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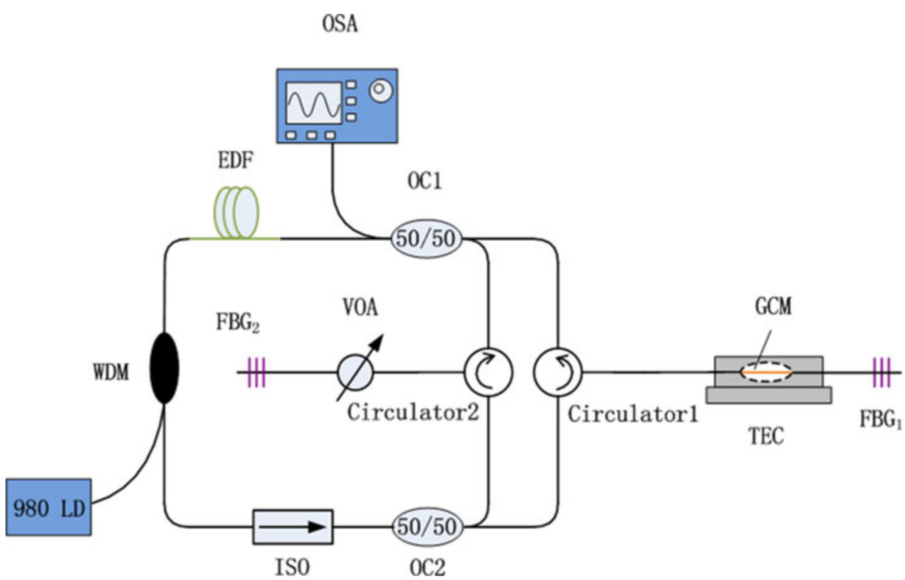

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Highly Sensitive Temperature Sensor Based on Gain Competition Mechanism Using Graphene Coated Microfiber

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Abstract: Graphene-based temperature sensor is characterized by low absorption coefficient and large thermal conductivity. We report a grapheme-coated microfiber (GCM) structure based sensor, which is demodulated with a dual-wavelength erbium-doped fiber laser (DWEDFL). The "thermophoresis effect" of GCM and gain competition between the two lasing wavelengths allow us to achieve an ultrahigh temperature sensitivity up to 2.10 dB/°C. To the best of our knowledge, it is the highest one among the intensity-type temperature sensors reported so far. The sensor has the potential in sensing application for its merits including high sensitivity and convenience of demodulation. Our results demonstrate that the GCM structure combined with the gain competition scheme offers an alternative way for high-sensitivity optical fiber sensing applications.

Index Terms: Fiber temperature sensor, gain competition mechanism, graphene coated microfiber.

1. Introduction

In recent years, temperature sensors have become an important research field because of their diverse applications in many fields of modern industry, e.g., furnace operation, ocean thermal energy conversion, turbo engines, and material processing systems. Optical fiber temperature sensor (OFTS) is currently the main research direction for temperature sensors, owing to various important advantages of the fiber: light weight, small size, anti-electromagnetic interference, resistant to high temperature and high pressure [1]–[5].

In light of the current research status, OFTS can be classified into four categories based on their mechanisms:(1) Wavelength type, such as FBG [6], LPG [7]. They are usually simple and reliable yet relatively low in sensitivity. (2) Interference type. Due to the ease of obtaining high sensitivity, most fiber-optic temperature sensors belong to this category, such as MZI [8], Sagnac

[9], [10], FP [11], [12], MMI [13], and so on. Nevertheless, they suffer from external interference and cross interference problem due to other parameters, such as strain, stress, etc. (3) Beat frequency demodulation type. These schemes are based on dual wavelength or polarization characteristics. They are generally stable, reliable and easy to be demodulated. However, it is difficult to obtain the matched wavelength [14]. (4) Intensity-modulated type, such as D fiber [15] or microfiber [16]. They can be monitored in real-time and coupled with simple structure, but has relative low sensitivity. In this work, we have developed a novel and highly sensitive interference-type optical fiber sensing system combining the advantages of simple structure, real-time monitoring in intensity-type OFTS and the high sensitivity in interference-type, meanwhile avoiding their disadvantages.

