Distributed Optical Fiber Temperature Measurement

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The development of sensing technologies is rapidly expanding the IoT (Internet of Things) system market. Especially in monitoring temperatures of manufacturing lines and factories or monitoring temperatures/strains of social infrastructures such as bridges and roads over long distances/wide range in real-time raising expectations it will improve product quality and contribute to a safer, secure society. As one of the solutions to these expectations, OKI is focusing on the development of an optical fiber sensing technology. This article will explain the "SDH-BOTDR (Self-delayed Heterodyne Brillouin Optical Time Domain Reflectometry) system," an optical fiber sensing technology utilizing a high-speed optical communication technology that OKI has long worked with in the telecommunications market, and introduce case examples.

Optical Fiber Sensor Features and Applications

(1) Features of Optical Fiber Sensors

Optical fiber is widely used as a transmission medium for optical communication technology, and it serves an important role in the information infrastructure. A technology that has undergone independent development alongside the advancement of optical communication technology is the optical fiber sensing technology, which uses the optical fiber itself as a sensor head. Various physical quantities can be monitored using optical fiber sensors such as temperature, strain, vibration, and inclination. These physical quantities can be observed by measuring the intensity and properties of light. Although these physical quantities can be measured with general electric sensors, the optical fiber sensors have the following advantages[1].

- Small diameter and light weight facilitates integration into structures
- Excellent durability and corrosion resistance results in long service life
- High electromagnetic compatibility and explosion resistance, and highly reliable measurement is possible under harsh environments (-200~800°C)
- Remote distributed measurement is possible without power supply (~ dozens of km)

Among them, the distributed measurement is particularly noteworthy. A general electric sensor is said to be a point sensor, and only the place of installation is measured. On the other hand, the optical fiber sensor can continuously measure along the length of the optical fiber. This is very advantageous in temperature monitoring of manufacturing lines and plants or monitoring bridges, roads and other social infrastructures. For example, when monitoring bridges or roads, it is usually necessary to install multiple point sensors. This makes wiring complicated leading to high installation and maintenance costs. With optical fiber sensors, only a single optical fiber needs be laid out. This enables simple, flexible construction and larger the construction size, smaller the implementation cost will be.

(2) Applications of Distributed Temperature Sensors[2]

Figure1 shows areas of optical fiber sensor applications. Particularly, the following are examples of the distributed temperature sensor applications in manufacturing and disaster prevention areas.

- Early detection and control of fires in tunnels/common passages
- Work efficiency improvement through air-conditioning control in factories
- Maintenance through constant monitoring of pipelines
- Securing traceability of temperature quality in the manufacturing lines

All the application examples are areas with high demand for IoT conversion. However, since monitoring range is wide, it is difficult to realize with point sensors.

For this reason, fiber optic sensors have high affinity with smart factories and social infrastructure monitoring raising expectations for market expansion. Furthermore, technology that makes full use of big data analysis to properly obtain situational awareness and diagnose abnormalities in structures from the enormous volume of sensing data is advancing, and deployment to disaster prevention/reduction is accelerating.

