Technical Note

Anritsu Advancing beyond

Wavelength Swept Light Source

Operation Principles

and

OFDR Measurement Application

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1 Introduction

In recent years, optical interferometry method called Optical Frequency Domain Reflectometry (OFDR) has begun to apply in various fields such as dimensional metrology and optical fiber sensing. The Wavelength Swept Light Source (WSLS) is one of the key devices of OFDR. With the development of WSLS, high-speed and high-precision OFDR measurement has become possible. As a result, there has been remarkable progress with more commercial applications in fields such as precision shape measurement, thin-film measurement, fine-structure shape measurement and especially ophthalmology diagnostics.

The WSLS used for OFDR requires careful selection according to the measurement objective. Higher spetial resolution requires a light source with a wider wavelength sweep width. For faster measurement in real-time of fast-moving objects, a light source with a higher wavelength sweep frequency is needed. In addition, measurement over a wide distance range requires a light source with a longer coherence length than the distance range. Using long-coherence-length light sources for OFDR measurement can also improve interference signal to noise ratio (SNR) and the spatial resolution and accuracy.

Using a Micro Electro-Mechanical System (MEMS) scanning mirror, we have commercialized the WSLS with a high wavelength sweep frequency, a wide sweep width and a high coherence length. This technical note outlines our WSLS and describes the OFDR measurement application.

Fig. 1-1 External View of Wavelength Swept Light Source

2 Operation Principles

Figure 2-1 shows a schematic diagram of the wavelength swept light source.

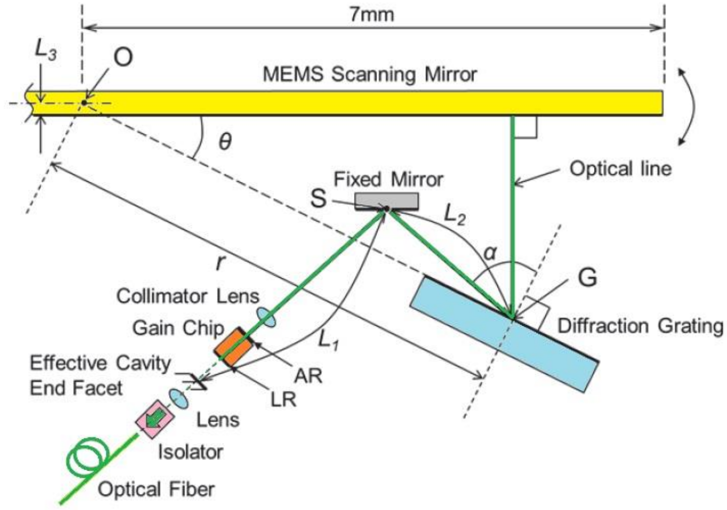


Fig. 2-1 Schematic Diagram of Wavelength Swept Light Source

The high sweep frequency is achieved by a unique Littman-Metcalf configuration using a MEMS scanning mirror. An external cavity is configured between the effective cavity end facet of gain chip and the reflective surface of the MEMS scanning mirror. In our light source, each optical component is arranged so that only one of the multiple longitudinal modes determined by the cavity length selectively oscillates. Moreover, as shown in Fig. 2-1, the optical parts can be arranged to satisfy Eq. (1) by locating the rotation center of the MEMS scanning mirror *O* on an extension line of the diffraction grating surface.

$$L1 + L2 + L3 = r \cdot \sin\alpha \tag{1}$$

where, *L1* is the effective optical path length from the effective cavity end facet of gain chip, taking into account the gain-chip refractive index to the incident point *S* on the fixed mirror, *L2* is the optical path length from the point *S* to the incident point *G* on the diffraction grating, *L3* is the distance from the rotation center of the MEMS scanning mirror *O* to the mirror surface, *r* is the distance from point G to point *O*, and *α* is the incident angle of the optical path from the fixed mirror to the diffraction grating.

When equation (1) holds, $d\lambda_{mode}/d\theta$ is equal to $d\lambda_{filter}/d\theta$, where *θ* is the angle between the MEMS scanning mirror surface and the diffraction grating surface, λ_{mode} is the vertical mode wavelength λ_{mode} determined by the external cavity path length and λ_{filter} is the peak wavelength of the wavelength filter that consists of the MEMS scanning mirror and the diffraction grating. Consequently, a single longitudinal mode selected by the filter is swept continuously without mode-hopping only by rotating the MEMS scanning mirror. (see Figure 2-2)

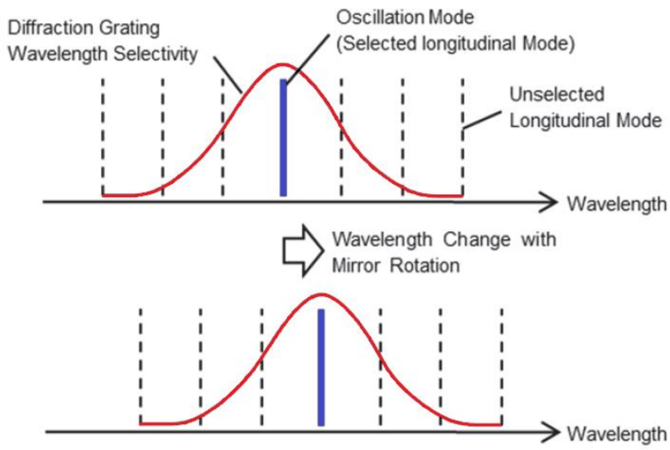


Fig. 2-2 Wavelength Selectivity of Etalon with Mirror Rotation and Change in Selected Oscillation Mode

To perform wavelength sweeping while suppressing mode hopping, it is necessary to achieve micron meter order stabilization of the rotation center position. This light source uses a MEMS scanning mirror to achieve both a stable rotation center position as well as high sweep frequency. The MEMS scanning mirror consists of a rotatable mirror part and a pair of torsion bars on a straight line. This simple and lightweight structure can rotate the mirror by twisting torsion bars as the axis to achieve high speed rotation without rotation center displacement. Additionally, rotating the MEMS scanning mirror at the resonance frequency achieves a large rotation angle, or in other words, a wide wavelength sweep width.

Figure 2-3 shows the sinusoidal change of rotation angle of the MEMS scanning mirror with time, where θ_0 is stationary angle of the scanning mirror, f_{res} is the resonance frequency, and $\Delta\theta$ is amplitude of the rotation angle. Since the oscillation mode wavelength changes almost linearly with the rotation angle, output wavelength from the light source is also sweptsinusoidally. Consequently, wavelength sweep rate reaches maximum where the change in the speed of the angle of rotation is highest ($\theta = \theta_0$), and becomes higher in proportion to the range of the rotation angle, or another words, the wavelength sweep width.

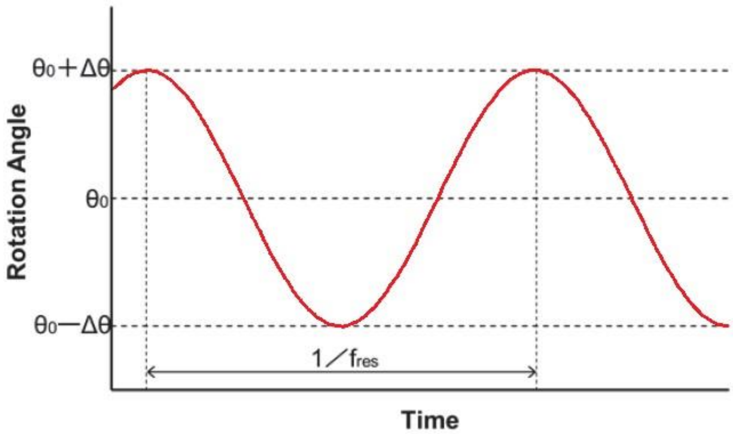


Fig. 2-3 MEMS Scanning Mirror Rotation Axis Time Variation

3 OFDR Measurement Application

This section outlines Optical Frequency Domain Reflectometry (OFDR) measurement and describes some measurement methods when using our swept wavelength light source.

3.1. OFDR Measurement Outline

OFDR measurement is one type of optical measurement method using laser-light interference. Figure 3.1-1 shows an example of a measurement system.

