

Plasmonic Optical Fiber Sensors using Different Nanoparticles

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ABSTRACT

This paper present an investigation on Localized Surface Plasmon based optical fiber sensor and comparative performance of design with nanoparticles of different material on the tip of fiber. It is found that the Silver nanoparticles have higher sensitivity of 300nm/RIU and 10.7 figure of merit when refractive index of surrounding varies from 1.33 to 1.36. Whereas the copper and aluminum has the sensitivity of 133nm, 333nm, figure of merit of 2.7 and 8.1 respectively. It is also observed that the Surface Plasmon Resonance curve of silver nanoparticles has narrow width which improves the detection of accuracy as compared to copper and aluminum.

Keywords

Optical fiber sensor, nano-particles, refractive index, Surface Plasmon Resonance.

1. INTRODUCTION

With the event of glass fiber technology and communication technology, the optical fiber sensing technology has been replacing variety of detector. In which surface Plasmon resonance sensor take more attention because of less susceptible to external factors like light fluctuations, environment and so on. It has several advantages due to label free, high selectivity, high speed responsibility. In SPR technique, a TM (transverse magnetic) or p-polarized light causes the excitation of electron density oscillations (known as surface Plasmon wave, SPW) at the metal-dielectric interface. In optical fiber to excite SPR metal dielectric surface formed near to the core. Firstly a prism was used to excite the surface plasmons [1–9]. The prism-based SPR detector has many of disadvantages such as big in size and the existence of some optical and moving parts. In remote sensing application prism based SPR sensor cannot be applicable. To overcome this prism is replaced by optical fiber [10]. SPR probe can be miniaturized in optical fiber, which can be advantageous for samples which are available in small quantity or are costly. The motivating optical properties are determined by the localized and propagating surface Plasmon resonances (SPR). These Plasmonic resonances of the metal surfaces can be adapted by proper tuning of the physical and geometrical parameters of such structures [11, 12]. Because of these benefits the surface Plasmon resonance-based optical fiber sensors have drawn a lot of attention [13–18]. For LSPR sensor various type of metals like silver, copper and aluminium used at the surface near sensing layer to excite these waves. Pradeep Kumar Teotia et al [19] obtained high sensitivity using multilayer grating configuration. Peipei Jia et al [20] found that Sensitivity of SPR based sensor highly affected by changing the shapes and thickness of the metal.

In previous work, J. Gabriel Ortega Mendoza et al [21] used silver nano particles at the tip of fiber and sensitivity found to be 67.5nm/RIU. To extend the work, new design of LSPR based optical fiber has been proposed, in which resonance sensitivity enhances to 330nm/RIU and 28nm FWHM which increase FOM for better sensitivity of sensor.

2. DESIGN AND SIMULATION METHOD

Figure 1(a) depicts the 2D design of LSPR based optical fiber sensor modeled within OptiFDTD simulation by solving Maxwell equation. This is the FDTD method based simulator employed for determining the electromagnetic behavior of the design.

Plasmonic properties of the noble metal are used for detection in this proposed structure of optical fiber sensor. Plasmonic is the study and application of the interactions of optical-frequency electromagnetic field oscillations with the free electrons in a metal, which behave like a charge-separated gas, or plasma. Nanoparticles of silver, copper and aluminum of size 100nm are used at the tip of fiber to excite LSPR and detection plane used behind the Gaussian source input for comparative result of these different material. The observation plane z-x is used to detect the excitation of LSPR. Bragg grating formed with in core by uniformly changing the refractive index from 1.46 to 1.48 as shown in design.

The relative permittivity $\epsilon_r(\omega)$ of the different Nano-particles was determined using the multi-oscillator Lorentz-Drude model [22].

$$\epsilon_r(\omega) = \epsilon_\infty + \sum_{m=0}^M \left(\frac{f_m \omega_p^2}{\omega_m^2 - \omega^2 + i\omega\Gamma_m} \right)$$

Where

ϵ_∞ = Permittivity at infinite frequency

f_m = Oscillator strengths

Γ_m = Damping frequency

ω_p = Plasma frequency

ω = Incident wave frequency

ω_m = resonant frequency

The plasma frequency (ω_p) used for the Silver 0.14 x10¹⁷rad/sec, copper 0.164 x10¹⁷rad/sec and aluminium 0.227 x10¹⁷rad/sec respectively. The rest of the parameters for these metals are given in table1 [22]. The input wave is

continuous and centred at 680 nm which is linearly polarized in y-direction and convolved with a Gaussian envelope function. The mesh size is to be small enough to catch the wave attenuation within the skin depth.

