# High-Accuracy and Fast Measurement of Optical Transfer Delay

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***Abstract*—Measurement of optical transfer delay (OTD) is crucial to applications such as fiber-distributed multiantenna systems, fiber-optic sensors, and high-capacity optical fiber communications. However, present OTD measurement techniques are inadequate for the demands of high accuracy, high speed, and large measurement range, simultaneously. Here, we propose a novel method based on nonlinear frequency sweeping and phase derived ranging to achieve all the above-mentioned performance. A continuous-wave light modulated by a microwave signal propagates in a device under test. Then, the OTD is mapped into the phase variation of the microwave signal by photodetection. A microwave phase discriminator is used to extract the phase variation from the microwave signal, while the nonlinear frequency sweeping and a novel phase unwrapping algorithm are proposed to resolve $2\pi$ phase ambiguity caused by phase detection. Frequencies of the microwave swept signals are set at four selected points in a range of 10 MHz, which ensures high speed and large measurement range. Our experiment results verify an accuracy of ±0.05 ps in measuring an ultrahigh-accuracy optical delay line. In addition, long fiber is also tested, which proves that a measurement range of at least 37 km (theoretically 100 km) can be achieved. Moreover, the measurement speed reaches milliseconds per measurement.**

***Index Terms*—Nonlinear frequency sweeping, optical transfer delay (OTD) measurement, phase derived ranging.**

## I. Introduction

ACCURATE optical transfer delay (OTD) measurement is essential to applications in optical device fabrication, fiber-optic sensors, fiber-distributed multiantenna systems, and high-capacity optical fiber communications [1]–[4]. In the past decades, a variety of OTD measurement technologies have been proposed [5]–[13], among which the optical time domain reflectometry (OTDR) [5], [6] and optical frequency domain reflectometry (OFDR) [7], [8] are the two most widely used methods. The resolution of the OTDR is about ns, which is limited by the pulsewidth and the sampling rate. In addition, as the light pulse will be broadened after transmission in a long optical device due to the dispersion, the OTDR has a low accuracy in long fiber measurement (typically 10 ns at 20 km). The OFDR converts the time delay into the beat frequency between a probe light and a reference light. Benefitting from the wide frequency scanning range of the tunable laser, the OFDR has a relatively high accuracy on the short-distance measurement. However, as the fiber length increases, the accuracy of the OFDR would be significantly degraded (typically 5 ps at 2 km) due to the relatively large linewidth of the tunable laser. Recently, some OTD measurement techniques in the frequency domain have been proposed to meet requirements of large measurement range and high accuracy, such as mode-locking method [11], free-running-laser-configuration-based approach [12], and phase-locked-loop-based technique [13]. In general, these frequency-based methods have a good performance in the large OTD (e.g., long fiber) measurement (typically 0.2 ps at 50 km). However, almost all such methods are time-consuming (typically several minutes per measurement), inconvenient, and environmentally sensitive. Phase shift methods for dispersion measurement [14], [15] can also be used to measure relative delay at different wavelengths, which is achieved by the wavelength-dependent phase shift of a fixed-frequency modulated light beam when propagated through a fiber. However, when measuring the absolute OTD at a fixed wavelength, the maximum unambiguous measurable delay is determined by the period of the RF signal. To overcome this problem, we proposed an absolute OTD measurement method [10] by linearly sweeping the frequency of the RF signal, which achieves an accuracy of ±0.1 ps and a measurement speed of several seconds at 20 km.

In this article, an OTD measurement approach based on nonlinear frequency sweeping and phase derived ranging is proposed. Different from [14], the proposed method scans the frequency of the RF signal instead of the wavelength of the optical carrier. Compared with [10], a method for selection of the optimal modulation frequencies and a phase unwrapping algorithm to calculate the $2\pi$ phase ambiguity are proposed to reduce the redundant frequencies, which dramatically improves the measurement speed. In an experiment,

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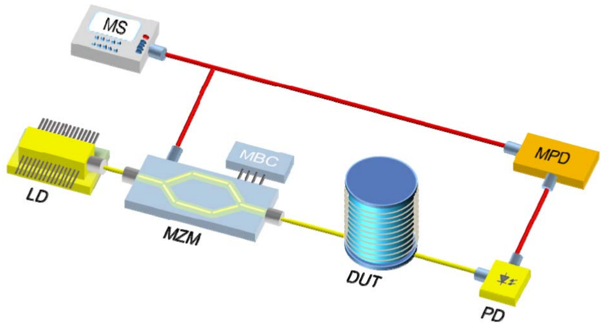


