

# Design study and Modeling of Surface Plasmon Resonance (SPR)-based Optical Fiber Sensor Utilizing Zinc Oxide and Gold Layers

Murtadha F.S. Al-saaidy<sup>1</sup>, Shehab A. Kadhim<sup>2</sup>, Ali A.D. Al-Zuky<sup>3</sup>, Anwar H.M. Al-saleh<sup>4</sup>

Department of physics, Collage of Science, Al-Mustanasiya University, Iraq<sup>1,3,4</sup>

Laser & Optoelectronics Research Center, Ministry of Science & Technology, Iraq<sup>2</sup>

**ABSTRACT:** A surface plasmon resonance (SPR) based fiber optic sensor for physical, chemical and biological sensing applications using a gold layer coated around a small unclad portion of an optical fiber and the zinc oxide layer coated over it has been presented and theoretically analyzed using four layer model designed and modeled using Matlab. The complete analysis of the sensitivity of sensing for various values of gold and zinc oxide layer thickness has been done numerically within the range of refractive index between 1.3 and 1.4. In this study the optimized values of gold and zinc oxide layer thicknesses were 40nm and 20nm respectively and the sensitivity was 3.556 $\mu$ m/RIU.

**KEYWORDS:** surface plasmon resonance, sensor, fiber optic, zinc oxide.

## I. INTRODUCTION

In sensing, surface plasmons resonance is one of the most promising optical techniques which refers to the excitation of surface plasmons, and it has broad applications in biology, environment, chemistry, medicine, etc. [1-4], due to the high sensitivity to the refractive index changes in the surrounding medium. When a light wave is reflected in the metal film and the coupling conditions are satisfied, a sharp dip is observed at a resonance angle due to the energy transferred from the incident photons to surface plasmons, which reduces the energy of the reflected optical signal [5]. Two types to interrogate this dip, there are angular and spectral interrogations. Spectral interrogation is mostly used in optical fibers where the angle is kept and to track the resonance wavelength. Any change in the refractive index of the surrounds led to shifting in the position of the resonance wavelength. The Kretschmann configuration based on attenuated total reflection is generally used for excitation of surface plasmons [6]. In this configuration the base of the high refractive index prism is coated with a thin layer of metal and the dielectric medium in the surround to be sensed is kept contact with the outer side of the metal layer. To excite the plasmons on this side of the surface, the p-polarized light is incident on the prism base through one of its surfaces. In the case of a prism-based SPR sensor evanescent wave required to excite surface plasmons is resulted due to the total internal reflection taking place at the prism-metal interface when the angle of incidence of the beam is greater than the critical angle. The evanescent wave is present in an optical fiber because the light guidance occurs due to the total internal reflection of the guided ray at the core-cladding interface. In the case of optical fiber the evanescent wave propagates along the core-cladding interface [1]. The combination of surface plasmon resonance technique and optical fiber technology has been intensively used for the sensing of various entities such as refractive index of the fluid, film thickness, surface roughness, pH, temperature, urea, glucose, pollutions and different type of gases. The first study on fiber optic chemical sensor based on SPR was reported in 1993 by Jorgenson and Yee [7]. After that, many theoretical and experimental researches are carried out. Noble materials such as gold (Au), silver (Ag), copper (Cu), etc. are used to fabricate the SPR sensors because the Nobel metal possesses a dense assembly of negatively charged free electrons in an equally charged positive ion background with the condition of quasi-neutrality and then can be compared with plasma of particles [8]. Selection of

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

the suitable material limited by some limitations like it is chemically vulnerable against oxidation and corrosion, therefore, its protection is required for a stable sensing application. Gold has a good feature in these types of sensors. Zinc oxide has also attracted the significant interest of research, community due to being widely used in numerous applications such as transparent conducting films, photonic crystals, gas sensors, bio sensors, light emitting diodes, solar cells, lasers, photo electrochemical cells and electrodes [9,10,11,12 ]. Besides, zinc oxide does not get easily oxidized when comes in contact with the surrounding ambience.

