On the sensitivity of optical fiber surface plasmon resonance based sensor for detection of dielectric analytes using COMSOL Multiphysics

Armin Agharazy Dormeny, Parsoua
Abedini Sohi, Mojtaba Kahrizi
Department of Electrical and Computer
Engineering
Concordia University
Montreal, Canada
a_aghar@encs.concordia.ca

***Abstract*— Due to the importance of the public health toward the exposure to hazardous gases, real-time and sensitive gas sensors are among the priorities at present. Among different types of gas sensors, optical sensors with advantages like high sensitivity, low cost, miniaturization, and online monitoring have received great attention between the researchers. In this article, a fiber optic sensor based on surface plasmon resonance (SPR) of gold thin film is simulated by COMSOL Multiphysics. For this purpose, a single-mode optical fiber was considered to be uncladed on its middle part and coated with a thin film of gold and the sensitivity and resonance condition of the device was investigated as a function of thickness of the metal.**

Keywords—Optical Fiber, Surface Plasmon, Sensor, Gold, COMSOL Multiphysics

I. Introduction

Surface Plasmon Resonance is the oscillations of surface charges excited by p-polarized (transverse magnetic) wave at the metal-dielectric interface. These oscillations propagate along the metal-dielectric interface, therefore; it is called surface plasma oscillations. By solving Maxwell equations it is found that these oscillations are supported at the interface between the materials with positive dielectric constant and the materials with negative dielectric constants such as gold (Au), Silver (Ag) and aluminum (Al) [1,2].

To excite surface plasmon, the wave vector of the electric field at the surface (k_x) should be along the direction of wave vector of the surface plasmon (k_{sp}). In the other word, at resonance condition, the frequency of the incident light matches the frequency of the oscillations of the electrons at the metal surface [3,4]. The resonance condition depends not only on the refractive index of the material being analyzed, but also on the shape (thin film, nanoparticle, nanowire, and etc.) and thickness of the metal, and temperature of the experiment [5]. The wave vector of light traveling in medium n_1 with incident angle of θ and wavelength of λ, could be tuned by varying the value of θ or λ as

$$k_x = \frac{2\pi}{\lambda}(n_1)(\sin\theta) \quad (1)$$

The wave vector of the plasmon depends on the refractive index of the metal (n_{metal}) and the testing medium (n_2)

$$k_{sp} = \frac{2\pi}{\lambda}\frac{(n_{metal}\times n_2)}{(n_{metal}^2+n_2^2)^{1/2}} \quad (2)$$

Hence for a given angle of incident, SPR could be seen as a reduced intensity of the light at a specific wavelength [6].

In this work, SPR-based optical fiber sensor is proposed and simulated via COMSOL Multiphysics (optics module). The obtained results indicate the importance of optimum thickness of the metallic layer for detecting small changes in refractive index of the sensing media.

II. Model Setup

Figure 1 shows the geometry of the designed model. The Model has constructed in 2D environment of COMSOL 5.3a and shows the cross section of a single mode fiber. It consists of a silica glass core (n = 1.45), Au thin film, and sensing material which is on the unclad region of the fiber. In order to efficiently achieve accurate results, free triangular has been chosen as the mesh style for the entire geometry. To avoid memory loss and after investigating the dependency of simulations on meshing size, maximum element size of 10nm and minimum of 2nm were chosen for the entire geometry.

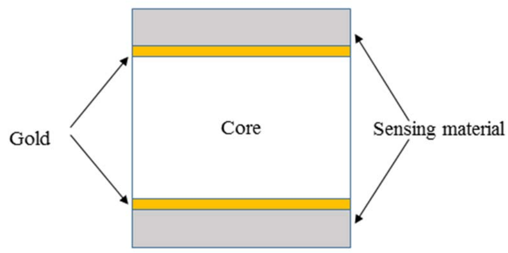


Fig. 1. Geometry of the designed model

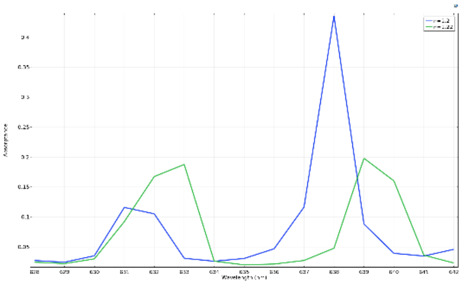
III. Results and Discussion

One of the main challenging parts of producing SPR-based sensors is finding the appropriate film thickness for the metal. The most important issue with the thickness of the metal is the ability of the sensor to differentiate between the changes in the refractive index of its environment. To investigate the sensitivity of the SPR-based optical fiber sensor, two imaginary materials with refractive indexes of 1.2 and 1.22 were considered and three different thicknesses were investigated for the gold thin film.