Fig. 1. Proposed OTD measurement approach. LD: laser diode; MZM: Mach–Zehnder modulator; PD: photodetector; MS: microwave source; MPD: microwave phase discriminator; DUT: device under test; and MBC: modulator bias controller.

benefitting from the nonlinear four-point sweep, the proposed method obtains a speed of milliseconds per measurement. The accuracy reaches ±0.05 ps, while the measurement range is more than 37 km. Compared with [10], the proposed method features higher accuracy, higher speed, and larger measurement range.

## II. Principle

The schematic of the proposed OTD measurement approach is shown in Fig. 1. A laser diode generates an optical carrier with an angular frequency of $\omega_c$. Then, it is sent to a Mach–Zehnder modulator (MZM) biased at the quadrature point and modulated by a microwave signal with an angular frequency of $\omega_m$. Mathematically, the electric field at the output of the MZM can be written as

$$E_p(t) = E_o(1 + A\cos\omega_m t)\exp j(\omega_c t) \tag{1}$$

where $E_o$ is the amplitude and $A$ is the modulation index. After traveling through the DUT, the optical field can be expressed as

$$E_d(t) = \alpha E_o\left(1 + A\cos\omega_m(t-\tau)e^{-j\frac{1}{2}\beta_2 L\omega_m^2}\right) \times \exp j(\omega_c(t-\tau)) \tag{2}$$

where $\alpha$, $L$, $\tau$, and $\beta_2$ are the loss, length, transfer delay, and group velocity of the DUT, respectively. A photodetector with a responsivity of $\eta$ is used to convert the optical signal into an electrical signal. The photocurrent at the frequency of $\omega_m$ can be given by

$$i(t) = 2\eta A\alpha^2 E_o^2 \cos\left(\frac{1}{2}\beta_2 L\omega_m^2\right)\cos\omega_m(t-\tau). \tag{3}$$

According to (3), the phase variation of the microwave signal is

$$\varphi(\omega_m) = -\omega_m\tau. \tag{4}$$

A microwave phase discriminator (MPD) is used to extract the phase variation. Because the output value of MPD is located in [-$\pi$, $\pi$], the phase change is rewritten as

$$\varphi(\omega_m) = 2\pi N(\omega_m) + \theta(\omega_m) \tag{5}$$

where $N(\omega_m)$ is an unknown integer and $\theta(\omega_m)$ is the output value of MPD. To calculate the $2\pi$ phase ambiguity, we nonlinearly sweep the microwave frequency and measure the phase shift. The least frequency points can be achieved if

$$\begin{aligned}\omega_1 &= \left(1 - \frac{\Delta\theta}{2\pi}\right)\frac{\Delta\theta}{\Delta\tau}\\ \omega_i &= \omega_1 + \frac{\pi}{\tau_{\max}}\cdot\left(\frac{2\pi}{\Delta\theta}\right)^{i-2}, \quad i = 2, 3, \ldots, M-1\\ \omega_M &= \frac{\Delta\theta}{\Delta\tau}\end{aligned} \tag{6}$$

where $\Delta\theta$ is the accuracy of the MPD, $\Delta\tau$ is the required measurement accuracy, $\tau_{\max}$ is the maximum measurable delay, and $M$ is the number of frequency points. Because $\omega_{M-1} < \omega_M$, the number of points is

$$M = \mathrm{ceil}\left[\log_{2\pi/\Delta\theta}((\omega_M - \omega_1)\tau_{\max}/\pi)\right] + 2 \tag{7}$$

where ceil[.] denotes round toward plus infinity. From (7), it can be seen that the number of swept points increases in logarithm. In contrast, when using linear frequency sweeping, the number of points is $[(\omega_M$-$\omega_1)\tau_{\max}/\pi]$, which is linear growth. Therefore, the proposed method can greatly reduce the number of redundant frequencies when measuring large OTD, enabling fast OTD measurement.

