Miniaturization of Distributed Optical Fiber Sensor

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Social issues such as aging infrastructures and labor shortages are becoming more serious. In an aim to improve the maintenance and management of social infrastructures, OKI has been working on the commercialization of distributed temperature and strain sensors[1] as well as the research and development of distributed vibration sensors[2].

In distributed optical fiber sensors, the optical fiber, which is as thin as a human hair, serves as the sensor. In addition to detecting the location of an anomaly, it can sense physical quantities as well. This function is not limited to applications in large conventional equipment, but it can also be applied to production equipment, mobile, and robotics, creating a potential market for next-generation edge optical sensors. However, distributed optical fiber sensors are very expensive and large in size compared to point-type electrical sensors, hence limiting their applications. Therefore, OKI is working on research and development of an optical integration technology to realize a low-cost, miniature, high-performance distributed optical fiber sensor for use as a next-generation general-purpose edge optical sensor.

This article introduces a distributed optical fiber sensing method suitable for optical integration and presents the results of the verification.

Optical Integration Technology and Distributed Optical Fiber Sensors

(1) Optical Integration Technology

Optical integrated circuit technology is attracting attention as a technology for realizing functions such as optical wiring, signal modulation/demodulation, and signal reception as a single optical functional element. In particular, silicon photonics technology, which uses semiconductor processes to manufacture optical integrated circuits on SOI (Silicon On Insulator) substrates, is expected to be applied to various optical products from the perspective of miniaturization, fabrication yield, and mass production of optical wiring. Since various benefits are expected from integration and miniaturization in distributed optical fiber sensors, investigation was conducted on the core optical circuits that can be realized with silicon photonics technology.

(2) Distributed Optical Fiber Sensors

Distributed optical fiber sensors use backscattering lights generated by the propagation of light waves to determine the length-wise location of an anomaly affecting the fiber, as well as continuously measuring information on strain, temperature, and vibration along the fiber. Backscattering light is classified as Rayleigh scattering, Brillouin scattering, or Raman scattering light. Generally, Rayleigh scattering is used for vibration observation, Brillouin scattering and Rayleigh scattering for temperature and strain observation, and Raman scattering for temperature observation.

Representative methods of sensing using optical fibers are OTDR (Optical Time Domain Reflectometry) method, which measures in the time domain, and OFDR (Optical Frequency Domain Reflectometry)[3] method, which measures in the frequency domain. In general, the OTDR method is used for long-distance measurements with a measurable distance of several to 100 kilometers and a spatial resolution of one to tens of meters. On the other hand, the OFDR method's measurable distance is several to hundreds of meters, but a spatial resolution of several to tens of centimeters is possible. Furthermore, the OFDR method is capable of high-sensitivity strain measurement on the order of $\mu\varepsilon$, which is equivalent to a point-type electrical sensor.

Until now, OKI's work to commercialize distributed optical fiber temperature/strain sensors based on its proprietary Brillouin OTDR method, and research and development of distributed optical fiber vibration sensors based on the phase OTDR method were aimed at large structures. However, to achieve high spatial resolution with the OTDR method, a high-frequency circuit is required to generate short optical pulses. Even if the optical core function can be miniaturized, it is difficult to reduce cost, making it unsuitable for mass production. On the other hand, the OFDR method does not require expensive high-frequency circuits, and it is suitable for optical integration. Furthermore, since the OFDR method's performance is for short distances and high spatial resolution, it can make maximum use of the benefits of mass production through integration, and is expected to lead to a wide range of applications. Therefore, this article focuses on the development of a distributed temperature/strain sensor using the OFDR method.

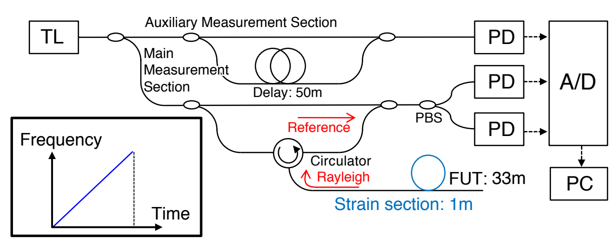
Principles of OFDR and Verification

(1) Principles of OFDR

This section describes the principles of OFDR and verification of a fiber optics system for optical integration of the core circuits. The OFDR method performs measurements by acquiring the intensity waveform of the Rayleigh backscattering light generated in an optical fiber. When there is no strain or temperature change in the Fiber Under the Test (FUT), the waveform acquired for each measurement is ideally the same. On the other hand, when a temperature or strain change occurs in the FUT, the intensity waveform shifts linearly in time in proportion to the amount of change. The temperature and strain change can be calculated from the amount of shift. A typical OFDR experimental system is shown in **Figure 1(a)**.

