Fire detector based on serial FBG temperature sensors optical cabling

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Abstract: Fiber Bragg Grating (FBG) is directly made into low-cost and high-efficiency cable with temperature detection function without secondary packaging. Using the linear relationship between the reflected wavelength of FBG and temperature in the cable, the temperature is calculated, and the alarm of fixed temperature, differential temperature and consistency is determined by software. This system is realized through the design of optical cable structure and algorithm.

1. Introduction
The Code for the Design of Automatic Fire Alarm (GB50116-2013) stipulates that places where the rapid development of fires can produce a large amount of heat, smoke and flame radiation and need early detection and warning, places where timely alarm is needed in case of fires, and places such as underground space, petrochemical tank area and tunnel where environmental temperature needs to be monitored, should be equipped with equipment, like the Fiber Bragg Grating Linear Temperature Sensitive Fire Detector with Real-time Temperature Monitoring Function or its Composite Fire Detector with Smoke Sensor, Flame Detector, etc. The Linear Temperature Sensitive Fire Detector (GB16280-2014) was released on June 24, 2014 and implemented on June 1, 2015, which stipulates the product types, technical requirements, test methods, inspection rules and signs of the Linear Temperature Sensitive Fire Detector. It can be seen that the use of FBG linear temperature-sensitive fire detector for real-time monitoring of environmental temperature in industrial sites is very necessary, if not timely controlled or extinguished, it will have a negative impact on local life and economy [1-2].

Fig.1 FBG Sensing principle

Fig.2 Serial FBG sensing system
2. The principle of FBG temperature measurement and the technical means of traditional FBG temperature sensor

2.1. Principle of FBG temperature measurement
FBG sensing technology realizes the absolute measurement of the strain and temperature of the measured structure by detecting the reflected or transmitted Bragg wavelength spectrum written in the fiber [3]. Its sensing principle is shown in Fig. 1. The reflection or transmission wavelength spectra of FBG mainly depend on the effective refractive index neff of grating period and reverse coupled mode. Any physical process that changes these two parameters will cause the shift of grating Bragg wavelength as follows:

\[ \Delta \lambda_B = 2n_{eff} \cdot \Delta \Lambda \] (1)

Among all the external factors that cause the wavelength shift of grating Bragg, the most direct one is the strain parameter. Whether the grating is stretched or compressed, it will inevitably lead to the change of grating period. Moreover, the elasto-optic effect of the fiber itself makes the effective refractive index neff change with the change of the external strain state. This is the reason for the change of the effective refractive index neff. The optical fiber strain sensor made of fiber Bragg grating provides the most basic physical characteristics. Bragg wavelength variation due to temperature change:

\[ \Delta \lambda_B T = K_T \Delta T = (\alpha + \xi) \Delta T \] (2)

\( K_T \) sensitivity coefficient of wavelength change caused by temperature T, \( \alpha \) represents thermal expansion coefficient of FBG, \( \xi \) represents the thermo-optical coefficient of FBG. Formula (2) shows that the FBG strain sensor based on this principle takes the wavelength of light as the minimum unit of measurement. At present, the detection of FBG wavelength shift has reached the high resolution of pm magnitude. Therefore, it has the characteristics of high measurement sensitivity, and only needs to detect the exact location of the peak in the grating wavelength distribution in the fiber. It has nothing to do with the light intensity, is insensitive to the fluctuation of the light intensity, and has higher anti-interference ability than the general optical fiber sensor [4-6].

FIG. 2 is a schematic diagram of the serial FBG sensing system. Quasi-distributed multiple FBGs, with different wavelengths of FBG’s reflected light (\( \lambda_1, \ldots, \lambda_n \)), with the structure to be tested at each measurement point (1,……n) correspondingly, feel the stress and strain at each point along the distribution line of the structure to be measured, so that the wavelength of the reflected light will change, the altered reflected light is transmitted through a transmission fiber from the measurement site[7]; FBG demodulator is used to detect the wavelength change and convert it into electrical signal. The stress and strain at each measuring point of the structure to be tested and the distribution state of the whole structure to be tested are calculated by the secondary instrument.
2.2. The technical means of traditional FBG temperature sensor

