High-Temperature Measurement Technology with Distributed Optical Fiber Sensors Employing Brillouin Scattering

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Silica-glass optical fiber is attracting attention as a high-temperature sensor because of its high melting point (1,000°C or above). With optical fibers used as distributed temperature sensors (DTSs), Raman optical time domain reflectometry (ROTDR) employing the temperature dependence of Raman scattering intensity has already been put into practical use. However, it is difficult for ROTDR based on measurement of Raman scattering intensity ratio to accurately measure temperatures above 300°C for a long period of time due to several issues, such as the attenuation of optical fibers at high temperatures. A different type of DTS employing Brillouin scattering can determine temperature based on the frequency difference between incident and Brillouin scattered light and is less susceptible to attenuation, making this approach promising for measuring temperatures above 300°C. In this paper, we describe high-temperature measurement technology with distributed optical fiber sensors employing Brillouin scattering and introduce our efforts to determine the feasibility of this technology for practical use.

INTRODUCTION

In recent years, there has been increasing demand for temperature measurements in high-temperature environments in the chemical plant, steel, and upstream oil, and natural gas industries. Because optical fiber can be used in high-temperature environments and can measure temperature distributions, it is attracting increasing attention for use in distributed high-temperature sensors. Figure 1 shows an example of temperature monitoring using a distributed temperature sensor with optical fiber sensors surrounding a target (an iron smelting furnace in a steel mill). This type of temperature monitoring may provide potential maintenance management solutions, including predicting the remaining thickness or extent of erosion in heat-resistant bricks, detecting hot spots, and predicting metal runner leaks.

DISTRIBUTED FIBER-OPTIC TEMPERATURE SENSORS

Light propagating through an optical fiber will scatter in minute amounts at locations along the optical fiber. There are three major types of light scattering: Rayleigh, Brillouin, and Raman. Raman optical time-domain reflectometry (ROTDR) uses the temperature-dependent nature of the intensity ratio of
two types of light (Stokes and anti-Stokes) produced by Raman scattering to measure temperature. Generally, attenuation in optical fibers changes over time in high-temperature environments exceeding 300°C. Such changes become measurement errors in ROTDR, making it difficult to measure temperature with high accuracy\(^\text{(2)}\). In contrast, distributed temperature sensors using Brillouin scattering calculate temperatures from the Brillouin frequency shift (BFS), which is the difference in frequency between incident and Brillouin-scattered light. Because changes in attenuation do not affect the measurements, it becomes possible to measure temperatures above 300°C. Indeed, several research institutes have recently reported experimental results on distributed high-temperature sensors using Brillouin scattering\(^\text{(3)(4)}\).

**RESEARCH AND DEVELOPMENT OF HIGH-TEMPERATURE MEASUREMENT TECHNOLOGIES**

**Overview**

Against that background, with the goal of realizing distributed temperature sensors for high-temperature ranges that cannot be achieved using ROTDR, we have been investigating the applicability of optical fiber temperature sensors utilizing the temperature dependence of Brillouin scattered light. In this paper, we present experimental evaluations of the BFS behavior of optical fibers exposed to high-temperature environments, clarify the performance of distributed optical fiber temperature sensors using Brillouin scattering light and factors affecting their performance, and describe our efforts toward identifying issues to be addressed for their practical application.

**Brillouin Optical Correlation Domain Analysis**

We have developed measurement systems based on Brillouin optical correlation domain analysis (BOCDA)\(^\text{(5)}\). BOCDA is characterized by its fast measurement speeds, high spatial resolutions, and capability for random access\(^\text{(6)}\). Here, we used a BOCDA measurement system with a distance range of 500 m, a spatial resolution of 30 mm, a measurement accuracy of ±1 MHz (approximately ±1°C in terms of temperature), and a sampling rate of 70 Hz (Figure 2).

