Distributed Optical Fiber Sensing Technology for Social Infrastructure Monitoring

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Aging of the social infrastructure developed during the high economic growth period is now a major problem, and construction of monitoring systems has become an urgent task. In particular, health-monitoring tests using various sensors are being conducted to prevent collapse of bridges and tunnels due to structural degradation[1]. Additionally, in wake of the 2011 Great East Japan Earthquake, high importance has been placed on real-time monitoring technology for disaster prediction.

This article gives an overview of distributed optical fiber sensing and describes OKI's own work in applying distributed optical fiber sensing technology to social infrastructure monitoring.

Features and Market Trend of Fiber Optic Sensing

Optical fibers are widely used as a transmission medium in optical communication technology playing an important role in the information infrastructure. On another front, sensing technology that uses optical fibers as a sensor medium also developed in parallel with optical fiber communication technology. Compared with electrical point sensors, optical fiber sensors have the following advantages[2].

- Thin and lightweight construction enables easy integration into structures
- Excellent durability and corrosion resistance enables long-term measurements
- Flame-proof nature of passive measurement ensures safety
- Resistance to electromagnetic induction enables stable measurements under electromagnetic noise
- Telemetering and distributed measurements are possible (several dozen km)

For these reasons, optical fiber sensors have been attracting attention for health monitoring of large structures such as high-rise buildings, bridges and tunnels as well as for use at oil refineries and other scenes where electrical sensors may not be appropriate. In turn, there is expectation for the realization of optical fiber sensor networks that will provide communication with various sensors. **Figure 1** shows an example of an optical fiber sensor network.

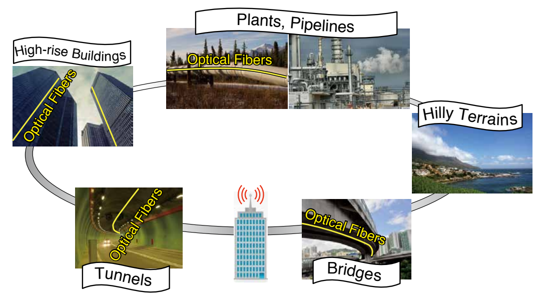


Figure 1. Optical Fiber Sensor Network

Types of Distributed Optical Fiber Sensors and Measurement Technologies

(1) Measurement Principle for Distributed Optical Fiber Sensors

Distributed optical fiber sensing is a technology that continuously measures physical quantities along an optical fiber attached to a structure. Accordingly, unlike point sensors, which can only take discrete point measurements, physical quantities of the entire object can be measured.

The optical fiber sensor developed by OKI measures the backscattered light (light scattering in the opposite direction of the incident light) that is generated when light propagates through the optical fiber and allows continuous distributed measurement along the optical fiber.

Scattered light inside an optical fiber is classified either as Rayleigh, Brillouin or Raman scattering, and each type of scattered light has different intensity, frequency and phase behavior depending on the physical quantities inside the optical fiber such as temperature, strain and pressure. Therefore, the sensor can be applied to various uses by measuring the scattered light type that matches the measurement purpose. The measurable physical quantities of the scattered light types and applications are shown in **Table 1**. Health monitoring of social infrastructures requires the measurements of strain and temperature, and from **Table 1**, it can be seen that the use of Brillouin scattering is appropriate. The Brillouin scattered light in the optical fiber occurs about 11 GHz away from the carrier frequency of the incident light. Frequency shift (Brillouin Frequency Shift: BFS) with respect to the optical fiber's internal strain and temperature are known to be 0.058 MHz/$\mu\varepsilon$ and 1.18 MHz/°C, respectively[3), 4)]. Hence, focusing on the frequency variation of the Brillouin scattered light inside the optical fiber, strain and temperature along the optical fiber direction can be measured. However, since the scattered light is very weak, ensuring the SN ratio necessary for accurate measurement requires substantial averaging process, which results in long measurement times.