The traditional structure of FBG temperature sensor structure is mainly divided into several parts: 1. The FBG is made according to the interval; 2. The FBG is encapsulated in the metal matrix to make the sensor; 3. The FBG is connected into a series by welding machine and welding contact protection points. The structure is shown in figure 3. This structure, however, has some obvious defects in the long run: (1) The packaging technology based on 353ND hot curing adhesive affects the strength of grating. The grating method using ultraviolet light exposure requires the removal of the coating layer on the surface of the fiber to make the fiber more photosensitive and easier to write. However, the removal of the coating layer usually adopts fiber stripping pliers or thermal stripping pliers, but either way, it is impossible to achieve zero damage to the fiber, mainly to the fiber cladding. The cracks under the microscope are shown in figure 4. This crack will increase during the process of 353ND rubber 150 degree fixed-line phone, which will directly lead to the FBG sensor more vulnerable in the process of application.

(2) Packaging efficiency is low, but the cost is high, it is difficult to meet the actual engineering needs.

Due to the complexity of packaging steps and the large number of assembly devices, and most of them are manual, both device and labor costs are high. Packaging efficiency is low because the production is a single form of packaging.
3. Design of Temperature Sensor for Direct Cable-forming Fiber Bragg Grating

Optical fiber communication has become one of the main pillars of modern communication and plays an important role in modern telecommunication network. As the basic material of optical fiber communication, according to statistics, since 2006, the global optical fiber cable has maintained a compound annual growth rate of 15%. Optical fiber cable has become a stable and mature market-oriented product, and the production line has been formed. Cooked, high production efficiency.

As a specially processed optical fiber, if it can be directly manufactured by using communication optical cable, it will greatly improve efficiency and reduce costs, but at the same time, the following problems need to be solved:

1. The flow and stress of FBG in the cable. According to the mechanical characteristics of FBG, the wavelength shift of FBG caused by stress and strain can be described by the following formula:

\[ \Delta \lambda_B = \lambda_B \left(1 - P \varepsilon \right) \Delta \varepsilon = k \varepsilon \Delta \varepsilon \]

In the formula, \( P \varepsilon \) represents the elasto-optic coefficient of optical fibers, \( k \varepsilon \) represents sensitivity coefficient. The value of \( P \varepsilon \) is 0.22. If the incident light is 1550 nm, the wavelength shift of 1 micro-strain effect is 1.209 pm, which is converted into temperature equal to about 0.12 degrees, which will greatly affect the temperature accuracy.

2. Fiber is very fragile after fibre stripping. The production speed of fibre optic cable is very fast, and there is a certain tension on the fibre. Whether the fiber grating can be guaranteed continuously is also the key of this technology.

3. FBG is wrapped in the innermost layer of the cable. The thickness and quantity of the middle layer will directly affect the temperature transfer. It is difficult to design the alarm software in the later stage.

3.1. The design of encapsulating optical cable

Cable design as shown in figure 5, fiber optic sheath as naked fiber outer case, protect the fiber in the subsequent steps into a cable is not easy to damage, its diameter is about 0.7 mm, inside the control cable fiber length of about 0.1%, can effectively guarantee the optical fiber and optical fiber grating in the optical fiber sheathed internal won't have too big floating up and down, the rest of the mature design reference for fiber optic cable technology, in the end is about 3.3 mm in diameter, temperature accuracy and calibration results will be in the subsequent analysis of the experiment.

3.2 Process Design of Fiber Bragg Grating Cabling

(1) The femtosecond laser direct-write technology is used to make 24 series grating strings with 10-meter interval without damage, as shown in figure 6. The wavelength coding is shown in table 1.
Table 1. Temperature sensor string wavelength coding

| Wavelength  | 1527.8 | 1529.4 | 1531 | 1532.6 | 1534.2 | 1535.8 |
|-------------|--------|--------|------|--------|--------|--------|
|             | 1537.4 | 1539 | 1540.6 | 1542.2 | 1543.8 | 1545.4 |
|             | 1547 | 1548.6 | 1550.2 | 1551.8 | 1553.4 | 1555 |
|             | 1556 | 1558.2 | 1559.8 | 1561.4 | 1563 | 1564.6 |

Fig. 6 The FBG writing system

Table 2. -20°C—95°C, Temperature calibration data

| Temperature (°C) | Wavelength1 (nm) | Wavelength2 (nm) | Wavelength2 (nm) | Wavelength2 (nm) |
|------------------|------------------|------------------|------------------|------------------|
| -20              | 1527.391         | 1529.503         | 1531.599         | 1533.55          |
| -10              | 1527.475         | 1529.587         | 1531.692         | 1533.645         |
| 0                | 1527.56          | 1529.679         | 1531.784         | 1533.733         |
| 10               | 1527.653         | 1529.781         | 1531.886         | 1533.826         |

