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Multi-Response Nanowire Grating Coupled Surface Plasmon Resonance by Finite Element Method

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Abstract

In this paper, surface plasmon resonance has been applied for sensing acetone liquid by changing refractive index, based on nanowire grating. This sensor is proposed and numerically analyzed using finite element method. The SPR sensor is composed of multi-nanowires distributed in a parallel order at specific distance. These wires were deposited onto the dielectric material and tested using laser light at wavelengths range from 500 to 700 nm. Dual SPR dips were emerged at two different SPR angles after further tuning of incident angle. The multi SPR dips are angularly wide but spectrally very sharp results. Sensor results were compared at four different plasmonic materials gold, silver, aluminum and copper using 532 nm wavelength. These plasmonic materials were tested using acetone at 100%, 50%, 10% concentrations. The sensitivity measurements of the sensor have shown that the dual SPR dips can be used efficiently to increase the sensitivity of the designed sensor. Both dips were also used to increase the detection sensitivity of different types of liquids. The sensitivity of SPR causes a shift in dip or intensity due to any small change in refractive index. This shift is varying according to the material and liquid concentration. The sensitivity of nanowire grating was measured by varying the refractive index with the resonance angle (θ°) at a single wavelength. The highest sensitivity has been discovered for gold which is 290.57°/RIU. This work is adopted for the improvement of the surface plasmon sensor using nanowire technology. The structure is easy and simple and can be apply to different applications.

Keywords

Surface plasmon, sensor, SPR, grating, nanowire,

Introduction

Optical sensors play a distinguish role in our life due to unprecedented changes in recent years have witnessed in the way of sensors work [1]. To create a remarkable change in sensors has led to the intensification of efforts to researchers to design new sensors can best meet our needs. Different optical sensors have been designed to reduce time, cost and enhanced the daily processes [2]. However, laboratory design methods normally need significant efforts as well as different scientific fields which are mostly solved by computer simulation[3].

Simulation programs have proved to be a crucial adjunct in analysis and fully understand sensor properties. Modeling programs solve sensor problems efficiently, safely and easily verified. Therefore, sensor modeling programs are important aspect in many nano applications for developing selective sensors [4]. By using simulation programs, plasmonic behavior can be tested under different surface shape of plasmonic materials for instance circle, square and flat surface.

Surface plasmon Resonance (SPR) is an electromagnetic phenomenon that occurs in a thin flat layer of conducting films deposited at the interface between two different refractive indices layers. Fiber, prism (Kretschmann and Otto configurations), grating, and waveguide configurations are convenient for generating SPRs [5][6][7]. The kretschmann configuration is consists of a plasmonic material film deposited directly on the prism or on the glass slide and attached to the prism [8][9]. When an incident (transverse magnetic) TM polarized light strikes conducting layer such as gold at a given angle, a plasmonic wave will generate and propagate along the interface of a thin metal layer [10]. SPRs dissipate their electromagnetic wave foremostly through metal layer interaction. This loss is due to scattering of free-electron in the plasmonic layer and, by optical absorption throughout electronic interband transitions [11]. This barrier has encouraged researches to understand the physics of SPR from amplification and feasibility achieving SPR of loss compensation.

Since the first SPR sensor which was invented in 1982 [12], different approaches are proposed from several groups to enhance SPR sensitivity. Each approach has its unique design among a wide range of variables in SPR design, such as plasmonic materials, optical design (multipath), nanomaterials, supercontinuum exciting SPR, magneto optic SPR, Fabry Perot based SPR, and Bragg grating based SPR. Furthermore, SPR measurement sensitivity significantly varied according to the type dielectric for instance (liquid or gas) as well as to the type of configuration (prism, optical fiber and diffraction grating).

Light losses and propagation are general properties of surface plasmon resonance. These properties can be enhanced by depending on shape design of metal nanowires [13]. Au nanowire has attracted substantial attention in sensor applications [14] due to the ability to absorb more than 50% of low energy photons[15]. According to the literature, the benefit achieved in sensitivity throughout nanowire is ~800°/ RIU [16]. The angular sensitivities sensors were reported below 100/RIU for diffraction grating-based SPR, and mostly are enhanced by making the SPR dips of the +1st order of the diffraction grating better [17]. Massive efforts have been devoted to achieve perfect sensitivity, including changing the plasmonic materials [18], and their geometrical shapes, dimensions, and interval between the structures [19]. A comparison of acetone sensitivity, based on SPR principle under different configuration, is shown in table 1.

