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# High Temperature Sapphire Optical Fiber Sensor

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**Abstract:** A sapphire fiber optic sensor for ultra-high temperature is developed, which owns the advantages of high temperature tolerance and compact. The detecting fiber is manufactured by fusing the sapphire fiber for detector head. The developed infrared radiation light is detected and the high temperature optical fiber sensor is placed in the ultra-high temperature furnace. The sensor signal will be transmitted to the display device through a photoelectric conversion module, and data acquisition module. As a result, the temperature response sensitivity is 2.292 $uV^{1/2}/K$ The measurement results show that the repeatability of the sensor is good. The maximum temperature measured by the sensor is 1823 K. The sensor can withstand 10 hours at high temperature and the error is less than 1 %. The development of common optical fiber sensor can stably exist at high-temperature. The sensor owns the advantage of simple, compact, easy to fabricate, what's more, it can tolerate ultrahigh temperature for a long time.

**Keywords:** Temperature measurement, Sapphire optical fiber, Optical fiber sensor, High temperature sensing, Radiation measurement.

## 1. Introduction

In extremely harsh environment, the requirement of temperature measurement can reach over 1000 ℃. In various fields such as aerospace and hot air detection [1-3], the stability of engine in high temperature environment is affected by temperature. Optical fiber temperature measurement method is a new temperature measurement method developed in recent years. It is gradually replacing some traditional temperature sensors to realize temperature measurement. The physical principle of temperature measurement is that the characteristic parameters of light wave, such as amplitude, phase, polarization state and wavelength, transmitted in optical fiber, are sensitive to the external environment temperature. When the external temperature changes, they will have a certain function relationship with the temperature.

In the process of industrial production and machine condition monitoring, the temperature information is important, which can provide the date for the temperature sensing. The working environment of large generator blades is ultra-high temperature and strong electromagnetic interference [4-8]. The high temperature sensor has good linearity, high precision, corrosion resistance, wide range of temperature response, anti-interference, safety and so on, which can be applied to severe temperature environments, for example, the severe vibration, high temperature and pressure, strong electromagnetic interference [9-15]. The contact type and non-contact type are the two main types of optical fiber temperature sensor. The contact Fabry-Perotsensor (FPI) [9], Bragg grating sensor (FBG), Michelson sensor [10], Mach-Zehnder interference (MZI) [11]. Due to the advantages of wide temperature response range and high precision, anti-interference, corrosion resistance, good linearity and so on, a sapphire fiber FBG is manufactured based on femtosecond laser, although the sensor manufactured by femtosecond laser can withstand high temperatures of 1500 ℃ [12] for a long time and 1900 ℃ instantaneously [13], it is difficult for the fiber sensor to be stably work at high temperatures for long-term use. Because of structure and material limitations, FBG structure will lose their sensitive properties.

Optical fiber, radiation temperature sensor [22-26] has been paid attention to in the field of sensing. However, the development of radiation temperature sensor is limited due to the complex structure and the difficulty of the focusing lens in the sensor segment to withstand extreme environment. Subsequently, researchers combined mature radiation temperature measurement technology with advanced optical fiber temperature measurement to form optical fiber blackbody radiation temperature measurement [27-32]. Shenyongxing, *et al.*, of Zhejiang University successfully produced the sapphire single-crystal fiber for the first time in China in 1987, and made the high temperature fiber black body cavity sensor by high temperature sintering of ceramics, which could reach a large temperature range of 500 ℃ to 1800 ℃. In 2002, Xi'an University of electronic science and technology [40-41] also successfully solved the production technology of sapphire high-temperature fiber black body cavity. They made ceramic black body cavity on one end of sapphire rod with a diameter of 3 mm, which can be used for material thermal analysis and temperature measurement during heat treatment. In 2015, China aerospace dynamics research institute [42] made an ultra-high temperature sapphire fiber sensor by plasma spraying ceramic film on the surface of sapphire fiber, which can achieve high precision temperature measurement within the range of 800 ℃ to 1600 ℃. In 2016, s. a. Ogarev, *et al.*, [45] have made the high-temperature radiation sensor that can measure the temperature response from 800 ℃ to 2800 ℃. During the experiment, the intensity was positively correlated with the change of temperature.

In this paper, a sapphire optical fiber sensor is developed, which works stably at 1923 K for 10 hours. The sensor has the advantages of compactness, simplicity, convenience and long-term high temperature resistance.

## 2. Experiment and Discussions

The principle for thermal radiation is one of the basic methods of temperature measurement. Temperature is related to the radiation energy of the object. Therefore, the accurate measurement of temperature can be achieved by measuring infrared energy.