**BOCDA Measurement Principles**

The Brillouin scattering used in this BOCDA is scattering due to acoustic waves in the optical fibers. Induced Brillouin scattering is scattering due to the interaction between pump light entering from one end of the optical fiber and opposing probe light from the other end. In BOCDA, induced Brillouin scattering is generated only at arbitrary positions by frequency modulation of the pump and probe light. The frequency of the probe light is set to about 11 GHz below that of the pump light, and the Brillouin scattering spectrum is obtained by measuring the difference in frequency between the probe and pump light and the power of the scattered light. The BFS is the difference in frequency when the Brillouin scattering spectrum is at its peak. Because the BFS varies with the temperature and strain applied to the optical fiber, the temperature and strain can be converted from the measured BFS. Both BFS and temperature have generally been considered to have a linear relation, but recent studies\(^\text{(7)}\) have reported nonlinearity at temperatures exceeding 500°C. This is believed to be due to a nonlinear dependence of Young's modulus for the optical fiber material on temperature.

**Evaluation Experiment**

To ascertain whether optical fiber temperature sensors can be used at high temperatures, we conducted experiments to assess the temperature response of BFS and the temperature dependence of BFS in high-temperature environments.

**Evaluation System**

Figure 3 shows the evaluation system for BFS behavior. We used an electric furnace to create a high-temperature environment in the laboratory, and a Ge-doped synthetic fused silica single-mode fiber (SMF-28e+; Corning Inc.) coated with a UV-curing resin as the fiber under test (FUT). To reduce any influence of the coating, we completely burned it off by exposing the FUT to 600°C for 1 h before starting the experiment. The FUT was approximately 21 m long and was left unfixed so that a segment 7.8–12.5 m from the probe light side was wound several times in the electric furnace.
The measurement conditions were a 50-mm spatial resolution, 50-Hz point sampling rate, 6–14 m measurement sections, and a 10-mm measurement interval. We programmed the electric furnace to increase the temperature from room temperature to 800°C in 100°C increments and then lower the temperature back to room temperature in 100°C increments. Each 100°C-increment increase occurred over 1 h, while each 100°C-increment decrease occurred over 4 h (except that from 100°C to room temperature). Once the target temperature was reached, it was maintained for 10 h, except for 800°C, which was maintained for 20 h.

**Evaluation Results**

a) BFS temperature response

Figure 4 shows the BFS temperature response at about 10 m (near A in Figure 3) from the end of the probe-light side obtained from the BFS distribution measurements. The red dots (a–q) in Figure 4 illustrate the temperature dependence Figure 5. The BFS changed with temperature during both temperature rise and fall, and except immediately after the temperature rise to 800°C, the BFS fluctuated by only a few megahertz (or several degrees Celsius in terms of temperature) while the specimens were left at each temperature. The dotted line in Figure 4(a) illustrates the stepwise change in BFS over time during the temperature increase to 800°C. This might be due to relaxation under the high-temperature environment of internal stresses remaining from fiber fabrication. In a separate evaluation experiment, we observed similar stepwise changes below 800°C, but the times until those changes occurred were longer than those observed during the temperature increase to 800°C.

![Figure 4](image_url)

(a) At temperature increase from room temperature to 800°C

(b) At temperature decrease from 800°C to room temperature

**Figure 4** BFS temperature response at about 10 m from the end of the probe-light side

b) BFS temperature dependency

Figure 5 shows the BFS temperature dependency, created based on the red dots in Figure 4. There was hysteresis in the BFS temperature dependency, and we observed differences between the temperature rise and fall even in the same temperature environment. As mentioned in Section 3.3, this is likely because BFS is sensitive to strain applied to the optical fiber, and thus detects changes in the internal stress associated with the relaxation of residual stress at 800°C. When raising and lowering the temperature multiple times, BFS during the second and subsequent temperature increases and decreases was nearly the same (within a few megahertz) as that during the temperature decrease in Figure 5, confirming good reproducibility.

