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Sensitivity enhancement of cylindrically-symmetric optical fiber refractive index sensors by utilizing graphene

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ABSTRACT

This paper presents a new method of using graphene coating to enhance the sensitivity of the cylindrically-symmetric refractive index (RI) sensors. Previously, it was implicitly considered that graphene coating can only enhance the sensitivity of RI sensors in the polarization differentiating configuration. Many of the conventional RI sensors, including the cylindrical symmetric ones, are incapable of differentiating between the polarization modes. To address this issue, the enhancement in RI sensitivity of a graphene-coated cylindrically-symmetric configuration is studied by modifying the Fresnel coefficients. The theoretical calculations show the possibility of improving the cylindrical symmetric sensors with graphene coating. The proposed coating is quite simple and can be used for the improvement of a major fraction of conventional RI sensors.

1. Introduction

Disease diagnosis and contamination monitoring usually can be addressed through measuring the concentration of specific chemicals. The concentration variation modulates the refractive index (RI) of the solution directly or by amplification with specific receptors in the sensing region [1,2]. Due to the optical interactions in RI measurements, RI sensors are often non-invasive, bio-compatible and label-free making them an ideal option for biological applications [3]. The outstanding importance and the bright future of this kind of sensors have attracted a lot of interests in improving their sensitivity and accuracy, alongside their miniaturization.

Considering the role of the reflection coefficient in the sensitivity of reflection based RI sensors, every modification which increases the changes of the reflection coefficient in response to the RI variation can potentially lead to the development of more accurate devices. Coating different materials on the sensing region of the reflection-based RI sensors is a current approach to achieve more sensitivity. There have been many efforts to fulfill this task including coating noble metals and immobilizing metallic nanoparticles to excite surface plasmon resonance (SPR) and localized surface plasmon resonance (LSPR), respectively [4–6]. However, the innovation of new coatings for further improvement of RI sensors is still challenging.

In recent years, graphene, the 2D structure of carbon atoms in a honeycomb lattice, has attracted a lot of attention. The main benefit of graphene coated sensor over SPR sensors is more than ten times larger penetration depth of evanescent field [7]. Also, due to the simple immobilization of biomolecules and biocompatibility, graphene is a suitable material for biological applications [8]. In the recent researches on RI sensors, graphene has been used to enhance the sensitivity of reflection-based sensors. The most outstanding ones include the theoretical and experimental investigations on graphene SPR excitation in terahertz and far-infrared regions [9], the sensitivity enhancement of SPR sensors by adding graphene to the multilayered SPR structures [10,11], the SPR excitation in graphene nanoribbons [12], photonic crystal sensors [13], Fano resonance [14], and polarization-dependent sensors [15–17]. In an inspiring paper, Xing et al. [15] have used polarization-dependent absorption property of graphene in a polarization-differentiating configuration to achieve a sensitive RI sensor. Although the fabricated sensor does not need complicated coatings or lithographic patterning and is highly sensitive, it requires the precise alignment of optical elements and employing this method in the conventional miniaturized RI sensors is quite challenging.

Optical fiber RI sensors are the most popular miniaturized RI sensors that have been used in a wide range of applications [18,19]. These sensors can be candidates for coating graphene on the surface to enhance their sensitivity. But, the cylindrical nature of optical fiber sensors

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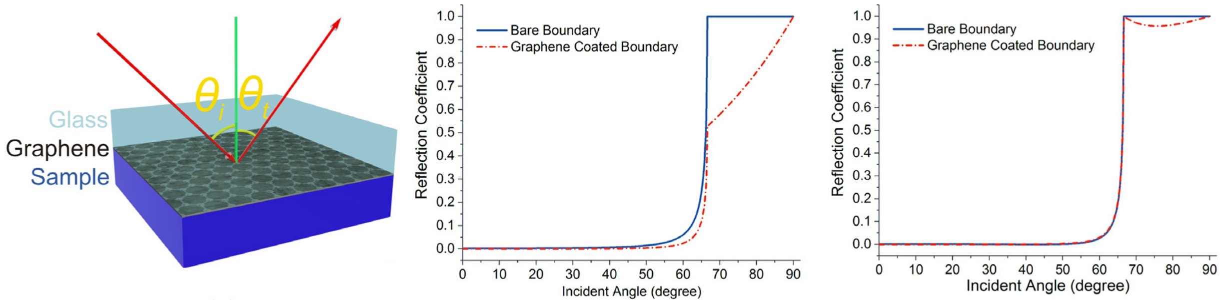

(a) (b) (c)

Fig. 1. (a) Schematic view of the graphene boundary. Power reflection coefficient with and without graphene coating for (b) TE polarization and (c) TM polarization.

prevents them from benefiting the polarization-dependent absorption sensitivity of graphene (as was used in [15]). However, there exists several experimental reports which show that even with cylindrical symmetry, optical fiber refractive index sensors become more sensitive as graphene is coated on their surface [10,20]. However, the theory behind this enhancement has not been fully studied yet.

