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Carbon-nanotube-deposited long period fiber grating for continuous refractive index sensor applications

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ABSTRACT

We present a carbon-nanotube-deposited long period fiber grating for refractive index sensing applications in liquid. Carbon nanotubes are deposited around the surface of a long period fiber grating to form the refractive index sensing element. The sensing mechanism relies mainly on the high refractive index properties of the carbon-nanotube thin film, which enhances the cladding mode of the long period fiber grating in order to have a significant interaction between the propagating light and the target medium. A sensitivity of 31 dB/RIU and 47 dB/RIU are obtained for the refractive index ranges of 1.33–1.38 and 1.38–1.42, respectively, which have not been demonstrated with normal long period fiber gratings as the sensing element. As the sensing mechanism is based on the change of the transmitted optical power, our proposed scheme can intrinsically solve the limitations of the free spectral range commonly seen in other reported schemes, and continuous and repeatable measurements can be obtained while only acquiring errors mainly from the power fluctuations from the light source. The fiber grating also does not require any further mechanical modification like etching or tapering, which allows the sensing element to have the advantage of mechanical strength for practical applications. The experimental results are consistent with the modeling of the sensing mechanism.

1. Introduction

Optical fiber based refractive index (RI) sensors have attracted a lot of research attention over the years due to the advantage of remote and real-time monitoring capabilities [1–13]. In particular, detecting of RI variations in water is important for water treatment plants as different RI values would indicate the purity level of the water being treated. A variety of optical fiber based sensing schemes such as multimode interference [10], fiber tapering [3,5,8,12], surface plasmon resonance (SPR) [1,13], and dielectric multilayer films [7,9] have been previously reported to construct the sensing probe in order to detect RI variations. However, most of these schemes like tapering, which involves the stretching of the fiber to very thin diameters, and SPR, which commonly involves the etching of the fiber cladding, lead to the modification of the fiber structure to enhance the sensitivity, but make the sensing element mechanically weak and hence prone to damage in practical applications [2,12,13]. Also, some of the proposed schemes rely on the measurement of interferometric wavelength shifts with RI variation within a certain spectral range. These fiber sensors, though extremely sensitive to external perturbations and immune to power fluctuations as long as a certain extinction ratio is achieved, are usually limited by a certain free spectral range (FSR) of the transmission or reflection spectrum [5,8,12]. This poses a considerable challenge when measurements over a wide range of refractive indices are needed.

In order to meet the conditions of a robust fiber sensor, a sensing element using a long period fiber grating (LPFG) is one of the solutions as it does not affect the mechanical strength of the fiber while providing interaction between the propagating light and the outside medium through the cladding mode of the LPFG [14]. However, one major limitation of such a RI sensing scheme is that the LPFGs only display a significant response to ambient RI changes for RI values close to that of the fiber cladding's RI and very little variation in wavelength for RI values near that of pure water of around 1.33 [15–17]. Such low sensitivity at the RI of 1.33 makes the conventional LPFG unsuitable as a RI sensor for applications for water quality monitoring. Previous reports show that the assembling or specific coating of thin films on the LPFGs can enhance the RI sensing range, sensitivity, or specificity [18–23]. However, most of these methods require very precise fabrication techniques with long and complex fabrication processes [18–23].

In this paper, we propose and demonstrate a novel RI sensing scheme using LPFG with carbon nanotubes (CNTs) deposited on the LPFG grating region as the sensing element. CNT is known to be a dark material with high absorption of light and high RI [24]. On the

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other hand, it was found that CNTs are highly compatible to silica and able to form thin films on silica surfaces [25,26]. In our experiment, a relatively simple and effective deposition method was used to coat a layer of CNT around the grating region of the LPFG, making the overall sensor easily reproducible and requiring little mechanical modifications of the fiber structure. Furthermore, due to its sensing principle, the sensor was able to register variations over a range of refractive indices (RIs) and was also not limited by the FSR of its spectrum during the detection of perturbations in its external environment. The sensor also demonstrated good repeatability and a continuous RI sensing with a sensitivity of 31 dB/RIU and 47 dB/RIU obtained within the ranges of 1.33–1.38 and 1.38–1.42, respectively.

2. Principle of RI sensing using CNT-deposited LPFG

The working principle of RI sensing using CNT-deposited LPFG is based on the light extraction of propagating cladding modes of the LPFG by the deposited CNTs. As light propagates through a LPFG, the fundamental core mode (LP01) would be coupled with the co-propagating cladding modes (LP0m). This coupling occurs when the following phase matching condition is satisfied [27]:

$$\beta_{01} - \beta_{clad}^{m} = \frac{2\pi}{\Lambda}, m = 2, 3, 4\ldots \quad (1)$$

where β_{01} and β_{clad}^{m} are the propagation constants of the fundamental mode and the mth co-propagating cladding mode, respectively, and Λ is the grating period. Due to the high attenuation of the cladding modes, distinct attenuation bands centered at discrete resonant wavelengths in the transmission spectrum can be observed. These resonant wavelengths can be described by the relation:

$$\lambda_{m,res} = [n_{eff,core}^{01}(\lambda_{m,res}, n_1, n_2) - n_{eff,clad}^{0m}(\lambda_{m,res}, n_2, n_3)]\Lambda \quad (2)$$

where $\lambda_{m,res}$ is the resonant wavelength due to the coupling between the fundamental core mode and the mth cladding mode. $n_{eff,core}^{01}$ and $n_{eff,clad}^{0m}$ are the effective RIs of both the fundamental core mode and the mth cladding mode, respectively. n_1, n_2 and n_3 are the core RI, cladding RI and the RI of the surrounding medium, respectively. Consider the case where the refractive index of the surrounding medium does not exceed that of the cladding. According to equation (2), with the increase of the RI of the surrounding medium, the effective index of the cladding will increase while the effective index of the core remains the same. This results in a blue shift of the resonant wavelengths with respect to the increase in the surrounding RI.

