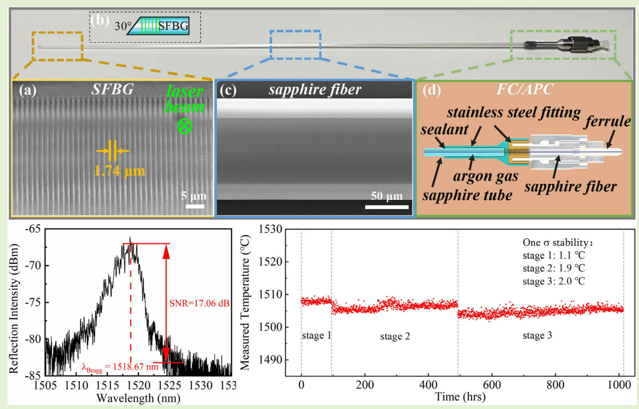
Sapphire Fiber Bragg Gratings Demodulated With Cross Correlation Algorithm for Long-Term High-Temperature Measurement

Xizhen Xu, Qingming Tan, Zhuoda Li, Jiafeng Wu, He Li, Jia He, Zhengxi He, Yue Qin, Tao Xu, Zengling Ran, Yiping Wang, *Senior Member, IEEE*, and Jun He, *Member, IEEE*

***Abstract*—The sapphire fiber Bragg grating (SFBG) is a promising high-temperature sensor for application in aviation and power industries; however, the multimode characteristics of SFBG result in a broadband reflection envelope, including multiple peaks, which have a strong impact on the sensing accuracy. In this article, we propose and experimentally demonstrate a cross correlation algorithm (CCA) for the demodulation of SFBG, with the benefit of enhancing the stability of wavelength detection, and hence, the sensing accuracy can be improved. The SFBG high-temperature sensor was created by using the femtosecond laser line-by-line method and sealed in an argon gas-infiltrated sapphire tube. Such a device was demodulated by using the CCA, and the findings show that the Bragg wavelength dispersion of ±12 pm could be obtained; furthermore, before the calibration process, the SFBG sensor was annealed at 1500 °C for 50 h to enhance the stability of reflection spectrum. The temperature calibration experiment has been carried out. In that case, a dry-block calibrator with high stability was employed to calibrate the temperature uncertainty of SFBG is ±0.7 °C. Compared to the calibrated thermometer, the maximum difference is less than 2 °C. In that case, a tube furnace was used to test the SFBG; the temperature uncertainty increased to 2.2 °C, and the maximum difference increased to 7 °C. This is due to the larger temperature fluctuation of this tube furnace. A 1000-h (i.e., 42 days), 1500 °C stability test was carried out. The SFBG exhibited excellent long-term high thermal stability (temperature deviation less than 2.0 °C). A cycling temperatures test was performed, which exhibited good repeatability in temperature measurements. Hence, such an SFBG sensor and the demodulation algorithm are prospectives for applications in harsh environments.**



***Index Terms*—Cross correlation algorithm (CCA), high-temperature measurement, sapphire fiber Bragg grating (SFBG).**

I. Introduction

HIGH-TEMPERATURE measurement is significant in aviation, petrochemical, metallurgical, and power industries [1], [2], [3], [4]. There is a growing demand for online ultrahigh-temperature sensors, which is able to ensure safety and improve the efficiency of operations. For example, the high-temperature gas-cooled reactor is one of the candidates of advanced reactor generation IV; its core has the capacity for operating in extremely harsh environments with high temperatures (i.e., up to 1200 °C) and neutron irradiation. Actual measurement and analysis of the core temperature are key aspects for the validation of the reactor physical and thermal model and the introduction of the core uncertainty factors [5]. Optical fiber sensors, such as fiber Bragg gratings (FBGs), are more attractive for high-temperature measurement since they have various advantages,i.e., high-temperature resistance, compact size, capability of multiplexing, and immunity to electromagnetic interference. It is, however, frustrating that conventional silica-based FBGs can only

Manuscript received 23 December 2023; accepted 14 January 2024. Date of publication 30 January 2024; date of current version 14 March 2024. This work was supported in part by the National Natural Science Foundation of China (NSFC) under Grant 62222510, and Grant 62375176; in part by the National Key Research and Development Program of China under Grant 2023YFB3208600; in part by the Department of Science and Technology of Guangdong Province under Grant 2022B1515120050; and in part by the Shenzhen Science and Technology Program under Grant RCYX20200714114538160, Grant JCYJ20200109114201731, and Grant 20220810164735001. The associate editor coordinating the review of this article and approving it for publication was Prof. Arnaldo G. Leal-Junior. *(Corresponding author: Jun He.)*

Please see the Acknowledgment section of this article for the author affiliations.

