Accurate Measurement of Fiber Length and Effective Index Using Equalized Ring-Down Enhancement and Pulse Sequence Methods

Yuhang Wang, Kuan Liu, Xing Rao, George Y. Chen, *Senior Member, IEEE*, and Yiping Wang, *Senior Member, IEEE*

***Abstract*—Distributed fiber-optic sensors are widely used for mining safety monitoring, civil engineering structural health monitoring and environmental monitoring. The position accuracy of measurements is of critical concern, as errors can lead to expensive decisions at the wrong location. Accurate fiber length measurement is key to calibrate distributed fiber-optic sensors. Existing methods suffer from time resolution or component delay errors. Optical time-domain reflectometry (OTDR) and its variants are widely used but needs calibration for practical applications. We propose two new methods that can self-calibrate, and can be used to calibrate other methods such as those based on OTDR. One based on a differential pulse loop using dual pulse statistical signal processing, and another is based on a differential pulse loop with multi-pulse sequence analysis, to enhance the timing accuracy. In addition, it is possible to determine the effective index of a single-mode fiber with known fiber length, which is important prerequisite information for practical applications in the field with uncertain laser wavelength and ambient temperature. When using a low-end oscilloscope with a nominal 26 MS/s sampling rate, compared with the measurement results of optical frequency domain reflectometer (OFDR) (LunaOBR4600), the double pulse method has an error of ±6 cm. For the multi pulse method, the measurement error can be as low as 1.75 mm for a fiber length of 2.049 km (relative error of 8.54×10^{-7}).**

***Index Terms*—Differential pulse loop, effective index measurement, fiber length measurement, optical frequency domain reflectometer (OFDR) calibration, optical time-domain reflectometry (OTDR) calibration.**

I. Introduction

DISTRIBUTED fiber-optic sensors with their real-time massive data gathering ability are paving the way for smart cities, mining and agriculture. Vibration, strain, temperature and pressure data provide the backbone of the Internet of Things. To ensure reliable measurements and informed decision making, distributed sensors require precise calibration, notably absolute positioning feedback of perturbations along the optical fiber. In practical applications such as oil or gas hydrate extraction [1], [2] where the underground position or layer of interest can be less than a meter, measurements without calibration could result in failed expensive undertakings.

Optical time domain reflectometry (OTDR) [3], [4], [5] is one of the earliest distributed sensing technologies and widely considered to be the classic fiber length measurement technology. An OTDR system operates by sending pulses of light through an optical fiber, then by detecting the Rayleigh backscattered light as a function of time, determine the distributed optical losses as well as the fiber length. Existing commercial OTDRs have a measurement range of tens of kilometers, but the spatial resolution is relatively low, and there is a measurement dead zone [6]. optical frequency domain reflectometer (OFDR) [7], [8], [9] can achieve micrometer level measurement accuracy, but the measurement range is only a few meters and the performance requirements for devices limit their application scenarios. Theoretically, phase-based measurement methods can achieve high accuracy, but most of these methods are often subject to environmental interference and pose significant challenges in practical engineering applications. Relatively, technology based on time-of-flight (TOF) [10], [11] typically has high stability. The combination of TOF and the anti-interference ability of the optical fiber is suitable for most scenarios, but its accuracy is limited by the performance of devices such as optoelectronic conversion. Andrea Zanobini presented using the recirculating delay line to calibrate the distance scale. When the test fiber length is 25 km, its uncertainty is 52.44 m. Results show that the instrument can effectively perform distance scale evaluation [12]. K. H. Yoon et al. measured the length of an optical fiber from the modulation frequency changes required to induce single-mode laser oscillations through an optical closed-loop including the fiber and the laser diode. The maximum error of the proposed technique is less than 0.24% for various fiber lengths from 0.1 km to 75 km [13]. Y. L. Hu et al. used a mode-locked fiber laser configuration to measurement optical fiber, achieved a large measurement range, over hundreds of kilometers, and a high spatial resolution, of the order of centimeters, as well

Manuscript received 15 August 2023; revised 8 November 2023; accepted 29 November 2023. Date of publication 4 December 2023; date of current version 2 April 2024. This work was supported in part by the research start-up fund for high-end talent at Shenzhen University, in part by the Scientific Instrument Development Project of Shenzhen University under Grant 2023YQ027, and in part by the National Natural Science Foundation of China under Grant 62275172. *(Corresponding author: George Y. Chen.)*

This work did not involve human subjects or animals in its research.

