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Silver and Gold Coated Plasmonics Based Optical Fiber Sensors: A Review

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Abstract: This survey focuses on the most valuable contribution in the field of fibre optic plasmonic sensors recent years. Fibre optic plasmonic (FOP) sensor use optical field to test the biological agents. Due to high sensitivity, high figure of merit and high resolution and low cost, FOPs turn out to be potential alternatives to conventional biological fibre optic sensors. The work is focussed on review of type of plasmonics based optical fibre. The important characteristics of plasmonic based FOPs are discussed in this article. The different types of structures fibre sensors like single mode fibre, multimode fibre, microstructure fibre. The different structures, their performance parameters and experimental results related to some important works have been discussed here. Based on the present view, the future scope, its different applications and related aspects have been discussed. SPR fiber sensors can have variety of structures such as D-shape, cladding-off, fiber tip or tapered fiber structures. Major applications of these include chemical sensors, bios sensors and gas-sensors. The surface plasmon resonance (SPR) property of metallic nano-particles is widely useful for chemical and biological sensing. Selective bio-sensing of molecules using these nano-particles has become a major research interested area between chemistry, biology and material science. Noble metals, especially gold (Au) and silver (Ag) nano-particles, exhibit unique and tunable plasmonic properties; the control over these metal nanostructures size and shape allows manipulating their LSPR and their response to the local environment. In this review, we will focus on Ag-based nano-particles, a metal that has probably played the most important role in the development of the latest plasmonic applications, owing to its unique properties. These nano-structured fiber sensors have attracted considerable research and development interest, because of their unique advantages and unique properties, which include high sensitivity, small sensor head footprint and the flexibility of the optical fibers. They are also of academic interest, and many novel ideas are continuously developed.

Keywords- SPR, FOP (Fibre optic plasmonic sensor), FBG,LPG, PCF, SP, LSP, MMF(Multi-mode fibre), Plasmonics, LSPR

1 INTRODUCTION

The present trends, the surface Plasmon resonance (SPR) based biosensors have attached much attention due to its rapid real time sensing performance [1, 3, 5]. There are lots of application of SPR sensors in different field of practical life like medical diagnostic, gas detection, organic chemical sensing, water testing, maintain food quality, bio-sensing ,bio-imaging, environment monitoring, glucose monitoring, diseases detection, real time monitoring and so on. The researchers have been developing many effective applications based on SPR sensors, terahertz sensors, and optical sensors for the improvement of current technology. Ritchie et. Al in 1950's first observed about SPR theoretically [4-6]. On the basis of prism coupling, Lied berg et. Al in 1983first, introduced about SPR. Usually, the prism is used to activate surface Plasmon's [6-7]. Prism is used to pass the light to the metal surface interface whereas transverse magnetic or p-polarized light is induced in the metal surface and the free electrons of the metal absorb the light and generate surface Plasmon's wave (SPW)[7-10]. But there are some limitations to used prism based SPR sensing devices such as; it provides a bulky size devices with various kinds of optical and mechanical parts [9, 10]. So it is not suitable for remote sensing applications [10, 12].

In a fiber optic SPR sensor probe, a small portion of cladding is removed in optical fibre and the unclad portion is coated with a thin metal layer [14, 21, 24]. The characteristics of SPR optical fiber sensor are admirable sensitivity to the refractive indices of the surrounded dielectric medium. Thus with the PCF based sensor, one can have the miniaturization of the device, compatibility and portal, rapid and multi–sample testing with sensing performance etc.[15-17]. This optical sensing is known as phase-matching which can be easily achieved in the PCF based SPR sensor by engineering the effective refractive index of the core guided mode and the plasmonic mode. Recently, great interests in engineering the geometrical and material properties of the PCF-SPR sensors are numerically investigated with different biological samples to monitor the medical conditioning. PCF has gained its importance because it has different appealing characteristics e.g. controllable bire fringes, high confinement and single mode propagation. Utilizing these special characteristics an evanescent field can be manipulated easily. The effective sensing performance of the fibre is controlled by the evanescent field. SPR sensors give high sensitivity rather than fibre based sensors [20-22]. The sensing application of optical fibre depends upon metal layer properties, fibre

