Optical Interference Measurement using High-Coherence Wavelength Swept Light Sources

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[Summary] Conventional contact measurement is replacing product shape inspection by non-contact optical measurement as part of the evolution of "smart factories". Optical measurement includes various non-contact and non-destructive optical interferometry methods. Conventional methods feature accuracies ranging from nm to µm-order levels, but measurement distances are short, and high measurement accuracy is difficult to achieve due to meter-level measurement distances for targets with large surface areas. Our Wavelength swept light source with high coherence length supports accurate measurement over distances of several meters. This article explains the basic principles of OFDR as a typical optical interferometry measurement method and discusses the results of some actual measurement examples. A block gage with 2-µm or less surface level steps was measured with high accuracy by OFDR using this light source. To demonstrate long-distance measurement on relatively large object, the side of a car body was measured at high accuracy. Furthermore, when the measured material transmits the measurement light, it is shown that the internal structure can be visualized, and the application example to the industrial OCT is also discussed.

1 Introduction

Production lines are introducing various sensing technologies due to the rapid digital transformation (DX) progress in manufacturing industry. The real-time data captured by these sensors is analyzed and fed-back to the manufacturing processes to improve productivity and product stability through advances in smart factory automation, which is expected to cut workforce requirements. Conventionally, measurement of product dimensions, displacement, and surface roughness on production lines has used sensors touching the product with a probe to measure positional displacement. This contact method has a problem with the vibration source. In addition, since it takes a long time to measure, a sampling inspection is performed. Therefore, it is difficult to completely eliminate non-spec products. More recently, the appearance of smart factories has seen replacement of conventional contact measurements by optical non-contact measurements, enabling in-line shape measurement of all products performed previously by testing product samples, while also cutting workforce size and improving productivity.

In addition to shape inspection at manufacturing, non-destructive inspection of internal structure is also required. Optical Coherence Tomography (OCT) is a well-known method for measuring internal structure. OCT is commonly used to obtain cross-section images of biological structures and is often used in ophthalmology for its merits of fast and precise measurement. Recently, these features are finding new applications in industrial fields[1)].

Concrete examples of optical methods for measuring shape and internal structure are white-light interferometry, Spectral Domain Optical Coherence Tomography (SD-OCT), and Swept Source Optical Coherence Tomography (SS-OCT). Table 1 lists typical optical non-contact measurement methods and their specifications. The measurement ranges and accuracies in the table are typical values for commercial products in the market.

Table 1 Optical Non-Contact Measurement Methods and Typical Specifications

Measurement Method	Light Source	Measurement Range	Measurement Accuracy
OFDR	Wavelength Swept Light Source	Several meters	Several µm
White-Light Interferometry	White Light Source (SLD*1, LED*2, etc.)	1 µm	1 nm
SD-OCT	White Light Source (SLD)	5 mm	5 µm
SS-OCT	Wavelength Swept Light Source	10 mm	5 µm
Time of Flight (ToF)	Pulse Light Source	100 m	10 cm
Optical Comb	Pulse Light Source	6 mm	1 µm

*1: Super Luminescent Diode
*2: Light Emitting Diode

White-light interferometry, SD-OCT, and SS-OCT have measurement ranges from several μm to several mm, and can realize high-precision measurement on the order of nm to μm. Consequently, they are ideal for close-range precision measurements of shallow depths and small areas. On the other hand, when the target object has a large area of cm^2 to m^2, measurement can require a long time because the target must be divided into small sections that can be measured one-by-one. Additionally, if the condition of the measurement target can affect the measurement system, such as when measuring a hot object, the target must be measured from a greater distance. In this case, it is difficult to measure with these methods. Time of Flight (ToF) using a pulse light source is one method for measuring from a distance. The ToF method measurement range is 100 m and has been developed mainly for self-driving automobile Light Detection And Ranging (LiDAR) applications. However, it is unsuitable for industrial quality-inspection applications due to the relatively low measurement accuracy of about 10 cm. Despite being a form of ToF, the optical comb method can measure with μm-order accuracy. It uses optical pulses generated by an optical frequency comb to achieve very high accuracy, but the measurement range is only mm-order. Optical Frequency Domain Reflectometry (OFDR) is the ideal method for industrial applications because it combines a good measurement range with high accuracy. It is commonly described as a Frequency Modulated Continuous Wave (FMCW) method. It measures the distance to the target object with high accuracy using the interference signal between the light reflected from the target and the reference light, achieving an accuracy on the order of several μm over distance ranges from several cm to several meters, explaining why it is being developed for LiDAR applications. The specifications of the light source used by these wavelength swept light sources must be chosen according to the required measurement resolution and speed. For example, achieving a high positional resolution requires a light source with a wide wavelength sweep width, while a light source with a high wavelength sweep frequency is required to measure a target moving at high speed. Additionally, measurement over a wide range requires selecting a light source with high coherence. Using a high-coherence light source supports measurement of the OFDR interference signal with a high Signal to Noise Ratio (SNR), which improves the positional resolution and accuracy.