Digital Object Identifier 10.1109/JSEN.2024.3358294

withstand 1000 °C, which is limited by the glass-transition temperature (1330 °C) [6]. To solve this problem, a single crystal sapphire fiber with a high melting temperature of 2045 °C was proposed to prepare FBGs, which can withstand more than 1500 °C [7], [8], [9]. It could be noted that the highest short-term operating temperature of sapphire FBGs (SFBGs) reported so far was 1900 °C [10]. In the case of long-term stability, Yang et al. [11] proposed the alumina tube packaged SFBGs, which could survive at 1000 °C for 110 h. Lossy spots would, however, form on the sapphire fiber surface induced by high-temperature oxidation, resulting in serious deterioration in the optical transmission performance of the sapphire fiber [12], [13]. To cover this problem, we reported an inert gas-sealed packaging method to suppress the formation of lossy spots, and then such an SFBG can stably operate at 1600 °C for up to 20 h [14].

Since the reflection spectrum of SFBG is broad (i.e., −3 dB bandwidth of 7 nm) and includes multiple peaks induced by the multimode operation in sapphire fiber [7], [8], [9], the conventional peak detection algorithm of single mode FBG, moreover, is not suitable to realize demodulation of SFBGs [15]. Hence, the interrogation process, including curve smoothing, fitting, and peak searching, has been proposed to detect the Bragg wavelength positions of SFBG [16], [17], [18], [19]; however, the peak shape will change easily due to external influences, which results in the fluctuations of wavelength position.

Two methods, i.e., spectra averaging and long-wavelength edge detection, were proposed to enhance the stability of peak searching [18], [19]. The spectra averaging method is effective in improving the stability of peak wavelength; however, it would cost much more time to measure and record spectra. In addition, fluctuations of the wavelength can be reduced by using the long-wavelength edge detection method since the fundamental mode has a more stable transmission performance. It is noted that such a demodulation algorithm is still susceptible to the distortion of the SFBG spectrum profile shape. The cross correlation algorithm (CCA) can be used for measuring the similarity between two signals. In the case of FBG sensing, the CCA measures the similarity of two spectra as a function of wavelength shift, which was suitable for processing the complicated FBG spectrum, such as multimode FBGs [20], [21], [22].

In this article, we propose and experimentally demonstrate a CCA for demodulation of SFBG, which is attributed to improving the stability of wavelength detection. A femtosecond-laser-inscribed SFBG was sealed in an argon gas-infiltrated sapphire tube. Then, the annealing process was implemented to enhance the thermal stability of this device. The CCA was, moreover, used to detect the Bragg wavelength of SFBG, and the deviation was evaluated. The temperature calibration experiment has been, furthermore, carried out by using the dry-block calibrator and tube furnace. At last, in order to investigate the long-term high thermal stability of the SFBG sensor, a 1000-h (i.e., 42 days), 1500 °C high-temperature test was implemented.

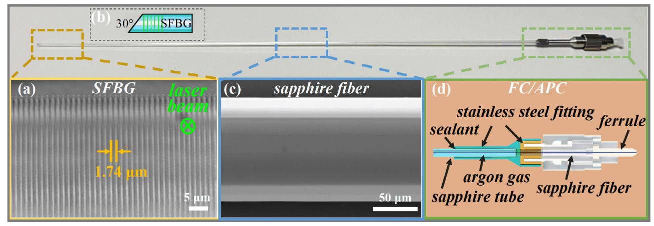


Fig. 1. Photograph of the inert gas-sealed SFBG (Insets: (a) top-view microscopy image of the femtosecond-laser-inscribed SFBG, (b) sapphire fiber tip with 30° polished angle, (c) scanning electron microscopy image of the surface of the sapphire fiber, (d) schematic of FC/APC).

II. Fabrication of SFBG High-Temperature Sensors

The SFBG high-temperature sensor was fabricated by using a femtosecond laser line-by-line scanning technique and sealed in an argon gas-infiltrated sapphire tube (Crytur, inner diameter: 1.3 mm), as shown in Fig. 1. The femtosecond laser inscription experimental setup is referred to [8]. A sapphire fiber with a diameter of 100 μm and a length of 40 cm was employed to prepare the SFBG sample. The SFBG fabrication parameters, including pulse energy, scanning velocity, track length, and grating length, were set as 30 nJ, 0.1 mm/s, 60 μm and 4 mm. As shown in Fig. 1(a), the period of the grating was measured as 1.74 μm. Such a grating was located on the tip of a sapphire fiber, which serves as the sensing point. To reduce the Fresnel reflection at the fiber tip, and thus, increase the signal-to-noise ratio (SNR) of Bragg reflection peak, the output end of the sapphire fiber was polished to 30°, as shown in Fig. 1(b) [23].

Note that sapphire fiber has no protective cladding, and the thermal reaction at the fiber-air interface would occur when the SFBG operates at temperatures more than 1500 °C. The lossy spots would form on the sapphire fiber surface, resulting in deterioration in the transmission performance of sapphire fiber in high-temperature environments. To cover this issue, argon gas was employed to insulate the SFBG and air [14]. By using such a packaging process, the formation of lossy spots could be suppressed, and the surface topography of sapphire fiber after high-temperature test can remain smooth as the pristine sapphire fiber, as shown in Fig. 1(c), and then the SNR of SFBG would not degenerate [14].

