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Design and optimisation of integrated hybrid surface plasmon biosensor

T. Gorman [a], S. Haxha [b,*]

[a] University of Greenwich, Department of Engineering Systems, Medway Campus, Chatham Maritime, Chatham ME4 4TB, United Kingdom
[b] University of Bedfordshire, Computer Science and Technology Department, University Square, Luton LU1 3JU, United Kingdom

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ABSTRACT

In this paper we present a novel idea for an integrated surface plasmon biosensor. The proposed hybrid sensor aims to couple the high sensitivity of the well known Kretchmann prism excitation design with the more robust integrated waveguide design. The sensor is modelled and simulated using a 2D Finite Element Method (FEM) in order to establish the devices sensitivity, resolution and signal-to-noise-ratio.
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1. Introduction

The surface plasmon resonance (SPR) technique for bio-sensing applications has experienced a resurgence of interest over the last decade or so mainly due to advanced manufacturing techniques capable of producing the required nano-scale components and interconnects. The attraction of the SPR sensors is primarily due to their high sensitivity and reliability in a relatively simple and compact sensing element. Surface plasmon resonance (SPR) sensors provide high sensitivity without the use of molecular labels [1]. Biosensors have found widespread application in the analysis of biomolecular interactions and detection of chemical and biological analytes [2,3], where they provide benefits of real-time, sensitive and label-free technology. SPR biosensors have been used for detection of various chemical and biological compounds in areas such as environmental protection [2,4], food safety [5,6] and medical diagnostics [7–11].

For these particular reasons these new sensing devices are now becoming commonplace in many medical and military applications. A number of methods have been proposed for the excitation of SPR in an integrated device; however all rely on the key requirement of matching the incident wave vector to the surface plasmon wave vector. This can be achieved by using a prism coupler or, as is the case for integrated waveguide devices, by using materials that in combination closely match the SPR effective index condition [12]. However the addition of 'tuning materials' in order to match the resonant condition in the desired aqueous environment inevitably results in reduced sensitivity. The Kretchmann excitation technique makes use of a prism in order to excite SPR. Using this method tuning layers are no longer required as wave vector matching is achieved by adjusting the angle of incidence of the incoming wave [13].

The motivation behind this paper is to develop an integrated Kretchmann type device that offers the convenience and robustness of a waveguide sensor with the high sensitivity of a prism based device.

2. Theory

Our proposed integrated optical biosensor is presented in Fig. 1. The device consists of a central hemispherical prism coupled to input and output waveguides. A thin gold layer extends across the surface of the device, and its upper surface is in contact with the analyte under examination.

In order to interrogate the analyte, TM polarised light at wavelength 550–850 nm is coupled to the input waveguide and the power reflected from the gold surface towards the output port is detected. At a certain angle of incidence and at a particular wavelength much of the input power will be absorbed as SPR is achieved. The wavelength of excitation is highly dependent upon the analyte in contact with the gold surface. When the analyte changes the SPR condition also changes in sympathy. In order to optimise the device for the desired aqueous environment and operating wavelength the waveguide arms of the sensor are

* Corresponding author.
E-mail address: shyqyri.haxha@beds.ac.uk (S. Haxha).

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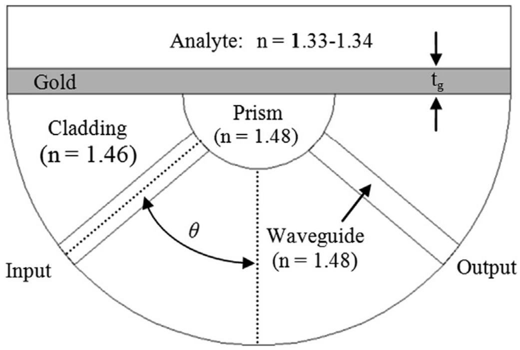

Fig. 1. Integrated hybrid biosensor.

rotated, during simulation, about the central prism. In the final fabricated design the arms are then fixed at this position.

Excitation of surface plasmons at the interface between a metal and dielectric requires a number of conditions to be fulfilled. Of prime importance is the real component of the complex permittivity of the metal at the wavelength of operation. Surface plasmons can be excited only when the permittivities of the metal and dielectric are of opposite sign. This requirement means that either one must have a negative permittivity, a condition that can be readily achieved by certain noble metals across a particular range of wavelengths. Gold and silver are the most commonly used metals, though gold is preferred due to its resistance to oxidisation and chemical attack. SPR can also only be achieved if the x-component (x–y plane) of the incident wave vector (k_x) matches the wave vector of the surface plasmon wave (k_{sp}), where the wave vector of the incident wave is given by [14]

$$k_x = k_o\sqrt{\varepsilon_p}\ \sin\theta \tag{1}$$

$k_o=2\pi/\lambda$, ε_p is the permittivity of the prism, θ is the angle of incidence of the incoming wave and

$$k_{sp} = k_o n_{eff} \tag{2}$$

is the wave vector of the surface plasmon wave. The effective index of the surface plasmon wave (n_{eff}) can be determined by modal analysis of the analyte/metal/prism interface. From Eq. (1) it is clear that by adjusting the angle of incidence of the incoming wave, k_x can be made equal to k_{sp}. A final requirement for SPR is that the incoming wave must be TM or p-polarised.

