Graphene-Assisted Microfiber for Optical-Power-Based Temperature Sensor
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Abstract—Combined the large evanescent field of microfiber with the high thermal conductivity of graphene, a sensitive all-fiber temperature sensor based on graphene-assisted microfiber is proposed and experimentally demonstrated. Microfiber can be easily attached with graphene due to the electrostatic force, resulting in an effective interaction between graphene and the evanescent field of microfiber. The change of the ambient temperature has a great influence on the conductivity of graphene, leading to the variation of the effective refractive index of microfiber. Consequently, the optical power transmission will be changed. The temperature sensitivity of 0.1018 dB/°C in the heating process and 0.1052 dB/°C in the cooling process as well as a high resolution of 0.0098 °C is obtained in the experiment. The scheme may have great potential in sensing fields owing to the advantages of high sensitivity, compact size, and low cost.

Index Terms—Microfiber, graphene, evanescent field, temperature sensor.

I. INTRODUCTION

The past decades have seen increasing applications of microfiber in all-fiber filters, sensors and modulators, etc. due to its simple fabrication technique, compact size, low loss, large evanescent field and easy integration with fiber systems [1]. Featured with the advantages of flexibility, small footprint and immunity to electromagnetic interference, all fiber temperature sensors have been widely used in material processing, food testing, greenhouse monitoring and other fields. Zeng et al. achieved a temperature sensitivity of 0.27 nm/°C in the heating process and 0.98921 nm/°C by immersing highly bi-refringent D-shaped microfiber in sucrose solution [3]. However, both of them are difficult to fabricate, as well as require expensive wavelength detecting systems. Considering the limit of resolution of the optical spectrum analyzer, the temperature resolution can just reach to 0.02°C. Zhu et al. proposed a single-mode tapered fiber coated by thermo-sensitive material and the output power monotonically increased 1.2 dB with the temperature variation from −20 °C to 80 °C [4]. Harun demonstrated a microfiber-loop-resonator-based temperature sensor with the sensitivity of 0.043 dB/°C by detecting the extinction ratio of the comb spectrum [5]. Nevertheless, the achieved results are relatively nonlinear and the sensitivity is not high enough.

On the other hand, graphene has been hailed as a super-thin optical material in electronics and photonics due to its unique valence bands structure and strong inter-band transitions. Based on the mature platform of fiber optics, graphene is especially flexible to be incorporated with fiber as a new composite waveguide, applied as polarization controller [6], wideband saturable absorber [7], and etc. Li et al. reported a graphene-clad microfiber based all-optical modulator at ∼1.5 μm with a response time of ∼2.2 ps, which could achieve a modulation depth of 38% owing to the enhanced light-graphene interaction [8]. Since the optical conductivity of graphene can be easily influenced by the environment due to its two-dimensional structure, it also has great potential in sensing fields. Xiao et al. demonstrated a reduced graphene oxide based side-polished fiber for humidity sensing with sensitivity of 0.31 dB/%RH in high relative humidity range (70-95%) [9]. Yavari et al. employed a macro graphene foam-like network for parts-per-million level detection of NH3 and NO2 with good sensitivity and durability [10]. Zhang et al. demonstrated a temperature sensor based on a side-polished fiber coated with reduced graphene oxide film, achieving a high sensitivity of 0.134 dB/°C [11]. However, there are few reports on microfiber combined with graphene for temperature sensors yet, which is further miniaturized to be suitable for integration and probe.

In this letter, by taking advantage of the super-high thermal conductivity of graphene, we propose an all-fiber temperature sensor based on graphene assisted microfiber (GAMF). The refractive index of graphene can be changed along with the surrounding temperature, leading to the variation of transmission power of the GAMF. Theoretically analysis and experimental demonstration of the sensor are carried out and achieve high sensitivity higher than 0.1018 dB/°C. Meanwhile, GAMF presents special superiorities including easy fabrication, miniaturization and low cost.
According to Refs. [14]–[16], the optical conductivity of graphene can be modeled by Kubo formula:

\[
\sigma_{\text{intra}}(\omega, \mu_c, \tau, T) = \frac{e^2}{\pi \hbar^2 (\omega + i \tau^{-1})} \frac{\mu_c}{K_B T} + 2 \ln(\exp(-\frac{\mu_c}{K_B T}) + 1)
\]

\[
\sigma_{\text{inter}}(\omega, \mu_c, \tau, T) = \sigma_{\text{intra}} + \sigma_{\text{inter}} = \sigma_{\text{intra}} + i \sigma_{\text{intra}}
\]

