SENSITIVITY ENHANCEMENT OF A D-SHAPE SPR-POF LOW-COST SENSOR USING GRAPHENE

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Abstract: **A surface plasmon resonance biosensor, using graphene layers coated over the multilayer base of the plastic optical fibre (POF) has been analyzed. The force of adherence between sputtered gold and POF was increased using Microposit S1813 photoresist buffer layer. The photoresist increase the sensitivity of the SPR and graphene layer enhance the adsorption of the biomolecule from sensing medium. A setup with a broadband halogen light source was considered. An optimized performance was obtained for geometry with 40nm gold layer, buffer layer of 1500nm and two graphene layers. The sensitivity was improved in comparison with the value reported in literature for the POF based SPR biosensor.**

Keywords: *SPR, POF fiber (plastic optical fiber),numerical simulation, sensitivity, biosensor, graphene.*

1. INTRODUCTION

Surface plasmon resonance (SPR) has become a popular tool for large sensing applications including physical, chemical, biological parameters of interest monitoring [1]. A plasmonic phenomenon refers to collective oscillations of electrons. It has a contribution in the dynamic responses of electron systems and forms the basis of research into new optical metamaterials, enabling potentially optoelectronic and photonic sensors based applications.

In the last decade a large interest in developing fibre-based plasmonic sensors by using different shapes optical fibres (ex. H-shaped [2] or D-shape [3]) template was encountered. The alternative large used prism-based configuration has a number of drawbacks such as: large size, high costs due to the positioning system, which makes it unsuitable for miniaturized applications and remote sensing. Recently the graphene-based photonic devices, such as ultrafast photodetectors [4], optical modulators and tunable surface plasmon polariton devices, have experienced rapid development due to graphene's strong ability to confine light strongly and thus to obtain field-controlled optical response benefit. Graphene is a material with good electrical and optical properties. The structure consists of a single sheet of carbon atoms organized in a honeycomb lattice.

Because the reported performances of tunable-graphene-based plasmonic devices are still looking more promising than those of the simple metal-based structures [5–10], this paper works deals with exploiting graphene as part of a plasmonic sesing area in order to obtain a sensitivity parameter enhancement. We explore the plasmonic response of a PMMA fiber based (POF) biosensor in the visible range. It is used a graphene, gold and buffer multilayer stack, in different dimension configuration, coating the sensing area. The gold metallic layer is preferred because of its low oxidation feature in comparison with silver. In this paper it was considered the graphene thickness d_G=0.34nm that was reported in [11]. The spectral interrogation method configuration, using a broadband light source was used. The Microposit **S1813** photoresist buffer layer enhanced the field intensity of the excitation light at the sensing surface and increase the sensitivity of the SPR sensor. The simulation has been carried out for different configuration and thickness of multilayer structure (photoresistor or silicon, gold and graphene layer) in order to report an optimized structure.

2. SIMULATION AND OPTIMISATION OF THE SENSOR STRUCTURE

The SPR probe is considered a multi-layer system consisting of a D-shape PMMA fiber core coated by different stack geometries, in two basic configurations (with and without buffer layer of about 1500nm) , gold and graphene layers. The configuration is depicted in *Figure 1*.

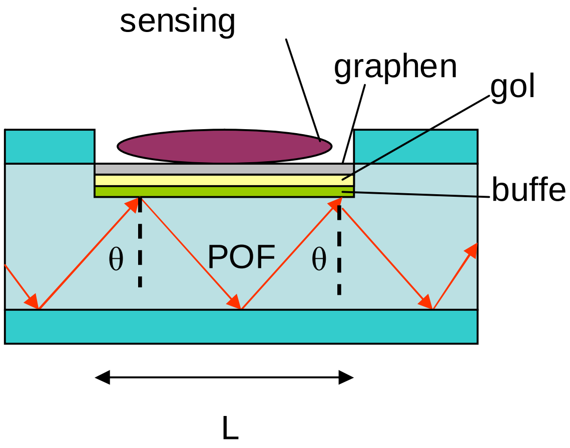

Figure 1. Schematic view of the second geometry of the POF based, SPR sensor.

