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ブリルアン光相関領域解析法による単一光ファイバを用いた広温度レンジ分布測定

Wide Temperature Range Distribution Measurement Using Single Optical Fiber by Brillouin Optical Correlation Domain Analysis

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1. Introduction

The measurement of physical quantities using optical fibers has been steadily expanding its application worldwide, and R&D activities for the construction of the so-called "Fiber Optic Nerve Systems for Materials and Structures that can Feel Pain" have been actively conducted[1-6]. Under these circumstances, various methods have been proposed for distribution measurement using optical fibers. For example, Brillouin Optical Time-Domain Reflectometry (BOTDR) [7-12], Brillouin Optical Time-Domain Analysis; BOTDA) [13-16], Brillouin Optical Correlation Domain Reflectometry (BOCDR) [17-22], etc. In addition to BOCDR, we have developed Brillouin Optical Correlation Domain Analysis [23-29]. In BOCDA, strong induced Brillouin scattering is generated locally at an arbitrary position in an optical fiber by frequency modulation of the light source. The induced Brillouin scattering from that position is measured. BOCDA selectively measures only the induced Brillouin scattered light from that position and thus has features such as good signal-to-noise ratio (S/N), high speed, high spatial resolution, and random accessibility.

BOCDA has been used to measure temperatures in various temperature ranges. However, most of the measurements have been made only in the low-temperature region for low temperatures or only in the high-temperature region for high temperatures. And measurements over a wide temperature range from low to high temperature with room temperature in between have not been reported. In this paper, we report the results of actual distribution measurement and random-access function using a single optical fiber over a wide temperature range of approximately 400°C from low to high temperatures, including -196°C (liquid nitrogen temperature), 25°C (room temperature), and 200°C (high temperature) in an electric furnace, using BOCDA. The results of simultaneous measurements of three points in each temperature range by pseudo-simultaneous multi-point measurements are also shown below. The results show that BOCDA can be used for applications such as anomaly detection using a single optical fiber over a wide temperature range from low to high temperatures.

2. Configuration of BOCDA

2.1. System configuration

Figure 2 shows an overview of the BOCDA used in this experiment [24]. A commonly available 1550-nm band DFB laser is used as the light source, and the LD light is optically frequency modulated by applying a sinusoidal variation to the injection current of the DFB laser. The optical frequency modulated LD light is bifurcated by an optical coupler, and one is used as the probe light and the other as the pump light.

The probe light is shifted to the lower frequency side by about 11 GHz, which corresponds to Brillouin frequency shift, using an optical frequency shifter. Then, the frequency-shifted LD light is injected into the sensing fiber via an optical isolator. On the other hand, the pump light is chopped using an optical switch. The chopping timing is synchronized with the reference signal input to the lock-in amplifier described below. Finally, the chopped pump light is amplified by the optical amplifier and injected into the optical fiber under test (FUT) via the optical circulator.

The probe light, which is gained by induced Brillouin scattering, is converted into an electrical signal by the light-receiving circuit via an optical isolator, then passed through an electrical RF switch and synchronously detected by a lock-in amplifier to detect the peak frequency by spectral analysis. The electrical RF switch extracts only the desired scattered light from multiple induced Brillouin scattering generation positions in the sensing fiber, thus extending the measurement distance.

