A system for measuring temperature and strain separately by BOTDR and OTDR

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ABSTRACT

Brillouin optical time domain reflectometer (BOTDR) using microwave heterodyne detection is able to measure the longitudinal strain distribution along an optical fiber with high accuracy and high stability, and is thus regarded as an effective tool for structural monitoring. However, the frequency shift of Brillouin scattered light varies in proportion to the fiber’s temperature as well as to the strain applied to it, and thus the measured Brillouin frequency shift simultaneously includes strain and temperature information. By combining BOTDR with OTDR, we propose a method whereby it is possible to make precise separate measurements of the temperature distribution and strain distribution along an optical fiber.

This method involves making simultaneous measurements of an optical fiber’s Brillouin scattering distribution and Rayleigh scattering distribution (loss distribution). The net change in the Brillouin scattering light power is then determined using the Rayleigh scattered light, which does not depend on temperature or strain. In this way, it is possible to accurately separate the temperature and strain effects by solving a simultaneous equation related to Brillouin frequency shift and Brillouin scattering light power. Since the measurement of the loss distribution by OTDR is affected little by polarization noise and fading noise, the net fluctuation of the Brillouin scattered light power can be determined with greater accuracy.

We have used this method to measure temperature and strain distributions with a spatial resolution of 1 m. The strain measurements have an accuracy of ±50 με, and the temperature measurements have an accuracy of ±5°C.

Keywords: Brillouin scattering, optical fiber sensor, strain, temperature, distributed sensor

1. INTRODUCTION

The biggest advantage of distributed strain sensors using Brillouin scattering is that strain can easily be measured at a large number of points (several thousand or more) simply by running an optical fiber to each location where strain measurements are to be made. Attention has also been focused on the applicability of these sensors to structural monitoring. However, since the frequency shift of Brillouin scattering is proportional to temperature as well as to the strain applied to the optical fiber, it is impossible to separate the strain and temperature by only measuring the Brillouin frequency shift. To make separate strain and temperature measurements, the principle candidates currently being studied are a technique wherein the Landau Placzek Ratio method is used in conjunction with an interference filter method to detect the power fluctuation of the Brillouin scattered light and the fluctuation of the Brillouin frequency shift, allowing the temperature and strain to be measured separately, and a technique in which separate measurements are made of the variation of Brillouin scattered light power with temperature or strain and the variation of Brillouin frequency shift with temperature or strain, and then the temperature and strain components are separated by solving a simultaneous equation. By the report until now, When the BOTDR technique is used to separate the temperature and strain based on single-ended measurements of a sensor fiber, the achievable limits with a resolution of 1 m are a strain accuracy of ±260 με and a temperature accuracy of ±1°C. For a wide variety of fields, such as structural monitoring, there is consequently a need for a measurement technique that has better accuracy and stability, and is more practical for use in the field.

To address this need, we propose a measurement system that combines the use of BOTDR and OTDR. This system is basically configured as follows: 1) The power of the Brillouin scattered light is measured with an accuracy of ±0.05 dB
by using BOTDR with microwave heterodyne detection.\(^{(1)}\) OTDR is performed with a low coherent light source to measure the Rayleigh scattered light power, which is affected little by polarization noise or fading noise, thereby accurately compensating for fiber losses.\(^{(2)}\) The Brillouin backscattered light is then corrected according to the Brillouin spectrum width.\(^{(3)}\) Finally, the temperature and strain are separated by solving a simultaneous equation.

In tests with a spatial resolution of 1 m, we have achieved a strain measurement accuracy of \(\pm 50 \mu \varepsilon\) and a temperature measurement accuracy of \(\pm 5^\circ C\). This paper discusses the implementation and performance of the measurement system.

2. PRINCIPLE

When an optical pulse is launched into an optical fiber, some backscattered signals come back to the input end. There are three main types of scattering — Rayleigh scattering, Brillouin scattering and Raman scattering — which are caused by different scattering mechanisms.

Rayleigh scattering is caused by density fluctuations in the glass (silica) — i.e., refractive index fluctuations — and is not associated with any shifts in the wavelength.

