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Regular Articles

Graphene based chalcogenide fiber-optic evanescent wave sensor for detection of hemoglobin in human blood

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ABSTRACT

Fiber optic evanescent wave sensor with graphene as an absorption-enhancing layer to measure hemoglobin concentration in human blood is proposed. Previous modal functions and experimental results describing the variation of optical constants of human blood with different hemoglobin concentrations in the near-infrared spectral region are considered for sensor design simulation. The sensor's performance is closely analyzed in terms of its absorption coefficient, sensitivity, and detection limit. It is found that the proposed sensor should be operated at longer light wavelength to get more enhanced sensitivity and smaller detection limit. At 1000 nm wavelength, a detection limit of 18 μg/dL and sensitivity of 6.71×10^{-4} per g/dL is achievable with the proposed sensor. The sensitivity is found to be better for larger hemoglobin concentrations. The results are correlated with the evanescent wave penetration depth.

1. Introduction

As mentioned by *New Global Nutrition Report 2017*, anemia is a serious health problem faced globally by 614 million women aged 15–49 years, especially pregnant women and children [1]. Anemia is also an important biomarker for various diseases [2]. So, an accurate and continuous sensor probe with high sensitivity and specificity is required for measuring hemoglobin (Hb) concentration in human blood. Fiber optic evanescent wave (FOEW) based sensing technique has been extensively used for environmental, biomedical, and biochemical measurements [2–4]. FOEW sensors are based on optical absorption *via* evanescent wave, which is an exponentially decaying electromagnetic (EM) field generated at the interface with a small penetration depth when light propagates through a fiber core by means of total internal reflection (TIR), and interacts with the medium present in its vicinity [5].

The optical properties of blood sample depend upon the Hb concentration and light wavelength. The real and imaginary parts of refractive index (RI) have been separately measured through various experiments at different Hb concentrations in visible to the near-infrared (NIR) wavelength ranges. The real part (n_{Hb}) of the RI is written in the following form:

$$n_{Hb}(\lambda, c_{Hb}) = n_{H_2O}(\lambda)[\beta(\lambda)C_{Hb} + 1] \tag{1}$$

In above expression, β denotes the specific refractive increment which is wavelength-dependent [6], and C_{Hb} represents the Hb concentration in g/dL. Further, the imaginary part (k_{Hb}) of the RI (*i.e.*, extinction coefficient) is described as:

$$k_{Hb}(\lambda, c_{Hb}) = \frac{2.303 \times \mu \times C_{Hb} \times \lambda}{4\pi \times 6500} \tag{2}$$

where μ represents the wavelength-dependent molar extinction coefficient [7]. The variation of complex RI with wavelength for different hemoglobin concentrations is demonstrated in Fig. 1. The curves shown in Fig. 1 indicate that the RI varies significantly with Hb concentration. In particular, the magnitude as well as variation in imaginary part of RI are substantial, which is necessary for evanescent wave sensor based on optical absorption.

One of the important requirements while designing an FOEW sensor is that the propagating light should be absorbed by the analyte (*i.e.*, the sample under measurement) as strongly as possible. This absorption is facilitated by the presence of evanescent wave in the vicinity of the analyte. In order to achieve an enhanced absorption of light leading to greater sensitivity of the sensor, different mechanisms such as dye-encapsulated xerogel [8] and absorption-modulated luminescence [9] have been utilized. In this context, 2D material such as graphene can also be considered for application in FOEW biosensor due to its very high electron mobility, high specific surface area, excellent biological compatibility, and tunable optical properties [10,11]. Graphene has been extensively explored in surface plasmon resonance (SPR) based

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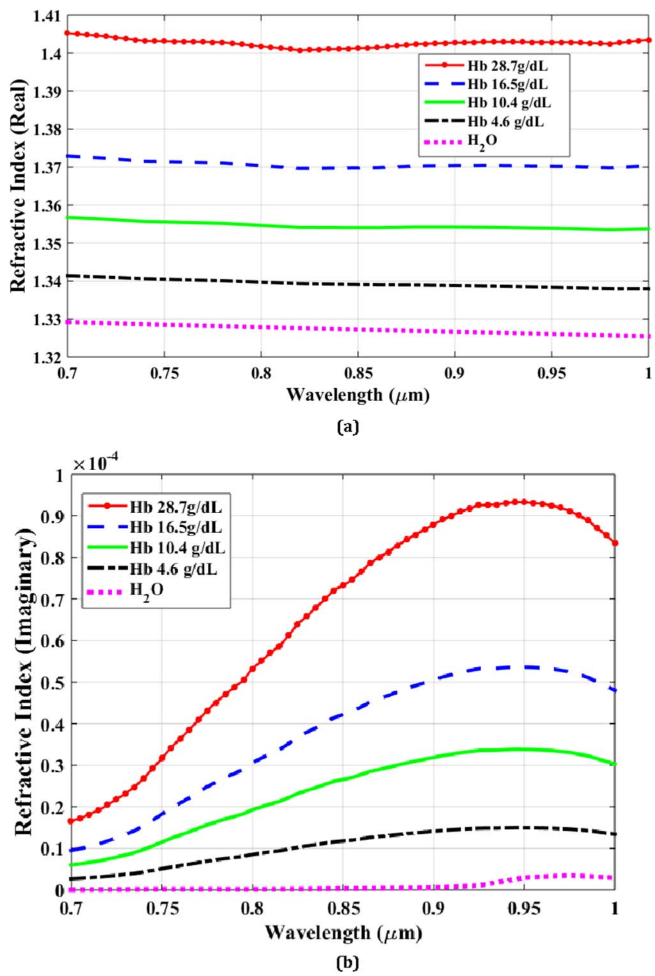