## II. THEORETICAL CONCEPTS

The principle of surface plasmon resonance sensor based on attenuated total reflection (ATR) with Kretschmann's configuration. This configuration consists of a coupling prism, which can be replaced by the core of optical fiber, a metal layer of thickness ( $d_1$ ) and dielectric function ( $\epsilon_m$ ) and an outermost absorbing medium of dielectric function ( $\epsilon_s$ ). The cladding around the core from the middle portion of an optical fiber is removed and coated with a thin film of metal like gold, this film is finally surrounding by the sensing medium. The light from polychromatic source is launched into one end of the fiber using proper optics (lens) and the transmitted light is detected and analyzed at the other end of the fiber. The idea, is when the incident light makes total internal reflection at the metal-dielectric interface, the evanescent waves excite the surface plasmons on the metal surface and when the propagation constant of the wave of these plasmas matched to that of the evanescent wave, a strong absorption of light takes place as a result of energy transferring and then the output signal demonstrates a sharp dip at certain wavelength known as resonance wavelength.

## III. MODELING AND SIMULATION

As shown in figure (1) the sensing region of SPR-based optical fiber sensor can consist of four layers mainly are Fiber core, Metal layer, Sensing layer and the analyte.

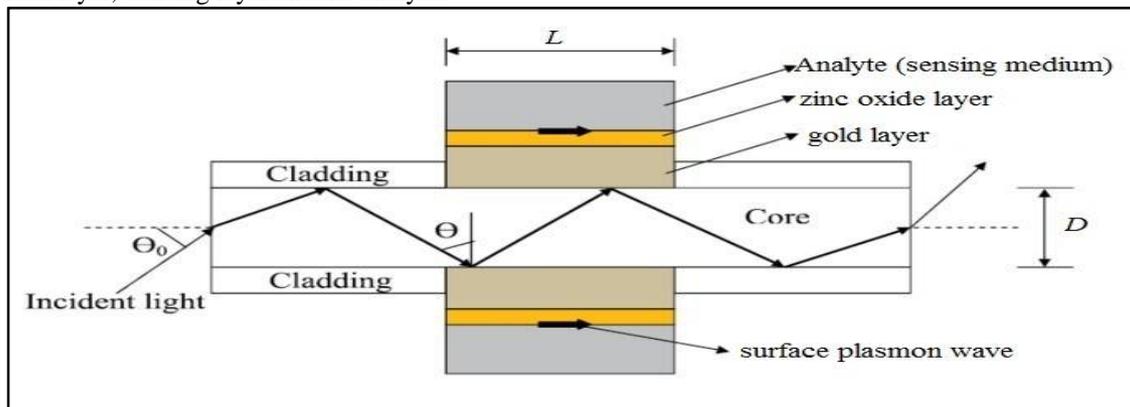


Figure (1): schematic diagram of four layer SPR-based fiber optic sensor.

### III.I.I. THE CORE OF OPTICAL FIBER

The core of optical fiber considered to be made of fused silica in which the refractive index variation with wavelength as shown in the dispersion relation [13].

$$n_1 = \sqrt{1 + \frac{a_1 \lambda^2}{\lambda^2 - b_1^2} + \frac{a_2 \lambda^2}{\lambda^2 - b_2^2} + \frac{a_3 \lambda^2}{\lambda^2 - b_3^2}} \dots \dots \dots (1)$$

Where:  $a_1=0.6961663$ ,  $a_2=0.4079426$ ,  $a_3=0.8974794$ ,  $b_1=0.0684043$ ,  $b_2=0.11622414$ , and  $b_3=9.896161$  are slimmer coefficients.

And  $\lambda$  is the wavelength (in  $\mu\text{m}$ ) of light propagating in the medium.

