Sensors and Actuators B 211 (2015) 456–461

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Optical waveguide biosensor based on modal interference between surface plasmon modes

Manoj Kumar [a,*], Arun Kumar [a], Saurabh Mani Tripathi [b]

[a] Department of Physics, Indian Institute of Technology Delhi, New Delhi 110016, India
[b] Department of Physics, Indian Institute of Technology Kanpur, Uttar Pradesh 208016, India

ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form 21 January 2015
Accepted 22 January 2015
Available online 31 January 2015

Keywords:
Surface plasmons
Waveguide sensors
Interaction length
Coupling length

ABSTRACT

A detailed theoretical study on an optical waveguide biosensor utilizing the modal interference between surface plasmon modes is presented. It is examined that the interaction length i.e. longitudinal dimension of the metallic layer plays a very crucial role in determining the transmission characteristics of such sensors. And as expected, to get a dip in the transmission spectrum around a desired wavelength, the interaction length should be nearly an odd integer multiple of the coupling length corresponding to the surface plasmon modes. It is found that the minimum possible length (equal to one coupling length) of the sensor may not always give the highest figure of merit. Knowing this, we then show that the sensitivity of such a sensor can be further enhanced by optimizing the thicknesses of metal and intermediate layers.

1. Introduction

Surface plasmon resonance (SPR) based sensors are continuously attracting great interest because of the numerous advantages they offer, such as small size, high sensitivity, multichannel sensing capabilities etc. [1–5]. Amongst these, optical waveguide based SPR sensors have extra advantage of their possible integration with other optical components on a single chip [6,7]. These sensors primarily rely on coupling of power between the waveguide and surface plasmon modes. Generally, the sensing region of optical waveguide SPR sensors supports two surface plasmon modes. One of them, having its real part of effective index comparable to the waveguide mode, is the so called long range surface plasmon (LRSP) mode while another one having very high real part of effective index as well as high loss in comparison of LRSP mode is known as short-range surface plasmon (SRSP) mode [8]. In such sensors, mainly the LRSP mode contributes to the output power and a dip in the transmission spectrum is observed at a wavelength for which the real part of effective indices of the wave-guide mode and LRSP mode are closest. The position of the wavelength dip in such sensors is not affected by the length of the metal layer [4,9]. To maximize the sensitivity of such sensors, research studies have been mainly focused on the choice of metal, optimization of metal thickness and introduction of a high refractive index intermediate layer etc. For example, Fontana [10] has reported the optimum thicknesses of gold, copper, silver, and aluminium metal films to maximize sensitivity of such sensors. Combination of different metals has also been reported to enhance the sensitivity [11,12]. Nenninger et al. [13] have shown that by introducing an intermediate buffer layer of Teflon, the sensitivity can be increased by about 7 times than that of conventional SPR sensors. In Ref. [14] Lahav et al. have demonstrated that the sensitivity can even be improved up to 1 order of magnitude by introducing a thin, high refractive index layer of silicon in between cover dielectric layer and metal layer. All of these studies focus mainly on optimizing the transverse dimensions with the basic idea being to enhance the evanescent field near the top layer-analyte interface to enhance the sensitivity. Spectral tuning of such sensors can be achieved by selecting the intermediate dielectric layer appropriately. Weiss et al. [15] have reported that the resonance wavelength of SPR sensor can be changed from 545 nm to 700 nm by introducing an intermediate layer (TiO_2) of thickness 80 nm. Ctyroky et al. [16] have reported that a thin layer of Ta_2O_5 (10–40 nm) can tune the resonance wavelength in the range 600–900 nm.

In some SPR sensor designs, more than one LRSP modes may be involved. For example, in the SPR sensor proposed by Nesterov et al. and Čtyroký et al. [17,18], two LRSP modes and one SRSP mode are excited. In such designs, the transmission spectrum is mainly the result of interference between two LRSP modes and will be highly dependent on interaction length of the sensor. Nesterov and co-workers [17] have made a detailed study of such sensors

* Corresponding author. Tel.: +91 1126596579.
E-mail addresses: epmanoj888@gmail.com (M. Kumar), akumar@physics.iitd.ac.in (A. Kumar), smt@iitk.ac.in (S.M. Tripathi).

http://dx.doi.org/10.1016/j.snb.2015.01.088
0925-4005/

and proposed extremely short length SPR devices by selecting the metallic layer's length equal to one coupling length corresponding to the two LRSP modes excited in the SPR region. They anticipated that this should also give the best sensing performance (in terms of sensitivity and detection accuracy) for SPR sensors. This, however, requires a detailed investigation.

In this paper we examine the effect of the metallic layer's length on the sensing characteristics of a planar optical waveguide SPR biosensor based on Otto configuration involving more than one LRSP modes. As expected, it is observed that in order to get a dip in the transmission spectrum around a desired wavelength, the interaction length (L) between the waveguide and the metal layer should be nearly an odd integer multiple of the coupling length (L_c) corresponding to LRSP modes. However, our calculations on the figure of merit (FOM) corresponding to various possible interaction lengths show that the minimum possible interaction length ($L = L_c$) may not necessarily give the highest FOM for such a biosensor. In the following we also examine the effect of thicknesses of metal and intermediate layers on the sensing performance of such a sensor.

2. Analysis

We consider a SPR based planar optical waveguide sensor (Fig. 1) consisting of two identical, input (I) and output (III) waveguide sections with a SPR multilayer section (II) of length L in between them. The SPR section consists of an intermediate layer of higher refractive index (thickness, t_i) between the core (thickness, t_{co}) and metal layer (thickness, t_m), above which lies the sensing medium. Input and output waveguide sections are selected such that they support only one guided TE and one TM polarized mode. Light coupled to the TM mode of section (I) excites the surface plasmon (SP) modes of section (II), which after interacting with the sensing medium over a length L, couple energy to the TM mode supported by the output section (III), and is detected.