The material characteristics of sapphire fiber determine that it has many advantages that ordinary fiber does not have, such as high strength, high temperature resistance, multimode transmission, and corrosion resistance. The sapphire fiber is shown in Fig.1.

**Fig. 1.** The sapphire fiber.

Different from the ordinary optical fiber. Since the melting point of sapphire fiber is 2040 ℃, we will also pay attention to sapphire fiber in the high temperature field. If we want to add sapphire fiber structure to the sensing system, the coupling point is very important. Therefore, it is of great significance to study the coupling characteristics of sapphire fiber in order to reduce the loss. In addition, its refractive index is between 1.76 and 1.78, and there are certain difficulties in coupling with ordinary fibers. Sapphire fiber is solid and needs to be grinded with a special grinder. The physical picture of the grinder is shown in Fig. 2.

The sapphire fiber with diameter of 100 um is selected to fabricate the sensor. When light is transmitted in an optical fiber, the optical power gradually decreases with the transmission distance increases. This phenomenon is called the loss of the optical fiber. In order to reduce the loss, the grinding machine is used to pretreat the sapphire fiber end face. A common commercial optical fiber splicing machine (Furukawa S177B) is used to splice the detection optical fiber to a common single mode optical fiber as a transmission optical fiber. As shown in Fig. 3 the thermal radiation intensity can be used to determine the temperature change based on Planck's radiation law.

**Fig. 2.** The sapphire fiber.

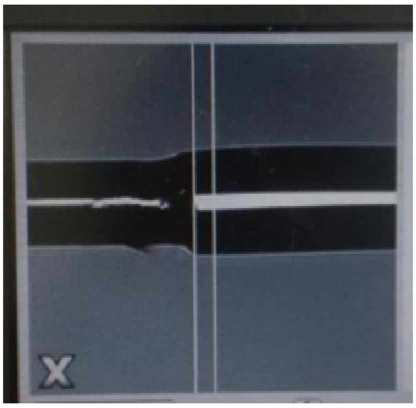

**Fig. 3.** The melting process between sapphire fiber and ordinary fiber.

Finally, we chose the direct fusion method to weld the sapphire fiber to the common fiber. A high-temperature welding machine with an electrode discharge temperature of 2000 ℃ or higher was selected. The fabrication process of the sapphire and multimode fiber coupler is shown in the figure. The sapphire fiber radiation is coupled into the multimode fiber on the multi-dimensional precision mobile platform built into the fusion splicer. The thermal imager is used to verify the coupling effect between ordinary fiber and sapphire fiber. Place the coupling point in the center of the field of view of the camera. One end of the fiber is illuminated with a 2 watt laser. The bright line in the middle is the sapphire fiber we tested and the photo taken through the thermal imager. It can be found that there is no bright spot indicating, which means that the light loss is small and the coupling point is well welded.

The static measurement system has been established to determine the temperature performance of the high temperature sensing point, as shown in Fig. 5. The temperature control precision of high temperature furnace can reach 1 ℃, and the highest can be measured to 1750 ℃. The system also includes photoelectric conversion module, data acquisition module and display device. The system is used to analyze the response of the high temperature sensor. The optical fiber radiation sensor made by us is put in the furnace, and the temperature is detected by setting different temperatures. First, it is heated to 1823 K, then it is kept at this temperature for 10 hours, and then it is cooled to room temperature. The detected optical signal is acquired and stored by the acquisition device, as shown in Fig. 4.