Our company has developed and sells wavelength swept light source models (AQA5500P, AQB5500P, AQA5500D, and AQB5500D). These wavelength swept light sources are Littman-type external resonator lasers with a Micro Electro-Mechanical System (MEMS) scanning mirror and etalon grating to achieve the following features[2), 3)]:

(1) kHz-order high-speed wavelength sweeping (AQA5500P and AQA5500D)
(2) High coherence due to single-vertical-mode, narrow-line-bandwidth laser
(3) Mode-hopping (wavelength shift) free, continuous wide wavelength sweep width

This article introduces the specifications of our wavelength swept light sources and explains the basic principles of OFDR surface shape measurement using these wavelength swept light sources in actual measurement examples. The first example explains precision surface measurement of a block gage with step level differences of 2 μm or less. The next example explains measurement of a comparatively large car side body with μm-order precision from long-distance. The last example shows measurement of the internal cross-section structure of a target that transmits light as an industrial application of OCT.

2 Wavelength Swept Light Source Specifications

Figure 1 shows the external appearance of our wavelength swept light sources and Table 2 lists the main specifications. The model line includes two designs: a standalone benchtop type (Figure 1(a)), and a built-in type for installing in users' products (Figure 1(b)). Two wavelength sweep frequency models, 1250 Hz and 150 Hz, have been developed to meet the measurement requirement of different markets.

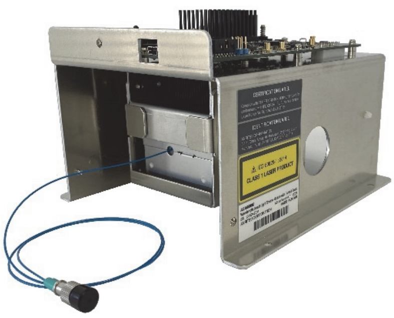
These wavelength swept light sources are configured from a wavelength swept light source module using a MEMS scanning mirror and a control board for driving the light source module. Use of this light source module requires precise control of the module's internal temperature and current source for Laser Diode (LD) oscillation, as well as the signal levels and frequency to drive the MEMS scanning mirror. Therefore, to improve users' convenience, the product configuration includes a control board to simplify control of the optical module internal temperature and LD current.

Table 2 Main Specifications of Wavelength Swept Light Source

Item	Specification				Remarks
Model	AQA5500P	AQB5500P	AQA5500D	AQB5500D	
Type	Benchtop standalone		Built-in		
Appearance					
Dimensions	137.4 (W) × 131.4 (H) × 219.4 (D) mm		160 (W) × 118.6 (H) × 175 (D) mm		Excluding projections
Optical characteristics					
Sweep Center Wavelength	1550 ±5 nm				AQA5500P/AQA5500D: At 110 nm sweep AQB5500P/AQB5500D: At 70 nm sweep
Wavelength Sweep Width	30 to 110 nm	15 to 70 nm	30 to 110 nm	15 to 70 nm	Setting Resolution: 1 pm Set from PC software via USB
Sweep Frequency f_{res}	1250 ±50 Hz	150 ±20 Hz	1250 ±50 Hz	150 ±20 Hz	Fixed non-adjustable value
Average Optical Output	≥10 mW				CW Class 1 (IEC 60825-1:2014)

The bench-top models include an internal cooling fan along with the optical module and control board to stabilize operation within the operating-environment temperature range. The built-in models do not have a case and internal fan to facilitate matching the wavelength swept light source with the user's product implementation.

(a) Benchtop Type (AQA5500P/AQB5500P)



(b) Built-in Type (AQA5500D/AQB5500D)

Figure 1 External Appearance of Wavelength Swept Light Sources

These wavelength swept light sources are powered by +12 Vdc. When first supplying power, calibration starts automatically to stabilizing the temperature of the light source module and setting the appropriate current value for the LD according to the usage environment. Although wavelength sweeping starts at the wavelength sweep width set initially at shipment (110 nm for 1250-Hz models, or 70 nm for 150-Hz models), the wavelength sweep width can be changed using control software running on a Personal Computer (PC) connected via USB cable to the USB connector on the front of the main unit.

Figure 2 shows the control software screen. Except for setting the wavelength sweep width, this software uses Standard Commands for Programmable Instruments (SCPI) commands to monitor normal operation and error conditions of the light source. Up to four wavelength swept light sources can be connected to one PC running the control software sending separate commands to each light source.

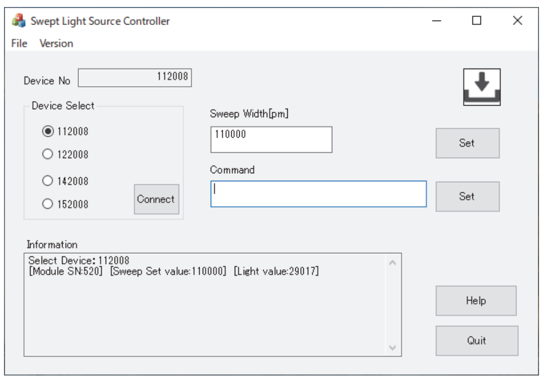
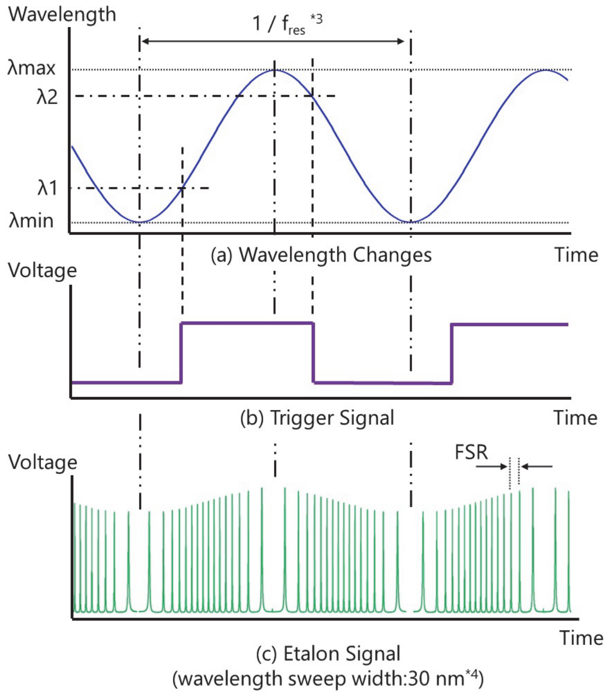


