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Fiber Bragg grating assisted surface plasmon resonance sensor with graphene oxide sensing layer

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ABSTRACT

A single mode fiber Bragg grating (FBG) is used to generate Surface Plasmon Resonance (SPR). The uniform gratings of the FBG are used to scatter light from the fiber optic core into the cladding thus enabling the interaction between the light and a thin gold film in order to generate SPR. Applying this technique, the cladding around the FBG is left intact, making this sensor very robust and easy to handle. A thin film of graphene oxide (GO) is deposited over a 45 nm gold film to enhance the sensitivity of the SPR sensor. The gold coated sensor demonstrated high sensitivity of approximately 200 nm/RIU when tested with different concentrations of ethanol in an aqueous medium. A 2.5 times improvement in sensitivity is observed with the GO enhancement compared to the gold coated sensor.

1. Introduction

Optical fiber sensors are currently very popular due to their unique characteristics such as low attenuation, immunity to radio frequency or electromagnetic interference, high sensitivity and easy adaptability for various sensing parameters on a single platform [1,2]. Another distinctive benefit of using optical fiber sensors is their remote sensing capability where they can be integrated into an optical transmission system [3,4].

Fiber optic based surface plasmon resonance (SPR) sensors are garnering a great deal of interest due to their ability for label free detection of chemical and biological sensing applications [5–11].

Most fiber optic SPR sensors are fabricated using decladded single mode or multimode optical fibers with a metal layer (usually gold or silver) deposited on it. Cladding is removed either by chemical etching [12,13] or side polishing [2,7] a fiber optic cable until the core is exposed. While these SPR sensors demonstrate good sensitivity for both biological as well as chemical sensing applications, they are some handling problems due to their fragility.

In recent years, grating based optical fiber sensors have been gaining interest due to several advantages such as high sensitivity as well as self-referencing capabilities. Various types of gratings such as fiber Bragg gratings (FBG) [15–17,19], long period gratings (LPG) [18], and tilted FBGs [12,13] were written on single and multimode fibers and utilized for measurement of physical parameters such as strain, temperature, pressure and vibration. FBGs have also been used for refractive index sensing to detect sugar in water [21] and alcohol concentrations [22,23]. Lately, there has been much interest in surface plasmon resonance sensors using FBGs [24–27] and long period gratings [28,29].

Lately, we see an emerging trend of using nanomaterial for sensing applications. Nanomaterials have large surface area to volume ratio that is ideal for sensing. Graphene is a carbon material with excellent electrical and mechanical properties that has attracted a great deal of attention and has the potential for application in highly sensitive and selective detection.

Graphene oxide (GO) is derived from graphene and has similar properties such as a single atomic plane which could provide a large surface area for chemical sensing environment. GO also allows fast water permeation within its layers making it very suitable for sensing water based mediums [30]. It also demonstrates unique behavior towards ethanol making it a good choice for ethanol sensing [31,32]. Recent work on GO based optical sensors show that it is a highly sensitive sensing medium with fast response time [33,34].

In this paper we propose a fully cladded, single mode gold

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coated FBG SPR sensor with an input from a broadband white light source. Enhancement of the sensing performance is investigated by adding a nanostructured GO sensing layer. Scattering of the light by the FBG introduces multiple rays into the cladding region of the FBG. This phenomenon is exploited to produce SPR. A 45 nm layer of gold is applied over the grating area and a thin film of GO is drop casted on the gold film. To the best of our awareness, there has been no experimental study on FBG enhancement of SPR using fully cladded single mode fibers with a GO sensing layer.

2. Background

2.1. Fiber Bragg grating (FBG)

The single mode FBG is designed to work in telecommunications wavelengths, where a single wavelength is reflected back based on the period of the grating and the effective index of the core and the cladding [35]. In this research, the FBG is used at a much lower wavelength generated by a white light source.

The gratings in this case, do not act as optical filters but instead refract the light traveling in the core out to the cladding. Due to total internal reflection between the cladding and the surrounding medium, the light does not escape out of the fiber but is guided back to the core of the fiber. Total internal reflection (TIR) between the cladding and the surrounding produces an evanescent wave that can be exploited to produce surface Plasmon resonance.