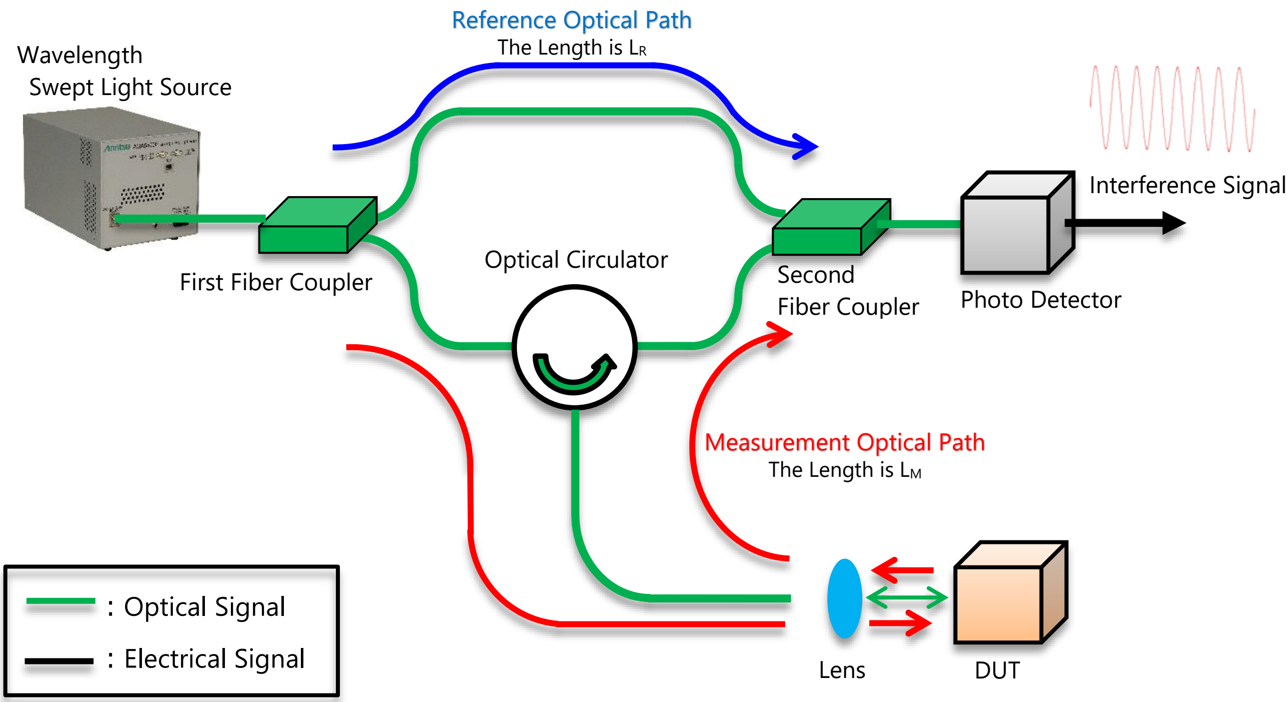


Fig. 3.1-1 OFDR Measurement System

The light output from the swept wavelength light source is split by the first fiber coupler into reference light and measurement light. The measurement light propagates the measurement optical path with a length of L_M (Red curve), then is output from the optical fiber after passage via a lens, etc., then is reflected by the DUT. This reflected light passes back through the lens and coupled to the optical fiber. Other hand, the reference light propagates the reference opical path with a length of L_R (Blue curve). The measurement light and reference light are combined by the second fiber coupler and occur interference, then detected by the photo detector. The interference signal output from the photo detector has the frequency according to the difference *z* in the lengths of the reference optical path and the measurement optical path found as

$$(L_M - L_R) = z \tag{2}$$

The propagatrion times of the measurement optical path and reference optical pass are deferent. This time difference τ is expressed by Eq. (3),

$$\tau = \frac{(L_M - L_R)}{c} = \frac{z}{c} \tag{3}$$

where, *c* is the velocity of light in vacuum. The frequency of the interferometer signal f_{Beat} is the difference between the optical frequencies of the measurement light and the reference light at the photo detector. When frequency sweep speed of the light is represented as *V* [Hz/s], f_{Beat} is expressed by Eq. (4).

$$f_{Beat} = V\tau = \frac{Vz}{c} \tag{4}$$

So, z can be measured by counting f_{Beat} (Fig. 3.1-2).

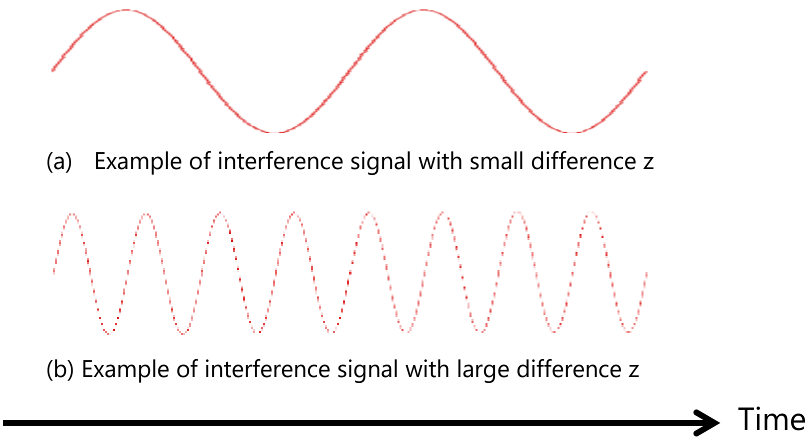


Fig. 3.1-2 Example of Interference Signal Observed at Photo Detector

Figure 3.1-3 (a) shows wavelength change against to time. The wavelength increases linealy from short wavelength to long wavelength. Other hand, the optical frequency decreases linealy from high frequency to low frequency as shown Fig. 3.1-3 (b).

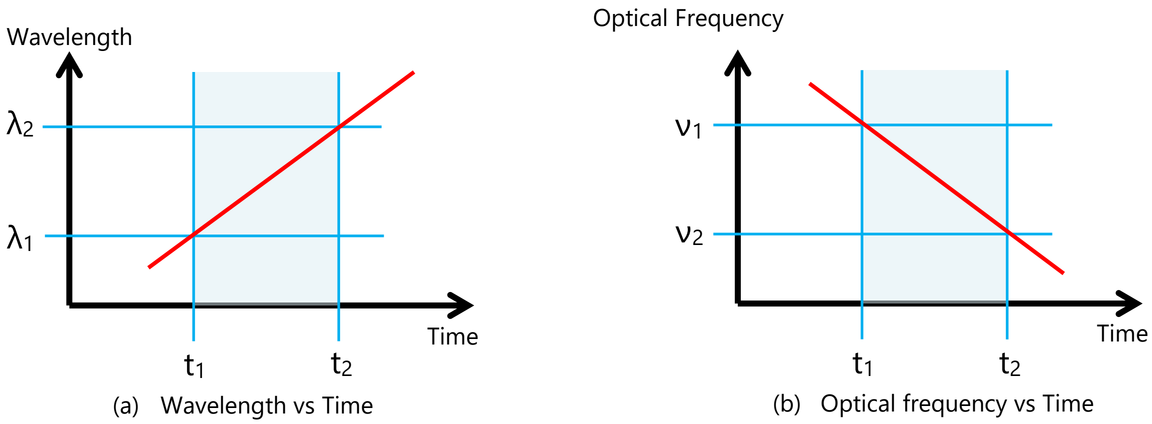


Fig. 3.1-3 Changes of Wavelength and Optical Frequency against to Time

When the interference signal is sampled from time t_1 to t_2 as shown Fig. 3.1-3, the number of waves *M* of the interference signal is expressed by Eq. (5)

$$M = f_{Beat}(t_2 - t_1) = \frac{Vz}{c}(t_2 - t_1) \tag{5}$$

The sweep speed *V* [Hz/s] is expressed by Eq. (6)

$$V = \frac{\nu_1 - \nu_2}{t_2 - t_1} = \frac{\frac{c}{\lambda_1} - \frac{c}{\lambda_2}}{t_2 - t_1} \cong \frac{c\Delta\lambda}{{\lambda_c}^2(t_2 - t_1)} \tag{6}$$

where the swept wavelength width $\Delta\lambda = \lambda_2 - \lambda_1$, λ_c is expressed as the sampling center wavelength. Consequently, *M* can be expressed by Eq. (7).

$$M = \frac{\Delta\lambda}{{\lambda_c}^2} z \tag{7}$$

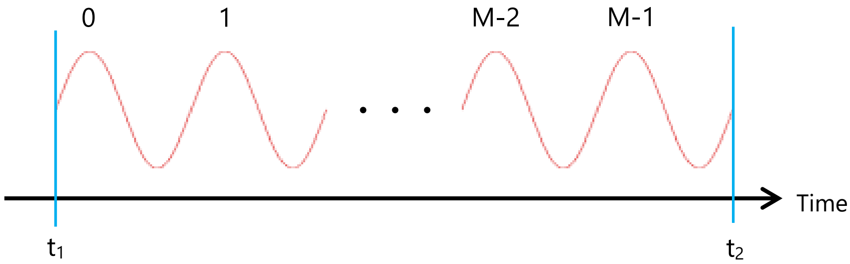
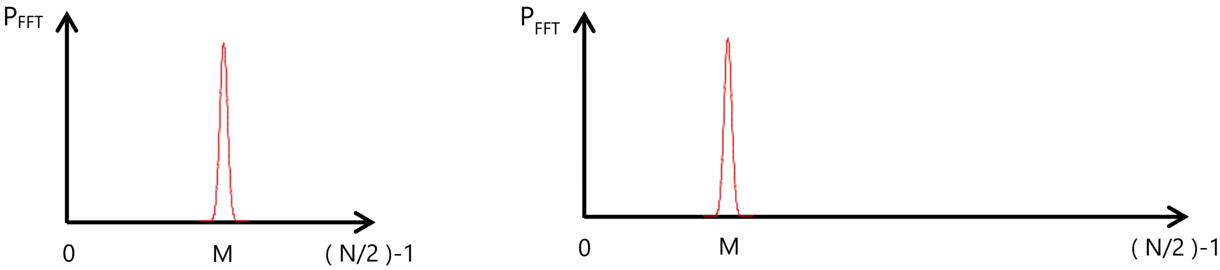


Fig. 3.1-4 Example of Sampled Interference Signal

The number of samples *N* from time t_1 to t_2 at sampling frequency f_s is expressed by Eq. (8).

$$N = f_S(t_2 - t_1) = f_S \frac{c\Delta\lambda}{V{\lambda_c}^2} \tag{8}$$

When performing FFT analysis on the sampled data, a peak in the FFT spectrum is observed at the position of *M*. As a note, although *N* increases as f_s increases, the value of *M* is unaffected. Since the measurement band width becomes wider as f_s increases, larger distance differences can be measured as shown Fig. 3.1-5.