Figure 2 Control Software Screen

The wavelength swept light source has an optical output connector, a power supply input socket, and a USB connector as well as signal output connectors for the trigger signal and etalon signal. Figures 3(a) and (b) show the wavelength changes and the trigger-signal at sweeping, respectively. Wavelength sweep is realized by the reciprocating motion of the MEMS scanning mirror, and the wavelength is swept in a sinusoidal shape as shown in Figure 3(a). The trigger-signal is output at the same timing as the wavelength sweep as shown in Figure 3(b). As shown by λ1 and λ2 in Figure 3(a), the timing of the rising and falling edges of the trigger signal is set by the wavelength value using SCPI commands from the control software. The trigger signal can be used to specify the measured data acquisition range for the wavelength sweep width.

The light source module in this wavelength swept light source has a built-in etalon which have a transmission spectrum with a periodic peak at a constant wavelength interval (Free Spectral Range: FSR) when the swept wavelength optical signal is incident to it. The transmitted light from the etalon is converted to an electrical signal and output. Figure 3(c) shows the etalon signal when the wavelength sweep width is 30 nm. On the wavelength axis, the etalon signal FSR constant, but since this wavelength swept light source sweeps wavelengths sinusoidally over time, the etalon signal FSR is also observed in the corresponding interval. As understood from Figure 3(a), since the wavelength sweep speed is relatively slower at the turnback point compared to near the center of the sweep wavelength, the observed etalon signal FSR is widened. Based on this correlation, the etalon signal can be used to compensate nonlinearity of the wavelength sweep. Moreover, the etalon signal FSR is calibrated precisely at shipment using a hydrogen cyanide (HCN) gas cell.



*3 : $1/f_{res}$ = 1/1250 Hz = 0.8 ms (AQA5500P/D typ. value)
$1/f_{res}$ = 1/150 Hz = 6.7 ms (AQB5500P/D typ. value)
*4 : λmax − λmin = 30 nm

Figure 3 Swept Wavelength, Trigger Signal, and Etalon Signal at Sweeping

3 Basic Principles of OFDR

This section explains the basic principles of OFDR measurement using a wavelength swept light source. Figure 4 shows the basic OFDR configuration.

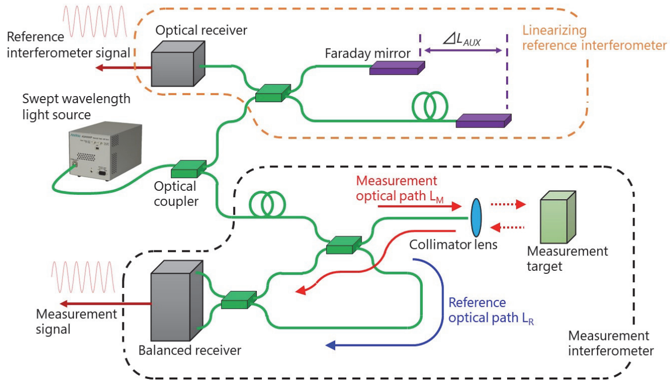


Figure 4 Basic OFDR Configuration

The light output from the wavelength swept light source is split by an optical coupler into the two paths to a reference interferometer[4)] for linearizing and to a measurement interferometer where the light is split again by another optical coupler into a reference optical path L_R, and a measurement optical path L_M. The light split to the reference path is inserted to an optical coupler for combining. The light that is split to the measurement path is emitted into free space from a collimator lens. The light emitted into free space is reflected by the target to be measured, passes through the collimator lens again, and then is incident on the optical coupler. Each light from the reference path and the measurement path is combined by an optical coupler, and then converted into an electric signal by a balanced receiver. As the frequency of the light emitted from the wavelength swept light source increases linearly over time, the optical frequency $\nu(t)$ at time t can be expressed by Eq. (1).

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

where, ν_0 is the optical frequency at time 0, and k is the sweep speed. Since the reference and measurement optical paths have different lengths, time difference τ occurs when the light of each optical path is combined by the photoreceiver. Assuming that the difference between the reference optical path length L_R and the measured optical path length L_M considering the refractive index is ΔL and the speed of light in vacuum is c, the time difference τ is expressed as follows.

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

In addition, when the electric field strengths of the light passed via the reference and measurement optical paths are E_R, and E_M, the interference intensity P detected by the optical receiver is represented by the following equations.

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

Assuming the interference signal DC components are filtered-out, only the last third term of Eq. (3) is observed. In other words, sweeping the optical frequency linearly as shown in Eq. (1), the interference signal with a frequency f_{Beat} proportional to ΔL is output from the optical receiver as shown in Eq. (4).

