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NOVEL CONCEPT OF MULTI-CHANNEL FIBER OPTIC SURFACE PLASMON RESONANCE SENSOR

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ABSTRACT

A novel multi-channel fiber optic surface plasmon resonance (SPR) sensor is reported. The sensing structure consists of a single-mode optical fiber, covered with a thin gold layer, which supports a surface plasmon (SP) and a Bragg grating. The Bragg grating induces coupling between the forward-propagating fundamental core mode and the back-propagating SP-cladding mode. As the SP-cladding modes are highly sensitive to changes in the refractive index of the surrounding medium, the changes can be accurately measured by spectroscopy of these hybrid modes. Multichannel capability is achieved by employing a sequence of Bragg gratings of different periods and their reading via the wavelength division multiplexing. Theoretical analysis and optimization based on the coupled-mode theory (CMT) is carried out and performance characteristics of the sensor are determined.

KEYWORDS

Surface plasmon resonance, fiber optic, Bragg grating, biosensor

1. INTRODUCTION

Over the past decade, surface plasmon resonance (SPR) sensors have become a powerful tool for biomolecular research and affinity biosensing [1]. SPR sensors are thin-film refractometers that measure refractive index changes in the proximity of metal surface supporting a surface plasmon (SP). As light cannot be coupled to an SP directly, prism [2], grating [3] or waveguide couplers are typically used in SPR sensors. The first SPR sensors based on coupling of light guided in a multimode optical fiber and a surface plasmon on a thin metallic overlayer were reported in early 90's [4]. Subsequently, a fiber optic SPR sensor based on a single-mode optical fiber was proposed [5]. In the following years, this geometry was reduced to a miniature SPR fiber optic probe [6] which represents the highest degree of miniaturization of SPR sensors achieved so far. An SPR sensor based on a side-polished polarization-maintaining single-mode fiber was developed to suppress the sensitivity of the fiber to deformations [7]. These advances resulted in considerable improvements in the performance of fiber optic SPR sensors; however, the exploitation of the fiber optic SPR sensors for biosensing remained rather limited, mainly due to the lack of referencing channels. Recently, an alternative approach to excitation of SPs in fiber optic structures has been reported which consists of the coupling of a core mode of a single-mode optical fiber with a long-period grating [8] or a Bragg grating [9] to an SP-coupled-cladding mode.

In this paper, we propose a fiber optic SPR sensor based on spectroscopy of back-propagating SP-cladding modes which are excited by a guided core fiber mode via a Bragg grating. In this sensor, spectrum of the transmitted light is measured and changes in the refractive index of analyte are observed as a spectral shift of the transmission dips associated with the excitation of SP-coupled-cladding modes. The sensor offers multiple sensing channels which can be simultaneously accessed through the wavelength division multiplexing. Theoretical analysis and optimization of the sensing structure is carried out by means of the coupled-mode theory (CMT).

2. PRINCIPLE OF OPERATION

The proposed SPR sensing device consists of a single-mode step-index optical fiber with a Bragg grating inscribed into the fiber core. A thin gold layer supporting a SP is deposited around the fiber cladding (Figure 1). When the axial component of the propagation constant of a cladding mode matches that of a SP, a coupled SP-coupled-cladding mode arises. Due to the coupling with SP, the propagating constant of this mixed mode is highly sensitive to refractive index changes of analyte. Fiber grating allows the transfer of power between modes in the fiber by perturbing the propagation constant of one mode so that it matches the propagation constant of the other. The coupling condition for the Bragg grating-mediated coupling between the forward-propagating fundamental core mode and the back-propagating ith cladding mode is fulfilled at resonance wavelength which can be expressed as

$$\lambda_{res}^{i} = \left(n_{eff}^{CO} + n_{eff}^{CL^i} \right) \Lambda , \qquad (1)$$

where n_{eff}^{CO} and $n_{eff}^{CL^i}$ are effective refractive indices of core and cladding modes, respectively. The coupling gives rise to dips in the transmission spectrum.

