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Multilayer graphene refractive index tuning by optical power*

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Graphene's optical absorption coefficient increases linearly with the number of layers making it more effective in the construction of optical tuning graphene-based devices. Refractive index (RI) is one of the important optical parameters of the graphene for accurately describing its optical characteristics and further applications. In view of the RI research of the multilayer graphene is lacking and existing measurement methods are complicated. Optical power tuning RI of multilayer graphene is investigated using a simple measurement and no temperature cross sensitivity all optical fiber sensing structure. Optical power tuning RI characteristics of multilayer graphene are studied by tuning the introducing broad band light power from 0.57 mW to 22.7 mW. Different thickness graphene coating shows different tuning efficiency. At 4.86-μm thickness, a 3.433-nm Bragg wavelength shift is obtained with 156.2-pm/mW wavelength *versus* optical power tuning sensitivity corresponding to 3.25×10^{3} RI change and 0.154 URI/W (URI, unit of RI) RI optical power tuning efficiency.

Keywords: multilayer graphene, fiber Bragg grating, graphene cladding, refractive index

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1. Introduction

Single-layer graphene can be considered as a mix of a semiconductor (zero density of states) and a metal (gapless) with symmetric conical band structure, which leads to good tunable optical characteristics.[1–6] Conductivity and refractive index (RI) are two important and useful optical parameters for accurately describing the optical characteristics of the graphene, and can be deduced each other.[7–9] Therefore, a lot of researches have focused on the measurement and calculation of conductivity or RI of graphene. In 2008, through investigating the reflectance and transmission of graphene samples on an SiO_2/Si substrate as a function of gate voltage, graphene optical conductivity and refractive index (RI) is demonstrated.[10] In 2009, graphene optical conductivity modulated by electrical-bias and electron injection characteristics are studied.[11] In 2011, graphene optical conductivity modulation characteristics are studied over wavelength from 1.35 μm to 1.6 μm based on a graphene integrated Si waveguide by electrically tuning the Fermi level of the graphene.[12] In 2014, a large modulation bandwidth (> 100 GHz) graphene optical modulator is realized through controling the optical conductivity of the graphene based on a grapheneclad microfiber, in which the signal light absorption of the graphene can be tuned by a pumping light.[13] Meanwhile, some studies have shown that the optical conductivity of the graphene can be tuned by varying the number of the graphene layers.[10,11,14] These optical tuning efficiencies are small for the atomically thin grapheme.[15,16] Finite or infinite number of graphene layers, such as bilayer and multilayer, have been shown to enhance the efficiency.[17,18] Moreover, the optical response of graphene is broadband and ultrafast, the photo-carriers are generated on an ultrashort times scale of tens of femtoseconds and the photocarrier generation is driven by optical absorption, which is governed by the averaged light intensity.[19–21] All of the above properties make graphene interesting for photoelectric technological applications.

However, so far, the demonstrations of graphene optical conductivity or refractive index are mainly focused on the monolayer graphene. The study of multilayer graphene is lacking. Meanwhile, their measurement methods are universally very complex.[9,22–24] Therefore, the investigation of optical conductivity or RI characteristics of multilayer graphene in detail using simple measurement structures are urgently needed.

In this study, we investigate the optical power tuning refractive index (RI) characteristics of multilayer graphene

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based on a graphene cladding optical fiber Bragg grating (FBG), in which a large part cladding of a half-length FBG is etched and coated with multilayer graphene, the other remaining half-length FBG is used as a contrast measurement. Through measuring the wavelength difference between these two parts, a temperature insensitivity, simplicity, low cost, compact, and high sensitivity RI sensing structure is achieved. In our experiments, by introducing optical power tuning from 0.57 mW to 22.7 mW, the wavelength of multilayer graphene coating etched FBG (eFBG) exhibits obvious shift. This means that the refractive index of the multilayer graphene can be continuously tuned by the input optical power. The optical power tuning RI efficiency of different graphene coating thickness is also studied. The maximum Bragg wavelength shift and wavelength versus optical power tuning sensitivity are 3.433 nm and 156.2 pm/mW, respectively. These results imply that the maximum refractive index value change and refractive index versus optical power tuning efficiency are 3.25×10^3 and 0.154 URI/W, respectively.

2. Experimental results and discussions

Our RI sensing structure is composed of a multilayer graphene coating half-length etched FBG (eFBG), which is illustrated in Figs. 1(a), 1(b), and 1(c). Figure 1(a) is the original FBG and its reflective spectrum with one Bragg wavelength at 1550.5 nm. Figure1(b) is the half length eFBG and its reflective spectrum. It can be found that compared with the original FBG, reflection spectrum of the eFBG is broadened and there are two Bragg wavelengths at 1549.82 nm (according to etched FBG) and 1550.5 nm (according to unetched FBG), respectively. This is essentially because of the stress released when the fiber cladding is reduced by the chemical etching.[25] As shown in Fig. 1(c), after multilayer graphene coating, the FBG spectrum is broadened further with two FBG wavelengths at 1550.5 nm (according to unetched FBG) and 1550.96 nm (according to etched FBG), respectively. This is mainly attributed to the reason that the effective refractive index of the eFBG is a function of RI of graphene cladding and optical fiber core. The RI of the graphene is greater than that of air, as a result, graphene coated eFBG wavelength moves to the right side of the unetched FBG Bragg wavelength from its left-side.