Method	Sensitivity	Ref.
noninvasive screening and monitoring of diabetes with doped polyaniline (PANI) layer by use acetone sensor	The sensor sensitive was measured from the penetration depth through the dielectric (2.68 µm). By using WinSpall SPR simulation software, the results were built based on Fresnel equations at Mid infrared wavelength (3000nm). The shift in SPR angle for the modelling is 6.410, while it is 80 for the simulation.	[20]
Acetone Sensor based on Hierarchical 3-D TiO2 Nano flowers is tested for Volatile Organic Compound (VOC) sensing under a low temperature hydrothermal process	The practical results have shown fast response/ recovery of ~6-15s / ~15-39s authenticated the potentiality of the sensor devices under 60ºC optimum operating condition. The response magnitude was found to be 3.45% (66.58%) with the corresponding response time of 33s (19s) and recovery time of 11s (37s) for 1ppm and 700ppm acetone	[21]
Dual Sensing Arrays Based on Nano-wire / Nano-rod Hybrid Nano structures for Surface Plasmon Resonance and Surface-Enhanced Raman Scattering	This configuration indicated that both Raman signals and thickness sensitivity can be enhanced by adding Nano rod structures into nano-wire arrays. Furthermore, It was noted that the Surface-Enhanced Raman Scattering sensitivity can be further improved when reducing the width of nano-wires and the gap width between nano-rods.	[22]
Detection of Acetone Vapor based on the reflectance on the optical and geometric properties of the sensitive over layered of the graphene film when the vapor molecules are absorbed on it.	The sensor shows accepted response upon exposure to various concentrations of acetone vapor from 44 ppm to 352 ppm. Also It is clear that the greater the dilution of the acetone vapor, the smaller the variation in the reflected optical power	[23]

Table 1. Comparison of acetone sensitivity under different configuration

In this work, we report the nanowire grating using surface plasmon resonance in liquid sensor (refractive index sensor). The experiment was conducted to use dual sensing points at different concentrations of acetone. The results also proved that SPR depends on the shape of the excited surface. Conventional mounted nanowire grating dual sensing point was first time proposed theoretically for single wavelength. In this design, the parallel notches or steps in conventional grating were replaced by the parallel nanowires.

Theory

The main condition for the generating of plasmon waves in wire grating technique is coupling of the tangential component of incident light with real part of plasmonic surface material [16][20]. These waves will generate if the incident light from the side of the plasmonic material with a higher refractive index, typically a glass material. At a specific angle, the optical absorption of incidence light will increase. When this angle equals the SPR angle of the specific material and wavelength, the plasmonic dip reaches to the maximum. The reflectivity of the plasmonic film is normal at all angles except for short range of angles around theta SPR (θ_{SPR}) where the absorption at maximum [21]. This maximum absorption will happen under occurrence matching between wavevector of the incident light and the wavevector of the surface plasmons. The criterion for positive interference is that the difference in optical path length along the two paths equals an integer number of vacuum wavelengths, or [22]:

$$\boldsymbol{m\lambda_0 = \mathrm{d}(n_\beta\, sin\beta_{\,m} - n_\alpha sin\alpha)......1}$$

With m = 0, ±1,± 2,..., $\lambda 0$ the vacuum wavelength, and βm the transmitted diffracted beam of order m. For m = 0, this reduces to refraction, as described by Snell's law Figure 1[20]:

$$\boldsymbol{n_\beta sin\theta_\beta = n_\alpha sin\theta_\alpha.........2}$$

$$\boldsymbol{2\lambda_0 > dna\ (1 + \ \mathrm{sin}\alpha)......3}$$

The SP wave via a diffraction grating is [23]:

$$\boldsymbol{n_d sin\theta_\alpha + m\frac{\lambda}{\Lambda} = \pm\sqrt{\frac{\varepsilon_m n_d^2}{\varepsilon_m + n_d^2}}\ ....4}$$

where $\theta\alpha$ is the SPR angle, Sign '+' related to orders of diffracted waves ($m > 0$) and sign '−' related to orders of diffracted waves ($m < 0$). Eq. (4) represent that the resonant angle $\theta\alpha$ relies on the refractive index of dielectric n_d medium, thus, the diffraction configurations can be used as a refractive index sensor in angular interrogation method.