If two Bragg gratings of different periods (Λ_1 and Λ_2) are inscribed into two regions of the fiber core, each of back-propagating modes can be excited at two different wavelengths (λ_{res}^{SP-CL}), which enables the spectral division of signals from different channels (Figure 2).

3. THEORY

If the Bragg grating is a circularly symmetric refractive index perturbation in any transverse plane of the fiber, the coupling only occurs between HE_{11} and the cladding modes with azimuthal order l=1. This Section presents theoretical analysis of the sensing structure in the approximation of the “equivalent” planar waveguide (Figure 3). The simulations were carried out using coupled mode theory (CMT) for the planar waveguide „equivalent“ to a single-mode, step-index fiber with cladding diameter, d_{CL} = 125 μm and index of refraction, n_{CL} = 1.443 (silica), numerical aperture, $NA = \sqrt{n_{CO} - n_{CL}} = 1.4$, covered with a thin gold film of thickness, d_G = 30 -70 nm. The refractive index of surrounding medium was set to 1.32 (water). The length of Bragg grating, L, was varied between 1 and 3 mm. The modulation of the refractive index of grating, was assumed to be $\Delta n = 10^{-3}$ - 5.10^{-3} [12]. The period of the Bragg grating Λ was set to excite the 47th SP-coupled-cladding mode at 810 nm.

In order to determine the diffraction efficiency and spectral dependence of transmission, the coupled-mode theory [10] was used. It suggests, that the transverse component of the electric and magnetic field can be written as a superposition of the modes of a waveguide without the grating (perturbation). Propagation of light along the fiber grating is described by the unconjugated form of the coupled-mode equations

$$\begin{aligned} \frac{dA_\mu}{dz} &= i \sum_v B_v \kappa_{v\mu}^{*} \exp(-i\Delta\beta z) \\ \frac{dB_\mu}{dz} &= -i \sum_v A_v \kappa_{v\mu} \exp(i\Delta\beta z) \\ \Delta\beta &= \beta_v + \beta_\mu - \frac{2\pi}{\Lambda}, \end{aligned} \tag{2}$$

where the coefficients A_μ, B_μ are slowly varying amplitudes of the μth mode, $\kappa_{v\mu}$ is the coupling constant between μth and νth mode

$$\kappa_{v\mu} = \frac{i\omega\varepsilon_0}{4} \frac{|\beta_\mu|}{\beta_\mu} \iint_A \Delta\varepsilon \mathbf{e}_{\mu\perp} \cdot \mathbf{e}_{v\perp} \tag{3}$$

and $\mathbf{e}_{\mu\perp}$ denotes the transverse field distribution of μth mode and $\Delta\varepsilon$ is the perturbation of permittivity, e_v?.

The field distribution and dispersion curves of the effective refractive indices may be obtained by the transfer matrix method [11].

If the cladding mode resonances do not overlap, each resonance can be calculated separately retaining only the core mode and appropriate cladding mode and the problem reduces to the two-mode coupling. The transmission of the μth coupled mode can then be written as

$$T_{\mu} = \frac{\delta \exp\left(-\frac{1}{2} i L \Delta\beta_{1\mu}\right)}{\frac{1}{2} i \Delta\beta_{1\mu} \sin(\delta L) - \delta \cos(\delta L)}, \delta = \sqrt{\left(\frac{\Delta\beta_{1\mu}}{2}\right)^2 - |\kappa_{1\mu}|^2}, \quad (4)$$

where $\kappa_{1\mu}$ and $\Delta\beta_{1\mu}$ are the coupling constant and the phase detuning between the core and μth mode and L denotes the length of the grating.

4. RESULTS AND DISCUSSION

The coupling between the fundamental mode and the hybrid SP-coupled-cladding modes were optimized in the terms of the design parameters of the sensing structure. The strongest coupling of cladding modes with SP resulting in the sensitivity and absorption occurs between 46^{th} - 49^{th} modes. The following calculations therefore focus on the region of the transmission spectrum that corresponds to these modes.