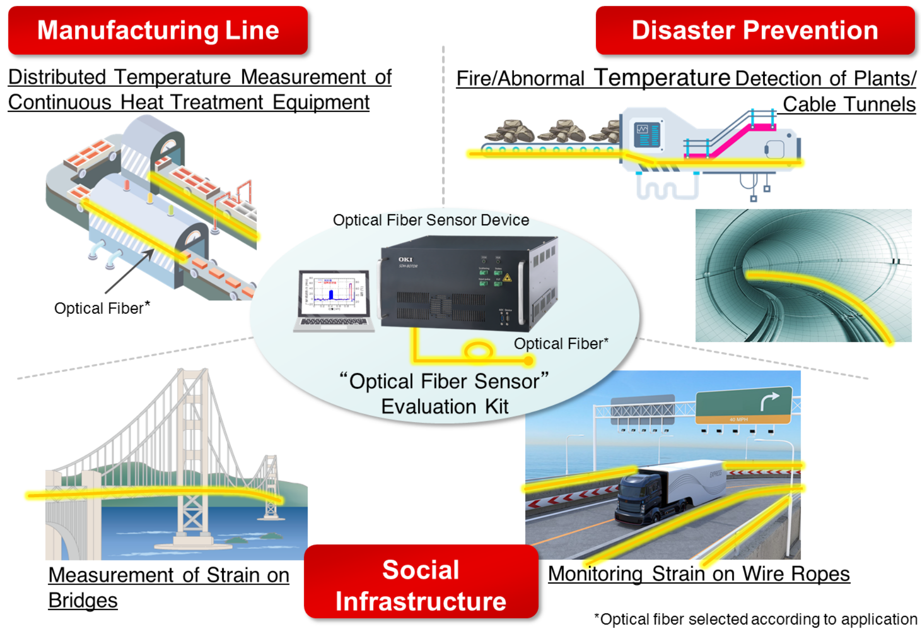


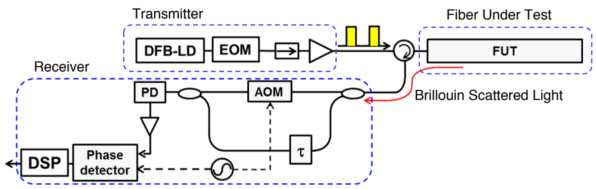
Figure 1. Areas of Optical Fiber Sensor Applications

Distributed Optical Fiber Temperature Sensing

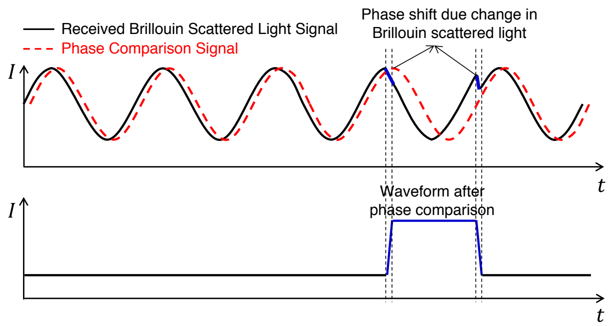
(1) Principle behind Distributed Optical Fiber Temperature Sensing[3), 4)]

In order to measure continuous temperature along an optical fiber, either the Brillouin or Raman scattered light generated in the process of light propagating through the optical fiber is detected. Since Brillouin and Raman scattered lights change in frequency and intensity with change in temperature of the optical fiber, the frequency/intensity changes can be detected to measure temperature. Additionally, Brillouin scattered light also changes frequency when subjected to strain, therefore expanding its use to diagnose conditions of structures is highly anticipated.

For this reason, OKI has focused on Brillouin scattered light and developed a distributed optical fiber temperature sensing technology using the new proprietary "SDH-BOTDR system." A schematic diagram of the system is shown in **Figure 2(a)**. The system is composed of a transmitter, a fiber under test and a receiver. The transmitter consists of a Distributed Feed Back Laser Diode (DFB-LD) that outputs a continuous wave (CW) of light and an Electro-Optic Modulator (EOM). This transmitter generates a light pulse that is input to the fiber under test (FUT) via a circulator, and the back propagation component of the Brillouin scattered light generated in the optical fiber is returned to the incident side as reflected light. Since the reflection point can be calculated from the time taken by the reflected light to return to the incident side using the time when the light pulse is input as a reference, the temperature and strain at each point can be measured. Brillouin backward scattered light is output from the circulator output port and input to the self-delay interferometer. In the previous BOTDR[5)] system, the frequency change of the Brillouin scattered light is measured with the frequency sweep method, whereas in the new system, it is measured with the phase detection method using a self-delay interferometer. Since the new system can measure frequency changes without requiring a frequency sweep, measurements can be performed faster than the previous system. In the interferometer, a frequency shift is applied to one of the two-branched lights by means of an Acousto-Optic Modulator (AOM) and an appropriate delay time is given to the other branched light by an optical fiber delay line. As a result, a sine wave signal corresponding to the frequency shift appears at the interferometer output, and the frequency change of the Brillouin scattered light is detected as a phase change of the sine wave signal. The sine wave signal possessing this phase shift information is converted into an intensity signal via Phase Detector and then converted into a frequency shift quantity. **Figure 2(b)** shows the output image from the SDH-BOTDR.