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geometry, light wavelength and fibre parameters. The fibre properties also depend upon no. of modes transmitted in a fibre Therefore the coupling mechanism is different for single mode and multimode optical fibre. A tapered fibre shows a substantial variation in evanescent field penetration along the tapered sensing region length whereas an un-tapered fibre exhibits a uniform penetration of the evanescent field along the sensing region. So the penetration of evanescent field and the strength of light coupling with surface Plasmon's depend upon the numerical aperture [21-24]. In 2010, Gupta and Verma reported the various designs of fibre optic SPR probes. The main aim of these reviews is on the effect of doping, selection of metal and the various effect of bimetallic coating. Roh et. Al. Reviewed the SPR sensor based on Kretcchmann prism configuration and ring resonator. In 2013, Mescia and Pruden Zano reported the recent advances in optical fibre sensors based on fibre Bragg grating(FBG), long period grating(LPGs), and evanescent field.

2. SURFACE PLASMON RESONANCE OPTICAL FIBRE SENSOR:

SPR refers to the excitation of surface Plasmon polaritron, which are electromagnetic waves coupled with free electron density oscillations on the layer between a metal and a dielectric. SPP or surface Plasmon wave (SPW) propagates along the interface of the metal and dielectric material.

Ritchie in 1957 was introduced a term called surface Plasmon's (SPs), a quantum of collective oscillations of free electrons that are confined evanescently on the surface of a metal surface induced by an electromagnetic field is known as surface Plasmon's(SPs), SPs that propagate in the transverse magnetic(TM) direction(p-polarized) are known as surface Plasmon's.

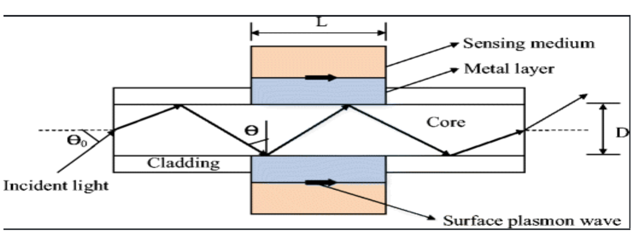

Fig 1: Schematic of a typical SPR based optical sensor[28].

3. SURFACE PLASMON POLARITRON

The interactivity between photon and polar excitation of electric dipoles in a semiconductor at the metal surface is known as polariton. When the electromagnetic field hit the free electron in the interface of two medium having negative and positive real parts of permittivity. At the interface the plasma oscillations is excited, which consists of positively charged ions on the metal layer. So the density of electromagnetic field at the metal surface is not the same. At the background the positively charged ions attract the negative charge free electron so the movement of electron take place in a given volume. These attracted electrons forms bunch of electrons and gain additional momentum and density is gradually increases. Therefore, a large no. of negative electrical charges is formed. Therefore, an electromagnetic surface wave is generated due to plasma oscillations.

4. RESONANCE CONDITION

The resonance phenomenon for the surface Plasmon and localized surface Plasmon resonance have different coupling mechanism:

4.1 Surface Plasmon Polaritron

The resonant oscillation of the conduction electron at the interface between the dielectric and metal stimulated by an electromagnetic wave is known as SPR. Under the resonance condition surface Plasmon's are excited by evanescent wave. When propagation constant of the incident light is equal to the collective oscillations of surface electron. At that moment the resonance condition can be achieved.

4.2 Localized Surface Plasmon Resonance

When the incidence light whose wavelength is smaller than that of wavelength of light is trapped within the conductive nanoparticles, then the LSP phenomenon has occur. Under the resonance condition, the metal nanoparticles present a very powerful absorption band of light that will magnify their damping amplitude.