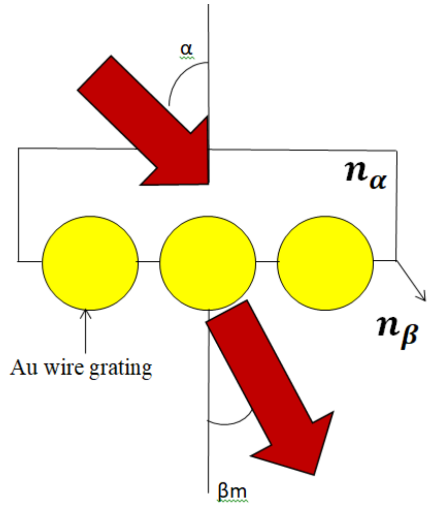

Fig.1. Optical path of Au wire grating at the plane of incidence

The plasmonic capability of the nanowire grating depends on the polarization effects of the incident wave. For this reason both a transverse magnetic mode (TM) and transverse electric mode (TE) are applied. The electric field vector of the TE wave has Z direction existing of the XY- modeling plane. Whereas the electric field component of the (TM) wave is perpendicular to the direction of propagation and forming in the XY-plane. While the magnetic field component establishes only in the z-direction.

Simulation work

FEM (Finite Element Method) was adapted to enhanced nanowire grating SPR. The sensor consists of four different layers as shown in Figure 2. These sensor layers are air, glass 0.3 mm thickness, Au nanowire 80 nm diameters and the last one is dielectric substrate.

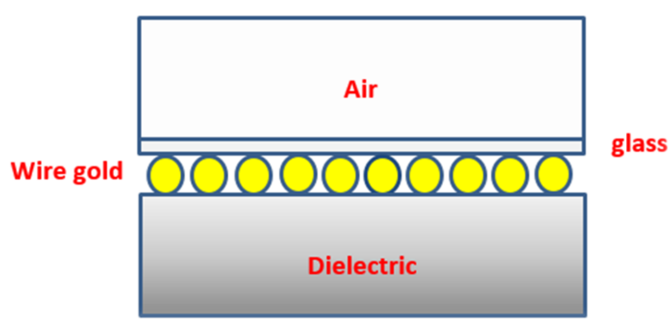

Fig.2 nanowire grating sensor

The model of the nanowire uses $n\alpha = 1$ for air and $n\beta = 1.2$ for the dielectric substrate. Furthermore, acetone and acetone are used as a dielectric substrate with different concentrations and multiple materials (Au, Ag, Al, and Cu) at circular nanowire shape.

The laser beam is projected on the first layer from the top of the designed sensor. Approximately half of the wave is absorbed in the gold wires. The presence of free electrons at the interface of two materials (gold wire with dielectric) in practice this almost always implies that one of these materials is a metal where free conduction electrons are abundant. This condition follows naturally from the analysis of a metal dielectric interface. The angle of incidence is taken from 0 to π/2, with a pitch of π/1000. The nano-gold wire is designed with radius 40nm and the permittivity of the gold ε = −4.6810 – 2.4266*i*.
The refractive index of acetone is measured by Lorentz-Lorenz equation Eq.5 and listed in table 1

$$\frac{n_{mix}^2-1}{n_{mix}^2+2} = q1\left[\frac{n_1^2-1}{n_1^2+2}\right] + q2\left[\frac{n_2^2-1}{n_2^2+2}\right] \quad \textbf{5}$$

Where n_1 and n_2 are the refractive indices of the two liquid and q1,q2 are the percentage of the liquid.

concentration	acetone
100%	1.359000
50%	1.343889
10%	1.332768

Table1. The concentration of acetone used in the experiment

Results and discussion

Surface plasmon response to the angle of incident and reflectance of sensing film which is a nanowire. The coupling between the incident light and the material of the nanowire depends on the wavelength of incident light and the type of plasmonic materials. Figure 3 showed the difference between the TM mode and TE mode using nanowire grating. The SPR excitation was clearly appeared in TM mode as shown in the red and yellow regions. These colors of SPR waves generated in nano wire appeared around the top half of circle shape (where the light falls). The shape of the material surface was change to a square shape as shown in Figure 4A and 4b. The SPR curve shows a large and wide dip compared to the nanowire (circle shape) that have dual dips. The nanowire circle shape will be used and applied to SPR sensor for detection acetone but -the primer key of the experiment will be the wavelengths at different plasmonic materials.

