Numerical Investigation of a High Performance Subwavelength Grating Based Plasmonic Biosensor

Mahin Tahmasebpour and Manouchehr Bahrami
Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
Email: {tahmasebpour, mbahrami}@tabrizu.ac.ir

Asghar Asgari
Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran
School of Electrical, Electronic and Computer Engineering, The University of Western Australia, Crawley, WA 6009, Australia
Email: asgari@tabrizu.ac.ir

Abstract—A Localized Surface Plasmon Resonance (LSPR) biosensor based on a subwavelength grating structure is studied numerically for detection of bulk refractive change of aqueous environments such as biological buffer solutions. A high grating thickness of 40nm and a short grating period of 50nm are selected to evaluate numerically the effect of the other grating structural parameter i.e. fill factor (f.f) on the sensor performance including dispersion curve, sensitivity, FWHM, MRR and resonance angle. Evaluation shows that corresponding wavelength to the effective resonance of surface plasmons which locating in near infrared (NIR) wavelength range is displaced with f.f value. Also, as shown for some f.f values sensitivity is enhanced slightly whereas FWHM, MRR and resonance angle is increased. Thus with adjusting both of operating wavelength and f.f value, it is possible to get a better performance for the plasmonic sensor.

Index Terms—subwavelength grating, localized surface plasmon, biosensor, near infrared wavelengths

I. INTRODUCTION

Surface Plasmon Resonance (SPR) is one of the most advanced label free, real time detection technologies for measurement of a refractive index change near the noble metal surfaces caused by an aqueous solution concentration or biomolecular adsorption. Useful characteristics of metallic nano-structures including local field enhancement and their metamaterial-like behavior have enhanced the sensitivity of SPR based sensors [1], [2]. In the field of LSPR sensors Kim et al. presented a nanowire-based SPR configuration in which the combination of a prism coupled method with a nano-grating coupled method enhances the sensitivity [3]. After that, this structure has been the topic of recent theoretical and experimental studies which the most focused on the sensitivity enhancement [4]-[9]. Since a narrow Full Width at Half Minimum (FWHM) and a low Minimum Reflectance at Resonance (MRR) are desired for designing a practical SPR sensor [10], [11], these performance parameters have to be enhanced as well as sensitivity.

As verified in our recent work [12], overall performance of the nano-grating based SPR sensor can be improved for higher grating thicknesses and lower grating periods in NIR wavelengths. Based on the results of that work, a high grating thickness of 40 nm and a short grating period of 50 nm are selected to evaluate the effect of the other grating structural parameter i.e. fill factor (f.f) on the sensor performance including dispersion curve, sensitivity, FWHM, MRR and resonance angle which leads to achieve a high performance LSPR with adjusting f.f and operating wavelength.

Figure 1. Proposed model for subwavelength grating based SPR sensor

II. MODELING AND SIMULATION

A schematic diagram for our SPR biosensor device is shown in Fig. 1. It shows a krestchmann configuration in combination with a nanograting structure on top of it. In the diagram, dm is the intermediate metal layer thickness which is stetted to 40nm. As shown in Fig. 1 this thin gold film layer is placed on a SF10 glass substrate with the refractive index of \( n_p \) after a 2-nm thick chromium...
adhesion layer shown by \( d_{Cr} \). A metallic nano-grating structure locating on top of the thin metal layer is presented in Fig. 1 with geometrical parameters of grating thickness, grating period and metallic filling part of the grating shown by \( d_g \), \( P \) and \( w \), respectively. \( w \) is used to define the f.f parameter which is defined as \( w/P \). Gold (Au) is used as the material of the metallic part of the sensor because of its excellent biocompatibility and wide availability of linker molecules [13]. Refractive indexes of gold, chromium and SF10 glass are taken from [14]. The proposed sensor is used to detection of biological buffer solution as a bulk refractive index (n_s) varying from 1.33 to 1.36.