However, when the RI of the surrounding medium is higher than that of the cladding, the phase matching condition will no longer be satisfied. The surrounding medium of higher RI than the fiber cladding will result in a loss of the total internal reflection condition of the light guided by the cladding of the LPFG. These guided cladding modes will then behave as radiation modes (leaky cladding modes). A portion of the cladding modes will be reflected at the cladding/external medium interface while the rest will be transmitted and lost to the surrounding medium. The amount of reflectance, which affects the attenuation of the attenuation band at the resonant wavelength, will vary based on the Fresnel reflection coefficients [14,16]. Thus far, the treatment of the system can be understood to be that of the LPFG being surrounded by a medium of infinite thickness.

If an additional thin film with higher RI than that of the cladding of the LPFG and of finite thickness is coated on the LPFG, the phase matching condition of equation (1) will again not be satisfied. In our scheme, CNTs are deposited on the surrounding of the grating region of a LPFG to form a thin film. By this approach, the system can be modified to incorporate an additional dielectric layer of finite thickness between the cladding and the surrounding medium of infinite thickness as shown in Fig. 1. The system can then be modeled as a four layer cylindrical waveguide where the coupled-mode equations can be solved through the calculation of the LP modes, cross-coupling coefficients, and self-coupling coefficients to determine the transmission spectrum [19]. The power of each mode can be expressed as:

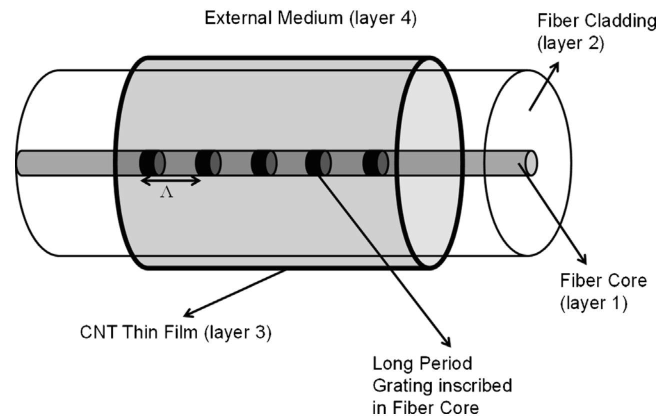

Fig. 1. Schematic illustration of a carbon-nanotube (CNT)-deposited long period fiber grating (LPFG).

$$P_{0j} = \frac{\beta_{oj}}{2\omega\mu_0}\int_{r=0}^{2\pi} d\phi \int_{r=0}^{r_1} R_{0j}^{2}(r) r dr, \; j = 1, 2, 3\ldots \quad (3)$$

where β_{0j} is the propagation constant of the LP_{0j} mode, μ_0 is the permeability of free space, $\omega = k_0 c$, where c is the speed of light in vacuum, $R(r)$ is the radial variation of the modal field, and ϕ is the azimuthal angle.

The behavior of the LPFG would be similar to the case of a LPFG surrounded by a medium of higher RI, and a portion of the power of the cladding mode will be reflected by the CNT layer while the rest will be transmitted [14]. The amount of reflectance of the cladding mode at the fiber cladding/thin film interface can be determined by reference [28]:

$$R = \left| \frac{r_{23} + r_{34} e^{-i\tilde{k}_{film}}}{1 + r_{23} r_{34} e^{-i\tilde{k}_{film}}} \right|^2 \quad (4)$$

with

$$r_{2,3} = \frac{n_{clad} - \tilde{n}_{film}}{n_{clad} + \tilde{n}_{film}} \quad (5)$$

$$r_{3,4} = \frac{\tilde{n}_{film} - n_{ext}}{\tilde{n}_{film} + n_{ext}} \quad (6)$$

$$\tilde{k}_{film} = \frac{4\pi\tilde{n}_{film} d_{film}}{\lambda} = \frac{4\pi n d_{film}}{\lambda} - i\frac{4\pi k d_{film}}{\lambda} = \beta_{film} - i a d_{film} \quad (7)$$

where $a = 4\pi k/\lambda$ is the absorption coefficient of the thin film, $\tilde{n}_{film} = n - ik$, n_{clad} and n_{ext} are the RIs of the cladding and the surrounding medium, respectively. $r_{x,y}$ in equations (5) and (6) is the amplitude reflection coefficient of the interface between layer x and layer y as shown in Fig. 1. From equations (4), (5), (6), and (7), it can be seen that R would vary with n_{ext}. This leads to a variation in the amount of attenuation of the cladding modes, which would result in a change in the attenuation depth of the attenuation band. Therefore, the sensing of the RI of the external surrounding medium can be obtained by monitoring the amount of attenuation in the attenuation bands of the LPFG.