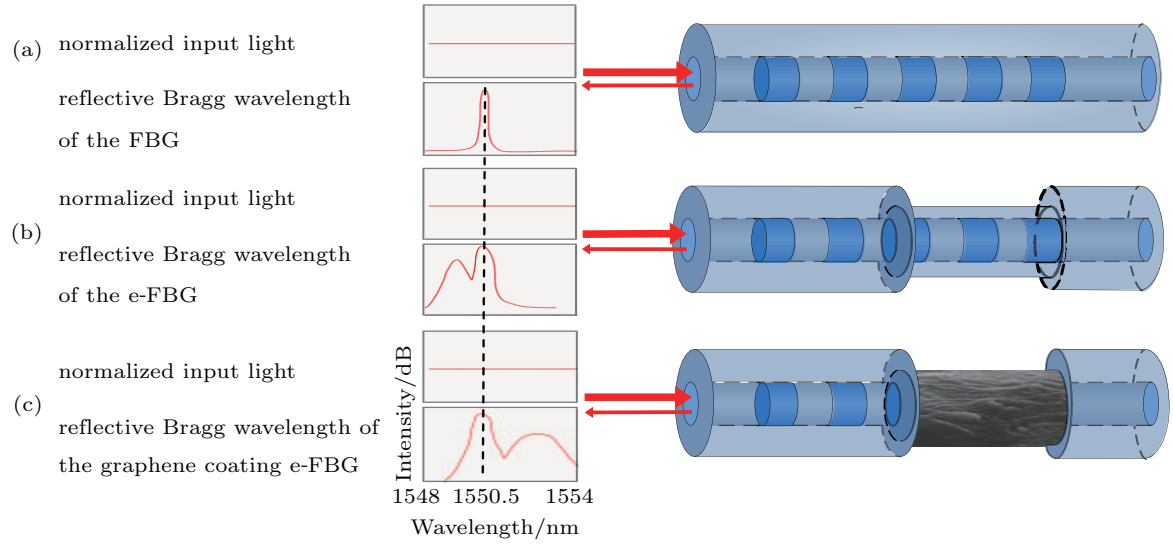


Fig. 1. (color online) Schematic illustration of (a) FBG, (b) half-length eFBG, and (c) graphene coating eFBG and their reflective spectra.

In our experiments, a 10-mm length FBG is used and divested its surface acrylate coating. A half length of 5 mm of the FBG is protected and the remaining part with 5-mm length is put into a 40% concentration hydrofluoric acid (HF) solution. The optical fiber cladding diameter reduction is linear versus etching time and an etching rate of the order of 1.08 μm/min at 24 °C (room temperature). Balancing refractive index sensitivity and robustness of the sensing part, our etching time is fixed at approximately 90 min. After etching, the e-FBG section is washed with NaOH solution to neutralize the residual acid. The sensing part optical fiber diameter is measured by using scanning electron micrograph (SEM) analysis. SEM photograms are presented in Figs. 2(a), 2(b), and 2(c). Figure 2(a) is the SEM photogram of e-FBG section with 20.84 μm diameter, which revealed that about 104-μm cladding is removed. After the e-FBG section is put into NaOH solution for minutes at room temperature, which not only can neutralize the residual H^+, but also can make the fiber surface hydrophilic by creating a few OH^- groups on the surface of the optical fiber. The graphene is ultrasonic dispersed in pure dimethylformamide (DMF) solution for several hours to manufacture graphene coating solution. The e-FBG

is put in a V-type groove and deposited the graphene coating solution on the surface of it while keeps it in a constant temperature box. After graphene attached tightly on the surface of the fiber, the graphene coating e-FBG is obtained. In order to gain the requirement thickness, the coating process can be replicated numerous times. Figure 2(b) is the SEM of the multilayer graphene coating e-FBG. By subtracting the diameters of Fig. 2(b) and Fig. 2(a), a 1.62-μm the multilayer graphene thickness can be roughly estimated. Figure 2(c) is the high-resolution image of the graphene coating surface. From this figure, it can be found that a solid graphene coating is formed on the e-FBG surface.[26]

