

Development of High-Performance OFDR System with Phase Integration Coherence Compensation

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[Summary]

We devised a Phase Integration Coherence Compensation (PICC) method as an essential technology for OFDR systems and developed an OFDR system using this technique. This unique Anritsu PICC OFDR system can generate virtual reference interferometer signals with arbitrary delay lengths to help maximize the coherence of interference signals reflected from any location. Furthermore, high-quality OFDR spectra with coherence compensation across the entire measurement range can be captured by dividing the measurement distance (length) and implementing coherence compensation by generating reference interferometer signals with optimal delay lengths for each divided region. Additionally, we developed a strain and temperature distribution measurement system that calculates optical-fiber elongation and compression using this OFDR spectrum, enabling high-precision, real-time measurement of strain and temperature distribution over a 400-m optical fiber.

1 Introduction

Progressive aging of older large infrastructure, such as bridges, tunnels, and dams reaching the end of their design life, as well as social infrastructure, such as roads and railways, makes monitoring structural health increasingly important. Traditionally, strain is measured using a Fiber Bragg Grating (FBG)¹⁾ to monitor changes in the reflection profile of an optical fiber core caused by changes in the fiber refractive index resulting from fiber elongation and compression. As a result, attaching an FBG to the measurement target can monitor the target strain. Since an FBG is just several millimeters long, they are attached to monitor the structure only at key locations, and structural strain is not measured at locations with no attached FBG.

However, the monitored area could be increased greatly if, instead of making ‘point’ measurements using an FBG, an optical fiber itself could be used a strain sensor to measure the strain distribution along the full fiber length. Therefore, methods such as Distributed Acoustic Sensing (DAS)²⁾, Brillouin Optical Time Domain Reflectometry (B-OTDR)³⁾, Brillouin Optical Correlation Domain Analysis (B-OCDA)⁴⁾, and Optical Frequency Domain Reflectometry (OFDR)⁵⁾ have been developed to measure strain distribution along the full length of optical fibers. While DAS can detect impact-type strain over a range of several tens of kilometers, it cannot measure static strain, and its distance resolution is low at several meters. B-OTDR and B-OCDA can measure

strain over a range of several kilometers, but their strain resolution is approximately $100 \mu\epsilon^*$, which is low sensitivity.

OFDR has a measurement range of about 100 m, which is shorter than the other methods, but it is superior in terms of strain and distance resolutions. Anritsu is experienced in developing a 3D shape measurement system^{6), 7)} based on the OFDR method. Consequently, we leveraged our existing technological assets to develop an OFDR system to measure strain and temperature distribution, which is expected to see growing future demand.

When measuring the strain and temperature distribution using the OFDR method, Rayleigh scattered light generated in the optical fiber is detected by an interferometer, but its polarization differs depending on the position within the optical fiber. Therefore, polarization compensation is required. Also, coherence compensation technology is required to detect interference signals beyond the coherence length of the light source. This article discusses OFDR principles, polarization-compensation methods, Anritsu’s proprietary phase integration coherence compensation method (patent pending), and methods for calculating strain and temperature distribution.

* $1 \mu\epsilon$ is the amount of strain when an object 1 m in length stretches by $1 \mu\text{m}$.

2 OFDR Principles

2.1 OFDR Optical System

Figure 1 shows the OFDR basic optical system.

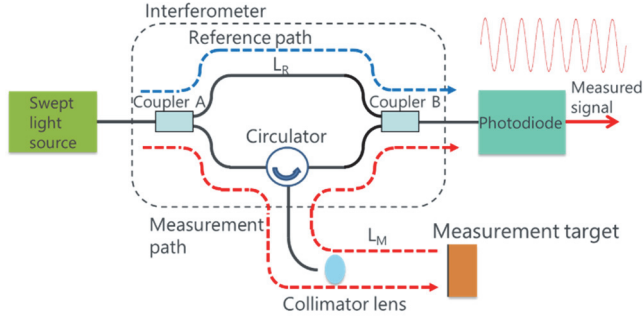


Figure 1 OFDR Optical system

The swept light emitted from the swept light source is split into two paths at coupler A; one path goes directly to coupler B (reference path), while the other path passes through a circulator, is emitted into free space through a collimator lens, and after being reflected by the target object, returns through the collimator lens and circulator to coupler B (measurement path). The swept light propagating through the reference path and the measurement path is combined at coupler B, and then converted to an electrical signal by a photodiode.

Assuming that the optical frequency of the swept light changes linearly with time, the optical frequency $\nu(t)$ at time t is expressed as:

$$\nu(t) = \nu_0 + k \cdot t \quad (1)$$

where ν_0 is the optical frequency as time 0 and k is the sweep speed (Hz/s). If we define the difference between the optical path length L_R of the reference path and the optical path length L_M of the measurement path as $\Delta L = |L_M - L_R|$, the difference in propagation time τ from the swept light source to the photodiode is:

$$\tau = \frac{\Delta L}{c} \quad (2)$$

where c is the velocity of light in vacuum.

If we denote the electric field intensities of the swept light passing through the reference path and the measurement path as E_R and E_M , respectively, the interference intensity P detected by the photodiode is:

$$\begin{aligned} P &= |\vec{E}_R + \vec{E}_M|^2 \\ &= |E_R e^{i2\pi\nu(t) \cdot t} + E_M e^{i2\pi\nu(t-\tau) \cdot t}|^2 \quad (3) \\ &= |E_R|^2 + |E_M|^2 + 2E_R E_M \cos\left(2\pi \frac{k\Delta L}{c} t\right) \end{aligned}$$

If the DC component of the interference signal is cut off, only

the third term in the final expression of Eq. (3) is observed.

In other words, an electrical signal with a frequency of

$$f_I = \frac{k\Delta L}{c} \quad (4)$$

is output from the photodiode. Therefore, after sampling the electrical signal, if the OFDR spectrum is calculated by FFT (Fast Fourier Transform), a peak is detected at the position of f_I on the OFDR spectrum and the optical path difference ΔL can be calculated from Eq. (4).

The above assumes that the optical frequency of the swept light changes linearly. However, in reality, the optical frequency is swept nonlinearly. Therefore, linearization correction must be applied to the measurement signal either through sampling methods or by software processing. This process is called linearization or resampling.

2.2 Linearization

Figure 2 shows the OFDR optical system including linearization and polarization compensation systems. The swept light emitted from the swept light source is split into two paths at coupler C; one path enters the measurement interferometer like that shown in Figure 1, and the other path enters the reference interferometer for linearization.

The measurement interferometer has a built-in polarization switch. The half-frequency signal of the sweep signal output from the swept light source is input to the polarization switching port of the polarization switch, causing the polarization of the reference path to switch between 0° (P polarization) and 90° (S polarization) with each sweep. Polarization is compensated by adding the calculation results from the measurement interferometer signals of each polarization state. Also, to ensure that the swept light input the polarization switch has linear polarization, the connection between the swept light source and the polarization switch uses polarization-maintaining fiber.

The reference interferometer is a Michelson interferometer design using Faraday mirrors (FR) as reflectors; the light from each FR returns to coupler D in the same polarization state regardless of the delay length ΔL_{AUX} with the advantage of eliminating variations in the interference signal due to polarization fluctuations.