Table 1. Scattered Light Types and Applications

Scattered Light Type	Measurement Target	Measurable Physical Quantities	Applications
Rayleigh Scattering	Intensity (Phase)	Loss	• Mudslides, landslides • Flooding
Brillouin Scattering	Frequency	Strain Temperature	• Mudslides, landslides • Tunnel and building strains • Equipment damage at oil refineries • Pipelines
Raman Scattering	Intensity	Temperature	• Oil tanks, pipelines • Frozen road surfaces • Building fires • Power cable temperatures

(2) Localization Technology for Distributed Optical Fiber Sensors

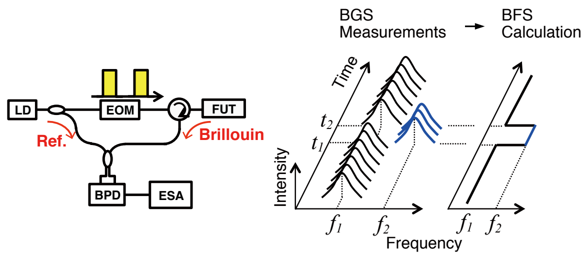
Distributed optical fiber sensors require a method to identify the position where a local change has occurred. Typical methods are OTDR (Optical Time Domain Reflectometry), OFDR (Optical Frequency Domain Reflectometry) and OCDR (Optical Correlation Domain Reflectometry). Since these methods have advantages and disadvantages with respect to each performance indicator such as measurement range, accuracy, speed and spatial resolution, it is necessary to select the appropriate method to suit the measurement target.

In the OTDR method, which is the most common of these methods, optical pulses are sent through the optical fiber and difference between the incident time and time the scattered light is detected at the optical receiver (delay time) is used to calculate position on the optical fiber. The method is widely used for loss measurements and fracture inspections inside optical fibers.

Principle and Features of BOTDR

This section explains the Brillouin OTDR (BOTDR) as the distribution sensing technology for strain and temperature[5)]. As mentioned in the previous section, strain and temperature change of an optical fiber appears as a frequency shift, BFS, of the Brillouin scattered light. Therefore, it is common practice to measure the frequency spectrum along the optical fiber. A schematic diagram of a typical BOTDR is shown in **Figure 2(a)**. BOTDR consists of a transmission unit, an optical fiber measurement unit and an optical receiving unit. A laser diode (LD) that outputs continuous wave (CW) light and an electro-optic modulator (EOM) make up the transmission unit, which generates optical pulses. At the optical fiber measurement unit, as optical pulses enters via a circulator, Brillouin scattering occurs in the fiber under test (FUT). Part of the scattered light returns to the incident side as backward Brillouin scattered light and then exits from the circulator's output port. It then enters the balanced photodiode (BPD) along with reference light from the LD. In order to measure the Brillouin gain spectrum (BGS) of the Brillouin scattered light, optical receiving unit uses heterodyne detection to convert optical frequency to an intermediate frequency in the GHz band that can be observed with electric signals. Utilizing a fast electrical spectrum analyzer (ESA), BGS is obtained every few nanoseconds. **Figure 2(b)** shows an image of an obtained BGS data. For each time (corresponds to length within the optical fiber) and frequency, the ESA measures intensity to obtain a number of BGS (**Figure 2(b)** left). From the peak frequencies of all the measured BGS, the BFS can be calculated (**Figure 2(b)** right).

Generally, the minimum spatial resolution of the BOTDR is 1m and measurement accuracy is ±50~±100 $\mu\varepsilon$, but have been improved by devising modulation and optical reception methods[6), 7)]. On the other hand, as much as ten minutes can be required for measurement, and therefore, dynamic changes such as strain cannot be observed in real-time. The measurement time is composed of the round trip time of the optical pulse, the number of averaging process and the steps of frequency sweep. The use of a faster ESA necessitates investment in larger and costlier equipment compared with conventional electrical strain sensors. This is one factor preventing the spread of optical fiber sensors.



