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Polymer microfiber bridging Bi-tapered refractive index sensor based on evanescent field

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ABSTRACT

A PDMS/graphene enhanced PMMA micro optical waveguide sensor is reported in terms of fabrication method and optical characteristics. The micro optical waveguide with a diameter of 6 μm and a length of 800 μm is used as the sensing probe to realize refractive index (RI) measurement suspended in NaCl solutions with different concentrations. Experimental results show that the refractive index sensing sensitivity can reach 2027.97 nm/RIU within the refractive index ranging from 1.3333–1.3426. Research results show that PMMA/graphene micro optical waveguide doped with PDMS is an excellent high sensitive sensing technology in refractive index detection field.

1. Introduction

With the development of bioscience and clinical medicine, the biochemical have attracted the attention of more and more researchers at home and abroad. In the field of environmental monitoring, clinical testing, food testing and other scientific researches, refractive index is an important parameter that reflects the nature of liquid information. Therefore, refractive index sensors play an increasingly important role in the experiment research and practical application [1]. Optical fiber refractive index sensor has been widely studied due to the advantages of high sensitivity, corrosion resistance, high temperature resistance, small size and fast response. A number of fiber refractive index sensors based on different fibers have been proposed in recent years. In 2012, C. R. Liao et al. proposed a refractive index sensor based on optical fiber Fabry–Perot interferometer, the refractive index sensitivity obtained is 994 nm/RIU [2]. In 2015, Haiwei Fu et al. fabricated a novel refractive index Michelson interferometer is achieved 178.424 dB/RIU [3]. In 2016, Farid Ahmed et al. proposed a miniaturized tapered photonic crystal fiber Mach–Zehnder interferometer, whose sensitivity reached 334.03, 673.91, and 1426.70 nm/RIU within the RI range of 1.3327–1.3634, 1.3634–1.3917, and 1.3917–1.4204, respectively [4]. In 2017, Yong Zhao et al. made a spectrum online-tunable Mach–Zehnder interferometer with a sensitivity of 185.79 nm/RIU in the RI range of 1.3333–1.3673 [5]. However, these reported refractive index sensors exhibit low sensitivity and complex fabrication. In recent years, polymer optical fibers have attracted increasing research interest [6–8] for its advantages of easy handling, lower cost, great flexibility and have great potential application in optical sensing [9–11]. With the rapid development of material science, many excellent optical materials were found or developed for the preparation of polymer optical sensors, especially graphene [12,13] and Polydimethylsiloxane (PDMS) [14,15], etc.

Graphene as a single atomic plane has superior optical, mechanical and electrical properties, such as high surface to volume ratio, high electron mobility, and stable structure a single atomic plane which could provide a large surface area for physical and chemical sensing. [16]. PDMS [17] is optically transparent, excellent biocompatibility, easy bonding with a variety of materials at room temperature and high elasticity (structural flexibility) because of the low Young's modulus. In addition, PDMS is easy to concentrate in the air interface, and produce hydrophobic surface protective coating to improve the anti-fouling resistance. In 2014, Yao et al. [18] introduced a highly sensitive all-optical interferometric NH_3 sensor based on a graphene/microfiber hybrid waveguide. Highly sensitive detection of NH_3 concentration with a resolution of 0.3 ppm is achieved. In 2015, Liu et al. [19] introduced a compact light intensity controlled microfiber Mach–Zehnder interferometer, and experimental results indicate that the interference transmission spectra are highly sensitive to the applied excitation laser power density. An optimal ethyl orange weight percentage of 0.5 wt% has been experimentally acquired, with which the largest interference dip wavelength sensitivity reaches 0.02576 nm/(mW·cm^{-2}).

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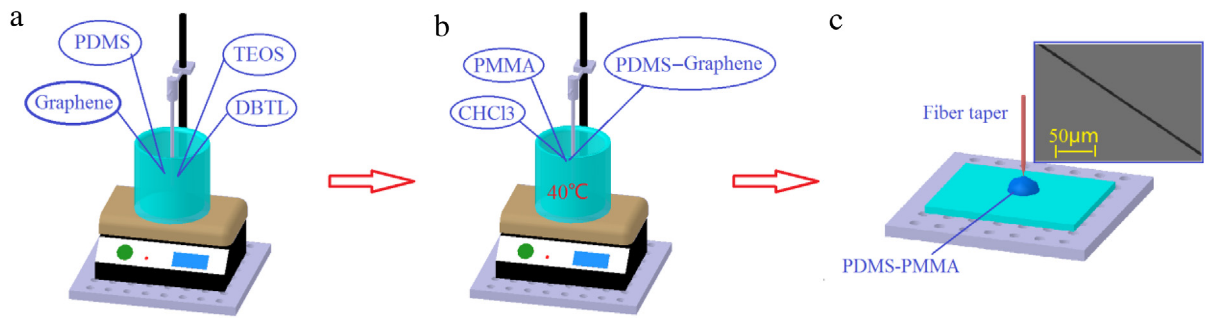

Fig. 1. The preparation process of graphene reinforced PDMS–PMMA elastomer.

In this article, we studied the fabrication process, optical characterization and applications of PDMS/graphene enhanced PMMA micro optical waveguide. Experimental results show that the refractive index sensitivity can reach 2027.97 nm/RIU within the refractive index ranging from 1.3333 to 1.3426. Predictably, the rise of new optical materials will bring a great improvement in optical fiber sensing field.