3.3 Calibration test of temperature sensor string

Data calibration is carried out by using standard platinum resistance thermometer with accuracy of 0.01 C. The method is as follows:

1. The refrigeration thermostat is set to be stable as follows: -20°C→-10°C……→80°C→95°C
2. After the refrigeration thermostat reaches the set temperature in turn, each temperature point needs to record the current calibrated temperature wavelength value (the first four branches) after the spectral curve is stable and no fluctuation:

Fig. 7 The FBG is threaded into the sheath

Fig. 8 Conventional fiber cabling technology for encapsulation

3) The fiber optic cable forming process is adopted to encapsulate the grating string in the fiber optic cable, as shown in figure 8.
The least square method is used for fitting of a polynomial to find the optimal solution. The fitting results are as follows:

| Temperature | y1  | y2  | y3  | y4  | y5  | y6  | y7  | y8  | y9  | y10|
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 20          | 1527.76 | 1529.867 | 1531.972 | 1533.921 | 1533.76 | 1534.124 | 1534.48 | 1534.76 | 1535.02 | 1535.28 |
| 30          | 1527.845 | 1529.964 | 1532.07 | 1534.013 | 1533.87 | 1534.234 | 1534.59 | 1534.87 | 1535.13 | 1535.39 |
| 40          | 1528.045 | 1530.171 | 1532.271 | 1534.216 | 1534.07 | 1534.434 | 1534.79 | 1535.06 | 1535.32 | 1535.58 |
| 50          | 1528.148 | 1530.266 | 1532.375 | 1534.329 | 1534.18 | 1534.544 | 1534.9 | 1535.16 | 1535.42 | 1535.68 |
| 60          | 1528.359 | 1530.478 | 1532.582 | 1534.539 | 1534.39 | 1534.754 | 1535.11 | 1535.37 | 1535.63 | 1535.89 |

The fitting result formula is used to calculate the temperature accuracy in the calibration process:

As shown in figure 9, the maximum error is less than 1 degree, which is slightly lower than that of the conventional FBG temperature sensor. However, the goal of this system is fire detection, which can meet the requirement of temperature accuracy of fire detection.

4. Introduction of Alarm Types and Analysis of Algorithms

This chapter mainly carries out laboratory experiments according to the alarm requirements by using FBG direct cable temperature sensor and synchronous 1 Hz demodulation frequency instrument, and realizes the system function through the original data analysis and algorithm design.

4.1. The design of encapsulating optical cable

Existing fixed temperature, differential temperature alarm requirements are as follows.

(1) Fixed temperature alarm: the test starts from 25 °C, and the temperature rises at the rate of 1 °C /min. When the temperature reaches 85 °C, the alarm time is ≤30s, with an allowable error of 10%.
In other words, when the temperature displayed in the temperature test box is within the range of 76.5 °C ~ 93.5 °C, the equipment will alarm and judge the time is ≤30s.

(2) Differential temperature alarm: the test starts from 25 °C, and the temperature rises at the rate of 10 °C/min. The response time ranges from 30s to 180s. In other words, when the temperature experiment is conducted in the temperature chamber at 10 °C/min, the alarm needs to be given within 30s to 180s.

The existing FBG temperature sensor and FBG demodulator directly cabled may have the following defects and risks in the system design:

(1) The wavelength stability of the demodulator is about ±1pm, that is, 0.1℃, and the sampling frequency of the demodulator is 1Hz in the full channel. It can be calculated that the temperature rise rate of the demodulator caused by the stability is ±6℃/min.

(2) The response rate of temperature rise of the fiber Bragg grating temperature sensor directly cabled is slower than the heating rate of the temperature box of 10℃/min, which will lead to the failure of alarm.

4.2. Differential temperature experiment and data analysis

The sensing part of the directly cabled FBG temperature sensor was placed in the temperature box. The temperature box was set for 10℃/min. The experiment lasted for 8 minutes. Measurement results are shown in figure 11 (a), can be obviously seen from the figure that exist in the process of temperature rising dithering phenomenon, the stability of this kind of phenomenon may come from the demodulation instrument, also can come from the performance of the sensor itself. For example, the sensor receives a slight vibration that causes the change of grating strain. If the conventional temperature rate change calculation formula is adopted, the temperature appreciation at each time point can be obtained as shown in figure 11 (b). It can be seen from the data chart that the temperature rise rate at each point is chaotic, and the actual temperature rise rate has been completely submerged by systematic error, which makes it impossible to determine the temperature rise rate.