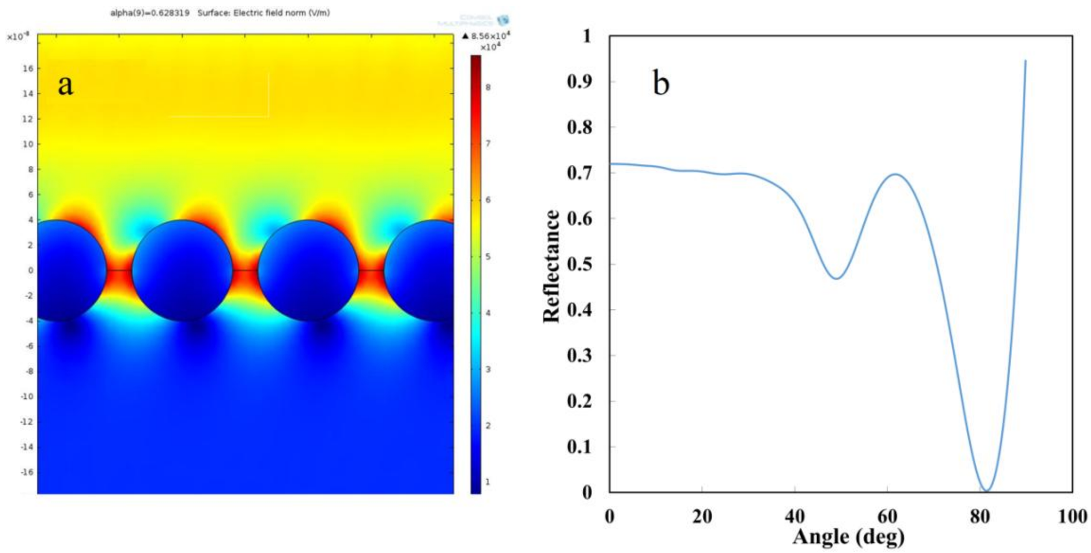

Fig.3. nanowire grating surface plasmon circular shape

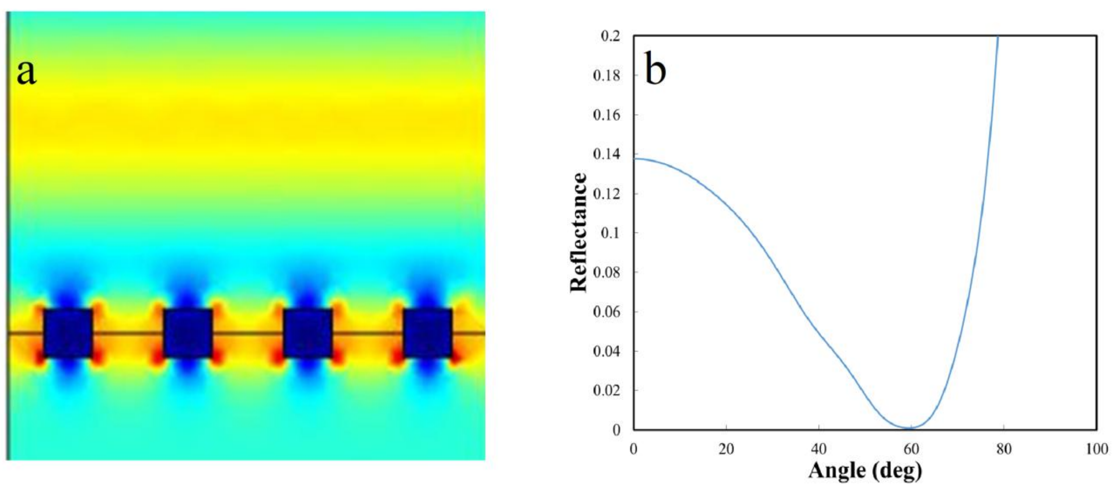

Fig.4. nanowire grating surface plasmon square shape

The SPR has an effective relation with wavelength i.e. type of excited wavelength short or long wavelength. In Figure 5 the reflection of the gold nanowire is varied with a wavelength between 200 to 700 nm. The result shows higher reflection for the gold nanowire at 500 nm. Plasmonic material which is the second important reference for generating surface plasmon is presented. This figure proves that using nanowire grating gives two absorption points for plasmonic materials gold, copper, aluminum, and silver. These absorption points have different characteristic according to the type of plasmonic material and wavelength that used to excite the plasmonic waves. The best absorption points