Graphene has been widely applied in many areas owing to its merits of high electrical conductivity, excellent mechanical properties, and large specific surface area. Long-range π conjugation in graphene results in its extraordinary thermal, mechanical, electrical, and optical properties. For example, the high carrier mobility in graphene makes it suitable for ultra-fast switching [17]. As a mechanical stable material, graphene is convenient to integrate with other optical nanodevices [18]. Graphene are also used in the Enhanced photocatalytic activity [19] and sensing. Graphene-based optical waveguide (GOW) is shaping up as an important field due to its excellent performance [20]–[26]. Firstly, the thermal conductivity of graphene is one of the best among all materials so far [27], which makes it suitable for high sensitive temperature sensing. Secondly, it has very low absorption coefficient, which perfectly fits the fiber optical waveguide. Therefore, large optical loss won't be introduced to damage the waveguide structure. Because of these properties, graphene coated microfiber (GCM) structure can be used for temperature measurement applications. In 2015, Li *et al.* [28] proposed a fiber FP temperature sensor based on graphene film, which achieved a high sensitivity of 1.87 nm/°C. Later that year, the sensitivity of this structure is further improved by Li *et al.* [29], using multilayer graphene films (352 nm/°C). However, these sensors all have optical interference structure based on graphene thin film. They often require complex fabrication process and are susceptible to cross interference among external parameters.

To address this problem, simple and direct intensity sensors have been investigated by Sun *et al.* [30], [31]. First they utilized "thermophoresis effect" of graphene powder in water environment based on a microfiber structure, while the temperature sensitivity is relatively low (0.03 dB/°C). Later, they proposed a graphene-film-assisted microfiber approach. The sensitivity was enhanced to 0.1 dB/°C. Therefore, we incorporated the GCM structure into a dual-wavelength fiber laser. Due to the gain competition between the two lasing wavelengths, the optical output power at a specific wavelength is extremely sensitive to external perturbation, e.g., temperature change. Our experimental results demonstrate a high sensitivity -1.83 dB/°C and 0.27 dB/°C in the range of 22–40 °C. In addition, the proposed sensor has advantages of high sensitivity and convenience of demodulation, which makes it potential for sensing application.

2. Experimental Setup and Principle

Fig. 1(a) shows the photograph of the graphene powder sample, purchased from Changzhou MoZhiCui Technology Co., LTD with the minimum particle diameter of $\sim$5 μm. From the Raman spectrum of the graphene powder presented in Fig. 1(b), three dominant peaks (D peak, G peak and 2D peak) can be clearly observed. The intensity ratio of D peak to G peak is about 0.2419, implying that our graphene powder has good uniformity and quality. The microfiber was unilaterally stretched from a standard single-mode-fiber (SMF) by using flame-heating and taper-drawing technology until the waist diameter was reduced to $\sim$6.7 μm with $\sim$30 mm tapering length, as shown in Fig. 1(c). A GCM structure can be seen in Fig. 1(d) where the taper waist of the microfiber is coated with graphene powder.

The coating process can be described as below: First, the microfiber is fixed between two fixtures, both of which are on the three-dimensional micrometer stages to keep the microfiber straight. Second, the taper region of the microfiber hangs on a V-groove controlled by a thermoelectric controller (TEC) setting at a constant temperature of 45 °C. Then a mixed solution ($\sim$0.1 mg/ml) of graphene and anhydrous ethanol is prepared and then a few drops are carefully dropped into