Consequently, the complex conductivity of graphene is

\[
\sigma(\omega, \mu_c, \tau, T) = \sigma_{\text{intra}} + \sigma_{\text{inter}} = \sigma_{\text{intra}} + i \sigma_{\text{intra}}
\]

Where \( \sigma_{\text{intra}} \) and \( \sigma_{\text{inter}} \) are the real part and imaginary part of the conductivity. With the complex effective electrical permittivity \( \varepsilon_{\text{eff}} = 1 + i \varepsilon_{\text{refractive \ index}} \) and the refractive index \( n = \sqrt{\varepsilon_{\text{eff}}} \) [17], [18], the real part of refractive index of graphene can be calculated as

\[
n_{\text{refractive \ index}} = \sqrt{(\sqrt{\sigma_{\text{intra}} - \sigma_{\text{inter}}} + 2 \varepsilon_{\text{refractive \ index}})^2 - 4 \varepsilon_{\text{eff}}^2}
\]

Where \( \varepsilon_{\text{eff}} = 8.85 \times 10^{-12} \text{F/m} \) is the vacuum dielectric constant, and \( d \) is the thickness of the graphene. Here, we assume \( \omega = 2 \pi c / \lambda, \lambda = 1550\text{nm}, c = 3 \times 10^8 \text{m/s}, d = 1\text{nm}, T = 0 \sim 100^\circ \text{C} \) and then calculate the variations of the conductivity and refractive index of graphene along with the temperature change. From the simulation results in Fig. 2(a) and (b), it is obvious that both the real part and imaginary part of the conductivity are increased with the rise of temperature. Therefore, the real part of the refractive index of graphene is inversely proportional to the temperature with the coefficient of \(-7.385 \times 10^{-6^\circ \text{C}^{-1}}\) and linearity of 96.94% as depicted in Fig. 2(c).

When the surrounding temperature changes, both of the MgF\(_2\) substrate and graphene film will affect the effective refractive index of the MNF. However, the thermo-optic coefficient of MgF\(_2\) is around \( 3.2 \times 10^{-7^\circ \text{C}^{-1}} \) when the operating wavelength is set from 1.15\(\mu\text{m} \) to 3.39\(\mu\text{m} \) [19], which is much smaller than that of the graphene. Therefore, the effect of the temperature on MgF\(_2\) can be negligible.

In order to analyze the effect of \( n_{\text{gr}} \) on the optical field distribution of the GAMF, we use the finite element method—COMSOL to numerically calculate the effective refractive
Fig. 2. (a) $\sigma_r$ and (b) $\sigma_i$ as a function of temperature, (c) $n_{gr}$ as a function of temperature at $\mu_c = 0.15 eV$.

Fig. 3. (a) The real part of the effective refractive of GAMF varies with the real part of the refractive of graphene; (b) and (c) the electrical field distributions of the GAMF at $\text{Re}(n_{eff}) = 1.354926$ and $\text{Re}(n_{eff}) = 1.35451$, respectively.

The microfiber diameter is optimized around 2µm both in theoretical analysis and experimental demonstration, based on the overall consideration of single mode operation [20], larger evanescent field and lower transmission loss. Here, we assume the fiber diameter is 2µm, the thickness of graphene film is 1nm, the refractive indices of the MNF, MgF$_2$ and air are 1.44, 1.370032 and 1.0 at 20°C, respectively. Along with the reduction of $n_{gr}$, the real part of $n_{eff}$ decreases linearly with the linearity of 99.6%, as depicted in Fig. 3(a). In addition, Fig. 3(b) and (c) present the optical field distribution of the GAMF at different $n_{eff}$. It can be seen that the central electric energy of the GAMF are respectively $2.4738 \times 10^8 V/m$ at $\text{Re}(n_{eff}) = 1.354926$ and $2.5587 \times 10^8 V/m$ at $\text{Re}(n_{eff}) = 1.35451$, which means that the transmissivity of the GAMF is linearly enhanced with the increase of the temperature. Based on the above analyses, the surrounding temperature can be simply demodulated from the variation of the transmitted optical power through the GAMF.

