Performance analysis simulation of new SPR microstructured D-type optical fiber sensor configurations for refractive index measurement

D. F. Santos[a,c], A. Guerreiro[b,c], J. M. Baptista[a,c*]

[a]Centro de Ciências Exatas e da Engenharia, Universidade da Madeira, Funchal, Portugal 9000

[b]Faculdade de Ciências da Universidade do Porto, Porto, Portugal, 4169

[c]INESC TEC, Porto, Portugal 4200.

ABSTRACT

This paper presents the performance analysis of two new sensing configurations of refractive index based on surface plasmon resonance (SPR) in microstructured D-type optical fiber with a thin gold layer using simulations obtained with COMSOL Multiphysics. The configurations are analyzed in terms of the intensity of the electric field. The results are compared with a conventional SPR D-type optical fiber sensor for refractive index measurement.

Keywords: microstructured D-type fiber; surface plasmon resonance; optical fiber sensor; refractive index sensor; COMSOL Multiphysics.

1. INTRODUCTION

Surface plasmon resonance is one of the most promising mechanism for optical sensing for the measurement of the refractive index of a gaseous or liquid medium. It has been known to achieve sensitivities as high as 10^{-7} RIU [1].

During the past decade, there has been a great effort to adapt and optimize conventional bulk SPR sensing configurations into implementations based on optical fibers. In many of these later configurations, the cladding of the fiber is removed (partial or totally) to allow the deposition of a thin metallic layer that supports the excitation of SPR [1] and their interaction with the core electromagnetic modes. These configurations include D-type fiber [2], modified fiber end [3] and tapered fiber [4]. Other kind of sensing configurations use microstructured fibers where the metallic layer is positioned/deposited in the holes of the fiber [5].

The geometry of the SPR sensors in optical fibers is more complex than the Otto and Kretschmann configurations [1] where a beam of light is focused directly on the thin metal layer. Instead the distribution of light inside the fiber depends on the optical modes allowed by the shape and dimensions of the fiber which do not necessarily provide higher intensities on the metal layer and strong excitation of the surface plasmon. As a result, the sensitivity of the sensor is far from optimal. So far, most of the studies of optimization of SPR sensor in optical fibers rely on geometrical optics and use a model based on transference matrices, developed for multilayer planar sensors [6], and are mainly concerned with the fine tuning of the resonance frequency of the plasmon to the operation frequency or wavelength of the device by optimizing the metal thickness and add supporting layers. As we have shown in [7, 8], this approach has strong limitations since it does not take into account the modal structure of the fiber, and consequently the intensity profile that actually reaches the metallic layer. As a result, using the transference matrix approach, the efficiency of the sensor is underestimated, since it assumes that all the light shines on the metal surface, and also it disregards how a particular fiber mode adjusts to the presence of that layer. Empirically, we can expect a sensor to be more sensitive if, at the resonance frequency of the plasmons, most of the light inside the fiber can be tunneled through the metal into the exterior medium. In principle this can be achieved not only by adjusting the geometry and constitution of the multilayers that separate the core and the exterior, but also by introducing structures inside the fiber that scatter the light and change the spatial structure of the modes towards the exterior of the fiber.

In this paper, we present two new microstructured D-type fiber configurations for refractive index measurement based on SPR, whose performance is analyzed using COMSOL Multiphysics, a commercial software that uses the finite element method (FEM) [9]. Using these simulation tools allows testing new sensing concepts and configurations with higher accuracy and considerable economy of time and resources. The two new fiber configurations aim to increase the electromagnetic field in the sensing zone and therefore the sensitivity of the sensor in relation to variations of the refractive index of the external medium.