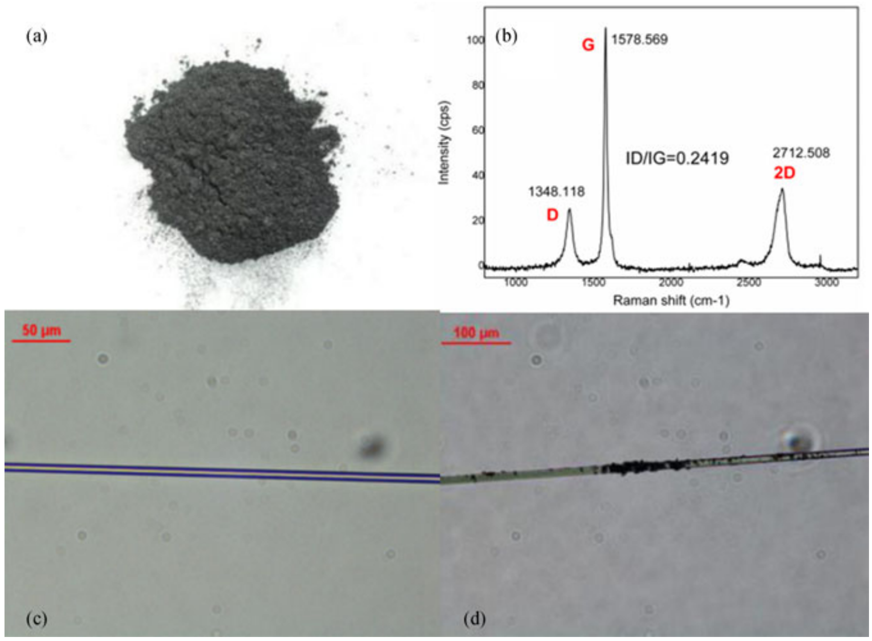

Fig. 1. (a) Photograph of the graphene powder sample, (b) Raman spectrum of the graphene powder, (c)(d) microscope lateral view of the microfiber before (c) and after (d) graphene coating.

the V-groove. "Thermophoresis effect" occurs based on optical absorption to keep the graphene depositing onto the microfiber. Lastly, to ensure full coating, this dropping process is repeated three times every time after ethanol is fully evaporated. The GCM structure therefore is formed and the taper waist is coated with graphene, yielding a large evanescent field for sensing application. The criteria for the dimensions of the graphene coated on the microfiber, that is the graphene powder form a relative uniform and thin film fully wrapped on the microfiber. In this way GCM forms a good optical waveguide structure for sensing application. The poor coating uniformity or completeness reduce the stability and repeatability of our subsequent temperature sensing. Due to the excellent thermal properties of graphene, the GCM structure can be applied for temperature measurement.

To further improve the sensitivity and reliability, the GCM sensing structure is incorporated into a dual-wavelength Erbium-doped fiber laser (DWEDFL), which has a ring cavity configuration as shown in Fig. 2. Two filter devices, i.e., FBG1 and FBG2, are introduced into a common Erbium-doped fiber ring laser through two fiber circulators, ensuring dual-wavelength lasing. The central wavelengths of two FBGs are slightly different ($\lambda 1 = 1551.02$ nm, $\lambda 2 = 1550.12$ nm), with similar reflectivity of ~85% and 3-dB bandwidth of <0.15 nm. A 980 nm laser diode (LD) pumps the 10 m EDF (gain factor 6.5 ± 1.0 dB/m, OFS Fitel, LLC.) through a wavelength division multiplexing (WDM). The fiber isolator (ISO) is embedded to keep the ring cavity laser only lase in counterclockwise direction. The optical couplers (OC1 and OC2, both with 50:50 splitting ratio) here divide the laser into two ring cavities: cavity C1 (980-WDM-ISO-OC2-Circulator1-TEC&GCM-FBG1-OC1-EDF) and cavity C2 (980-WDM-ISO-OC2-Circulator2-VOA-FBG2-OC1-EDF). The variable optical attenuator (VOA) in cavity C1 is used to realize cavity loss control during the gain competition process. A thermoelectric controller (TEC, Column oven LCO 102 SINGLE, ECOM Co., Ltd) is used in cavity C2 to control the temperature around the GCM. Range of temperature regulation of the TEC is from ambient temperature up to 99 °C with temperature stability ±0.1 °C. Actual oven temperature is shown on display. Since both cavities share the same gain medium EDF, a gain competition mechanism is formed [29], [30]. Attributed to the gain competition caused by the homogeneous gain broadening of EDF, the optical power at the two lasing wavelengths compete with each other. In our case, the optical power is very sensitive to the loss induced by external temperature.

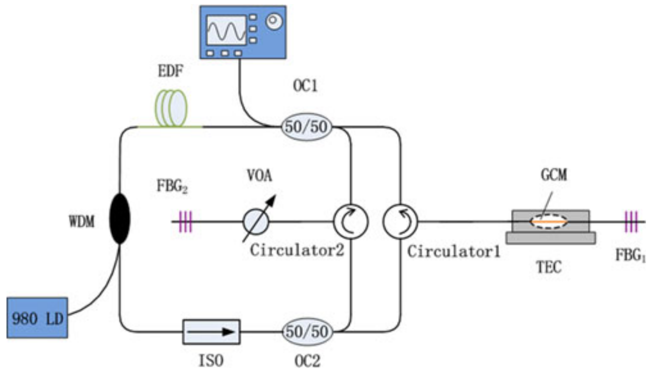

Fig. 2. Schematics of the DWEDFL. WDM: wavelength division multiplexer; EDF: Erbium doped fiber; FBG: fiber Bragg grating; VOA: variable optical attenuator; OC: fiber output coupler; GCM: graphene coated microfiber; ISO: fiber isolator; OSA: optical spectrum analyzer; TEC: Thermoelectric controller.