Plasmonic Metal:

According to the drude's theory, the dielectric constant of any metal is given by:

$$\varepsilon m = 1 - \frac{\lambda^2}{{\lambda_p}^2}\frac{\lambda_c}{(\lambda_c + i\lambda)} \quad (1)$$

Where λ_c and λ_p are the collision and the plasma wavelength of metal respectively. The comparison of collision and plasma wavelength of gold and silver are as under:

Table 1
Comparison of collision and plasma wavelength of silver and gold

Metal	Plasma Wavelength	Collison wavelength
gold	1.682×10^{-7}	8.9342×10^{-6}
Silver	1.4541×10^{-7}	17.614×10^{-6}

Compared to the two other plasmonic nano metals, *i.e.*, gold and copper, silver nano particles have a higher refractive index sensitivity (RIS). Silver and gold have very efficient role in surface Plasmon resonance sensor. Comparing to the other noble metals, Ag shows a good response towards changes of refractive index of surrounding material: hence it is widely used in SPR sensors. The indication of good response is on its performance of its sensitivity and detection accuracy.

TABLE 2
PARAMETERS AND COEFFICIENT FOR THE DRUDE MODEL OF METALS

Parameters	Silver	Gold
High frequency dielectric constant, ε_∞	2.48	7.0
Plasma Frequency, ω_p	1.35×10^{16}	1.40×10^{16}
Damping Frequency, ω_d	7.62×10^{13}	
Fermi velocity, V_f	1.40×10^{6}	1.40×10^{6}

5. Figure of Merit Performance Evaluation

(1) **Sensitivity**: Sensitivity can be defined as the change in resonance wavelength per unit change in refractive index of the sensing medium.

S (nm/RIU) = $\Delta\lambda/\Delta n$.

Here, Δn is the analyte RI variation for an RI-based FOPS system and $\Delta\lambda$ is the resonance wavelength peak shift.

The sensing sensitivity can be defined by the degree of enequality of resonance wavelength shift of the variation of RI of the analyte, namely wavelength interrogation and amplitude interrogation method [2][4][8].

(2) **Linearity**: Linearity presents the ratio between the transducing parameters and measurand. A high linearity response shows a good sensor [4][7][8].

(3) **Figure of Merit**: FOM can be evaluated by introducing the spectral width. It is also related to the signal to noise ratio (SNR).

FOM = S/FWHM,

where S represents the wavelength interrogation sensitivity and FWHM represents the full width at half-maximum of the spectra [25].

(4) **Resolution**: The resolution of the sensor can be described as the minimum of change in refractive index can be detect by the sensor and given by:

$$R = \frac{\Delta n}{\Delta r}\Delta\lambda$$

where Δr is the spectral resolution of the optical spectrometer analyzer used to measure the resonance wavelength and it considered to be equal to 0.01μm[16][18].

(5) **Repeatability**: When a sensor gives similar results when put in the same analyte is called the repeatability. The sensor performs very excellent with high degree of repeatability [17][20].

(6) **Limit Of Detection**: It is defined as the minimum detectable unit of the analyte by a sensor.SPR based sensors have been found very low limits of detection [21][22].

The performance of surface Plasmon resonance based fiber optic sensor depends on various factors such as choice of optical fibre, metals for coating , dopands in the core of fiber, addition of a high index dielectric layer between metal and sensing medium. The study showed that the as the core diameter increases ,the sensitivity and figure of merit of the sensor increases while the width of SPR curve decreases because due to increase the core diameter the no. of reflections in the core decreases. The sensing length performs opposite role as that of the core diameter. As the length of the sensing region increases, the sensitivity and figure of merit of the sensor decreases. The cause of increasing sensing length is same as that of decreasing the diameter of fiber core.

6. SPR Sensor Based on Single Mode Fibre

A single mode fibre has only one fundamental mode consisting of two orthogonal polarizations to achieve high sensitivity and maintain proper polarization of light. SMF has core diameter in the range of 1-10 m. In SMF, the field of the fundamental mode is Gaussian shaped distributed across the core and cladding.

Chiu and shih reported the single mode D-type SPR based fibre optic sensor using the phase measurement method. Results showed that the variation of gold film thickness on the sensitivity. Allsop et. Al. reported SPR based fibre optic sensor device based on ultraviolet of grating type structure into both single layered and multilayered D-shaped fibres. The result showed that how polarization depends on Ge-Sio_2 and Ge-Sio_2-Ag coated fibre. Ahn et. al. reported a waveguide coupled surface Plasmon resonance sensor with dielectric layer between two metals that allowed to tune the resonance wavelength in visible range.

