Novel Photonic Crystal Fiber Sensors Using Splitting of a Degenerate Plasmonic Doublet

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Abstract: The concept of honeycomb photonic crystal fiber-based plasmonic sensor, having a sensing mechanism based on the detection of breaking of an degeneracy between the two near-IR plasmonic excitations with the resolution of $7.2 \cdot 10^{-6} RIU$, is developed.

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Surface plasmons, propagating at the metal/dielectric interface, are extremely sensitive to changes in the refractive index of the dielectric. To excite efficiently a surface plasmon, the phase matching condition between a plasmon and a waveguide mode has to be satisfied. Over the past decade, driven by the need for miniaturization of SPR sensors, various compact configurations enabling coupling between optical waveguide modes and surface plasmonic waves [1, 2, 3, 4] and, recently, holey fibers [5] have been investigated. In a single mode waveguide-based sensor, phase matching between plasmon and fundamental waveguide mode is typically hard to realize. This is related to the fact that the effective refractive index of a core guided mode is close to the refractive index of the core material, which is typically larger than 1.45. The effective refractive index of a plasmon is close to the refractive index of an ambient medium which is typically air $n_a = 1$ (gas sensing) or water $n_a = 1.3$ (biological sensing). Thus, large discrepancy in the effective indices makes phase matching between the two modes hard to achieve, with an exception of the high frequencies ($\lambda < 650nm$), where the plasmon dispersion relation deviates towards higher refractive indices.

In this paper, we present design principles of a novel photonic bandgap fiber-based SPR sensors, and show, in photonic bandgap fiber-based SPR sensors, fundamental Gaussian-like leaky core mode can be phase matched with a plasmon at higher wavelength, thus enabling sensing even in near-IR. The effective refractive indices of the leaky core modes can be arbitrarily smaller than that of a waveguide core material, thus enabling phase matching with a plasmon at any desirably frequency. Using such a leaky mode for sensing can also give the additional advantage of an effectively single mode propagation regime [6]. Our proposed design is a SPR sensor based on a honeycomb photonic crystal fiber operating at $1060nm$. We further demonstrate a novel sensing mechanism based on the detection of breaking of an degeneracy between the two plasmonic excitations, the plasmonic excitations on the analyte/metal and the glass/metal interfaces.

In Fig.1(a) the schematic of the honeycomb photonic crystal fiber-based SPR sensor is presented. The design parameters are chosen as follows, the center to center distance between adjacent holes is $\Lambda = 0.77\mu m$, the cladding hole diameter is $d = 0.55\Lambda$, the diameter of the hole in the core center is $d_c = 0.35\Lambda$. The fiber is made of silica glass with a refractive index of $n_{glass} = 1.45$, the core and cladding holes are filled with air $n_{air} = 1$, while the large semi-circular channels are plated with a $40nm$ thick layer of gold and filled with an aqueous analyte $n_a = 1.32$. The central hole in the fiber core lowers its effective refractive index compared to that of a silica cladding. Under certain conditions, such a core can support a mode confined by the bandgap of the honeycomb reflector. Guided by the bandgap of the fiber reflector, the effective refractive index of the core mode can be made much lower than that of the silica material. Moreover, radiation loss of a bandgap guided core mode can be reduced by adding more layers into the honeycomb reflector. The main reason why we chose a honeycomb structure of the fiber reflector is because it enables a very large photonic bandgap [6], thus simplifying considerably phase matching of the core guided and plasmonic modes. We design the fiber so that two plasmonic peaks are degenerate at $1009nm$ with $n_{analyte} = 1.32$. Fig. 1(b) shows the dispersion relations of the Gaussian-like core mode (thick solid line), analyte bound plasmonic mode (thin solid line with circles) and cladding bound plasmonic mode (thick solid line).Corresponding flux distributions of the core guided and plasmonic modes are presented in Fig. 1(c). The core mode loss shows a single plasmonic peak (solid curve in Fig. 1(d)). When the refractive index of the analyte is varied, this affects the two plasmonic dispersion relations differently. Particularly, the analyte bound plasmon mode is affected much