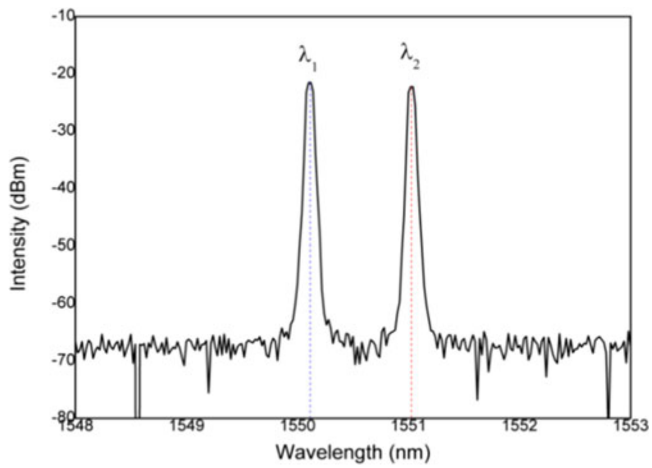

Fig. 3. Output optical spectrum of the DWEDFL.

The output optical spectrum of the DWEDFL is shown in Fig. 3, the two peaks represent two lasing wavelengths when the laser is pumped by 980 LD at 91 mA with power 42 mW. The emitting power of the two wavelengths are almost equivalent at ~ -22 dBm with signal-to-noise ratio (SNR) about 45 dB. The central wavelengths and 3-dB bandwidths of the two wavelengths are consistent with that of the two FBGs. It is worth noting that a relatively large gain coefficient of the DWEDFL may make the system more sensitive to external disturbances, thereby reducing the power stability of the dual wavelengths; A small gain coefficient, however, reduces the power values of the dual wavelengths, thus reducing the measurement range of the system. Therefore, the gain coefficient needs to be compromised according to the requirements of the measurement environment.

3. Temperature Sensing Experiment Results and Discussion

Before performing a temperature measurement, maintaining the power stability of the dual-wavelength laser output is crucial to the reliability and accuracy of the experiment. The output optical spectra of the DWEDFL was recorded in every 5 mins for 50 minutes. The lasing wavelengths and intensities are summarized in Fig. 4. In Fig. 4(a), one can observe stable dual wavelength output both in wavelengths and intensities. Fig. 4(b) shows the maximum fluctuation at two lasing wavelengths: $\sim$0.75 dB at $\lambda 1$ and $\sim$0.96 dB at $\lambda 2$. The intensity fluctuations of the dual wavelengths can stems from these issues: (1) The ambient temperature fluctuation affects the gain

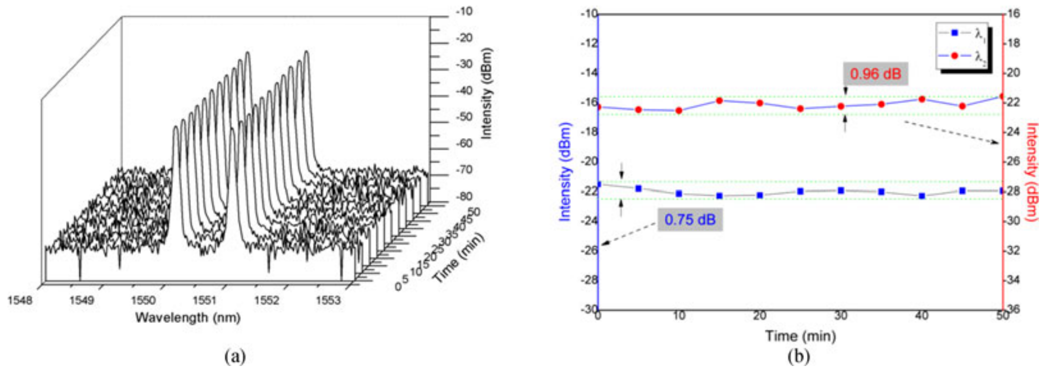

Fig. 4. (a) Output optical spectrum of the DWEDFL taken every 5mins for 50 minutes, (b) Dual-wavelength power fluctuation in 50 minutes.