At first, dependence of the shape of the transmission dips on the parameters of the structure (*L* Δn *and* d_G *)* was studied (Figure 4). Clearly, the coupling efficiency increases with an increasing length of the grating *L* or grating refractive index contrast Δn. The stronger coupling is also accompanied by widening of the transmission dips. With an increasing thickness of the gold layer, coupling efficiency decreases, transmission dips become wider and sensitivity increases (Figure 5).

To illustrate the response of the structure to refractive index changes at the gold film, transmission spectra corresponding to 46th-49th SP-coupled-cladding modes for refractive indices of the surrounding medium between 1.32-1.325 were calculated (Figure 6). The spectral shift and change in the shape of transmission dips depends on the refractive index of sample. As expected, modes of structure with thinner gold layer shows lower sensitivity, narrower and deeper dips.

To compare the potential resolution of different configurations of SPR sensing devices, the figure of merit χ defined as $\chi = S/w$ was introduced [12]. SPR sensing configurations exhibiting higher χ are expected to provide higher resolution. It was shown that for SPR prism and grating -based systems the figure of merit χ is $83 RIU^{-1}$ and $48 RIU^{-1}$, respectively (λ=850 nm) [12]. The sensing structure proposed herein, can a provide a superior χ as high as $700 RIU^{-1}$. Even with a low-cost spectrometer and resolution in the resonant wavelength shift of 1pm [13], the sensor is expected to achieve a refractive index resolution of $5x10^{-6}$ RIU.

5. CONCLUSIONS

We report the concept of novel optical fiber SPR sensor, which enables reference-compensated biosensing in a highly miniaturized format. The structure consists of a standard single-mode optical fiber, thin gold layer, deposited around the cladding and Bragg gratings inscribed in different regions of the fiber core. The measuring of refractive index change in the proximity of sensor’s surface is based on spectroscopy of SP-coupled-cladding modes. Theoretical analysis of the sensing structure has been carried out using the coupled-mode theory. The sensing properties of the structure have been optimized in ~~the~~ terms of length and refractive index contrast of the grating and thickness of the gold film. The refractive index resolution of the optimized sensing structure was estimated to be $5\text{x}10^{-6}$ RIU.

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Biography

Barbora Špačková (MS 2007) graduated in optics at Faculty of Nuclear Sciences and Physical Engineering of Czech Technical University in Prague. Since 2007, she is a PhD student of the Institute of Photonics and Electronics in Prague. Her research is focused on SPR sensors.

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Christos Themistos is an assistant professor at the Frederick Institute of Technology, Cyprus. His research interests are in the development of finite element based vectorial models in conjunction with perturbation technique for the analysis of surface plasmon modes in optical waveguides at optical and terahertz frequencies. He is also a visiting fellow at the photonics modeling group at City University, London.

Muttukrishnan Rajarajan is the head of the biophotonics group at City University, London. His research interests are in the finite element modeling and characterization of biosensors for healthcare applications. He is in the editorial board of the international journal of healthcare. He has published more than 120 conference and journal papers and is a regular speaker at international conferences. He is a member of the Optical Society of America and a Senior Member of the IEEE.

Jiří Homola (MS 1988, PHD 1993) is Head of Photonics Division and Chairman of Department of Optical Sensors at the Institute of Photonics and Electronics, Prague (Czech Republic). He also is Affiliate Associate Professor at the University of Washington, Seattle (USA). His research interests are in photonics and biophotonics with emphasis on optical sensors and biosensors. He has edited 2 books and authored over 60 research papers in scientific journals and over 100 conference contributions. J. Homola is an Associate Editor of Journal of Sensors, member of Editorial Boards of Sensors and Actuators B, and Senior Member of IEEE.