dwell between 40^{o} and 80^{o}. The best plasmonic material as shown in this figure was the Silver which has the minimum resonance dip compared with Aluminum, Gold and Copper.

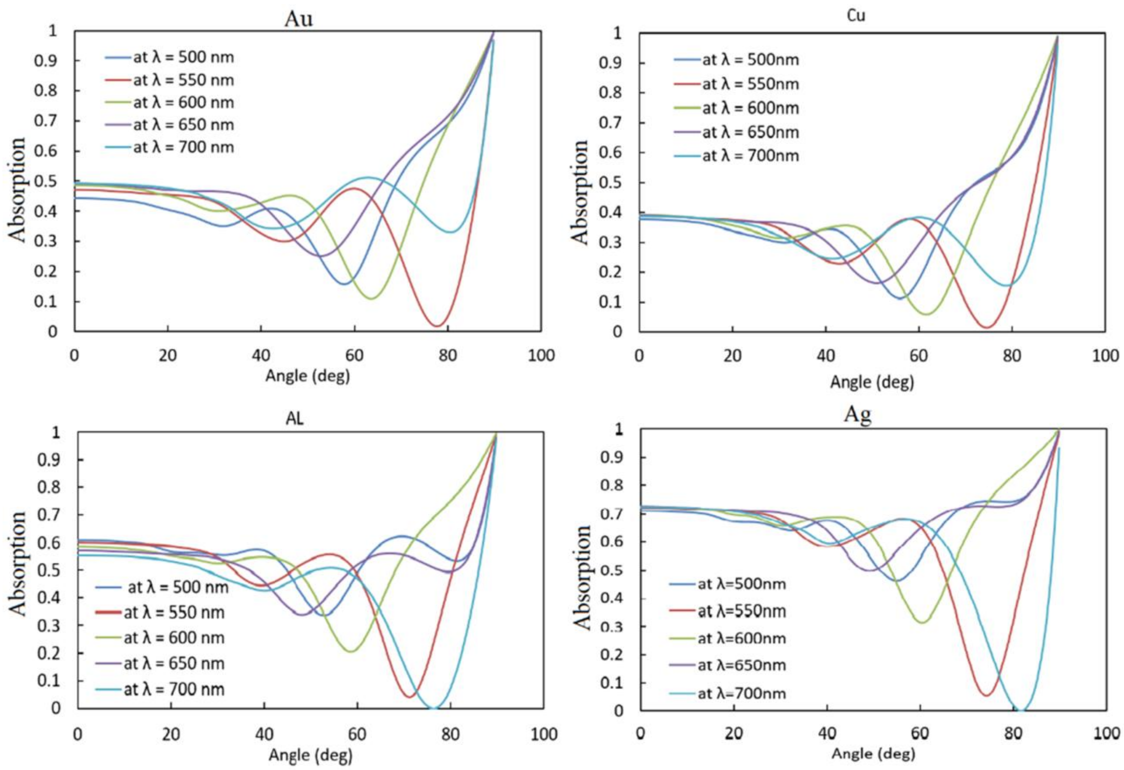

Fig.5. Absorption of different plasmonic material using nanowire grating

These plasmonic materials have a very strong plasmonic effect varied according to the incident wavelength. In this research plasmonic materials were excited using 532 nm laser wavelength as shown in Figure 6. The two-dips (a) and (b) point appeared by this wavelength at two different angles (different positions). The first dip (a) appeared after total internal reflection point for all test materials, the best minimum dip was copper. The second dip (b) was sharper and deeper than the first one except for gold and copper, the best minimum dip was Aluminum at an angle near to 80^{o}.