As shown in Fig. 1(d), the input end of the sapphire fiber was fixed in the ceramic ferrule, and then both of them were polished to 8°. This structure, together with other metal parts, forms a ferrule connecter/angled physical contact (FC/APC). Such a male standard FC/APC connector eliminates the need for on-site splices, which can simplify the installation process for the sensor probe. Stainless steel fitting was used to connect FC/APC and the sapphire tube. The high-temperature sealant (Shuoxian, SX-8301) was filled in the gap between the fitting and the sapphire tube, preventing leakage of argon gas.

The reflection spectra of the SFBG sample were measured by using a 2 × 2, 3 dB 105/125 μm multimode silica fiber coupler connecting a broadband source (Fiber Lake) and an optical spectrum analyzer (OSA, Yokogawa AQ6370C). The

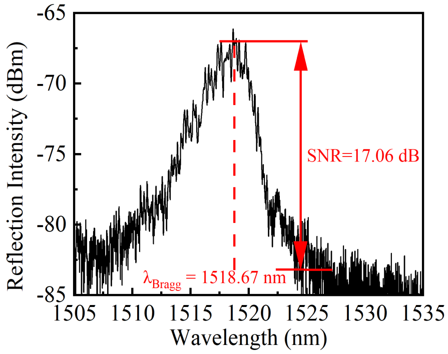


Fig. 2. Reflection spectrum of the SFBG sample with a period of 1.74 μm.

resolution and the wavelength step were set as 20 pm and 1 pm, respectively. The scanning span ranged from 1505 to 1535 nm, and the corresponding sampling was 30 001. The values of resolution and the wavelength step were used in the subsequent experiments. As shown in Fig. 2, the reflection spectrum exhibits an SNR of 17.06 dB and a Bragg wavelength of 1518.67 nm, respectively. Such a high value of SNR can be realized since the Fresnel reflection was removed via angle-polish of the fiber end. Hence, this result demonstrates that the greatly improved quality of the reflection spectrum of SFBG was obtained, ensuring precise demodulation of Bragg wavelength.

III. CCA FOR DEMODULATION OF SFBG

The CCA was employed to evaluate the Bragg wavelength shift $\Delta\lambda$ in the reflected spectrum of SFBG in the high-temperature test. The spectrum is recorded as an array with N samplings length $R(\lambda_i)$ for $i = 0, 1, 2, \ldots, (N-1)$. The principle of this algorithm is that the Bragg wavelength shift $\Delta\lambda$ can be calculated by cross correlation product between the undisturbed spectrum $R(\lambda_i)$ and the perturbed spectrum $R(\lambda_i - \Delta\lambda)$ of the SFBG by implementing the following equation:

$$C_j = \sum_{i=0}^{N-1} R(\lambda_i) R'(\lambda_{i+j}) \tag{1}$$

for $j = -N+1, -N+2, \ldots, 0, \ldots, N-2, N-1$ and C_j is an output sequence containing $2N-1$ samplings. The values of the cross correlation product C_j are distributed in accordance with a Gaussian profile. Subsequently, Bragg wavelength shift $\Delta\lambda$ can be calculated by the following equation:

$$\Delta\lambda = p \cdot \delta\lambda \tag{2}$$

where p is the x-coordinate of the center peak in the Gaussian profile, $\delta\lambda$ is the wavelength step. Note that the resolution of this algorithm was dependent of this value of $\delta\lambda$.

The stability of Bragg wavelength detection of SFBG was evaluated. Sixty spectra were measured by using OSA with the above-mentioned resolution, wavelength step and sampling. The first recorded spectrum was used as a reference, and the correlation spectra were calculated based on (1) via MATLAB, as shown in Fig. 3(a). Note that there are

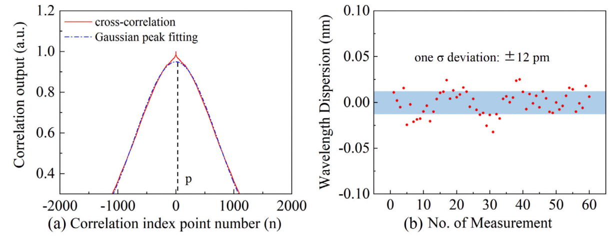


Fig. 3. (a) Correlation spectra of SFBG. (b) Wavelength dispersion of 60 measurements.

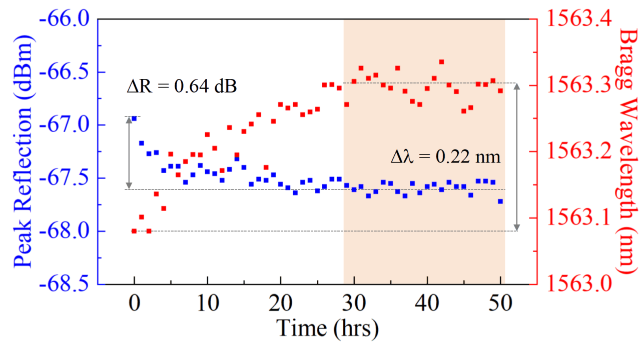


Fig. 4. Change in the Bragg wavelength and peak reflection of the SFBG sample over a 50 h period at an annealing temperature of 1500 °C.

some minor fluctuations in this curve. This phenomenon results from that the shape of the reflection peak of SFBG will be changed slightly in various measurements. Hence, a Gaussian peak fitting was implemented on the correlation spectra, as shown in the dashed line in Fig. 3(a), and then the accuracy in detecting the peak location of correlation spectra can be improved. By using these procedures, the Bragg wavelengths of 60 individual measurements were calculated. As shown in Fig. 3(b), the one σ deviation is $\pm$12 pm (approx. $\pm$0.67 °C), which is close to that achieved by using the spectra averaging method [19]. This result demonstrates the robustness and reliability of the CCA.

