Surface-Plasmon-Resonance Sensor Based on H-shaped Optical Fibre

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ABSTRACT

We propose and theoretically study a novel surface-plasmon-resonance sensor based on an H-shaped, elliptical-core optical fibre. The two grooves of the H-fibre are coated with a thin, uniform metal layer that in turn is covered with a high-index dielectric layer to allow broad spectral tunability. The sensor maintains linear polarization and facilitates effortless splicing. Electromagnetic mode analysis indicates a sensitivity of 1800 nm/RIU (refractive-index unit) for aqueous analytes.

Keywords: Surface plasmon resonance, transfer matrix method, modal analysis, finite element method.

1. INTRODUCTION

Recently, there has been increasing interest in developing fibre-based plasmonic sensors by using specialty or microstructured optical fibres as a template [0–3]. These sensors make use of a surface plasmon polariton that is bound to propagate along a metal-dielectric interface with highly dielectric-dependent characteristics. In closed all-in-fibre sensors, the dielectric substance (analyte) is infiltrated into the metalized pores of the fibre, and hence, such structures might be best employed with very small sample volumes or as packaged (end-sealed) sensor heads. Despite recent advancements [4], it is still challenging to fabricate and employ the closed structures, and thus, open metal-coated sensor fibres that are embedded into an ambient analyte have retained their popularity. The microstructured-fibre-based open sensors can be operated in the same way as, e.g., those based on the D-fibre [5] or a tapered circular-core fibre [6].

In this work, we propose a novel surface-plasmon-resonance (SPR) sensor structure based on a highly birefringent H-shaped optical fibre. Such polarization-maintaining fibres are typically fabricated in two steps. First, an appropriate preform is prepared with the stack-and-draw technique so as to yield a fibre with two large pores running through its length (a.k.a. the side-hole fibre) [7]. If the preform originally embodied a circular up-doped core, it will assume an elliptical shape in the final drawing process. Second, the two holes are opened and exposed to the outside environment by chemically etching a segment of the fibre from opposite sides [8]. For SPR sensor operation, a uniform metal layer is then deposited via the etched openings. Also, in order to flexibly tune the SPR wavelength and the resonance characteristics, an additional high-index dielectric layer is assumed to be deposited on top of the metal layer. The principle of using such a thin auxiliary layer is described in Ref. [9]. With both of these material layers in place, the structure is expected to support a plasmonic (non-degenerate) fundamental mode that would spatially extend all the way to an ambient analyte in the etched openings. Our goal is to find a sensor structure for aqueous analytes that would operate in the O-band near the 1.3-micron wavelength.

This paper is organized as follows. In Section 2, we detail the proposed design and use the customary transfer matrix formalism to understand the dependence of the SPR characteristics on the relevant design parameters. Once the right parameters for the operation in the O-band are found, a rigorous electromagnetic mode analysis is performed in Section 3 to assess the sensitivity of an example sensor fibre. The paper is concluded in Section 4.

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2. SENSOR DESIGN

The structure of the SPR-based sensing device is schematically shown in Figure 1. It consists of an H-shaped optical fibre that is obtained by chemical etching of the side-hole fibre, a thin metallic layer supporting a surface plasmon (SP), and a dielectric coating. When the axial component of the propagation constant of the core mode matches that of a SP, the field inside can tunnel through the metallic layer and couple resonantly to the field outside the optical fibre. As a consequence, the propagation constant of this mixed mode is highly sensitive to refractive index changes of the analyte. In this work, gold and titanium dioxide layers are considered in order to generate a SPR at the near infrared spectral region. The thickness of the metallic layer is set to 19 nm and the thickness of the dielectric layer is varied to tune the SP resonance to the desired 1.3-micron wavelength region.

