

Basic Study on Position Estimation of Fire Source using Fiber Bragg Gratings

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Abstract

The aim of this study was to construct a system for estimating the position of a fire source by using an optical fiber sensor with multiple fiber Bragg gratings (FBGs). In this report, a system for measuring temperature by using multiplexed FBGs is described, and the results of a basic investigation on estimating the position of a fire source by applying that system with an indoor model are presented.

Keywords: Optical fiber sensor, fiber Bragg grating, temperature measurement, position estimating system, fire detection

Introduction

As for fires that break out in buildings that are elongated in one direction (e.g., vertically or laterally), such as skyscrapers and utility tunnels, the flow of the thermal air current generated by the fire is fast, and it is difficult to comprehend the status of progress of the fire. Particularly in the case of a fire in a service tunnel, the damage due to loss of infrastructure (namely power utilities and communication services) becomes enormous [1][2].

Furthermore, during the Kaprun disaster, in which a fire that occurred in an ascending train in the tunnel of the Gletscherbahn Kaprun funicular railway in Kaprun, Austria, on 11 November 2000, the fire spread to the tunnel rapidly, and the number of dead or wounded due to the spreading fire surpassed one-hundred people [3]. From that disaster too, it was learned that because tunnels are characterized as large elongated spaces, evacuation guidance, firefighting, and saving lives are very difficult to perform effectively in them.

Accordingly, a technology for, most importantly, speeding up initial fire extinguishing as well as providing evacuation guidance and other assistance - on the basis of detecting and estimating the position of a fire - is demanded. As for sensors for detecting fires, several types, such as air-inflated, fixed-temperature, and photoelectric, have been

proposed. However, simultaneously measuring a wide area with these sensors is difficult, and estimating the position of a fire, so that evacuation routes can be planned, is also difficult.

The authors have applied an optical-fiber sensor that is suitable for measuring temperature from a long distance. As well as featuring outstanding explosion resistance and corrosion resistance, this sensor does not need a power source. As a result of these features, the optical-fiber sensor is effective for measuring temperature in large spaces [4-6]. As an optical-fiber sensor, fiber Bragg gratings (FBGs) were utilized. A FBG can function as a diffraction grating because it incorporates a periodic refractive-index change in the core of the optical fiber. Accordingly, when a light with a broad bandwidth is incident to the FBG, only the light with the Bragg wavelength is reflected.

Moreover, if the temperature at the FBG changes the reflected wavelength shifts. Since the extent of that shift is proportional to temperature, the FBG can be utilized for measuring temperature. As another feature of a FBG, wavelengths other than the reflected wavelength are transmitted. Exploiting these features of a FBG, in particular, multiplexing FBGs with different Bragg wavelengths, makes it possible to measure temperatures at multiple points with a single multiplexed optical fiber [4][7][8]. The authors' aim is to construct a "fire-position estimating system" using FBGs. In this report, the results of a basic experiment on estimating the position of a fire - by arranging multiple FBGs in a model of the interior of a room and taking simultaneous temperature measurements at multiple points - are presented.

Experiment

The experimental setup is shown schematically in Fig. 1. It consists of an optical system and a model of a room interior. The optical system is configured with an amplified spontaneous emission (ASE) light source, an optical circulator, four FBGs (for measuring temperature), and a wavelength monitor (WM). The ASE light source houses an optical fiber with doped rare-earth (erbium) ions. By optically exciting these ions and inducing the optical medium to the population-inversion state, it is possible to emit wideband spontaneous emission light in the 1.55- μm wavelength band. Light from the light source propagates along the optical fiber, via the optical circulator, and is input into the four FBGs. The Bragg wavelengths (λ_{Bk}) of the FBGs [i.e., FBG_k ($k=1-4$)] are respectively 1540, 1545, 1550, and 1555 nm. The light reflected at each λ_{Bk} by the FBGs is input into the WM via the optical circulator. The WM (FB200, ANDO) is a spectroscopic type monitor mounting a diffraction grating and a photodiode array, and features wavelength resolution of 1 pm. The WM acquires data concerning the wavelengths of the FBGs every 0.5 s, and sends it to a PC via an RS-232C connection.

