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Analytical modelization of a fiber optic-based surface plasmon resonance sensor

Issam Haddouche, Lynda Cherbi [*], Mohamed Lamine Ferhat

Laboratory of Instrumentation, Institute of Electronics and Computer Engineering, USTHB University, Bab Ezzouar, Algeria

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ABSTRACT

In this paper, the design of an optical sensor for water analysis based on the Surface Plasmon Resonance (SPR) technique is discussed, the sensor is a metal-coated optical fiber. An analytical model is developed to study the performance of the sensor by carrying out a comparative study between the different materials that the sensor parts are made of, in order to investigate how they affect the sensitivity and resonance visibility of the SPR sensor. The credibility of results is verified using the TMM method. Calculation results of the two methods agree reasonably well with each other, and show that a smaller refractive index contrast between the optical fiber material and the outer medium can remarkably enhance sensitivity, they also reveal that working with metals having lower plasma frequency can as well improve sensor performance. Results also suggest that the visibility of the plasmonic resonance is reduced for wavelength values where light absorption by water is important.

1. Introduction

Surface plasmon resonance (SPR) is a label-free refractive index (RI) sensing technique [1], which has been extensively studied in the last years due to its various qualities. Among all existing RI sensing technologies, SPR is the most widely used, it is characterized by the lowest resolution ever achieved in the order of 10^{-7} refractive index unit (RIU) [1]. Like all label-free techniques, SPR sensing gives the ability to make analyses without having to bind target-analytes to special chemical markers such as fluorophores, this remarkably simplifies sensor setup and shortens sample preparation time [2].

When a surface plasmon (SP) wave propagating in a metal/dielectric interface is excited with an incident light wave, the later loses most of its energy to the SP wave if the two are phase matched at a given wavelength and angle of incidence, this is known as the resonance condition [3]. The wavelength and angle of resonance directly depend on the refractive index of the surrounding medium [4], as illustrated in Fig. 1. It is worth noting that metals are not the only materials supporting SP waves [5,6], graphene based plasmonics is also a new emerging research area that finds use in different applications such as tunable transmission applications [7] or even in fiber optic-based SPR sensing [8].

In the early years of SPR sensing, prisms were used to couple the incident light to the SP wave [9,10], subsequently optical fibers started to replace prisms in many works [11,12], providing a simplified experimental setup [13]. Besides the advantages that all optical sensors provide, optical fibers have even more interesting features to be employed in the field of bio and chemical sensing such as small size, remote sensing, mechanical flexibility, large bandwidth, high voltage insulation and strong light confinement [1,14,15].

In waveguide-based SPR sensing applications, the use of gold or silver coated silica waveguides is very common. When such structures are used for aqueous media analysis, the resonance usually takes place in the visible regime near 600 nm [13,16], at such a low wavelength range the wave-analyte interaction is limited because of the tighter mode confinement [17,18]. In this work we investigate the possibility of enhancing the performance of a waveguide-based SPR sensor for water analysis, by carrying out simulations for different sets of waveguide/metal layer materials. We also study the influence of light absorption by water on the behavior of the sensor in the visible and near infrared regimes.

An analytical model is derived for the estimation of the SPR sensor performance, the proposed model allows a direct characterization of sensitivity with respect to different parameters in the structure, the transfer matrix method (TMM) is used for comparison. By using two different simulation methods to solve the same problem, one can make a comparison between the two so the concluded results should have more credibility [19]. The use of the TMM for the modelization of

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[*] Corresponding author.
E-mail addresses: ihaddouche@usthb.dz (I. Haddouche), cherbi_lynda@hotmail.com (L. Cherbi), ferhat.mlamine@gmail.com (M.L. Ferhat).

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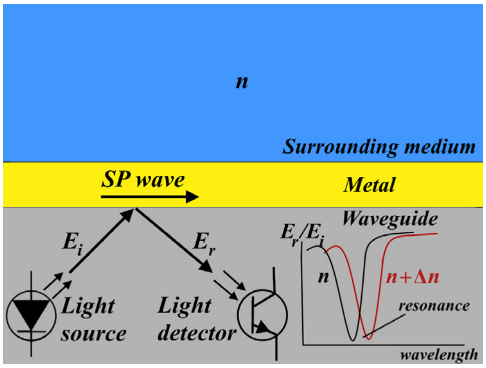

Fig. 1. The working principle of the surface plasmon resonance phenomenon, E_i and E_r are the incident and reflected beams. The incident wave loses part of its energy to the SP wave, the wavelength at which reflection is minimum, is called wavelength of resonance, and its value varies with the refractive index of the surrounding medium.

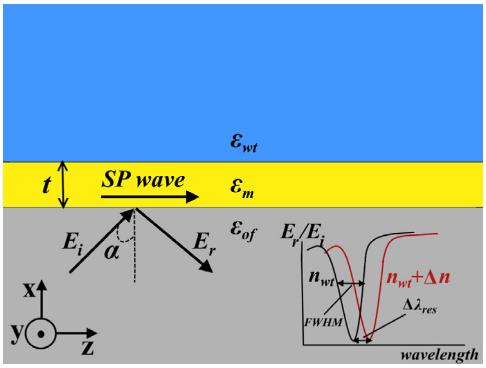

Fig. 2. Basic structure of an optical fiber based SPR sensor. ε_{of}, ε_m and ε_{wt} are dielectric constants of the fiber material, metal and water respectively, E_i and E_r are the incident and reflected beams, t is the thickness of the metal layer and α is the angle of incidence of the guided mode.

surface plasmon waveguides has already been demonstrated [20,21], it was employed in many works to predict SPR sensors responses where TMM simulation results were in good agreement with experimental results [13,22]. In reference [20] the full-vector finite element method (FV-FEM) was used to predict SP waves evolution with respect to wavelength and metal thickness in a gold coated photonic crystal fiber structure, the TMM was used as well for comparison, simulation results of the two methods were in good agreement, with the TMM exhibiting a very short calculation time (few seconds) compared to the FV-FEM (>30 min).

