Long Range Surface Plasmon Resonance Based Taper Fiber Optic Sensor with Enhanced Sensitivity using Au Nano-Layer through Radially Polarized Light

Deepak Chaurasia¹, Nabamita Goswami ², Ardhendu Saha³*
¹,²,³ Department of Electrical Engineering, National Institute of Technology Agartala, Barjala, Jirania, Tripura (west), Pin:-799046, India.

Abstract: A new theoretical approach towards the sensitivity enhancement of tapered fiber optic sensor based on the long range surface plasmon (LRSP) resonance technique in Teflon-metal coated tapered fiber structure using radially polarized is proposed, designed and simulated within Kretschmann-Raether geometry. The configuration comprising a fiber core coated with 690 nm and 70 nm thin Teflon layer and Au layer respectively where the uniform taper waist having diameter 330 µm and 350 µm with taper ratio of 1.7 (NA: 0.25, 10 mm long waist region) and a sensing layer having varying refractive index from 1.333 to 1.353. With the increase in refractive index the observed results indicates a 1.7 times better sensitive tapered fiber sensor as compared to the existing LRSP based fibre optic sensors using intensity interrogation technique. To the best of our knowledge several articles have been devoted in the field of LRSP based fibre optic sensor with p-polarized light whereas no such article has yet been reported with Teflon used as a dielectric between metal coated taper fiber optic sensors using radially polarized light with better sensitivity. Here sensitivity also analysed w.r.t wavelength interrogation technique where the sensitivity enhancement is about 1.7 times than the existing fiber optic sensors.

Keywords: Fiber optic based sensor, Long range surface plasmon resonance, Radially polarized light, Tapered multi-mode fiber.

1. INTRODUCTION

It is well known that surface plasmon is a coherent oscillation of electromagnetic wave at the metal-dielectric interface [1]. Only TM polarized light can excite them where the associated field has a maxima at the interface and decays exponentially in the metal and dielectric respectively [2]. For the elevation of surface plasmon in surface plasmon resonance (SPR) based sensor structures, Kretschmann’s configuration based on impaired total internal reflection is used in the preferred configuration [3]. In this method, over the base of high index coupling prism, a thin layer of metal is deposited and evanescent wave is produced which travel through the prism-metal interface and elevate SPR [4]. In case of SPR based fiber optic sensor, the cladding is removed from the middle part of the fiber and coated with required layer over the unclad core. When a light beam from a respective source (polychromatic) is incident on the one end of the fiber, the transmitted light spectrum is recorded at the other end. The SPR at the metal-dielectric interface is excited by evanescent wave created at core-metal interface [5]. At resonance condition, when the propagation constant of evanescent wave equal to the propagation constant of surface plasmon then SPR
excitation occurs. In case of wavelength interrogation method used in fiber sensor, at resonance wavelength a dip in the transmitted wavelength is obtained because of the maximum transfer of energy from evanescent wave to surface plasmon which occurs only at resonance wavelength [6], [7]. The resonance wavelength depends on the refractive index which leads to a change in the resonance wavelength. The refractive index of the dielectric medium can be recognized by evaluating the movement in the resonance wavelength [8]-[11]. By using the symmetric configuration of the radially polarized beam (RPB), in fiber also SPR can be excited more efficiently. Ascribed to the rotational symmetry of the fiber, the RPB has a polarization ordered on the optical axis. Computer generated hologram are one few of the method used to obtain radially polarized beam. SPR excitation can be possible only due to the TM polarized light in flat bulk system.

2. PROPOSED SCHEME

The fiction and characterization of fiber optic sensor based on SPR is reported in this article where a thin layer of Teflon AF-1600 coated over the fiber. A nanometer thin coated gold over it to intensify the sensitivity. A detailed theoretical study of sensing enhancement by modeling the SPR sensor with taper probe has been shown here. As an active SPR region, the transition region of the taper is taken in account to study the sole effect of the taper profile sensitivity. A plastic clad silica taper fiber of core diameter 330 µm and numerical aperture of 0.25 was used to invent the taper fiber SPR probe for sensing the refractive index varies from 1.333 to 1.353. Here around 10 mm of length of fiber is removed from the middle portion.

The unclad portion was cleaned by high tension bombardment on vacuum chamber after being cleaned by acetone. Then, using thermal evaporation technique the unclad portion of taper fiber was coated with Teflon layer of 690 nm thickness in vacuum coating unit which is kept at 5×10⁻⁶ mbar of pressure. Using the same technique, an additional layer of gold (Au) was coated over the Teflon of thickness 70 nm to intensify the sensitivity of the sensor which is
shown in Fig. 1. The several output from the proposed arrangement cab be identify using the following points.