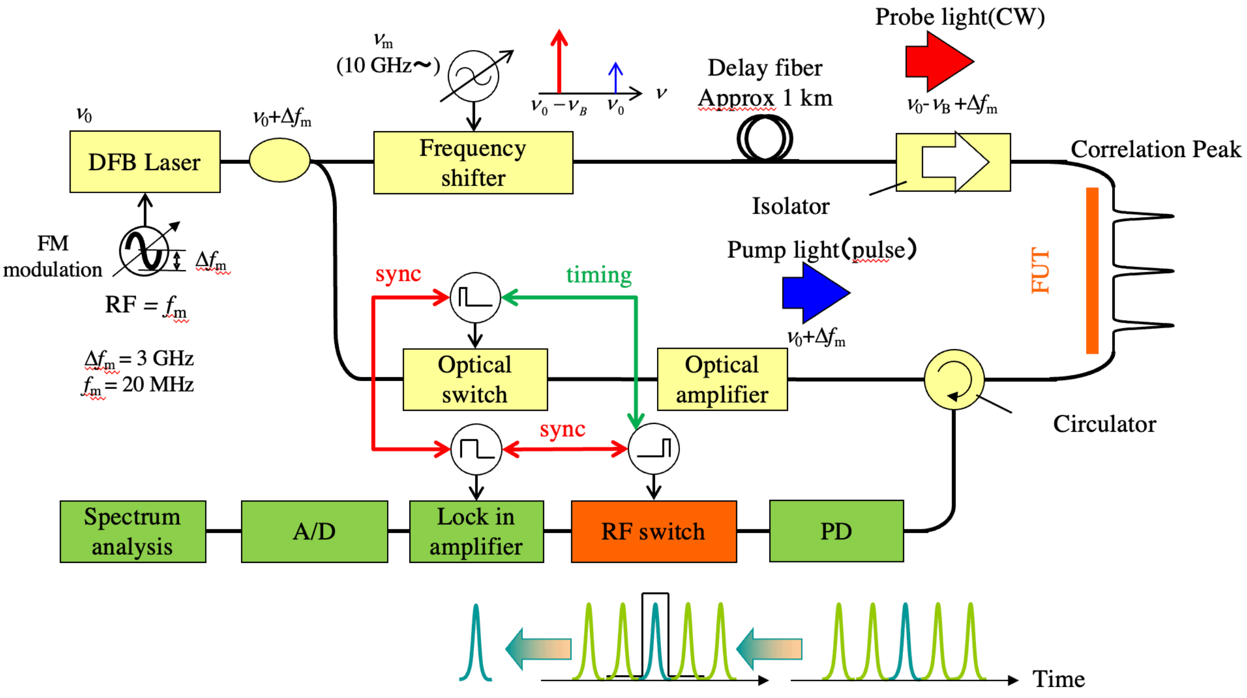

Figure 2. Schematic view of the BOCDA

2.2. pseudo-simultaneous multi-point measurement using the random-access function

In BOCDA, the measurement points on the FUT are determined by the FM modulation frequency of the LD light so that the measurement points are changed immediately when the FM modulation frequency is changed electrically. Since the speed of this change depends on the frequency switching of the electrical signal source used for FM modulation, it can be switched at a rate of less than msec. This feature is called the random-access function.

Using the random-access function, for example, by selecting several points on the FUT that are to be measured in particular and switching the FM modulation frequency for those several points at high speed, it appears as if the several points are being measured simultaneously. This function is called pseudo-simultaneous multi-point measurement.

3. Experiments and results

3.1 Measurement System

Figure 3 shows the measurement system used in this study. The main area is at room temperature (25°C), and the low-temperature (-196°C) and high-temperature (200°C) areas are included. The total length of the optical fiber under test is 127 m, and from the starting point, the room temperature region (34.5 m), low-temperature region (11.5 m), room temperature region (32 m), high-temperature region (11 m), and room temperature region (36 m).

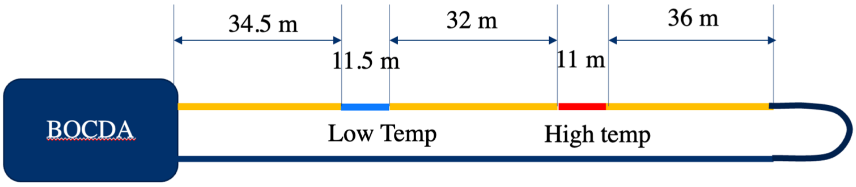

Figure 3. Temperature distribution measurement system used in the experiment

3.2 Distribution Measurement

Figures 4-5 show the distribution measurement results for the FUT placed in a room at room temperature (25°C), with a low-temperature area (liquid nitrogen tank, -196°C) and a high-temperature area (electric furnace, 200°C) at two locations. Figure 4 shows a spatial resolution of 1 m and a measurement time of 102 msec for one point in the distribution measurement. Figure 5 shows a spatial resolution of 5 cm and a measurement time of 12 msec for one point in the distribution measurement.