In order to monitor the amount of SPR activity with respect to the analyte under examination a number of methods have been proposed. Intensity interrogation is perhaps the simplest technique and involves a fixed input wavelength whose reflected intensity varies according to the interaction between the surface plasmon wave and the analyte. However this method has not been generally accepted within the sensing fraternity due to its susceptibility to surrounding conditions [14]. Wavelength or spectral interrogation is a more robust technique of analysis involving, as the name implies, a range of wavelengths in order to ascertain the nature of the analyte under examination. For this reason we have selected using wavelength interrogation throughout our simulations.

The performance of SPR sensors can be characterised by three main parameters: sensitivity, resolution and signal to noise ratio. Sensitivity can be measured by how much the resonant wavelength shifts with respect to a change in analyte and can be defined as [10]

$$Sn = \frac{\delta\lambda_{res}}{\delta n_{ana}} \tag{3}$$

where the units for Sn are nm per refractive index unit (RIU).

The resolution of the sensor can be determined by

$$Sn^{-1} \times \delta\lambda_a \tag{4}$$

where $\delta\lambda_a$ is the sensitivity of the device used to measure the shift in resonant wavelength of the sensor (typically 0.01 nm).

The signal to noise ratio (SNR) of the SPR sensor with wavelength interrogation can be calculated as the shift in the resonant wavelength divided by the width of the resonant curve at half-minimum reflected power or

$$SNR = \frac{\delta\lambda_{res}}{\delta\lambda_w} \tag{5}$$

For our simulations we have accounted for the dispersion of the gold film using data from Ref. [15] which has been shown by previous research to be more accurate than the more usual Drude model particularly when very thin metal films are involved as is the case with this type of sensor.

3. Results

For the purpose of our simulations the devices topographical parameters are as follows: the thickness of the gold film t_g= 40–50 nm, the radius of the prism r_p=6 μm, the diameter of the waveguides d_w=2 μm for single mode operation across the wavelength of operation and the refractive indices of the core, cladding and analyte are as presented in Fig. 1. The proposed structure can be fabricated from commercially available optical polymers.

In order to characterise the device we first need to obtain the required waveguide angle for optimum SPR absorption. This is achieved by using Eqs. (1) and (2). The effective index of the analyte/metal/prism interface is determined by modal analysis and was confirmed to be around 1.44 at λ=650 nm. This gives a propagation constant of 13.92×10^6. In order to excite SPR, the x-component of the incident wave vector must be made equal to this value. With $\sqrt{\varepsilon_p}$=1.48 this implies that the angle of incidence must be made equal to around 77°. Fig. 2 presents the response of the device as the angle of the waveguide is increased from 76° to 79°, with the analyte refractive index equal to 1.33. Clearly, as predicted from the theory, the greatest dip corresponding to the largest SPR activity is located at 78°.

It is also evident that the width of the dip is much narrower at this angle implying a better SNR. The arms of the sensor are fixed in the optimum position for maximum SPR absorption in the aqueous region and at the desired wavelength range. We next investigate

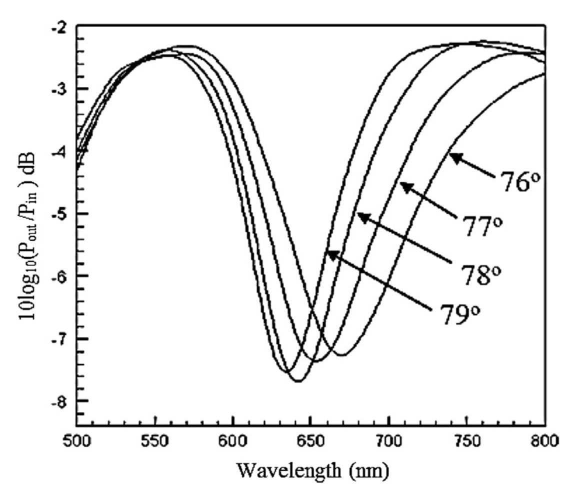

Fig. 2. Response of the sensor as the waveguide arms are rotated from 76 to 79°. The analyte in this case is fixed at n = 1.33 and the gold film is 48 nm thick.

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