The size of the indoor model (namely, 0.8 m square by 0.3 m high) is one-tenth scale in regard to a size of a general office. To simulate a heat source (25 mm square by 12 mm high), a ceramic heater (which can control temperature up to a maximum of 500 °C) was used. As for the arrangement of the FBGs, the floor space was divided into 16 zones, and the temperature of each zone was measured by one of the FBGs (one FBG covering four zones). As shown in Fig. 2, which shows a plane view of the model room, one FBG was installed in the center of the ceiling of areas A to D. Two thermocouples, TC₁ and TC₂, were respectively installed at the heater and near FBG₃ for measuring the temperatures at those positions.

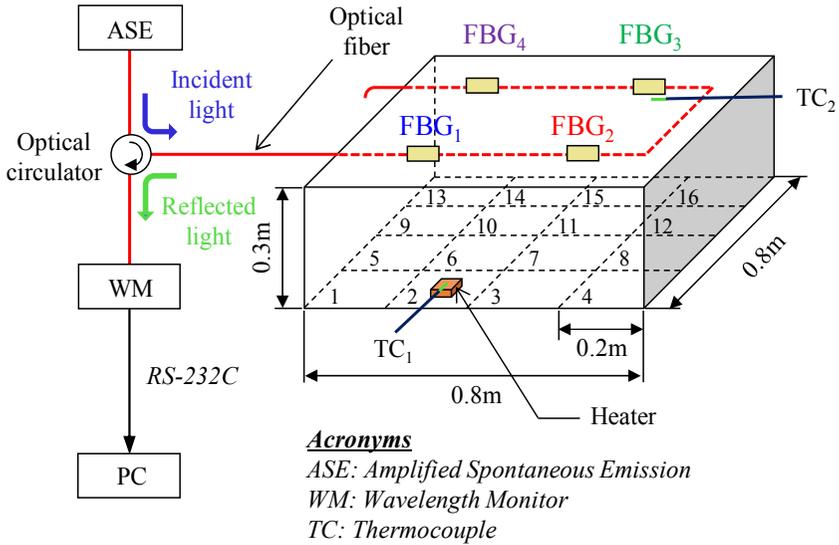


Fig. 1. Experimental setup.

A screenshot of the PC monitor of the temperature-measurement system, constructed by using a graphical programming language (LabVIEW, National Instruments), is shown in Fig. 3. The systems can measure the temperature at the two installed thermocouples and the four FBGs twice every second. By using this system in the experiment, it was possible to measure the temperature at each FBG after the position of the heater was changed, and since the temperature at the four FBG positions changed too, it was possible to estimate the position of the heat source.

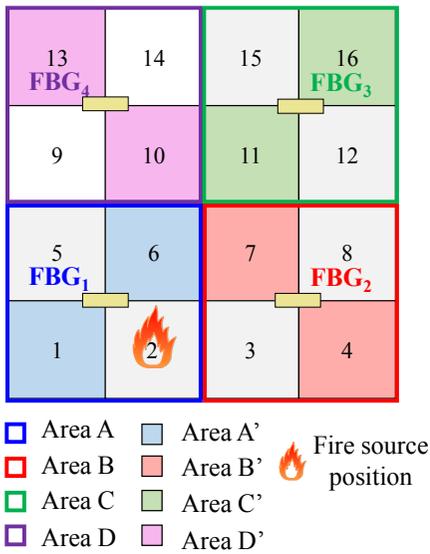


Fig. 2. Model room.

