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Theoretical analysis of surface plasmon resonance based fiber optic sensor using indium nitride

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ABSTRACT

An extremely sensitive surface plasmon resonance based fiber optic sensor with indium nitride (InN) layer coated on the core of the optical fiber is theoretically analyzed. The proposed sensor exhibits high sensitivity in the near infrared region of spectrum. The optimized value of thickness of InN layer is found to be 70 nm. Possessing high sensitivity of 4493 nm/RIU, the 70 nm thick InN layer based fiber optic SPR sensor illustrates good sensing behavior.

1. Introduction

Huge research studies have been made on various sensing techniques for rapid and correct measurement of numerous physical, chemical and biochemical parameters in last three decades. Surface plasmon resonance (SPR) has become a most extensive research interest in the field of optics and opto-electronics. Initially, Liedberg et al. demonstrated the exploitation of surface plasmon resonance for chemical sensing [1]. Since then, the surface plasmon resonance sensing principle has been studied rigorously [2–6]. Collective resonating oscillation of free electrons exists on the plasma surface (like metal), giving rise to a charge density wave propagating along the plasma surface. This transverse electromagnetic wave, propagating parallel to the metal-dielectric interface is known as the surface plasmon wave. Being transverse in nature, this surface plasmon wave can be excited by exponentially decaying evanescent field of the incident *p*-polarized light. When the wave vector and the frequency of the incident *p*-polarized light match with those of the surface plasmon wave, this light resonantly excites the surface plasmon wave, propagating along the metal-dielectric interface and a sharp dip appears in the transmitted light at the resonance wavelength/resonance angle. The wavelength or the angle at which the resonant excitation of surface plasmon takes place is very sensitive to variations in the refractive index of the dielectric adjacent to the metal. Therefore, the variations in the refractive index of the sensing medium (dielectric) can be noticed by measuring the resonance wavelength or resonance angle. To excite surface plasmon waves, a variety of optical techniques have been introduced. Kretschmann's configuration is most widely used over other SPR sensing structures for observing SPR [7–10]. In Kretschmann's configuration, a high refractive index prism is coated with a thin metal layer touching the sensing medium (sample). Surface plasmon waves are excited by evanescent wave from a high refractive index prism at the total reflection condition. The optical fiber based SPR sensing offers large number of advantages over the prism based SPR sensing like simple and flexible optical design, possibility of remote sensing, continuous analysis and in situ monitoring [11–14]. The optical fiber based SPR sensing has been reported both experimentally and theoretically in a number of research investigations [15–22].

In SPR measurements, an important parameter is choice of metal layer. Metals like gold (Au) and silver (Ag) have always been the first option for SPR based sensing applications in the visible range. In recent times, research on plasmonics has been extended to IR spectral region beyond the visible region. This leads to explore some new materials which could satisfy the SPR condition at lower plasma frequencies. Recently, Indium nitride (InN) has been found to be an attention-grabbing semiconducting material (band gap around 0.7-1.1 eV) because of its numerous advanced properties over other group-III nitrides, metals and transparent conducting oxides. InN is a potential candidate for plasmonics sensing applications not only in IR but also in THz regimes because of its smaller magnitudes of real permittivity than metals [23]. Further, InN possesses lower value of plasma frequency compared to that of metals, displaying greater confinement of surface plasmon waves to the interface and greater field enhancement in IR and THz regimes. In

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addition to this, Indium nitride is shown to have vast remarkable applications in various research fields like high speed transistor devices [24], solar cell industries [25] and optoelectronic devices for optical fiber communications [26]. Qian et al. showed that InN thin films are suitable for the application of plasma filters with different carrier concentration, mobility and film thickness [27]. The plasma filters are one of the most effective ways to increase the efficiency in Thermo Photo Voltaic (TPV) systems. InN shows good performance as a plasma filter material for widely employed GaSb or GaInAsSb photovoltaic cells. Lu et al. reported the utilization of InN as an appropriate material for biosensing owing to its high superficial electron concentration [28]. Besides, InN dielectric overlay has been used to demonstrate an Al-InN bilayers based SPR sensor experimentally [29].

In the present study, a SPR based fiber optic sensor with InN layer coated on the core of the optical fiber has been projected and theoretically analyzed. The surface plasmon resonance formed by coupling of evanescent light to surface plasmons is used as the sensing method. The wavelength interrogation scheme is exploited for the analysis of SPR sensor. In this scheme, the wavelength of the light from the polychromatic source is changed and the corresponding transmitted power through the optical fiber is measured. At resonance wavelength, a sharp dip in transmitted power takes place. The resonance wavelength depends on the refractive index of the sensing medium. The proposed SPR sensor with InN layer is shown to possess high sensitivity in the near infrared region of spectrum. For the best sensing performance of SPR sensor, the thickness of InN layer has also been optimized. The optimized value of thickness of InN layer of SPR sensor is unveiled to be 70 nm. Comprising high sensitivity of 4493 nm/RIU, the 70 nm thick InN layer based fiber optic SPR sensor demonstrates a good sensing performance.

2. Theory

The SPR sensing is based on the principle of attenuated total reflection (ATR) with Kretschmann's configuration. In the proposed SPR based fiber optic sensor, the sensing system consisting of a fiber core-InN-sensing medium is considered as shown in Fig. 1.