The relation between BFS and temperature during the first temperature rise is not linear, but can be expressed as

\[ f = -510T^2 + 1300 \times 10^3 T + 10.840 \]  

where \( f \) is the BFS (GHz) and \( T \) is the temperature (°C). BFS has a second-order dependence on \( T \), and the inverse function of this equation is the calibration curve used to convert BFS to temperature.

The above is one example of an evaluation experiment. We have also started experiments to evaluate BFS behavior over longer periods and will present those in the near future.

![Figure 5](image_url)

**Figure 5** BFS temperature dependence at about 10 m from the end of the probe-light side

**Summary of Evaluation Results**

The BFS was very stable, with a second-order dependence on temperature. We showed that BFS can be converted to temperature by using a calibration curve. Differences in the internal stress of the optical fiber can cause differences in BFS, even under the same temperature environment, but the reproducibility of BFS was good after relaxation of any residual stress.

**Future Work**

This technology is still in the research-and-development stage, so we are just beginning to see the potential for using optical fibers as high-temperature sensors. Because many issues need to be addressed for practical application, we will make the following efforts toward resolving them:
1. Verification of reliability after exposure to high temperatures for extended periods
2. Verification of performance under environmental factors other than high temperature (e.g., vibration, high temperature, corrosion)
3. Verification of the effect on temperature measurements due to strain applied to the optical fiber
4. Verification of values through proof-of-concept experiments
5. Establishment of methods for installing and maintaining sensors on measurement targets
6. Efforts toward lowering the price of heat-resistant coated fibers

HEAT-RESISTANT COATED FIBERS

Optical fibers are usually made of thin quartz glass with outer diameters of about 125 μm, making them very fragile. For this reason, they usually have a protective resin coating. However, resin coatings degrade at temperatures exceeding 350°C, making them unsuitable for applications in high-temperature environments. Metal-coated optical fibers are commercially available for high-temperature measurement applications. However, those are treated as a special fiber, and thus they are expensive. Furthermore, micro-bends due to differences in thermal expansion coefficients between metal and glass make attenuation as large as 10 dB/km, compared with just 0.5 dB/km for standard optical fibers. Table 1 shows the differences in heat-resistance temperatures for various commercially available optical fibers with different coatings.

Above, we described how heat-resistance temperatures depend on the coating, and we discussed the necessity of selecting a coating type according to the assumed temperature range. Although metal-coated fibers are presently a candidate for the high-temperature measurements we hope to realize, we look forward to future technological innovations, including attenuation improvements and reduced cost.

**Table 1 Differences in heat resistance temperature by coating**

<table>
<thead>
<tr>
<th>Coating type</th>
<th>Heat-resistance temperature</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV-curable resin</td>
<td>to 85°C</td>
<td>General purpose, inexpensive</td>
</tr>
<tr>
<td>Polyimide resin</td>
<td>to 300°C</td>
<td>General purpose</td>
</tr>
<tr>
<td>Aluminum</td>
<td>to 400°C</td>
<td>High transmission loss</td>
</tr>
<tr>
<td>Copper</td>
<td>to 500°C</td>
<td>High transmission loss</td>
</tr>
<tr>
<td>Gold</td>
<td>to 700°C</td>
<td>High transmission loss, expensive</td>
</tr>
</tbody>
</table>

**CONCLUSION**

We presented a high-temperature measurement technique for optical fiber sensors using Brillouin scattered light and described our efforts toward realizing feasibility. This technology is highly novel in that it uses optical fiber as a high-temperature sensor. However, the glass from which optical fibers are fabricated has unique characteristics at high temperatures, such as structural relaxation and changes in physical properties. It is thus necessary to evaluate the reliability of sensors over long-term use. We will continue to work toward achieving our goal of clarifying the performance of distributed optical fiber temperature sensors using Brillouin light scattering and factors that affect its performance, and we will continue activities toward realizing practical applications.

**REFERENCES**


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