### III.I.II. THE METAL LAYER

Choosing the suitable metals to work in the proposed sensor depend on the metal resistance to oxidation and corrosion and also depend on providing a good sensitivity. Many studies show that metals such as copper (Cu), aluminum (Al),

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

silver (Ag) and gold (Au) have ability to be used for an SPR sensor. The copper has some limitations like silver, it is chemically vulnerable against oxidation and corrosion. The gold is the most sensitive, whereas the aluminum is lost. The dielectric constant of any metal can be calculated according to the Drude model as[14]:

$$\epsilon_m(\lambda) = \epsilon_{mr} + i\epsilon_{mi} = \epsilon_\infty - \frac{\lambda^2\lambda_c}{\lambda_p^2(\lambda_c+i\lambda)} \dots\dots\dots (2)$$

Where  $\epsilon_{mr}$  and  $\epsilon_{mi}$  are the real part and imaginary part of the metal dielectric constant and  $\lambda_p$  and  $\lambda_c$  are the plasma wavelength and collision wavelengths of the metal respectively.  
 $\lambda_p = 1.6826 \times 10^{-7}$  and  $\lambda_c = 8.9342 \times 10^{-6}$  for the gold metal.  
 $\epsilon_\infty$  is the infrared constant and it is equal to one for the Au, Ag, Cu, and Al metal and equal to 3.8 for ITO.

### III.I.III. SENSING LAYER

In four layer model, over the metal layer there is the sensing layer. This layer should have a reversible reaction with the analyte.

The dielectric constant of this medium is ( $\epsilon_s$ ). If ( $n_s$ ) is the refractive index of the sensing medium, then  $\epsilon_s = n_s^2$ .

The resonance condition for the excitation of surface plasmon wave is given by:

$$\frac{2\pi}{\lambda} n_1 \sin\theta = \text{Re}\{K_{sp}\} \dots\dots\dots (3)$$

Where  $\text{Re}\{K_{sp}\}$  is a real part of the propagation constant of the surface plasmon wave which can be written as:

$$K_{sp} = \frac{\omega}{c} \sqrt{\frac{\epsilon_m \epsilon_s}{\epsilon_m + \epsilon_s}} = \frac{2\pi}{\lambda} \sqrt{\frac{\epsilon_m n_s^2}{\epsilon_m + n_s^2}} \dots\dots\dots (4)$$

Where  $c$ ,  $\omega$ ,  $\lambda$  are the speed of light in vacuum, angular frequency and wavelength of incident light respectively. The left hand side of equation (3) denotes the propagation constant of the light incident at an angle  $\theta$  and the right hand side is the real part of the propagation constant of the surface plasmon wave.

### III.I.IV. THE ANALYTE

Chemical, biological, or environmental element that needs to be sensed are called the analytes and it is the surrounding material over the sensing layer. The reaction between this material and the material of the sensing layer result in a new material of different refractive index which leads to shifting in resonance wavelength.

### III.II. TRANSMITTED POWER

The p-polarized from a collimated source is launched into the fiber at an axial point through a microscope objective (lens). The power,  $dP$ , arriving to the fiber end between the angle  $\theta_0$  and  $\theta_0+d\theta_0$  is given by [15]:

$$dP \propto \frac{n_1^2 \sin\theta \cos\theta}{(1-n_1^2 \cos^2\theta)^2} \dots\dots\dots (5)$$

Where  $\theta$  is the angle of the ray with the normal to the core-cladding interface, and  $n_1$  is the refractive index of the core of the fiber.

For p-polarized light, the general expression for the normalized transmitted power in an SPR-based optical fiber sensor is given by:

$$P_{trans} = \frac{\int_{\theta_c}^{\pi/2} R_p^{N_{ref}(\theta)} [n_1^2 \sin\theta \cos\theta / (1-n_1^2 \cos^2\theta)^2] d\theta}{\int_{\theta_c}^{\pi/2} [n_1^2 \sin\theta \cos\theta / (1-n_1^2 \cos^2\theta)^2] d\theta} \dots\dots (6)$$

Where  $N_{ref}(\theta)$  is the total number of reflections performed by a ray making an angle  $\theta$  with the normal to the core-metal interface in the sensing region, and given as:

$$N_{ref}(\theta) = \frac{L}{D \tan\theta} \dots\dots\dots (7)$$

Where  $L$  and  $D$ : are the length of sensing region and the fiber core diameter respectively.

