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Research Paper

High-performance fibre-optic humidity sensor based on a side-polished fibre wavelength selectively coupled with graphene oxide film

Yaoming Huang[a,c,1], Wenguo Zhu[b,c,1], Zhibin Li[c], Guanglei Chen[c], Liheng Chen[c], Junjie Zhou[c], Hai Lin[c], Junwen Guan[c], Wenxiao Fang[d], Xin Liu[d], Huazhuo Dong[c], Jieyuan Tang[a,b], Heyuan Guan[b,c], Huihui Lu[b,c], Yi Xiao[b,c], Jun Zhang[b,c], Hongcheng Wang[e], Zhe Chen[b,c], Jianhui Yu[a,b,*]

[a] *Guangdong Provincial Key Laboratory of Optical Fiber Sensing and Communications, Jinan University, Guangzhou 510632, China*
[b] *Key Laboratory of Optoelectronic Information and Sensing Technologies of Guangdong Higher Education Institutes, Jinan University, Guangzhou 510632, China*
[c] *Department of Optoelectronic Engineering, Jinan University, Guangzhou 510632, China*
[d] *Electronic Produce Reliability and Environmental Testing Research Institute (CEPREI), Guangzhou 510610, China*
[e] *School of Electrical Engineering and Intelligentization, Dongguan University, 523808, China*

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ABSTRACT

A high-performance humidity sensor based on a side-polished single-mode fibre (SPF) coated with graphene oxide film was fabricated with a wheel side-polishing technique and spontaneous evaporation. The wavelength-selective coupling gave rise to a loss dip in the transmitted spectrum when a phase match condition was satisfied at a given resonant wavelength. The swelling effect of GO under high RH, which was confirmed by XRD and a spectroscopic ellipsometer, could increase the GO film thickness and led to a redshift at resonant wavelength. Experimental results show that the GO-film-coated SPF (GFC-SPF) is capable of working in two modes: tracing-wavelength mode and intensity variation mode. For the two working modes, the GFC-SPF has high sensitivity, good reversibility, good repeatability and excellent linearity. For the tracing-wavelength mode, a very high sensitivity of 0.145 nm/RH% and a high linear correlation of 99.6% were achieved in a low RH range of 32%–85%, while an ultrahigh sensitivity of 0.915 nm/RH% and a linear correlation of 98.7% were achieved in a high RH range of 85%–97.6%. For the intensity variation mode, a high sensitivity of 0.427 dB/RH% and an excellent linearity correlation of 99.8% were achieved in a wide RH range of 58.2%–92.5%. Such a high performance allows GFC-SPF to have widespread potential applications, such as in the fields of biology, chemical processing and food processing.

1. Introduction

Humidity sensing is an important part of many practical applications, which range from air conditioning control, chemical processing and food production to semiconductor industries [1–4]. Recently, fibre-optic humidity sensors have attracted widespread interest and extensive investigation due to their many advantages, such as compact size, high sensitivity, good chemical inertness, immunity to electromagnetic interference, seamless connection to mature optical fibre networks and easy implementation of remote sensing. However, humidity-induced changes in the refractive index are usually ultra-small, leading to significant difficulties in directly measuring relative humidity (RH). Therefore, many kinds of materials combined with various fibre structures have been investigated and exploited to enhance the sensitivity to RH. These fibre-optic humidity sensors include polymer-coated Bragg grating fibre [5,6], long-period grating coated with poly/cobalt chloride [7,8], agarose-infiltrated photonic crystal fibre (PCF) interferometers [9], PVA-coated PCFs [10], polyvinyl alcohol-coated PCFs [11], nonadiabatic tapered fibre coated with PDDA/Poly R-478 film [12], HEC/PVDF hydrogel-coated no-core fibre [13], U-shaped bare fibre

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* Corresponding author at: Department of Optoelectronic Engineering, Jinan University, Guangzhou, 510632, China.
E-mail addresses: kensomyu@gmail.com, 10404531@qq.com (J. Yu).
[1] These authors contribute equally to the work.

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coated with $CoCl_2$-doped PVA film [14], WS_2-coated side-polished fibre (SPF) [15], U-shaped fibre coated by phenol red-doped PMMA [16], and agarose gel-coated tapered fibre [17]. However, the poor permeability of the reported material to the water molecules leads to a heavy hysteresis, which results in very poor linearity and reversibility for these sensors. In addition, the poor permeability also prevents water molecules from penetrating into the inside of the material, which limits changes in the refractive index of the material and thus leads to low RH sensitivity.

In recent years, graphene has attracted significant attention and has become one of the most intriguing materials because of its many excellent electronic and photonic properties [18–21], such as the ambipolar field effect [18], quantum hall effect [22–24], and extremely high carrier mobility [25]. Owing to its unique properties, graphene has been widely used to build various devices with high performance, including photonic modulators [26–28], polarisers [29], gas and temperature fibre-optic sensors [30,31], individual gas molecule detection devices [32], and pressure sensors [33].

Graphene oxide (GO), as one of the most important derivatives of graphene, has also attracted considerable attention and is considered a promising material for biological applications because of its excellent aqueous processability, amphiphilicity, surface functionalisability, surface-enhanced Raman scattering properties and fluorescence quenching ability [34,35]. The two-dimensional atomic structure and oxygen functional groups in GO, such as hydroxyl, carboxyl, epoxide, and carbonyl make GO film super-permeable and super-adsorptive to water molecules [35–37], allowing it to be an outstanding candidate for RH sensing [38]. Recently, different fibre structures coated with rGO and GO have been demonstrated to implement fibre-optic RH sensors. These fibre structures include SPF [39], hollow-core fibre [40], and in-line Mach–Zehnder interferometer (MZI) fibre [41], whose sensitivities are, respectively, 0.31 dB/RH%, 0.22 dB/RH% (0.11 nm/RH%) and 0349 dB/RH% with linear correlation coefficients, respectively, of 96%, 98.2% and 98.9%. For the SPF [39] and hollow-core fibre [40], the RH sensing relies on the variation in transmission intensity, which is induced by variation of the charge carrier density in rGO as the RH changes [39,40]; whereas, the GO-coated in-line MZI fibre works on intensity variation caused by the change in effective refractive index of the GO film under different RHs [41].