Fig. 1. Spectral Variation of (a) real part, and (b) imaginary part of RI of blood sample for different hemoglobin concentrations. The above figures also contain the plots corresponding to H_2O sample, which is considered to be reference solution (*i.e.*, with $C_{Hb} = 0$ g/dL).

fiber-optic sensors [12–14]. Recently, some work has been reported in context of graphene's use in FOEW sensors also [15,16].

However, these works are limited in visible spectral regions while using silica-based optical fibers. Since, biological analytes suffer photodamage or phototoxicity when exposed to visible wavelength and show transparent behavior in IR region [17], therefore, graphene-enhanced evanescent wave fiber optic sensors in NIR should be explored with suitable fiber materials other than silica.

In this paper, a design of chalcogenide glass-based fiber-optic evanescent wave sensor with a graphene monolayer has been simulated and analyzed for precise and reliable detection of Hb concentration in NIR. The IR optical data reported previously has been utilized. Owing to its excellent biological affinity, graphene monolayer is envisaged as a bio-enricher material in the proposed sensor design. The influence of different NIR wavelengths on sensor's performance in terms of sensitivity and detection limit has been studied. A detailed comparison of sensor's performance with and without graphene layer has been carried out.

2. Design considerations

A three-layer structure based fiber optic sensor with intensity interrogation method is considered. In this method, the cladding of chalcogenide fiber is stripped off from a small portion of the fiber length in order to expose the fiber core. A thin monolayer of graphene (thickness, $d_{Gr} = 0.34$ nm) is deposited symmetrically over the stripped off area and is in direct contact with the analyte (sensing region) as shown in Fig. 2.

In the following sections, the modalities of different components of the proposed sensor are discussed along with their optical properties.

2.1. Chalcogenide glass

For modeling a fiber optic sensor, the core and clad materials are chosen keeping in mind that their RI values satisfy the TIR condition, *i.e.*, Core RI (n_{core}) > Clad RI (n_{clad}). In this model, we have considered sulphide based chalcogenide glass materials, *i.e.*, $As_{40}S_{60}$ for core and $Ge_{20}Ga_5Sb_{10}S_{65}$ (also known as 2S2G) for cladding of the fiber. The wavelength dependent RI of above chalcogenide glasses is represented in terms of following dispersion relation [18,19]:

$As_{40}S_{60}$

$$n_{core} = 2.304 + \frac{6.8218 \times 10^{-2}}{\lambda^2} \tag{3}$$

2S2G

$$n_{clad} = 2.24047 + \frac{2.693 \times 10^{-2}}{\lambda^2} + \frac{8.08 \times 10^{-3}}{\lambda^4} \tag{4}$$

where λ denotes the wavelength in μm. The RI variation as per above expressions is depicted in Fig. 3 that indicates sufficiently large difference between n_{core} and n_{clad} leading towards a large numerical aperture (NA = $\sqrt{n_{core}^2 - n_{clad}^2}$). Larger value of NA ensures significantly greater light power gathering capacity of the fiber, which is a crucial element while designing intensity-modulation based fiber optic sensors.

2.2. Graphene layer

Atomically thin graphene monolayer (thickness, $d_{Gr} = 0.34$ nm) consists of carbon atoms arranged in 2D honeycomb crystal lattice structure. As mentioned earlier, its enhanced electrical and optical properties make it a good candidate to be used in optical fiber biosensors. The complex RI of graphene in NIR (up to 1000 nm wavelength) has been adopted from an earlier work [20].

2.3. Blood sample layer (Analyte)

The analyzing medium in the present three-layer fiber optic sensor is a human blood sample. The spectrally varying complex RI of blood

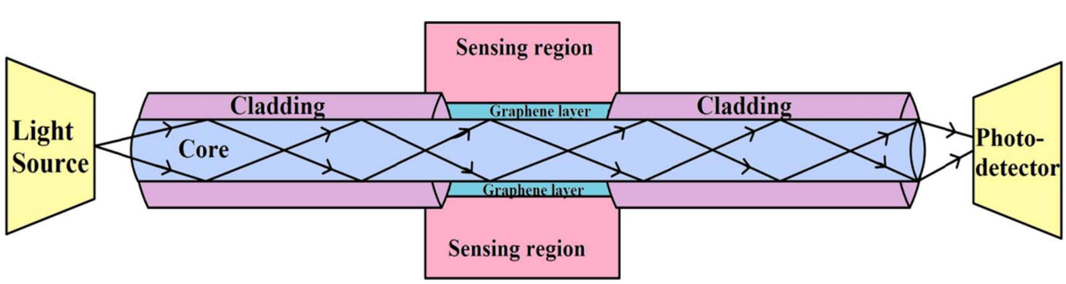

Fig. 2. Schematic diagram of three-layer evanescent wave-based fiber optic sensor for hemoglobin detection using graphene layer.