2.2. Surface plasmon resonance (SPR)

SPR is a physical process that occurs when a p-polarized light hits a metal film under the conditions of total internal reflection such as in an optical fiber [36]. The wavevector of the plasmon wave, k_{sp} is shown in Eq. (1) [37].

$$k_{sp}=\left(\frac{2\pi}{\lambda}\right)\sqrt{\frac{\left(n_{metal}^2\times n_2^2\right)}{\left(n_{metal}^2+n_2^2\right)}} \tag{1}$$

where n_{metal} is the refractive index of metal film and n_2 is the refractive index of the dielectric material and λ is the wavelength of the incident light. The SPR occurs if the energy transfer between incident light and surface plasmon wave at the dielectric-metal interface satisfies the relationship in Eq. (2) [37].

$$n_p k_0 \sin\theta_{sp}=k_{sp}=k_0\left[\frac{\epsilon_m\epsilon_s}{\epsilon_m+\epsilon_s}\right]^{1/2} \tag{2}$$

The wavevector of an electromagnetic wave in vacuum is represented by $k_0=2\pi/\lambda_0$, where λ_0 is the wavelength in a vacuum. The dielectric constants of the metal and sample are represented by ϵ_m and $\boldsymbol{\varepsilon_s}$ respectively. There are two ways for equating the light wavevector to the plasmon wavevector, which are varying either the angle of incidence, θ, or the wavelength of the light. In a fiber optic SPR sensor, wavelength interrogation is used where SPR is observed as a dip in the intensity at a certain wavelength. This is the feature that enables the exploitation of the SPR phenomena for sensing. Material adsorbed on the thin metal film on the SPR sensor will influence the resonance conditions of the SPR. A linear relationship can be observed between resonance wavelength and the refractive index of the analyte surrounding the sensor.

The performance of the fiber optic SPR sensor is based on spectral interrogation. The power or intensity detected by the receiver normalized to the source power is given by the transmission function in Eq. (3) [38].

$$T(f)=\frac{\frac{1}{2}\int real\left(P(f)^{Monitor}\right).\,dS}{\text{source power}}=\exp\left(-\frac{4\pi}{\lambda_0}\text{imag}(n_{eff})L\right) \tag{3}$$

The poynting vector *P(f)* is integrated with respect to the surface normal S to obtain average power flow over the surface. The length of the sensing region, L the effective index of the sensing region n_{eff}, and the wavelength of the light source, λ_0 are also taken into account for the power calculation. The resonant wavelength of the SPR sensor can be derived from this equation, where the transmit power or intensity of the fiber output will sharply drop at the SPR wavelength. In this research the sensing region length, *L*, is the length of the FBG grating, which is kept constant.

The sensitivity (S_n) of the SPR sensor using wavelength interrogation is given by Eq. (4) [38].

$$S_n=\frac{\delta\lambda_{res}}{\delta n_s} \tag{4}$$

If the refractive index of the sensing layer is altered by δn_s, the resonance wavelength shifts by $\delta\lambda_{res}$. The sensitivity (S_n) of an SPR sensor with spectral interrogation is then defined as the change in resonance wavelength per unit change in refractive index of the sensing region. The SPR phenomenon is illustrated in Fig. 1.

The accuracy of the sensor is determined by the signal-to-noise ratio (SNR) of the sensor. The narrower the SPR curve, the higher the sensitivity. The SNR can be calculated by using Eq. (5) below [38].

$$SNR(n)=\frac{\delta\lambda_{res}}{\delta\lambda_{sw}} \tag{5}$$

where $\delta\lambda_{sw}$ is calculated as the full width at the half maximum (FWHM) of the SPR curve.

3. Experimental details

3.1. Investigation of FBG's beam profile

This experiment is carried out to confirm that under broadband white light conditions, the light passing through the FBG is scattered out to the cladding and therefore can be exploited for SPR. The behavior of the light traveling in the gold coated FBG is investigated using a beam profiler. The FBG is aligned to the lens of a Thorlabs (BC 106-VIS) beam profiler using an adjustable stage as shown in Fig. 2.

The beam profiler has a wavelength range from 350 nm to

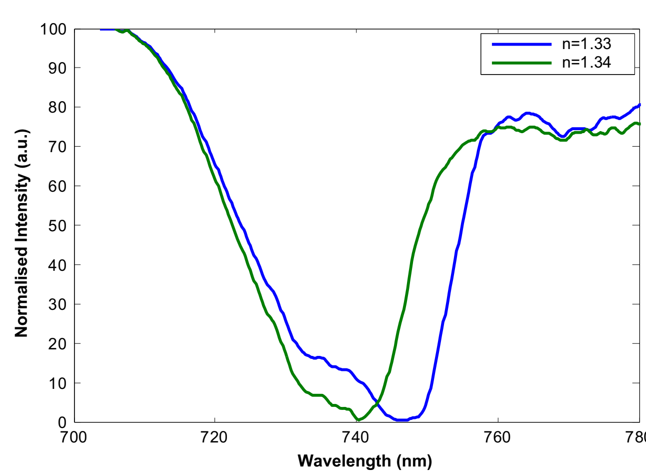

Fig. 1. Wavelength shift due to SPR.