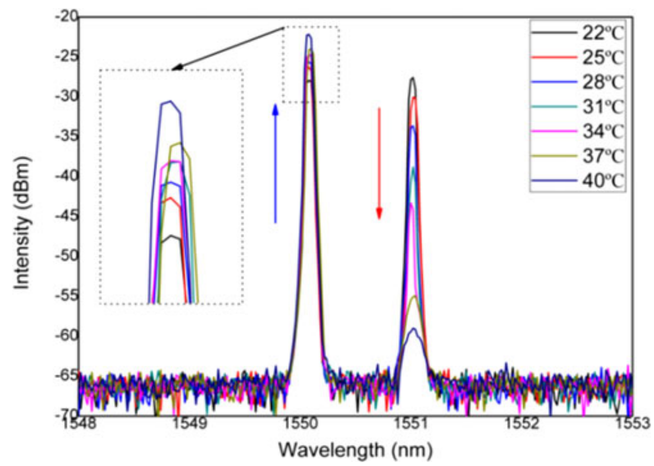

Fig. 5. Transmission spectra of our sensor with temperature in 22∼40 °C.

coefficient of the EDF and then causes power fluctuations; (2) Cavity losses of dual wavelengths due to vibration or air fluctuations can also cause dual-wavelength intensity instability; (3) Fewer experimental data samples increase the chance of reading errors. So the stability can be improved by controlling the ambient temperature more precisely, keeping the cavity loss stable, and data averaging.

The experimental setup for temperature sensing is illustrated in Fig. 2. The TEC at cavity C2 is adjusted in a step of 3 °C from 22 °C to 40 °C. The corresponding spectra variation of the dual wavelengths is shown in Fig. 5. It can be noted that the intensity increases at λ1 yet decreases at λ2 as the surrounding temperature increases. The reason why sensing wavelength λ1 increases along with the temperature can be explained as the following: The temperature causes a decrease in the refractive index of the graphene, which results in an increase in the ability to restrain light of the GCM structure. In other words, the optical loss decreases. This effect has been theoretically explained and experimentally verified [30], [31]. Thanks to our dual-wavelength gain competition mechanism, the intensity at λ2 reduce correspondingly. The slight wavelength shift at the two wavelengths may be due to ambient temperature changes around the gratings, but this has little effect on the temperature measurement at our GCM structure for intensity demodulation.

In order to quantitatively analyze the output power variation of dual-wavelength with temperature, Fig. 6 illustrates the intensity changes of the two wavelengths with the change of temperature. It implies that intensity variation is proportional to the temperature change at λ1 and inversely proportional to temperature change at λ2. This has been explained in the preceding discussion. High sensitivities of 0.27 dB/°C and −1.83 dB/°C within the range 22–40 °C are realized, which is

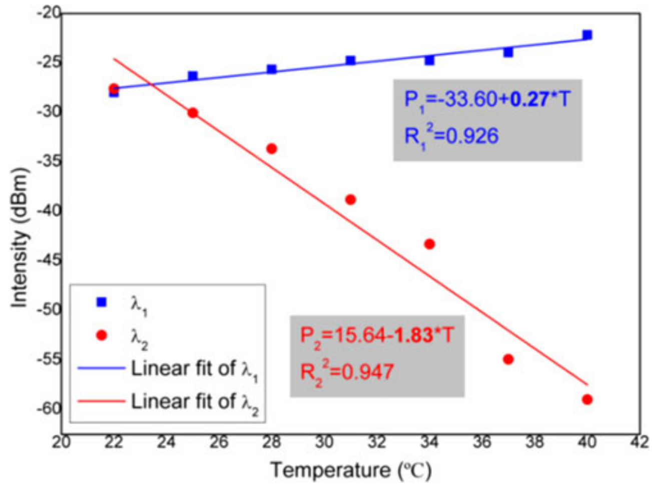

Fig. 6. Intensity of the peak power at dual wavelengths as a function of the surrounding temperature.