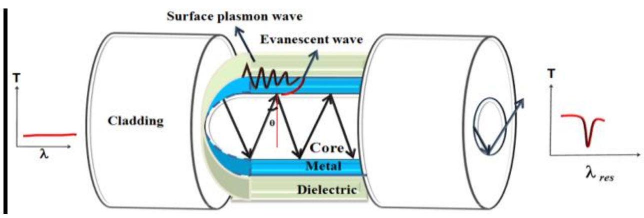

Fig. 2: Schematic of a typical single mode fibre optic SPR sensor[5]

7. SPR Sensors based on multi-mode fibres (MMF)

Due to temperature variation or mechanical deformation SMF suffers polarization instability. The complex steps used in fabrication of SMF, the researchers finds the features of multi mode fibres in the application of SPR sensors. The MMF has a diameter in the range of 75-200m. In MMF, the lights propagate through many paths. Kanso et. al. Reported the response of SPR curves and studied dependence the roughness of metal layer on the performance of SPR sensor. Suzuki et al. Evaluated the performance of multimode fibre SPR sensor for different gold thickness for RI range of 1.33-1.3469.The maximum sensitivity of 1557nm/RIU was reported for 65 n.m. gold layer thickness in reflection type sensor. Sharma et. al. Reported the fibre optic SPR based sensor for precise and errorless determination of A, B and O human blood groups. Yanase et. al. proposed the detection of living cell reaction.liu. et. Al. Proposed a different structure based on in-series double cladding (DC) fibre for measurement of various range of RI and temperature variation. A low cost side polished and U-shaped multimode fibre sensor was studied by Munoz-Berti.

Yuan et. al. Studied the fibre optic SPR sensor and evaluate the influence of metal layer thickness and sensing layer on the performance of sensor.

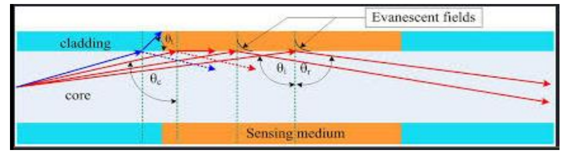

Fig 3: Schematic of a typical multi mode fibre optic SPR sensor[15].

8. SPR Sensor based on microstructure optical fibre (MOF)

A MOF is a optical fibre structure in which holes are arranged in a particular and some unique fashion. We can change the optical properties of MOF by changing the size, shape and arrangement of holes. There are many advantages of MOF than conventional optical fibre. Effective mode area is small in order to provide enhanced nonlinear effects. Mode field diameter is other important parameters for splices loss, beam divergence and bending loss. Hassani and skorobogotry et. al. Present the single mode MOF sensor based on SPR with a good resolution. Due to small effective indices in MOF, the sensor based on MOF can be made to operate in visible to near infrared range. Akowuah et. Al. Explored PCF SPR-Biosensor consisting of two micro-fluidic slots made up of bimetallic combination of Au (5nm)-Ag (45nm). Present the single mode MOF sensor based on SPR with a good resolution. Due to small effective indices in MOF, the sensor based on MOF can be made to operate in visible to near infrared range. Akowuah et. Al. Explored PCF SPR-Biosensor consisting of two micro-fluidic slots made up of bimetallic combination of Au (5nm)-Ag (45nm).

Fig 4:Schematic of a typical micro-structured optical fibre sensor [23].