The plastic cladding around the core from the middle portion of a step index multimode plastic clad silica (PCS) fiber (Numerical aperture = 0.24 and fiber core diameter = 600 μm) is removed and is then coated with a thin InN layer. This InN layer is finally surrounded by the sensing medium. The light from a broadband (polychromatic) source is launched into one of the ends of the optical fiber with proper optics and the transmitted light is detected at the other end of the optical fiber.

2.1. Layer I (fiber core)

This layer is made of core of optical fiber. The core of the optical fiber is assumed to be made of fused silica. The refractive index of fused silica varies with wavelength according to Sellmeier dispersion relation as,

$$n_1(\lambda) = \sqrt{1 + \frac{a_1\lambda^2}{\lambda^2 - b_1^2} + \frac{a_2\lambda^2}{\lambda^2 - b_2^2} + \frac{a_3\lambda^2}{\lambda^2 - b_3^2}} \quad (1)$$

where λ is the wavelength in μm and a_1, a_2, a_3, b_1, b_2 and b_3 are Sellmeier coefficients. The values of these coefficients are given as, $a_1 = 0.6961663$, $a_2 = 0.4079426$, $a_3 = 0.8974794$, $b_1 = 0.0684043$ μm, $b_2 = 0.1162414$ μm and $b_3 = 9.896161$ μm [30].

2.2. Layer II (InN layer)

This layer is made of InN. The dielectric constant of InN is written according to the Drude model as [31],

$$\varepsilon(\omega) = \varepsilon_\infty \left[1 + \frac{(\omega_{LO}^2 - \omega_{TO}^2)}{(\omega_{LO}^2 - \omega^2 - i\omega\gamma)} - \frac{\omega_p^2}{(\omega^2 + i\omega\Gamma)}\right] \quad (2)$$

Here, ε_∞ is the high frequency dielectric constant, ω_{LO} and ω_{TO} are LO (Longitudinal Optical) and TO (Transverse Optical) frequencies of phonon mode, ω_p is the plasma frequency, γ and Γ are the two corresponding damping constants. Five sets of values of various parameters used for InN are: $\varepsilon_\infty = 6.7$, $\omega_p = 845\ \text{cm}^{-1}$, $\Gamma = 117\ \text{cm}^{-1}$; $\varepsilon_\infty = 6.7$, $\omega_p = 1170\ \text{cm}^{-1}$, $\Gamma = 64\ \text{cm}^{-1}$; $\varepsilon_\infty = 6.7$, $\omega_p = 1940\ \text{cm}^{-1}$, $\Gamma = 260\ \text{cm}^{-1}$; $\varepsilon_\infty = 7.5$, $\omega_p = 4100\ \text{cm}^{-1}$, $\Gamma = 1382\ \text{cm}^{-1}$ and $\varepsilon_\infty = 7.5$, $\omega_p = 5480\ \text{cm}^{-1}$, $\Gamma = 1054\ \text{cm}^{-1}$ [31]. Further for each set, the values of LO, TO frequencies and damping constants considered are: $\omega_{LO} = 590\ \text{cm}^{-1}$, $\omega_{TO} = 450\ \text{cm}^{-1}$ and $\gamma = 120\ \text{cm}^{-1}$.

2.3. Layer III (sensing medium)

This layer is made of sensing medium. The dielectric constant of the sensing medium is ε_s. If n_s is the refractive index of the sensing medium, then $\varepsilon_s = n_s^2$. The resonance condition for excitation of surface plasmon wave is given as,

$$\frac{2\pi}{\lambda} n_1 \sin\theta = Re\{K_{sp}\} \quad (3)$$

where $K_{sp} = (\omega/c)\sqrt{\varepsilon_m\varepsilon_s/(\varepsilon_m + \varepsilon_s)} = (2\pi/\lambda)\sqrt{\varepsilon_m n_s^2/(\varepsilon_m + n_s^2)}$ is the propagation constant of the surface plasmon wave and c is the speed of light in vacuum. The left hand side of Eq. (3) denotes the propagation constant of the light incident at an angle θ and the right hand side shows the real part of the propagation constant of the surface plasmon wave.

2.4. Transmitted power

The expression for the reflection coefficient (reflectance) of p-polarized incident light can be obtained by using the matrix method for N-layer model [32]. Considering that all the guided rays are launched in the fiber using a collimated source and a microscope objective, the angular power distribution of rays guided in the fiber is given as [33],

$$dP \propto \frac{n_1^2 \sin\theta \cos\theta}{(1 - n_1^2 \cos^2\theta)^2} d\theta \quad (4)$$

where θ is the angle of the ray with the normal to the core-cladding interface. Also, n_1 is the refractive index of the core of the fiber. To calculate the effective transmitted power, the reflectance (R_p) for a single reflection is raised to the power of the number of reflections the specific propagating angle undergoes with the sensor interface. Hence, for p-polarized light, the generalized expression for the

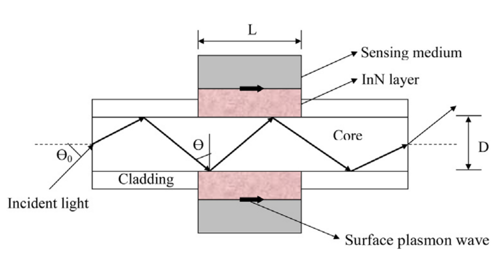

Fig. 1. Schematic diagram of SPR based fiber optic sensor.