(a) Small *N* (small fs)

(b) Large *N* (large fs)

Fig. 3.1-5 Example of FFT Calculation Result for f_s Size

Equation (9) expresses the number of waves of the interference signal *M′* when the DUT position in Fig. 3.1-1 is moved by dz.

$$M' = \frac{\Delta\lambda}{{\lambda_c}^2}(z + 2dz) \tag{9}$$

The dz is to be the distance resolution when M changes only 1. So, the distance resolution dz is expressed by Eq. (10).

$$M' - M = \frac{2\Delta\lambda}{{\lambda_c}^2} dz = 1$$

$$dz = \frac{{\lambda_c}^2}{2\Delta\lambda} = \frac{c}{2\Delta\nu} \tag{10}$$

In other words, the distance resolution is inversely proportional to the sampling wavelength width $\Delta\lambda$.

3.2. Wavelength Non-Linearity Calibration

When the relationship between the change in frequency of the light output from the wavelength swept light source and time is linear, the frequency of the interference signal output from the optical interferometer is constant and FFT analysis produces a peak matching this frequency. However, generally, the change in the frequency of the light is non-linear, the interference signal frequency changes with time, resulting in a wide peak after FFT analysis (Fig. 3.2-1) and making it difficult to evaluate the peak position. In general, this nonlinearity can be calibrated by adding a reference interferometer in addition to the measurement interferometer. This section describes the method for calibrating nonlinearity using the reference interferometer.

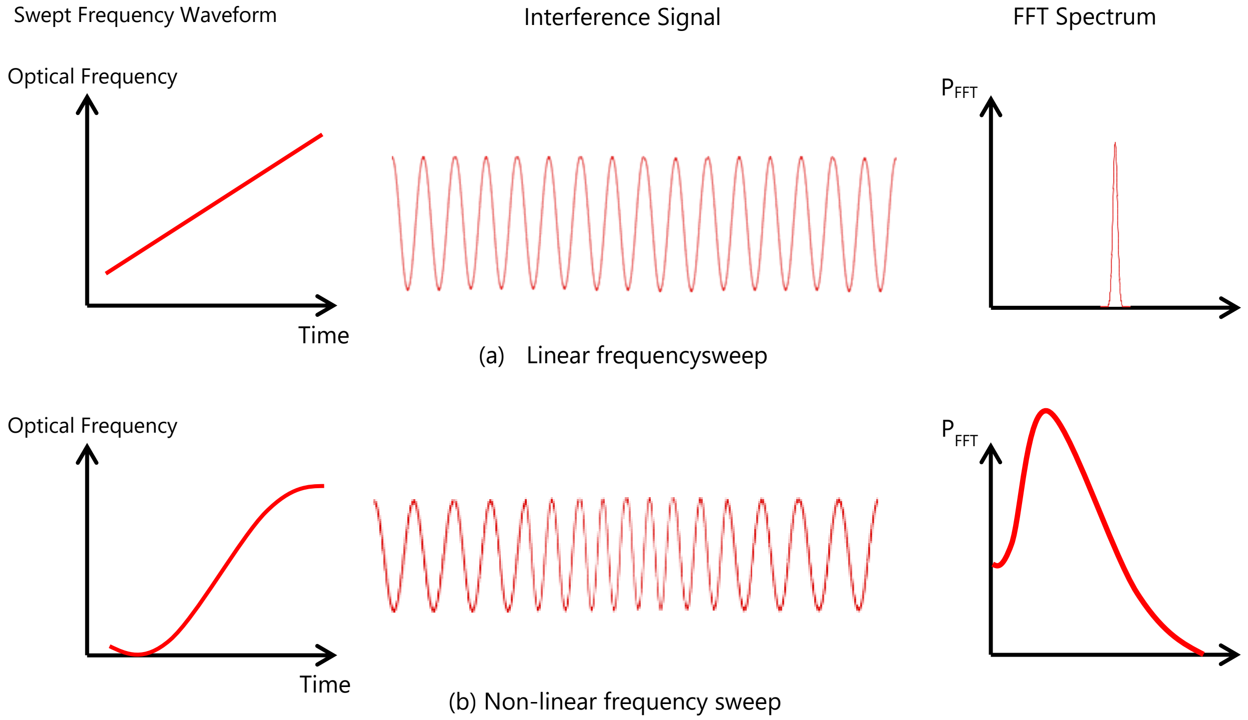


Fig. 3.2-1 Example of FFT Analysis Results vs Sweep frequency Linearity

Figure 3.2-2 shows an example of the measurement system with a reference interferometer. In this example, the reference interferometer is Michelson type. Faraday mirrors are used to eliminate the effects of polarization. The optial pass length of the reference interferometer is L_{AUX}, the Free Spectum Range (FSR) is

$$FSR = \frac{c}{2L_{AUX}} \tag{11}$$

So, the reference interferometer signal output from the reference interferometor repeats strength and weakness each time the optical frequency of light is swept by FSR.

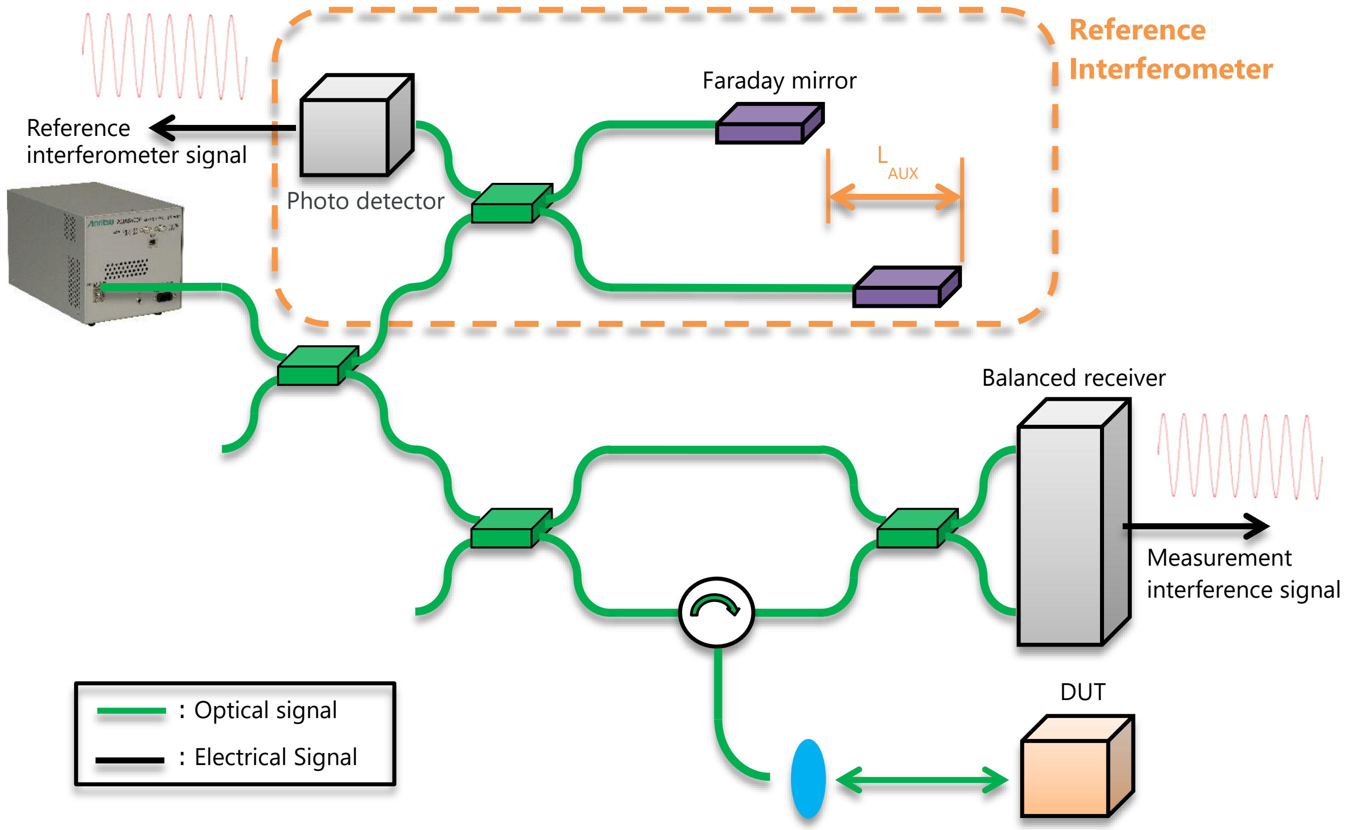


Fig. 3.2-2 Example of OFDR Measurement system with Reference Interferometer

As shown Fig.3.2-3, when the measured signal is extracted at the 0 crosspoint of the reference interferometer signal, the extracted data is the same as the data sampled every time the optical frequency is swept FSR. So, the data was resampled during the linear sweep.