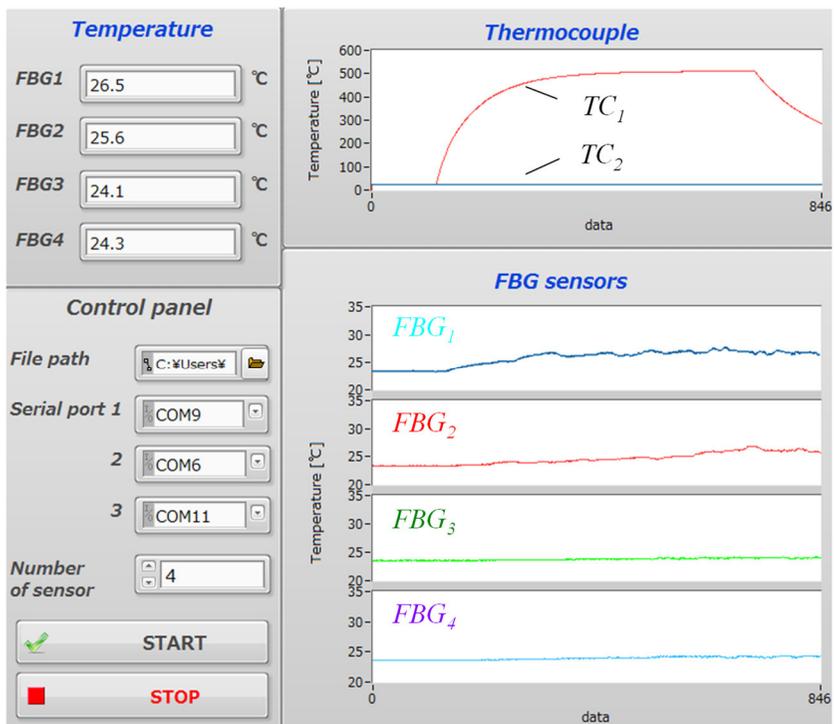


Fig. 3. Screenshot of temperature-measurement system.

Results

1. Temperature characteristic of FBGs

The characteristic reflection wavelength of the FBG in regard to temperature was measured first. As for the measurement, the FBGs were put in a Peltier constant-temperature chamber, and the temperature was controlled in the range of 3 – 65 °C.

The dependences of reflection wavelength on set temperature for the four FBGs are plotted in Fig. 4. The plots indicate that the reflection wavelength of each FBG increases linearly with increasing temperature. Moreover, an approximate straight line obtained by the least-squares method (and the accompanying equation representing the line) is also plotted in the figure. As for each FBG, the slope of reflection wavelength versus temperature is about 10 pm/°C. On the basis of this result, a conversion formula to obtain temperature from wavelength was established and incorporated in the temperature-measurement system. In this way, it is possible to measure the temperature at the four points from reflection wavelength of each FBG.

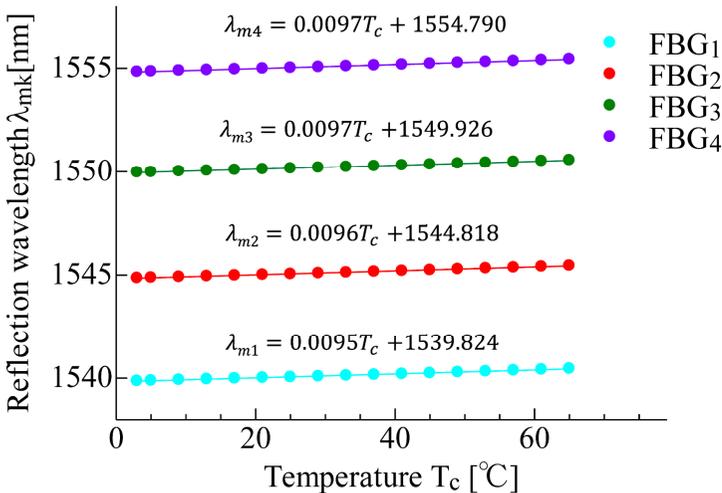


Fig. 4. Results of reflection wavelength to temperature.

2. Temperature measurement using FBGs

The position of the heater was changed, and the temperature was measured by using the temperature-measurement system. Fifty seconds after the measurement started, the power supply was applied to the heater. The measured temperatures in the case, the heater (simulating a fire source) was located at positions #1, #2, #5, and #6 in area A (see Fig. 2), are plotted in Fig. 5. In Fig. 5, the measurement data are plotted after moving-average treatment. It is clear from the figure that when the heat source is turned on, the temperature measured by each FBG rises.

It is also clear that in regard to any position in area A, the temperature at FBG₁ increases the most, and the temperature rises as the distance from the heat source to the sensor decreases. As for the other areas too, the same experiment was performed, and the same result was obtained.