The D-shaped can be easy obtained by polishing procedure at half circumference of a 10mm long surface of an ordinary POF fiber with 980um diameter [12]. POF is preferred to the glass multimode fiber since the dimensions of the samples can be easily controlled. Numerical aperture (NA) is 0.46 with PMMA[13] core and n=1.41 refractive index for the 20um fluorinated polymer cladding. As reference for data normalization, the spectrum-acquisition with no analytes (air) is considered.

The analyts consist of different glycerin concentration solution (with different refractive index, ranging from 1.332 to 1.372). The analyt is placed in contact with graphene layer. The graphene is a good absorbent of biomolecules. A monolayer of graphene absorbs Mx2.3% of white light where M=number of the grapheme layers. The complex refractive index of graphene is given as [15]:

$$n_g = 3 + i * \frac{C}{3}\lambda \tag{1}$$

The refractive index of silicon layer is a function of wavelength:

$$n_s = A_1 + A_2 e^{\frac{-\lambda}{t_1}} + A_3 e^{\frac{-\lambda}{t2}} \tag{2}$$

where:

A_1=3.44904, A_2=2271.88813, A_3=3.39538, t_1=-0.058304 and t_2=0.30384.

The field associated with SPR wave has maximum value at the metal-dielectric interface and decays in dielectric and metal layer. The P-polarized light component, incident to the sensing interface has great contribution for the surface plasmon phenomena. The resonance condition appears when the propagation constant of the generated evanescent wave becomes equal with that of the plasmonic wave according with the Eq 3.

$$K_{plasmon} = \mathrm{Re}\left[K_0 \left(\frac{\varepsilon_{metal} n^2_{sen\sin g}}{\varepsilon_{metal} + n^2_{sen\sin g}} \right)^{1/2} \right] \tag{3}$$

having the following notation:

ε_{metal} - real part of the metal dielectric constant,

$n_{sen\sin g}$ - refractive index of the sensing layer.

For theoretical design, the transfer matrix formalism was used [14].

The power at the fiber’s output at a specific wavelength can be approximated by integrating the product of the whole light reflectance with the angular power distribution corresponding to the light source used (Eq 4).

$$P_{out}(\lambda, n_{sen\sin g}) = \frac{1}{2}\left(\int_{\theta_1}^{\theta_2} R_p{}^N P_0(\lambda, \theta, n_{sen\sin g}) d\theta + \int_{\theta_1}^{\theta_2} R_s{}^N P_0(\lambda, \theta, n_{sen\sin g}) d\theta\right) \tag{4}$$

where:

$$N = \frac{L}{D \tan(\theta)} \tag{5}$$

is the number of reflections within the sensitive area, that is calculated as a function of L (the length of the sensitive area), D (the diameter of the fiber) and the angle interval $[\theta_{critical}, 90]$.

The sensitivity was calculated using Eq. 6:

$$S = \frac{\delta\lambda_{res}}{\delta n_s}\left[\frac{nm}{RIU}\right] \tag{6}$$

3. RESULTS AND DISCUSSION

There was considered a few number of design parameters of the sensors that may affect its performance, such as thickness and refractive index of different layers (gold, buffer, graphene and biomolecules sensing medium). The comparative results of a two analyzed structures are depicted in Fig 1 (without buffer) and Fig 4 (with buffer layer), for a resolution of Δn=0.001 RIU, for a number of M=2 layers of graphene (thickness=M*0.34).

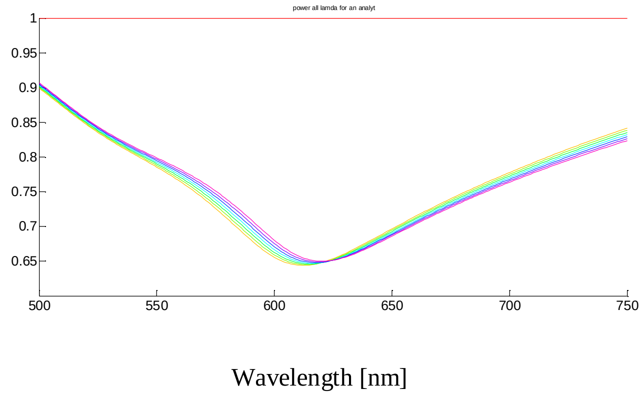

Figure 2. Normalized Transmitted Light Intensity graphic as a function of wavelengths [nm] – without buffer.