In addition, the SFBG sensor was annealed at 1500 °C for 50 h to stabilize the spectrum. The reflection spectra were recorded every 30 min by using OSA. The scanning span ranged from 1505 to 1570 nm, and the corresponding sampling is 65 001. The Bragg wavelength of the SFBG sample was calculated by using the CCA. The evolution of peak reflection and the Bragg wavelength of the SFBG sample is shown in Fig. 4. It can be seen that the Bragg wavelength exhibits a trend of redshift in the first 30 h, and the total value is 0.22 nm. In the last 20 h, it tends to stabilize, but a slight fluctuation of 0. 07 nm could be observed, resulting from the temperature change of the tube furnace and the dispersion in Bragg wavelength detection. The peak reflection, moreover, decreases slightly by 0.64 dB in the first 30 h and remains stable in the last 20 h. This phenomenon indicates that the femtosecond-laser-induced residual stress could be released by high-temperature annealing, and hence, a thermally stabilized SFBG ultrahigh-temperature sensor could be achieved.

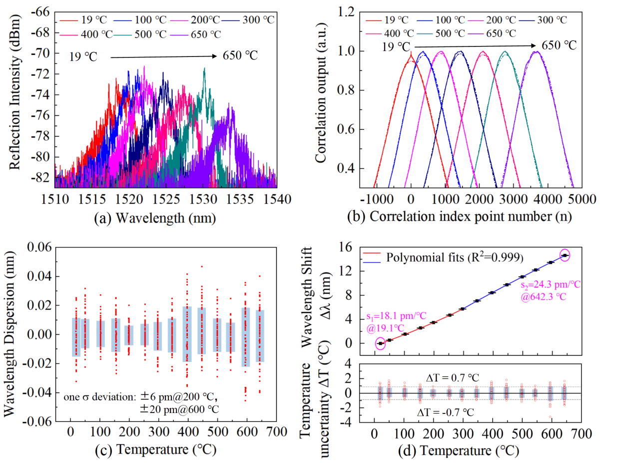


Fig. 5. Study of temperature calibration of the SFBG sensor at elevated temperatures ranging from 19 °C to 650 °C. (a) Evolutions of reflection spectra. (b) Correlation spectra. (c) Wavelength dispersion. (d) Temperature response with polynomial fit curve.

TABLE I

DIFFERENCE BETWEEN MEASURED TEMPERATURE BY USING SFBG AND PT100

	Mean of measured temperature (°C)					
PT100	19.07	198.03	296.04	446.33	543.54	642.32
SFBG	19.68	196.90	296.40	448.24	544.74	643.80
Difference	0.61	-1.13	0.35	1.91	1.20	1.48

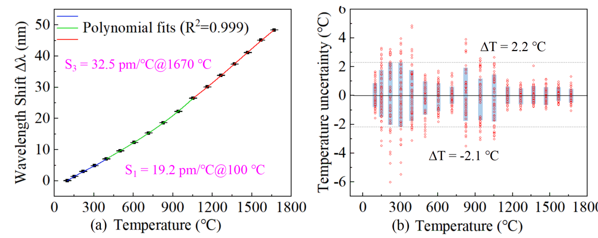


Fig. 6. Study of temperature calibration of the SFBG sensor at elevated temperatures ranging from 100 °C to 1670 °C. (a) Temperature response with polynomial fit curve. (b) Temperature uncertainty.

TABLE II

DIFFERENCE BETWEEN MEASURED TEMPERATURE BY USING SFBG AND B-TYPE THERMOCOUPLE

	Mean of measured temperature (°C)					
Thermocouple	98.4	304.6	605.6	942.0	1265.8	1669.4
SFBG	98.6	304.3	604.3	940.0	1270.9	1662.5
Difference	0.2	-0.3	-1.3	-2.0	5.1	-6.9

IV. STUDY OF TEMPERATURE CALIBRATION OF SFBG

In this section, the temperature response of the SFBG was tested by employing a dry-block calibrator (Isotech Gemini 4857-700). The fluctuation of temperature in this furnace is less than ±0.03 °C, which is suitable for sensor calibration. The temperature varied from room temperature to 650 °C and was maintained for 60 min at each measurement point. The reflection spectra of the SFBG sample were recorded every minute, and then 60 interval measurements could be obtained. The scanning span ranged from 1505 to 1540 nm, and the corresponding sampling is 35 001. A previously calibrated PT100 (Isotech, 935-14-72/DB) with an accuracy of 0.05 °C was placed along the SFBG sample to record the temperature for the in situ calibration. Fig. 5(a) displays the reflection spectra of the SFBG sample at various temperatures ranging from 19 °C to 650 °C. The first recorded spectrum at 19 °C was used as a reference, and the correlation spectra at various temperatures were calculated based on (1) via MATLAB, as shown in Fig. 5(b). The minimum and the maximum deviations are ±6 pm at 200 °C (approx. ±0.30 °C) and ±20 pm at 600 °C (approx. ±0.83 °C), respectively, as displayed in Fig. 5(c).