As well known, when a TM-polarized light is incident on the prism, the dispersion relation of the excited surface plasmons at resonance conditions is determined by

\[
K_{SPR} = \frac{2\pi}{\lambda} \sqrt{n_{D,eff}^2 - n_{AU}^2}
\]

where, \( K_{SPR} \) denotes the wave vector of surface plasmon and \( \lambda \) denotes the wavelength of incident light. \( n_{D,eff} \) is the effective refractive index of grating layer in combination of surrounding dielectric analytes and \( n_{AU} \) is the refractive index of the gold film. \( K_x \) denotes the wave number of the incident light on the grating surface in the \( x \) direction which given by

\[
K_x = \frac{2\pi}{\lambda} n_p \sin \theta
\]

where \( \theta \) is the angle of incident light. The evanescent light is diffracted by the grating and this diffraction increases the wave number of the evanescent light in the \( x \) direction by \( qK \) where \( K \) is the magnitude of the wave vector of diffracted light equals to \( 2\pi / P \) and \( q \) is the diffraction order. When the light is incident on the grating surface with angle \( \theta \), the wave number of the \( q \)-th diffracted evanescent light is given by

\[
K_q = K_x + qK, q = 0,\pm1,\pm2,\pm3,\ldots
\]

So, the incident light is coupled with the SPR whenever the wave numbers of the diffracted evanescent light and the surface plasmon satisfy the condition which described in (4) [16].

\[
K_q = \pm K_{SPR}
\]

Above equations are used to calculate SPR with considering higher diffraction orders in the proposed device configuration. However it has been determined that with selecting lower grating periods higher diffraction orders can be neglected. So, dispersion curve of the sensor is calculated numerically for TM-polarized light in a broad wavelength range from the visible wavelength of 400nm to NIR wavelength of 1500nm using above equations.

### III. RESULTS AND DISCUSSIONS

Investigation of the effects of f.f variation is done numerically for dispersion curve and sensor performance parameters in the cases of different f.f values when \( d_g \) and \( P \) keeping unchanged to their optimum values of 40nm and 50nm, respectively, based on our previous work [12]. Dispersion curve of the sensor is presented in Fig. 2 for three different values of f.f including 0.1, 0.4, and 0.9. As shown in Fig. 2, for all f.f values two separate parts are included in dispersion curve. One of them is located near the visible wavelengths and another one which named the flattened part is located near the NIR wavelengths. As plotted in Fig. 2, both parts of dispersion curve can be moved for different f.f values. Fig. 2 shows that the movement of the flattened part of the dispersion curve is much more than that of the part locating near the visible wavelengths. Thus, in addition to \( d_g \), f.f parameter can change the location of the flattened part and also sensor performance parameters.

As depicted in Fig. 2 upper part of the dispersion curve near the visible wavelengths is diminished slightly toward shorter wavelengths for the moderate f.f of 0.4. Also, it is extended again toward NIR wavelengths for lower and higher f.fs such as 0.1 and 0.9 whereas higher extension with deeper resonances occurs in the case of f.f equals 0.9. Similarly, the location of the flattened part of the dispersion curve moves toward visible wavelengths in the case of moderate f.f equals 0.4 and moves toward NIR wavelengths in the cases of f.f values of 0.1 and 0.9. Moreover, the flattened part of the dispersion curve has the farthest distance from the visible wavelengths in the case of f.f equals 0.9.

It has been demonstrated that the flattened part of the dispersion curve is the location of corresponding wavelength with high sensitivities i.e. band edge wavelength [17] which moves toward longer wavelengths with higher grating thicknesses [12]. Thus higher sensitivities can be obtained for higher \( d_g \)s in longer wavelengths. It is well known that higher sensitivities can be achieved in thicker metal wires because of dominantly excitation of LSPs modes which weakly perturbed by SPPs in thick nanowires [3]. From the movement of the dispersion curve with the f.f variation it is expected that higher sensitivities can be obtained in some special f.f values.

As mentioned, working a LSPR sensor near the flattened part of its dispersion curve can give a high sensitive LSPR sensor. Fig. 2 shows that it is possible to obtain a high sensitive LSPR sensor with adjusting the appropriate values of both f.f and operating wavelength. The movement of the dispersion curve due to the f.f variation can influence on the sensor performance parameters. So, the effect of the f.f variation from 0.1 to 0.9 (with step of 0.1) is evaluated numerically on the sensor performance parameters in details. The results of this evaluation are plotted in Fig. 3. As depicted in Fig. 3(a), the corresponding wavelength with the enhanced sensitivity is displaced with the f.f value whereas it moves toward shorter wavelengths with moderate f.fs and shifts toward longer ones with non moderate f.fs.
maximum movement toward shorter wavelengths and longer wavelengths is related to 0.4 and 0.9, respectively. This movement path of the band edge wavelength is similar to the movement path of the flattened part of the dispersion curve. As resulted from the band edge wavelength movement, the flattened part of the dispersion curve goes up toward shorter wavelengths with growing f.f values from 0.1 to 0.4 and it again comes back toward longer wavelengths with growing f.f from 0.4 to 0.9. Investigation of the location of the band edge wavelength shows that maximum displacement of the flattened part of the dispersion curve toward visible wavelengths occurs in the case of f.f equals 0.4. For the other f.f values, this part moves toward NIR wavelengths with the farthest distance from the visible wavelengths in the case of f.f equals 0.9. The influence of the f.f variation on the other sensor performance parameters can be observed clearly in Fig. 3.