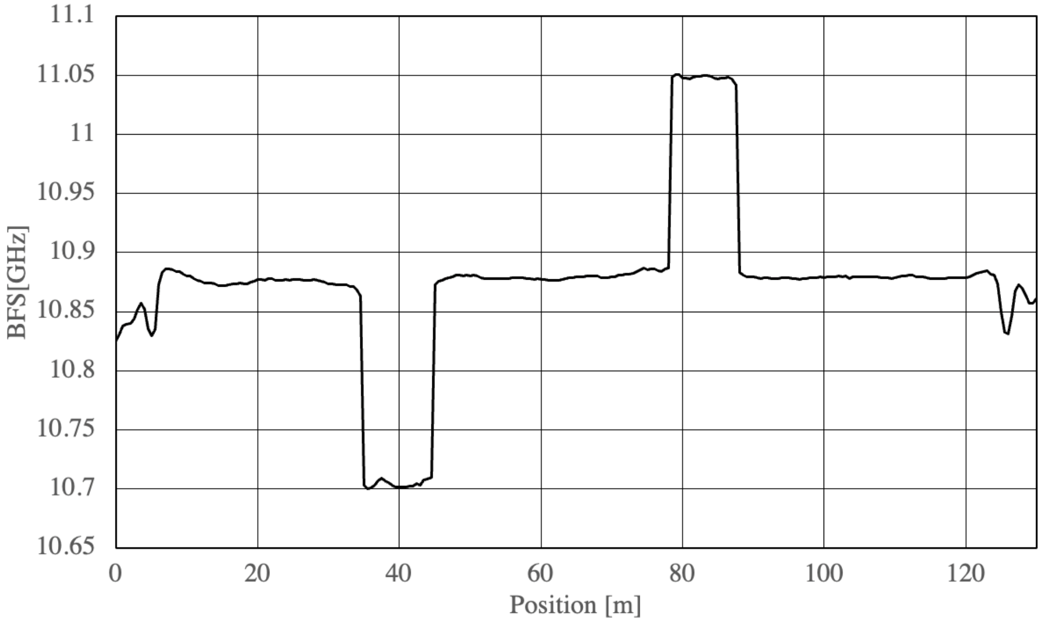

Figure 4. Results of distribution measurement including high and low-temperature areas (set spatial resolution 1 m)

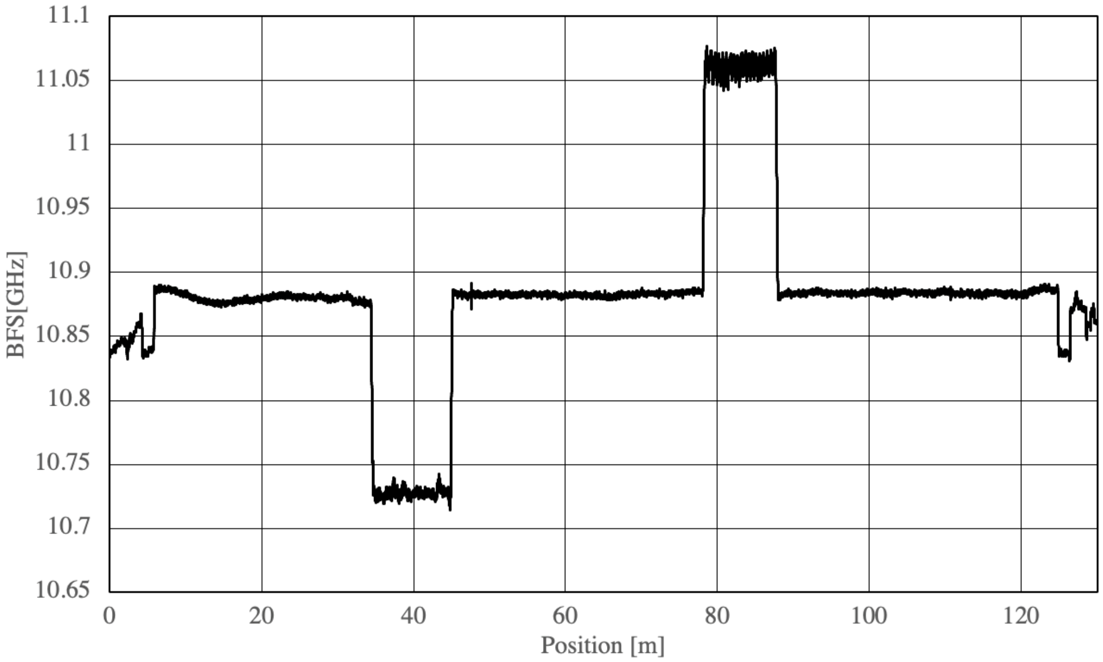

Figure 5. Result of distribution measurement including high and low-temperature areas (set spatial resolution 5 cm)

3.3. Pseudo-Simultaneous 3-point Measurement

Figures 6-7 show the results of pseudo-simultaneous 3-point measurement using the random-access function. Figure 6 and Figure 7 have a set spatial resolution of 1 m and 5 cm, respectively.