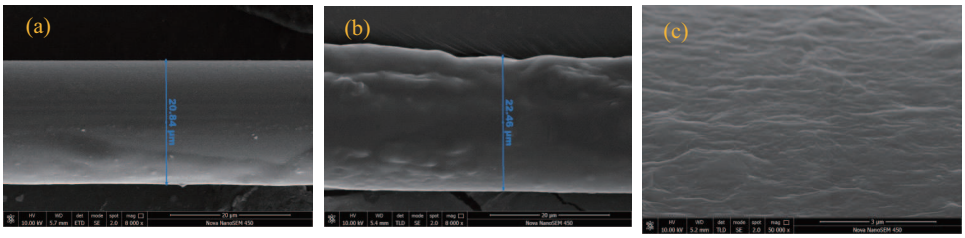


Fig. 2. (color online) SEM of the circular surface of (a) eFBG, (b) graphene coating eFBG and (c) High-resolution image of the graphene coating.

Our experimental setup is shown in Fig. 3. A broad band light (wavelength range from 1520 nm to 1620 nm) from a broad band source (BBS) passes through a single mode optical fiber (SMF) into the port 1 of an optical fiber circulator, which is a three ports all optical fiber circulator, and the light from the port 2 passes through an SMF and enters the FBG. After reflected light with sensing information returns to the port 2 and then comes out from the port 3 of the circular to the OSA (Optical Spectra Analyzer), by which the reflective spectra are observed.

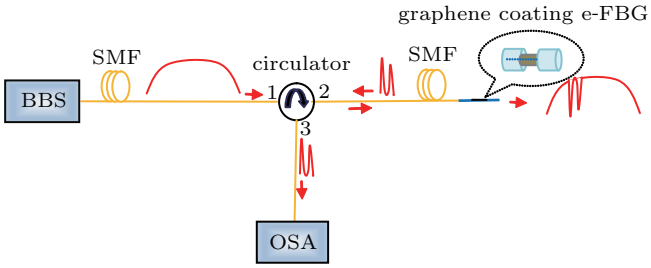


Fig. 3. (color online) The experimental setup

In-fiber optical power is tuning from 0.582 mW to 22.7 mW by gradually changing the output power of the BBS, in which the optical power is measured by truncation method using an optical power meter with ±1-μW resolution. As is well known, in common optical fibers, the effective refractive index of the fundamental mode is practically independent of the RI of the medium surrounding the cladding. However, if the cladding diameter is reduced, the effective refractive index will dependent on the surround RI, since fundamental modes are less confined in the core region leading to a higher evanescent field, thus, led to a more efficient interaction with the surrounding medium. Our sensing structure, the graphene coating eFBG can be seen as a double cladding optical fiber, in which the two claddings are remaining optical fiber cladding and graphene cladding, respectively. The RI of the graphene coating can be obtained by numerically resolving the dispersion equation of this double cladding fiber mathematical model. In our experiment, with in-fiber optical power increases, the Bragg wavelength red-shift of the graphene coating eFBG is observed. Figure 4 displays the variation of the FBG spectrum versus the in-fiber optical power. From this figure, it can be seen that the left-side reflection Bragg wavelength (corresponding to unetched FBG) is nearly no shift, as a contrast, the right-side Bragg wavelength (correspond to graphene coating eFBG) exhibits a red-shift upon the increasing of the in-fiber optical power. The maximum wavelength shift is 3.433 nm as the optical power reaches the maximum value corresponding to 3.25×10^3 refractive index increases and 0.154-URI/W tuning efficiency. Figure 5 shows the linear fittings of the eFBG Bragg wavelength versus the in-fiber optical power increase and decrease from 0.582 mW to 22.7 mW a round trip. From this figure, it can be found that these two linear fitting curves show good linearity and their wavelength versus power sensitivities are

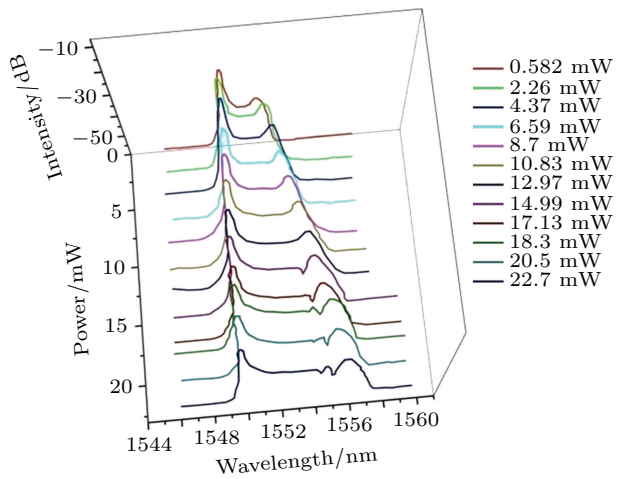


Fig. 4. (color online) Reflective spectra of eFBG changes with the optical power increase.