Subsequently, the piecewise third-order polynomial fitting was employed to evaluate the temperature response, as shown in Fig. 5(d), and the fit curve with the high fitness ($R^2 = 0.999$) was realized. The resulting sensitivity is determined by the thermal-optics coefficient and thermal-expansion coefficient of sapphire material. In this experiment, this value is between 18.1 pm/°C at 19 °C and 24.3 pm/°C at 650 °C, which is close to other published data [8], [17]. The fit residuals of each calibration point are not significant due to the high fitness of the curve. Hence, the temperature uncertainty results mainly from the dispersion of the Bragg wavelength. The maximum of temperature uncertainty with one σ error bar is ±0.7 °C. The means of temperature measured by using the SFBG, ranging from 19 °C to 650 °C, are shown in Table I. Compared to the temperature measured by using the calibrated PT 100, the maximum difference is less than 2 °C, which means an impressive accuracy of the SFBG sensor can be achieved.

In addition, a high-temperature response of the SFBG was evaluated by employing a tube furnace (Carbolite, Gero HTRH). A B-type thermocouple was placed along the SFBG to record the temperature as a reference. The accuracy of such a thermometer is ±0.25%T, where T is the measured temperature. The temperature varied from 100 °C to 1670 °C and was maintained for 60 min at each measurement point. In order to record the spectra at high temperatures up to 1000 °C, the scanning span ranged from 1505 to 1595 nm. When the wavelength step of OSA is set as 1 pm, it will take more than one minute to monitor and record the spectrum. Hence, in this test, the wavelength step $\delta\lambda$ and the sampling N were set as 10 pm and 9001, respectively, resulting in a decrease of the resolution of the Bragg wavelength.

By using the CCA and the piecewise third-order polynomial fitting method, as shown in Fig. 6(a), the fit curve together with the temperature uncertainties could be obtained, and the sensitivity is between 19.2 pm/°C at 100 °C and 32.5 pm/°C at 1670 °C. As shown in Fig. 6(b), the temperature uncertainty increases to ±2.2 °C, which is totally larger than that displaced in Fig. 5(d) since the temperature stability of the tube furnace is lower than the dry-block calibrator. In this calibration process, as shown in Table II, the maximum difference between the temperatures measured by using the SFBG and the thermocouple is less than 7 °C, which is higher than that calibrated by employing a dry-block calibrator. These results demonstrate that the accuracy of the SFBG sensor could be enhanced by using a furnace with higher temperature stability.

Additionally, a 1000-h (i.e., 42 days), 1500 °C stability test was carried out by using the SFBG sample. Based on

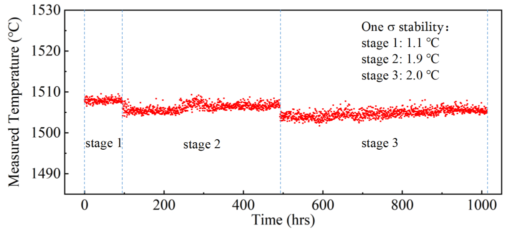


Fig. 7. Stability of the SFBG sensor at a temperature above 1500 °C over 1000 h (i.e., 42 days).

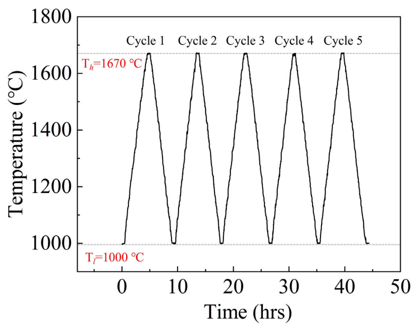


Fig. 8. Cycling temperatures test between 1000 °C and 1670 °C of SFBG.

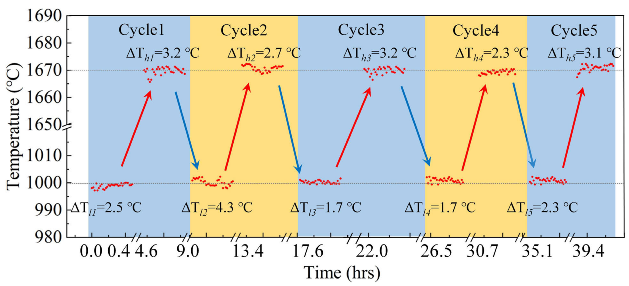


Fig. 9. Temperature uncertainty in cycling temperatures test.