As resulted dispersion curve moves upward with f.f varying from 0.1 to 0.4 and moves downward with f.f varying from 0.4 to 0.9. Fig. 3(a) shows that among f.f related to these two isolate movement path, f.f of 0.1 and 0.9 induce sensitivity to be improved slightly whereas FWHM and MRR are deteriorated.

As known, a slight enhancement in the excitation of LSP modes near two values of f.f equal 0.1 and 0.9 in comparison with moderate f.f is related to the enhancement of field intensity by individual nanowire and nanogrooves which is conjugated with large SPP damping [18]. As shown in FWHM and MRR plots in Fig. 3(b) and Fig. 3(c), respectively, this large SPP damping makes SPR curves broader and shallower and also induces the resonance at higher angles as shown in Fig. 3(d). Although the enhanced sensitivity of the sensor shows a slight decrement in moderate f.f such as 0.4 in contrary with non moderate f.f of 0.1 or 0.9 but FWHM and MRR are improved in these moderate f.f.

Figure 2. Displacement of dispersion curve with f.f variation a) 0.1, b) 0.4, c) 0.9 (dm=40nm, dg=40nm, P=50nm)

Figure 3. Effect of f.f variation on (a) sensitivity, (b) MRR, (c) FWHM, (d) resonance angle (dm=40nm, dg=40nm)

IV. SUMMARY

In this paper, the effect of f.f parameter on dispersion curve and performance parameters of a subwavelength grating based SPR biosensor is studied numerically. As resulted it is possible to obtain a high performance sensor in all grating f.f especially in moderate ones with adjusting the operating wavelength. These findings can be potentially useful for developing of an enhanced nanograting based LSPR biosensors with moderate f.f which are suitable for fabrication and also for detection whereas immobilization of the receptor molecules on the
narrow slits in the structures with low or high f.fs may be a challenge.

REFERENCES


Mahin Tahmasebpour received her BSc and MSc degrees in Electronic Engineering from University of Tabriz, Tabriz, Iran in 2001 and 2004, respectively. Recently, she got her Ph.D. in September 2014 from University of Tabriz, in Electronic Engineering. Her PhD research area was in design and modeling of a plasmonic biosensor. Her interest also includes Sensor design, Bio Micro Electromechanical Systems (BioMEMS), Numerical Modeling of Plasmonic devices and Biophotonics.

Manouchehr Bahrami received the BSc degree in electronics engineering from Iran University of Science & Technology, Tehran, Iran, in 1991 and his MSc degree in electronics engineering from Sharif University of Technology, Tehran, Iran in 1994. Then he obtained his PhD degree in MEMs from Southampton University, Southampton, United Kingdom. Currently he is an Assistant Professor of Department of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran. His research interests include Microelectromechanical Systems, Sensor design and RF circuits.

Asghar Asgari got his BSc and MSc degrees in Solid State Physics and Electronics from University of Tabriz, Iran. He got his PhD under Prof. M. Kalafi from University of Tabriz and Prof. L. Faraone from University of Western Australia, supervisions. In 2002 he joined Microelectronics Research Group in the University of Western Australia as research associate. In 2004, he started his work in Photonics group at the University of Tabriz in Iran. Currently he is Professor in Photonics Group at University of Tabriz and also Adjunct Professor in Microelectronics Research group at the University of Western Australia. His research interests include experimental and theoretical study of Crystal Growth, theoretical study of transport and optical properties of bulk and low-dimensional Semiconductors (Nitrde Material and Graphene), Modeling of Semiconductor devices, Nano-electronic and Nanophotonic devices.