The critical angle of the fiber  $\theta_c$  is given by:

$$\theta_c = \sin^{-1}\left(\frac{n_{cl}}{n_1}\right) \dots\dots\dots (8)$$

Where  $n_{cl}$  and  $n_1$  is cladding and core refractive index, respectively.

The reflectance  $R_p$  for a single reflection can be found using matrix method for N-layer model [16,17]. The matrix method is very accurate due to absence of approximations and can be applied to a system containing any number of layers. In the matrix method the layers are considered to be stacked along the z-axis. Here the important parameters for

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

any layer are: the thickness ( $d_k$ ), dielectric constant ( $\epsilon_k$ ), permeability ( $\mu_k$ ) and refractive index ( $n_k$ ). The tangential fields at the first boundary  $z=z_1=0$  are related to those at the final boundary  $z=z_{N-1}$  by the relation:

$$\begin{bmatrix} U_1 \\ V_1 \end{bmatrix} = M \begin{bmatrix} U_{N-1} \\ V_{N-1} \end{bmatrix} \dots\dots\dots (9)$$

Where  $U_1$  and  $V_1$  are the tangential components of the electric and magnetic fields respectively at the boundary of the first layer.  $U_{N-1}$  and  $V_{N-1}$  are the corresponding fields at the boundary of Nth layer.  $M$  is the characteristic matrix given by:

$$M = \prod_{k=2}^{N-1} M_k = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \dots\dots\dots (10)$$

With

$$M_k = \begin{bmatrix} \cos \beta_k & (-i \sin \beta_k) / q_k \\ -i q_k \sin \beta_k & \cos \beta_k \end{bmatrix} \dots\dots\dots (11)$$

Where

$$q_k = \sqrt{\frac{\mu_k}{\epsilon_k}} \cos \theta_k =$$

$$\frac{\sqrt{(\epsilon_k - n_1^2 \sin^2 \theta_1)}}{\epsilon_k} \dots\dots\dots (12)$$

and

$$\beta_k = \frac{2\pi}{\lambda} n_k \cos \theta_k (z_k - z_{k-1}) = \frac{2\pi d_k}{\lambda} \sqrt{(\epsilon_k - n_1^2 \sin^2 \theta_1)} \dots\dots\dots (13)$$

The amplitude reflection coefficient of p-polarized incident light is given by:

$$r_p = \frac{(M_{11} + M_{12} q_N) q_1 - (M_{21} + M_{22} q_N)}{(M_{11} + M_{12} q_N) q_1 + (M_{21} + M_{22} q_N)} \dots\dots\dots (14)$$

The reflectance of the p-polarized incident light is given by:

$$R_p = |r_p|^2 \dots\dots\dots (15)$$

## IV. THE SENSITIVITY

The sensitivity of surface plasmon resonance sensor is given by [18]:

$$S_n = \frac{\delta \lambda_{res}}{\delta n_s} \dots\dots\dots (16)$$

Where  $\lambda_{res}$  is the resonance wavelength corresponding to the refractive index of the sensing medium  $n_s$ .

## V. RESULTS AND DISCUSSION

For theoretical calculations, the refractive index of the sensing medium is changed from 1.30 to 1.4 in steps of 0.02 and the values of the parameters have been used are Numerical aperture of the fiber =0.77, fiber core diameter  $D=600 \mu\text{m}$  and length of the exposed sensing region  $L=10 \text{ mm}$ .

To optimize the thickness of the gold and ZnO layer, the transmitted output power of SPR based fiber optic sensor has been calculated for thicknesses of gold layer equal to 30nm, 40 nm, 50 nm and 60 nm at different thicknesses of ZnO equal to 0nm, 10nm, 15nm, 20nm and 25nm. Figure (2) shows the SPR resonance curves for 40nm gold layer and 20nm for ZnO. The SPR curve shifted to the right with the increase of refractive index.