2.1 Transmitted power:
Here it is assumed that most of the light is transmitted through the meridian plane that was introduced into the sensing fiber at the central. Then the effective light intensity to SPR excitation is defined as [12], [13]-

\[ I_{\text{eff},\perp} = \frac{1}{2\pi} \int_0^{2\pi} I \cos^2(\phi) d\phi = \alpha I \]  

(1)

Where \( I \) is the light intensity, \( \phi \) is defined as the angle between the polarization direction and a meridian plane. \( \alpha \) is the effective intensity coefficient. Therefore the normalized transmitted power is modified to-

\[ P_{\text{trans}} = \left[ \frac{\phi_2}{\phi_1} \int_R \frac{N_{\text{ref}}(\theta)}{\phi_1} P(\theta), d(\theta) + (1 - \alpha) \int_P(\theta),d(\theta) \right] \]

(2)

Here \( R \) is the reflection coefficient, \( N_{\text{ref}}(\theta) \) stands for the number of reflection inside the taper fiber at an angle \( \theta \), \( P(\theta) \) represents the incident power within the taper fiber at an angle \( \theta \), \( \phi_1 \) and \( \phi_2 \) are the transformed angle of propagating light over the taper waist region. For RPB the value of the effective intensity coefficient is 1 and \( \frac{1}{2} \) for p-polarized beam [13], [14].

2.2 Sensitivity Analysis:

The propagation constant of the surface plasmon rises significantly due to a charge in the refractive index, \( n_s = (\epsilon_j)^{\frac{1}{2}} \) of the surrounding media which results in the modification of SPR condition. As a result one or more of the property of the transmitted light changes which can be observed. The sensitivity can be defined as -

\[ S_{n_s} = \frac{\delta \zeta}{\delta n_s} \]  

(3)

Where \( \delta \zeta \) is the change in given property of light (intensity, phase and wavelength) due to the variation of refractive index \( \delta n_s \) in surrounding medium. The sensitivity analysis w.r.t intensity interrogation technique is given by -

\[ S_n = \left| \frac{\delta I_{\text{norm}}}{\delta n_s} \right| \]  

(4)
3. RESULTS AND DISCUSSION

By analytical method the simulated the transmitted power vs. wavelength spectra having 690 nm of Teflon layer thickness, 70 nm of gold layer thickness with 330 µm and 350 µm taper waist diameter have been represent in Fig. 2 and Fig. 3 respectively. With the increment of in refractive index from 1.333 to 1.353 the output power also increases. Analysis of the performance of the sensor can be done through different taper waist diameter. Fig. 4 indicates that the resonance wavelength linearly increase with the increased refractive index for 330 µm and 350 µm taper waist diameter of the taper fiber.

With more increased sensitivity using 330 µm taper waist region Fig. 5 shows the output power vs refractive index graph for sensing medium using radially polarized beam and p-polarized beam respectively. The analysis of sensitivity between radially polarized beam and p-polarized beam clearly depicts that using the radially polarized beam 1.7 times better sensitivity can be achieved as compared to p-polarized light beam.

Fig. 2: Transmitted power vs wavelength spectra of the taper SPR probe having 330 µm taper waist region with varying refractive index values at p-polarized light.

Fig. 3: Transmitted power vs wavelength spectra of the taper SPR probe having 350 µm taper waist region with varying refractive index values at p-polarized light.

Fig. 4: For 330 µm and 350 µm taper waist region variation of the resonance wavelength with refractive index.

Fig. 5: Variation of output transmitted power w.r.t change in refractive index for radially and p-polarized light beam for a taper waist region 330 µm.
4. CONCLUSION

With the radially polarized light the sensitivity analysis is investigated for wavelength as well as intensity interrogation technique on taper waist region (waist diameter of 350 µm and 330 µm) and Teflon-Au interface in proposed sensing probe. By wavelength and intensity interrogation technique with radially polarized light, the taper fiber probe increases the sensitivity 1.7 times as compared to the symmetrical fiber probe. This sensitivity enhancement is achieved owing to the radial field distribution of radially polarized light at the fiber surface. Moreover several articles have been reported to detect the refractive index variation through different fibre structures, but no such article has yet been reported with better sensitivity with radially polarized light for detecting the variation of refractive index of the sensing layer. Thus with the enhanced sensitivity the presented article is a unique SPR based taper fiber sensing probe to detect the refractive index variation using with radially polarized light where the sensitivity investigation is in wavelength and intensity interrogation techniques.

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**First Author:** Mr. Deepak Chaurasia, pursuing M.Tech in NIT Agartala. He has passed his B. Tech from Krishna Institute of Engineering and Technology, Ghaziabad India. Recently he is engaged with the project related to SPR based fibre optic sensor.

**Second Author:** Dr. Nabamita Goswami, is an Assistant professor at NIT Agartala, India. She received her M. Tech degree with Institute Gold medal as Institute topper and PhD degree in 2010 and 2015, respectively from Department of Electrical Engineering, NIT Agartala, India. She has published over 11 articles in International Journals and over 14 articles in International Conference proceeding. She serves a potential reviewer in several international journals.

**Third Author:** Dr. Ardhendu Saha, is an Associate professor in NIT Agartala, India and serves the institute till 1997. He received his M. Tech degree on 1992 from Applied Physics, University of Calcutta, India and PhD degree on 2007 from IIT Kharagpur, India. He has published over 17 articles in International Journals and over 17 articles in International Conference proceeding and 2 articles in National Conference proceeding. He serves a potential reviewer in several international journals.