Plasmonic Waveguide Based Optical Ring Resonator For Bio-sensing Application

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***Abstract*—The main aim of this work is to design and analyze a highly sensitive and miniaturized plasmonic ring resonator biosensor. Enhancement in field confinement due to plasmonic effect results in a considerable field confinement at the interface between metal (gold) and dielectric i.e. in the slot region. Hence, for this structure an average index sensitivity of 860 nm/RIU has been observed. Finite Element Method has been used for designing and performance analysis, investigated for the biological refractive index window of 1.34-1.35.**

***Keywords*—photonic bio-sensing ; ring resonator; silicon-on-insulator; surface plasmon resonance.**

I. INTRODUCTION

The contribution of Surface Plasmon Resonance (SPR) technology in the field of photonic bio-sensing is tremendously appreciable. The modern research interest in the field of bio-sensing requires a highly efficient technique, which can provide an escalated interaction with the analyte. This requirement can be fulfilled by the means of SPR [1]. SPR is basically defined as an oscillation of Surface Plasmon Polaritons (SPPs) or travelling charge density electromagnetic waves at the interface between a conductive and dielectric media [2]. SPR based bio-sensors offer extreme sensitivity towards the refractive index of the cladding material in the proximity of the surface of the conducting material [3]. Due to this advantageous fact, a lot of research investigations have been carried out on label-free bio-sensing using this technique. For instance, a Photonic Crystal Fiber (PCF) based SPR biosensor with a higher sensitivity has been reported and it has been noticed that the device could detect higher refractive index contrast of the analyte [4]. Afterwards, a research has been performed on a plasmonic biosensor using a PCF structure consisting of a supremely conductive material graphene which resulted in an extremely high sensitivity of 7.8 μm/RIU [5]. On the other hand, plasmonic waveguide structures have been introduced to SPR bio-sensing application incorporating the advantage of stable and robust structure. Such as; an optical ring resonator based hybrid plasmonic biosensor with a sensitivity of 687.5 nm/RIU has been experimentally reported [6].

The present work aims towards a highly sensitive and miniaturized plasmonic ring resonator based bio-sensor which is potentially efficient. The structure has been optimized thoroughly in order to enhance the field confinement in the cladding region using FEM analysis so that, an immensely improved sensing could be guaranteed. The considered range of the operating wavelength to analyze the index sensitivity of this device is 1500 nm-1600 nm. For the excitation of SPPs waveguide coupling method is being used [7].

II. DESIGN AND METHEDOLOGY

As far as the proposed structure is concerned, it is a Silicon-On-Insulator (SOI) ring resonator configuration incorporated with a metal (gold) ring in the outer radius of the ring as shown in fig. 1. All the dimensions taken for the device are optimized through modal analysis parametric optimization technique. The straight waveguide is a ridge waveguide, 400 nm wide, made up of *Si* (n_{si} = 3.477) material. The ring portion consists of a *Si* ridge waveguide having a width of 200 nm and a gold (n_{Au}=0.55+11.5i) ring of a width of 20 nm placed in the outer ring part after leaving a gap of 60 nm in between. The reason behind choosing gold (*Au*) as a conducting material for this biosensor due to the advantage of being bio-compatible as well as it does not oxidize. The ring

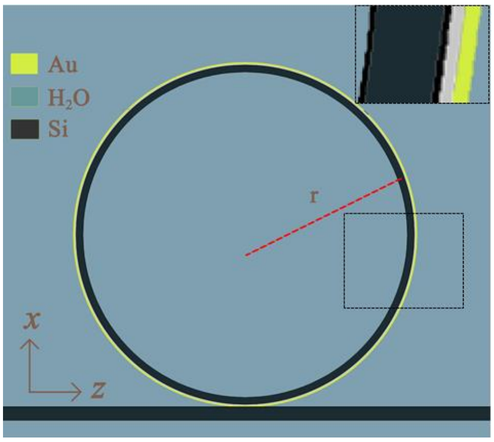

Fig. 1. Schematic of the plasmonic ring resonator biosensor.

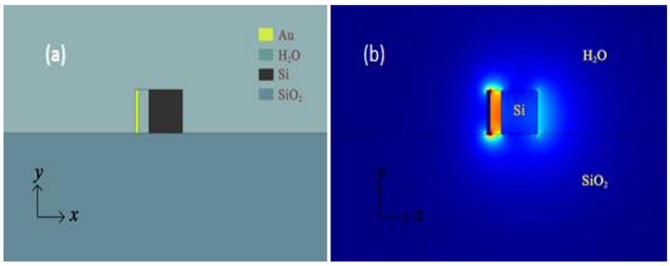

Fig. 2. Optimized plasmonic waveguide; (a) Cross-sectional view; (b) Normalized E-field.

radius *'r'* is the distance from the center of the ring to the center of the *Si* ridge which is 5 µm. The cladding material is considered as water (n_c = 1.33+1.2E-4i) [7], which is moreover preferred for bio-sensing. The substrate taken here is SiO_2 (n_{SiO2} = 1.444). All the mentioned refractive indices values are considered for 1550nm wavelength. The cross-sectional view of the structure considered during modal analysis is shown in fig. 2(a). The height of the waveguides considered here is 220 nm. Figure 2(b) shows the normalized field confinement for the optimized dimensions and it can be noticed that for these dimensions, the maximum confinement was observed is in the slot region. So, the probability of interaction of the electric field with the analyte has been maximized.

For the excitation of surface plasmons on a dielectric-metal interface to take place, their permittivities should be of opposite signs [8]. In order to satisfy this condition we have taken Gold and *Si* materials. The excitation of resonant surface plasmon waves can only occur through incidence internally reflected of *p*-polarized light [9]. One of the main advantages of using SPR in bio-sensing is it results in enhanced electric field confinement at the interface [11]. It helps in increasing the interaction of incident light to the analyte which further improves the sensitivity to a great extent.