Estimating the position of the heat source from the integrated value of measured temperature (integral temperature, hereafter) was experimentally attempted. Since the initial temperature in the room varied from one experiment to the next, the integral temperature was calculated by subtracting the initial temperatures at the start of measurement from the measured temperatures. The integral temperatures calculated from the measurements taken at position #2 in Fig. 5 are plotted in Fig. 6. It is clear from these results that the rise in temperature depends on distance from the heat source to the FBG in the following ascending order of magnitude of dependence: FBG₁, FBG₂, FBG₄, and FBG₃. The procedure for estimating the position of the fire source - on the basis of the results plotted in Fig. 6 - is explained as follows.

Area A

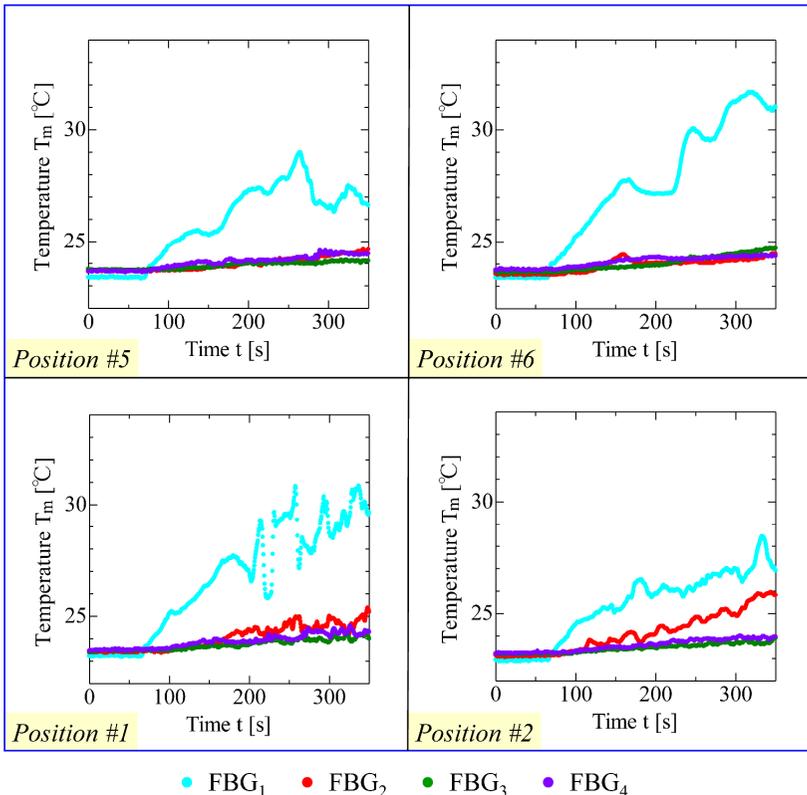


Fig. 5. Results of temperature measurement in area A.

Step 1:

A threshold value (Th-a) is set, and areas A to D are determined according to the areas containing the FBG with the maximum integral temperatures in the designated areas. (As for the results in Fig. 6, area A gives the maximum integral temperature from FBG₁.)

Step 2:

The area containing the FBG with the second-largest integral temperature is determined, and candidate positions for the fire source are selected. (In Fig. 6, the second-highest integral temperature measured by FBG₂ is narrowed down to positions #1, #2, and #6 of area A, and position #5 is excluded from the candidates.)

Step 3:

Next, the third- and second-largest integral temperatures of the FBGs are calculated, and the differences (G_{ST}) between the two values are obtained. Then, the value of the G_{ST} and the threshold value (Th-b) are compared, and the potential positions are narrowed down. (In Fig.6, the difference (G_{ST}) between the integral values of FBG₂ and FBG₄ is obtained, position #2 is selected as the candidate position if the difference (G_{ST}) is greater than or equal to Th-b, and position #1 and #6 (area A' in Fig. 2) are selected if the difference (G_{ST}) is less than Th-b.)

