Optical Fiber Technology 43 (2018) 163–168

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Regular Articles

Chalcogenide fiber-optic SPR chemical sensor with MoS_2 monolayer, polymer clad, and polythiophene layer in NIR using selective ray launching

Anuj K. Sharma*, Baljinder Kaur

Department of Applied Sciences (Physics Division), National Institute of Technology Delhi, Narela, Delhi 110040, India

ARTICLE INFO

Keywords:
Plasmon
Sensor
Alcohol
Optical fiber
MoS_2
Infrared

ABSTRACT

Surface plasmon resonance (SPR) based chalcogenide fiber-optic sensor with polymer clad and MoS_2 monolayer is simulated and analyzed in near infrared (NIR) for detection of mixture of alcohols (ethanol and methanol) dissolved in water solution. The proposed fiber optic sensor is analyzed under angular interrogation method, which is based on selective ray (on-axis) launching of monochromatic light into the fiber core at varying angle followed by measuring the loss of power (in dB) after passing through the SPR probe region. The performance of the sensor is analyzed in terms of its figure of merit (FOM). The sensor's specificity towards alcohols along with considerably larger FOM is achieved by utilizing a polythiophene (PT) layer. The results indicate that longer NIR wavelength (λ) provides superior sensing performance. The sensor's performance is better for larger volume fraction of methanol in the water solution. The proposed fiber optic SPR sensor has the capability of providing much greater FOM compared with the previously-reported SPR sensors.

1. Introduction

Optical fibers being compact, easy to handle, less prone to electromagnetic interferences, having fast response, cost effective, and robust structure can be used for various opto-electronic applications. In order to be used for sensing purpose, an appropriate technique should be combined with the optical fibers. In this context, the technique of surface plasmon resonance (SPR) is an ideal candidate due to its advantage of better selectivity, non-invasiveness, and higher sensitivity compared to other existing techniques such as infrared spectroscopy *etc.* [1]. Optical fibers with SPR phenomenon have been explored widely for the variety of sensing media [2,3].

Further, it is reported previously that sensing in near-infrared (NIR) region is advantageous due to chemicals and biological species having their fingerprints in IR region [4], longer probe depth of plasmons (1.5–2 µm), and sensitivity enhancement [5]. For designing an SPR-based sensor probe in NIR, appropriate materials (*i.e.*, glass substrate, metal, and dielectric layers) need to be selected for optimal and stable sensing performance. Taking this into consideration, chalcogenide glasses have been recognized to provide better performance in NIR due to their excellent optical properties such as transparency in IR region, high refractive index (RI), higher chemical and thermal stability, and low phonon energy (330–380 cm^{-1}) to be used as substrate material for SPR based sensors [6–9].

In view of above discussion, chalcogenide fiber optic SPR sensor can be explored for sensing different chemical compounds with minimal interference with the environment. Ethanol and methanol are two important organic compounds used for different purposes and their detection has been an area of considerable interest for applications in several fields, ranging from environment to food to chemical industries [10]. Ethanol is used as an antiseptic, antitussive agent, antidote to methanol poisoning, precursor for other organic solvent, and as fuel [11]. The detection of organic compounds (*e.g.*, methanol and ethanol) should be carried out in infrared (IR) because they have their characteristic absorption bands in IR enabling a label-free and real time sensing procedure [12]. The SPR sensing phenomenon has been explored for binary mixtures of ethanol and methanol [13].