The authors are with the Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education/Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China, and also with the Shenzhen Key Laboratory of Photonic Devices and Sensing Systems for Internet of Things, Guangdong and Hong Kong Joint Research Centre for Optical Fibre Sensors, Shenzhen University, Shenzhen 518060, China (e-mail: 2100453052@email.szu.edu.cn; 2110456067@email.szu.edu.cn; 2250453012@email.szu.edu.cn; gychen@szu.edu.cn; ypwang@szu.edu.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2023.3338854.

Digital Object Identifier 10.1109/JLT.2023.3338854

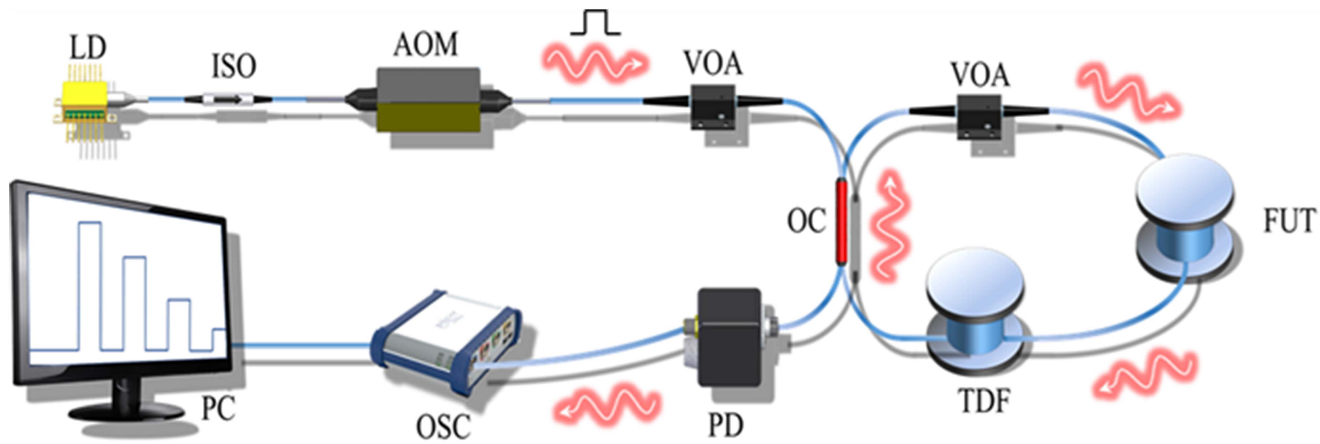

Fig. 1. Basic experiment setup. LD: Laser diode; ISO: Optical isolator; AOM: Acousto-optic modulator; VOA: Variable optical attenuator; OC: Optical couple; TDF: Time delay fiber; FUT: Fiber under test; PD: Photodetector; OSC: Oscilloscope; PC: Personal computer.

as no measurement dead zone [14]. X. Wang et al. proposed a new method of sawtooth wave phase modulation, convert the measurement of polarization maintaining fiber length into the measurement of time delay, and the measurement accuracy of optical fiber length is about 8 ppm, which is lower than 10 ppm [15].