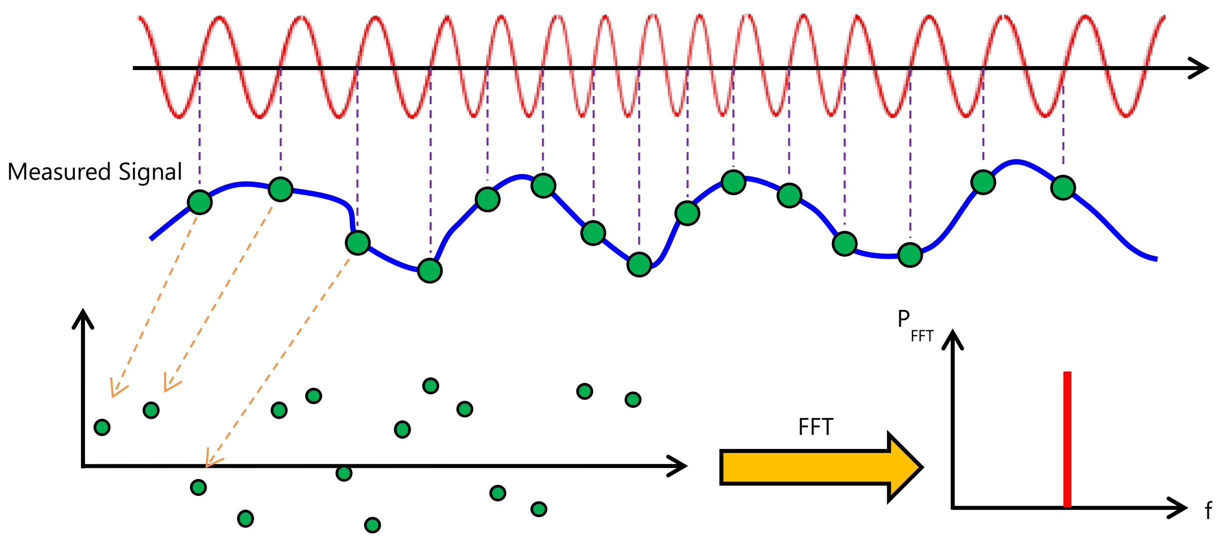


Fig. 3.2-3 Resampling Schematic

There are two resampling methods: 1. Software resampling, and 2. Hardware resampling.

- **Software resampling:** In this method, after sampling the reference interference signal and measurement signal by A/D conversion, the measurement signal is resampled based on the reference interference signal. In comparison to hardware resampling, although this method has the advantage of supporting calibration of the effect of wavelength dispersion caused by the optical fiber, it has the disadvantage of imposing a heavy load on the PC.
- **Hardware resampling:** In this method, the reference interference signal is input to the A/D sampling clock and the measurement signal is sampled by synchronizing with the reference interferometer signal. In comparison to software resampling, this method has the advantage of reducing the load on the PC for a wide band, but it has the disadvantage of not being able to calibrate for the effect of wavelength dispersion caused by the optical fiber.

These two resampling methods are explained below.

3.2.1. Software Resampling

At software resampling, after sampling the reference interference signal and measurement signal by A/D conversion, the measurement signal is re-sampled based on the reference interferometer signal as described below.
Hilbert transformation is performed on the reference interferometer signal to calculate -90 deg phase shift wave form of the reference interferometer signal. The phase of the reference interfrometer signal is calcurated from the reference interferometer signal and -90 deg phase shift wave form. 2π is added at the jump from $+\pi$ to $-\pi$ (unwrap processing) of the phase signal to calculate the continuous phase P_R (Fig. 3.2.1-1).

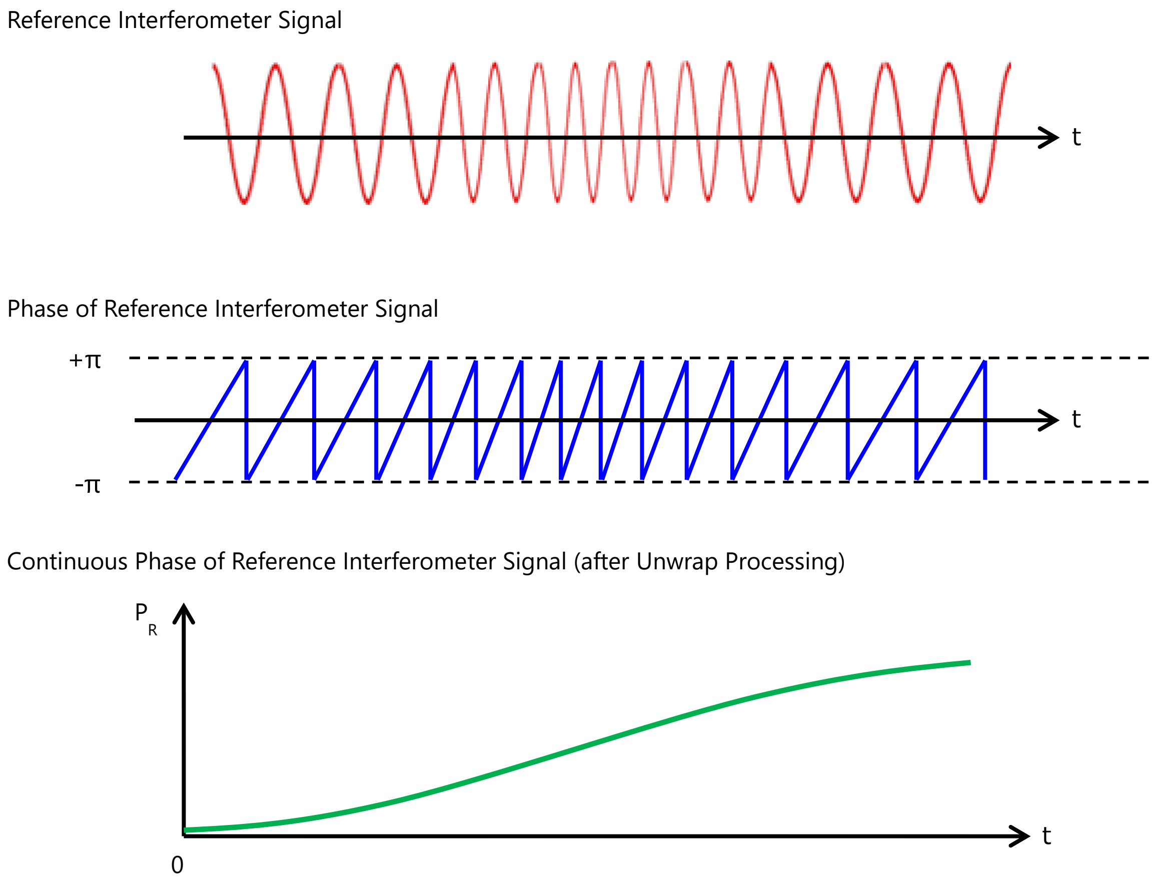


Fig. 3.2.1-1 Reference Interferometer Signal Phase

P_R is divided into N_{FFT} equal parts and the divition time corresponding to the P_R division point are calculated. Then, the resampled data are extracted from the measured signal at devition time. Performing FFT analysis on resampled data, the peak at the frequency proportional to $\boldsymbol{z}\ (= \boldsymbol{L_M} - \boldsymbol{L_R})$ (Fig. 3.2.1) appeares in the FFT spectrum.