FIGURES AND LEGENDS

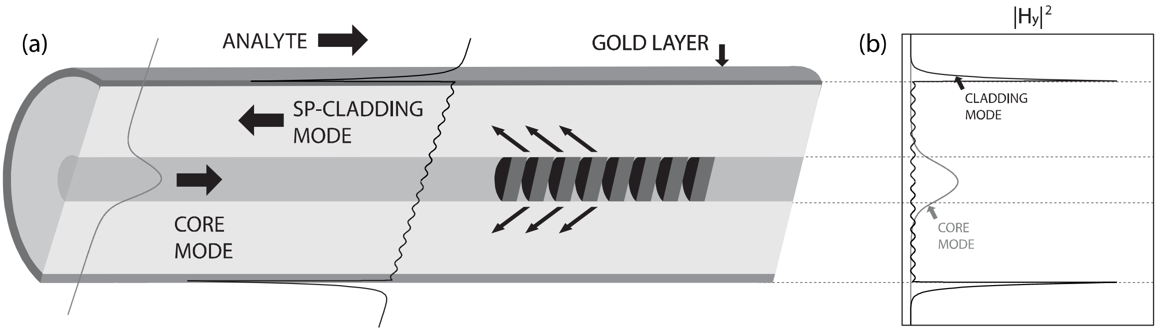

Figure 1 *(a) Multi-channel fiber optic SPR sensor with Bragg grating. (b) Field distribution of core and cladding mode.*

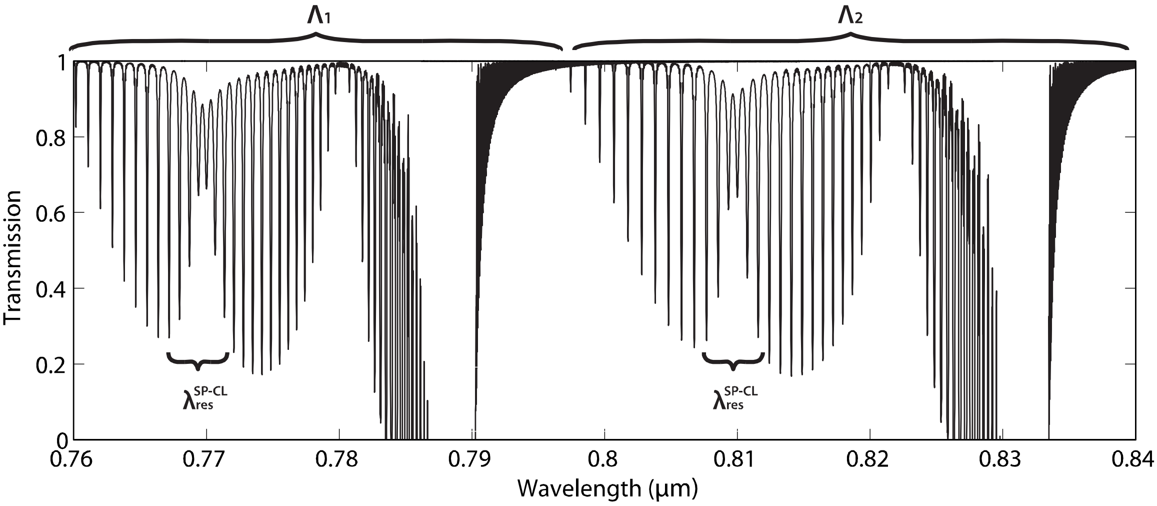

Figure 2 *Typical transmission spectrum of proposed structure with two Bragg grating with periods of refractive index modulation* Λ_1 *and* Λ_2*. SP-coupled-cladding modes are excited at wavelengths* $\lambda_{res_1}^{SP-CL}$ *and* $\lambda_{res_2}^{SP-CL}$.