In this paper, a GO-film-coated SPF (GFC-SPF) is demonstrated to implement a fibre-optic RH sensor. Unlike the fibre sensors mentioned above, such a GFC-SPF relies on wavelength-selective coupling between the fundamental mode of the SPF and the guided mode of the GO film. The coupling gives rise to a resonant dip in the transmitted spectrum when the phase match condition is fully satisfied at a resonant wavelength. The swelling effect of GO film with RH increases the GO film thickness thus leading to a redshift of the resonant wavelength, which allows the GFC-SPF capable of working on both resonant wavelength and intensity variations. For the two working modes, the experimental results show that the GFC-SPF achieves high performance in RH sensing, and exhibits good reversibility, repeatability, high linearity and high sensitivity. In the tracing resonant wavelength mode, the sensitivity and linear correlation coefficient of the GFC-SPF are respectively 0.145 nm/RH% and 99.6% in the RH range of 32%–85%; whereas, they are 0.915 nm/RH% (~9 times larger than that in [40]) and 98.7% in the RH range of 85%–97.5%. If working in intensity variation mode, a large intensity variation of up to 14.5 dB in the range of 58.5%–92.2% is achieved for GFC-SPF, yielding to a high sensitivity of 0.427 dB/RH% with a high linear correlation coefficient of 99.8%. It is worth noting that such a GFC-SPF possesses simultaneously high sensitivity, high linearity and excellent reversibility across a wide dynamic range, which is usually difficult to reach for most RH sensors due to the RH hysteresis of the material (see the performance in Table 1). In addition, the relatively fast response and recovery time are measured, respectively, at 2.73 s and 7.27 s for the GFC-SPF sensor. Such high performance allows the GFC-SPF to be an outstanding RH sensor for research in the fields of chemistry, medicine and biology.

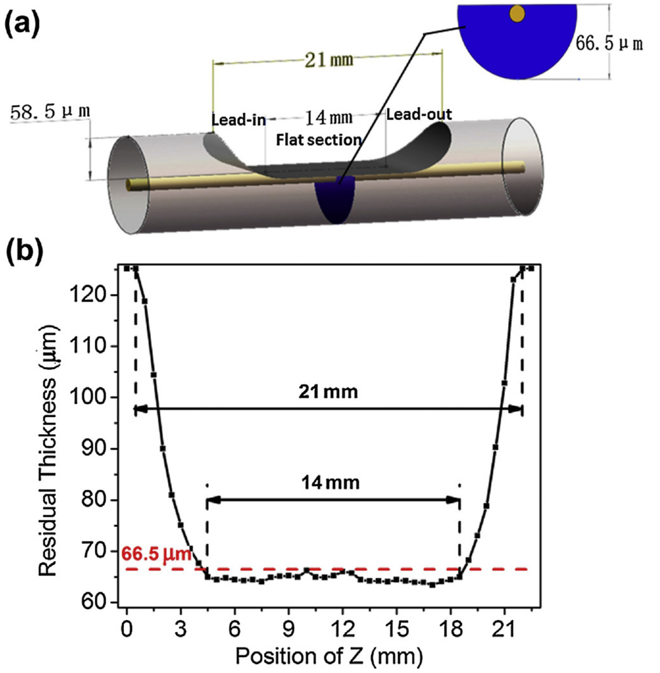

Fig. 1. Structure of the side-polished fibre: (a) three-dimensional schematic of the SPF structure and (b) the measured lateral profile of the SPF.

2. Device fabrication

2.1. Fabrication of side-polished fibre

The 3 cm long coating was stripped off of a standard single-mode fibre (SMF). An in-house developed wheel-based polishing system was used to side polish a section of the coating-removed single-mode fibre (Corning SMF-28e) having a core diameter of 8.2 μm and a cladding diameter of 125 μm. During fabrication, the two ends of the SMF were double clamped on a movable stage, and the movable stages were controlled by computer to adjust the longitudinal tension of the SMF. In the polishing system, a polishing wheel, to which is affixed 6-μm particle size abrasive paper, was moved from the bottom, close to the midpoint of the double-clamped SMF until the SMF was bent and had a 2–3 cm long section overlapped with the abrasive paper. The polishing wheel was then controlled by computer to rotate clockwise and anticlockwise to polish the surface of the SMF. To reduce the possibility of breaking the SMF, the rotation speed was kept at 94 RPM with RPM feedback to the computer. After ~10 min of continuous wheel rotation, the abrasive paper was replaced with 1-μm particle size abrasive paper to finely polish the SMF for more than 50 min. The fine polishing made the side-polished surface smoother and reduced the insertion loss of the side-polished fibre (SPF). This process resulted in the successful fabrication of SPF with a residual thickness of ~66.5 μm.

Fig. 1(a) shows a schematic of the three-dimensional structure of the SPF. Part of the cladding of the SMF is polished off and the remaining SMF has a D-shaped cross-section. As shown in Fig. 1(b), the residual thickness along the SPF was measured by microscope (Zeiss Axio Scope A1). Here, the residual thickness is defined as the maximum distance from the polished surface in the flat section to the bottom of the SPF. It can be seen that the SPF has three sections: lead-in transitional section, flat section and lead-out transitional section. Fig. 1(b) shows that the lengths of the lead-in transitional