(a) SDH-BOTDR Configuration



(b) Image of Output Data

Figure 2. SDH-BOTDR Configuration and Image of Output Data

(2) Optical Fiber Sensor Evaluation Kit

An optical fiber sensor evaluation kit utilizing the new system has been developed. The external view is shown in **Photo 1**, and the specifications are given in **Table 1**. Time required to measure a 1km optical fiber is 1 second or less, therefore measurements are almost in real-time. This is due to the adoption of the phase detection method described above, and it is a dramatic improvement over the previous BOTDR system. As a result, it can be applied to scenes that require real-time monitoring such as fire detection. Furthermore, the system can be configured from generic devices used in optical communication, and maintenance cost can be reduced.

Photo 1. Optical Fiber Sensor Evaluation Kit

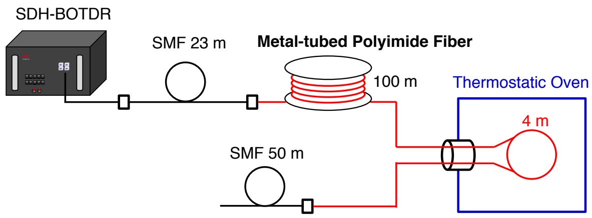
Table 1. Optical Fiber Sensor Evaluation Kit Specification

Items	Specifications
Measurement Time	1 second
Measurement Distance	1km (extendable up to 10km)
Spatial Resolution	1m
Temperature Range	-65~300°C (Depends on optical fiber coating)
Temperature Accuracy (σ)	±1°C

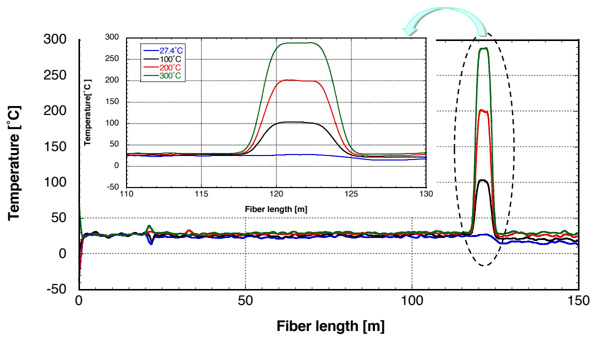
(3) Types of Optical Fibers for Temperature Measurement

The softening point of quartz glass, which is the material used for optical fibers, is 1650°C allowing it to withstand sufficiently high temperatures. However, it is common to coat the fiber to provide flexibility, thus as a distributed optical fiber temperature sensor, the heat resistance is limited by the coating material. For this reason, it is necessary to select an optical fiber that is most optimal for the intended application. Coating of the single mode fiber (SMF) commonly used for communication applications consists of resin and PVC (polyvinyl chloride). Although it is the least expensive, heat resistance is only about -40~85°C. On the other hand, with polyimide-coated fiber, heat resistance up to 300°C is possible. Furthermore, under severe environments the optical fiber can become damaged from additional pressure and strain. In such situations, it is conceivable to protect the optical fiber with metal tubing.

As an example of distributed temperature sensing using the new system, the result of temperature measurements taken with a polyimide-coated optical fiber inserted in a metal tube is presented. **Figure 3(a)** shows the configuration of the evaluation system. The optical fiber used for measurement has a total length of about 200m and is a combination of SMF and metal-tubed polyimide fiber. Four-meter end of the metal-tubed polyimide fiber was inserted into a thermostatic oven. Then the temperature change was observed as the temperature was raised in stages up to 300°C. **Figure 3(b)** shows the result of distributed temperature measurement and the temperature change around the thermostatic oven. As the temperature of the thermostatic oven was raised in stages, it was confirmed that the temperature at each stage was measured in real-time, and there was no problem with heat resistance.



