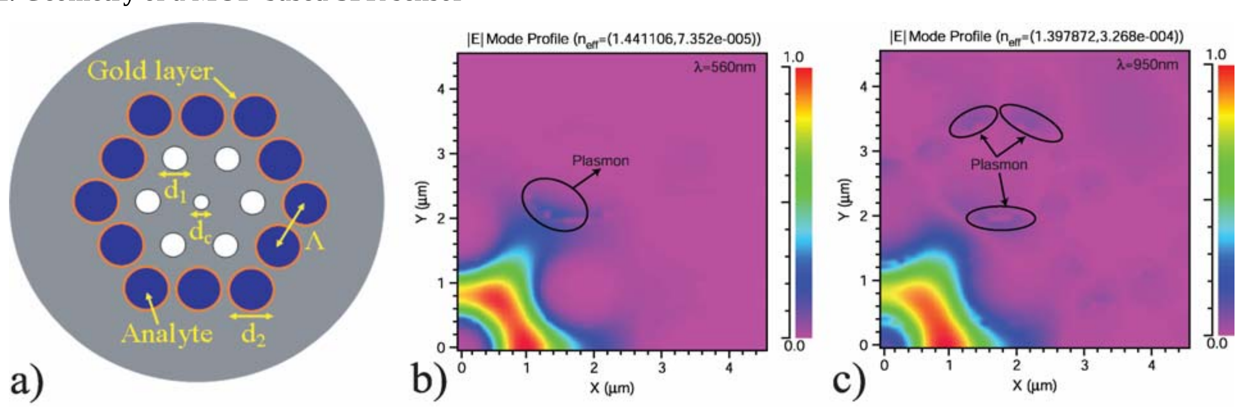
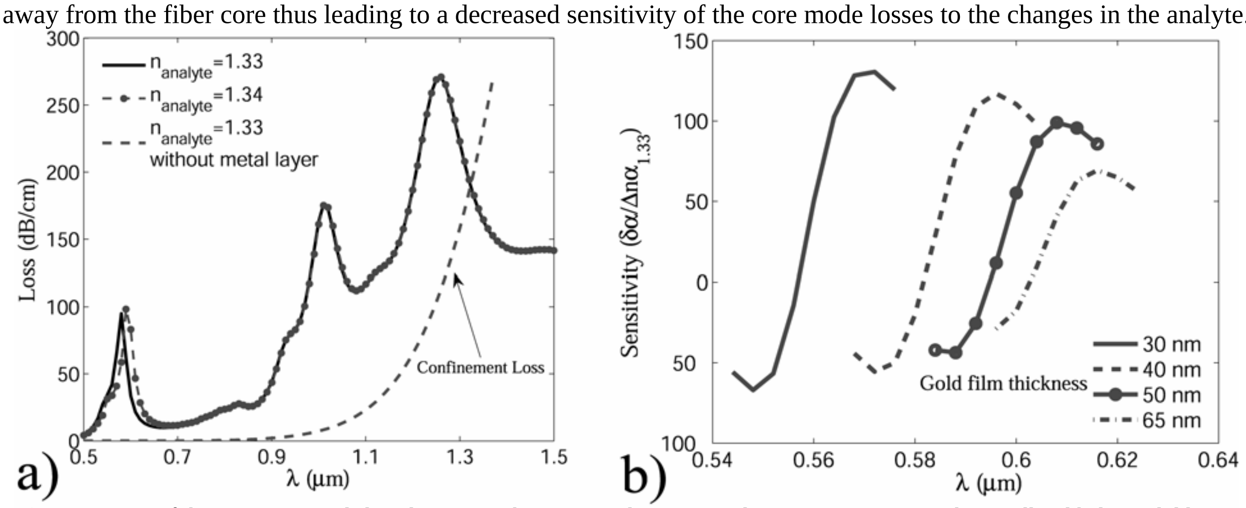


Fig. 1. a) Schematic of a MOF-based SPR sensor. Holes in the second layer are filled with analyte and metallized for plasmon excitation. Small air filled hole in the fiber core is used to lower the refractive index of a core guided mode to facilitate phase matching with a plasmon. b) Field distribution of a core mode at the first and second resonances with a plasmon at λ=560nm and λ=950nm.

Fig. 1(a) shows schematic of a proposed hexagonal solid-core MOF based SPR sensor made of silica. Fiber core is surrounded by the two layers of holes. Holes of the second layer are metallized with 40nm of gold and are considerably larger than these of the first layer to simplify the flow of analyte (water, n_a=1.33) through them. To lower the refractive index of the core mode (for phase matching with a plasmon) we introduce a small hole in the core center. Holes in the core and the first layer are filled with air. 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 $d_c=0.45\Lambda$, where pitch $\Lambda=2\mu$m. By changing the size of the central hole, one can tune the effective-index of a core mode. 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).

We use finite element method to find complex propagation constants of the guided modes assuming Drude model [2] for the dielectric constant of a gold layer. In Fig. 2(a) loss of a core guided mode is presented 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. For comparison, in dotted line we present confinement loss of a core mode in a non-metallized fiber. Resonant frequency of the first plasmonic peak near 560nm is the most sensitive of the three to the changes in 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. Modal field distribution at the second plasmonic resonance is shown in Fig. 1(c). In this case most of the plasmon intensity is concentrated away from the fiber core thus leading to a decreased sensitivity of the core mode losses to the changes in the analyte.



a) Loss spectra of the MOF core guided mode. Loss peaks correspond to various plasmonic excitations in the metallized holes. Solid line - n_a=1.33, doted line with circles - n_a=1.34. For comparison, 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.

3. 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 thus very sensitive to the changes in the analyte. Let $\alpha(\lambda,n_a)$ be transmission loss of a core mode as a function of wavelength and analyte refractive index. Remaining power in a core mode after propagation along the sensor length L is $P(L,\lambda,n_a)=P_0\exp(-\alpha(\lambda,n_a)L)$. Relative sensitivity to the dn_a change in the analyte refractive index is defined as $S(\lambda)=[P(L,\lambda,n_a+dn_a)-P(L,\lambda,n_a)]/P(L,\lambda,n_a)/dn_a$. Sensor length L is limited by the modal loss and can be chosen as $L=1/\alpha(\lambda,n_a)$. In Fig. 2(b) sensitivity of the MOF-SPR sensor for various thicknesses of the metal layers is presented. The maximum of sensitivity shifts to shorter wavelengths for thinner metal films, while being weekly dependent on the metal film thickness. 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.

4. References

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