the calibration curve of the sensors, the temperature could be demodulated, as shown in Fig. 7. The mean and one σ deviation of the measured temperature in stage 1 (i.e., first 100 h) are 1507.9 °C and 1.1 °C, respectively. Note that, at the 100th and 500th h, the chamber (i.e., alundum tube) of the furnace was broken. After changing the alundum tube, the stability test was continued to perform. In stage 2 and stage 3, the mean temperatures were 1506.2 °C and 1504.8 °C, respectively, which decreased slightly; moreover, the one σ deviations of the measured temperature in stage 2 and stage 3 were 1.9 °C and 2.0 °C, respectively. The reason for the temperature change in the three stages is the difference in the temperature distribution of various furnace chambers. As a result, the proposed SFBG sample exhibits excellent long-term high thermal stability; moreover, the repeatability of SFBG was investigated via cycling temperatures test. At first, the temperature increased to 1670 °C and was maintained for 30 min, and then it decreased to 1000 °C. Five cycles were performed, the experimental results are shown in Fig. 8. The maximum of the temperature uncertainties at high-temperature point (i.e., 1670 °C) ΔT_h is 3.2 °C, and this value at low-temperature point (i.e., 1000 °C) ΔT_l is 4.3 °C, which can be observed in Fig. 9. These results demonstrate that the SFBG has the good repeatability in temperature measurements.

V. Conclusion

In this article, we proposed the CCA method for demodulation of a high-temperature sensor based on an SFBG sealed in an argon gas-infiltrated sapphire tube, and the experimental results show that the Bragg wavelength dispersion of ±12 pm could be achieved. The SFBG sensor was, moreover, annealed at 1500 °C for 50 h to improve the stability of the reflection spectrum; furthermore, the temperature calibration of the SFBG was studied. The results show that the temperature uncertainty of ±0.7 °C can be obtained by using the dry-block calibrator. Compared to the calibrated thermometer, the maximum difference is less than 2 °C. It is noted that the maximum difference increases to 7 °C by using the tube furnace since the temperature stability of the tube furnace is lower than the calibration furnace. A 1000-h (i.e., 42 days), 1500 °C stability test was carried out, and the temperature deviation is low, i.e., 2.0 °C, which demonstrates that SFBG has excellent long-term high thermal stability. A cycling temperatures test was performed, and the results exhibit good repeatability in temperature measurements. As a result, such an SFBG sensor demodulated by the CCA is promising for applications in harsh environments.

Acknowledgment

Xizhen Xu, Qingming Tan, Zhuoda Li, Jiafeng Wu, He Li, Jia He, Yiping Wang, and Jun He are with the Shenzhen Key Laboratory of Photonic Devices and Sensing Systems for Internet of Things, Guangdong and Hong Kong Joint Research Center for Optical Fiber Sensors, State Key Laboratory of Radio Frequency Heterogeneous Integration, Shenzhen Key Laboratory of Ultrafast Laser Micro/Nano Manufacturing, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education/Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China (e-mail: xizhenxu@szu.edu.cn; tanqingming2022@email.szu.edu.cn; lizhuoda2021@email.szu.edu.cn; wujiafeng2021@email.szu.edu.cn; 2070456093@email.szu.edu.cn; hejia2019@email.szu.edu.cn; ypwang@szu.edu.cn; hejun07@szu.edu.cn).

Zhengxi He is with the Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institute of China, Chengdu 610213, China, and also with the School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China (e-mail: hezhengxi0002@163.com).

Yue Qin and Tao Xu are with the Science and Technology on Reactor System Design Technology Laboratory, Nuclear Power Institute of China, Chengdu 610213, China (e-mail: qyqinyue@foxmail.com; xutaonpic@163.com).

Zengling Ran is with the School of Information and Communication Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China (e-mail: ranzl@126.com).

References

[1] D. M. Van Wie, D. G. Drewry Jr., D. E. King, and C. M. Hudson, "The hypersonic environment: Required operating conditions and design challenges," *J. Mater. Sci.*, vol. 39, no. 19, pp. 5915–5924, Oct. 2004.

[2] J. Sun, X. Xing, Y. He, Y. Wang, J. Chen, and Y. Zhu, "Experimental study on high-temperature gasification and melting characteristics of the pyrolysis residue from petrochemical sludge," *Fuel*, vol. 296, Jul. 2021, Art. no. 120680.

[3] M. Wang et al., “Influence of temperature and CO_2 on high-temperature behavior and microstructure of metallurgical coke,” *ACS Omega*, vol. 6, no. 30, pp. 19569–19577, Aug. 2021.

[4] H. Zhang, W. Liang, J. Liu, and J. Wang, “Modeling and energy efficiency analysis of thermal power plant with high temperature thermal energy storage (HTTES),” *J. Thermal Sci.*, vol. 29, no. 4, pp. 1025–1035, Aug. 2020.

[5] Y. Zhang, X. Fang, T. Ma, B. Xia, and C. Li, “Study on on-line temperature measurement technology for core of pebble bed high temperature gas-cooled reactor,” *Nucl. Eng. Des.*, vol. 371, Jan. 2021, Art. no. 110944.

[6] J. He et al., “Review of femtosecond-laser-inscribed fiber Bragg gratings: Fabrication technologies and sensing applications,” *Photonic Sensors*, vol. 11, no. 2, pp. 203–226, 2021.