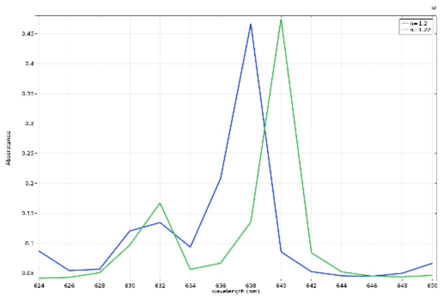
In order to investigate the effect of thickness of the gold on the sensitivity of the device, three thicknesses of 5nm, 10nm and 20nm were selected and simulated to see if there is any changes in the resulting spectrum of the sensor.

Figure 2 shows the effect of metallic film thickness on the sensitivity and absorbance of the device. At resonance condition the plasmon wave is generated due to the absorbance of photon energy by metal layer. Consequently, the intensity of light reduces significantly at resonance response curves. At the resonance wavelength, there is an increase in propagation loss that results in a sharp peak in the absorbance curve (or a sharp dip in the intensity curve) with respect to wavelength. This dip is due to a strong reduction of the reflected light from the metal-dielectric interface and it is strongly dependent on the refractive index (RI) of the analyte [8]. When the thickness is 5nm, although the sensor

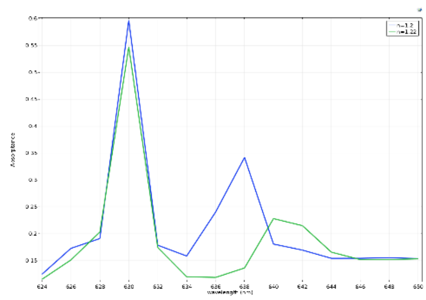
has good sensitivity to the changes in the refractive index, but the amount of absorption is not high enough due to the confinement effects in the thin film and lack of enough electron oscillations. Increasing the thickness to 10nm has resulted in proper sensitivity as well as high amount of absorption. However, as the thickness was increased to 20nm, both curves were resulted in nearly same peaks which indicates the reduction in the sensitivity of the device. When the metal layer is too thick, since the evanescent field cannot reach the other side of the film and the sensor is become insensitive to the changes of the refractive index of its surrounded media.



(a)



(b)



(c)

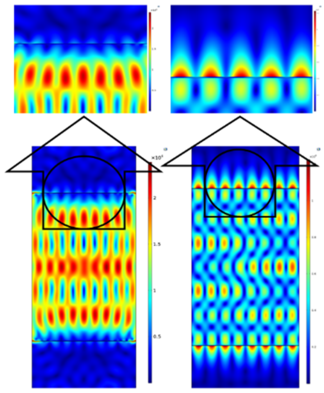
Fig. 2. Surface plasmon resonance absorbance curves for the simulated sensor with different metallic thicknesses. (a) d= 5nm,(b) d= 10nm, (c) d= 20nm. Refractive indexes are 1.2 (blue line) and 1.22 (green line).

Table 1 indicates the positions of the peaks and maximum absorbance value in the absorbance curves with different gold thicknesses. As it has been observed, selecting inappropriate thickness of the gold layer not only reduces the sensitivity of the sensor, but also changes the position of the resonance greatly which induces inaccuracy on the calibrating the device. Since thickness of 10nm had the best results in terms of sensitivity and absorbance value, the simulations were performed again with refractive index of 1.25 for this model and its results are represented in table 1.

TABLE I. POSITION OF PEAKS AND ABSORBANCE MAXIMUM VALUES IN DIFFERENT THICKNESSES. T STANDS FOR THE THICKNESS OF GOLD, P STANDS FOR POSITION OF THE PEAK (IN NANOMETER) AND A STANDS FOR ABSORBANCE VALUE.

T	RI= 1.2		RI= 1.22		RI= 1.25	
	P	*A*	*P*	*A*	*P*	*A*
5nm	638	0.436	639	0.198	-	-
10nm	638	0.467	640	0.476	643.5	0.449
20nm	630	0.597	630	0.546	-	-

Figure 3.a and 3.b shows the electric field of the light inside the sensor with gold thickness of 10nm at non-resonance (lambda= 588nm), which has nearly zero absorption, and resonance (lambda= 638nm) conditions respectively. As it is shown in figure 3.b, at resonance condition, the light is absorbed at the boundary of gold intensively.



(a) (b)

Fig. 3. Electric field of the light at the (a) non-resonance condition and (b) resonance condition. Insets show the magnified picture of the electric field at the boundary of gold.

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