Numerical simulation of silicon grating-based plasmonic sensor

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***Abstract*— This work reports on the application of silicon grating-enabled nanostructure for refractive index sensing application in the near-infrared region. This grating helps in launching the plasmon modes efficiently towards the flat metal film deposited with a thin Al_2O_3 layer. The normal incidence light is used which can be helpful for its integration with optical fiber. Numerical simulation is performed using the rigorous coupled-wave analysis (RCWA) method. The proposed structure has shown sensitive and precise sensing behavior.**

Index terms— grating, RCWA, sensing, plasmon

I. Introduction

The current optical sensing has emerged as a result of advancements in various optical methods such as spectroscopy, microscopy, and plasmonics for biological sample and gas sensing applications. Microfluidic technologies are making the integration of miniaturized sensors possible. The occurrence of conduction electrons oscillations on coupling with electromagnetic wave (EMW) is generally referred to as surface plasmon resonance (SPR). SPR-based sensors are being used as a preferable choice due to their precise and sensitive behavior, cost-effective integration, and label-free detection. The ease of fabrication and sensitive behavior have made the Kretschmann configuration a preferable SPR sensing configuration. However, a drawback associated with it is poor integration capabilities (due to bulky structure) and limited spatial resolution. In addition, the use of the angular interrogation method will restrict this configuration for integration with an optical fiber system. Another approach that can be utilized for SPR sensors is the grating enhanced coupling method which provides high ease of miniaturized integration (with optical fiber also). Metallic and dielectric nanostructures have shown tremendous growth in their application in plasmonic sensors [1]. This growth is related to the availability of advanced fabrication facilities for design. Large area patterning for mass production can be accomplished by employing nanoimprinting, templating, and soft lithography techniques [1]. Grating coupling methods usually utilize periodic metallic and/or dielectric corrugations. An important advantage of grating-based SPR sensors is tunability by playing with the grating variables (shape, periodicity, width, height) [2]. These grating variables are responsible for controlling the resonance characteristics of the surface plasmons (SPs). The proposed work is focused on the near-infrared (NIR) region of operation which has the advantages of large penetration depth towards sample size [3], no phototoxicity to biosamples. Moreover, normal incidence operation is focused for noise reduction and grating nanostructures multiplexing with miniaturized devices.

II. Sensor Configuration And Theoretical Insights

Figure 1 represents the schematic of the proposed structure consisting of Si grating on Ag deposited over Al_2O_3. The novelty lies in the backside sensing application. Wavelength interrogation method is used considering a normal incident transverse magnetic (TM) light. In the case of bulk material, SPs excitation relation for grating structure is given as:

$$\frac{2\pi}{\lambda} \times n_s \sin\theta_{inc} + m\,\frac{2\pi}{\Lambda} = \pm Re\left(\frac{\omega}{c}\sqrt{\frac{\epsilon_m \epsilon_s}{\epsilon_m + \epsilon_s}}\right) \quad (1)$$

In the above expression, the incident light wavelength is λ, the angle of incidence is θ_{inc}, ω and m are the angular frequency and diffraction order, respectively. c is the velocity of light in a vacuum. ϵ_m and ϵ_s are the dielectric constant of the metal layer and sensing medium, respectively. The reflectance (R) computation is based on rigorous coupled-wave analysis (RCWA) using MATLAB with normal consideration of incident light (i.e., $\theta_{inc} = 0°$). The resonance wavelength (λ_{SPR}) is the point at which the minimum reflectance is attained. A change in the position of λ_{SPR} ($\Delta\lambda_{SPR}$) is experienced on a small change in the analyte's RI (Δn_s). Experimental wavelength-dependent dielectric constant values of Si, Ag, and Al_2O_3 are taken from ref [4]. In the proposed structure the Al_2O_3 layer will act as a protective layer of Ag against the analyte medium.