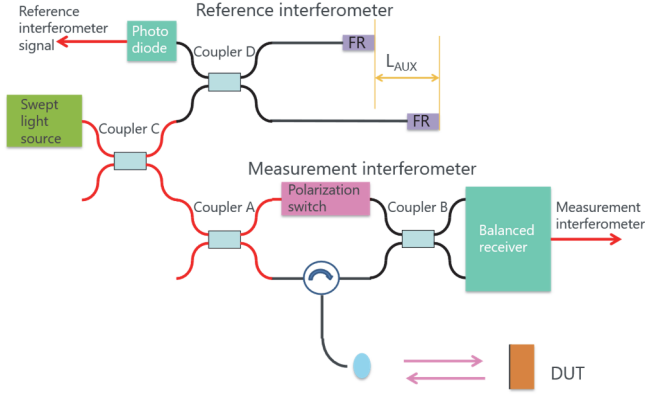


Figure 2 OFDR optical system including linearization system

From Eq. (4), the reference interferometer signal has the frequency

$$f_{AUX} = \frac{2k\Delta L_{AUX}}{c} \quad (5)$$

The frequency is doubled compared to Eq. (4) due to the round trip through ΔL_{AUX} . Also, since the FSR (Free Spectral Range) of the interferometer, that is, the optical frequency required for the interference signal to change by one cycle of a sine wave, can be expressed as:

$$FSR = \frac{c}{2\Delta L_{AUX}} \quad (6)$$

Eq. (5) can be expressed as:

$$f_{AUX} = \frac{k}{FSR} \quad (7)$$

The right-hand side represents 'how many times the sweep speed k corresponds to the FSR' or in other words, f_{AUX} can be described as the frequency of 'the interference signal that reaches a maximum each time the optical frequency is swept by FSR'.

Equation (4), which represents the frequency of the measurement interferometer signal, and Eq. (7), which represents the frequency of the reference interferometer signal, are both proportional to the sweep speed k . Therefore, it is possible to linearize the measurement interferometer signal from the change in frequency of the reference interferometer signal.

There are two linearization methods using either software or hardware^(6), 7). The biggest difference between the two is the interference signal sampling method where software linearization samples at equal time intervals, while hardware linearization samples at equal optical frequency intervals.

As described later, strain measurement requires multiple linearization cycles while shifting the measurement interferometer signal and reference interferometer signal

along the time axis, and this process can be simplified by sampling each interferometer signal at equal time intervals. Consequently, software linearization is better for strain measurement.

2.3 Software Linearization

Software linearization samples the reference interferometer signal and measurement interferometer signal simultaneously at equal time intervals using an A/D converter. Then, based on the reference interferometer signal, which serves as a ruler for optical frequency, the measurement interferometer signal is linearized so that it becomes linear with respect to optical frequency. The specific method is described below.

First, the phase of the reference interferometer signal is calculated. Next, FFT is performed on the reference interferometer signal, and the latter half of the FFT calculation result is replaced with zeros before performing inverse FFT on this. The phase angle of the complex number calculated by inverse FFT is the phase of the reference interferometer signal.

Since the calculated phase of the reference interferometer changes repeatedly between $-\pi$ and $+\pi$, unwrapping is performed by adding 2π to the phase at points where it jumps from $+\pi$ to $-\pi$, and conversely, by adding -2π to the phase at points where it jumps from $-\pi$ to $+\pi$, to calculate a continuous phase χ (Figure 3).

The continuous phase quantity increases by 2π each time the optical frequency is swept by the FSR of the reference interferometer, and is proportional to the optical frequency.

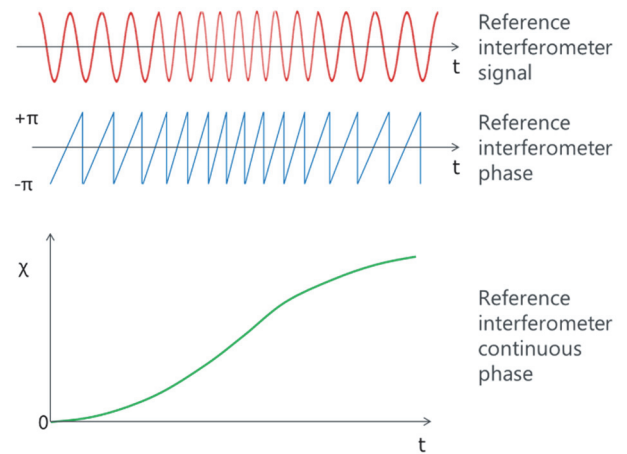


Figure 3 Reference interferometer signal phase calculation

Next, the continuous phase χ is divided equally, and the strength of the measurement interferometer signal at the

division points is extracted (green circles in center of Figure 4). The extracted data is not at equal intervals on the time axis, but becomes data sampled at equal intervals on the optical frequency axis. Sharp peaks are observed at frequency positions corresponding to reflection points on the OFDR spectrum, which is the FFT calculation result for this data.

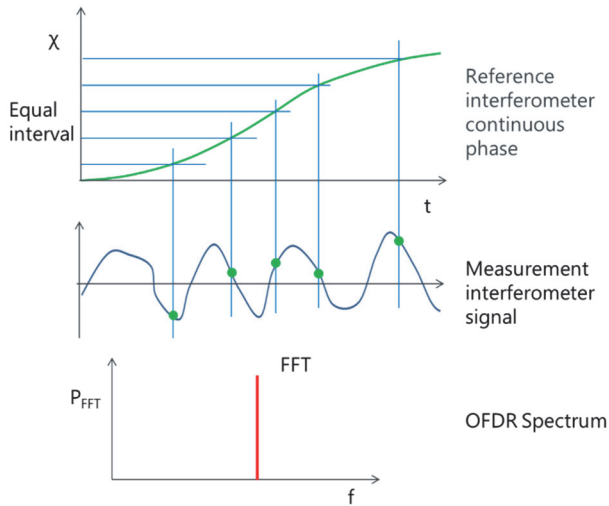


Figure 4 Data extraction

2.4 Anritsu Swept Light Source

Anritsu has developed and released a high-coherence optical frequency swept light source⁸⁾. Figure 5 shows the external appearance of the light source, which can sweep the optical frequency continuously in phase without mode hops over almost the entire sweep range. Table 1 lists the main specification of this light source.