The guided modes supported by each waveguide section can be obtained by solving the TM vector wave equation given by [19]:

$$\frac{d}{dx}\left(\frac{1}{n^2}\frac{dH_y}{dx}\right) + k_0^2\left(1 - \frac{\tilde{\beta}^2}{n^2}\right)H_y = 0 \quad (1)$$

where k_0, n, and $\tilde{\beta} = \beta/k_0$ represent the free space wave vector, transverse refractive index distribution of the waveguide section, and the effective index of the mode, respectively. The direction of propagation is taken along z axis and the (z, t) dependence of the fields is taken as $\exp\{i(\beta z - \omega t)\}$. The solutions of Eq. (1) in sections (I) and (III) are well known [19] while for section (II) are obtained as discussed below. In each layer of the SPR multilayer section (II), solutions are of the form

$$H_y = A_k \exp(\gamma_k x) + B_k \exp(-\gamma_k x) \quad (2)$$

here, A_k and B_k are field coefficients in the kth layer, and $\gamma_k = k_0\sqrt{\tilde{\beta}^2 - n_k^2}$; n_k representing the refractive index of the kth layer.

The effective indices of guided modes $\tilde{\beta}$ are obtained by employing the continuity of H_y and $(1/n^2)dH_y/dx$ at every dielectric discontinuity which in the kth layer, can be written in the matrix form as:

$$\begin{bmatrix} H_y \\ \dfrac{1}{n^2}\dfrac{dH_y}{dx} \end{bmatrix} = M_k \begin{bmatrix} A_k \\ B_k \end{bmatrix} \quad (3)$$

with the matrix M_k given by,

$$M_k = \begin{bmatrix} \exp(\gamma_k x) & \exp(-\gamma_k x) \\ \dfrac{\gamma_k}{n_k^2}\exp(\gamma_k x) & -\dfrac{\gamma_k}{n_k^2}\exp(-\gamma_k x) \end{bmatrix} \quad (4)$$

Satisfying the above mentioned continuity condition at the junction of the two neighbouring layers l and k, the field coefficients are connected as:

$$M_l \begin{bmatrix} A_l \\ B_l \end{bmatrix} = M_k \begin{bmatrix} A_k \\ B_k \end{bmatrix} \quad (5)$$

where M_l and M_k are evaluated at the junction. Thus, field coefficients in the first and last layer are connected by:

$$\begin{bmatrix} A_1 \\ B_1 \end{bmatrix} = M \begin{bmatrix} A_5 \\ B_5 \end{bmatrix} \quad (6)$$

where, M is given by

$$M = (M_1^{-1}M_2)_{x=0}(M_2^{-1}M_3)_{x=t_{co}}(M_3^{-1}M_4)_{x=t_{co}+t_i}(M_4^{-1}M_5)_{x=t_{co}+t_i+t_m} \quad (7)$$

Now, since for physically acceptable solutions, the fields should be zero at $x = \pm\infty$, that requires the field coefficients B_1 and A_5 in the first and the last layer, respectively, must be zero. Using this condition, Eq. (6) gives us the eigenvalue equation as:

$$M_{22} = 0 \quad (8)$$

We solved the above equation for complex roots ($\tilde{\beta}_m$), using an accurate and fast converging method recently developed by us [20]. Finally the transmission spectrum of the sensor is obtained by calculating the output power P_o in waveguide section (III) using the following equation,

$$P_o = P_{in}\left|\sum_{m=0}^{2} a_m b_m \exp(ik_0\tilde{\beta}_m L)\right|^2 \quad (9)$$

where a_m (b_m) are the fractional modal coupling coefficients between the TM_0 mode of the waveguide in section-I (section-III) and the TM_m mode supported in section-II of the sensor, given by

$$a_m = \frac{\int E_{xm}^{II} H_y^{I} dx}{\sqrt{\int E_{xm}^{II} H_{ym}^{II} dx}\sqrt{\int E_x^{I} H_y^{I} dx}}, \quad b_m = \frac{\int E_x^{III} H_{ym}^{II} dx}{\sqrt{\int E_x^{III} H_y^{III} dx}\sqrt{\int E_{xm}^{II} H_{ym}^{II} dx}}.$$

Fractional power coupled from section I to various modes of section II at $z = 0$, can thus be calculated by $|a_m|^2$. In Eq. (9) H_y^j and E_x^j represent the magnetic and electric field component, respectively, in the jth section of the waveguide sensor and in each section H_y and E_x are related as:

$$E_x(x) = \frac{\tilde{\beta}}{c\varepsilon_0 n^2(x)} H_y(x) \quad (10)$$

Having obtained the transmission spectrum of the sensor structure (using Eq. (9)) its refractive index sensitivity defined as the spectral shift of a transmission dip per unit change in the refractive index of the sensing medium can be calculated.

3. Results and discussion

In our calculations, thicknesses of the core region (3.1 mol% GeO_2 doped silica), intermediate layer (19.3 mol% GeO_2 doped silica) and that of the metallic (gold) layer are taken as $t_{co} = 5\ \mu m$, $t_i = 2.5\ \mu m$ and $t_m = 30$ nm, respectively. The wavelength dependent refractive indices of various dielectric regions are calculated by using Sellmeier relation [21] and the refractive index of gold is modelled by using the experimental data from Johnson and Christy [22]. Keeping in bio-sensing applications in view, the refractive index of sensing layer is considered to be 1.33 [23]. For such a configuration the SPR section is found to support three guided TM polarized surface plasmon (SP) modes [17,18], and using the procedure as