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Enhancement in performance of an evanescent wave fiber optic sensor in the near-infrared region by graphene's chemical potential

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ABSTRACT

An intensity interrogation-based fiber optic evanescent wave sensor with graphene monolayer is simulated and analyzed in the near-infrared spectral region. Chalcogenide glasses are considered as fiber's core and clad materials. Dispersion relations of normal and malignant human liver tissues are considered for analysis. The effect of graphene's chemical potential (μ) on sensor's performance is examined, which is evaluated in terms of sensitivity and resolution. The analysis of simulation results indicates that if μ is set around 0.45 eV at 1550-nm light wavelength (λ), the sensitivity achieved is nearly 47 mW/RIU (real index) and 280 mW/RIU (imaginary index), and the resolution achieved is of the order of 10^{-9} RIU (real index) and 10^{-10} RIU (imaginary index). Even further improvement in the sensing performance can be achieved around μ = 0.6 eV. The analysis shows that it is preferable to use p-polarized light as it provides significantly better values of sensitivity and resolution than s-polarized light. In addition to smaller photodamage and reduced Rayleigh scattering (due to being operated in NIR), the proposed fiber optic sensor probe has the capability to provide considerably superior resolution than existing fiber optic sensors based on different techniques.

1. Introduction

Fiber optic sensors based on intensity interrogation method have been widely used in the sensing of several important chemical, environmental, physical, and biological parameters/processes [1–3]. The high sensitivity of these sensors is because of a considerable change in the intensity of an electromagnetic (EM) wave when it is guided through the fiber core [4]. One of the most popular sensing techniques under intensity interrogation is based on the application of an evanescent wave, which is a non-propagating, exponentially decaying EM field that emerges at the interface of two optical media because of the occurrence of total internal reflection (TIR) [5]. A fiber optic evanescent wave (FOEW) sensor is extremely sensitive to the external environment, where the transmitted power varies according to the optical absorption of the evanescent wave by the surrounding medium. The extent of evanescent wave absorption primarily depends on the refractive index (RI) of the surrounding medium [6]. A high sensitivity can be obtained by increasing the fraction of propagating power in the evanescent wave so that maximum absorption occurs [7,8]. To enhance the sensitivity of fiber optic sensors, several methods have been employed such as tapered fiber geometry [9] and bending of fiber [10]. In this context, 2D materials such as graphene and molybdenum disulfide (MoS_2) have the ability to enhance the optical absorption leading to a larger variation in the output power and, consequently, greater sensitivity [11].

Graphene, with its novel optical properties, has become an excellent candidate for different sensing applications [12]. Graphene is a chemically stable 2D material that possesses great biocompatibility, resistance to EM interference, and excellent mechanical strength [13]. Graphene has a very low density of states at its Dirac point, and small changes in carrier densities will provide large variations in its Fermi energy, thus leading to a large variation in its optical properties, which can be exploited to enhance the sensitivity of an FOEW sensor [14]. The chemical potential (μ) of graphene plays a considerable role in controlling its optical properties owing to a significant dependence of optical conductivity (σ) on μ. The variation in μ (varying between 0 and 1 eV) has recently been exploited in significantly enhancing the performance of a plasmonic sensor in the near-infrared (NIR) region [15]. Therefore, it is worthwhile to explore the effect of graphene's chemical potential on evanescent wave absorption-based optical fiber sensor also.

In this work, we simulate and analyze an FOEW sensor with graphene monolayer by changing its chemical potential in the NIR. The sensor is directed at diagnosing malignancies in the human liver tissue.

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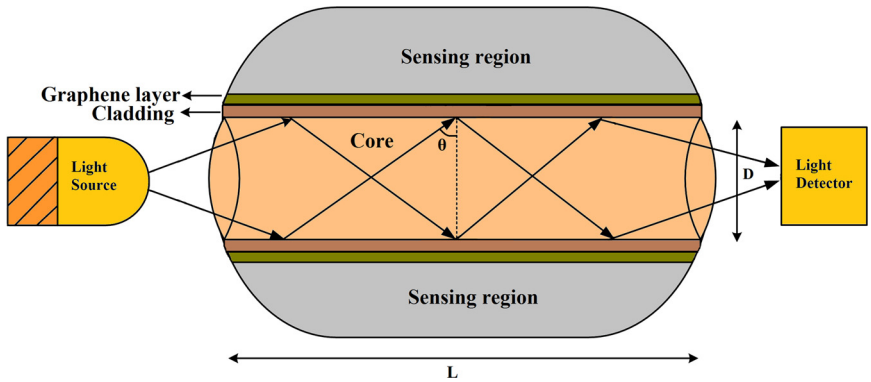

Fig. 1. Schematic diagram of an evanescent wave-based fiber optic sensor with graphene monolayer. For the present analysis, D = 300 μm and L = 5 cm. The clad thickness is 50 nm and the light source is considered to be a laser diode emitting at λ = 1550 nm with an optical power of 10 mW.