Further, the performance of SPR sensor depends upon the interaction of incident light with surface plasmons (SPs), therefore, many two dimensional (2D) materials such as graphene, $MoSe_2$, and MoS_2 *etc.* are being explored for sensor's performance enhancement [14]. MoS_2 is bonded in the form of S-Mo-S (*i.e.*, chalcogen–metal–chalcogen) with strong intralayer bonding and weak interlayer van der Waals force, and such arrangement is considered as monolayer [15,16]. MoS_2 possesses strong absorption characteristics; therefore, it may be integrated with optical fiber sensors to achieve considerably larger variation in transmitted power [17]. Monolayer of MoS_2 (0.71 nm thick) with large surface to volume ratio [18], tunable energy band gap, large work function (5.1 eV), high absorption efficiency, and good stability add to its compatibility in highly sensitive bio-sensors [19]. Significant

* Corresponding author.
E-mail address: anujsharma@nitdelhi.ac.in (A.K. Sharma).

https://doi.org/10.1016/j.yofte.2018.05.003
Received 20 March 2018; Received in revised form 27 April 2018; Accepted 6 May 2018
1068-5200/

changes in its above-mentioned optical properties in monolayer form makes MoS_2 an excellent choice to be used as performance enhancement material [20].

In the present work, chalcogenide fiber optic SPR sensor with MoS_2 monolayer is simulated and analyzed to sense the ethanol-methanol 'binary' mixture solution in water. It has been studied earlier that polythiophene (PT) films can be used for interfacing with alcohols to achieve the feature of specificity [1]. In this context, the influence of using a PT layer on the sensor's performance has also been examined. Further, the sensor structure has been analyzed at different NIR wavelengths.

2. Theoretical background and design considerations

Surface plasmons, which are electron density oscillations at the metal-dielectric interface, are resonantly excited when following condition is fulfilled:

$$\frac{2\pi}{\lambda} n_c \sin\theta_{SPR} = \mathrm{Real}\left(\frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_m \varepsilon_s}{\varepsilon_m + \varepsilon_s}}\right) \quad (1)$$

In Eq. (1), n_c is the RI of fiber core, ε_s and ε_m represent the permittivities of the dielectric and metal respectively, λ is the wavelength of incident light, and θ_{SPR} is resonance angle. In a fiber-optic sensor, the analyte property is detected by measuring the variation in optical power transmitted after getting plasmonically modulated. In the present study, a monochromatic beam of light is considered for evaluation and the angle (α) with which the light beam is launched into the fiber is varied (Fig. 1). Such sort of arrangement based on angular interrogation method is known as selective ray launching.

In order to obtain the normalized reflection coefficient (R) for p-polarized incident light, the transfer matrix method for multilayer system (see Appendix A for details) is used [21]. The (normalized) power transmitted by the SPR region (of length L) can be calculated as:

$$P(\theta) = R(\theta)^{N_{ref}(\theta)} \quad (2)$$

In above equation, $N_{ref}(\theta) = L/(D \tan\theta)$ is the number of reflections undergone by the light ray propagating inside the fiber core at an angle θ (as shown in Fig. 1), where D is the fiber core diameter. Further, the power loss (in dB) with reference to maximum normalized power (=1) can be obtained using:

$$Power\ Loss\,(in\ dB) = 10\ \log_{10}\left(\frac{1}{P(\theta)}\right) \quad (3)$$

Since, the step-index fiber is considered, therefore, with the help of Snell's law, the power loss spectrum at the output end can be conveniently mapped with the angle of incidence (α). At the point where SPR occurs (*i.e.*, $\alpha = \alpha_{SPR}$), the loss in transmitted power will be maximum and a change in the analyte RI leads to a shift in α_{SPR} (as shown in Fig. 1). This concept of angular interrogation (Power loss *vs.* α) employed in fiber optic sensors can be considered a dependable way of carrying out the analyte detection.

In the following sections, the different components of the proposed SPR sensor are discussed:

2.1. Fiber core

Several chalcogenide glasses having very large RI values in NIR spectral region are available but a chalcogenide glass with smaller RI is preferable one because in IR region, the sensitivity under angular interrogation (selective ray launching) is largely dictated by the RI values of analyte and substrate material as per following relationship [22]:

$$S_\theta = \left(\frac{d\theta}{dn_a}\right)_{\lambda\to\infty} \to \frac{1}{\sqrt{n_p^2 - n_a^2}}\,(\mathrm{rad/RIU}) \quad (4)$$

In Eq. (4), n_p and n_a are the RI of substrate and analyte, respectively. It clearly suggests that sensitivity becomes higher if smaller RI substrate material is used. For sensing in NIR region, samarium doped chalcogenide ($Se_{95}Te_5Sm_{0.25}$) is chosen as fiber core in view of the above-mentioned point. Wavelength dependent RI of $Se_{95}Te_5Sm_{0.25}$ has been calculated using the data reported by Isayev et al. [23]. The RI values of $Se_{95}Te_5Sm_{0.25}$ vary from 1.6437 (at λ = 900 nm) to 1.6031 (at λ = 1200 nm).