TABLE-3 : COMPARISON OF SENSORS BASED ON PERFORMANCE

Sensor configuration and its application	Operating Wavelength	RI Range	Performance	Ref
Gold coated Duplex core photonic crystal fiber plasmonic sensor		1.39-1.40	Wavelength sensitivity-10,700nm/RIUby using wavelength interrogation method Maximum amplitude sensitivity-1770/RIU Resolution-9.34x10^{-6}	[2]
Air core photonic crystal fiber based plasmonic sensor for high refractive index sensing		1.33-1.41	Spectral sensitivity-11,700nm/RIU Resolution-8.55x10^{-6}	[4]
Coating of indium tin oxide film based photonic crystal fiber sensor	(1380-2260)nm	1.26-1.38	Maximum wavelength sensitivity-35,000nm/RIU Amplitude sensitivity-1120.73/RIU Wavelength Resolution-2.86x10^{-6} Amplitude Resolution-8.92x10^{-6}/RIU	[5]
Gold in filled in one hole in cladding based photonic crystal fiber sensor		1.39-1.43	Sensitivity-21,200 nm/RIU Resolution-4.72x10^{-6}	[7]
Only one ring in cladding based photonic crystal fiber based refractive index sensor	0.5-0.75	1.31-1.35	Wavelength Sensitivity-12,000 nm/RIU Amplitude sensitivity-11,412/RIU Resolution-8.76x10^{-8}/RIU	[8]
Coreless fiber based surface Plasmon resonance sensor	$\Delta\lambda$=-200	1.335-1.409	Average refractive sensitivity-2836nm/RIU	[9]
Concave shaped PCF for low refractive index detection. ITO is used in place of gold		1.19-1.29	Maximum wavelength sensitivity-1700-10,700	[10]
D-shaped photonic crystal fiber with circular layout		1.420-1.435	High average sensitivity-14,600nm/RIU Resolution-6.80x10^{-6}RIU	[11]
Ex-centric core photonic crystal fiber sensor with gold nanowires and ex-centric core lie in gold nano wire		1.33-1.4	Average spectral sensitivity-7428nm/RIU Max spectral sensitivity-14,200nm/RIU hgResolution-7.04x10^{-6}RIU Quality factor-140	[13]
Combination of gold and graphene layer based photonic crystal fiber sensor			Maximum sensitivity when only gold is used-4657.14nm/RIU. After a layer of graphene on the gold layer the sensitivity increases to 8600nm/RIU. The sensitivity increases by 84.66%. The average sensitivity increases by 75.97%.	[14]
Comparison of gold and silver based photonic crystal fiber based photonic crystal fiber plasmonic biosensor		1.33-1.40	Amplitude sensitivity-1086/RIU when gold is used and 1656/RIU when silver is used. Maximum wavelength sensitivity-12,000nm/RIU Resolution-8.33x10^{-6}RIU	[15]
Three core photonic crystal fiber surface Plasmon resonance sensor	1.33-1.34		Average refractive index sensitivity-3435nm/RIU	[16]

9. CONCLUSION

In this paper, we have evaluated the theoretical model in the successful realization of FOPS for biological applications. In this review, we have explained the different SPR technique in different media, namely, prism-based SPR FOPS, grating-based SPR FOPS, and optical fiber-based SPR FOPS. Currently, the novel SPR-based FOPS geometries and approaches are being explored by several groups to model sensors for achieving high sensitivity and high resolution with better performance. Nowadays, the unique properties of the metal nano particles are used to explain the phenomenon of LSPR in FOPS. Several functionalization strategies for metal-based LSPR have been established. In this line, engineering the optical properties and thin-film thickness are carried for such lamellar SPR-based FOPS for Recent trends concerning several geometries of the FOPS have been discussed. We have found that the

applications of FOPS in medical diagnosis, such as characteristics of particular bio molecular species, have been analyzed on buffered samples instead of clinical samples. With the SPR-based FOPS, the penetration depth is limited. Identifying a specific molecule among groups of molecules with less interaction between the unwanted molecules remains difficult. Besides high sensitivity and better performance, compactness is also a challenging task for future research. For the early detection of cancer and cardiovascular problems such as tissue perfusion, blood pressure, heart rate, etc., novel biosensors can be developed by exploiting the optical properties of recently proposed materials such as TMDC, hBN, black phosphorus, etc. Furthermore, new fiber designs may also be introduced for achieving low-cost biosensors. FOPS shall also be considered for understanding the role of several characterizations of optical fibers during the sensing process. Finally, we believe that this review will help encourage further research in the field of SPR-based FOPS.

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