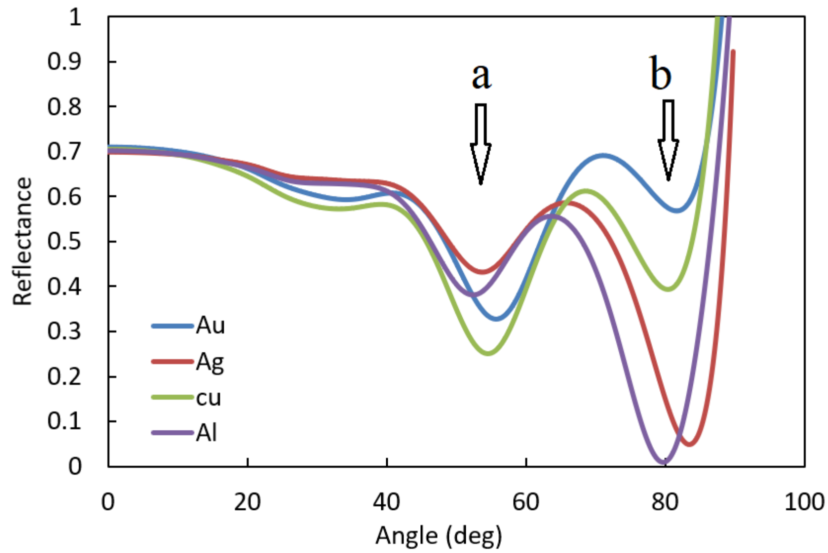

Fig.6. Plasmonic materials excited at 532 nm

Both dips that generated from this design can be used to increase the detection sensitivity to different types of liquids, gas, and vapors. The sensitivity of SPR to any small change in refractive index will cause a shift in dip or intensity or both. In some tests, the variation in SPR dip is very difficult to recognize it, especially if in 10^{-5} degree. So the existing of four detection points two for angle and two for intensity may help to increase the sensitivity especially at part per billion concentrations. Acetone was tested at different concentrations 10%, 50% and 100% using dual dip design is curved in Figure 7. The plasmonic materials Au, Cu, Al, and Ag show different shift according to the different concentrations. The first dip shifted down by increasing acetone concertations. However, the second dip shifted up by increasing the concentrations. This shift is varying according to the material and concentration. This shift can measure by measuring the sensitivity which depends on the variation between the angle shifts. The sensitivity measurements for the tested materials were presented in Figure 8.