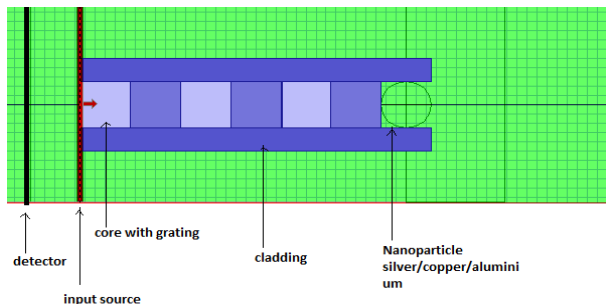


Fig.1 Design of SPR sensor with silver nanoparticles

3. RESULT AND DISCUSSION

The LSPR sensor response curve is plotted as relative power versus wavelength. When resonance occurs then at particular wavelength, a sharp dip reflected known as resonance wavelength. The position of dip is changing by varying the refractive index of surrounding. This change highly affects the parameters of SPR optical fiber sensor. For the most effective performance of the sensor, resonance sensitivity and figure of merit should be high. Sensitivity depends upon the change in resonance wavelength when refractive index (ns) of surrounding varies as given in equation (5).

$$S_n = (\Delta \lambda_{res}) / (\Delta n_s) \dots\dots\dots (5)$$

$\Delta \lambda_{res}$ = change in Resonance wavelength

Δn_s = change in Refractive index of surrounding

A figure of merit (FOM) is presented to calculate and measure the sensing capability of the Plasmonic sensor. Formally, FOM is a dimensionless quantity that counts the effects of line width or FWHM (Γ) and the shift in the resonance wavelengths. It is often calculated as equation 6.

$$FOM = S_n / \Gamma \dots\dots\dots (6)$$

After modeling and simulating the Plasmonic structure of optical fiber sensor, performance parameter is numerically analyzed using nano particles of different materials such as copper, silver and aluminum as shown in figure 2 ,3 and 4 respectively. Resonance Sensitivity for the proposed structure with copper is 133nm/RIU, with aluminum is 333nm/RIU, and with silver is 300nm/RIU on varying refractive index from 1.33 to 1.36.

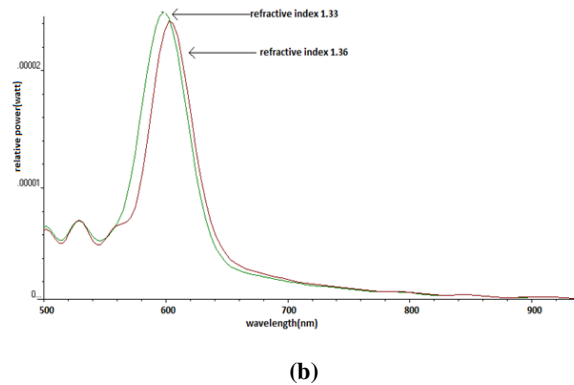


Fig 2. Excitation of LSPR in x-z plane with copper in fig (a), Reflectance of LSPR sensor at refractive index 1.33 and 1.36 using copper nanoparticles in fig (b)

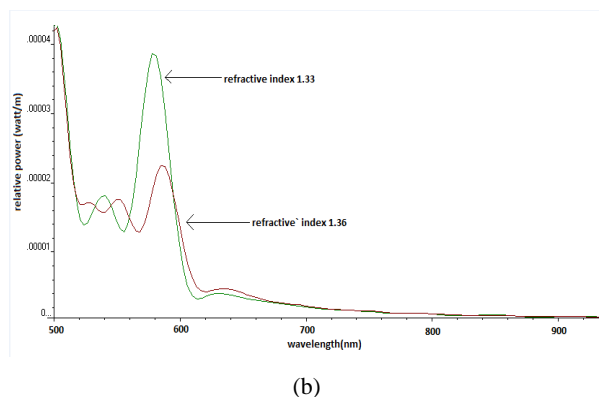
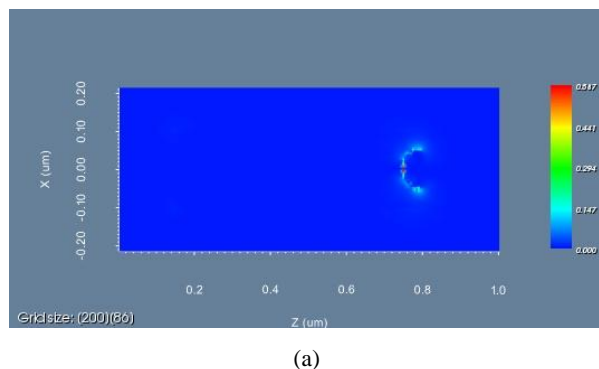
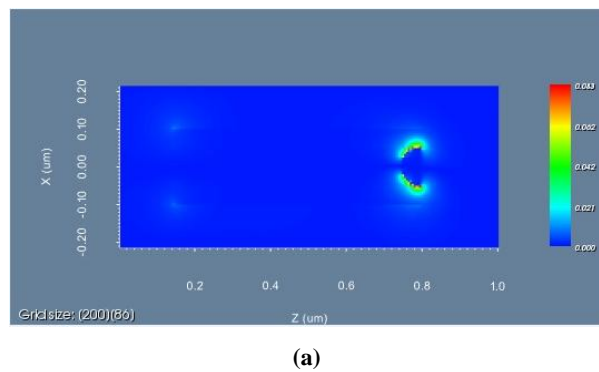
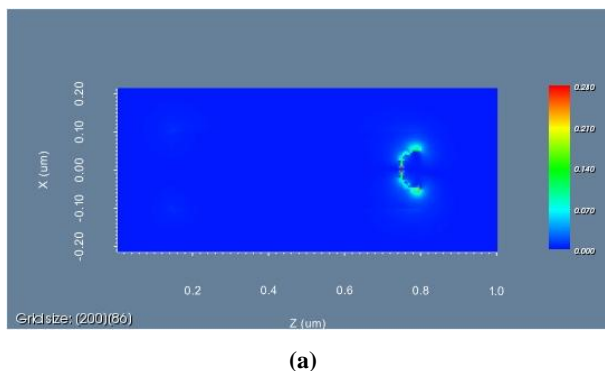