Figure 5 AQB5500P External view

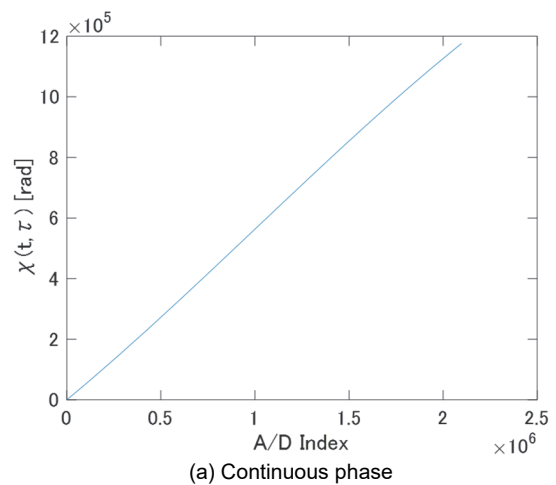
Table 1 AQB5500P Specifications

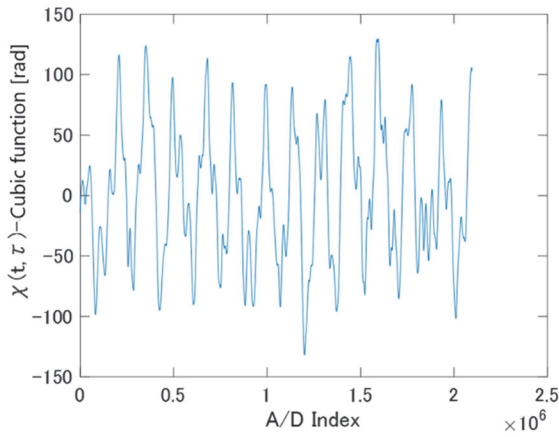
Center wavelength λ_c	1550 $\pm$ 5 nm (Fixed factory setting)
Wavelength sweep width W	10 to 50 nm
Sweep frequency f_R	150 $\pm$ 20 Hz (Fixed factory setting)
Optical output power	>10 dBm
Coherence length	>100 m
Trigger setting resolution	1 pm

The trigger signal output from this light source allows the timing between High and Low switching to be specified as wavelength. While sweeping from short to long wavelength, the trigger becomes High when the swept light wavelength reaches an arbitrarily set wavelength; while sweeping from long to short wavelength, the trigger becomes Low when the swept light wavelength reaches another arbitrarily set wavelength. It is possible to always sample in the same wavelength range by using this trigger signal to start sampling of the A/D converter.

The optical frequency sweep waveform of this light source is sinusoidal. Therefore, the optical frequency near the center of the sweep changes according to a cubic function.

Figure 6(a) shows the continuous phase measured using an Anritsu swept light source and a reference interferometer with a delay length of 83.5 m. It changes according to a cubic function, similar to the sweep waveform. Figure 6(b) shows the value obtained by subtracting the cubic function component from this continuous phase. The fluctuation amplitude of about 100 rad is typical of individual light sources and is reproducible.





(b) Continuous phase with cubic function component subtracted

Figure 6 Continuous phase of Anritsu light source

3 Phase Integration Coherence Compensation

The effect of linearization at the DUT position is maximum when the distance to the DUT matches the delay length of the reference interferometer. The effect decreases as the distance from this position increases due to the effect of the light-source coherence. When the distance to the DUT is limited, such as in OCT measurements, it is sufficient to prepare a reference interferometer with a delay length matching the position of the DUT. However, this becomes a significant problem in distance measurement systems where the measurement point position is undefined, or in strain-distribution measurement systems where measurement points span the entire optical fiber.

NTT has commercialized a software-linearization Phase Noise Compensation (PNC)⁽⁹⁾ method in which the linearization effect is maximum at integer-multiple positions of the reference interferometer delay length. While this method significantly expands the measurable strain-distribution range, the coherence decreases at half-integer multiple positions of the reference interferometer length, which are intermediate positions.

Anritsu has also developed an OFDR distortion distribution measurement system⁽¹⁰⁾ that compensates for coherence using hardware linearization, but requires addition of one more interferometer.

Therefore, this time, while maintaining the conventional optical system, we devised a PICC method that artificially generates reference interferometer signals with arbitrary delay lengths. By linearizing the measurement interferometer signal through software linearization from

the generated reference interferometer signal, it is possible to maximize coherence at any DUT position, which is especially useful for distortion distribution measurements.

The principle of the phase integration method is described below.

If the light phase is $\phi(t)$, the velocity of light is c , and the delay time of the reference interferometer with delay length L_{ref} is $\tau = 2nL_{ref}/c$, the reference interferometer signal phase $\chi(t, \tau)$ can be expressed as:

$$\chi(t, \tau) = \phi(t) - \phi(t - \tau) \quad (8)$$

Approximating Eq. (8) gives Eq. (9)

$$\chi(t, \tau) \simeq \frac{d\phi}{dt} \tau \quad (9)$$

And integrating Eq. (9) gives Eq. (10)

$$\phi(t) \simeq \frac{1}{\tau} \int \chi(t, \tau) dt = \Phi(t) \quad (10)$$

where the middle and right-hand terms are the phase integration.

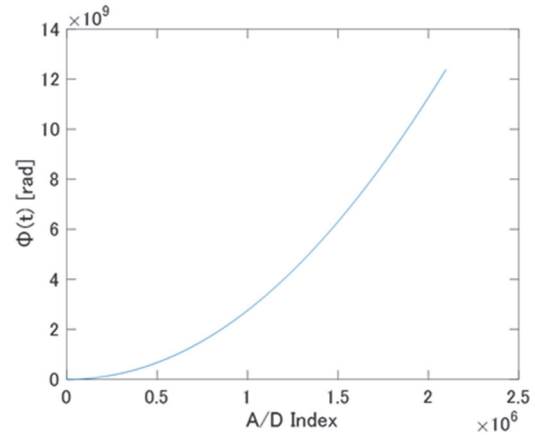


Figure 7 Phase integration

Figure 7 shows the phase integration $\phi(t)$ calculated from $\chi(t, \tau)$ shown in Figure 6. Since $\chi(t, \tau)$ is nearly linear, the phase integration takes the form of a quadratic curve.

The phase $\chi(t, \tau')$ of the interferometer signal that would be output by an interferometer with delay length L' , and delay time $t' = 2nL'/c$ can be calculated using Eq. (11)

$$\begin{aligned} \chi(t, \tau') &= \phi(t) - \phi(t - \tau') \\ &= \frac{1}{\tau} \int_{t_0}^t \chi(t, \tau) dt - \frac{1}{\tau} \int_{t_0}^{t-\tau'} \chi(t, \tau) dt \\ &= \frac{1}{\tau} \int_{t-\tau'}^t \chi(t, \tau) dt \end{aligned} \quad (11)$$

In other words, based on the reference interferometer signal with delay length L_{ref} , the reference interferometer signal with any arbitrary delay length can be calculated from the phase integration.

If FFT is performed after software linearization of the measurement interferometer signal based on the reference interferometer signal calculated by Eq. (11), an OFDR spectrum can be calculated where coherence is maximized at any arbitrary distance L' . As shown in Figure 8, at that time it is necessary to shift the linearization timing by the time $\delta t = 2n(L' - L)/c$ corresponding to the delay length difference between L' and L .