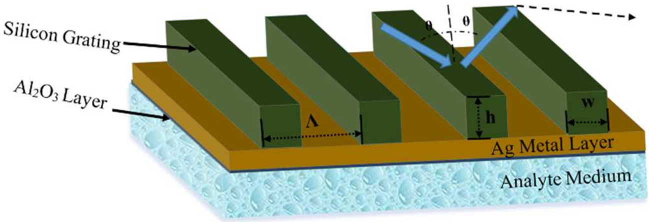

Fig.1. Schematic of the proposed Si-grating based structure

III. Results And Discussions

For preliminary calculation of reflectance (R), the values of grating width (w), grating period (Λ), grating height (h), and metal layer thickness (t) is set to be 700 nm, 1000 nm, 300 nm, and 50 nm, respectively. The thickness of the Al_2O_3 layer is 5 nm. These values are selected based on optimization and coupling equation (1). In addition, minimum reflectance (R_{min}) should also be taken into account, as a low reflectance value indicates almost complete absorption and field enhancement. The performance of a plasmonic grating-based sensor is evaluated based on three parameters: Sensitivity (S), detection accuracy (D.A.), and quality factor (QF). These parameters can be defined as follows:

$$D.A. = {}^{1}\!/_{(FWHM)}\,;\, S = \left({}^{\Delta\lambda_{SPR}}\!/_{\Delta n_s}\right)\,(in\,\frac{nm}{RIU}) \quad (2)$$

Here, FWHM is the full width at half maximum, i.e., width of reflectance curve. D. A. is measured in 1/nm. The combined performance is QF; $QF = \frac{S}{D.A.}$ (in 1/RIU).

Figure 2 indicates the simulated variation of reflectance with wavelength for different refractive indices of analyte considering incident angle as 0°. Further, it is assumed that for a given range of wavelength 1300 nm -1450 nm, the variations in refractive indices values are negligible. λ_{SPR} values of 1335.0 nm and 1415.50 nm are calculated for refractive index (RI) values of 1.32 and 1.40, respectively providing an 'S' value of 1006.25 nm/RIU (80.5/0.08). Considering the average FWHM value of 1.70 nm, calculated D.A. and QF values are 0.59 nm^{-1} and 591.91 RIU^{-1}, respectively assuring precise sensing behavior of the proposed sensor.

Furthermore, to visualize the effect of Au layer (instead of Ag in the structure) the reflectance analysis is shown in Fig.3 with Au (40 nm) as the analyte interacting layer. Au layer thickness is optimized to achieve R_{min}. It should be noted that the Au layer is oxidation resistant, and Al_2O_3 coating is not taken into account. In this continuation, λ_{SPR} values of 1335.30 nm and 1416.50 nm are calculated for RI values of 1.32 and 1.40, respectively providing an 'S' value of 1015 nm/RIU (81.2/0.08). A marginal increase in the 'S' value is obtained as compared with that of the Ag-based structure. However, the Au layer is also responsible for the increase in FWHM. Considering the average FWHM value of 7.7 nm (n_s = 1.32 and 1.40), calculated D.A. and QF values are 0.13 nm^{-1} and 131.82 RIU^{-1}, respectively. Thus, utilizing Ag metal enhances the QF by ~78% as compared with that of Au metal.

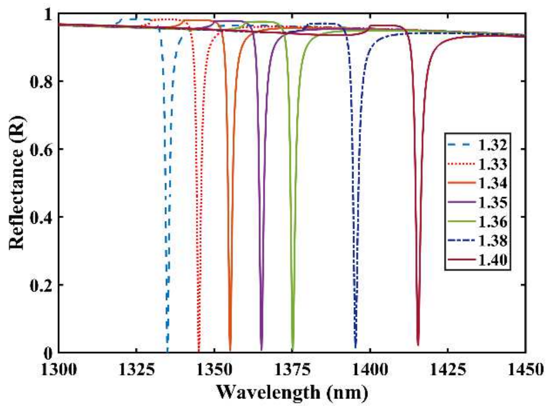

Fig. 2. Variation of reflectance with wavelength for different analyte refractive indices in case of Si-Ag-Al_2O_3 system.

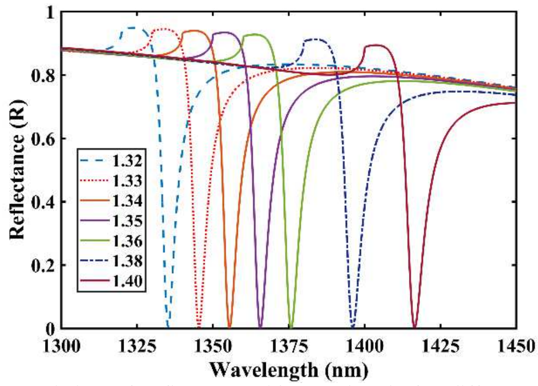

Fig. 3. Variation of reflectance with wavelength for different analyte refractive indices in case of Si grating-Au system.