Fig.11 The experimental data, (a) There is a significant dithering in the rising temperature (b) The data obtained at each point by using the conventional temperature rate calculation formula
We adopt a method to take several consecutive temperature data points and fit a curve with the minimum deviation square sum of each node, whose slope is the temperature rise rate. Once the number of temperature points is determined, a recursive method is adopted.

For instance, \(a=x_1, x_2, x_3, x_4, x_5... X_n-4, x_n-3, x_n-2, x_n\), the fitting points is 5, that is, \(x_1\) to \(x_5\), determine a fitting curve, \(x_2\) to \(x_6\), determine a fitting curve, \(x_n-5\) to \(x_n\) determine a fitting curve. The above errors can be eliminated by continuous data fitting, so the determination of fitting points will be the key of this system. If the fitting points is 2, the result of figure 11(b) above is obtained, and the error cannot be eliminated. If the fitting points is set at 20, and the temperature of field sensor changes rapidly, the slope after fitting will be too much to ignore the temperature change, resulting in data misjudgment and alarm delay. It can be seen that too few or too many points will affect the system test effect. In the data analysis, data of 30~180s are intercepted. 5, 10, 15 and 20 points are selected for data fitting, and the data are put in the same data chart as the original temperature rise data for analysis, as shown in figure 12. As can be seen from the figure, the more points taken, the better the fitting degree. The data of ten points are closest to the original data, and 10 points are selected as the points of the recursive formula.

![The experimental data. The fitting results of different recursive fitting points](image)

**4.3. Temperature rise rate and temperature threshold setting in differential temperature alarm time**

The response time of differential temperature alarm is 30s~180s. The temperature rise rate in the time range of 30s~180s is delimited as shown in Fig. 13(a) and the range of temperature value is shown in Fig. 13(b). The temperature rise rate is 0.763 C/min~5.236 C/min, and the range of temperature value is 25.4 C~32.5 C.

![Temperature rise rate and temperature threshold setting](image)(a)
4.4. Fixed temperature experiments and data analysis

The sensing part of the FBG temperature sensor directly cabled is placed in the temperature box. The temperature box is set at 90 degrees and the heating rate of the temperature box is 1 degree/min. The measurement results are shown in Fig. 14. Besides some delay of response speed in the initial stage, the temperature of the temperature box can be basically guaranteed after 40 degrees, so the temperature of the temperature box is the same as that of the temperature box. The alarm interval of 76.5 °C ~ 93.5 °C is the alarm interval of temperature sensor, which is 76.5 °C ~ 93.5 °C. We only need to prevent the wavelength demodulation instrument wavelength demodulation caused by low probability mutation phenomenon, such as wavelength temperature sensor for 1550, due to a 1550.500 data demodulation mutation of wavelength demodulation, according to chapter 3 temperature calibration data, this will directly lead to changes in temperature is about 50 °C, can directly reach the fixed temperature alarm condition. In order to solve this problem, we still need to introduce the concept of heating rate in the implementation of the algorithm, that is, when the heating rate and the temperature value meet the alarm conditions at the same time, we can make an alarm judgment.

4.5. Set the temperature rise rate and temperature threshold within the fixed temperature alarm time

The alarm condition of the fixed temperature experiment is 76.5°C~93.5°C, that is, within this range, the alarm time is ≤30s. Since we use swept tunable laser, which can achieve synchronous sampling of 1Hz, the problem of frequency is not involved. According to the analysis of 4.4 76.5 °C to 93.5 °C temperature range for the fixed temperature alarm experiment, within the time interval of this temperature range, temperature rise rate as shown in figure 15, range of temperature rise rate is -0.3 °C / min ~ 1 °C / min.
5. Conclusion
The sensor part of the system improves the production mode of the existing traditional FBG temperature sensor, which has low cost and high efficiency. It can meet the growing demand of fire detection sensors. The design of the algorithm part can reduce the false alarm rate of the system, and can reflect the temperature rise and temperature in the field more truly.

The sensor part has been designed and formed. Next, we will implement the algorithm part of our system through software, and improve the other functions of alarm linkage.

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