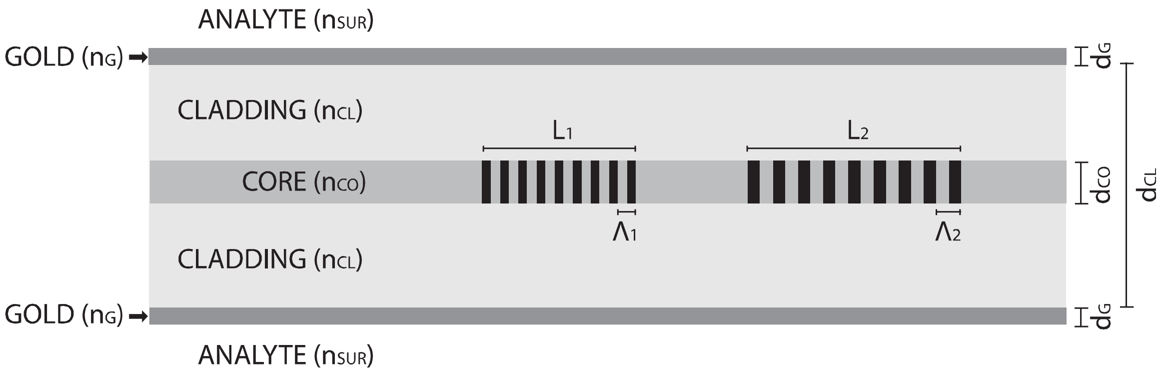

Figure 3. *Schematic of the four-layer planar waveguide, equivalent to fiber optic.*