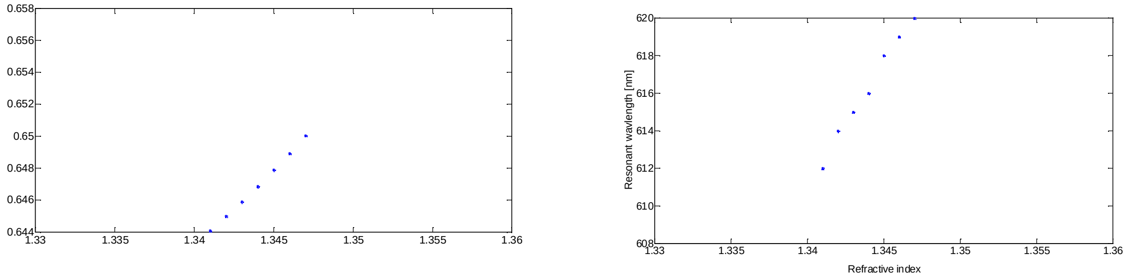

Figure 3. A). Normalized Transmitted Light Intensity at resonance as a function of refractive index– without buffer. B. Resonance Wavelength as a function of refractive index

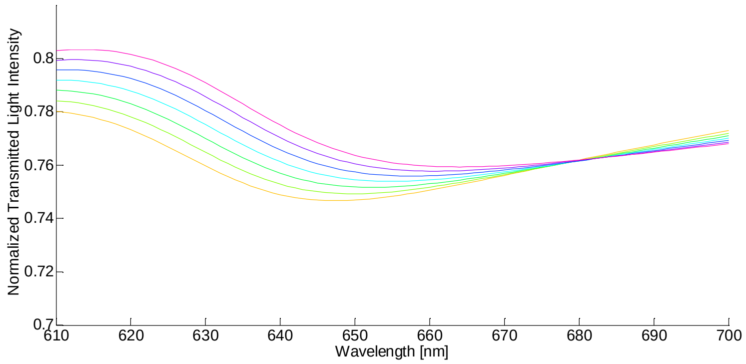

Fig 4. Normalized Transmitted Light Intensity graphic as a function of wavelength[nm] – with buffer

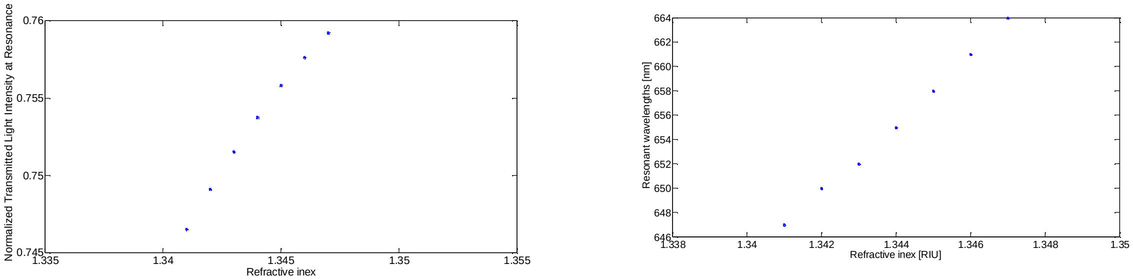

Figure 5. A. Normalized Transmitted Light Intensity graphic as a function of refractive index– with buffer. B. Resonance Wavelength as a function of refractive index

Table 1

Buffer	Resolution range: n=1.332-1.372	Sensitivity[nm/RIU]	Number of graphene layers
Yes	Δn=0.001	$2.8*10^3$	2
No	Δn=0.001	$1.18*10^3$	2
Yes	Δn=0.0004	$0.8*10^4$	2

For the biomolecule it was chosen Δn=0.001 RIU and Δn=0.0004 RIU, to study the biosensor response. The optimized value for gold layer in literature [3][12] was mentioned for 40nm of gold. At the same thickness, using graphene layer it is obtained more than two times improved value of the sensitivity. The decrease in the thickness of the gold layer can be correlated with the addition of graphene layers (required for the complete transfer of energy in biomolecule sensing medium).