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

Here, the length of the optical reference path from the wavelength swept light source to the optical receiver (blue solid line in Figure 4) and the length of the optical measurement path to the collimator lens and from the collimator lens to the optical receiver (red solid lines in Figure 4) are adjusted to the same length using optical fiber so information on the distance of the measurement target from the collimator lens is included in the interference signal f_{Beat}. After sampling the interference signal f_{Beat}, Fast Fourier Transformation (FFT) reveals the f_{Beat} peak position and the distance from the collimator lens to the measurement target by calculating ΔL from Eq. (4).

On the other hand, after the light that was split to the reference interferometer for linearizing is reflected by the Faraday mirror, it is output from the optical receiver as the reference interference signal with a frequency corresponding to the difference in the length of the optical path ΔL_{AUX}. The reference interferometer signal for linearizing is used to compensate sweep wavelength non-linearity. If the sweep wavelength changes linearly with time, the frequency of the interference signal output from the measurement interferometer is constant and a sharp peak is obtained at the position corresponding to the frequency found from the results of FFT. However, since the frequency of the light output from the wavelength swept light source is generally nonlinear over time, the interference signal frequency changes with time and a broad peak is observed after FFT. As a result, it is difficult to evaluate the peak position accurately. For example, as shown in Figure 3(a), the shape of the sweep wavelength from our wavelength swept light source is a sine wave over time and the nonlinearity is especially apparent at the wavelength turnback point. Consequently, at actual measurement, it is very important to calibrate for the effect of nonlinearity using both the measurement interferometer including the measurement target and the reference interferometer[3]. Sampling the measurement signal at the rise timing of the reference interferometer signal can be used to calibrate the effect of nonlinearity. Therefore, the reference interferometer optical path length difference ΔL_{AUX} is set according to the distance to the measurement interferometer measurement target. In concrete terms, when the distance from the measurement interferometer collimator lens to the measurement target is 1 m, ΔL is the two-way distance of 2 m. At this time, ΔL_{AUX} must be 2 m (4 m for return) because sampling theory requires twice the reference interferometer signal frequency from the Nyquist frequency viewpoint.

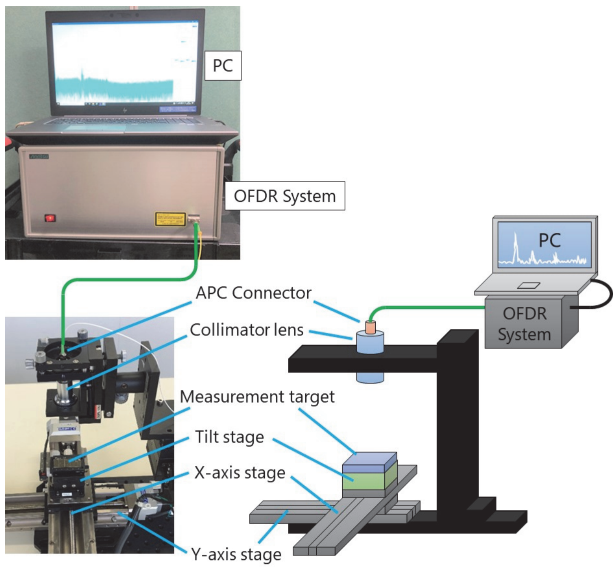
The maximum measurement distance is affected by the measurement system bandwidth and the wavelength swept light source coherence length. The frequency of the interference signal f_{Beat} increases in proportion to the distance from the collimator lens to the target to be measured, and the upper limit of the measurable f_{Beat} frequency is limited by the response bandwidth of the A/D conversion board or the receiver. Consequently, the maximum measurement distance is limited by the measurement system bandwidth. Since the reference interferometer signal is also limited similarly, the same investigation is necessary when setting the reference interferometer signal optical path length difference ΔL_{AUX}. Additionally, the coherence length of the wavelength swept light source is an important factor. When the measurement interferometer optical path length difference ΔL is the coherence length or longer, since the correlation between the light passing along both optical paths is lost, the peak line width after FFT widens by up to twice the actual laser line width and the peak position detection accuracy is severely degraded. Since the optical path length difference ΔL must consider the round trip path distance to the measurement target, if the distance from the collimator lens to the measurement target is equivalent to at least half the coherence length, this phenomenon becomes very conspicuous. Consequently, when the distance to the measurement target is large, as well as increasing the measurement system bandwidth for the optical receiver and A/D conversion board, it is also necessary to select a light source with a long coherence length. Our single-vertical-mode wavelength swept light source with narrow-line-width laser has high coherence and is an excellent light source for OFDR measurements[4), 5)].

The reference Interferometer uses a Faraday mirror and variations in the interference signal due to polarized waves are eliminated because reflected light is inserted to the optical receiver in the same polarization state regardless of the optical path length difference.