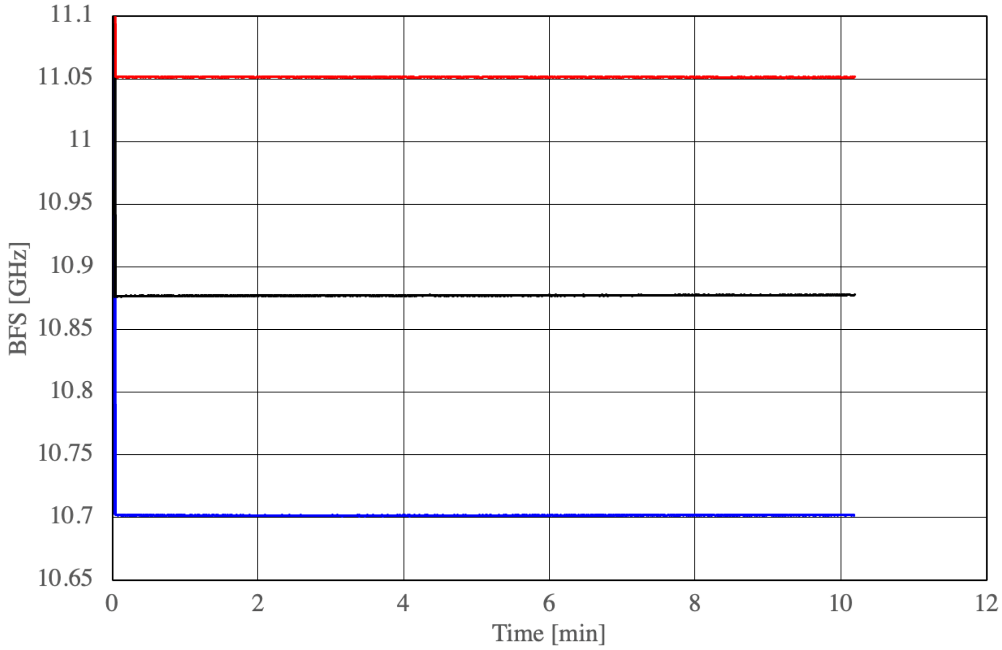

Figure 6. Results of pseudo-simultaneous 3-point measurements (Spatial resolution 1 m, the red line is high-temperature, the black line is room temperature, and the blue line is low-temperature)

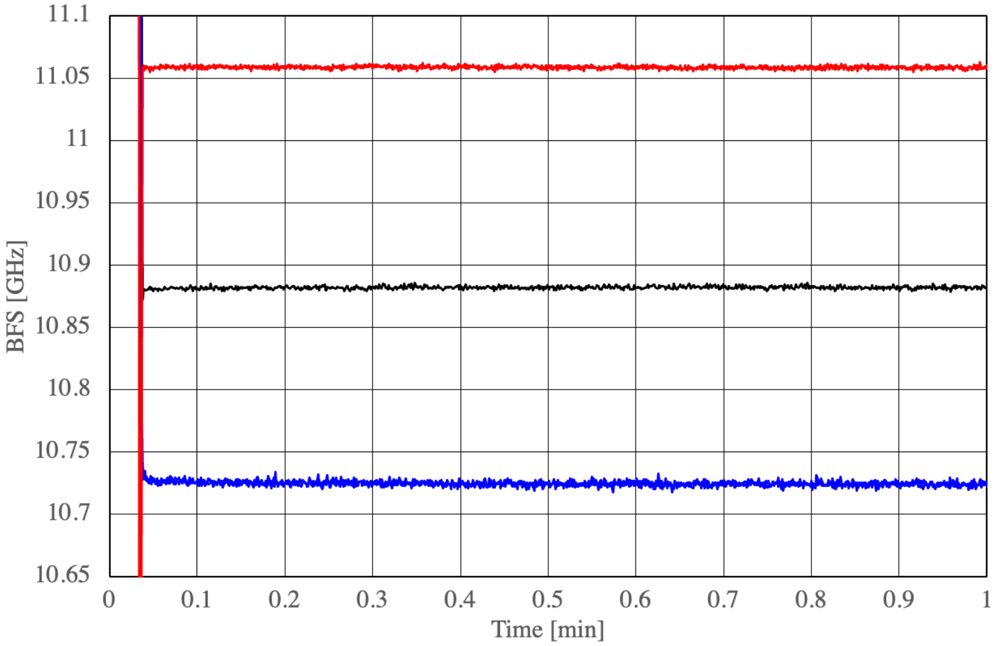

Figure 7. Results of pseudo-simultaneous 3-point measurements (Spatial resolution 5 cm, the red line is high-temperature, the black line is room temperature, and the blue line is low-temperature)