*jmb@uma.pt; phone +351 291 209 401; Fax + 351 291 209 410

2. MODELING

In this work we present a 2D analysis of the mode structure and the electromagnetic field modes along the transverse plane of three different configurations, based on D-type fiber using the mode analysis utilities of COMSOL Multiphysics. The electromagnetic fields in optical fiber waveguides are governed by the macroscopic Maxwell equations for monochromatic time-harmonic fields in the absence of currents or external electric charges,

$$\nabla \times \boldsymbol{E}(\boldsymbol{r},\omega) = j\omega \boldsymbol{B}(\boldsymbol{r},\omega) \tag{1}$$

$$\nabla \times \boldsymbol{H}(\boldsymbol{r},\omega) = -j\omega \boldsymbol{D}(\boldsymbol{r},\omega), \tag{2}$$

where ω is the frequency of the field, $\boldsymbol{E}(\boldsymbol{r},\omega)$, $\boldsymbol{B}(\boldsymbol{r},\omega)$, $\boldsymbol{H}(\boldsymbol{r},\omega)$ and $\boldsymbol{D}(\boldsymbol{r},\omega)$ are respectively the electric, magnetic induction, magnetic and dielectric fields. It is also assumed the fields satisfy the local constitutive relations for a linear isotropic and nonmagnetic media given by

$$\boldsymbol{D}(\boldsymbol{r},t) = \varepsilon_0 \tilde{\varepsilon}_r \boldsymbol{E}(\boldsymbol{r},\omega) \tag{3}$$

$$\boldsymbol{B}(\boldsymbol{r},t) = \mu_0 \boldsymbol{H}(\boldsymbol{r},\omega), \tag{4}$$

where ε_0 and μ_0 are the permittivity and permeability in free space and ε_r denotes the relative permittivity of the material. Using Equations (1 – 4), we can obtain the wave equation for the Fourier components electric field [9]:

$$\nabla \times (\nabla \times \boldsymbol{E}(\boldsymbol{r},\omega) \; - \; k_0^2[\tilde{\varepsilon}_r(\boldsymbol{r},\omega)]\boldsymbol{E}(\boldsymbol{r},\omega) \; = \; 0, \tag{5}$$

where $k_0 \; = \; \omega/c$ is the wave-number of the mode of the field $c = 1/\sqrt{\varepsilon_0\mu_0}$ is the speed of light. The term $\tilde{\varepsilon}_r\,(\boldsymbol{r},\omega) \; = \varepsilon_r(\boldsymbol{r},\omega)j\sigma(\boldsymbol{r},\omega)/\omega\varepsilon_0$ represents the complex relative dielectric function written in terms of the material-dependent (real valued) relative permittivity (ε_r) and the Ohmic conductivity of the material $\sigma(\boldsymbol{r},\omega)$. The solution of equation (5) and knowing that light propagates in direction z can be written as

$$\boldsymbol{E}(\boldsymbol{r},\omega) \; = \widetilde{\boldsymbol{E}}(\boldsymbol{r}_\perp,\omega)\exp(jk_z \cdot z), \tag{6}$$

where $r_\perp$ and $\tilde{E}(r_\perp,\omega)$ refer to the position vector and amplitude profile of the electric field in the direction perpendicular to the optical axis (zz'), respectively. Also, k_z is the wave number of the mode along the optical axis. The value of k_z can be related with the total wave number of the eigenmode k_0 by $k_z = n_{eff}k_0$, where $n_{eff}$is the effective index of the D-type fiber section, which is computed by the COMSOL Multiphysics. In general n_{eff} is a complex quantity and can be decomposed into real and imaginary parts, by $n_{eff} = n'_{eff} + jn''_{eff}$, where n''_{eff} is in fact the extinguish coefficient of the mode as it propagates through the fiber. From this result one can compute the transmission coefficient T for a segment of fiber with length L as

$$T = \exp\left(-2n''_{eff}k_0L\right) = \exp\left(-4\pi n''_{eff}L/\lambda_0\right). \tag{7}$$

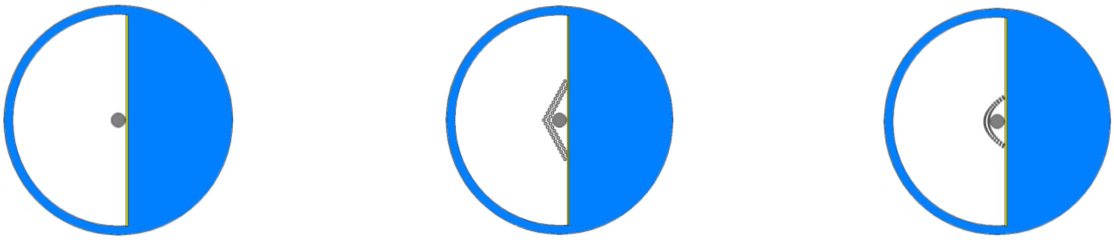
This model provides a more adequate description of the propagation of light in the sensing section of the optical fiber than the transference matrix approach, since it can take into account the field distribution of each mode of the fiber and the impact of the metallic layer, as well as any others microstructures introduced in the fiber, in the exchange of power from the core of the fiber and the exterior medium. By manipulating these structural parameters of the fiber it is possible to alter the optical response of the sensing section, allowing to fine tune the spectral response of the sensor.