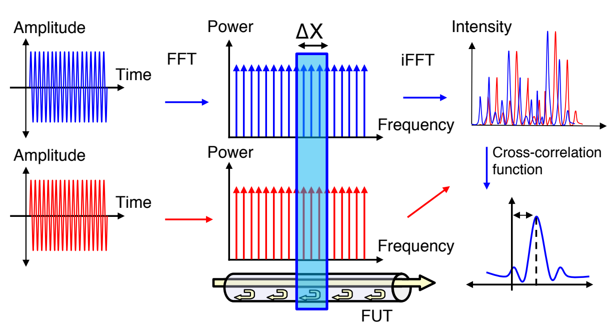
The OFDR method is composed of a transmitter, a main measurement section, an auxiliary measurement section, and an optical receiver. The transmitter uses a laser light source called a tunable laser (TL), which can change the oscillation frequency over time at high speed. In the main measurement section, one of the split light beams enters the FUT via an optical circulator, causing scattering in the FUT, and the Rayleigh backscattered light is output from the output port of the circulator. The output light is then combined with the other split light and input to a photodetector (PD) as a beat signal. This beat signal is generated by frequency sweeping the laser light, therefore beat signals of different frequencies are generated depending on the location of the Rayleigh backscattered light. There is a linear relationship between the location and frequency, and the frequency increases in proportion to the distance. The beat signal is generated throughout the FUT and is acquired by the PD as a superposition of multiple beat signals. The acquired signal is then converted to the frequency domain using a Fast Fourier Transform (FFT). Since the frequency corresponds to the distance, it is possible to identify the location where the Rayleigh backscattered light was generated by extracting only the signal of a certain frequency. Hence, the position of the optical fiber can be calculated.

Next, the calculation method of temperature and strain is shown in **Figure 1(b)**. The OFDR method is a relative measurement, and it is necessary to obtain the intensity waveform without changes as reference data in advance. The reference data and the measurement data frequency spectrum are cut out at frequency intervals corresponding to the distance ΔX on the frequency axis, and inverse fast Fourier transform (iFFT) is performed on each. Then, cross-correlation function is used to calculate the amount of the waveform shift on the time axis. If there is a change in temperature or strain, the amount of change appears as a shift in the time waveform, and using the cross-correlation function to calculate this shift, the change in temperature and strain can be obtained. Additionally, the auxiliary measurement section monitors fluctuations in the frequency sweep of the light source, called the sweep nonlinearity. In an ideal state, the frequency changes linearly over time, and the position is uniquely determined by the frequency of the beat signal. However, in reality, there are slight frequency fluctuations during the sweep. As a result, the distance cannot be uniquely determined from the frequency making accurate measurement difficult. For this reason, in the OFDR method, a technique of correcting the signal of the main measurement section using the signal of the auxiliary measurement section is widely used to suppress the sweep nonlinearity of the light source[4), 5)].



PD: Photodetector
A/D: Analog-digital converter

(a) OFDR Experimental System



(b) Temperature and Strain Calculation

Figure 1. Measurements using OFDR Method

(2) Verification of OFDR Strain Measurements

In the verification system, the output power, frequency sweep range, and sweep speed of the TL in the transmitter were set to 13dBm, 1THz, and 5THz/s, respectively. The FUT used in the main measurement section is a 33m single-mode fiber. A mechanism using a stepping motor in the intermediate 1m section enables generation of quantitative strain. The Rayleigh backscattered light generated in the FUT is interfered with the reference light, and the generated beat signal is received by the PD. Similarly, a delay of 50m is added to one side in the auxiliary measurement section to generate a beat signal equivalent to 1.2MHz, which is also received by the PD. The beat signals are then sent to a PC via an ADC (Analog-to-Digital Converter), where the sweep nonlinearity is corrected and the Rayleigh backscattered light for the entire section is calculated. The sweep nonlinearity is corrected by correcting the signal on the main measurement side based on the phase of the signal from the auxiliary measurement section. This process is performed on both the reference and measurement signals, and the strain value for the entire section is calculated using the cross-correlation function. **Figure 2** shows the distribution measurement results when three levels of strain were applied to the FUT at 100$\mu\varepsilon$ intervals. The spatial resolution of this verification system was 5cm, which is a substantially higher resolution compared to the 1m spatial resolution of the OTDR method. The estimated strain accuracy in this study was approximately 13$\mu\varepsilon$. OKI is now working to achieve high strain sensitivity, comparable to that of a point-type sensor, as well as distributed measurements in an aim to realize a strain accuracy of ±1$\mu\varepsilon$ and a measurement distance of 200m.