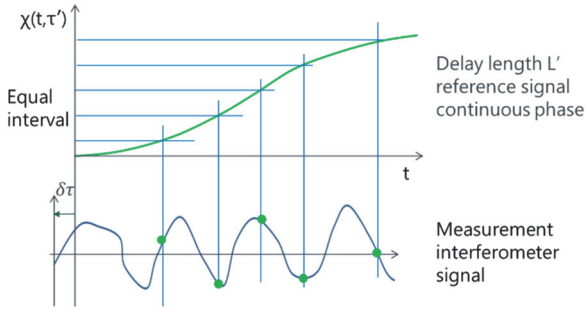


Figure 8 Delay length difference correction

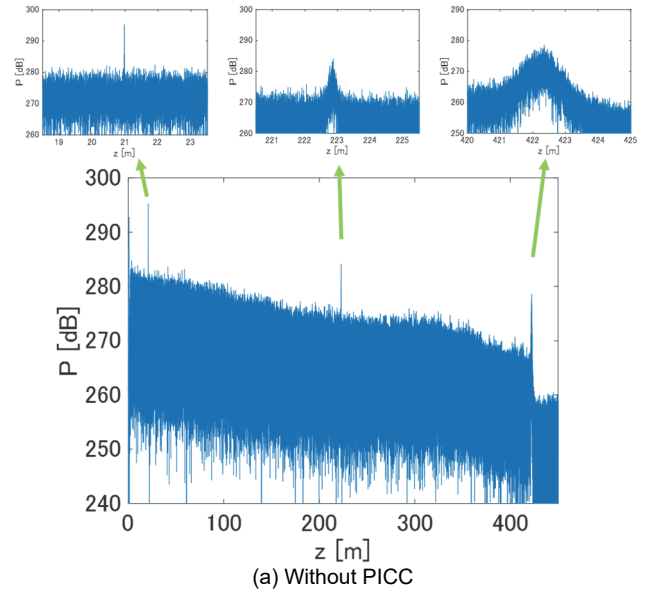
4 Measuring Reflection Peak using PICC OFDR

We configured an OFDR system using an Anritsu wavelength-swept light source with a sweep center wavelength of $1.55 \mu\text{m}$ and a sweep width 10 nm, a reference interferometer with a delay length of 83.5 m, and a high-speed A/D converter (TELEDYNE ADQ35) with a sampling frequency of 5 GS/s. This OFDR system configuration can monitor the reflection distribution from optical fibers as an OFDR spectrum over a range of approximately 450 m.

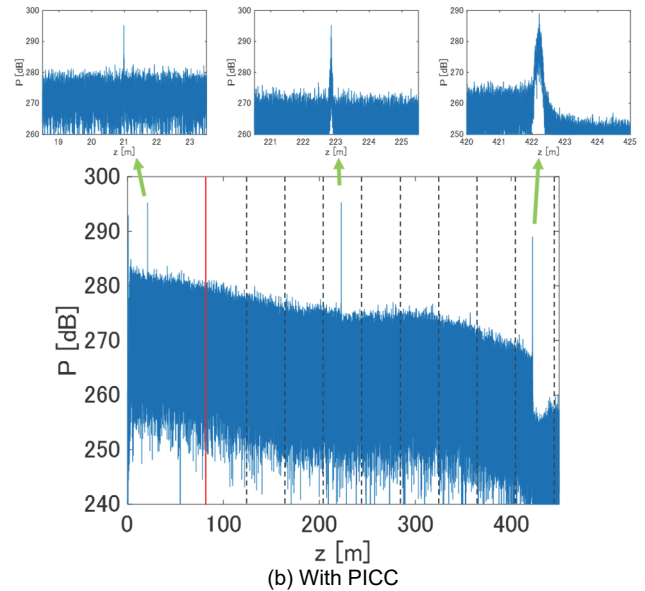
The reflection distribution and reflection peaks from the optical fiber connection points were observed when three optical fibers with lengths of 20 m, 200 m, and 200 m were connected in series. Figure 9(a) shows the OFDR spectrum without coherence compensation. Rayleigh scattering distribution in the optical fiber is observed in the range of 0 to 420 m, and strong reflection peaks are observed at the optical fiber connection points. The coherence length of the wavelength swept light source in air is about 100 m, and the round-trip distance that can be traveled without degraded coherence in an optical fiber is 30 m. Therefore, while the reflection peak at 20 m has a sharp shape, the reflection peaks at 220 m and 420 m are spread out by about 0.5 to 1 m due to degraded coherence.

Next, Figure 9(b) shows the OFDR spectrum with PICC, which was implemented at points every 40 m from the position of the reference interferometer delay length (red

line in figure). The OFDR spectrum in the figure is an integrated OFDR spectrum created by connecting the 0 to 103.5-m region of the OFDR spectrum measured without PICC and the regions of ± 20 m around the implementation points of the OFDR spectra measured with PICC performed every 40 m. All three reflection peaks were sharper, and the peak widths became several centimeters.



(a) Without PICC



(b) With PICC

Figure 9 OFDR Spectrum

5 Strain Distribution Measurement Method

The OFDR spectrum in Figure 9 shows the Rayleigh scattering light intensity distribution from the connected SM fiber between 0 m and 420 m at the base of the reflection peak. This Rayleigh scattering light spectral shape, which

appears to be white noise at first glance, reflects the refractive index distribution of the SM fiber. Since the refractive index distribution is determined during SM fiber manufacturing and is virtually unchangeable, this OFDR spectrum intensity is reproducible. While strain distribution measurement is possible using changes in the OFDR spectrum intensity, if, for example, shape changes in a 100-mm region are measured with 100- μm precision, the strain resolution is 1000 $\mu\epsilon$.

Therefore, to measure strain, the phase of the OFDR spectrum is observed rather than its intensity. The phase of the measurement interferometer signal observed by OFDR changes depending on the optical path from the light source to the reflection point. If the wavelength of the swept light is λ and the refractive index of the optical fiber is n , the phase of the measurement interferometer changes by 2π [rad] when the distance from the light source changes by $\lambda/2n$ (≈ 0.5 μm). Since phase can be measured with an accuracy of about 0.1 [rad], strain can be measured with an accuracy of 0.1 $\mu\epsilon$.

The actual calculation method is described below.

The measurement interferometer signal, which has been linearized after coherence compensation by the phase integration method described in the previous section, is subjected to FFT to calculate the OFDR spectrum. As an example, Figure 10 shows the real part (blue line) and imaginary part (red line) of the OFDR spectrum for a 10-cm region from 50 to 50.1 m. Unlike the OFDR spectrum intensity, this shape changes with slight external disturbances.

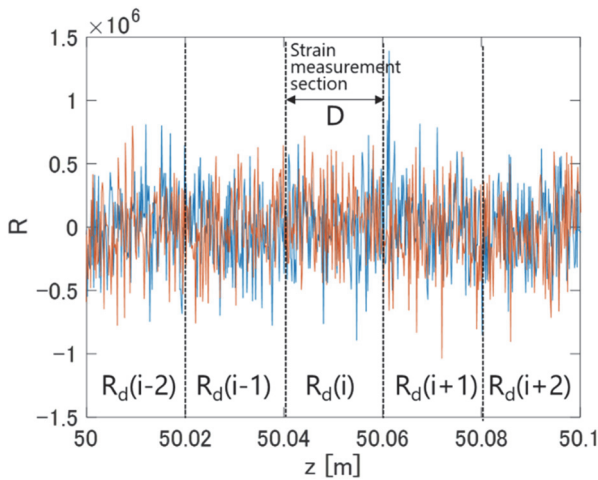


Figure 10 Real and imaginary parts of OFDR spectrum

As shown in Figure 10, the OFDR spectrum is divided into sections of desired length D . This section length becomes the distance resolution of the strain distribution measurement.

For example, when the section length $D = 20$ mm and the OFDR resolution $\Delta z = 0.446$ mm, there are 44 data points in each section.

Next, zero padding is applied to the data within the section length to make the number of data points a power of 2. This is done to implement the subsequent FFT effectively, but also to increase the number of data points and improve the resolution after FFT. If the number of data points after zero padding is N_{RDz} , then $Dz = \Delta z \times N_{RDz}$ becomes the calculated section length and is the parameter that determines the strain resolution as described later (Figure 11).