Furthermore, because of the much smaller photodamage of biosamples in the NIR [16], the wavelength of light is chosen as 1550 nm (*i.e.*, fiber optic communication wavelength). The effect of chemical potential on the sensor's performance is examined in terms of sensitivity and resolution for different polarizations of incident NIR light, and the best optimum working conditions are identified for a precise and reliable diagnosis of malignancies in the human liver tissue.

2. Theoretical framework and design considerations

The working of an FOEW sensor is based on the principle of attenuated total internal reflection as shown in Fig. 1.

Light coming from a source is guided through the fiber, and its intensity is modulated because of the presence of a sensing region (*i.e.*, analyte). The detector receives the modulated light, which carries the information regarding analyte property [6]. To build a strong interaction of the fiber core with the analyte medium, only a small thickness (≈few tens of nm) of the clad is left, and its majority extent is removed. This ultrathin clad is followed by a monolayer of graphene (d_2 = 0.34 nm), which is in direct contact with the analyte as shown in Fig. 1. In an evanescent wave sensor, the power transmitted (P_{trans}) at the output end of the fiber is usually calculated as follows [7,8]:

$$P_{trans} = P_o \exp(-\gamma L) \tag{1}$$

where p_o is the reference power (*i.e.*, when no modulation of light occurs), γ is the absorption coefficient of the evanescent wave, and L is the sensing region length. However, in the present sensor model, we employ the multilayer transfer matrix method (TMM) to calculate the output power. The TMM is very accurate as it contains no approximations and facilitates highly precise calculations for a variety of multilayer structures (*e.g.*, insulating and conducting layers) [17]. In this method, a layer is characterized by thickness d_k, RI n_k, and dielectric constant ε_k. The characteristic transfer matrix (M) is defined as [17,18] :

$$M = \prod_{k=2}^{N-1} M_k \tag{2}$$

$$\text{with} \quad M = \begin{pmatrix} \cos\beta_k & -i\sin\beta_k/q_k \\ -iq_k\sin\beta_k & \cos\beta_k \end{pmatrix} \tag{3}$$

$$\text{where} \quad q_k = \left(\frac{\mu_k}{\varepsilon_k}\right)^{1/2} \quad \cos\theta_k = \frac{(\varepsilon_k - n_1^2\sin^2\theta_1)^{1/2}}{\varepsilon_k} \tag{4}$$

$$\text{and} \quad \beta_k = \frac{2\pi d_k}{\lambda}(\varepsilon_k - n_1^2\sin^2\theta_1)^{1/2} \tag{5}$$

The amplitude reflection coefficient corresponding to p-polarized incident light is given as follows [17,18]:

$$r_p = \frac{(M_{11} + M_{12}q_N)q_1 - (M_{21} + M_{22}q_N)}{(M_{11} + M_{12}q_N)q_1 + (M_{21} + M_{22}q_N)} \tag{6}$$

Consequently, the reflected light intensity is expressed as follows:

$$R_p = |r_p|^2 \tag{7}$$

The layers in the present 4-layer optical system are (1) chalcogenide glass core (RI = n_1), (2) chalcogenide glass clad (RI = n_{cl}), (3) graphene monolayer (RI = n_{Gr}), and (4) analyte layer (malignant liver tissue measured with reference to normal liver tissue) of RI represented as n_a.

Further, a collimated light source is considered for transmitting light through the fiber sensor. The power distribution for the collimated source is given as follows:

$$p(\theta) \propto \frac{n_1^2\sin\theta\cos\theta}{(1 - n_1^2\cos^2\theta)^2} \tag{8}$$

Considering N_{ref} as the total number of reflections a ray undergoes with the sensing medium interface, the total normalized power transmitted at the output can be calculated as follows [7]:

$$P_{trans} = \frac{\int_{\theta_{cr}}^{\pi/2} R_p^{N_{ref}(\theta)} p(\theta)d\theta}{\int_{\theta_{cr}}^{\pi/2} p(\theta)d\theta} \tag{9}$$

$$\text{where,} \quad N_{ref}(\theta) = \frac{L}{D\tan\theta} \tag{10}$$

$$\text{and} \quad \theta_{cr} = \sin^{-1}\left(\frac{n_{cl}}{n_1}\right) \tag{11}$$

Next, we discuss the different components of the proposed 4-layer sensor along with their relevant properties and parameters.

2.1. Layers 1 and 2 (Core and Clad): chalcogenide glass

Chalcogenide glasses, which are based on group IV materials containing chalcogens (S, Se, and Te) as one of elements and formed with the addition of other elements such as Ge, As, and Ga, have favorable optical properties in the NIR, such as high transparency, large RI, high chemical and thermal stability, and low phonon energy [19]. We consider $As_{40}Se_{60}$ and $Ge_{33}As_{12}Se_{55}$ chalcogenide glass materials as the core and clad of the optical fiber, respectively. At λ = 1550 nm, the RI values of $As_{40}Se_{60}$ and $Ge_{33}As_{12}Se_{55}$ glasses are n_1 = 2.84199 RIU and n_{cl} = 2.54373 RIU, respectively [20,21]. The fiber core diameter is taken as 300 μm, and the clad is assumed to be 50 nm thick.

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