2. Simulation

The sensor's basic structure consists of three layers, the lower layer is the waveguide material, the metal in the middle, and the top layer is the external medium which is water in this case. The waveguide is supposed to be a one material optical fiber, e.g. tapered fiber, the external medium and the fiber geometry parameters are supposed to be large enough compared to the metal layer thickness (few tens of nanometers) that they can be considered as semi-infinite media [20]. The structure layers have dielectric constants of ε_{of}, ε_m and ε_{wt} for the optical fiber material, metal layer and water respectively as illustrated in Fig. 2.

The sensitivity of an SPR-based sensor is generally defined by the shift of the wavelength of resonance (λ_{res}) with respect to refractive index perturbation in the sensed medium (wavelength interrogation) [1].

$$S = \frac{d\lambda_{res}}{dn_{wt}}, \tag{1}$$

n_{wt} ($= \sqrt{\varepsilon_{wt}}$) is the refractive index of water.

The visibility of the resonance is also important, it is estimated by the *FWHM* of the resonance dip, as shown in Fig. 2. The sharper resonance is, the more accurate the determination of λ_{res} will be.

In order to evaluate the performance of the SPR sensor in a more proper way, we define the figure of merit (*FOM*) [1]:

$$FOM = S/FWHM. \tag{2}$$

So a high performing SPR sensor should have a low *FHWM* value with high sensitivity.

2.1. Analytical model

In order to have a better knowledge on our SPR sensor, it is advantageous to develop a model that allows us to determine the influence of the structure parameters on the sensing operation in a direct way.

We start by introducing the effective indices of the SP mode propagating in the metal/water interface and the guided mode propagating in the optical fiber, estimated by Eqs. (3) and (4) respectively [3,13]:

$$n_{sp} = \sqrt{\frac{\varepsilon_{wt}\varepsilon_m}{\varepsilon_{wt} + \varepsilon_m}}, \tag{3}$$

$$n_g = n_{of} \sin\alpha, \tag{4}$$

n_{of} ($= \sqrt{\varepsilon_{of}}$) is the refractive index of the optical fiber material and α is the angle of incidence of the guided mode.

We approximate the dielectric function of the metal, ε_m, by Drude model for free carriers [1,23]:

$$\varepsilon_m = 1 - \frac{\omega_p^2}{\omega^2 + i\Gamma\omega}, \tag{5}$$

where ω is the angular frequency, Γ is the electron relaxation rate given by $\Gamma = 1/\tau$, τ is the electron relaxation time and ω_p is the plasma frequency given by [24]:

$$\omega_p^2 = \frac{Ne^2}{\varepsilon_0 m}, \tag{6}$$

N, e and m are electron density, charge and mass respectively, ε_0 is the permittivity of free space.

At resonance, we have $\omega = \omega_{res}$ (ω_{res} is the frequency of resonance), the two waves are phase-matched i.e. $n_{sp} = n_g$:

$$\sqrt{\frac{\varepsilon_{wt}\varepsilon_m}{\varepsilon_{wt} + \varepsilon_m}} = n_{of} \sin\alpha, \tag{7}$$

we replace ε_m by its value from Eq. (5) and ω by ω_{res} in Eq. (7) to derive Eq. (8):

$$\omega_{res}^2 + i\Gamma\omega_{res} - \omega_p^2 \frac{\varepsilon_{wt} - \left(n_{of}\sin\alpha\right)^2}{\varepsilon_{wt} - \left(n_{of}\sin\alpha\right)^2\left(1 + \varepsilon_{wt}\right)} = 0, \tag{8}$$

Eq. (8) has the following solution:

$$\omega_{res} = \frac{1}{2}\sqrt{-\Gamma^2 + 4\omega_p^2 \frac{n_{wt}^2 - \left(n_{of}\sin\alpha\right)^2}{n_{wt}^2 - \left(n_{of}\sin\alpha\right)^2\left(1 + n_{wt}^2\right)}} - i\Gamma/2. \tag{9}$$

From Eqs. (1) and (9), we derive the sensitivity formula:

$$S_{AM} = \frac{d\lambda_{res}}{dn_{wt}} = -\frac{\lambda_{res}^2}{2\pi c}\frac{d\omega_{res}}{dn_{wt}}, \tag{10}$$

$\lambda_{res} = 2\pi c/\omega_{res}$ and c is light velocity.

We find:

$$S_{AM} = \frac{A^2\left(\omega_p\lambda_{res}\right)^2 n_{wt}}{\pi c\left(n_{wt}^2 - AB\right)^2\sqrt{-\Gamma^2 + 4\omega_p^2\frac{n_{wt}^2 - A}{n_{wt}^2 - AB}}}, \tag{11}$$

with $A = n_g^2$ (Eq. (4)) and $B = \left(1 + n_{wt}^2\right)$.