A novel phase unwrapping algorithm is proposed to calculate the $2\pi$ phase ambiguity. The phase shift $\theta_2$ is corrected by subtracting $2\pi$ when the absolute phase difference between $\theta_1$ and $\theta_2$ is greater than or equal to $\pi$ radians. In addition, the residual phase shift $\theta_i$ are corrected by

$$\phi_i = 2\pi\cdot\mathrm{round}\left[\frac{(\omega_i - \omega_2)(\phi_{i-1} - \theta_1)}{2\pi(\omega_{i-1} - \omega_1)} + \frac{\theta_1 - \theta_i}{2\pi}\right] + \theta_i \tag{8}$$

where round[.] denotes round toward nearest integer. Finally, the $2\pi$ phase ambiguity of $\omega_{\mathrm{M}}$ can be calculated by

$$N_M = \mathrm{round}\left[\frac{(\omega_M - \omega_2 + \omega_1)(\phi_M - \theta_1)}{2\pi(\omega_M - \omega_1)} - \frac{\theta_M}{2\pi}\right]. \tag{9}$$

According to (4), (5), and (9), $\tau$ can be given by

$$\tau = -\left(N_M + \frac{\theta_M}{2\pi}\right)\frac{2\pi}{\omega_M}. \tag{10}$$

## III. Experimental Results and Discussion

An experiment based on the setup shown in Fig. 1 is performed to verify the proposed OTD measurement approach. An optical signal from a 1550-nm laser diode (Newkey Photonics, NLC13) with a linewidth of <100 kHz is modulated at an MZM (Fujistu, FTM7928FB) by a sinusoidal signal. The bias point of the modulator is kept at the quadrature point using an automatic modulator bias controller. After the DUT, the modulated signal is detected in a photodetector with a bandwidth of 12 GHz, and the resultant electrical signal is sent to an MPD with an accuracy of ±0.1°. In addition, the temperature of the measurement system is maintained at 25 °C using an incubator.

The frequencies of the sweep points are set to $f$ and $f$+1 kHz and $f$+1 MHz and $f$+10 MHz, where $f$ = 5.59 GHz after considering redundancy. Theoretically, an accuracy of ±0.0496 ps can be obtained with the highest

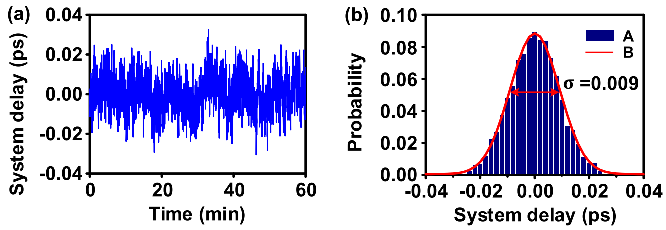


Fig. 2. Evaluation of system stability. (a) System delay fluctuations. (b) Probability distribution of the system delay. B is the fitting line of A.

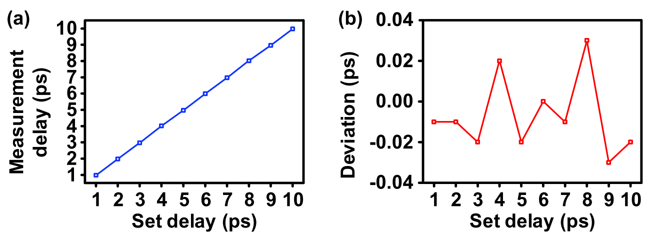


Fig. 3. Evaluation of measurement accuracy. (a) Measured MDL delay when it changes with a step of 1 ps. (b) Measurement deviation.

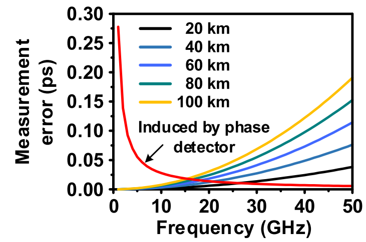


Fig. 4. Measurement error induced by the high-order dispersion in fibers.