156.2 pm/mW and 153.2 pm/mW, respectively. These two linear fitting curves are almost coincided due to the reason that the optical response of the graphene is ultrafast and the photocarriers generate and degenerate caused by the increase and decrease tunings of the in-fiber optical power on an ultrashort time.

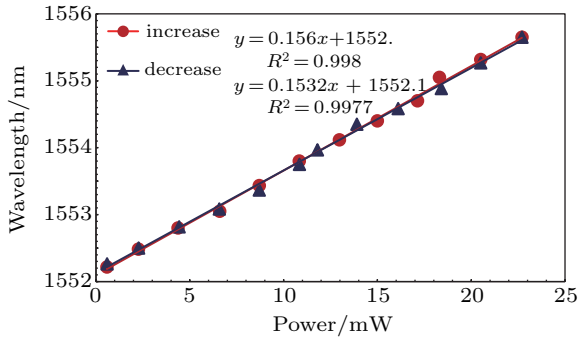


Fig. 5. (color online) Linearly fitting curves of graphene coating eFBG reflection Bragg wavelength versus light power increase and decrease, respectively.

Similarly, wavelength versus power linear fitting curves for different graphene layer thicknesses are shown in Fig. 6. It can be found that the sensitivity increases with the thickening of the multilayer graphene coating, as it reaches the maximum value, which limited by the in-fiber optical power, which means that it is no longer increased, even if the thickness of the film further increases.

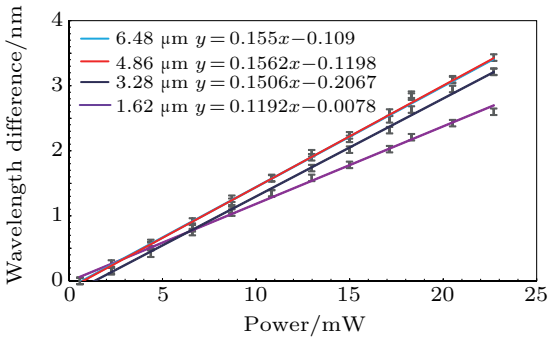


Fig. 6. (color online) Linearly fitting curves of different thicknesses of graphene coating eFBG reflection Bragg wavelength versus light power.

3. Theoretical analyses

Bragg resonance wavelength of the FBG can be expressed as[25]

$$\lambda_{\text{Bragg}} = 2\Lambda n_{\text{eff}}, \tag{1}$$

where λ_{neff} is the Bragg wavelength of the FBG, Λ is the grating period, and n_{eff} is the effective refractive index.

In our experiments, a large part of cladding about 104 μm of the FBG is reduced, the effective refractive index will sensitive to the graphene coating. Therefore, this graphene coating eFBG can be seen as a double cladding optical fiber, in which the RI of the graphene coating can be obtained by detecting the Bragg wavelength shift.

In the graphene coating, photo-induced carriers' density changes with the intensity of the evanescent light field in the graphene film. The relation expression of this evanescent light intensity and the photo-induced carriers density can be written as[26,27]

$$N = \alpha I \tau / \hbar\omega, \tag{2}$$

where N is the photo-induced carriers density, α is the absorption coefficient of graphene film, I is the light intensity, τ is the carrier recombination time, and ω is the radiation frequency of the light.

The relationship between conductivity σ and absorption coefficient is

$$\sigma = ac/4\pi, \tag{3}$$

where c is the light velocity in the vacuum.

The permittivity ε of the multilayer graphene can be written as

$$\varepsilon_{\text{eff}} = 1 + \sigma/\omega\varepsilon_0 d, \tag{4}$$

where ε_0 is the vacuum dielectric constant and d is the graphene film thickness. The relationship between permittivity and the refractive index of graphene is

$$n = \sqrt{\varepsilon}. \tag{5}$$

From above expressions, it can be deduced that the refractive index of the multilayer graphene can be adjusted by tuning the interaction optical power.

4. Conclusions

In conclusion, our work is focused on the optical power tuning RI characteristics of multilayer graphene at a broad band light wavelength from 1520 nm to 1620 nm, using an easy fabrication all optical fiber structure at room temperature. In the process of changing the power of the light, an obvious graphene RI tuning effect is observed. A linearity relationship between Bragg wavelength shift and optical power is obtained with high RI tuning efficiency and good repeatability. The maximum RI change is 3.25×10^3 with 0.154-URI/W optical power tuning efficiency. Based on these studies, it can be inferred that the RI change of the multilayer graphene may continue to be increased with the further increasing of the optical power before reaching saturated absorption. The RI versus optical power tuning efficiency can be improved as further decreases the cladding of the sensing structure. We believe that

the optical power tuning effect may have many potential applications in graphene physical optics and optical communications, such as ultrafast optical control sensing, micronano photochemistry sensing, optical single processing, optical switching, and so on.

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