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

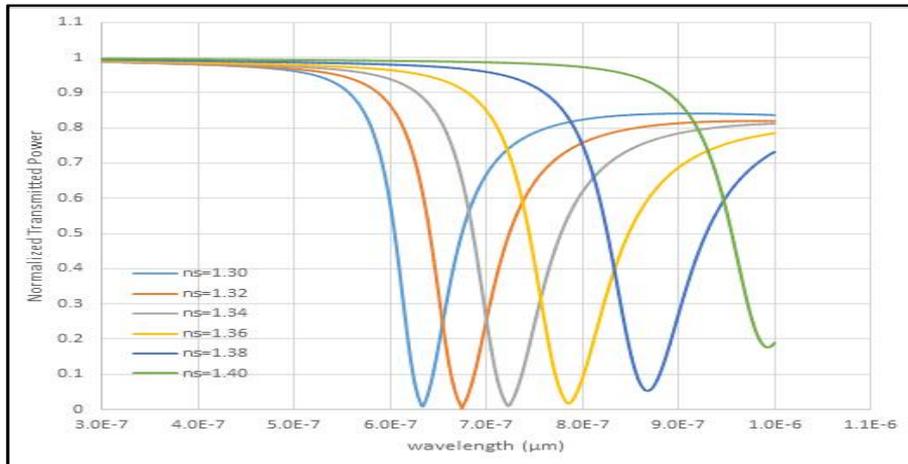


Figure (2): surface plasmon resonance curve at different refractive index values (1.3, 1.32, 1.34, 1.36, 1.38, and 1.4 from left to right) for thicknesses 40nm and 20nm for gold and ZnO layer respectively.

Figure (3) shows the plot of SPR resonance wavelength for 30nm, 40nm, 50nm and 60nm thickness of gold layer and for 0nm, 10nm, 15nm, 20nm, and 25nm thickness of ZnO layer. The resonance wavelength increases linearly with the increase in refractive index of the sensing medium. The slope of each curve in the figure (3) represents the sensitivity of sensing.