2. Preparation

Bi-tapered fiber Mach–Zehnder interferometer structure [20,21] with taper diameter under 10 μm is very difficult to be prepared by the bunsen burner or fusion splicer, and can be easily broken in the experimental process due to its fragile characteristics as a quartz material. Based on the above considerations, a polymer microfiber sensor is presented in this paper. Manual stretching is the most convenient, fast and low-cost preparation method of polymer microfibers, but the polymer microfibers prepared by manual stretching are fragile due to the material properties defects of Polymethylmethacrylate (PMMA) collosol. Based on the above considerations, adding PDMS to enhance elasticity of PMMA [22] and adding graphene to improve optical sensitivity of organic microfiber [23] have been successfully implemented in this paper.

The microfiber preparation steps are shown in Fig. 1: (a) PDMS collosol and graphene are mixed together at fraction ratio of 1:0.12; Adding minute quantities of cross-linking agent Tetraethyl orthosilicate (TEOS) and catalyst Dibutyltin dilaurate (DBTL), and stirring with a magnetic stirrer for 10 min, then getting Graphene–PDMS collosol. It is important to emphasize that Graphene–PDMS collosol after curing is the key materials of soft sensor; (b) Trichloromethane solution ($CHCl_3$) and PMMA powder are mixed together at fraction ratio of 1.5:1; then mixing with trace Graphene–PDMS collosol and stirring with a magnetic stirrer for 15 h at constant temperature of 40 °C, obtaining PDMS–PMMA collosol. (c) Using the fiber taper to rapid pull PDMS–PMMA collosol, then microfibers are got. Two fiber cones are drawn in optical fiber fusion splicer and overlapped with PDMS–PMMA microfiber by UV-lamp.

3. Principle and sensor structure

A PDMS–PMMA microfiber connects two tapered optical fibers, and the two connection points are cured by UV adhesive, as shown in Fig. 2.

Based on Schrödinger Equation Eq. (1) [24,25], a wave function ψ_T can go through the barrier. $\hbar$ is Dirac constant, m is quality, d is derivative.

$$\hat{H}\psi = E\psi \ ; \hat{H} = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + U(x) \tag{1}$$

The wave function Ψ can be obtained by solving Eq. (1).

$$\Psi = \begin{cases} Ae^{ik_1x} + A'e^{-ik_1x} \\ Be^{ik_2x} + B'e^{-ik_2x} \\ Ce^{ik_1x} + C'e^{-ik_1x} \end{cases} \tag{2}$$

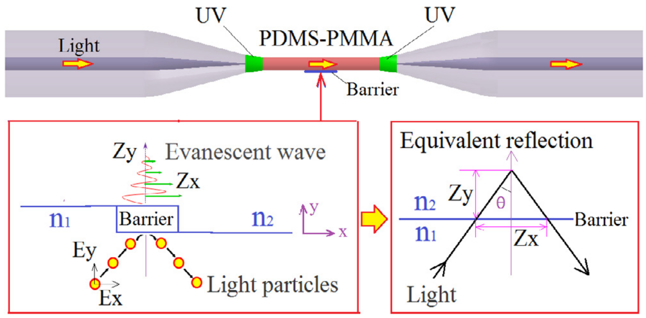

Fig. 2. The schematic diagrams of sensor probe structure and sensing principle. The barrier refer to the refractive index interface.

where $k_1 = \sqrt{\frac{2mE}{\hbar^2}}$, $k_2 = \sqrt{\frac{2m(E-U_0)}{\hbar^2}}$, U_0 is initial barrier, incident wave: $\psi_I = Ae^{ik_1x}$, reflected wave: $\psi_R = A'e^{-ik_1x}$, transmission wave:$\psi_T = Ce^{ik_1x}$. Eq. (2) shows that the transmitted wave rapidly attenuates, and penetration depth is of the wavelength order. Equivalent reflection model is shown in Fig. 2. Penetration depth of evanescent wave [26] is shown as

$$Z_y = \frac{\lambda}{2\pi}\frac{1}{\sqrt{\sin\theta^2 - n_{21}}}, \tag{3}$$

where θ is the incident angle, $n_{21} = n_2/n_1$. Equivalent wave distance, also known as Goos–Hä nchen Shift [27] is shown in

$$Z_x = \frac{\lambda}{\pi}\frac{\tan\theta}{\sqrt{\sin\theta^2 - n_{21}}}. \tag{4}$$

As the ambient refractive index increases, the penetration depth of fundamental mode and low order modes will increase.

The output interference intensity can be expressed as Eq. (5):

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2 \cos\frac{2\pi\Delta n_{eff}L}{\lambda}} \tag{5}$$

where I_1 and I_2 are the light intensity transmit in the fiber core and fiber cladding, respectively, Δn_{eff} is the difference between effective refractive index of fiber core and cladding, $\Delta n_{eff} = n_{eff}^{core} - n_{eff}^{clad}$. $\varphi = \frac{2\pi\Delta n_{eff}L}{\lambda}$ is phase difference. Δn_{eff} will decrease along with ambient refractive index increases. So, Eq. (5) shows that output spectrum power will decrease more rapidly along with ambient refractive index increases. Therefore, optical path difference between fundamental mode and low order modes decreases leading to spectrum blue shift [28].

Sensor probe design includes two steps: fiber taper size programming and microfiber size programming. Firstly, the fiber taper with a cutting-edge cladding diameter of 15 μm and a length of 400 μm is prepared by fusion splicing mechanism. The key of fiber taper design is to ensure that fundamental mode could be excited into microfiber. The preparation process conforms to the law of Newton fluid mechanics, so the diameter