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Analysis of surface plasmon resonance based bimetal coated tapered fiber optic sensor with enhanced sensitivity through radially polarized light

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ABSTRACT

The presented proposal of surface plasmon resonance (SPR) configuration with tapered fiber structure and radially polarized light beam is a new and different analysis towards the sensitivity enhancement in the field of SPR based fiber optic sensors. Here the taper waist region of optical fiber having diameter around 330 μm is deposited with 40 nm thin Ag layer, 10 nm thin Au layer and the sensing layer with refractive index 1.333–1.353 respectively for achieving the bimetal coated taper fiber optic sensor with SPR configuration. The cylindrical symmetry and special radial field distribution of radially polarized light make its more interesting SPR study and leads to the enhanced excitation of surface plasmon wave. This results 10 times better sensitivity of fiber optic sensor output response as compared to p-polarized light beam with wavelength interrogation technique and 2.307 times better sensitivity with intensity interrogation technique. Also including the temperature effect in proposed taper bimetallic structure, this sensitivity analysis provides an evidence, for exploring a new idea towards the enhanced excitation of SPR which expedites the new avenues in the field of sensor applications with radially polarized light.

1. Introduction

In the era of optical technology based sensing and measurement techniques related to the field of scientific research, industrial as well as commercial applications, surface plasmon resonance (SPR) is one of the optical techniques that attracted a great deal of attention with new avenues of measurement and sensing techniques of various surface related phenomena. SPR based sensor was first employed in gas sensing by Nylander in the year of 1983 and till date various SPR based sensors were proposed in the field of biochemical and biomedical sensing [1]. Although conventional prism based SPR configuration explained by Kretschmann and Otto were generally used in sensing applications with its bulky sensor structures which makes it unable to in-situ monitoring and confined its use in laboratory sensing applications [2–4]. However, optical fiber based SPR sensor configurations are extensively preferred over conventional one owing to its sensor structure miniaturization, flexibility in multiplexing, remote sensing applications, in-situ monitoring, small sample requirement as well as low cost [5–7]. Use of (i) bimetallic layer configuration, (ii) addition of extra dielectric layer, (iii) incorporation of D-shaped, (iv) tapered fiber, (v) fiber grating or side polished fiber structure were enhance the performance parameters like sensitivity, dynamic range and signal to noise ratio (SNR) etc. of SPR based sensors [8–10]. Theoretically in case of taper fiber, by broadening the angular range of light propagation and transforming the incident angle very close to critical angle near taper waist region, a powerful interaction between evanescent wave and surface plasmon wave are build up. This in turn enhance the performance by increasing the sensitivity of measurement several times as compared to symmetrical fiber SPR based sensors [11]. Single metal layer SPR based sensors have limitations around chemical instability, environmental oxidation and limited response properties of the used metals. However, extra dielectric or metal layer may grant the hardness of sensor configuration and also protects the whole arrangement from environmental condition and added up the response properties of used each metal/dielectric layer which collectively enhance the overall performance i.e. detection accuracy, SNR and robustness of the sensor [12].

It is well known that SPR is a highly sensitive phenomenon concerned with plasma oscillation as it can only be excited by the TM polarized light beam on metal-dielectric interface [13]. In similar fashion, the special polarization vector and field distribution of the radially polarized beam also responsible for the excitation of SPR. The radially polarized light enables tight focal spot and strong

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longitudinal field component conversion at focal point which expedites its application in the fields of tip enhanced Raman spectroscopy, charged particle acceleration, metal cutting, molecular orientation analysis etc [14–17]. Its polarization property is such that the field oscillation is always radially outwards from the center of the beam with cylindrical symmetry forming doughnut shaped beam having inhomogeneous spatial distribution, so that the field distribution is always p-polarized at spatial circumference of the beam [18]. Excitation of SPR based sensors with radially polarized beam enhanced the output sensitivity of fiber optic sensor more than twice as compared with the excitation via p-polarized light beam [19].

2. Proposed scheme

A first theoretical approach regarding the sensitivity realization of the exciting SPR based sensor in case of bimetal coated tapered fiber structure with radially polarized light has been proposed here. The tapered fiber sensor probe having core diameter of 600 µm, diameter of taper waist region is around 330 µm, tapering angle is 0.707 rad. and the consecutive thin layers deposition of silver and gold (Ag–Au) with thicknesses of 40 nm and 10 nm respectively over taper waist region are shown in Fig. 1. This thin Au layer removes the degradation of Ag layer from oxidizing or chemical environment which protects the sensor structure and also helps in improving the overall performance of the sensor by increasing detection accuracy as compared to single metal coated structure. Here a multimode optical fiber (Thorlab 0.22 NA, 600 µm) of length (L) 10 mm is converted into a taper structure by using heat-and-pull traveling burner technique for adiabatic tapering condition [20]. Radially polarized broadband light source with varying wavelength can be obtained from extra-cavity generation technique using radial polarization convertor (RPC) manufactured by ARCoptix [21,22] and within the taper waist region the sensing layer having varying refractive index from 1.333 to 1.353.