Fig 3. Excitation of LSPR in x-z plane with silver in fig (a), Reflectance of LSPR sensor at refractive index 1.33 and 1.36 using silver nanoparticles in fig (b)



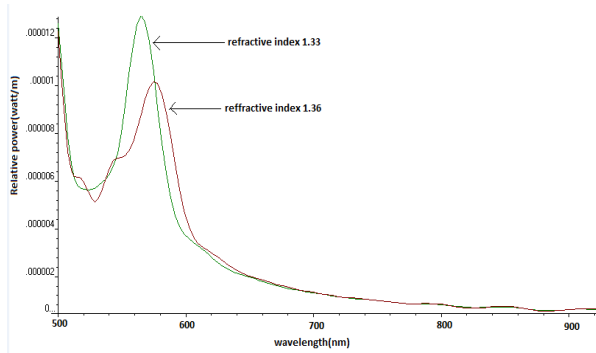


Fig 4. Excitation of LSPR in x-z plane with aluminum in fig (a), Reflectance of LSPR sensor at refractive index 1.33 and 1.36 using aluminum nanoparticles in fig (b)

Comparison for different materials is as shown in fig 5. From the observation, it is concluded that silver has lowest value of FWHM that is 28nm and better FOM as compared to copper and aluminum as shown in table 2. LSPR sensor using silver

particles having sensitivity of 300nm/RIU which is comparatively better than the previous work [19].

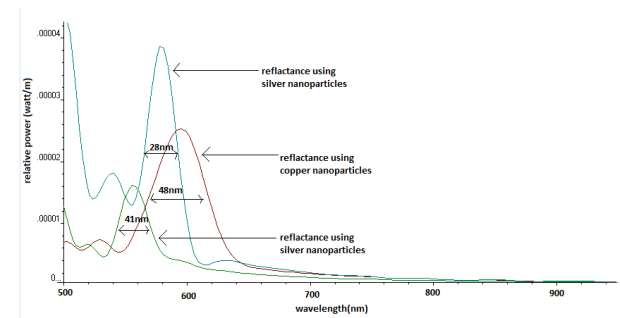


Fig. 5 Comparison of FWHM using copper, silver and aluminum nanoparticles.

Table 1. Plasmonic parameters for different material

Material		Strength (f_m)	Resonant frequency (ω_m)	Plasma frequency (ω_p)	Damping frequency (Γ_m)
silver	Term 0	0.8450	0.00000	0.14×10^{17}	0.729×10^{14}
	Term 1	0.0650	0.123×10^{16}	0.14×10^{17}	0.590×10^{16}
	Term 2	0.1240	0.680×10^{16}	0.14×10^{17}	0.686×10^{15}
copper	Term 0	0.5750	0.00000	0.164×10^{17}	0.455×10^{14}
	Term 1	0.0610	0.444×10^{15}	0.164×10^{17}	0.574×10^{15}
	Term 2	0.1040	0.449×10^{16}	0.164×10^{17}	0.160×10^{16}
aluminium	Term 0	0.5230	0.00000	0.227×10^{17}	0.714×10^{14}
	Term 1	0.2270	0.246×10^{15}	0.227×10^{17}	0.505×10^{15}
	Term 2	0.0500	0.234×10^{16}	0.227×10^{17}	0.474×10^{15}

Table 2. Evaluation parameters of localized surface Plasmon based sensor with different material

material of nano particles	Resonance wavelength at refractive index 1.33	Resonance wavelength at refractive index 1.36	Change in refractive index (Δn)	Change in resonance wavelength ($\Delta \lambda_{res}$)	Sensitivity $\frac{\Delta \lambda_{res}}{\Delta ns}$	FWHM	FOM
Aluminum	564nm	574nm	0.03	10nm	333nm/RIU	41nm	8.1
Copper	598nm	602nm	0.03	4nm	133nm/RIU	48nm	2.7
Silver	578nm	587nm	0.03	9nm	300nm/RIU	28nm	10.7

4. CONCLUSION

In this presented work, we analyzed parameters for LSPR based optical fiber sensor on three different nanoparticles. SPR sensor with higher sensitivity and figure of merit proposed for the future design. Design using fiber Bragg grating inscribed with in core and silver nanoparticles exhibits refractive index sensitivity of 300nm/RIU, 28nm FWHM and FOM of 10.7 which gives better performance than copper and aluminum. It is concluded that silver is better for design of LSPR sensor using grating within core than copper and aluminum in terms of refractive index sensitivity and figure of merit. There is also a scope to improve the detection limit by changing size and shape of the nanoparticles.

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