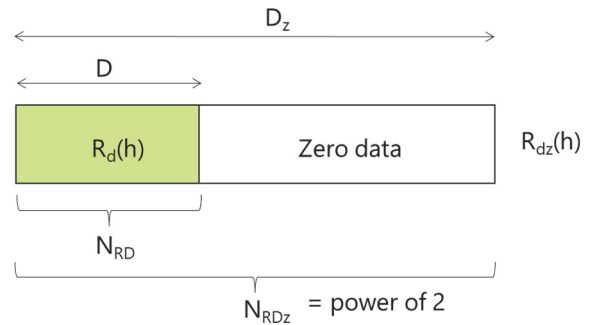


Figure 11 Zero padding

The zero-padded data is inverse-FFT transformed, and its real part is calculated as the frequency component of the phase change within the section.

The polarization-compensated M_d^{PS} is obtained by adding the frequency component intensity M_d^P calculated by the above method from the measurement interferometer signal measured in the P-polarization state, and the frequency component intensity M_d^S calculated similarly from the measurement interferometer signal measured in the S-polarization state.

If the frequency component intensity phase change (M_d^{PS}) is gradual, the low-frequency components become larger; if the change is rapid, the high-frequency components become larger. Additionally, if a section is compressed, the phase changes become denser, shifting the overall spectrum towards the high-frequency side; if a section is stretched, the phase changes become sparser, shifting the spectrum towards the low-frequency side.

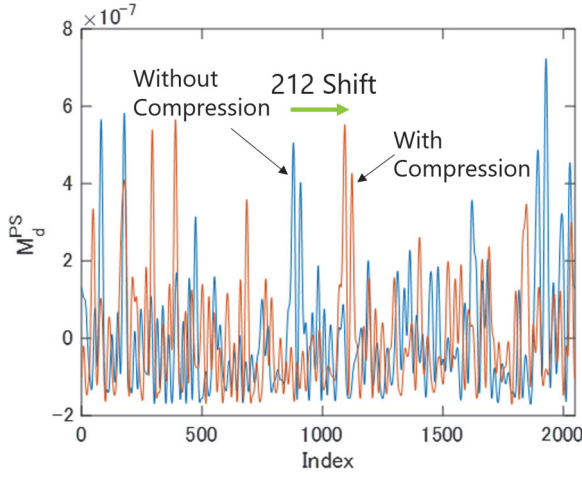
Figure 12 M_d^{PS} Shift

Figure 12 shows M_d^{PS} measured with no external force applied to the optical fiber (blue line) and with compression applied (orange line). There are 2048 data points after zero padding. Multiple peaks are seen in each state, but in this example, M_d^{PS} has shifted by 212 toward the high-frequency side due to compression.

A commonly used method for calculating the amount of shift in M_d^{PS} calculates the cross-correlation function S_{xc} and determines the position showing the maximum value as the shift amount. In other words, the value of m for which $S_{xc}(m)$ becomes maximum is taken as the shift amount.

$$S_{xc}(m) = \int g(t)f(t-m)dt \quad (12)$$

One method for calculating Eq. (12) is to perform FFT on the M_d^{PS} (Eq. (13)) for each state, multiply the results and perform inverse-FFT on that result.

$$S_{xc}(m) = FFT^{-1}\{FFT(g(t)) \times (FFT(f(t)))^*\} \quad (13)$$

This method calculates the cross-correlation rapidly. Figure 13 shows the cross-correlation during elongation and compression. The peak position of the cross-correlation shifts to the negative side during elongation and to the positive side during compression.

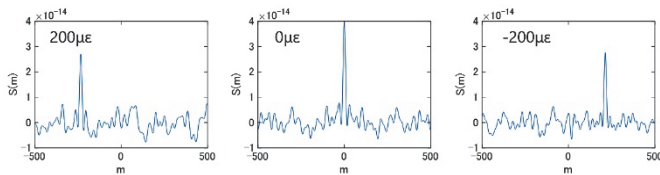


Figure 13 Cross-correlation function

When a section is compressed and the phase increases by 2π it means the phase rotation has increased by one complete rotation, meaning that its frequency component has increased by 1. Additionally, an increase in phase by 2π

means that the optical path length within the section has increased by $\lambda/(2n)$. During compression, not only does the fiber length become physically shorter, but also the refractive index increases. If the coefficient indicating this photo-elastic effect is denoted as ρ (≈ 0.78), the relationship between the shift amount m and the strain amount s is given by Eq. (14).

$$s = \frac{\delta D}{D} = \frac{m\lambda}{2nD_z\rho} = \frac{m\lambda}{2nN_{RDz}\Delta z\rho} \quad (14)$$

Additionally, since m is an integer, the strain resolution δs becomes

$$\delta s = \frac{\lambda}{2nN_{RDz}\Delta z\rho} \quad (15)$$

and the strain resolution improves as N_{RDz} is increased by zero padding.

Due to the nature of the cross-correlation function calculation, $-N_{RDz} < m < N_{RDz}$. Therefore, the maximum measurable strain s_{max} is:

$$s_{max} = \frac{\lambda}{2n\Delta z\rho} \quad (16)$$

and is about $1500 \mu\epsilon$ in this system. However, this is when the M_d^{PS} S/N is sufficiently large, and the typical maximum strain is 20% to 50% of this value.

The strain distribution applied to the optical fiber can be measured by performing the above calculations for each section.

The peak value in Figure 13 becomes smaller when the elongation and compression within the section length are non-uniform, or when there are many noise components in the frequency components, resulting in poor reproducibility. Therefore, the correlation coefficient, which is normalized by dividing the peak value by the square root of the sum of squares of M_d^{PS} , becomes an index of the quality of the OFDR spectrum.

The correlation coefficient was measured when a 400-m long SM optical fiber was connected. Figure 14 shows the difference in correlation coefficient with and without PICC. Without coherence compensation, the correlation coefficient deteriorates rapidly beyond the position of the reference interferometer delay length (85.3 m) where coherence is maximum. However, with PICC, the correlation coefficient is maintained above 90% through all regions of the connected optical fiber.