2.1. Theory

It is well known that, the first experimental implementation of fiber optics SPR sensing was governed by Villuendas and Palayo using four layer configuration for the measurement of sucrose concentration in aqueous solution and onwards various fiber based structure had been proposed and implemented for enhancing the performance in sensing techniques [23]. The response and characterization of fiber optics SPR based sensor are governed by the transmitted power through the sensor probe.

2.2. Normalized transmitted power

The normalized transmitted power in case of SPR excitation with p-polarized light for fiber optics sensor is defined by –

$$P_{trans} = \left[\frac{\int_{\theta_{cr}}^{\pi/2} {R_p}^{N(\theta)} P(\theta) d(\theta)}{\int_{\theta_{cr}}^{\pi/2} P(\theta) d(\theta)} \right] \tag{1}$$

Where R_P stands for the reflection coefficient for four layer structure, $N(\theta)$ represents the number of reflections at sensing region, $P(\theta)$ is the incident power within the optical fiber at an angle θ and θ_{cr} is the critical angle of optical fiber. Now in case of taper fiber, when a radially polarized light incident at an angle greater than the critical angle within the fiber core then after multiple bounces inside the taper waist region, light is reflected from the taper waist region. The generalized expression for the normalized transmitted power in case of SPR excitation with TM polarized light in tapered fiber optic sensor is given by [11,19] –

$$P_{trans} = \left[\frac{\alpha \int_{\phi_1}^{\phi_2} R^{N_{ref}(\theta)} \cdot P(\theta) \cdot d(\theta) + (1-\alpha) \int_{\phi_1}^{\phi_2} P(\theta) \cdot d(\theta)}{\int_{\phi_1}^{\phi_2} P(\theta) \cdot d(\theta)} \right] \tag{2}$$

here, α represents the effective intensity coefficient, ϕ_1 and ϕ_2 are the transformed angles of propagating light over tapered region. The effective intensity coefficient, α responsible for SPR excitation can be calculated from –

$$I_{eff,L} = \frac{1}{2\pi} \int_0^{2\pi} I \cos^2(\Phi) d\Phi = \alpha I \tag{3}$$

Here, angle Φ represents the angle between polarization direction and meridian plane, Istands for the total input intensity of light and $I_{eff,L}$ stands for the effective intensity responsible for SPR excitation. The value of effective intensity coefficient (α) is 1 for radially polarized beam and $\frac{1}{2}$ for p-polarized beam [19]. The

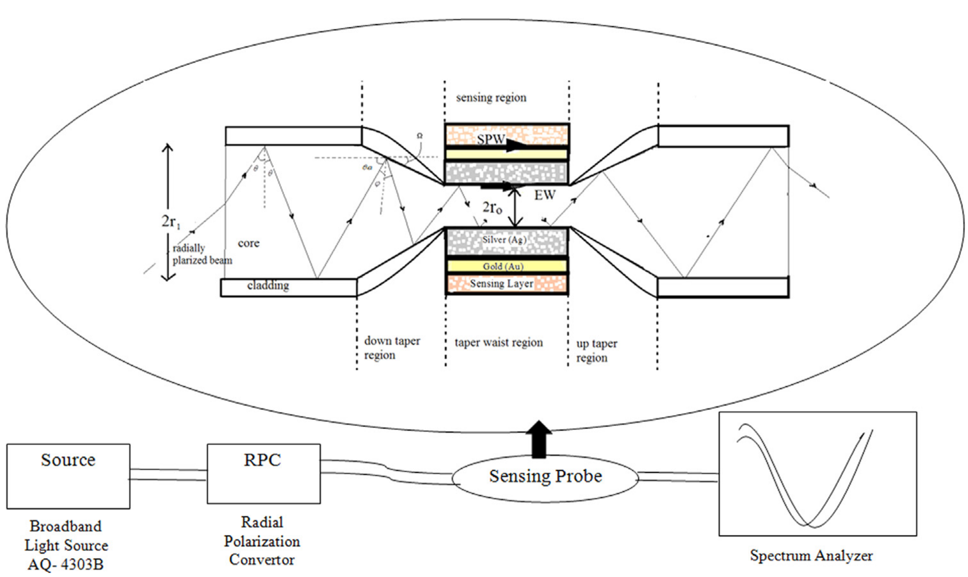

Fig. 1. Schematic arrangement of whole sensor assembly and ray tracing in case of bimetal (Ag–Au) coated tapered multi-mode fiber (MMF) with SPR and radially polarized beam.