4. CONCLUSIONS

Two sensors configuration based on SPR in plastic optical fiber (with and without a buffer layer between fiber core and gold film), have been numerically simulated. The sensing devices have been analyzed by considering a broadband halogen lamp to illuminate the optical fiber and the normalized transmitted spectra have been calculated. The results indicate that the configuration with buffer and grapheme layer shows a better performance (more than two times) in terms of sensitivity, in comparison with previous reported SPR based POF geometry. Work is in progress to extend the analysis to larger types of POF configurations.

REFERENCES

[1] N. Cennamo, G. D’Agostino, R. Galatus, L. Bibbò, M. Pesavento, L. Zeni, *Sensors based on surface plasmon resonance in a plastic optical fiber for the detection of trinitrotoluene*, Sensors and Actuators B: Chemical, Volume 188, November 2013, Pages 221-226, ISSN 0925-4005, http://dx.doi.org/10.1016/j.snb.2013.07.005.

[2] Diana Viegas, H. Ludvigsen et al., *Surface Plasmon Resonance Sensor Based on H-shaped Optical Fibre*, Proc SPIE vol 7653 76532J-1-4

[3] Cennamo, N.; Massarotti, D.; Galatus, R.; Conte, L.; Zeni, L. *Performance Comparison of Two Sensors Based on Surface Plasmon Resonance in a Plastic Optical Fiber*. *Sensors*, **2013**,*13*, 721-735.

[4] Thomas Mueller, Fengnian Xia, Phaedon Avouris, *Graphene photodetectors for high-speed optical communications,* Nature Photonics *4, 297 - 301 (2010), doi:10.1038/nphoton.2010.40*

[5] Yan, H. et al., *Damping pathways of mid-infrared plasmons in graphene nanostructure,* Nature Photon. 7, 394–399 (2013).

[6]. Ju, L. et al. *Graphene plasmonics for tunable terahertz metamaterials,* Nature Nanotech. 6, 630–634 (2011).

[7]. Yan, H. et al. *Tunable infrared plasmonic devices using graphene/insulator stacks, Nature Nanotech. 7, 330–334 (2012).*

[8]. Fei, Z. et al. *Infrared nanoscopy of Dirac plasmons at the graphene-SiO2 interface*, Nano Lett. 11, 4701–4705 (2011).

[9]. Chen, J. et al., *Optical nano-imaging of gate-tunable graphene plasmons*, Nature 487, 77–81 (2012).

[10] Xiaomu Wang, Zhenzhou Cheng, *High-responsivity graphene/silicon-heterostructure waveguide photodetectors*, *Nature Photonics* **7**, 888–891 (2013)[10]. Fei, Z. et al. Nature 487, 82–85 (2012)

[11]. M. Bruna, S. Borini, *Optical constants of graphene layers in the visible range,* Applied Phys Lett 94, 031901, 2009

[12] Cennamo, N.; Massarotti, D.; Conte, L.; Zeni, L. *Low Cost Sensors Based on SPR in a Plastic Optical Fiber for Biosensor Implementation*. *Sensors* **2011**, *11*, 11752-11760.

[13] S. N. Kasarova et al. *Analysis of the dispersion of optical plastic materials*, *Optical Materials* 29, 2007, pp. 1481-1490.

[14] M. Kanso et. al. *Sensitivity of Optical Fiber Sensor Based on Surface Plasmon Resonance: Modeling and Experiments*, Springer, Plasmonics 2008, 3:49-57.

[15] L. Wu,* H. S. Chu, W. S. Koh, and E. P. Li , *Highly sensitive graphene biosensors based on surface plasmon resonance*, 5 July 2010 , Vol. 18, No. 14 , OPTICS EXPRESS 14395