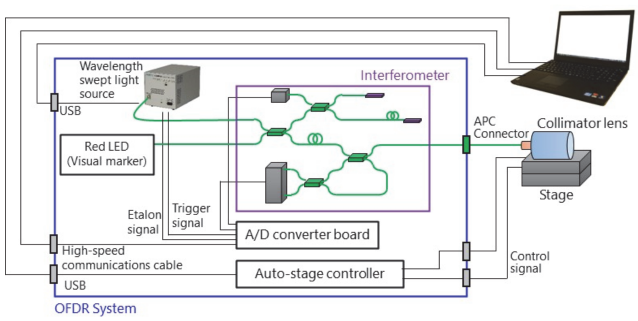
4 Surface Shape Measurement Using OFDR

4.1 Configuration of OFDR Measurement System

This section describes the configuration of an actual OFDR measurement system as well as surface shape measurement. Figure 5(a) shows the external appearance of the configured OFDR system and Figure 5(b) shows the internal configuration. For portability, the AQA5500P wavelength swept light source, optical interferometer, optical receiver, and the A/D conversion board for data acquisition, etc., are housed in a single cabinet with dimensions of 370 (W) × 180 (H) × 340 (D) mm. The collimator lens section for outputting light to the measurement target is placed outside the cabinet and fixed so as to face the target to be measured. The target to be measured is placed on a stage that operates in the x- and y-axis directions, and is controlled by an automatic stage controller mounted in the cabinet. As a result, this system setup scans the surface shape of the measurement target in two dimensions. Additionally, to verify the measurement position, red light from an LED is injected from the optical coupler in the optical interferometer. The red light is output from the collimator lens to visually indicate the current scan position. However, this red light has no effect on the measured OFDR results. Sampled data is analyzed by the A/D converter board and sent to an external PC for display. Data is transferred to and from the A/D converter board via high-speed communications cables. To facilitate high-speed data processing, a PC with a built-in high-performance Graphics Processing Unit (GPU) was selected.



(a) External Appearance and Configuration of Surface Shape Measurement System



(b) Internal Configuration of OFDR System

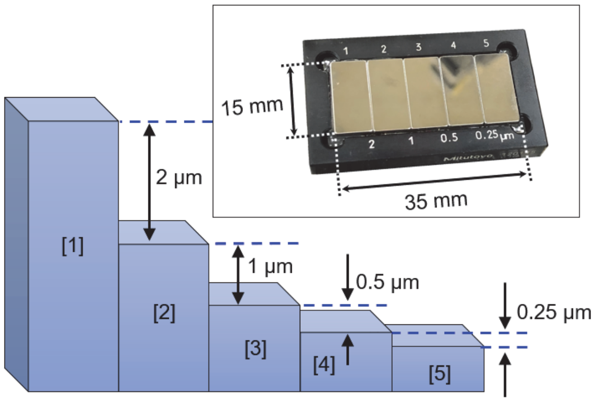
Figure 5 OFDR System Setup

4.2 Measurement of Block Gage Surface Shape

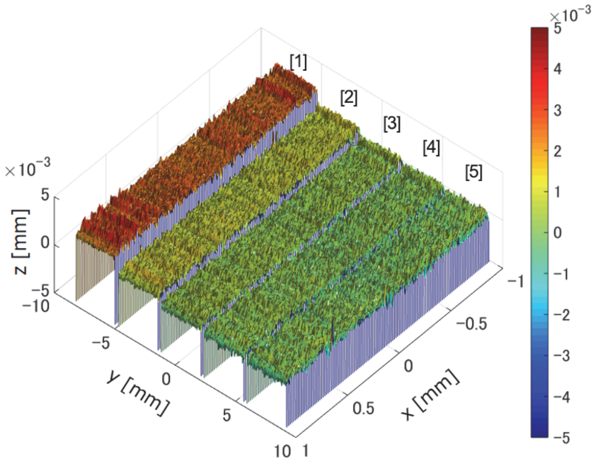
First, the surface shape of a block gage with nominal steps of 0.25 µm, 0.5 µm, 1.0 µm, and 2.0 µm was measured. The block gage was placed at 137 mm from the end face of an Angled Physical Contact (APC) optical fiber connector. The wavelength sweep width was set to 110 nm, and the range of 104 nm in the center with high linearity was used for sampling. The theoretical resolution Δz was 12 µm found[5)] from Eq. (5). where λc is the sweep center wavelength, and $\Delta\lambda$ is the sweep width. Although the theoretical resolution value is large with respect to the step of the block gage, it can be measured with high accuracy by detecting the peak position after FFT analysis with high accuracy.

$$\Delta z = \frac{1}{2}\frac{\lambda_c^2}{\Delta\lambda} \tag{5}$$

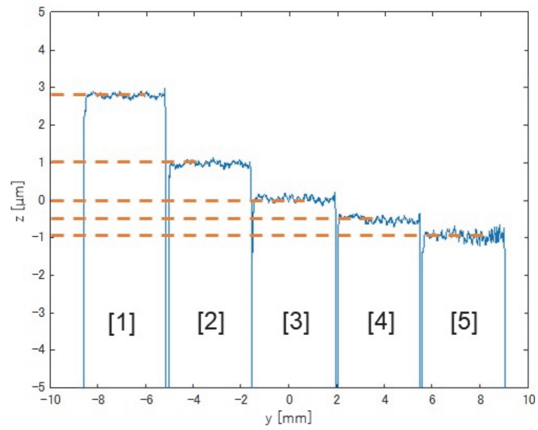
Figure 6(a) shows the external appearance of the block gage and the nominal surface shape; Figure 6(b) shows the measured surface shape. Analysis software was used to display the measured shape results. Five-hundred sample measurements were made in the y-axis direction (step direction) and 125 in the x-axis direction. The theoretical measurement time was 50 s calculated from the number of sampling points and the sweep frequency (500 points × 125 points ÷ 1250 Hz), but due to limitations of the automatic-stage movement speed, the actual measurement time was about 5 minutes. Figure 6(c) shows the averaged results for data in the x-axis direction. The y-axis is the relative height of the block gage referenced to the center height at [3]. Table 3 lists the block gage maker's actual measured heights from the product certificate, the heights measured by OFDR, and the respective differences between the two values. Table 4 lists the results at 609 mm between the end face of the APC connector and the block gage. The 609-mm distance set here was the maximum measurable range maintaining the high distance resolution. When the block gage was positioned at a range of 137 mm, the maximum difference from the maker's values was 0.14 µm. However, even at 609 mm, the maximum difference was still only 0.26 µm. As mentioned at the start of this article, the measurement range is only several millimeters for other optical interferometry methods featuring low coherence. Using our company's high-coherence wavelength swept light sources facilitates measurement using high-SNR OFDR optical interference signals to implement high-resolution measurement over a wide distance range.