Brillouin scattered light is caused by non-linear interaction between the incident light and phonons that are thermally excited within the light propagation medium. This scattered light is shifted in frequency by a Brillouin frequency shift of \(V_b\) and propagates in the opposite direction (backwards) relative to the incident light. The Brillouin frequency shift \(V_b\) is given by the following formula:

\[
V_b = 2nV_o/\lambda
\]

where \(n\) is the group refractive index, \(V_o\) is the acoustic velocity, and \(\lambda\) is the wavelength of the incident light.

Using the temporal sampling measurement technique by OTDR and a frequency spectrum measuring technique, the Brillouin backscattered light power at a specific frequency can be measured as a distribution along of the fiber. As Figure 1 shows, an approximated curve is determined from the Brillouin spectrum, and the Brillouin frequency shift \((V_b)\) and the Brillouin scattered light power \((P_b)\) are determined from this approximated curve.

![Brillouin spectrum](attachment://brillouin_spectrum.png)

*Figure 1: Brillouin spectrum (a) reference conditions (b) after temperature change was applied, using a 10ns (1m) pulse.*

The change of Brillouin frequency shift \(\delta V_b\) and the change of Brillouin scattering light power \(\delta P_b/P_b\) are expressed in terms of the strain \(\varepsilon\) and temperature \(T\) as \(V_b(\varepsilon, T)\) and \(P_b(\varepsilon, T)\), and satisfy the following simultaneous equations:

\[
\delta V_b(\varepsilon, T) = (\partial V_b/\partial \varepsilon) \cdot \delta \varepsilon + (\partial V_b/\partial T) \cdot \delta T
\]

\[
\frac{\delta P_b}{P_b} (\varepsilon, T) = \left( \frac{\partial P_b}{P_b} / \partial \varepsilon \right) \cdot \delta \varepsilon + \left( \frac{\partial P_b}{P_b} / \partial T \right) \cdot \delta T
\]
By solving the simultaneous equations (2) and (3) for the distance \( z \) along the optical fiber, it is possible to obtain the distribution data for the strain and temperature of the optical fiber.

3. SIMULTANEOUS MEASUREMENT OF STRAIN AND TEMPERATURE

When the loss of the fiber is uniform, the Rayleigh scattered light power \( P_r(z) \) and the Brillouin scattered light power \( P_b(z) \) are expressed as shown in Equations (4) and (5).

\[
P_r(z) = P_p \times \eta_r(z) \times \exp(-2\alpha z) \tag{4}
\]

\[
P_b(z) = P_p \times \eta_b(z) \times \exp(-2\alpha z) \tag{5}
\]

- \( P_p \): Input pulse power
- \( \eta_r(z) \): Rayleigh backscattering coefficient
- \( \eta_b(z) \): Brillouin backscattering coefficient
- \( \alpha \): Attenuation coefficient of fiber

Here, it is assumed that the attenuation coefficient of the fiber at the input pulse wavelength are the same as that at the Brillouin shift wavelength.

Since the effects of strain and temperature applied to the fiber are negligible in the \( P_r(z) \) distribution measured by OTDR, it is possible to determine \( \delta P_b(z) \) by making measurements of both OTDR and BOTDR. However, since the mechanism of the scattered light detected by OTDR and BOTDR is different, the absolute power of these scattered light is different. Therefore, the following level correction is performed in order to determine \( \delta P_b(z) \) by compensating the scattered light power in a reference fiber section (where the strain and temperature are already known).

\[
Cr_b = \frac{P_b(ref)}{P_r(ref)} \tag{6}
\]

\[
\frac{\delta P_b(z)}{P_r(z) \times Cr_b} = \frac{(P_b(z) - P_r(z) \times Cr_b)}{P_r(z) \times Cr_b} \tag{7}
\]

- \( P_r(ref) \): Rayleigh scattered light power in the reference section
- \( P_b(ref) \): Brillouin scattered light power in the reference section
- \( C_{rb} \): Scattered light power ratio at reference section
- \( P_r(z) \): Rayleigh scattered light power measured by OTDR
- \( P_b(z) \): Brillouin scattered light power measured by BOTDR

\( \delta \nu(z) \) obtained by BOTDR and \( \delta P_b(z) \) obtained by Equation (7) are substituted into Equations (2) and (3), and \( \delta \varepsilon(z) \) and \( \delta T(z) \) are obtained by solving the simultaneous equation. The strain \( \varepsilon(ref) \) and temperature \( T(ref) \) in the reference section are used to give Equations (8) and (9).