3. SIMULATION AND RESULTS

3.1 Microstructured D-type fiber configurations

The computational model, implemented in COMSOL Multiphysics, calculates the transverse structure of the core propagation modes of the sensing device using a finite element method, as described in [8]. The refractive index distribution structures used to model the refractive index SPR sensors, studied in this work, are shown in figure 1.

The two new fibers (figure 1 b) and 1 c)) are composed by a core with refractive index, (n_{core}) at the center and surrounded by an array of dielectric structures (corresponding to the holes in the microstructured fiber) with refractive index equal to the air and immersed in the cladding (n_c). The refractive index is calculated using the Sellmeier equation [6]. The fibers have a D-type profile where a metallic layer, with a refractive index ($\tilde{n}_m$) obtained from the Drude model [6], was deposited in the vertical surface. It assumed that the space outside the fiber is filled with the analyte medium to be studied, having a refractive index of n_{ext}. This model allowed to evaluate the impact in the sensing operation of the distance between the core center of the fiber and the gold layer (d - residual cladding), the thickness of the gold layer (d_m), the diameter of the holes (d_{hole}), the separation of the holes (Λ – pitch) [7, 8].

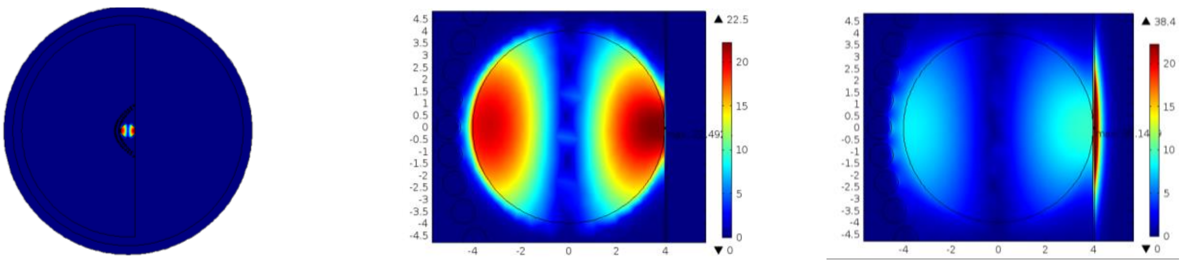


a) b) c)

Figure 1 D-type optical fiber: a) conventional, b) holes in triangular configuration and c) holes in parabolic configuration.

Figure 1 a) shows the configuration of the conventional D-type optical fiber. This configuration is the most studied in the literature [1]. Using COMSOL Multiphysics, the conventional D-type fiber was compared with the two new configurations (figure 1 b) and c)). The conventional D-type fiber is based on a singlemode configuration ($r_{core} = 4$μm and $r_{clad} = 62.5$ μm) where the cut of the fiber is placed at $d = 4$ μm, the index refraction of the core is $n_{core} = 1.450$ and for the cladding is $n_c = 1.442$. The thickness of the metal is $d_m = 65$nm. To determine the optical performance of the two new proposed configurations, the electric field intensity in the external medium is evaluated. The holes in the new configurations have the goal to create an optical mirror that reflects the light into the external medium. In the first new configuration, the cladding holes of the microstructured D-type fiber are placed in a triangular arrangement, while in the second configuration, are placed in a parabolic arrangement (figure 1 b) and c), respectively).