III. RESULTS AND DISCUSSION

In order to verify the sensing capability of this refractive index biosensor, a wavelength range 1500 – 1600 nm has been taken into the consideration with a resolution of 0.1 nm. At the first place, the sensor has been optimized for a water cladding and only four resonant peaks have been noticed satisfying the condition of resonance wavelength [12] for an optical ring resonator structure i.e.;

$$2\pi r n_{eff} = m\lambda_m \tag{1}$$

Where, r is ring radius, n_{eff} is effective refractive index, m is an integer representing the mode order, λ_m is the resonance wavelength of mode 'm'. The maximum power confinement in the slot (water as cladding material) region is achieved for the resonant wavelength 1561.4 nm. Figure 3 represents the nature of the power propagation through this ring resonator and it

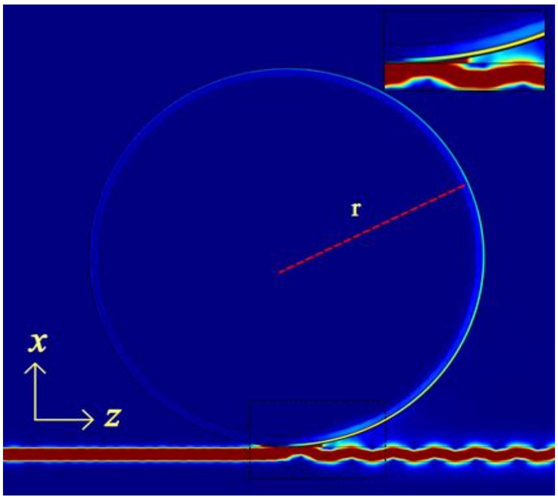

Fig. 3. Power propagation in plasmonic ring resonator with outer gold ring.

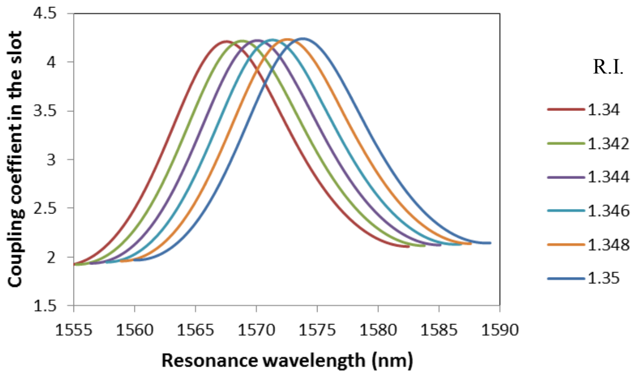

Fig. 4. Resonance wavelengths for different refractive indices.

could be observed that for this wavelength we are getting maximum power coupled at the surface of the outer gold ring. Which is the slot region and the power is getting evanescently confined in the *Si* ridge also up to the some distance. This distance can be termed as the penetration depth of the surface plasmon.

Next, the transmission spectra of the plasmonic ring resonator has been analysed for a refractive index of the cladding region that ranges from 1.34 to 1.35 at a step size of 0.002. The reason this range of refractive index is targeted is because most of the biological samples have refractive index in this range. As a consequence of changing the claading index, shifts occurs in the position of resonance wavelengths. Because in SPR for the resonance to take place the propagation constant of the incident light and the propagation constant of excited plasmon should essentially match [10]. And as we are changing the cladding refractive index the resonant wavelengths are also getting shifted in order to match the propagation constant in the similar manner. The shifts corresponding to all the indices can be predominantly seen in fig. 4. Which shows that with every increasing value of refractive index, the resonance positions is shifting towards the longer wavelengths.

Sensitivity is one of the key attributes for any sensor that helps in describing the sensing ability of the device. It can be defined as the shift occurred in the wavelength for per unit change in the refractive index and this can be expressed as;

$$S = \frac{\Delta\lambda}{\Delta n} \tag{2}$$

Where, $\Delta\lambda$ is the spectral shift for Δn change in the cladding refractive index.

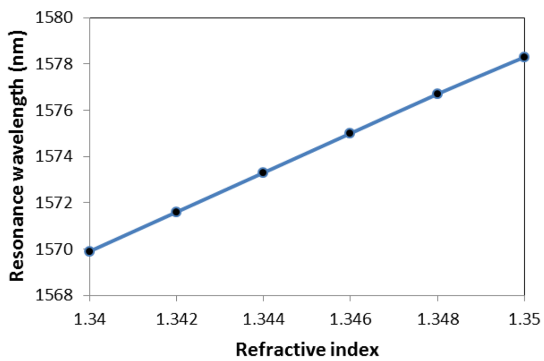

Fig. 5. Resonance wavelength as a function of cladding refractive index.

The graph related to sensitivity is given in fig. 5. Which shows the shift in the resonance wavelength is taking place with an unit increase in the refractive index with an average slope value of 860 nm/RIU. The graph also reflects that for higher value of refractive indices, the amount of shift in resonance wavelength is lesser.

IV. CONCLUSION

A number of research investigations especially on SPR sensors are taking place across the world just to increase the sensitivity of the devices. Adding on to this, we have proposed a plasmonic SOI ring resonator based biosensor in which the excitation of SPPs can be achieved by waveguide coupling method. Firstly, sensor has been optimized for a water cladding and further, sensing characteristic has been verified for the refractive index range 1.34 - 1.35 with a resolution of 0.002. The proposed device ensures an enhanced field confinement in the slot region and hence, ends up resulting in an average sensitivity of 860 nm/RIU. This biosensor is highly sensitive and serves the purpose of real time sensing.

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