In this paper, the RI sensitivities of the reflection coefficient for the polarized light interacting with a flat surface and one interacting with the cylindrical symmetric surface are calculated with and without coating graphene and the results are compared against each other. These theoretical results show that coating the boundary with graphene results in the enhancement of RI sensitivity even though, the unpolarized light or a cylindrical symmetric structure is employed. This can be achieved in conventional polarization-insensitive cylindrically-symmetric RI sensors, e.g. LPFG, tapered optical fiber, etc.

2. Theoretical calculations

Fresnel reflection coefficients describe the amount of reflected light in the reflection from an optical boundary. These coefficients for TE and TM polarizations are defined as

$$r_{TE} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \tag{1}$$

and

$$r_{TM} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}, \tag{2}$$

respectively. Where, n_1, n_2, θ_i, and θ_t are the RI of the first medium, the RI of the second medium, the incident angle, and the transmission angle, respectively [21]. To calculate the modified Fresnel coefficients of a boundary with graphene coating, the electrical conductivity of the graphene layer is considered as surface conductivity on the boundary and its thickness is neglected compared to the wavelength of the light. With these assumptions, Maxwell's boundary conditions do not change except for the parallel magnetic field, which changes to

$$n \times \left(H_1 - H_2\right) = K_s \tag{3}$$

where, H_1 and H_2 are the magnetic field strength in the first and the second medium, respectively, and K_s is the surface current, which obeys the Ohm's law:

$$K_s = \sigma_s E_t. \tag{4}$$

In this equation, E_t is the tangential electric field at the boundary, and σ_s is the surface conductivity of the coated graphene layer. For m layers of graphene ($m \le 5$), the surface conductivity is defined as $\sigma_s = m\sigma_l$, where σ_l is the conductivity of each graphene layer. For graphene coated on SiO_2 substrate at the wavelength of 1550 nm σ_l can be calculated from the results in [22] to be $(5.1 + 1.9i)\times10^{-5}$ S. For more graphene layers ($m > 5$), the surface conductivity is calculated by using the conductivity of bulk graphite in the direction parallel to its basal plane ($\sigma = 2.5\times10^5$ S/m) [23] and the surface conductivity is calculated by $\sigma_s = m\delta\sigma$ where δ is the thickness of each layer. Considering the above relations, along with Maxwell's boundary conditions, Fresnel reflection equations change to

$$r_{TE} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t - \sigma_s Z_0}{n_1 \cos\theta_i + n_2 \cos\theta_t + \sigma_s Z_0} \tag{5}$$

and

$$r_{TM} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i - \sigma_s Z_0 \cos\theta_i \cos\theta_t}{n_1 \cos\theta_t + n_2 \cos\theta_i + \sigma_s Z_0 \cos\theta_i \cos\theta_t} \tag{6}$$

where, Z_0 is the impedance of free space. And, the reflected power can be calculated with

$$R_{TE,TM} = \left|r_{TE,TM}\right|^2. \tag{7}$$

Due to the importance of RI measurements in the biological samples, i.e. water-based solutions, and using glass substrate in the majority of the RI sensors, the power reflection coefficient is calculated for a boundary between glass ($n_1 = 1.440$) and water ($n_2 = 1.316$@1550 nm) with 4 graphene layers coated on it ($m = 4$). These coefficients are plotted for TE and TM polarizations and are compared with uncoated boundary (Fig. 1). These results are in agreement with the results reported in [14], which were obtained with a different approach.

The sensitivity of reflection coefficient to the RI is the main parameter which influences the overall sensitivity of a reflection based RI sensor. This parameter is defined as the variation in reflection coefficient divided by the amount of RI change, or simply, derivative of $R_{TE,TM}$ relative to n_2:

$$S_R\left(n_2\right) = \lim_{\Delta n \to 0} \frac{R\left(n_2 + \Delta n\right) - R\left(n_2\right)}{\Delta n}. \tag{8}$$

With the above assumptions ($n_1 = 1.440$, $n_2 = 1.316$) and also assuming $\Delta n = 0.0001$, the sensitivity is plotted for the different number of graphene layers for TE and TM modes (Fig. 2).

It can be inferred from Fig. 2 that graphene coating does not change the critical angle. It only changes the amount of reflected power. The surprising result of Fig. 2 is the sensitivity of graphene coated boundary to the RI in the total internal reflection (TIR) region whereas, the bare boundary has zero sensitivity in these angles. This result implies the potential benefit of graphene coating on the evanescent-field based sensors, such as optical fiber sensors, in which incident angle is above the critical angle. To determine the optimum number of graphene layers, the sensitivity at a fixed angle in this region (70°) versus the number of graphene layers is plotted in Fig. 3(a). The absolute value of the sensitivity for TE polarization increases with increasing number of layers from zero to seven and then, decreases. For TM polarization, this increase in the sensitivity continues as the number of layers is increased. However these calculations are based on neglecting the thickness of graphene layer which is not valid for large number of layers and this rising trend does not necessarily continues for large number of layers.

For the optical fiber RI sensors which possess cylindrical symmetry or in the sensors working with unpolarized light, the contribution of TE