Using equation (5) with the FEM in a defined structure, we can obtain the field equations, which are discretized into an algebraic system of equations and then solved for their characteristic eigenvalues. The eigenvalues are calculated using the "mode analysis" of the COMSOL Multiphysics. Figure 2 a) shows the intensity of the electric field z (E_z) in 2D for the parabolic configuration, without SPR ($\lambda = 300$nm). In figure 2 b), also for the case without SPR ($\lambda = 300$nm), a zoom of the intensity of electric field in the fiber core shows the electric field is concentrated in the core and vanishes quickly in the external medium. In the case of figure 2 c), where SPR occurs ($\lambda = 650$nm), the core zoom shows the maximum of the intensity of electric field occurs in the transition of the metal-dielectric (M/D) and the energy is concentrated on the metal and on the external medium. These results clearly show the physical effect of the SPR in an optical fiber, where at specific resonant wavelengths, dependent on the refractive index of the external medium, the metallic film becomes in practice transparent, as light is tunneled from the core to the exterior, thus increasing dramatically the losses of the fiber.

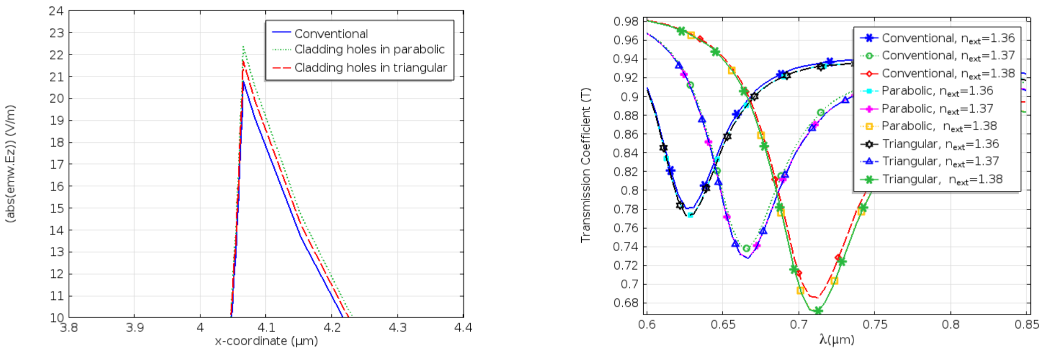


a) b) c)

Figure 2 a) Intensity of the electric field $E_z$in 2D (V/μm) with λ = 300nm, d_m = 65nm and $n_{ext} = 1.37$. b) and c) Zoom of the core of the intensity of the electric field E_z in 2D (V/μm) with: b) λ = 300nm, no SPR present and c) λ = 660nm, with SPR.

3.2 Microstructured D-type fibers: intensity of electric field and transmission coefficient

Figure 3 a) presents the intensity of the electric field z (E_z) in the following zones: core, thin metal layer and external medium in 1D dimension, for each configuration. This figure shows that the maximum of the E_z occurs in the interface M/D and the intensity in the parabolic configuration is stronger in comparison to the other two configurations (triangular and conventional D-type optical fibers).



a) b)

Figure 3 a) Intensity of the electric field E_z in 2D (V/μm) function of the longitudinal fiber x at $\lambda = 660$nm. b) Transmission coefficient T as a function of wavelength and of refractive index of external medium. The microstructured configurations had the following parameters: L = 1mm and d_m = 65nm.

Using equation (7) we can simulate the transmission coefficient in the end of the fiber as function of the wavelength for all configurations, as shown in figure 3 b). In all configurations the wavelength that generates the SPR is the same, since the SPR wavelength depends mainly on the metal type and thickness and on the external medium [7, 8]. The intensity of SPR deep changes for each configuration and the highest deeps are as expected for the parabolic and triangular configurations. Even though the effect is small for the configurations tested, this shows that we can fine tune the intensity of the SPR deep by changing the configuration of the D-type optical fiber.

4. CONCLUSIONS

COMSOL Multiphysics allowed testing two new sensing configurations with higher accuracy and considerable economy of time and resources. The two new microstructured D-type fiber configurations presented higher intensity of the electric field in the external medium and higher SPR intensity deep (parabolic and triangular configuration) when compared with the conventional D-type fiber. These results suggest new fiber configurations that include high refractive index contrast microstructures, such as holes, provide a way of optimizing the performance of SPR sensors based on optical fibers.

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