Here, the operating condition for the two types of spot-type sensors is 15 °C/min. Based on this operating condition, the threshold values Th-a was converted into integral values, and 450.00 °C·s was obtained. Accordingly, the alarm threshold was taken as 450.00 °C·s. The level of Th-a as a pre-alarm was investigated. As for Th-a, four values, namely, 225.00 (50 %), 112.50 (25 %), 56.25 (12.5 %), and 28.13 (6.25 %), were investigated. Th-b (which is the value compared with the difference (G_{ST}) of the second- and third-highest integral temperatures) was taken as 10 % of each Th-a.

3. Results of position estimation

The above-described method for estimating position was experimentally evaluated as follows. In the experimental evaluation, the heater was placed at 16 points in areas A to D, and three temperature measurements were taken at each position (thus totaling 48 measurements). The results of the position estimation are listed in Table 1. In the table, “○” indicates an exact match, “△” indicates an area-only match, and “×” indicates no match. In regard to five values of threshold Th-a, estimation accuracy was around 80 %. These results indicate that it is possible to sound a pre-alarm under the assumption that the fire source is in the initial stage. Moreover, as for identification in areas A to D, estimation rate was 100 % regardless of the value of Th-a. The results presented in this report demonstrate the applicability of temperature estimation using optical-fiber-sensor FBGs to estimating the position of a fire source.

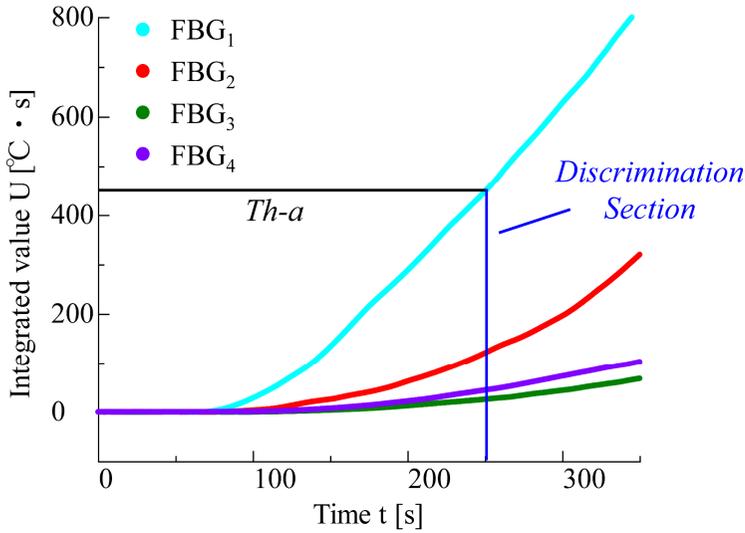


Fig. 6. Integrated values of temperature (position #2).

Table 1. Results of position estimation for fire detection.

Type	Threshold [$^{\circ}\text{C} \cdot \text{s}$]			Determination result			Accuracy rate
	No.	Th-a	Th-b	○	△	×	
Alarm	(1)	450.00	45.00	39	9	0	81.25%
Pre-alarm	(2)	225.00	22.50	42	6	0	87.50%
	(3)	112.50	11.25	39	9	0	81.25%
	(4)	56.25	5.63	38	10	0	79.17%
	(5)	28.13	2.81	38	10	0	79.17%

○: Exact match △: Match only area ×: No match

Conclusion

A temperature-measurement system using fiber Bragg gratings as optical-fiber sensors was developed. This system was demonstrated to be applicable to measuring temperatures at multiple points in a room and estimate the position of a fire source from those temperature measurements. According to an experimental evaluation of the system, position-estimation accuracy was about 80 %, and when the estimation target was limited to areas only, the estimation accuracy was 100 %. We obtained the prospect that this system can be applied to estimating the position of an actual fire.

As for the future, since temperature-measurement systems using FBGs use optical-fiber switches, it is possible to multiplex the optical fibers. Accordingly, by laying optical fibers in all floors of a building or in all

sections of a large space and installing FBGs at multiple points along those fibers, it will be possible to measure temperatures at those multiple points by means of several dozen FBGs. Consequently, it can be inferred that temperature measurement by using optical-fiber sensors with FBGs is an effective method of estimating the position of a fire in a large space.

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