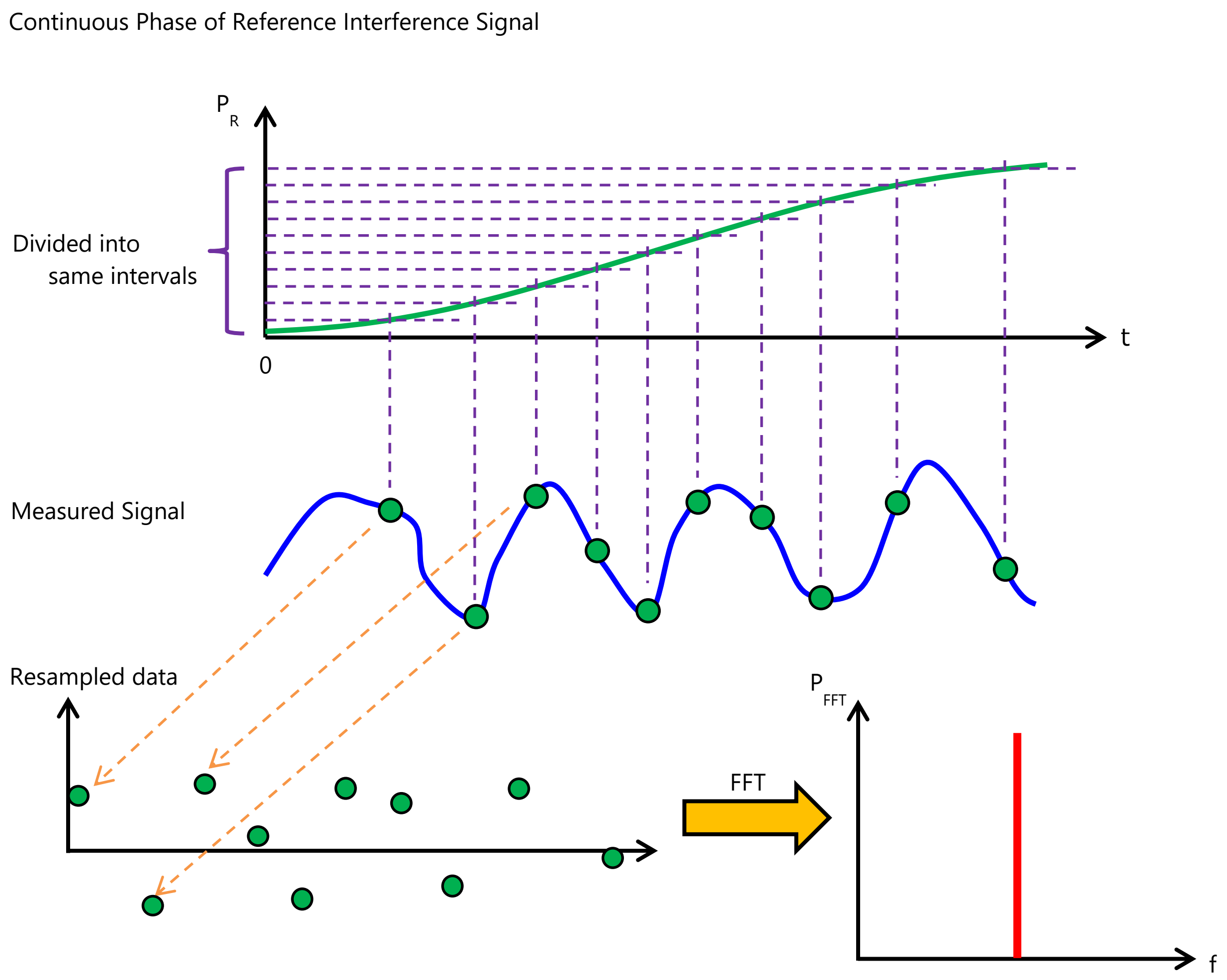


Fig. 3.2.1-2 Software Sampling Schematic Diagram

3.2.2. Wavelength Dispersion Calibration

Generally, interferometers constructed using optical fiber have wavelength dispersion, which can be a cause of degraded precision. The index of the fiber decreases as the wavelength increases. So, the optical path length in the fiber decreases as the wavelength increases. As a result, Optical frequency interval corresponding to which the continuous phase P_R is divided equally, increases as the wavelength increases.
Consequently, the observed width of the peak after FFT is wider than the true width (Fig. 3.2.2-1). In addition, the FFT peak frequency may also drift, depending on the sampling region (Fig. 3.2.2-2).

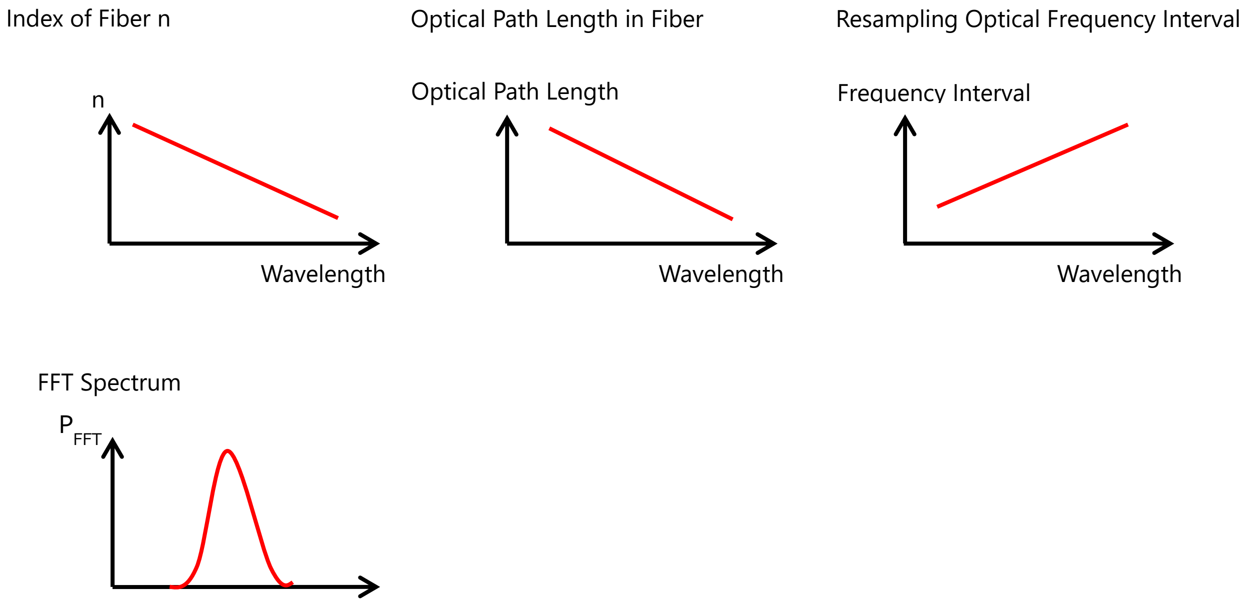


Fig. 3.2.2-1 Effect of Wavelength Dispersion

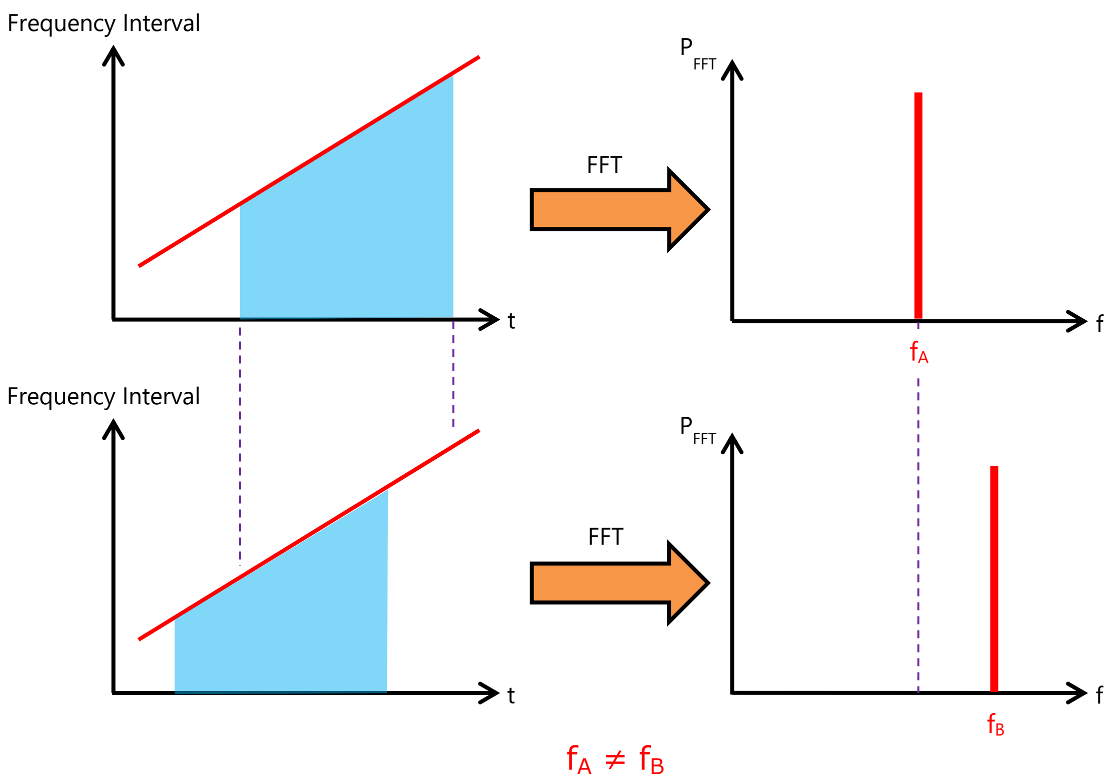


Fig. 3.2.2-2 Differences in FFT Peak with Differences in Sampling Interval

Removing the effect of wavelength dispersion requires calibration using a wavelength reference. The transmission spectra of an etalon and a gas cell can be used as the wavelength reference. Our wavelength swept light source has an etalon built into the module and the opto-electrically converted spectrum is output from the front-panel connector. This section describes calibration using the etalon spectrum.