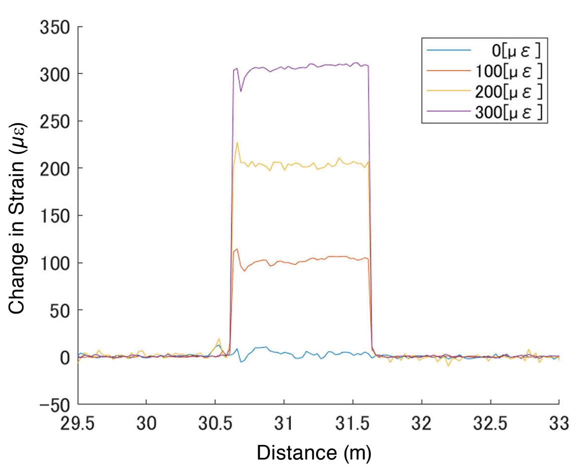
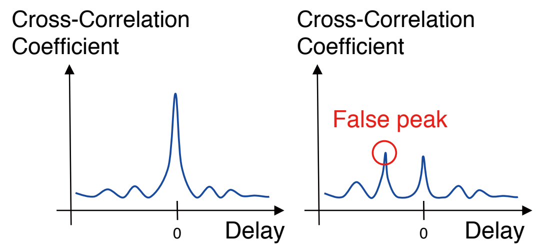


Figure 2. Strain in OFDR Method

Measurement Error Correction Technology

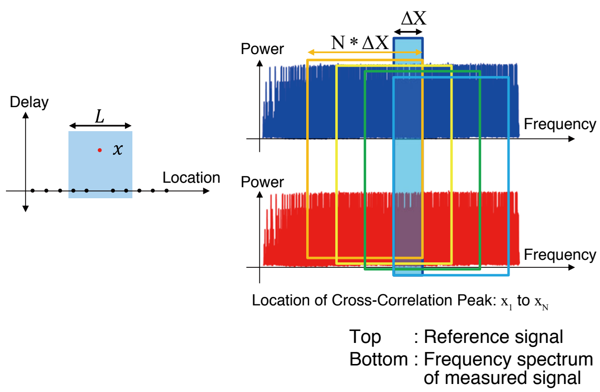
With the OFDR method, fluctuations in the light source sweep and external factors can cause false cross-correlation function peaks to occur, which result in measurement errors. In conjunction with the integration of core circuits, OKI is working on a measurement error correction technology to ensure a robust operation in the field. **Figure 3** shows a conceptual diagram of when a measurement error occurs. In a normal situation, a clear peak appears in the obtained cross-correlation function as shown in **Figure 3(a)**. However, depending on the environment, the value of the cross-correlation function may decrease causing the true peak to be buried in noise and a large false peak to appear as shown in **Figure 3(b)**. In order to calculate temperature and strain from the shift amount of the peak, such phenomena must be eliminated from the measurement. Therefore, OKI has proposed an algorithm to distinguish errors and correct the measurements using signal processing[6]. A conceptual diagram of this algorithm is shown in **Figure 4**.

After the cross-correlation function for distance is obtained, the proposed algorithm applies a process to correct measurement errors. First, for the cross-correlation function in the range L, an abnormal value x is extracted as a candidate for measurement error using threshold processing. Next, N frequency spectra are cut out so that they overlap with the frequency bands before and after the frequency interval $\Delta\mathrm{X}$ when x was obtained. For each of these N frequency spectrum bands, a new cross-correlation function x_1 to x_N is obtained. Finally, a process to determine the correctness of the original value x is performed from the N values x_1 to x_N. If x does not deviate significantly from the other N values, x is adopted as the normal value. On the other hand, if x is significantly different from the N values, x is replaced with a correction value based on the average value of N values. If the location where the temperature/strain change occurs is in the section that is subject to overlap, the values of the cross-correlation function among the N values will significantly differ. In this case, the value just prior to x is adopted as the correction value. Although this algorithm has the disadvantage of reducing the spatial resolution of the corrected location, it can eliminate the adverse effects of external factors on the measurement.