(a) Configuration (b) Image of Obtained Data

Figure 2. Typical BOTDR Configuration and Obtained Data

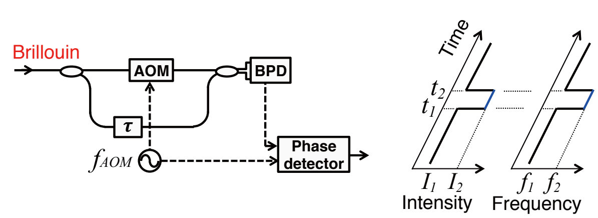
Proposal of Self-delayed Heterodyne BOTDR

OKI is working toward a fast, inexpensive BOTDR, and one proposal is the self-delayed heterodyne BOTDR (SDH-BOTDR)[8]. The SDH-BOTDR measurement method perceives BFS changes as phase changes and electrical processing unit is replaced with optical processing. Unlike conventional methods, BGS measurement process is unnecessary, and thereby speeds up measurement time. In this section, the principle of SDH-BOTDR and result of a verification test are described.

(1) Principle of SDH-BOTDR

Figure 3(a) shows the configuration of the SDH-BOTDR receiving unit. The transmission unit is identical to the BOTDR and has been omitted. With SDH-BOTDR, Brillouin scattered light from the fiber acting as the sensor is entered into the self-delayed heterodyne interferometer. In the interferometer, the entering light is split in two, and one light undergoes a frequency shift through an acousto-optical modulator (AOM). The other light is given an suitable delay time τ with an optical fiber delay line. Thus, a beat signal corresponding to a frequency shift appears at the interferometer output, and frequency changes to the interferometer input light become detectable as phase changes in the beat signal. That is, when strain or temperature change in the FUT causes a BFS in a signal, it can be detected as a phase shift in the beat signal. This enables BFS to be obtained directly without measuring the BGS, thus shortening the measurement time by a time required for a frequency sweep. Furthermore, since ESA for BGS measurement becomes unnecessary, configuration is extremely simplified, which contributes to reduction in cost. Beat signal holding the phase shift information is converted by a phase detector into an intensity signal before being changed to a frequency shift amount. **Figure 3(b)** shows the output image of a SDH-BOTDR.

In order to deal with phase information, the measurable frequency range is uniquely limited to $0\sim\pi$. Measurable range can be arbitrarily changed with delay length (time τ) in the heterodyne interferometer. **Figure 4** is a graph showing the relation between the delay length and frequency variation. When the phase change's minimum detection sensitivity is $2\pi/1000$ and maximum is π, the relation between delay length and measurement range falls within the blue shaded region of **Figure 4**. From the figure, it can be seen that longer delay length results in better minimum detection sensitivity. Therefore, the self-delayed heterodyne interferometer can be flexibly designed in accordance with the frequency variation to be observed. For example, if τ=1ns(Δl=20 cm) the measurable range of BFS obtained from **Figure 4** is 1MHz to 500MHz. This corresponds to an optical fiber's strain amount of 0.002~1% (20$\mu\varepsilon$~10mε), and shows the SDH-BOTDR to have the same sensitivity as conventional BOTDRs. Thus, higher speed can be realized without lowering the measurement sensitivity.



(a) Configuration (b) Image of Obtained Data

Figure 3. SDH-BOTDR Receiving Unit and Obtained Data

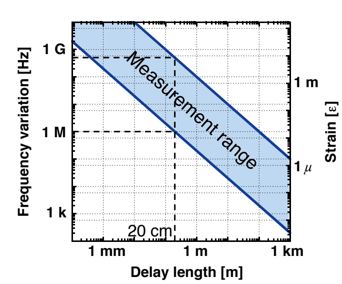
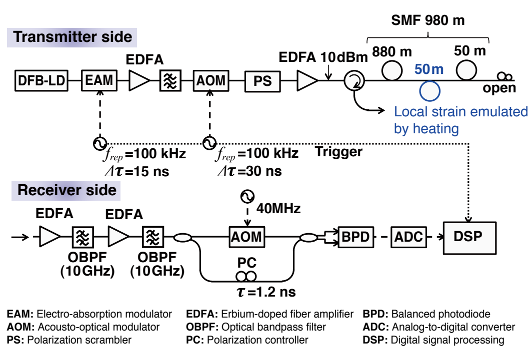