Although like the configuration of the measurement system shown in Fig. 3.2-2, this system uses the etalon signal output from the light source. The calibration procedure is described in Fig. 3.2.2-3.

It is calculated that the fitting function of the relationship between the etalon peak frequency fe and the PR value corresponding to the etalon peak frequency. The fourth-order fitting function is used here.

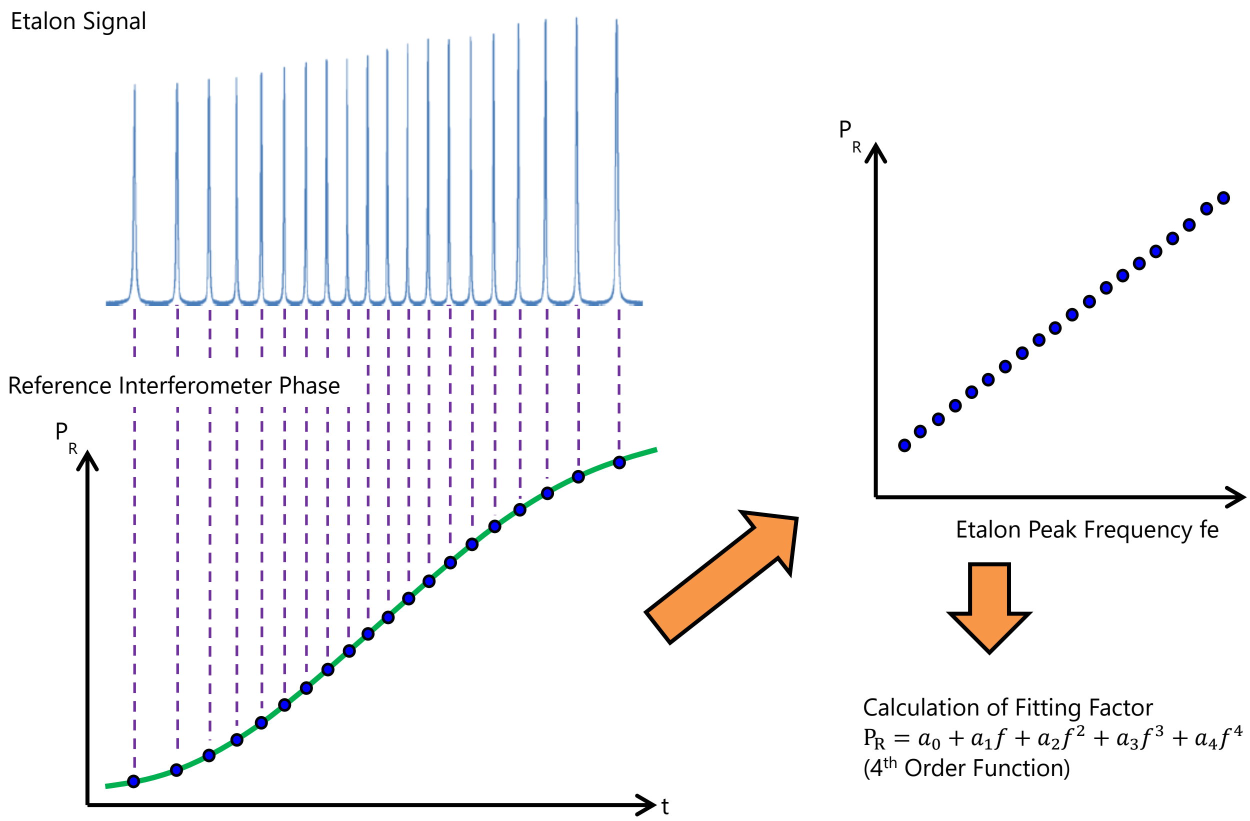


Fig. 3.2.2-3 Calibration using Etalon Signal

Next, this fitting function is used to calculate the P_R value corresponding to the equally spaced frequencies of the etalon peaks, that is, the evenly spaced optical frequencies (Fig. 3.2.2-4). Then, the interference signal data corresponding to the P_R value is extracted. Finaly, FFT spectrum is calucated from the extracted data.

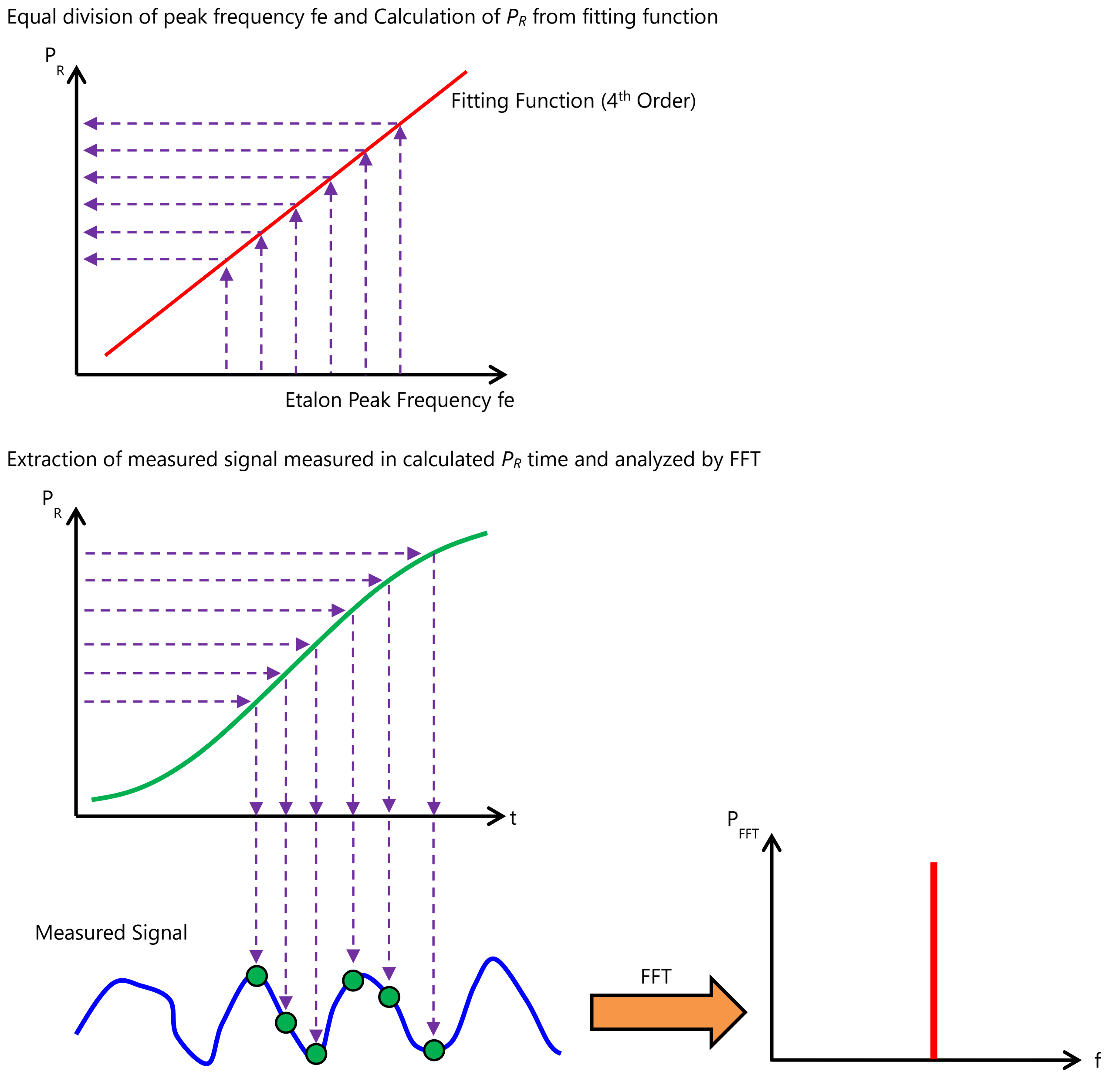


Fig. 3.2.2-4 Extraction of Reference Interference Signal Phase from Fitting Function

Since $\Delta \boldsymbol{P_R}$ represents the change in $\boldsymbol{P_R}$ for the frequency change $\Delta\boldsymbol{\nu}$ (Fig. 3.2.2-5) and $\Delta\boldsymbol{P_R}/(\boldsymbol{2\pi})$ is the number of phase rotations, the Free Spectral Range (FSR) of the reference interferometer (Fig. 3.2-2) is expressed by Eq. 12.

$$\boldsymbol{FSR} = \frac{\Delta\boldsymbol{\nu}}{\boldsymbol{\Delta P_R/(2\pi)}} \tag{12}$$