(a) External Appearance and Step Shape



(b) Surface Shape Measurement Result



(c) Average Values in x-axis Direction

Figure 6 Block Gage External Appearance and Measured Surface Shape

Table 3 Block Gage Measurements (at 137-mm Range)

Units: μm

Block Gage Relative Height (nominal)	[1]	[2]	[3]	[4]	[5]
	3.0	1.0	0	−0.5	−0.75
Maker's Value	2.94	1.0	0	−0.49	−0.83
OFDR Value	2.8	1.0	0	−0.5	−0.9
Difference	0.14	0	0	0.01	0.07

Table 4 Block Gage Measurements (at 609-mm Range)

Units: μm

Block Gage Relative Height (nominal)	[1]	[2]	[3]	[4]	[5]
	3.0	1.0	0	−0.5	−0.75
Maker's Value	2.94	1.0	0	−0.49	−0.83
OFDR Value	3.2	1.0	0	−0.4	−0.7
Difference	0.26	0	0	0.09	0.13

4.3 Car Surface Shape Measurement

This section explains measurement of the surface shape of a car body side as a relatively large object. The car body side dimensions are about 1.5 (H) × 4.4 (W) m. The measurement system was changed to that shown in Figure 7 to measure a large object from a long distance. A portable design was used to perform measurement outside. Cabinet parts such as the interferometer and A/D conversion board were the same as used in the measurement system shown in Figure 5(b). The collimator lens was mounted on a rotating stage with two degrees of freedom and scanning in two dimensions was performed using an auto-stage controller in the cabinet. The collimator lens was positioned at 4.5 m from the car and the focal point distance was adjusted to obtain the maximum power for light reflected from the measurement target. A measurement range of 1.9 m vertically and 4.6 m horizontally was achieved using an automatic stage with φ±12° of rotation in the vertical direction and θ±27° of rotation in the horizontal direction. The wavelength sweep width was set to 24 nm, and the central range of 10.5 nm with high linearity was used for the measurement. As a result, the theoretical resolution is 113 μm. Although the settings were outside the AQA5500P specifications, a lower resolution was used to facilitate long-distance measurement. When measuring, it was important to determine the optimum relationship between resolution, wavelength sweep width, measurement range, and optical signal frequency. From Eq. (5), resolution is inversely proportional to sweep width. However, since wavelength sweep speed is proportional to wavelength sweep width, from Eq. (4), the frequency of the interference signal can be found from the ratio to the wavelength sweep width and, consequently, since the resolution increases when the wavelength sweep width is wide, the interference signal frequency is also high. This is similarly true for the reference interference signal, so widening the wavelength sweep width increases the reference signal frequency. Additionally, the measurement range is determined by the difference of the reference interferometer optical path length ΔL_{AUX}. As described previously, ΔL_{AUX} requires a length of twice the distance from the measurement interferometer collimator lens to the measurement target. Although widening the measurement range requires increasing the length of ΔL_{AUX}, simultaneously, from Eq. (4) we know that the frequency of the reference interferometer signal increases. Since the frequencies of the measurement and reference interferometer signals are limited by the bandwidth of the measurement system, such as the A/D conversion board, this measurement was performed with a theoretical resolution of 113 μm so that both the resolution and the measurement range are compatible. However, since the maximum sweep width of the AQA5500P is 110 nm, so setting a shorter measurement range can improve the resolution by about 10 times.

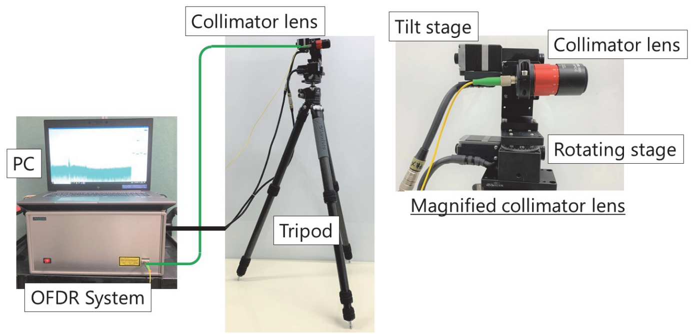


Figure 7 Car Body Surface Shape Measurement System

First, fixed point measurement was performed before measuring the shape of the car body. The position of the collimator lens was fixed and the car door part was measured for about 10 seconds; the results are shown in Figure 8. Since measurements were performed outside, the car body was vibrating slightly due to the effect of wind, etc., but this can be confirmed by the measured data with a standard deviation (σ) 5.6 μm.