Figure 4. Relation between Delay Length and Frequency Measurement Range

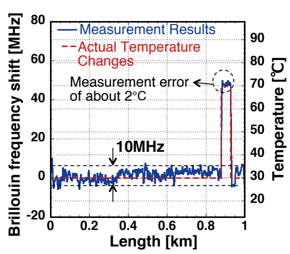
(2) SDH-BOTDR Verification Test

Figure 5(a) shows the configuration of the experimental SDH-BOTDR system. An electro-absorption modulator (EAM) and an AOM were used as EOMs in the transmission unit to generate an optical pulse with pulse width of 15ns (corresponds to spatial resolution of 1.5m) and high extinction ratio. Two erbium-doped fiber amplifiers (EDFA) amplify the optical pulse to 10dBm before it enters the FUT. Here, the polarization of the incident pulse is randomized using a polarization scrambler (PS) to reduce polarization dependency of the BGS. A 1km single mode fiber (SMF) was used for the FUT and local strain was emulated by heating the section between 880~930m. Output light from the fiber is passed through an optical bandpass filter (OBPF) and EDFA to extract only the Brillouin scattered light, and after amplification, entered into the self-delayed heterodyne interferometer. The AOM in the interferometer applies a 40MHz frequency shift and delay time of 1.2ns. The resulting beat signal is received at the BPD where it passes through an analog-to-digital converter (ADC) before phase comparison is performed with a digital signal processing (DSP) and BFS is measured. **Figure 5(b)** shows the distribution measurement result when temperature of the heated section was set to 70°C. Error in the measurement result was about 2°C, which is equivalent to the measurement accuracy of conventional BOTDRs. The time required for measurement was 40ms verifying a three-digit speed improvement over conventional methods. **Figure 5(c)** shows the measurement result when temperature was changed from 60~70°C in 2°C increments. It can be seen that linear characteristic is obtained.

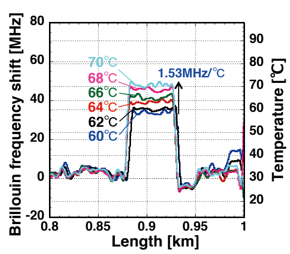
The above results indicate SDH-BOTDR can provide unprecedentedly fast measurements with sufficient accuracy, and thereby supports the validity of OKI's proposed method.



(a) Experimental SDH-BOTDR System



(b) 1km Distribution Measurement Result



(c) Relation between Temperature Change and BFS

Figure 5. SDH-BOTDR Strain Distribution Measurement

Conclusion and Future Technical Developments

Distributed optical fiber sensing, the expected technology for social infrastructure monitoring, along with the SDH-BOTDR method, a next-generation optical fiber sensing method capable high-speed measurements, were introduced. Additionally, result of a distribution measurement test conducted to verify the validity of the SDH-BOTDR method was presented and showed that 40ms distribution measurement, which is a three-digit speed improvement over conventional BOTDR methods, is possible while maintaining the same level of accuracy. Future R&D will focus on improving measurement accuracy.

Although this article has taken up the BOTDR method as an example of a distributed optical fiber sensing technology, OKI is proceeding with R&D of several other distributed sensing technologies and plans a diverse lineup of technologies to offer sensing methods that appropriately meet the needs of customers. ◆◆

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TIPS

【Glossary】

Scattering inside optical fibers

Scattering due to density fluctuations is referred to as Rayleigh scattering, scattering due to interaction between light and acoustic waves as Brillouin scattering, and scattering caused by vibration and rotation of molecules in the medium as Raman scattering.

OTDR

Technology to perform distribution measurement in optical fibers by calculating the position in the fiber from the difference between incident time and reception time of a optical pulse.

OFDR

Technology to measure phase information in a fiber by utilizing light interference. Sweeping the oscillation frequency of the incident light, distance is calculated from the beat frequency with the returning light.

OCDR

Technology to obtain correlation peak information by interference of frequency modulated light and returning light. Distance is calculated from the frequency modulation rate.

IEC

International Electrotechnical Commission