\[
\varepsilon(z) = \varepsilon(ref) + \delta \varepsilon(z) \tag{8}
\]

\[
T(z) = T(ref) + \delta T(z) \tag{9}
\]

4. MEASUREMENT SYSTEM

Figure 2 shows the configuration of the proposed measurement system. Optical pulses output from the BOTDR and OTDR are launched into an optical fiber via a channel selector. The fibers that connect them to the channel selector are kept to the same length to avoid any offsets in the measurement origins of the BOTDR and OTDR. The BOTDR and OTDR and the channel selector are made by Ando Electric Co., Ltd. (AQ8603, AQ7250, AQ3540), and were controlled by a PC. The PC also collects and processes the measurement data, and displays the results. Each measuring apparatus uses wavelength of 1.55 μm, and the pulse output power of the BOTDR and OTDR is +25 dBm and +17 dBm respectively. A pulse width of 10 ns was used for both. A single UV coated SM fiber was used for the sensor, and the strain and temperature distributions were separately applied to this fiber. A reference part of known strain and temperature was provided at the near end of the optical fiber. The loss distribution in this optical fiber was measured by
the OTDR, and the BOTDR measured the Brillouin backscattered light power distribution (which depends on the strain and temperature) and determined the Brillouin frequency shift distribution.

Based on the procedure outlined in Section 3, we solved the simultaneous equation based on the $\delta \nu_b(\varepsilon,T)$ and $\delta P_b(\varepsilon,T)$ obtained from the BOTDR and the $P_r(z)$ obtained from the OTDR.

This measurement system was constructed from ordinary catalog products, and was considered its potential application to practical use in the field. Table 1 shows the specifications of the equipment used in this measuring system. The configuration of the BOTDR is shown in Figure 3. This uses a highly stable and accurate measurement method based on microwave heterodyne detection and tunable electric oscillator.  

![Figure 2 Experimental setup for simultaneous strain and temperature measurement](image)

| Table 1: Specification of each measuring instrument |
|---------------------------------|---------------------------------|
| **BOTDR (AQ8603)**            | **OTDR (AQ7250 + AQ7255)** |
| Wavelength                     | 1.55 µm                         | 1.31/1.55 µm                   |
| Distance range                 | 1, 2, 5, 10, 20, 40, 80 km      | 2, 5, 10, 20, 40, 80, 160, 240 km |
| Pulse width                    | 10, 20, 50, 100, 200 ns         | 10, 20, 100, 200, 500 ns, 1, 4, 10, 20 µs |
| Dynamic range                  | 2dB@10ns ($\pm 0.004\% (2\sigma)$) | 10dB@10ns (SNR = 1) (typ.) |
| Strain measurement range       | $-1.5$ to $+1.5\%$ (typ.)       | $-$                           |
| Strain measurement accuracy    | $\pm 0.004\% (2\sigma)@10$ns    | $-$                           |

![Optical channel selector (AQ3540)]

<table>
<thead>
<tr>
<th><strong>Optical channel selector (AQ3540)</strong></th>
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<tbody>
<tr>
<td>Wavelength</td>
</tr>
<tr>
<td>Repeatability</td>
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<td>Return loss</td>
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<td>Insertion loss</td>
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5. MEASUREMENT OF STRAIN AND TEMPERATURE COEFFICIENTS

Since the proportionality coefficient differs slightly depending on the type of optical fiber being used and the coating material, we measured each of the coefficients in Equations (2) and (3). A UV coated SM fiber was used as the optical fiber. Strain was applied by pulling a 15 m section, and its temperature was varied by placing a (different) 15 m section of the fiber in a temperature-controlled chamber. Measurements were made of the relationship between the Brillouin frequency shift $\nu_b$, strain $\varepsilon$ and temperature $T$, and the relationship between the Brillouin scattered light power $P_b$, strain $\varepsilon$ and temperature $T$. We thereby obtained the following results (see Figures 4 and 5):

$$\frac{\partial \nu_b}{\partial \varepsilon} = 0.0506 \text{MHz/\mu e} \quad \frac{\partial \nu_b}{\partial T} = 1.0773 \text{MHz/}^\circ\text{C}$$

$$\frac{\partial P_b}{P_b} \frac{\partial \varepsilon}{\varepsilon} = -7.0 \times 10^{-6} \text{/\mu e} \quad \frac{\partial P_b}{P_b} \frac{\partial T}{T} = 0.0022/\text{C}$$

(10)

These results are almost the same as those given in earlier reports.\(^\text{(6,7)}\)

Since the photo detected part of the BOTDR has a slight frequency characteristic, we corrected the results from this frequency characteristic when determining $\frac{\partial \nu_b}{\partial \varepsilon}$ and $\frac{\partial P_b}{\partial T}$. The results in Figure 5 exhibit some degree of variation. This is thought to have arisen from measurement errors in the BOTDR due to the measurement of very small power fluctuations.