(a) Configuration of Evaluation System



(b) Result of Measurement

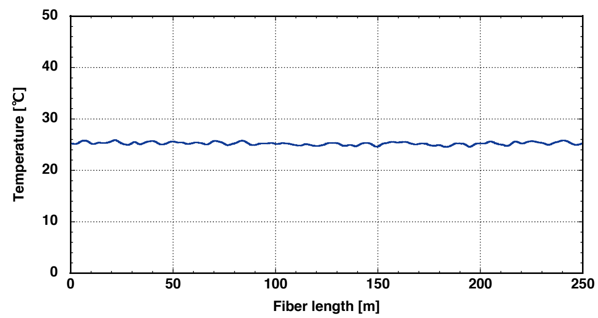
Figure 3. SDH-BOTDR Distributed Temperature Measurement Example

Application Example

As an application example, the distributed optical fiber temperature sensor in operation at OKI's factory is presented. Since the temperature sensing points of the factory air conditioning system are limited, it is difficult to make fine air conditioning adjustments for each section that would lead to efficient operation. Utilizing the beams and pillars in the factory, optical fibers were laid out in a meshed pattern. This provided high density distributed temperature measurements in real-time enabling the most efficient air conditioning (barrier zone level) adjustment for increased savings in energy.

Figure 4(a) shows an example of the installed optical fiber in the factory. Using cable-fixing jigs attached to the supporting rods of the fluorescent lamps hanging from the ceiling, a method was devised to lay out about 250m of optical fiber in midair. The result of the distributed temperature measurement is shown in **Figure 4(b)**. Although the fiber was laid in an area with relatively little temperature change, it can be confirmed that the distributed temperature inside the factory is measured. In the future, plan calls for extending the optical fiber to over 2km and measuring the temperature unevenness of the whole factory caused by seasonal variations.

(a) Optical Fiber Lay Out in Factory Ceiling



(b) Result of Distributed Temperature Measurement in Factory (Example)

Figure 4. Distributed Optical Fiber Temperature Sensing in a Factory

Conclusion

A distributed optical fiber temperature sensor using OKI's new proprietary "SDH-BOTDR system" has been described. Unlike conventional point sensors, the optical fiber sensor's ability to take continuous measurements of an area provides various benefits. Moreover, featuring a high-speed, real-time measurement that has not existed in the past, additional value will be created and application area expanded. Hereafter, importance will lie in constructing a system through analysis and visualization of the obtained sensing data. ◆◆

References

1) K.Hotate, H. Murayama, "Introduction to Optical Fiber Sensors," Photonic Sensing Consortium for Safety and Security, pp.18-27, 2012
2) H. Sato, "Rapidly Spreading Solution: Plant Utilizing Optical Fiber Temperature Sensors and Practical Examples," Keiso, Vol. 57, No. 4, pp. 59-64, 2014
3) K. Koizumi, H. Murai, "Distributed Optical Fiber Sensing Technology for Social Infrastructure Monitoring," OKI Technical Review Issue 226, Vol.82, No.2, 2015
4) K. Koizumi et al., "High-speed distributed strain measurement using brillouin optical time-domain reflectometry based-on self-delayed heterodyne detection," ECOC2015, pp. 1-7, 2015
5) T. Kurashima et al., "Brillouin optical-fiber time domain reflectometry," IEICE Trans. Commun., Vol. E76-B, No. 4, p. 382, 1993

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TIPS 【Glossary】

Types of scattering in optical fibers

Rayleigh scattering is scattering due to density fluctuation in the optical fiber.
Brillouin scattering is scattering due to interaction between light and acoustic wave.
Raman scattering is scattering due to vibration and rotation of molecules in the fiber medium.

BOTDR (Brillouin Optical Time Domain Reflectometry)

BOTDR is an optical fiber sensing method. It utilizes the property that the frequency of "Brillouin scattered light," which is one of the backscattered lights generated when a light pulse is input to the optical fiber, changes in proportion to temperature and distortion.