(a) Normal Measurement **(b) Error in Measurement**

Figure 3. Error Occurrence in Measurement



(a) Measurement Error Extraction **(b) Correction Process using Overlap**

Figure 4. Measurement Error Correction Algorithm

Figure 5 shows the occurrence of a measurement error and the result when correction is performed using the algorithm. The thin solid line shows the amount of strain calculated based on incorrect peaks caused by the cross-correlation error, whereas the thick solid line shows the result of applying the proposed algorithm, which enables correct measurement of the strain in the stretch of optical fiber.

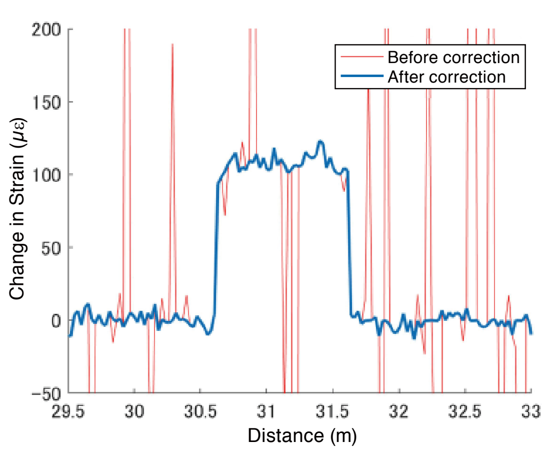
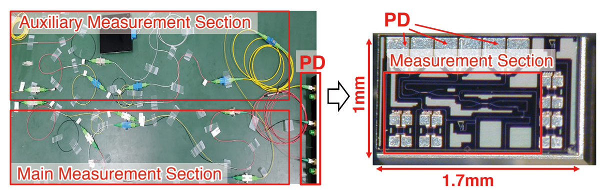


Figure 5. Measurement Error and Result of Correction

Prototype of Optical Integrated Chip

Based on the verification results of the OFDR method, the core function of the verification system consisting of the fiber optics shown in **Figure 6(a)** was prototyped using silicon photonics technology. **Figure 6(b)** shows the optical integrated core circuit. The upper part is the PD, and the lower part is the integrated circuit that implements the measurement section and the auxiliary measurement section excluding the delay fiber. The size of the optical integrated core circuit is a 1mm by 1.7mm rectangular unit allowing ultra-miniaturization compared to the fiber optic system shown in **Figure 6(a)**.

Verification using this optical integrated core circuit will be performed in conjunction with the application of a general-purpose frequency-tunable light source. Additionally, since the 50m optical fiber used in the auxiliary measurement section to generate optical delay as shown in **Figure 1(a)** is a hindrance to the miniaturization of this optical system, research and development will be conducted for a method to suppress the sweep nonlinearity of the light source without using an optical delay circuit.



(a) Verification System using Fiber Optics **(b) Optical Core Circuit of Distributed Optical Fiber Sensor Integrated using Silicon Photonics**

Figure 6. Effect of Optical Integration

Summary and Future Technological Developments

This article presented an optical fiber sensing method suitable for mass production using optical integrated circuits and described strain measurement using the OFDR method as a verification system for integration.

The article also described a method to suppress measurement errors in order to achieve robust operation and demonstrated its effectiveness. Furthermore, it introduced a prototype of an optical integrated core circuit for implementation in a distributed optical fiber sensor. OKI now plans to evaluate the optical circuits that have been integrated into an optical chip, and will work on investigating signal processing and improving methods in order to further achieve high performance, miniaturization, and low cost. ◆◆

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TIPS

【Glossary】

Unit of strain ε
Represents the amount of deformation of an object. The value indicates the ratio of deformation compared to the original length.

Spatial resolution
Minimum distance that separates two adjacent points. In the article, it represents the minimum interval for strain measurement.

Rayleigh scattering
Type of scattered light that occurs in optical fibers. It is caused by density fluctuations within the medium and has the same frequency components as the incident light.