The resonator length $\boldsymbol{L_{AUX}}$ of the reference interferometer is expressed by Eq. (13),

$$\boldsymbol{L_{AUX}} = \frac{\boldsymbol{c}}{\boldsymbol{2FSR}} \tag{13}$$

and, the resolution Δz can be found from the following derivation (Eq. 14).

$$\Delta z = \frac{L_{AUX}}{\Delta P_R/(2\pi)} = \frac{c}{2\Delta\nu} = \frac{{\lambda_c}^2}{2\Delta\lambda} \tag{14}$$

The maximum measurement length z_{max} is proportional to the Nyquist frequency of the FFT spectrum, which is given by Equation (15).

$$Z_{max} = \Delta z \cdot N_{FFT}/2 \tag{15}$$

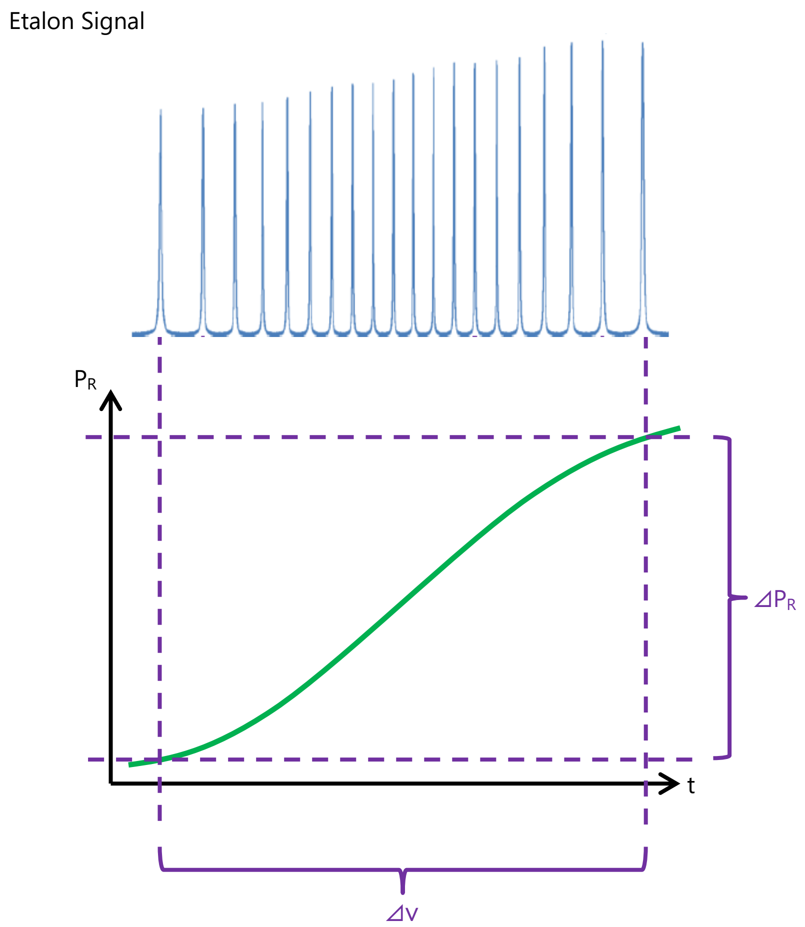


Fig. 3.2.2-5　Distance Conversion and Resolution

The above describes calibration of wavelength dispersion using an etalon signal, but for reference, Fig. 3.2.2-6 shows an example of a measurement system using a gas cell.

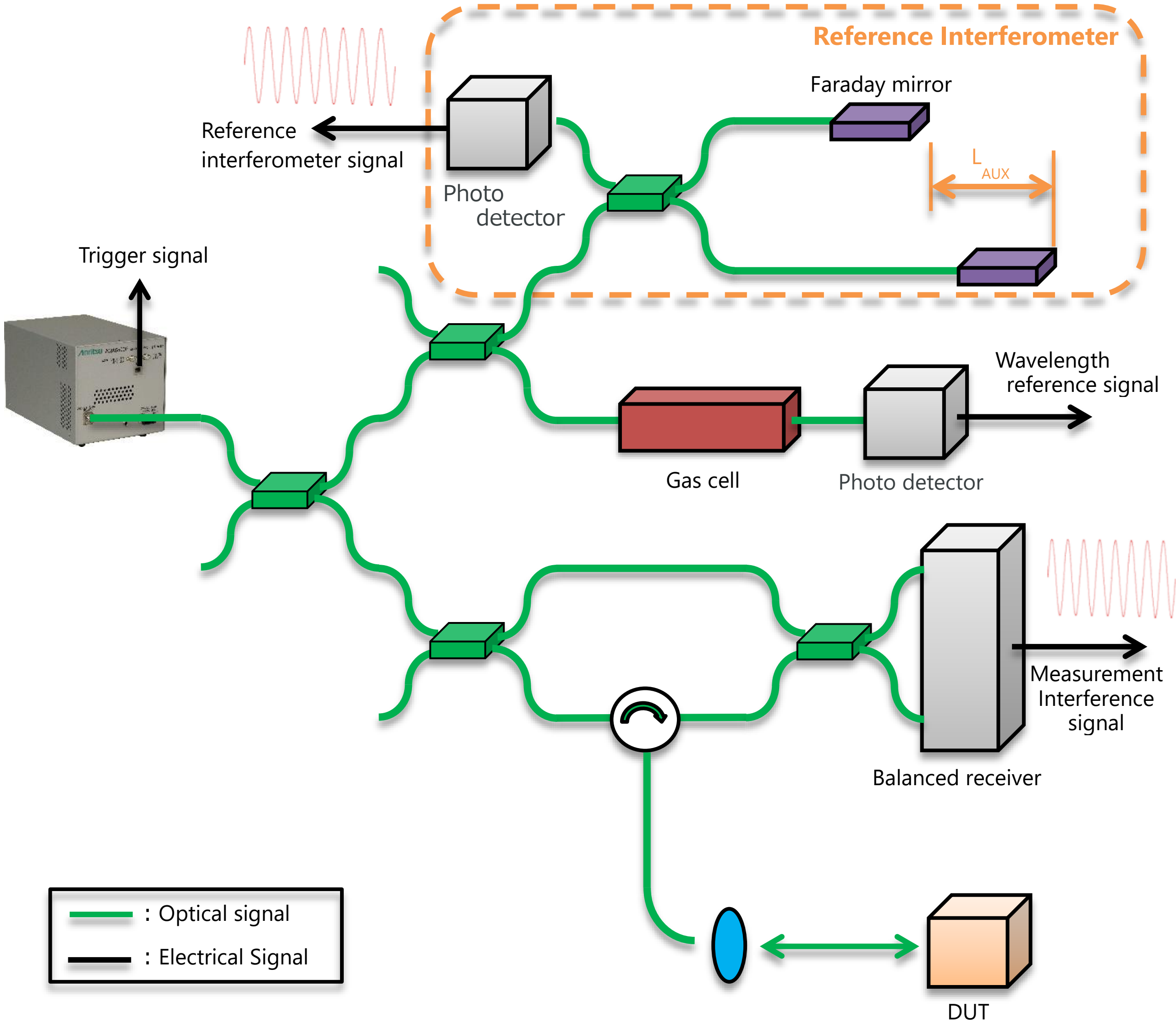


Fig. 3.2.2-6 Example of OFDR Measurement System using Gas Cell

3.2.3. Hardware Resampling

This section explains about hardware resampling. In this method, the reference interferometer signal is input to the clock of the A / D converter, and the measurement signal is input to the sampling channel of the A / D converter (Fig. 3.2.3-1). The A / D converter performs sampling at the timing when the reference signal rises. Therefore, the measurement signal is sampled each time the wavelength of light is swept by the FSR of the reference interferometer. If the variance is negligible, it will be sampled at equal frequency intervals.
Hardware resampling requires less computational resources on the PC than software resampling. In addition, the frequency of the reference signal can be increased to the band limit of the A / D converter, and the measurement distance of OFDR can be widened.