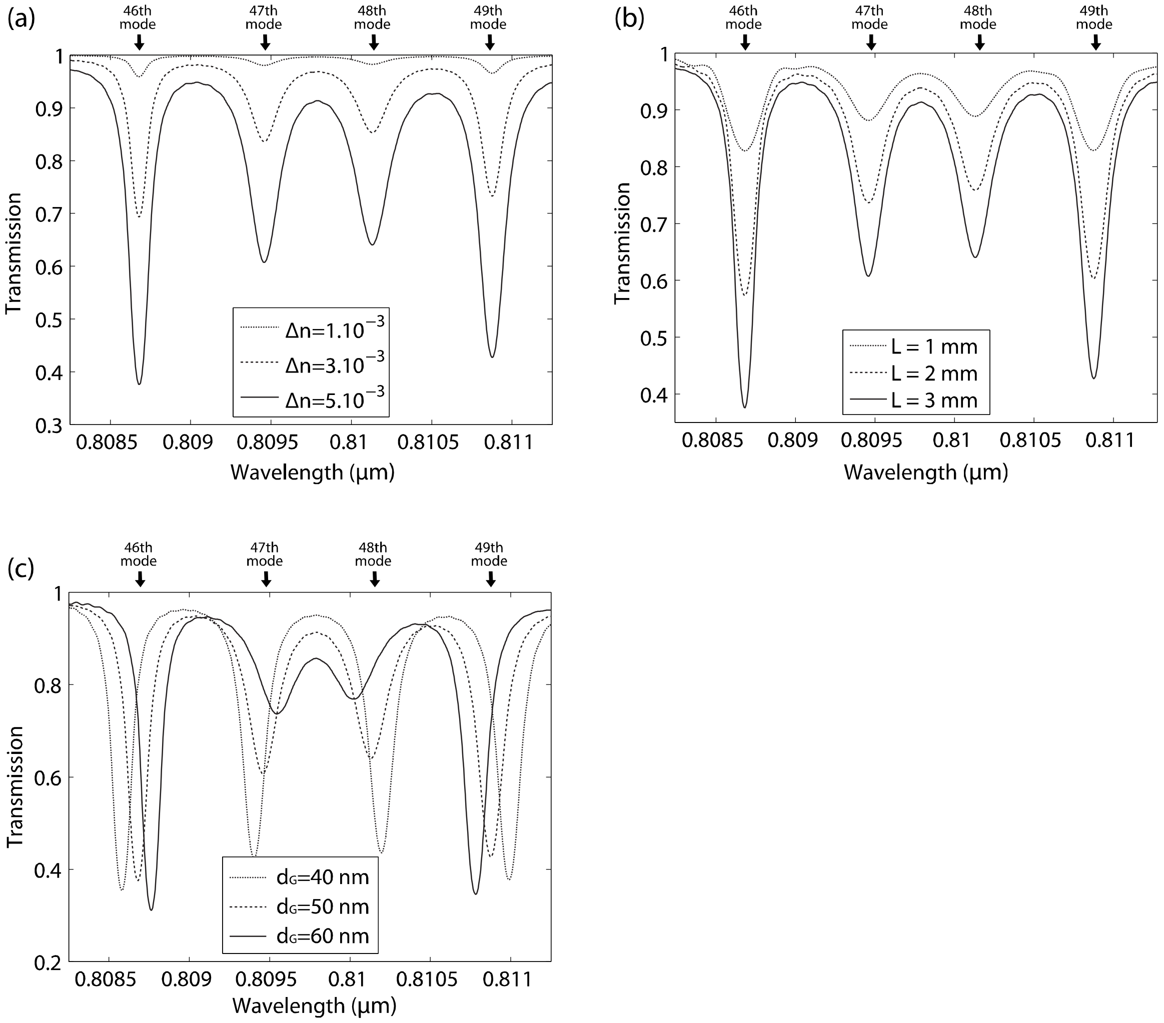

Figure 4. *Calculated spectral transmission for different (a) modulation of refractive index of grating Δn, (b) length of Bragg grating L, and (c) thickness of gold layer* d_G.

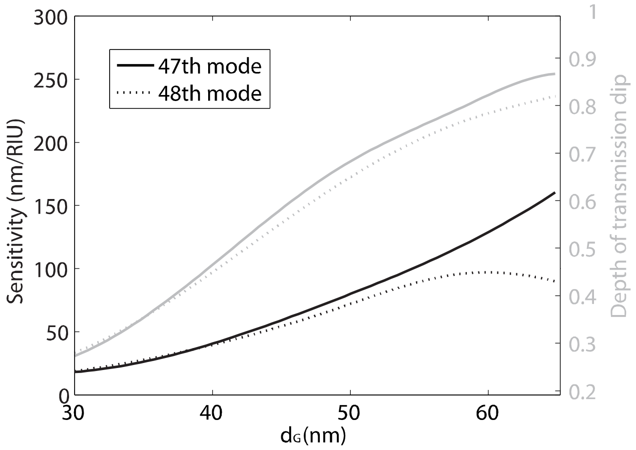

Figure 5. *Sensitivity and depth of transmission dips corresponding to 47^{th} and 48^{th} SP-coupled-cladding modes.*

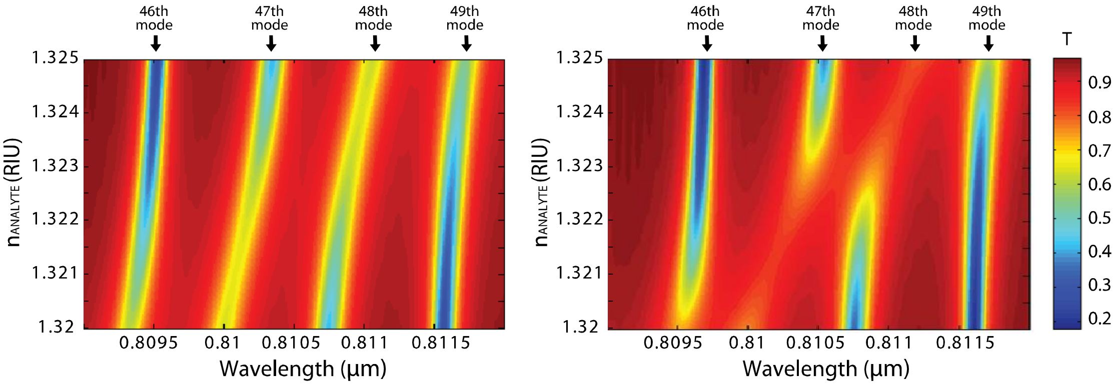

Figure 6. *Spectral position of transmission dips corresponding to 46th-49th SP-coupled-cladding modes as a function of refractive index of analyte calculated for two thickness of the gold layer - (a) 50 nm and (b) 60 nm.*

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