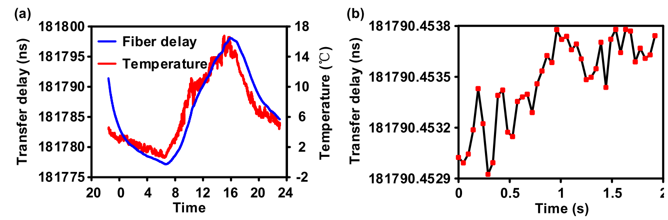


Fig. 5. Evaluation of measurement range and speed. Measured OTD of a 37-km fiber with a measurement interval of (a) 10 s and (b) 48 ms.

frequency of 5.6 GHz. The frequency difference of 1 kHz between the first two frequencies determines the maximum measurement range, which ensures a measurement range of 500 $\mu$s $= \pi/(2\pi \cdot 1$ kHz) due to the phase unwrapping algorithm. In addition, the microwave synthesizer has a frequency hopping speed of submilliseconds per point, so a measurement speed in milliseconds can be achieved, which ensures immunity to environmental disturbances. Therefore, compared with [10], the measurement accuracy can be improved when measuring large OTD.

Fig. 2 shows the measured system delay within 1 h. As can be seen, the fluctuation is below $\pm 0.04$ ps, and the standard deviation is 0.009 ps. To further verify the measurement accuracy, a motorized variable optical delay line (MDL, General Photonics MDL-002) serves as the ultrahigh accuracy reference. Its resolution is $<1$ fs, and the accuracy is $\pm 0.01$ ps. When the MDL is set at zero point, the MPD measurement results at four frequency points are $-143.1975°$, $-143.2017°$, $-147.0248°$, and $178.5359°$, respectively. After phase unwrapping, the corrected phase shifts are $-143.1975°$, $-143.2017°$, $-147.0248°$, and $-181.4641°$, respectively. Then, the phase ambiguity of 5.6 GHz can be calculated as $-60$. According to (10), we can achieve an OTD of 10.625726 ns $= -(-60+178.5359°/360°)/5.6$ GHz, which is mainly introduced by MDL pigtails. Fig. 3 demonstrates the measured MDL delay variations when it changes with a step of 1 ps. It is obvious that the measurement delay and the set delay agree well. The deviation between them is below $\pm 0.04$ ps. Therefore, the targeted accuracy of $\pm 0.05$ ps can be obtained.

According to (10), the measurement accuracy is proportional to the highest frequency of the microwave signal. However, the higher-order dispersion cannot be ignored as the frequency increases. Since the phase shift caused by the even-order derivatives of $\beta$ only affects the magnitude of the photocurrent, they will not degrade the measurement accuracy. If the third-order derivative of $\beta$ is considered, the phase variation should be rewritten as

$$\varphi(\omega_m) = -\omega_m \tau - \frac{1}{6}\beta_3 L \omega_m^3 \tag{11}$$

where the third-order derivative of $\beta$ is given by

$$\beta_3 = \left(\frac{\lambda}{2\pi c}\right)^2 \left(\lambda^2 S + 2\lambda D\right) \tag{12}$$

where $\lambda$ is the wavelength, $c$ is the light speed in vacuum, $D$ is the dispersion [ps/nm/km], and $S$ is the dispersion slope. Generally, the SMF-28 fiber has a dispersion of 16.5 ps/nm/km and a dispersion slope of 0.05 ps/nm$^2$/km. Then, the measurement error caused by $\beta_3$ can be simulated. As can be seen from Fig. 4, the measurement error will be increased with the frequency and the fiber length due to the higher-order dispersion, which limits the highest achievable measurement accuracy.

To verify the large measurement range and high speed of the proposed method, we also measured the transfer delay of a 37-km fiber. Since the delay variation of long fiber in the natural environment is of great interest in many applications, the fiber is placed outdoors and observed for more than 24 h. The results are shown in Fig. 5(a). As the fiber is moved from indoor to outdoor, the fiber delay changes fast during the first 3 h due to the large temperature variation. Then, the measured OTD varies linearly with the temperature. The temperature coefficient of delay is about 7.1 ppm/°C, very close to 7 ppm/°C in the datasheet. Fig. 5(b) shows the continuous measurement results within 1.92 s. The refresh rate reaches 48 ms each time, which is mainly limited by data transmission and processing.

## IV. Conclusion

A nonlinear frequency sweeping and phase derived ranging based OTD measurement method with high accuracy, fast speed, large measurement range, and simple structure has been proposed and demonstrated. In the experiment, an accuracy of $\pm 0.05$ ps was obtained. The OTD of a 37-km fiber was also measured, which verified the large measurement range and high speed of the proposed method. Moreover, benefitting from the nonlinear frequency sweeping, the measurement speed reached milliseconds.

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