2.2. Clad

In order to carry out the sensing of wide range of analyte RI values, allowed values of incident angle (α) should be as large as possible. The above range of α is decided by the numerical aperture ($NA = \sqrt{n_{core}^2 - n_{outer}^2}$), where n_{core} and n_{outer} are the RI values of fiber core and outer (clad) media, respectively. For any given value of NA, the value of α varies from 0 to $\sin^{-1}$(NA). The usual clad media have their RI values quite close to core RI, therefore, NA and the corresponding α-range cannot be very large. In this view, it is assumed that the clad is removed from a small region (of length L) and is replaced with a dielectric layer of smaller n_{outer} so that NA is sufficiently large. In the present case, this can be realized by using perfluorinated (PF) homopolymer layer atop the fiber core. The typical RI values of PF layer vary between 1.3381 and 1.3369 for the corresponding NIR wavelength variation between, respectively, 900 nm and 1200 nm [24] which leads to a NA in the vicinity of 0.88–0.95 with $Se_{95}Te_5Sm_{0.25}$ fiber core. The above estimation leads to an allowed α-range of 0^0–72.63^0 (θ-range: 54.5^0–90^0) at λ = 900 nm and 0^0–62.2^0 (θ-range: 56.5–90^0) at λ = 1200 nm.

2.3. Ag layer

A thin layer of Ag (thickness: 42 nm) is coated on the clad layer. The thickness of Ag layer is chosen so that the loss in transmitted power is maximum and the angular width of power loss spectrum for p-polarized light is minimum. The RI of Ag layer at different wavelengths are calculated using the Lorentz-Drude model that considers both interband

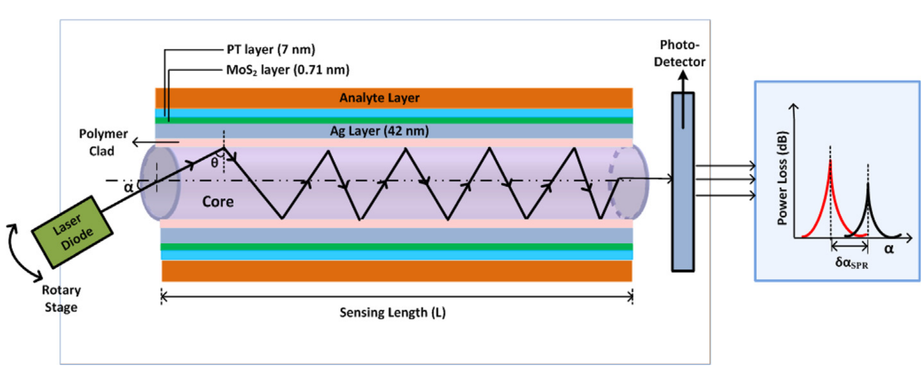

Fig. 1. Schematic of the proposed fiber-optic SPR sensor. The laser source is fixed on a rotary stage in order to 'on-axis' launch the light into the fiber core. The SPR sensing region is the multilayered one with a length 'L'. The detection mechanism consists of a photodetector connected with the computation system that displays the angular spectrum of power loss occurred in the SPR sensing region. At the corresponding resonance angle (*i.e.*, α_{SPR}), the power loss spectrum shows a sharp peak, which shifts to some other angle with a change in analyte RI. The corresponding SPR shift is denoted as $\delta\alpha_{SPR}$.