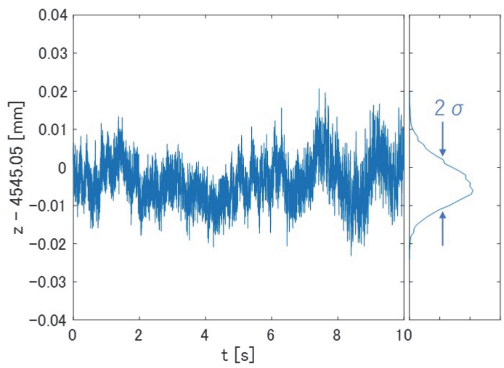
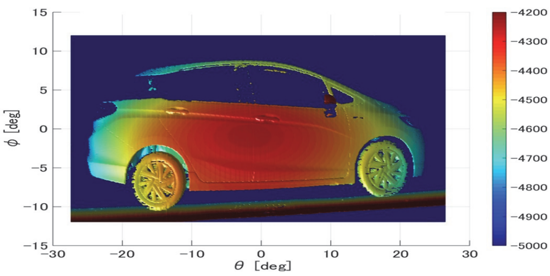


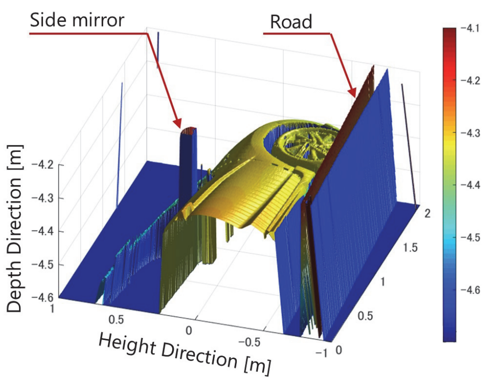
Figure 8 Fixed-Point Measurement Results

Figure 9(a) shows a photograph of the measured car and Figure 9(b) shows the shape measurement results with 500 × 500 pixels in the vertical and horizontal directions, respectively. The relatively large car body side can be measured at one time without dividing the measured areas by moving the OFDR system for each area. This measurement required about 12 minutes. It may be theoretically possible to shorten the measurement time to about 200 seconds (500 points × 500 points ÷ 1250 Hz) by using a faster automatic stage. Figures 9(c) to (e) show cross-sections near the car center. The magnified view in Figure 9(e) shows a ripple of about 50 μm, but shows high measurement precision even at long range.

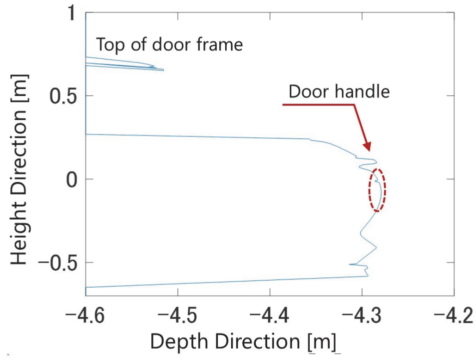
(a) Photograph of Measured Car



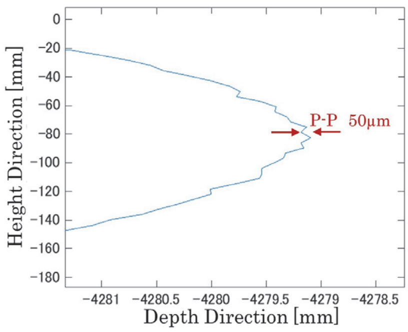
(b) Shape Measurement of Car Body



(c) Cross-Section Near Body Side Center



(d) Cross-Section Near Body Side Center



(e) Magnified Part of (d)

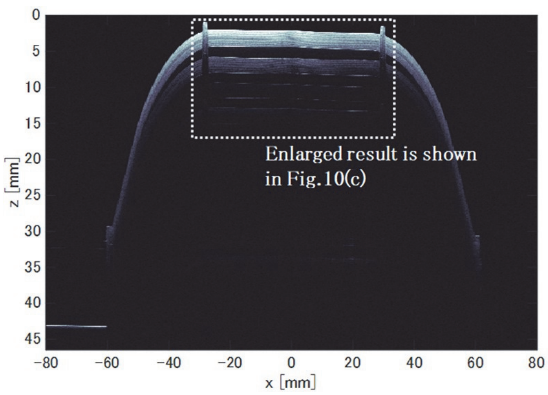
Figure 9 Car Surface Shape Measurement Results

5 Application to OCT

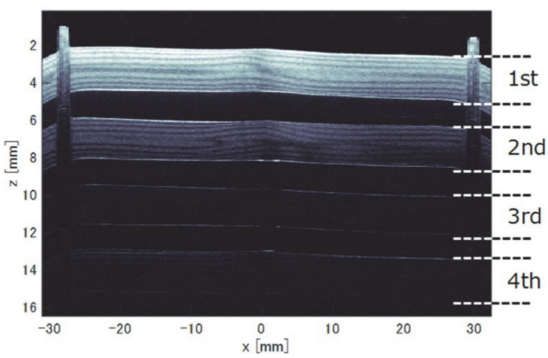
The examples of surface shape measurements so far have all used light reflected from the surface of the measurement target to measure the relative distance from the collimator lens to clarify the overall shape. When measuring targets made of materials that transmit light, the internal structure can be visualized by receiving reflected light from the internal refractive index boundary surfaces. Following the previous explanation of OFDR, this section presents an actual measurement example of using OCT to visualize internal structure. The measurement system setup is the same as shown in Figure 5. The wavelength sweep width was 110 nm with sampling centered around the high-linearity 104-nm range to give a theoretical resolution of 12 μm. The measurement target was positioned at about 100 mm from the collimator lens. First, four stackable thin polypropylene containers were measured. These containers transmit light at OCT measurement wavelengths. The maximum diameter of the containers was about 120 mm with a depth of 30 mm and thickness of 2 mm. The focal distance of the collimator lens was adjusted to obtain the maximum level for light reflected from the first container. The measurement time was limited by the rotation speed of the auto-stage and was about 1 second for the cross-section images shown here.