To optimize the dielectric thickness, we begin by approximating the centre region of the fibre device with a multilayer structure. This approach is acceptable as long as $b >> a$ rendering the analysis analogous to that of the D-fibre [5] or the slab sensor in the Kretschmann configuration [10], thus yielding similar results. The refractive index of the elliptical core is chosen to correspond to 10%-Ge-doped silica while the rest of the fiber is assumed to be pure silica. The geometry and the core doping were chosen best approximate a real situation. For gold, we use the tabulated refractive-index values [11] with linear interpolation between the data points. The value of the dielectric refractive index depends on the deposition conditions, and for the case of titanium dioxide it can vary from 2 to almost 3 [12]. We assumed a mean value of 2.65. A computer simulation was performed on a five-layer system: core – cladding – metal – dielectric – analyte. The thickness of the cladding was L = 3 μm, while the thickness of the dielectric layer varied between d_d = 60 nm and 130 nm. The analyte was assumed to be aqueous with a refractive index of ~1.33. The transmittance of the equivalent planar waveguide for TM polarization and for several thicknesses of the dielectric layer was computed using the transfer matrix formalism [13], consisting of the light propagation through a multilayer medium of (N−1) isotropic and homogeneous layers by solving the Maxwell's equations subjected to boundary conditions at the interface between two adjacent layers. Within the framework of this formalism, the amplitude of ***E*** and ***H*** vectors in the first (E_0 and H_0) and last (E_N and H_N) layers are related by:

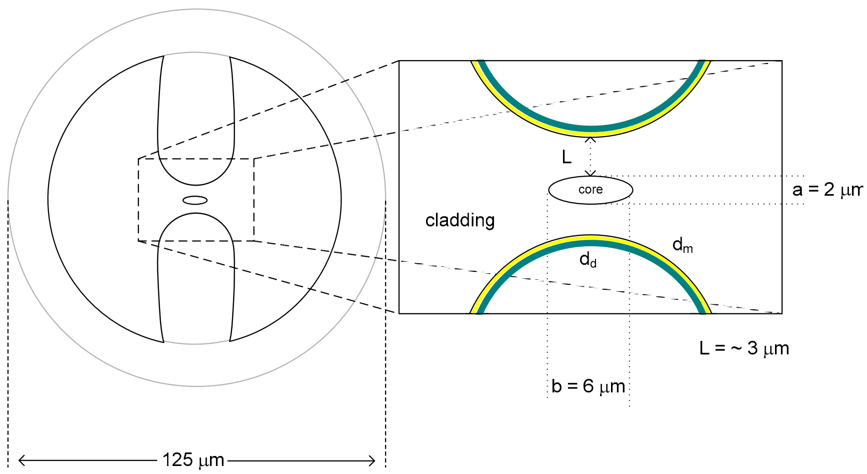

Figure 1. Cross-section of the sensor with typical template fiber dimensions. The parameters a and b stand for the minor and major axes of the elliptical core, respectively, with L being the distance between the core and the metal layer. The metal (dielectric) layer thickness is denoted with d_m (d_d).

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = [M] \times \begin{bmatrix} E_N \\ H_N \end{bmatrix} \tag{1}$$

where the transfer matrix M is computed as

$$[M] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \prod_{k=1}^{N-1} \left(\begin{bmatrix} \cos\delta_k & \frac{-i\sin\delta_k}{\eta_k} \\ -i\eta_k \sin\delta_k & \cos\delta_k \end{bmatrix} \right) \tag{2}$$

where δ_k is the phase in the k[th] layer given as $\delta_k = \frac{2\pi d_k}{\lambda}(\varepsilon_k - n_0^2 \sin^2\theta_0)^{1/2}$ and η_k is the optical admittance given as $\eta_k = \varepsilon_k/(\varepsilon_k - n_0^2 \sin^2\theta_0)^{1/2}$, where ε_k is the dielectric constant and d_k is the thickness of the k[th] layer, θ_0 is the incident angle, n_0 is the core refractive index and λ the wavelength. The reflectivity coefficient of the whole multilayer structure is given by:

$$R_p = \left|r_p\right|^2 = \left|\frac{(M_{11}+M_{12}\eta_k)\eta_0-(M_{21}+M_{22}\eta_k)}{(M_{11}+M_{12}\eta_k)\eta_0+(M_{21}+M_{22}\eta_k)}\right|^2 \tag{3}$$

The results of the simulations are shown in Figure 2, from which it can be seen that for a 19-nm-thick gold layer, the SPR can be tuned to the 1300 nm wavelength region by using a 94-nm-thick titanium dioxide layer. These coarse results were used as the starting point for a more accurate electromagnetic mode analysis described in the following section.