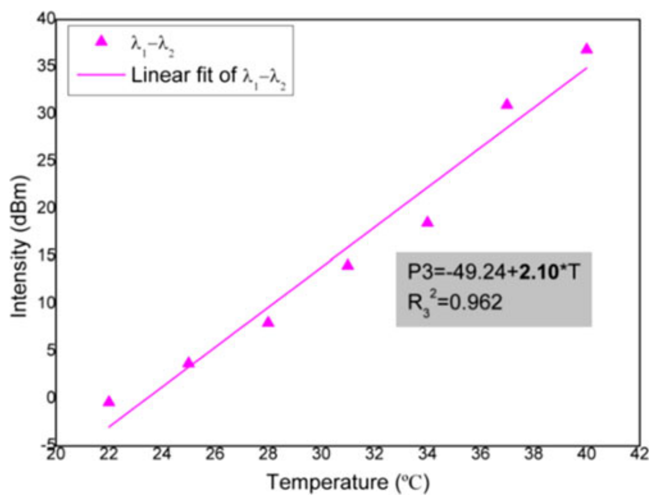

Fig. 7. Dual-wavelength power difference as a function of the surrounding temperature.

several times higher than the results in reference [31]. For intensity type temperature sensors, the temperature resolution and accuracy depends on the resolution of optical power measurement. For our sensor, because the resolution of a typical commercial optical power meter can reach 0.001 dB, the corresponding temperature resolutions at the two lasing wavelengths are 0.0037 °C and 0.0005 °C, respectively. But that is the theoretical data, in fact the operating accuracy of 0.1 °C comes from the TEC in our experiment.

Since the two wavelengths experience the same light source jitter and external environmental vary (such us temperature, humidity, pressure, etc.,), subtracting the power at two wavelengths eliminates the influence of the common environmental factors. What needs to be mentioned is that the following factors may affect the linearity here: A temperature growth yields a descent in the transmission loss of the sensing beam and changes the gain distribution between the two wavelengths due to gain competition which arises from the homogeneous broadening of EDF, giving rise to a change in the output power difference between the two wavelengths. The degree of gain competition, however, is related to the output power difference between the two wavelengths, thus changes during a temperature variation, finally affects the linearity.

The resulting power difference as a function of temperature is shown in Fig. 7. It shows that the overall sensitivity is as high as 2.1 dB/°C with a better linearity of 0.962. This is

TABLE 1
Comparison of Sensing Performance of Our Sensor With Recently Reported Isotype Schemes

Sensing type	Sensitivity	Minimum resolution	Measuring range	Reference
Only GCM	0.03dB/℃	0.03℃	20~75℃	[30]
Graphene film under Microfiber	0.1dB/℃	0.0098℃	30~80℃	[31]
FP with PDMS	0.13dB/℃	0.0077℃	22~60℃	[34]
Our scheme	**2.1 dB/℃**	**0.0005℃**	**22~40℃**	

the highest sensitivity among all intensity-type fiber temperature sensors reported, to our best of knowledge.

In order to compare the temperature sensing performance of our sensor with other recently reported intensity-type schemes, detailed parameters are listed in Table 1. It shows that our sensor has a significant improvement in the sensing sensitivity and resolution. This improvement is mainly due to the introduction of the novel sensitivity enhancement method (i.e., the dual wavelength gain competition mechanism), in which the optical loss of one wavelength modulated by outside temperature results in power changes of two wavelengths drastically in the opposite directions. It is worth to be mentioned that the relatively limited temperature range is restricted by higher sensitivity.

4. Conclusion

We proposed a novel temperature sensor based on dual-wavelength Erbium-doped fiber laser (DWEDFL), in which one cavity is embedded with a GCM structure. The sensing principle can be briefly described as follows: The increasing temperature causes the refractive index of graphene to decrease, resulting in a decrease in the optical loss of the GCM structure. Thus the lasing intensity changes with the temperature. Since the laser lases at two separate wavelengths, when the wavelength intensity related to GCM increases, the other wavelength intensity will decrease. The sensor's response to temperature was investigated experimentally from 22 °C to 44 °C. Benefiting from the gain competition of the dual-wavelength laser, our results show a highest sensitivity of 2.10 dB/°C (0.27 dB/°C and −1.83 dB/°C for two respective wavelengths), corresponding to a temperature resolution of 0.0005 °C. This is the highest sensitivity among all intensity-type temperature sensors reported so far, to the best of our knowledge. Being an intensity-type temperature sensor, demodulation of the sensing signal only requires an optical power meter measured at one of the lasing wavelengths. Meanwhile, our sensor has a sensitivity over a factor of 20 higher than other intensity type temperature sensors. Our scheme of dual-wavelength gain competition mechanism can be an effective way for increasing the measuring sensitivity for optical fiber sensing application in general, not only for temperature measurement, but also in other areas, e.g., refractive index, curvature, etc.

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