[7] D. Grobnic, S. J. Mihailov, C. W. Smelser, and H. Ding, “Sapphire fiber Bragg grating sensor made using femtosecond laser radiation for ultrahigh temperature applications,” *IEEE Photon. Technol. Lett.*, vol. 16, no. 11, pp. 2505–2507, Nov. 2004.

[8] X. Xu et al., “Sapphire fiber Bragg gratings inscribed with a femtosecond laser line-by-line scanning technique,” *Opt. Lett.*, vol. 43, no. 19, p. 4562, 2018.

[9] X. Xu, J. He, C. Liao, and Y. Wang, “Multi-layer, offset-coupled sapphire fiber Bragg gratings for high-temperature measurements,” *Opt. Lett.*, vol. 44, no. 17, p. 4211, 2019.

[10] T. Habisreuther, T. Elsmann, Z. Pan, A. Graf, R. Willsch, and M. A. Schmidt, “Sapphire fiber Bragg gratings for high temperature and dynamic temperature diagnostics,” *Appl. Thermal Eng.*, vol. 91, pp. 860–865, Dec. 2015.

[11] S. Yang et al., “Application of sapphire-fiber-Bragg-grating-based multi-point temperature sensor in boilers at a commercial power plant,” *Sensors*, vol. 19, no. 14, p. 3211, Jul. 2019.

[12] B. A. Wilson, C. M. Petrie, and T. E. Blue, “High-temperature effects on the light transmission through sapphire optical fiber,” *J. Amer. Ceram. Soc.*, vol. 101, no. 8, pp. 3452–3459, Aug. 2018.

[13] Y. Shen, L. Tong, and S. Chen, “Performance stability of the sapphire fiber and cladding under high temperature,” in *Proc. SPIE Conf. Harsh Environ. Sensors II*, Boston, MA, USA, 1999, pp. 134–142.

[14] J. He et al., “Stabilized ultra-high-temperature sensors based on inert gas-sealed sapphire fiber Bragg gratings,” *ACS Appl. Mater. Interface*, vol. 14, no. 10, pp. 12359–12366, Mar. 2022.

[15] H.-W. Lee, H.-J. Park, J.-H. Lee, and M. Song, “Accuracy improvement in peak positioning of spectrally distorted fiber Bragg grating sensors by Gaussian curve fitting,” *Appl. Opt.*, vol. 46, no. 12, p. 2205, 2007.

[16] M. Busch, W. Ecke, I. Latka, D. Fischer, R. Willsch, and H. Bartelt, “Inscription and characterization of Bragg gratings in single-crystal sapphire optical fibres for high-temperature sensor applications,” *Meas. Sci. Technol.*, vol. 20, no. 11, Nov. 2009, Art. no. 115301.

[17] S. Yang, D. Hu, and A. Wang, “Point-by-point fabrication and characterization of sapphire fiber Bragg gratings,” *Opt. Lett.*, vol. 42, no. 20, pp. 4219–4222, Oct. 2017.

[18] R. Eisermann et al., “Metrological characterization of a high-temperature hybrid sensor using thermal radiation and calibrated sapphire fiber Bragg grating for process monitoring in harsh environments,” *Sensors*, vol. 22, no. 3, p. 1034, Jan. 2022.

[19] T. Habisreuther, T. Elsmann, A. Graf, and M. A. Schmidt, “High-temperature strain sensing using sapphire fibers with inscribed first-order Bragg gratings,” *IEEE Photon. J.*, vol. 8, no. 3, pp. 1–8, Jun. 2016.

[20] J. M. Gong, C. C. Chan, W. Jin, J. M. K. MacAlpine, M. Zhang, and Y. B. Liao, “Enhancement of wavelength detection accuracy in fiber Bragg grating sensors by using a spectrum correlation technique,” *Opt. Commun.*, vol. 212, nos. 1–3, pp. 29–33, Oct. 2002.

[21] J. Lim, Q. Yang, B. E. Jones, and P. R. Jackson, “Strain and temperature sensors using multimode optical fiber Bragg gratings and correlation signal processing,” *IEEE Trans. Instrum. Meas.*, vol. 51, no. 4, pp. 622–627, Aug. 2002.

[22] C. Huang et al., “Demodulation of fiber Bragg grating sensor using cross-correlation algorithm,” *IEEE Photon. Technol. Lett.*, vol. 19, no. 9, pp. 707–709, May 2007.

[23] G. Shi, R. Shurtz, G. Pickrell, A. Wang, and Y. Zhu, “Point-by-point inscribed sapphire parallel fiber Bragg gratings in a fully multimode system for multiplexed high-temperature sensing,” *Opt. Lett.*, vol. 47, no. 18, pp. 4724–4727, Sep. 2022.

Xizhen Xu was born in Guangdong, China, in 1990. He received the B.S. degree from the College of Science, Zhejiang University of Technology, Hangzhou, China, in 2013, and the M.S. and Ph.D. degrees in optical engineering from Shenzhen University, Shenzhen, China, in 2016 and 2019, respectively.