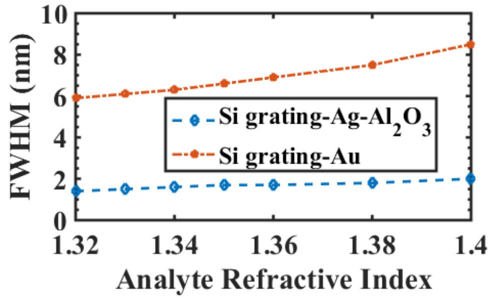

Fig. 4. Variation of FWHM with analyte refractive indices in case of Si grating-Ag-Al_2O_3 and Si grating-Au based sensor structures.

For an insight into the effect of the analyte refractive index on FWHM, the variation is depicted in Fig.4. In the case of the proposed structure (Fig.1) the FWHM value marginally increases from 1.4 nm (for n_s = 1.32) to 2.0 nm (for n_s = 1.40) assuring a considerable detection accuracy throughout the n_s range. A large value of FWHM is expected in the case of Au due to the presence of internal damping [5]. The FWHM value increases from 5.9 nm (for n_s = 1.32) to 8.5 nm (for n_s = 1.40) in the case of Si grating-Au-based structure which causes a reduction in D.A. and resulting QF values. For both the cases (Ag and Au), 'S' and QF values are significantly higher than those of recently reported ('S' = 720 nm/RIU, QF =73.47 RIU^{-1}) [6] grating structure based plasmonic sensor.

IV. Conclusion

This paper demonstrates a silicon grating-based plasmonic sensor for biosensing application. The sensing property is exploited from the backside of the thin metal layer so that the grating region can be easily integrated with a fiber optic system. The RCWA-based analysis for reflectance is carried out for a wide range of refractive indices. Average sensitivity values of 1006.25 nm/RIU and 1015 nm/RIU are calculated for Ag and Au-based structures. It is also observed that utilizing Ag metal (with Al_2O_3 coating) enhances the QF by ~ 78% as compared with that of Au metal. It is worthwhile to mention that the performance and operating wavelength region of the proposed sensor will be greatly influenced by grating parameters which are considered the future scope of the work. Additionally, calculation of field enhancement at resonance, effect of two-dimensional (2D) material in place of Al_2O_3, and application as a gas sensor will be carried out.

References

[1] A. K. Pandey and A. K. Sharma, "Advancements in Grating Nanostructure Based Plasmonic Sensors in Last Two Decades: A Review," *IEEE Sens. J.*, vol. 21, no. 11, pp. 12633–12644, 2021, doi: 10.1109/JSEN.2020.3045292.

[2] A. K. Pandey, A. K. Sharma, and C. Marques, "On the Application of Stacked Periodic Tungsten Grating Nanostructure in Wide-Range Plasmonic Sensing and Other Photonic Devices," *Plasmonics*, vol. 16, no. 1, pp. 9–17, Feb. 2021, doi: 10.1007/s11468-020-01248-x.

[3] M. Golosovsky et al., "Midinfrared surface-plasmon resonance: A novel biophysical tool for studying living cells," *J. Appl. Phys.*, vol. 105, no. 10, pp. 1–11, 2009, doi: 10.1063/1.3116143.

[4] "Refractiveindex.info." https://refractiveindex.info/ (accessed Apr. 26, 2022).

[5] A. K. Sharma and B. D. Gupta, "On the performance of different bimetallic combinations in surface plasmon resonance based fiber optic sensors," *J. Appl. Phys.*, vol. 101, no. 9, pp. 1–6, 2007, doi: 10.1063/1.2721779.

[6] A. K. Pandey and A. K. Sharma, "On the application of MoS2 monolayer for enhanced performance in metallic grating based plasmonic sensor structure," *Opt. Quantum Electron.*, vol. 54, no. 1, 2022, doi: 10.1007/s11082-021-03428-3.