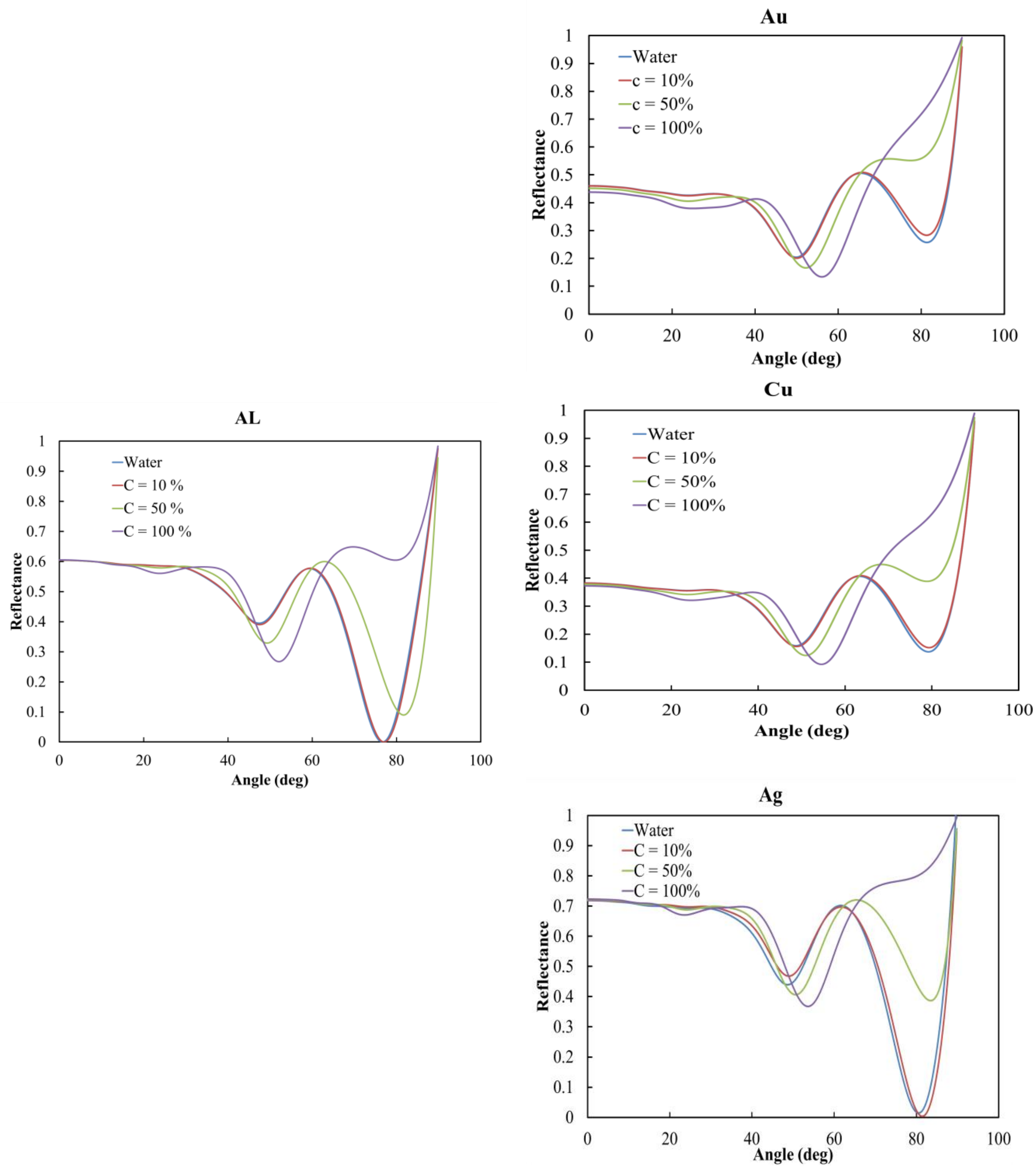

Fig.7 Acetone test at three concentrations of Au, Cu, Al, Ag

The sensitivity of nanowire grating-based SPR sensors variations in the refractive index can be determined by Eq. (4) in θ and n_d. This results in [24]:

$$S = \frac{d\theta}{dn_d} = \frac{1}{n_d \cos(\theta)} \left(\pm \left(\frac{\varepsilon_{mr}}{\varepsilon_{mr} + n_d^2} \right)^{3/2} - \sin(\theta) \right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{6}$$

The SPR sensors coated with Ag film shows higher sensitivity well known as compared with other plasmonic materials [25]. In Figure 8 the Au layer at point (a) shows higher sensitivity followed by Cu, Ag and Al for the first dip. The higher sensitivity gives higher stability as well as the sensitivity depends on the length of the sensing region and the thickness of the material. When sensitivity becomes higher the selectivity becomes better especially at shorter wavelengths [26]. However, the measurement of sensitivity using angle interrogation is possible by multi values. These values varied between point (a) and (b) as well as the intensity variation related to these two points. The maximum sensitivity value was at point (b) for Al layer at concentration 50%. However, the minimum sensitivity value was at point (a) for Au and Cu. The sensitivity starts and ends at low value and the maximum at the middle range of concentration.