Figure 8 shows some of the measurement results in Figure 6 in detail in terms of time. The graph shows the principle of pseudo-simultaneous multi-point measurement, i.e., the measurement points are switched at high speed every 0.1 sec (102 msec) to measure multiple 3 points in a short time.

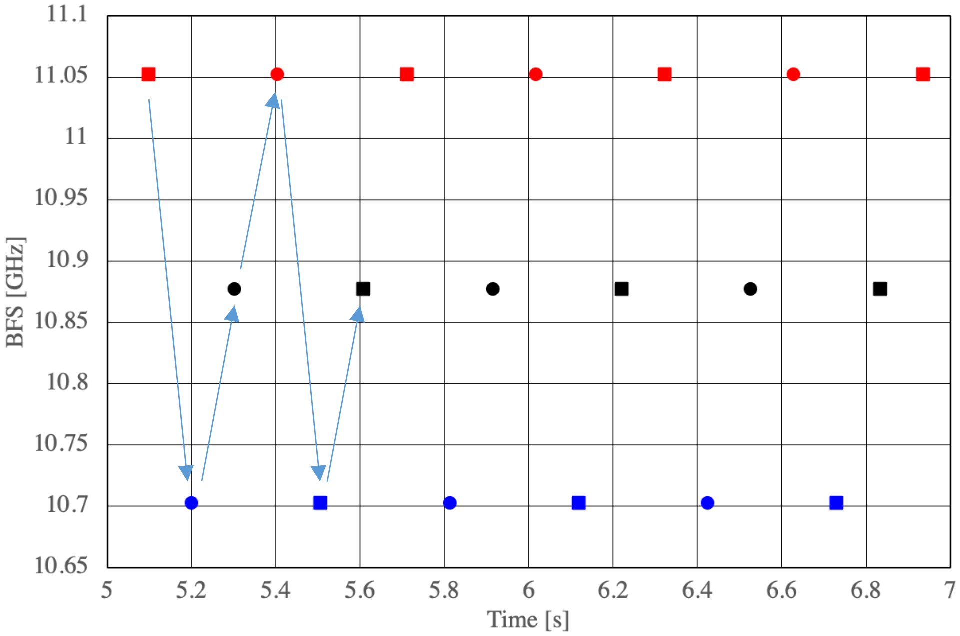

Figure 8. Detailed results of pseudo-simultaneous 3-point measurements (spatial resolution 1 m)

4. Discussion

From the experimental results in Chapter 3, it was demonstrated that distribution measurement and pseudo-simultaneous 3-point measurement could be performed with a single optical fiber (SMF) and a single device (BOCDA) over a wide temperature range of approximately 400°C, including about -200°C in the low-temperature range, 25°C in the room temperature range, and approximately 200°C in the high-temperature range. This indicates that distributed temperature sensing using BOCDA can be utilized for full-area temperature monitoring and constant temperature monitoring even when the environment to be measured includes both low and high-temperature areas. In addition, these methods allow temperature anomalies to be detected over a wide range of both low and high temperatures.

Until now, temperatures have been measured only in the high-temperature region or only in the low-temperature region, but these results suggest that temperature monitoring using optical fiber can be applied to a broader range of areas.

5. Summary

In this paper, the Brillouin Optical Correlation Domain Distribution Analysis (BOCDA) method was used to measure the actual distribution of an object in a wide temperature range of approximately 400°C from low to high temperatures, including the low-temperature range (liquid nitrogen temperature -196°C), room temperature range (25°C), and high-temperature range (electric furnace 200°C), using a single optical fiber. And we show the results of simultaneous measurement of three points in each temperature range using a pseudo-simultaneous multi-point measurement technique with a random-access function. The results show that BOCDA can be used for anomaly detection and other applications using a single optical fiber over a wide temperature range from low to high temperatures.

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