![Figure 4 Brillouin frequency shift versus (a) strain and (b) temperature.](image-url)
Figure 6 Brillouin power versus (a) strain and (b) temperature.

6. MEASUREMENT RESULTS

Figure 6 shows the test system used to make separate measurements of temperature and strain. Measurements were made on a 530 m length of UV coated SM fiber, of which 105 m at the near end were kept at constant strain and temperature as a reference section. $P_r(z)$ and $P_b(z)$ in a reference section (where the strain and temperature are already known) are defined as $P_r(\text{ref})$ and $P_b(\text{ref})$. A fiber is connected at the 105 m point, and its connection loss is approximately 0.6 dB. Since the same wavelength band is used by the BOTDR and OTDR, they both obtained the same results. Also, a fusion splice was provided at the 470 m point, where a slight loss was incurred.

To clarify the change of distribution caused by the intentionally applied strain and temperature, the section before and after the intentionally strained section and the temperature-controlled chamber were made strain-free. In the strained section, the fiber was uniformly pulled over a 15 m length. The section where a different temperature was applied was placed in a strain-free condition into a temperature-controlled chamber. The temperature of this section was controlled over the range 0—60°C. Section where temperature control was not performed were all placed under room temperature. A pulse width of 10 ns was used, and the spatial resolution was 1 m.

Figure 7 shows the backscattered signal measured by the BOTDR and OTDR (Here, traces are represented as a logarithmic values). Since they detect different types of scattered light, the two scattered light powers at the near end are different (34.75 dB for OTDR, and 42.2 dB for BOTDR). However, the loss distributions and Brillouin scattered light power distributions exhibit same slope. In the Brillouin scattered light power distribution, it can be seen that changes occur in parts where temperature and strain were applied (In Figure 7, A = strain, B = temperature.) In the OTDR trace, a Fresnel reflection was also measured at the 105 m point, but no Fresnel reflection was observed in the BOTDR

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Reference section
(strain free, temperature 28°C)

SMF 105m

Connector (0.6 dB)

Fiber end (530m)

Strain (pulling) +2000με (435m-450m)

SMF 315m-drum (About ±200με of strain is applied)

15m

20m

30m

15m

No reflection

Chamber : 0°C

Strain-free

15m

30m

15m

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because heterodyne detection was performed in a frequency band separated by over 10 GHz from the Rayleigh scattered light.

![Figure 7 Distributed backscattered power measurements of the test system shown in Figure 6.](image)

Figure 7 Distributed backscattered power measurements of the test system shown in Figure 6.

Figure 8 shows the strain distribution obtained by converting the $\delta V_b$ distribution measured by the BOTDR into strain values. In this example, measurements were made with a strain of 2000 $\mu$e applied in the region of 440 m and a temperature of 0°C applied in the region of 500 m. Normally it would be impossible to separate the applied strain and temperature, and they would be measured simultaneously. The temperature difference between the part where the temperature was applied (the chamber part) and room temperature was 28°C. Here, since 1°C is equivalent to a strain change of 20 $\mu$e from the results of $\partial V_b / \partial e$ and $\partial V_b / \partial T$, a temperature change of 28°C corresponds to a strain change of $-560 \mu$e, which matches the actual condition very well.

![Figure 8 strain distribution obtained by converting the $\delta V_b$ into strain.](image)

Figure 8 strain distribution obtained by converting the $\delta V_b$ into strain.