III. EXPERIMENTAL RESULT AND DISCUSSION

The system configuration of the GAMF based temperature sensor is illustrated in Fig. 4. The broadband optical source with optical power fluctuation less than 0.01dBm in one hour is employed to launch the light into the GAMF from port A, and the optical power meter with detection precision of 0.2dB is connected with port B of the GAMF. To precisely control the temperature variation, the GAMF sensing head is placed on the Thermoelectric Cooler (TEC). By controlling the direction and value of the operation current, the temperature can be adjusted to rise or fall between 30°C and 80°C with the step of 5°C and the resolution of 0.0625°C accurately. Then the refractive index of graphene will be changed, resulting in the variation of the transmissivity detected by the optical power meter.

The experimental results about the sensing performance are illustrated in Fig. 5. The amaranth solid dots and line demonstrate that the transmissivity of the GAMF and the temperature possesses a direct proportional linear correlation with the sensitivity of 0.1018dB/°C. The correlation coefficient of the linear fitting curve is as high as 99.06%. According to the definition of the temperature sensitivity, i.e. $S = \Delta P / \Delta T$, the measurement resolution of temperature can be calculated as $R_T = \frac{RP}{S}$, where $S$ is the sensitivity of the temperature sensor, $\Delta P$ is the relative variation of the optical power, $\Delta T$ is the relative variation of the temperature, $R_T$ is the resolution of the temperature sensor and $RP$ is the resolution of the optical power meter. Since the resolution of the commercial optical power meter can reach to 0.001dB, the corresponding temperature resolution is 0.0098°C.

Fig. 4. Schematic diagram of the GAMF based temperature sensor system.

Fig. 5. Transmissivity of the fiber changes along with the temperature variation in heating procedure (amaranth) and cooling procedure (green) from 30°C to 80°C. The solid line: GAMF; the dotted line: bare MNF.

The measurement resolution of temperature can be calculated as $R_T = \frac{RP}{S}$, where $S$ is the sensitivity of the temperature sensor, $\Delta P$ is the relative variation of the optical power, $\Delta T$ is the relative variation of the temperature, $R_T$ is the resolution of the temperature sensor and $RP$ is the resolution of the optical power meter. Since the resolution of the commercial optical power meter can reach to 0.001dB, the corresponding temperature resolution is 0.0098°C.
In order to evaluate the reversibility of the sensor, the temperature detection in cooling process is also investigated. As depicted by the green solid dots and line in Fig. 5, the linear fitting of the experimental data gives a sensitivity of 0.1052dB/°C with the linearity of 98.65%. Compared with the heating process, the coincidence between the two curves confirms that the GAMF temperature sensor has good reversibility and repeatability. The deviation between the heating and cooling process data may come from the instability of the optical source, the temperature difference between graphene and TEC, and the limited measurement accuracy of the optical power meter. Although the environmental humidity will also affect the performance of graphene, the sensitivity of the GAMF sensor will be less than 0.055dB/% RH [9].

In the experiment, the room humidity keeps around 60% with the fluctuation of only 1%, resulting in the optical power variation less than 0.05dB. Therefore, the temperature measurement error induced by humidity variation is no more than 0.49°C. Furthermore, in practical applications, the sensing head can be carefully packaged to avoid the influence of the humidity, and consequently enhance the reliability and accuracy of the temperature sensor.

Furthermore, to demonstrate the sensitivity enhancement of the GAMF, we also measure the temperature response of the bare MNF in the same way as a comparison. The experimental results are presented by circles and dotted lines in Fig. 5, with very low sensitivity of −0.006285dB/°C for heating process and 0.006254dB/°C for cooling process, respectively. It is clearly that the sensitivity of GAMF is enhanced about 16 times than the bare MNF. Therefore, the assistance of graphene greatly improves the sensitivity and stability of the temperature sensor. Moreover, the sensitivity can be further enhanced by fabricating more uniform microfiber with small optical loss, appropriately adjusting the contact length between the graphene and microfiber [21], and employing the directly grown on fiber method to make the graphene film more tightly with the microfiber.

IV. CONCLUSION

In conclusion, an all-fiber temperature sensor based on the GAMF is proposed and demonstrated. The change of the surrounding temperature has a strong influence on the refractive index of graphene, resulting in the transmission power change in the microfiber. By simply detect the variation of the transmission power, temperature sensitivity of 0.1018dB/°C in heating process and 0.1052dB/°C in cooling process with high resolution of 0.0098°C are achieved in experiment, which is 16 times higher than that of the bare MNF. With the advantages of high sensitivity, compact size and low cost, such GAMF based sensor has great potential in sensing fields.

REFERENCES