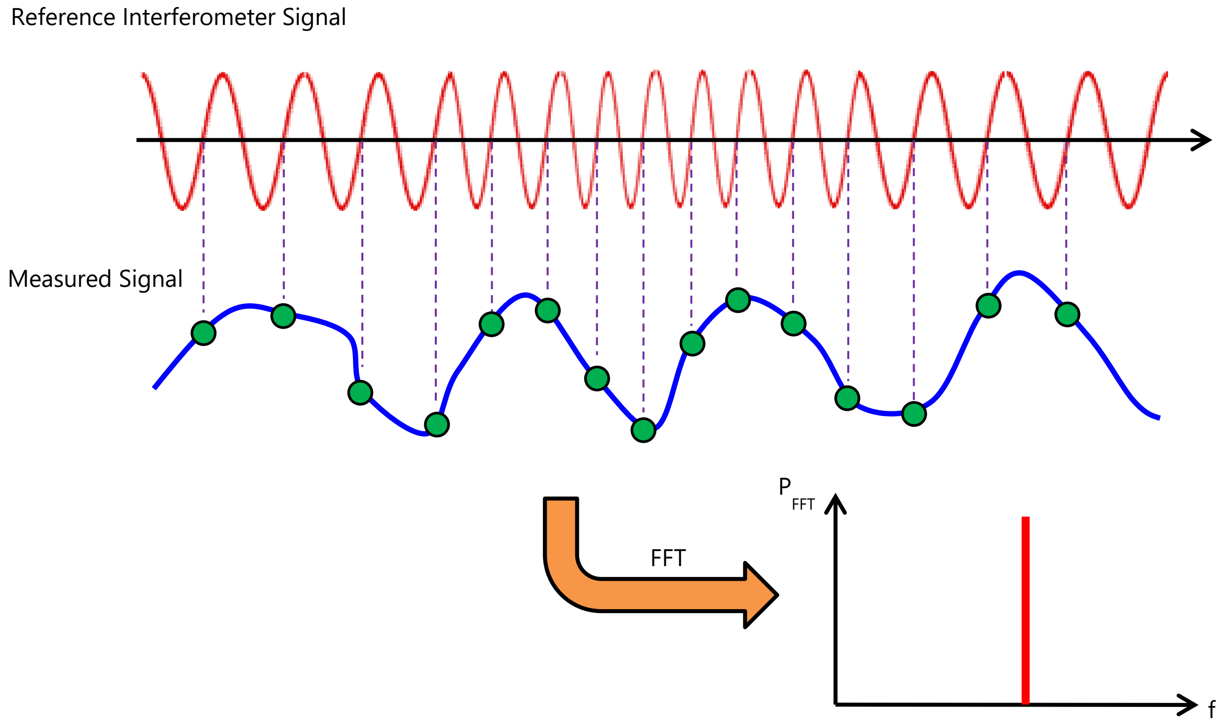


Fig. 3.2.3-1 Hardware Resampling Schematic

3.2.4. Latency (Delay) Calibration

At actual measurement, the optical frequenct of the light output from the wavelength swept light source is swept with phase modulation. So, if the propagation time of the reference interferometer is not same as the propagartion time of the measurement interferometer, the phase modulation ripple remains in the resampled data and a sideband is observed at a separate position from the peak. When the propagation times of both interference paths are the same, calibration can be perfectly performed by resampling even when the light output from the wavelength swept light source is phase modulated (Fig. 3.2.4-1). Accordingly, the propagation time from the wavelength swept light source via the reference interferometer to the A/D converter (path 1 in Fig. 3.2.4-2) must match the propagation time from the wavelength swept light source via the DUT interferometer to the A/D converter (path 2 in Fig. 3.2.4-2).

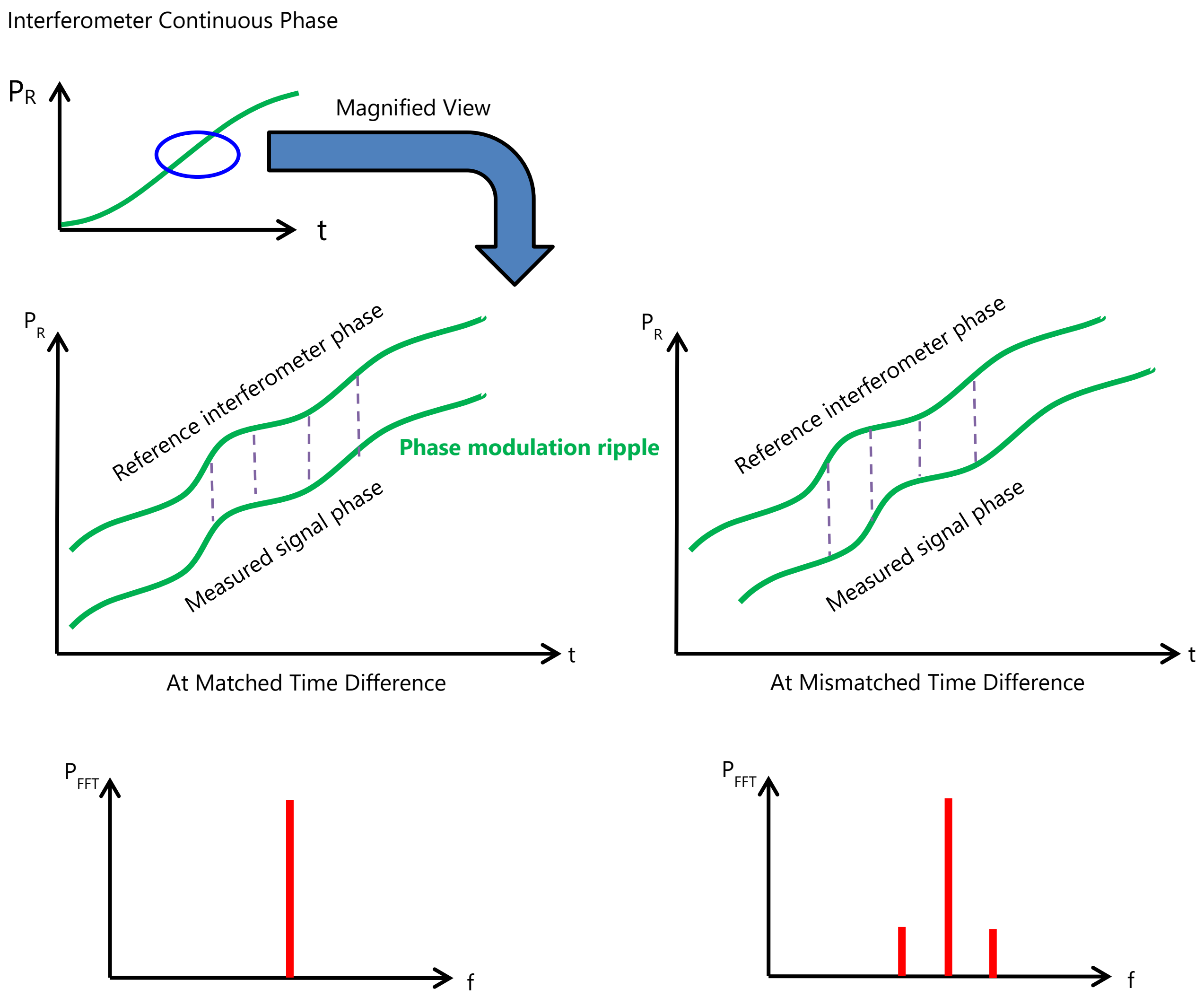


Fig. 3.2.4-1 Effect of Phase Modulation

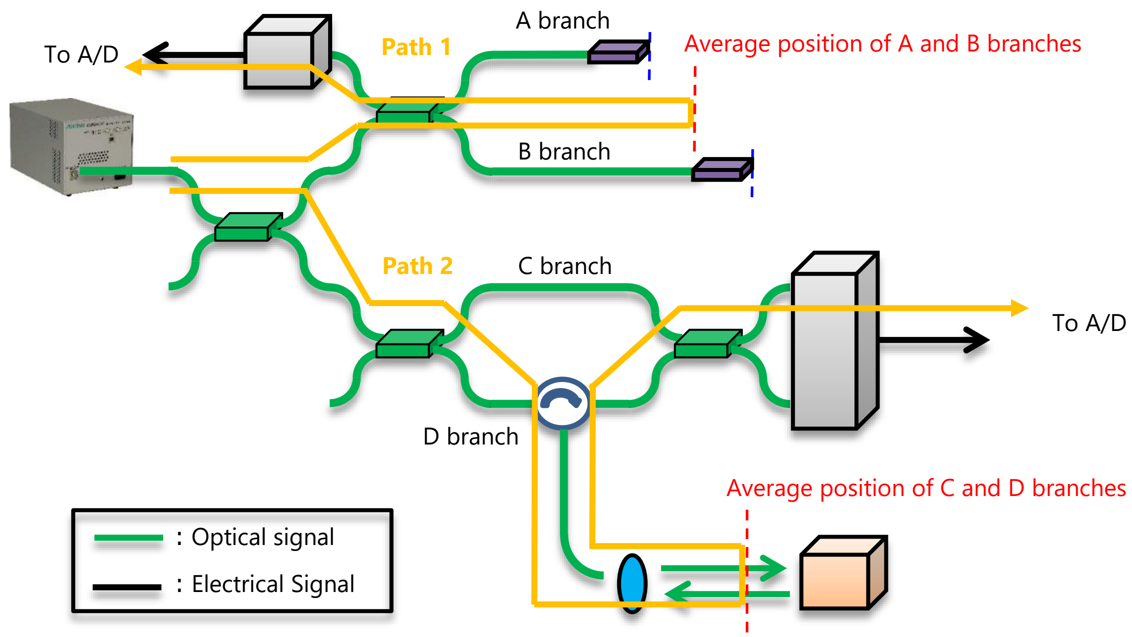


Fig. 3.2.4-2 Hardware Resampling Configuration

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