Generally, the fiber length of the fiber-under-test (FUT) can be determined by the measured time-of-flight along with knowledge of the effective index of the fiber core at the laser wavelength and a certain ambient temperature. However, there is a limitation to the timing accuracy when using a single pulse, (optical reflectometry methods), due to a fixed time error relative to the transit time of light set by electronic hardware, producing a relatively large relative (percentage) error. Hence, some methods rely on a recirculating pulse of light to increase the total transit time of light through the same length of optical fiber. Still, inline components induce time delays and contribute to the overall time error, and the effective index of the optical fiber can be uncertain under different laser wavelengths and environmental conditions, leading to cumulative time errors that increase with increasing fiber length. Therefore, to accurately calibrate the fiber length of an OTDR or other systems on site, it is necessary to first obtain the effective index of the fiber. If only the effective index provided by the fiber manufacturer is used, there may be a significant error, which is also a key point overlooked by many papers and practical testing.

To solve this problem, we present two new methods, both based on a differential pulse loop, such that the difference between the experiment setup with and without the FUT is taken into account to remove inline component contributions. The first method (dual pulse, slow-time enhancement) uses two successive pulses with statistical signal processing to reduce sampling time errors. The second method (multi-pulse, fast-time enhancement) uses a pulse sequence extrapolation to acquire a curve function for predicting timing information. Both methods provide highly accurate fiber length measurements, as well as effect index measurement of single-mode fibers with a known fiber length. The complete procedure for actual on-site calibration involves first using a high-precision ruler to measure a short fiber of the same type as FUT, then using one of the proposed methods to measure the effective index of the short fiber, and finally using this effective index to measure any FUT length. For the purpose of practical application, we deliberately used a relatively low sampling rate (larger enhancement) representing a low-end inexpensive oscilloscope rather than a high sampling rate (smaller enhancement) representing a high-end expensive oscilloscope, which produce comparable timing accuracy. The usage of inexpensive components and a compact system allows portability and deployment on oil rigs and other remote working environments.

II. Basic Concept

A basic transit-time measurement system to obtain effective index and fiber length is described as shown in the Fig. 1, a 1550 nm wavelength single-frequency continuous-wave laser (high coherence is not necessary) with an acousto-optic modulator to generate pulsed light. The light is looped using a ring-like structure formed by a fiber loop and a 2×2 coupler, which results in a sequence of optical pulses that are converted into electrical signals by the photodetector (400 MHz electrical bandwidth). Since each optical pulse launched into the fiber loop continues to recirculate (with attenuation), the time between each received pulse signal is the transit time of light in the fiber loop, including any FUT attached. The analogue signal is sampled and digitized by an oscilloscope for display, processing and storage.

To determine the transit time of the FUT, we first measure the pulse interval of the optical pulse propagating through the fiber loop, then splice the FUT to the middle of the fiber loop and measure the pulse interval again. The total transit time of light can be obtained by subtracting the first pulse signal arrival time from the final arrival time. Through division by the number of delayed pulses, the pulse interval is known. The transit time through the FUT can be calculated by the difference between the setup with and without the FUT, which removes the contributions of inline optical components. The advantages of this system include simple structure and high stability. However, this system also shares the common problems of other reported