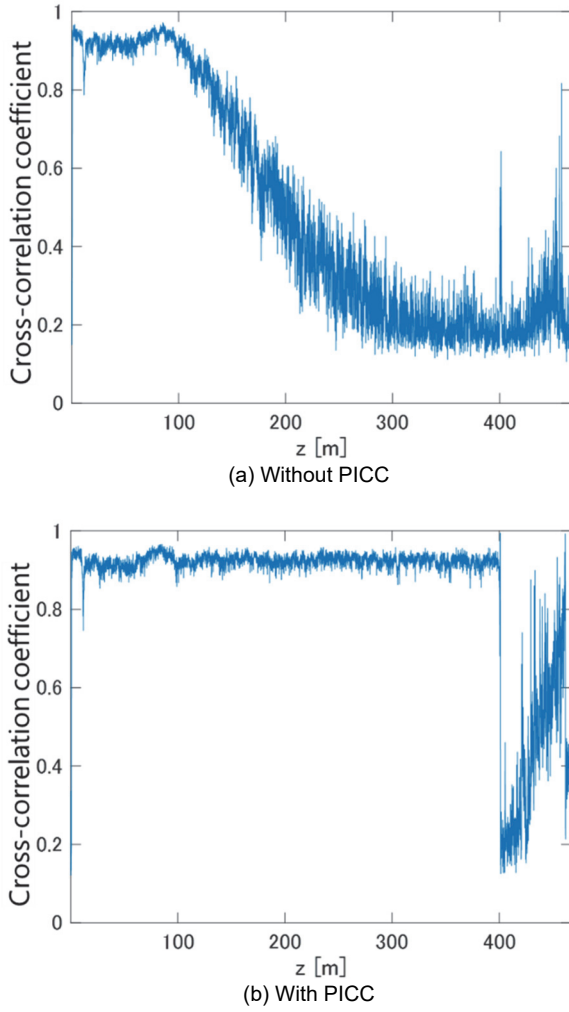


Figure 14 Cross-correlation function

6 Strain Measurement using PICC OFDR

6.1 Static Strain Distribution Measurement

Figure 15 shows the external view of the developed PICC OFDR-based strain distribution tester. The laptop workstation on the top of the tester has a built-in Graphics Processing Unit (GPU). The main unit under the workstation contains an Anritsu wavelength-swept light source (10-nm wavelength sweep width, 144-Hz sweep frequency), an interferometer (83.5-m reference interferometer delay length), and an A/D converter (2 channels, 5 GS/s sampling frequency). The number of A/D samples was set to 2 million and A/D sampling is performed over 1.7 nm near the approximate center of the 10-nm sweep width. The OFDR resolution is 0.446 mm, and the OFDR spectrum observation range is 450 m.

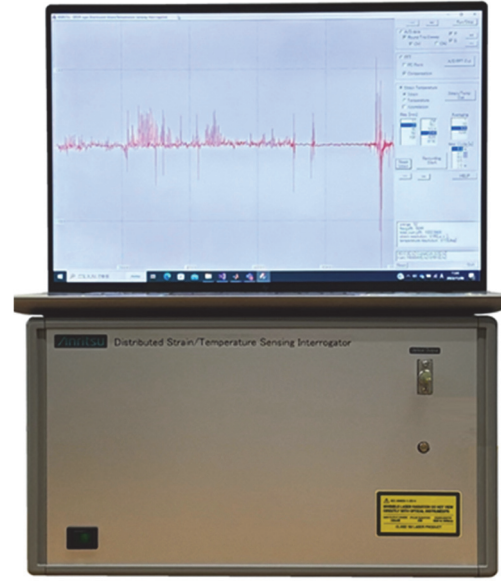


Figure 15 External view of strain distribution tester with PICC OFDR

To evaluate the static strain distribution measurement performance of the PICC OFDR strain distribution tester, the relationship between the strain value calculated by Eq. (14) and the actually applied value was measured using the optical fiber elongation/compression test rig shown in Figure 16. This test rig allows elongation of an optical fiber by fixing the SC connector parts of a 510-mm long optical fiber with SC connectors at both ends to a micrometer-equipped stage on an optical rail.

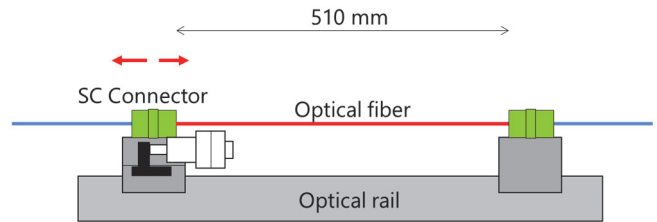


Figure 16 Optical fiber elongation/compression test rig

The actually applied strain value s_{App} is calculated from the micrometer value δl and the length l of the elongated section as:

$$s_{App} = \frac{\delta l}{l} \quad (17)$$

Figure 17 shows the strain distribution with this test rig connected to the ends of a 400-m long optical fiber while strain is applied measured with a spatial resolution of 100 mm and a strain resolution of 0.34 $\mu\epsilon$. Approximately 1500 $\mu\epsilon$ of tension was pre-applied as the reference state, and negative strain distribution was also measured from there by loosening the tension. Measurements were possible up to

+900 $\mu\epsilon$ on the elongation side and up to -800 $\mu\epsilon$ on the compression side, but when greater elongation or compression was applied, the cross-correlation deteriorated and normal strain distribution measurement was impossible. However, it reached 60% of the maximum measurable strain of 1500 $\mu\epsilon$ calculated from Eq. (17). This is because the PICC maintained the cross-correlation at a sufficiently large value even at a position of 400 m. Furthermore, without coherence compensation, the strain distribution could not be measured at all because it was buried in noise.

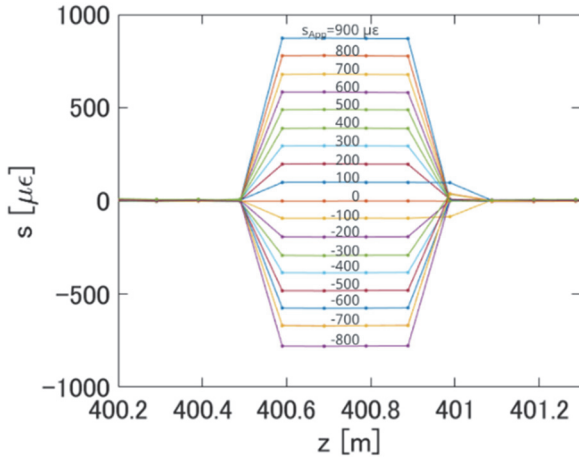


Figure 17 Strain distribution during strain application

Figure 18 shows the relationship between the applied strain s_{App} and the measured strain s . The two have a linear relationship, and measurement achieves high accuracy with an error of 1.3%.

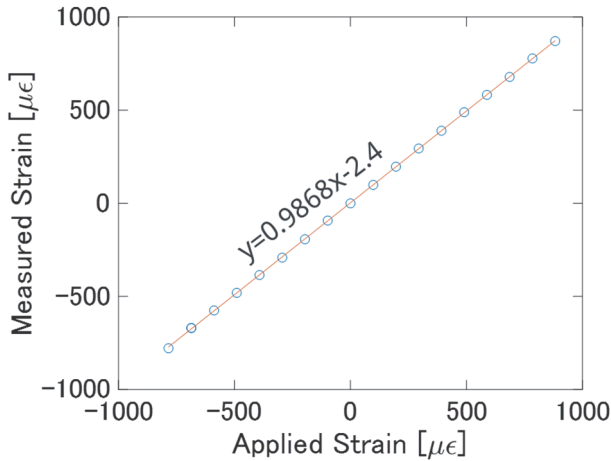


Figure 18 Relationship between applied strain amount and measured value

The relationship between spatial resolution and strain distribution was measured. Figure 19 shows the strain distributions measured with spatial resolutions set to 20, 50, 100, and 200 mm. As the spatial resolution becomes smaller,

the steep strain rise sections can be measured more accurately.