Figure 10(a) shows a photograph of the target container, Figure 10(b) shows the overall OCT image, and Figure 10(c) shows a magnified view of the top container. The OCT overall image in Figure 10(b) is 4027-pixels high and 500-pixels wide. Figure 10(c) clearly shows the polypropylene internal refractive boundaries visualized as a striped pattern. Additionally, although the sharpness drops as the light level decreases with measurement depth, all four stacked containers can be clearly seen. As described in section 4.3, although the measurement range is several meters in principle, absorption and scattering of light by the container back and internal surfaces limits the measurement depth in this case to about 13 mm.

(a) Photograph of Four Stacked Containers



(b) Overall View

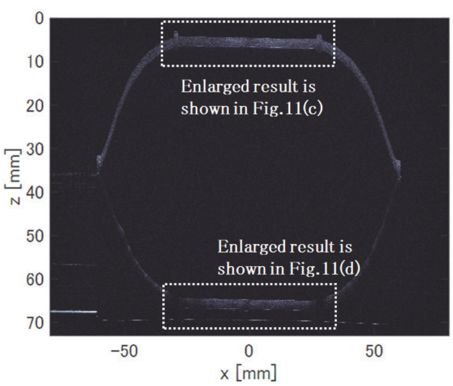


(c) Magnified View of Top Part of Upper Container

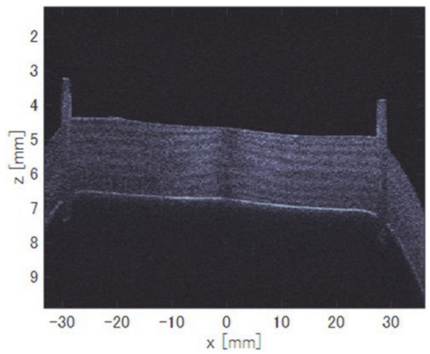
Figure 10 OCT Measurement of Four Stacked Polypropylene Containers

Next, we measured the container shown in Figure 10 with the lid fitted (Figure 11(a)). As a result, the overall height of the containers was doubled to 60 mm. In this measurement, since the depth of the target to be measured was wide, when matching the focal length of the collimator lens with the top and bottom of the container, the reflected power from the other side was very small, causing low cross-sectional sharpness in the measured results. Consequently, the focal length for measurement was adjusted to be near the center of the depth of field (z = 30 mm). Figure 11(a) shows a photograph of the measured container, Figure 11(b) shows the overall OCT cross-section, Figure 11(c) shows the magnified view of the top part of the container, and Figure 11(d) shows the magnified view of the bottom part of the container. The OCT cross-section in Figure 11(b) is 6330-pixels high and 500-pixels wide. The top side of the container is obviously the same as in Figure 10, but the internal structure of the bottom container can also be visualized from the refractive index boundary surfaces. These results were obtained using our high-coherence wavelength swept light sources supporting OCT measurements that other measurement methods cannot perform (Table 1).

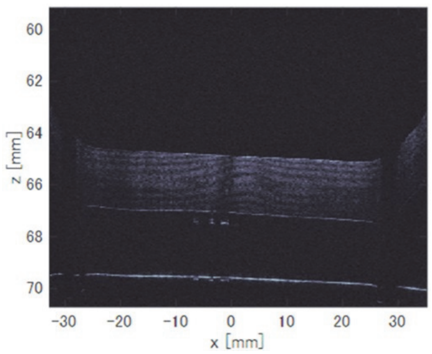
(a) Photograph of Measured Container



(b) Overall View



(c) Magnified View of Top Part of Upper Container



(d) Magnified View of Bottom Part of Lower Container

Figure 11 OCT Measurement of Two Layers of Polypropylene Containers with Closed Lid

Conclusions

After explaining the specifications of Anritsu's wavelength swept light sources, this article presents some actual shape measurements using OFDR. The surface of a block gage with fine step heights of 2 µm or less was measured first and an accuracy of better than 0.14 µm was achieved when the block gage was positioned 137 mm from the end face of an APC connector. Next, the overall shape of a relatively large side of a car body was measured in one scan from 4.5 m using the high-coherence feature of our wavelength swept light sources and achieved an accuracy of 5.6 µm. Additionally, an example of OCT measurement for industrial applications demonstrated visualization of the internal structure of a polypropylene container. In particular, a measurement range of better than 60 mm was achieved in comparison to a range of just a few mm from other manufacturers' OCT systems.

This wavelength swept light source is expected to have a wide application range in other fields. For example, the high-coherence feature will be useful for measurements in difficult-to-reach high places and for measurement of hot or vibrating parts that cannot be closely approached. Additionally, by using light transmissivity, it may be possible to measure temporal shape changes and vibration of targets in a case or temperature chamber through an observation window. Moreover, the maximum 110-nm wide wavelength sweep width is expected to have applications in instantaneous measurement of optical device reflection and transmission properties.

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