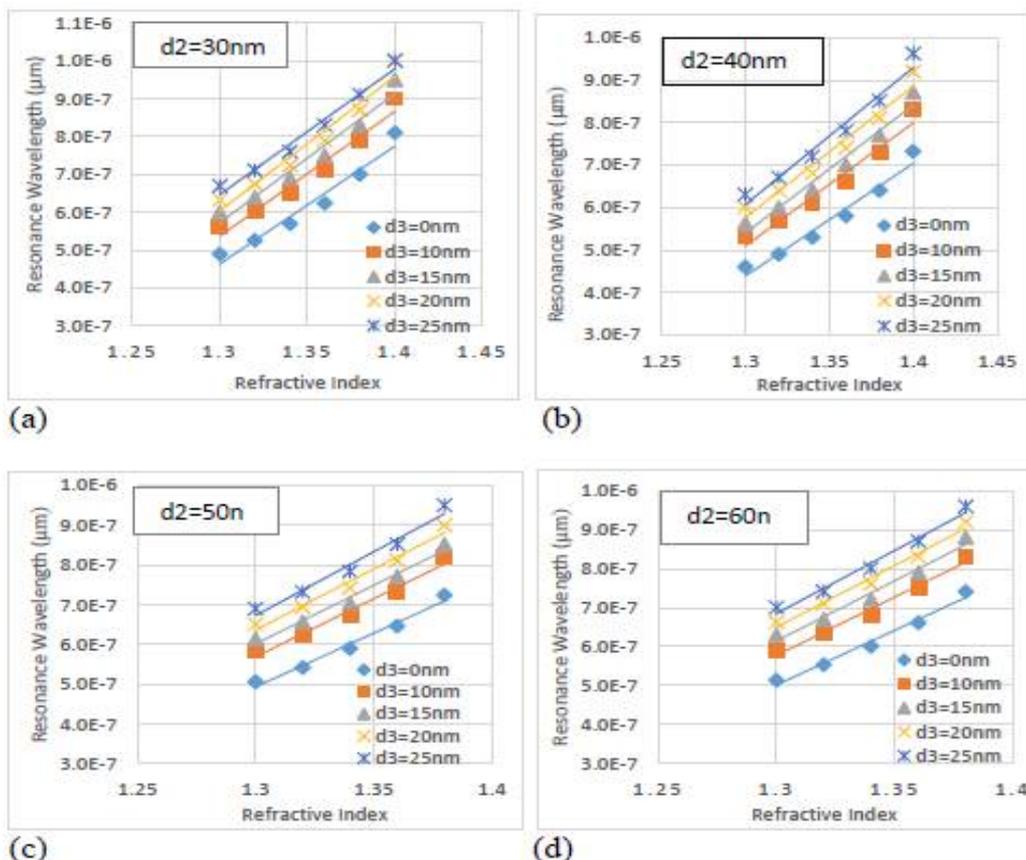


Figure (3): Variation of resonance wavelength with refractive index of sensing medium at thickness of gold and ZnO layers (30, 40, 50 and 60nm) and (0, 10, 15, 20, 25nm) respectively.

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 7, July 2016

As shown in the table (1) and also in figure (4) the sensitivity increase with the increasing of the thickness of ZnO layer. The largest value of the sensitivity gets in this study were 3.556  $\mu\text{m}/\text{RIU}$  at the thicknesses 20nm and 40nm of the ZnO and gold layer respectively.

Table (1): Sensitivity at different thicknesses of gold and ZnO layers.

Sensitivity ( $\mu\text{m}/\text{RIU}$ )				
	$d_2=30\text{nm}$	$d_2=40\text{nm}$	$d_2=50\text{nm}$	$d_2=60\text{nm}$
$d_3= 0 \text{ nm}$	2.657	3.109	2.700	2.820
$d_3= 10 \text{ nm}$	2.900	3.299	2.920	3.000
$d_3= 15 \text{ nm}$	3.013	3.393	2.950	3.100
$d_3= 20 \text{ nm}$	3.100	3.556	3.075	3.180
$d_3= 25 \text{ nm}$	3.229	3.314	3.200	3.245

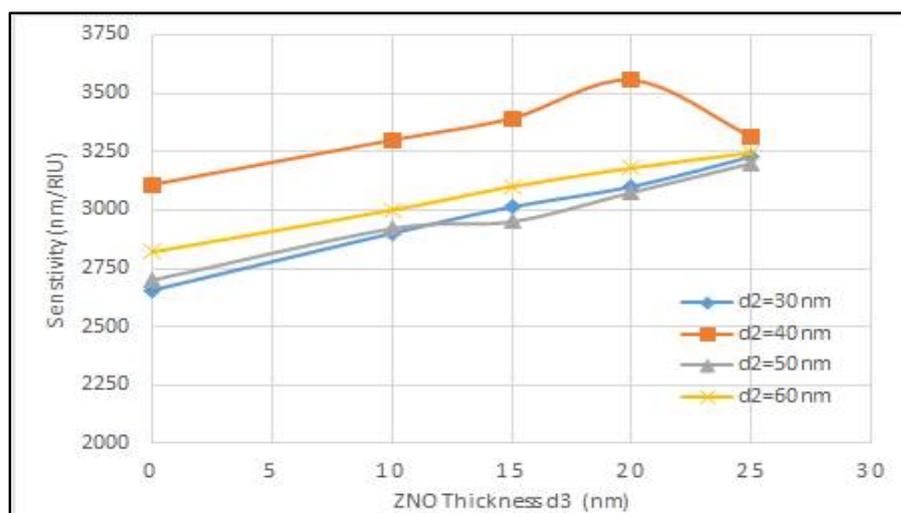


Figure (4): sensitivity variation with the ZnO thickness ( $d_3$ ) for different values of gold thickness ( $d_2$ ).

## VI. CONCLUSION

SPR-based optical fiber sensor utilizing gold and ZnO layers has been theoretically studied. The varying of ZnO and gold layer thicknesses leads to changing of the sensitivity of sensing. The sensitivity, increase as ZnO thickness increase for each thickness of gold layer within the studied ranges. The optimum thicknesses were 40nm for gold and 20nm for ZnO.