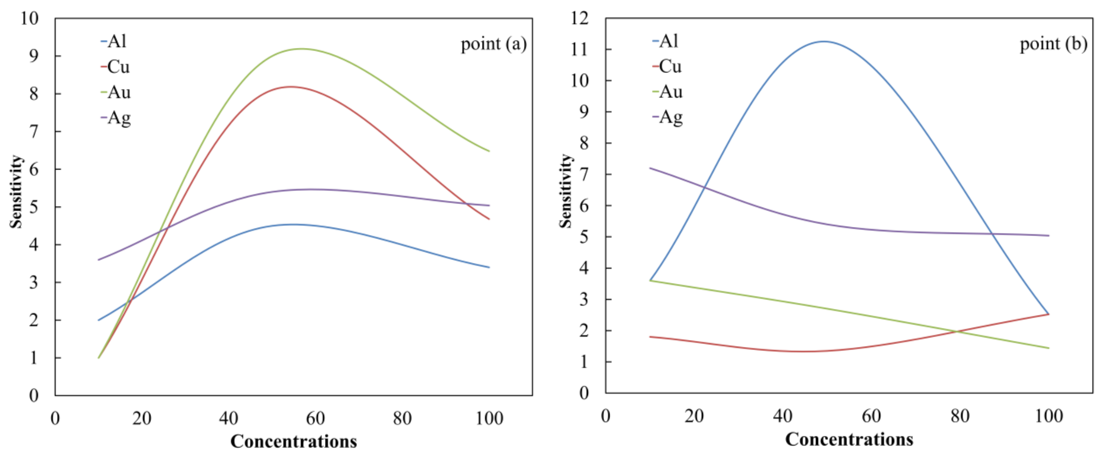

Fig.8. Sensitivity at point (a) and (b) for different plasmonic materials

SPR can be measured by coupling of resonance angle and intensity in angle interrogation method. When SPR excited at the interface between a dielectric medium and the metal surface, the optical properties for example reflectance are drastically changed [27]. This change can be observed as a shift in resonance angle then overall the sensitivity as shown in Fig. 9. The results of the Au, Al, Cu and Ag – based SPR diffraction grating sensors is represented as variation of angle shift with refractive index . And the sensitivities of the four cases are 290.57/RIU, 235.9/RIU, 239.95/RIU and 198.57/RIU, respectively. It is visible that in the plasmonic materials at the point (a) dip, there is a big influence on the sensitivity of the SPR sensors. From the overall materials, the Au is slightly better than the Al. however, the sensitivity at point (b) shows a lower shift in the resonance angle compared with point (a). The shift in reflectance intensity is more dependable and visibly in point (b).

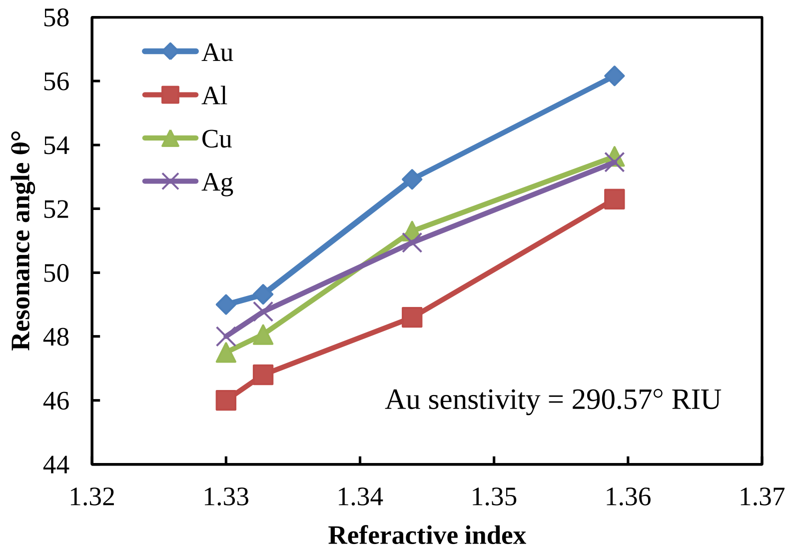

Fig 9. Analysis between SPR resonance angle and the refractive index of acetone

Conclusion

In summary, we have demonstrated that an enhancement in sensitivity can be obtained in nanowire grating when multi response points were obtained using a single wavelength. The shift in resonance angle and intensity are possible for these points. Although the lower shit in resonance angle we can still depend on an intensity shit in SPR dip. The sensitivity for gold was 290.57/RIU. Which is the better plasmonic material compared with tested materials. The improved of the nanowire grating SPR had a linear range of sensitivity for angle shift.

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