From 2019 to 2021, he was a Postdoctoral Research Fellow with Shenzhen University. He is currently an Assistant Professor with Shenzhen University. He has authored or coauthored three patent applications and more than 50 journals and conference papers. His current research interests include femtosecond laser micromachining, optical fiber sensors, and fiber Bragg gratings.

Qingming Tan was born in Guangdong, China, in 2000. He received the B.S. degree from the College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen, China, in 2022, where he is now pursuing the M.S. degree.

His current research interests focus on fiber Bragg gratings and optical fiber sensors.

Zhuoda Li was born in Inner Mongolia, China, in 1998. He received the B.S. degree from the College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen, China, in 2021, where he is now pursuing the M.S. degree.

His current research interests focus on fiber Bragg gratings and optical fiber sensors.

Jiafeng Wu was born in Guangdong, China, in 1998. He received the B.S. degree from the College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen, China, in 2021, where he is now pursuing the M.S. degree.

His current research interests focus on fiber Bragg gratings and optical fiber sensors.

He Li was born in Jilin, China, in 1998. He received the B.S. degree from the College of Physics and Optoelectronic Engineering, Changchun University of Science and Technology, Changchun, China, in 2021, and the M.S. degree from Shenzhen University, Shenzhen, China, in June 2023.

His previous research interests include fiber Bragg gratings and optical fiber sensors.

Jia He was born in Hunan, China, in 1997. She received the B.S. degree from the College of Physics and Optoelectronic Engineering, Xiangtan University, Xiangtan, China, in 2019. She is now pursuing the Ph.D. degree with Shenzhen University, Shenzhen, China.

Her current research interests focus on fiber Bragg gratings and optical fiber sensors.

Zhengxi He was born in Sichuan, China, in 1983. He received the B.S. degree from the Nuclear Power Institute of China, Chengdu, Sichuan, in 2007. He is now pursuing the Ph.D. degree with the University of Electronic Science and Technology of China, Chengdu.

He is working with the Nuclear Power Institute of China, mainly engaged in instrumentation and control professional research and design work.

Yue Qin was born in Sichuan, China, in 1994. She received the B.S. degree from the School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, in 2019.

She is now working with the Nuclear Power Institute of China, Chengdu, mainly engaged in instrumentation and control professional research and design work.

Tao Xu was born in Shanxi, China, in 1991. He received the B.S. degree from the School of Mechanical Engineering, Sichuan University, Chengdu, Sichuan, China, in 2016.

He is now working with the Nuclear Power Institute of China, Chengdu, mainly engaged in instrumentation and control professional research and design work.

Zengling Ran was born in Chongqing, China, in 1977. He received the M.Eng. degree from the Department of Optoelectronic Engineering, Chongqing University, Chongqing, in 2003, and the Ph.D. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2009.

He is currently a Professor with the Key Laboratory of Optical Fiber Sensing and Communications (Ministry of Education), University of Electronic Science and Technology of China. His current research interests include fiber-optic sensing and signal-processing technology.

Yiping Wang (Senior Member, IEEE) was born in Chongqing, China, in 1971. He received the B.Eng. degree in precision instrument engineering from the Xi'an Institute of Technology, Xi'an, China, in 1995, and the M.S. and Ph.D. degrees in optical engineering from Chongqing University, Chongqing, in 2000 and 2003, respectively.

From 2003 to 2005, he was a Postdoctoral Fellow with Shanghai Jiao Tong University, Shanghai, China. From 2005 to 2007, he was a Postdoctoral Fellow with The Hong Kong Polytechnic University, Hong Kong. From 2007 to 2009, he was a Humboldt Research Fellow with the Institute of Photonic Technology (IPHT), Jena, Germany. From 2009 to 2011, he was a Marie Curie Fellow with the Optoelectronics Research Center (ORC), University of Southampton, Southampton, U.K. Since 2012, he has been with Shenzhen University, Shenzhen, China, as a Distinguished Professor. He has authored or coauthored one book, 21 patent applications, and more than 240 journals and conference papers. His current research interests focus on optical fiber sensors, fiber gratings, and photonic crystal fibers.

Prof. Wang is a Senior Member of the Optical Society of America and the Chinese Optical Society.

Jun He (Member, IEEE) was born in Hubei, China, in 1985. He received the B.Eng. degree in electronic science and technology from Wuhan University, Wuhan, China, in 2006, and the Ph.D. degree in electrical engineering from the Institute of Semiconductors, Chinese Academy of Sciences (CAS), Beijing, China, in 2011.

From 2011 to 2013, he was a Research Engineer with Huawei Technologies, Shenzhen, China. From 2013 to 2015, he was a Postdoctoral Research Fellow with Shenzhen University, Shenzhen. From 2015 to 2016, he was a Visiting Fellow with The University of New South Wales (UNSW), Sydney, NSW, Australia. Since 2017, he has been an Assistant Professor/Associate Professor with Shenzhen University. He has authored or coauthored four patent applications and more than 80 journals and conference papers. His current research interests focus on optical fiber sensors, fiber Bragg gratings (FBGs), and fiber lasers.

Dr. He is a member of the Optical Society of America.