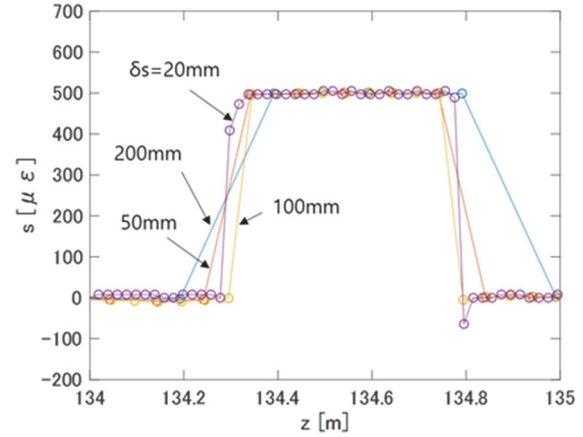


Figure 19 Spatial resolution dependency

Next, the relationship between strain resolution and strain distribution was measured. A fiber reel with a diameter of about 20 cm was placed in a location with a temperature gradient and the strain distribution due to thermal expansion was measured with a spatial resolution of 20 mm. Figure 20 shows the results measured with strain resolutions of 1.4, 5.3, and 23 $\mu\epsilon$. Naturally, the higher the measurement resolution, the more precisely strain changes can be measured.

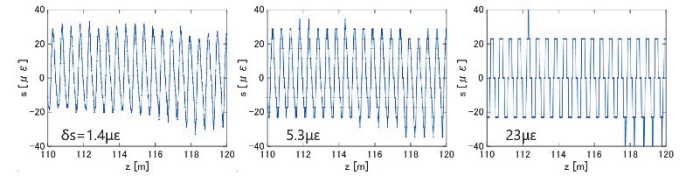


Figure 20 Strain resolution dependency

6.2 Dynamic Strain Distribution Measurement

The dynamic strain distribution was measured using the optical fiber elongation/compression test rig shown in Figure 16 operated with an automatic stage, which was programmed to repeatedly increase the strain linearly to 600 $\mu\epsilon$ over 2.4 s, pause for 0.2 s, and then decrease the strain to -600 $\mu\epsilon$ over 2.4 s. The strain distribution measurement settings were spatial resolution of 100 mm, strain resolution of 1.37 $\mu\epsilon$, phase integration coherence compensation interval of 40 m, and measurement frequency of 10 Hz.

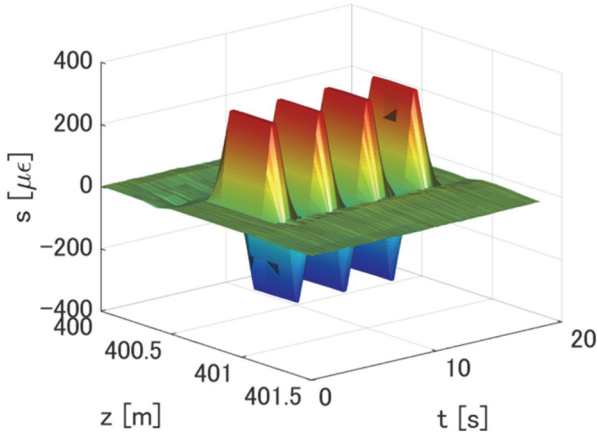


Figure 21 Dynamic strain measurement results

Figure 21 shows the dynamic changes in the measured strain distribution, indicating the applied dynamic strain is faithfully measured.

The blue line in Figure 22 indicates the temporal change in strain at a distance of 400.8 m, that is, the cross-section in the distance direction shown in Figure 21; the red line, indicates the strain applied from the automatic stage. The measured and applied strains match closely.

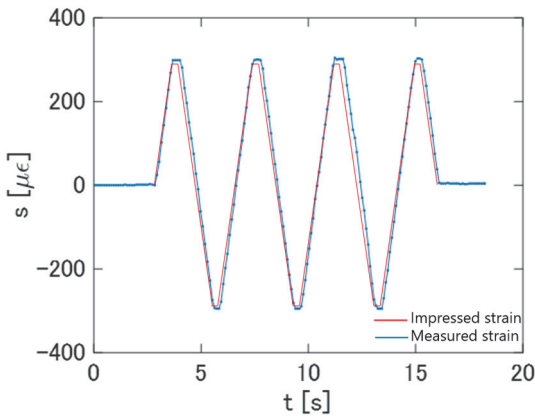


Figure 22 Temporal change in strain value at 400.8 m

Strain distribution measurement performs many FFT calculation cycles. Table 2 lists the number of FFT calculations for one strain distribution measurement when the number of A/D samples = 2 million, the OFDR resolution = 0.446 mm, the spatial resolution = 100 mm, the strain resolution = 1 $\mu\epsilon$ ($N_{RDz} = 2048$), and the PICC interval = 40 m. Ten real-time measurements per second are possible using the laptop built-in GPU built to process the enormous calculations.

Table 2 FFT Calculation Times

FFT Data Points	Calculation Times
2097152	58
2048	9000
4096	4500

The above calculation implements optimal linearization in all regions, but if the PICC implementation point is limited to one location, coherence compensation occurs only in its vicinity (about ± 20 m), and coherence deteriorates elsewhere. However, the measurement speed increases if the amount of computational processing is reduced by implementing limited PICC. Figure 23 shows the maximum value of the correlation function when PICC is implemented only at 400 m. The maximum cross-correlation value near 400 m exceeds 90%, but it decreases to 80% in the region from 100 to 300 m. However, the measurement speed was 20 Hz, which is twice as fast as when PICC is performed at 40-m intervals across the entire range.

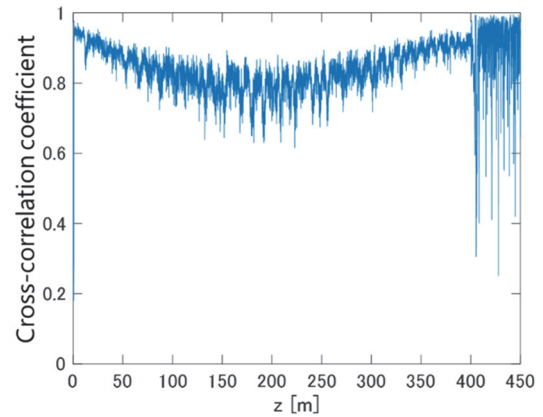


Figure 23 Cross-correlation coefficient when PICC applied only at 400 m

We created a cantilever (Figure 24) system capable of applying strain more rapidly than the test rig shown in Figure 16. This cantilever is a plastic plate with one end fixed, and optical fibers attached to the plate front and back surfaces, allowing strain to be applied to the fibers by flexing the plate.

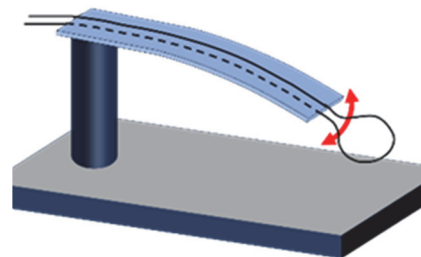


Figure 24 Cantilever

The strain distribution at the cantilever surfaces was measured by manually bending and then releasing the cantilever, causing it to vibrate. The strain distribution measurement conditions were set to a spatial resolution of 50 mm and a strain resolution of 1 $\mu\epsilon$. Figure 25 shows the temporal change in strain distribution, and Figure 26 shows the temporal change in strain at the center of the cantilever front and back surfaces. The detailed measurement captures how the strain at the front and back surfaces changes in a counter pattern during damping.