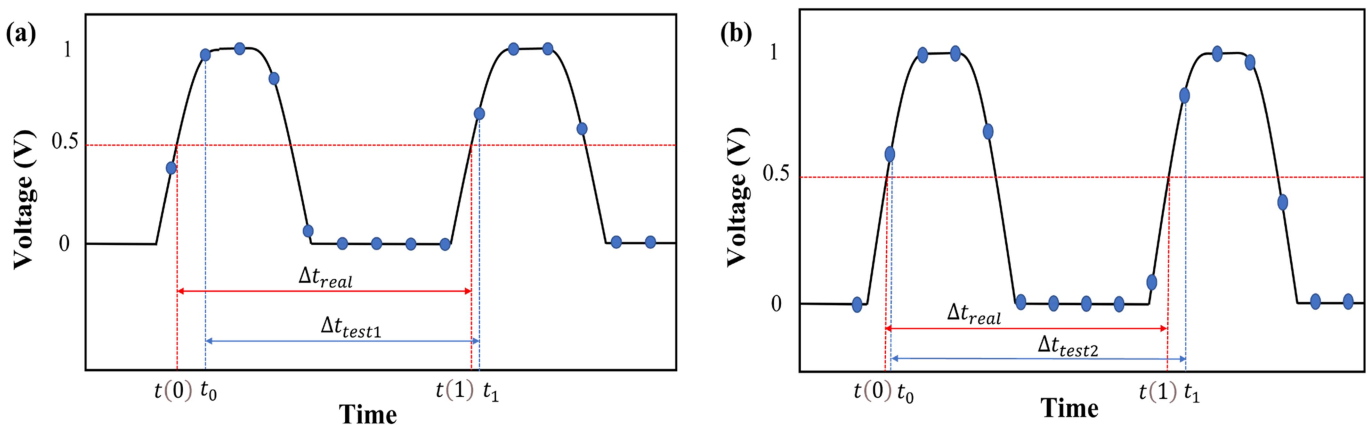

Fig. 2. Illustration of two situations when sampling signals with an oscilloscope: (a) Time interval between two pulses is 8 sampling intervals, and (b) time interval between two pulses is 9 sampling intervals.

systems based on time-of-flight methods. Its measurement error is closely related to the sampling rate of the oscilloscope. The propagation speed of light in optical fiber is approximately 2×10^8 m/s, while the sampling frequency of a typical oscilloscope is below 1 GHz. Therefore, the measurement error is usually in the order of centimeters. In this work, we propose two sub-methods to improve the measurement accuracy, sharing the same experiment setup shown in Fig. 1.

III. Dual-Pulse Principles

In practice, an oscilloscope converts continuous analogue signal into discrete digital signals. Therefore, the lower accuracy limit of the measurement method based on the TOF method is limited by the sampling frequency of the oscilloscope. We used the system in Fig. 1 to take the time interval between two pulses as the flight time of light in device A. We found that under multiple measurements, two different results were obtained. Below, this phenomenon was analyzed and statistical methods based on it were proposed, which can be used to obtain more accurate result for calculating fiber effective index or fiber length.

As shown in the Fig. 2(a), an ideal pulse series with a peak voltage of 1 V is sampled by the oscilloscope. A threshold voltage of 0.5 V is nominated as the positioning point, and thus the 0.5 V position of the rising edge of the first pulse is set as $t(0) = 0$. The first sampled position after $t(0)$ is t_0. As shown in Fig. 2(a) and (b), the time interval from $t(0)$ to t_0 varies with each measurement. Therefore, over multiple measurements, the value of t_0 fluctuates within the range of the sampling interval t_s, which depends on the arrival time of the signal and the initial time when the oscilloscope starts sampling. Over multiple measurements, there is a randomness expressed by:

$$t_0 - t(0) = t_0 \cdot rand \tag{1}$$

where rand represents a random number between [0, 1]. The 0.5 V position of the rising edge of the second pulse is denoted as $t(1)$. The time difference between $t(0)$ and $t(1)$ is equal to the roundtrip time of the optical pulse in the fiber loop.

$$t(1) - t(0) = t(1) = \frac{L \cdot n_{eff}}{c} \tag{2}$$

where L is the total length of the fiber loop, c is the speed of light in vacuum, and n_{eff} is the effective index of the optical fiber. The position of the first oscilloscope sampling point after point $t(1)$ is denoted as t_1. It can be deduced that the value of t_1 is:

$$t_1 = t_1 - t(0) = \left\lceil \frac{L \cdot n_{eff}}{c \cdot t_s} - rand \right\rceil \cdot t_s + t_s \cdot rand \tag{3}$$

Let $\lceil\ \rceil$ represent the round-up function. The transit time in the fiber loop can be expressed by the time difference T between the two pulses sampled by the oscilloscope:

$$T = t_1 - t_0 = \left\lceil \frac{L \cdot n_{eff}}{c \cdot t_s} - rand \right\rceil \cdot t_s \tag{4}$$