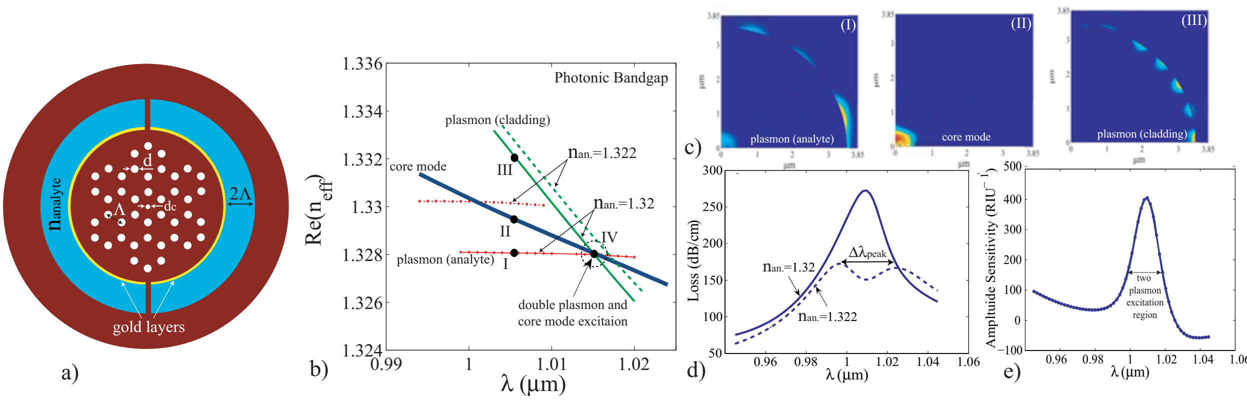

Fig. 1. Solid core honeycomb photonic crystal fiber-based SPR sensor. a) Schematic of the sensor. The solid core having a small central hole is surrounded with a honeycomb photonic crystal reflector. Two large channels are integrated to implement analyte access to the fiber reflector region. The channels are goldplated for plasmon excitation. The gold layer is bordered by an aqueous analyte. b) Band diagram of sensor modes. Dispersion relation of the fundamental core mode (thick solid curve), analyte bound plasmonic mode (dashed curve with circles), and cladding bound plasmonic mode (dashed curve). The bandgap of an infinitely periodic reflector is shown as a clear region. c) The energy flux distributions across the fiber cross-section are shown for the fundamental core mode (II) as well as the analyte and cladding bound plasmon modes (I,III) outside of the phase matching region. d) The solid curve shows loss of the fundamental core mode near the degenerate phase matching point with two plasmonic modes and $n_{analyte} = 1.32$. Due to degeneracy, only one peak is distinguishable in the loss curve. Dashed line shows splitting of the degeneracy in plasmonic modes when the analyte refractive index is changed to $n_{analyte} = 1.322$. e) Dependence of the sensor amplitude sensitivity on wavelength.

strongly by the changes in the analyte refractive index than the cladding bound plasmonic mode. As a result, degeneracy is lifted, and two closely spaced plasmonic peaks appear in the core mode loss curve (dashed curve in Fig. 1(d)). For example, a 0.002 change in the analyte refractive index splits a single plasmonic peak into two peaks separated by 27.5nm. This permits a novel spectral detection technique, where relative peak separation can be used to characterize changes in the analyte refractive index. By defining spectral sensitivity as: $S_\lambda = |\lambda_{peak1} - \lambda_{peak2}|/dn_{analyte}$, we find spectral sensitivity of $13750nm \cdot RIU^{-1}$. It is typically a safe assumption that a $0.1nm$ change in the position of a resonance peak can be detected reliably, which results in a sensor resolution of $7.2 \cdot 10^{-6} RIU$, which is, to our knowledge, the highest reported spectral sensitivity of an aqueous fiber-based SPR sensor. Finally, in Fig. 1(e), we present the amplitude sensitivity of the proposed honeycomb fiber-based sensor as defined by [5]: $S_A(\lambda)[RIU^{-1}] = -\frac{1}{\alpha(\lambda,n_a)}\frac{\partial\alpha(\lambda,n_a)}{\partial n_a}$. Where $\alpha(\lambda, n_a)$ and n_a are the transmission loss of the core mode and the refractive index of the analyte, respectively . The maximal sensitivity $400 \cdot RIU^{-1}$ is achieved at $1009nm$. It is typically a safe assumption that a 1% change in the transmitted intensity can be detected reliably, which leads to a sensor resolution of $2.5 \cdot 10^{-5} RIU$. Sensor length in this case is in $\sim 1mm$ range. In conclusion, The concept of honeycomb fiber-based surface plasmon resonance sensor operating at $1060nm$ with the gigantic resolution of $7.2 \cdot 10^{-6} RIU$ is developed.

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