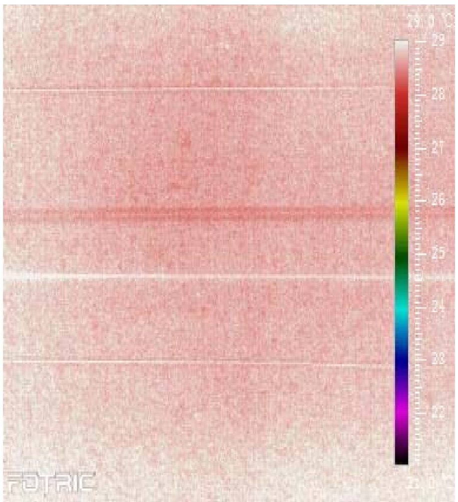

**Fig. 4.** The thermogram of the optical fiber point.

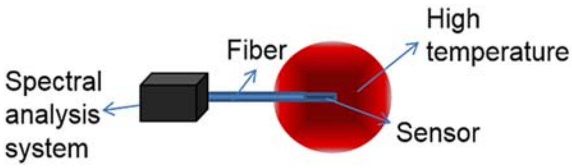


**Fig. 5.** The infrared radiation sensor of temperature sensing system.

The data acquisition and processing module is responsible for synchronous acquisition and subsequent processing of the photoelectric detection circuit and the output signal of the signal generator, which is an integral part of the demodulation system. In this system, the data acquisition and processing module includes data acquisition card and industrial control computer. The data acquisition card is installed in the industrial control computer. It inputs several synchronous signals collected into the industrial control computer for storage, processing and analysis. The design and selection of data acquisition and processing module need to be based on the signal characteristics and acquisition requirements of the system, and the final acquisition effect can be achieved by matching with the system. The resolution of data acquisition card has an important influence on the accuracy of data acquisition. The higher the resolution, the higher the accuracy of data acquisition.

Fig. 6 shows the change of the square value of the voltage with the temperature after the calibration data processing. The experimental results show that the spectral intensity of optical fiber high temperature sensor increases with the increase of temperature.

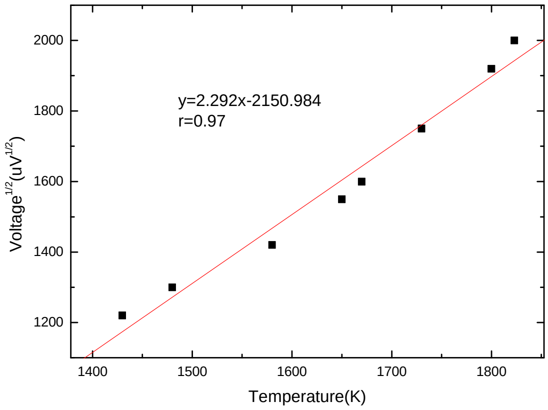


**Fig. 6.** The temperature response curve of optical fiber temperature sensor.

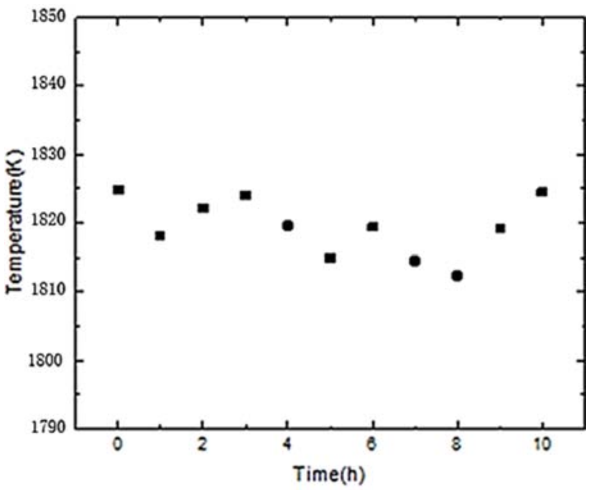


**Fig. 7.** The temperature response of optical fiber high temperature sensor at 1823 K for 10 h.

The black spot in the figure is the temperature measurement value in the process of heat preservation. The sensitivity of temperature response is 2.292 $uV^{1/2}/K$. Based on Fig. 7, the sensor can withstand 10 hours at 1823 K, and the experimental error is less than 1%. The experimental results show that the sensor can work stably for a long time at high temperature. It can be seen that the temperature measurement value of the sensor fluctuates around 1823 K in the process of heat preservation.

## 3. Conclusions

We fabricated a sapphire optical fiber for the high temperature field measurement. Sapphire fiber with higher melting point is used to design and produce the ultra-high temperature sapphire all-radiation sensor system, which is composed of sensor probe, photoelectric conversion, filtering, amplification, high-speed data acquisition and other modules. In view of sapphire fiber hardness, difficult to cut, and other characteristics, sapphire fiber end grinding technology, sapphire fiber and common fiber fusion, coupling technology research. The temperature response sensitivity is 2.292 $uV^{1/2}/K$, which can work in the temperature of 1923 K for more than 10 h, and the error is less than 1 %. The sensor owns the advantages of high temperature tolerance and easy to fabricate.

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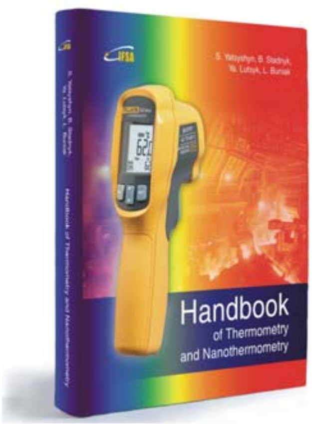


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