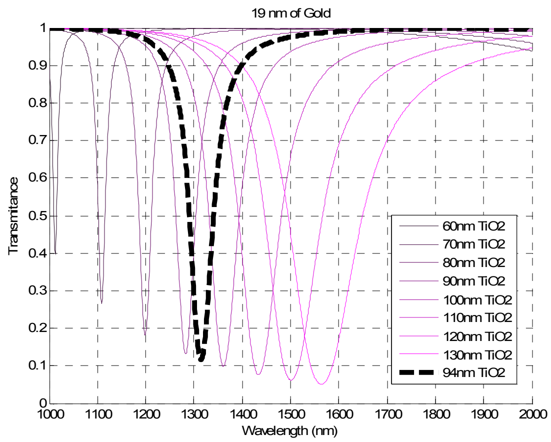

Figure 2. Transmittance of a multilayer structure with a 19-nm-thick gold layer for several dielectric thicknesses. The dashed line shows the data corresponding to the electromagnetic FEM simulation.

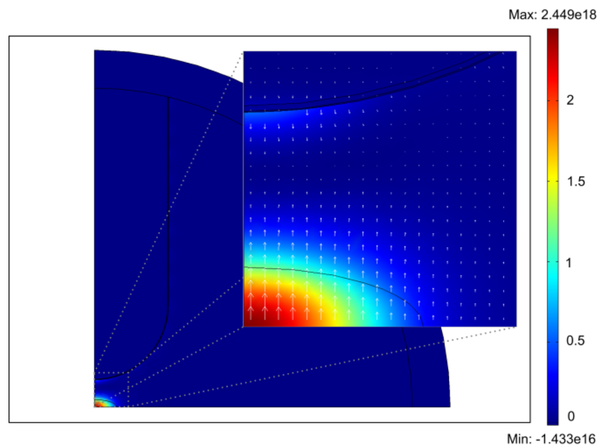

Figure 3. Mode profile of the H-shape fibre at λ = 1314 nm.

3. ELECTROMAGNETIC MODE ANALYSIS

We solve the electromagnetic mode of the fibre structure with the finite element method (FEM) by using the COMSOL Multiphysics software [16]. Only one quarter of the structure needs to be considered due to its symmetry properties [17]. The artificial boundaries are taken to be a perfect magnetic conductor and a perfect electric conductor, so as to yield a *y*-polarized mode. At the remaining outer border, a perfectly matched layer is chosen to handle the boundary condition. Within the computing region, continuity of the tangential field components across the material boundaries is assumed. The mode profile at the SP resonance (corresponding to the transmittance minimum in Figure 2) is shown in Figure 3. In Figure 4, we show the optical loss along with selected mode profiles. We then repeated the simulation by setting the refractive index of the analyte to 1.34. This change resulted in a shift of ≈ 18 nm in the spectral location of the plasmon loss peak as shown in Figure 5. This indicates a sensitivity of ≈ 1800 nm/RIU.

4. CONCLUSIONS AND FURTHER WORK

The results obtained from the theoretical analysis of the H-shaped optical fibre SPR structure indicate its high potential as a refractive index sensing element. Its geometry permits close distances between the core and the external environment due to the deep lateral fibre grooves. In view of all this, and the rather promising sensitivity figure (1800nm/RIU), this work is proceeding to another step centered on the fabrication of the proposed fibre structure and its experimental characterization.

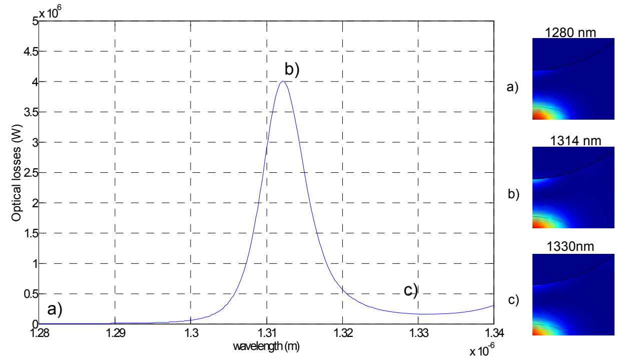

Figure 4. Modal loss as a function of wavelength. Also shown are the mode profiles for selected wavelengths.

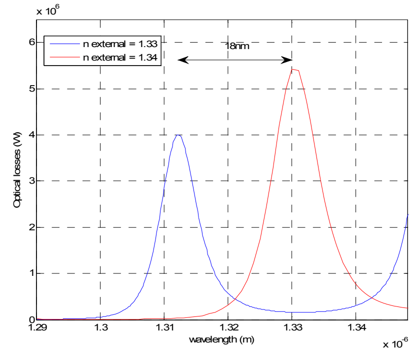

Figure 5. Modal loss with two different analytes.

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