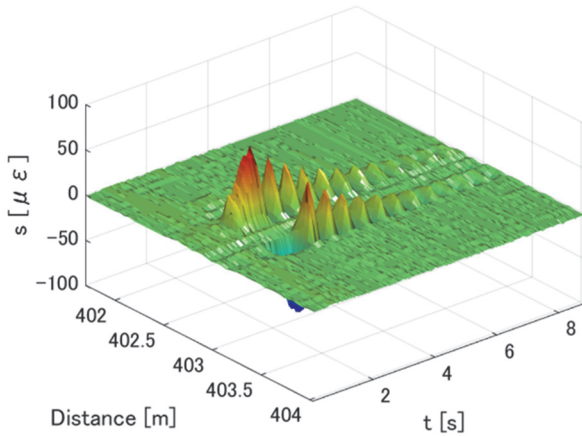


Figure 25 High-speed dynamic strain distribution measurement results

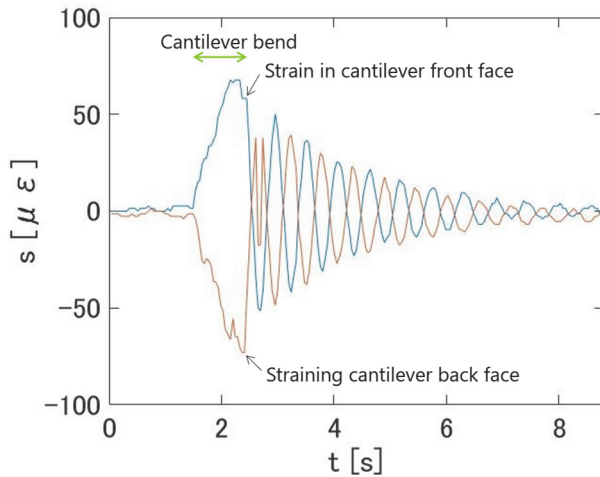


Figure 26 Strain at cantilever center front and back

7 Temperature Distribution Measurement using PICC OFDR

While the degree of optical-fiber elongation and compression can be measured at strain distribution measurement, it is impossible to distinguish whether the cause is due to external physical factors or thermal expansion.

Therefore, the measured strain assumes there is no thermal expansion. Conversely, if measurement assumes there is no strain, thermal expansion is causing elongation and compression and the temperature distribution can be measured from that strain. If the photo-elastic coefficient ρ for strain in Eq. (14) is changed to the thermoelastic coefficient ξ , the temperature distribution can be measured as:

$$T = T_{ref} + \delta T = T_{ref} + \frac{m\lambda}{2nD_z\xi} \quad (18)$$

where, T_{ref} is the temperature of the optical fiber when the frequency component reference value M_{dref}^{PS} was acquired.

Three fiber reels with optical-fiber lengths of 50, 30, and 20 m, each with a winding diameter of 12 cm were connected in series, and the temperature distribution was measured using this as a temperature-distribution sensor. As shown in Figure 27, device X with a heat source inside was placed on a wooden test table in the laboratory. The 50-m fiber reel was placed on the wooden test table (measurement point A), and the 30-m and 20-m fiber reels (measurement points B and C, respectively) were both placed on device X. The heat source inside device X was directly under measurement point C.

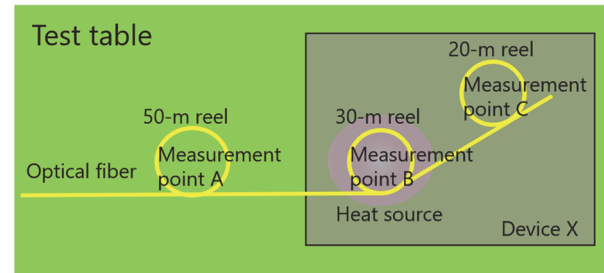


Figure 27 Temperature distribution sensor arrangement

Measurement of the temperature distribution was started at 20:00 in winter, and the power to device X was turned on at the same time. The overall temperature at that time was 22°C. The laboratory air conditioning stopped at 20:00 PM and restarted next morning at 07:00. The temperature resolution was set to 0.07°C, the spatial resolution to 50 mm, and the measurement time interval to 1 minute; measurements were continued for about 12 hours. Figure 28 shows the results.

Figure 28(a) shows the temperature distribution over 12 hours for all regions; (b) shows the temperature distribution at 1 minute and 5 hours after the measurement start; and (c) shows the temperature changes at the 25, 75, and 90 m points. The temperature at measurement point A (0 to 50 m) remained almost constant, but there was a temperature

increase of 3.5°C at measurement point B (50 to 80 m) and 3°C at measurement point C (80 to 100 m). The temperature increase at points B and C was completed in about 15 minutes after the start, and remained stable thereafter.

When the laboratory air conditioning started at 07:00 AM (11 hours after the measurement start), there was a temporary temperature drop of 0.6°C at all points. This is because cooler air rather than warm air is blown more strongly immediately after the air conditioning starts. The subsequent gradual cooling is thought to be due to cooling of device X by the air flow.

This test shows how the PICC OFDR system enables high-precision temperature distribution measurement over a wide range.

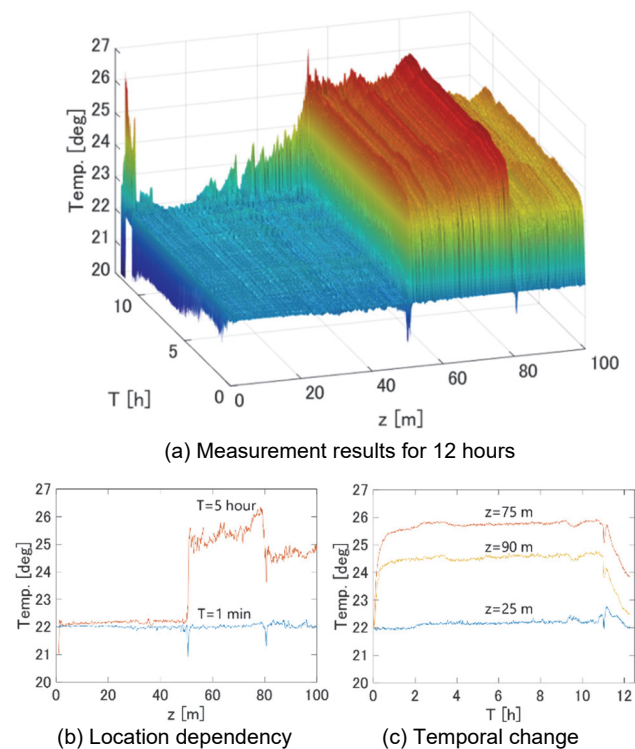


Figure 28 Measured temperature distribution results

While temperature distribution over a wide area can be measured relatively easily using thermal cameras, etc., the PICC OFDR method of measuring temperature distribution is useful for measurement targets that cannot be photographed from outside, such as batteries embedded in electric vehicles or underground power cables.

8 Conclusions

We devised a PICC method as an essential coherence compensation method for OFDR systems, and developed an OFDR system implementing this technique. This PICC OFDR system facilitates coherence compensation along the full fiber length, supporting high-quality measurement of OFDR spectra. Additionally, we developed a program to rapidly calculate the strain distribution of optical fibers from the obtained OFDR spectra, enabling real-time measurement of strain and temperature distributions.

Presented high-precision strain and temperature distributions measured using this PICC OFDR system demonstrate that it significantly improves OFDR performance.

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