By solving simultaneous equations for the strain and temperature respectively, we obtained the separated data shown in Figure 9. As shown by A and B in Figures 9(a) and 9(b), an accuracy of 2000 $\mu$e $\pm 50 \mu$e is obtained for the strain in the section where strain is applied, and 0°C $\pm 5^\circ$C for the temperature in the section where temperature is applied. The strain component disappears in the section where the temperature is applied, and it can be seen that the temperature remains at room temperature in the section where the strain is applied. Dead zones occurred at the location of the Fresnel reflections in the OTDR results, and in the region up to about 8 m (for a 10 ns pulse width) from the connector. In Figure 9(a) and Figure 9(b), whisker-shaped spikes can be seen before and after the section where strain was applied (A). This is explained as follows. When different strain or temperature distributions exist within a 1 m section, the
Brillouin spectrum width may become wider, resulting in two peaks. Figure 10 shows the actual measurements of changes in the spectrum at a boundary point.

In this figure, (1) is the condition where no strain at all is applied to the 1 m section, (2) is the condition where strain is applied to part of the 1 m section, and (3) is similarly the condition where strain is applied to part of the 1 m section. (4) is the condition where a uniform strain is applied over almost the entire 1 m section. The top part of the figure also shows the FWHM bandwidth obtained when approximate curves are drawn for each BOTDR spectrum. On comparing (1) and (2), it can be seen that the peak level ($P_b$) decreases due to spectral broadening. Furthermore, in (3) the FWHM bandwidth becomes 50 MHz larger, and the peak level decreases 28.8%. This change of peak level results in large errors when separating temperature and strain. The presence of different strains within a length of fiber comparable to the spatial resolution thus leads to the generation of two peaks. As a result, the energy of the Brillouin scattered light is split into two parts, causing the peak level to decrease and making separation less effective. The Brillouin scattered light power $P_b(z)$ obtained by BOTDR is the peak power of the spectrum, and does not consider the case where two peaks are present. To ignore these error factors, the results are corrected with the relationship between spectral broadening and peak level decrease. Figure 11 shows the separated data that has been corrected using the above relationship. By performing this correction, we were able to obtain correct values by eliminating the errors caused by the whisker-shaped spikes at the boundary points of the strain and temperature change.
Figure 12 shows the results obtained when the temperature of the temperature-controlled section was varied from 0°C to 60°C. The data in this figure was obtained after performing measures to separate the strain and temperature by calculation, and has a spatial resolution of 1 m. Although favorable results was obtained at 0°C and 15°C, the variation became larger as the temperature increased. This is assumed to be because the measurements were made before the fiber temperature had become uniform. The measured temperature accuracy in this temperature-controlled section was about ±5°C.

Figure 12: Temperature measurements for oven temperatures of 0°C, 15°C, 30°C, 45°C and 65°C

To confirm that this technique is also applicable to long distance fibers, we performed a similar experiment with the configuration shown in Figure 13. For this experiment we used a 4 km nylon-coated SM fiber, which was inserted after 105 m of SM fiber in the configuration of Figure 5. Since the 4 km fiber was of a different type (different manufacturer) to the fiber used in Figure 5, the end section of the 105 m fiber were taken as the reference points. These fibers were connected, and beyond 4 km the strain and temperature were individually applied.

Figure 14 shows the distribution trace over the entire 4.5 km. Figure 15 shows an enlarged trace of the section connected beyond 4 km. In the strain distribution of the optical fiber beyond 4 km, only a strain of 3000 με was measured (with an accuracy of ±200 με), and there was almost no strain in section where a temperature change was applied. The temperature was found to be distributed around 28°C, and we were able to confirm changes of temperature with an accuracy of ±10°C in section held at 0°C. In a long distance fiber, it is necessary to have techniques for measuring the Brillouin scattered light power more stably, but with our current set-up we were still able to confirm that this technique is effective in principle.
7. CONCLUSION

We have proposed a measuring system that combines BOTDR and OTDR in order to separately measure the strain and temperature applied to a sensor optical fiber. We have also discussed a method for correcting power variations in the reverse Brillouin scattered light that arise at the boundary points of the strain and temperature change. In tests we have achieved a strain measurement accuracy of ±50 με and a temperature measurement accuracy of ±5°C, both with a spatial resolution of 1 m. Furthermore, by providing a number of reference points, we have established that it is possible
to separate temperature and strain even in configurations where different types of fibers are connected together, and we have demonstrated the applicability of this technique to measurements in the field. Since this proposed scheme uses a measurement system with a simple configuration that is less expensive than conventional configurations, it is suitable for application to a diverse range of optical fiber sensing fields.

8. REFERENCES