## REFERENCES

1. Gupta, B.D.; Verma, R.K. Surface plasmon resonance –based fiber optic sensors: Principle, probe, designs and some applications. J. Sens. (2009) doi:10.1155/2009/979761.
2. Alireza, H.; Bertrand, G.; Majid Fassi, F.; Andrei, K.; Maksim, S. Photonic crystal fiber and waveguide-based surface plasmon resonance sensors for application in the visible and near-IR. Electromagnetics" (2008) 25, 198-213.
3. Homola, J.; Yee, S.; Gauglitz, G. Surface plasmon resonance sensors: Review. Sens. Actuators B: Chem. (1999), 54, 3-15.
4. Barnes, W.L.; Dereux, A.; Ebbesen, T.W. Surface plasmon subwavelength optics. Nature (2003), 424, 824-830.
5. Coelho, L.; de Almeida J.M.; Santos, J.L.; Ferreira, R.A.; Andre, P.S.; Viegas, D. Sensing structure based on surface plasmon resonance in chemically etched single mode optical fibers. Plasmonics (2014), doi: 10.1007/s11468-014-9811-3.
6. Kretschmann, E.; Raether, H. Radiative decay of non-radiative surface plasmons excited by light (surface plasma waves excitation by light and decay into photons applied to nonradiative mode). Z FuerNaturforschTeil (1968), A23:2135.

## International Journal of Innovative Research in Science, Engineering and Technology

*(An ISO 3297: 2007 Certified Organization)*

**Vol. 5, Issue 7, July 2016**

7. Jorgenson, R.C.; Yee, S.S. A fiber-optic chemical sensor based on surface plasmon resonance, *Sensors and Actuators B* 12 (1993) 213-220.
8. Sharma, A.K.; Jha, R.; Gupta, B.D. Fiber-optic sensors based on surface plasmon resonance: a comprehensive review, *Sensors Journal, IEEE* 7 (2007) 1118-1129.
9. Ma, Y.; Du, G.T.; Yang, S.R.; Li, Z.T.; Zhao, B.J.; Yang, X.T.; Yang, T.P.; Zhang, Y.T.; Liu, D.L., Control of conductivity type in undoped ZnO thin films grown by metalorganic vapor phase epitaxy, *J. Appl. Phys.* 95 (2004) 6268-6272.
10. Gupta, S.K.; Joshi, A.; Kaur, M. Development of gas sensors using ZnO nanostructures, *J. Chem. Sci.* 122 (2010) 57-62.
11. Sharma, R.K.; Patel, S.; Pargaien, K.C. Synthesis, characterization and properties of Mn-doped ZnO nanocrystals, *Adv. Nat. Sci.* 3 (2012) 035005.
12. Wang, J.X.; Sun, X.W.; Wei, A.; Lei, Y.; Cai, X.P.; Li, C.M.; Dong, Z.L. Zinc oxide nanocomb biosensor for glucose detection, *Appl. Phys. Lett.* 88 (2006) 233106.
13. Kimure, T. Basic concepts of the optical waveguide in optical fiber transmission, K.Noda (Ed), North Holland (1986).
14. Maier, S.A. *Plasmonics: Fundamentals and applications*, Springer (2007).
15. Gupta, B.D.; Sharma, A.; Singh, C.D. Evanescent wave absorption sensors based on uniform and tapered fibers: a comparative study of their sensitivities. *Int. J. Optoelectronic.* 8 (1993) 409-418.
16. Hecht, E. *Optics*, Addison- Wesley Publishing Company (1990).
17. Gupta, B.D.; Sharma, A.K. Sensitivity evaluation of a multi-layered surface plasmon resonance based fiber optic sensor: A theoretical study, *Sensors and Actuators B* 107 (2005) 40-46.
18. Sharma, A.K.; Gupta, B.D. On the sensitivity and signal to noise ratio of a step-index fiber optic surface plasmon resonance sensor with bimetallic layers. *Opt. Commun.* 245 (2005) 159-169.