Set:

$$a = \frac{L \cdot n_{eff}}{c \cdot t_s} \tag{5}$$

$$b = rand \tag{6}$$

We obtain:

$$T = \lceil a - b \rceil \cdot t_s \tag{7}$$

When we use the same oscilloscope to measure the same fiber multiple times, a is a constant, while b is a random number between [0, 1]. So over multiple measurements, any change in b will directly affect the result of the round-up function. As shown in Fig. 2(a) and (b), the same measurement method is used, but due to the difference in b, the pulse interval measured in Fig. 2(a) is 8 sampling intervals, while in Fig. 2(b) there are 9 sampling intervals. Set:

$$a = a_{\text{int}} + a_{dec} \tag{8}$$

where a_{int} is the integer part of a and a_{dec} is the fractional part of a. In multiple measurements, the rounded-up results of T

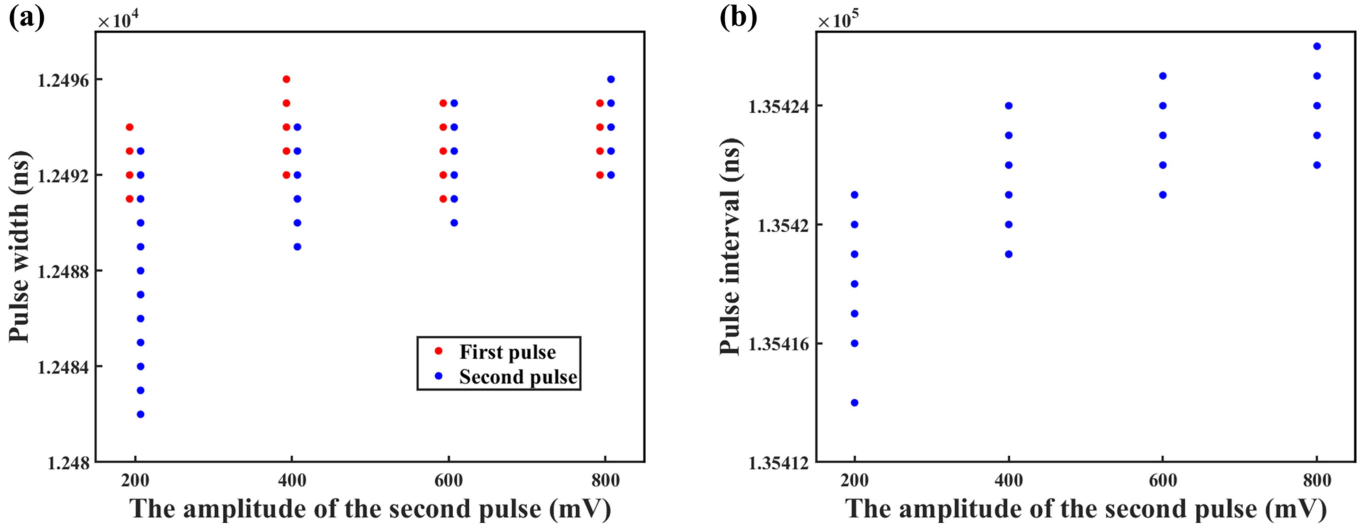

Fig. 3. (a) Width of the pulse measured by an oscilloscope varies with the amplitude of the pulse. (b) variation of pulse interval results measured by an oscilloscope with pulse amplitude.

TABLE I
Test Result of 20 km Optical Fiber

Measurement result (s)	Occurrence (count)	Probability (%)
9.83424e-5	47728	95.456
9.83808e-5	2272	4.544

will exhibit two values, $a_{\text{int}} \cdot t_s$ and $(a_{\text{int}} + 1) \cdot t_s$. In theory, we calculate the probability of these two values as follows:

$$P_1 = \Pr\left(\lceil a - b \rceil = a_{\text{int}}\right) = \Pr\left(b > a_{\text{dec}}\right) = 1 - a_{\text{dec}} \quad (9)$$

$$P_2 = \Pr\left(\lceil a - b \rceil = a_{\text{int}} + 1\right) = \Pr\left(b < a_{\text{dec}}\right) = a_{\text{dec}} \quad (10)$$

So according to the probability, we can find the expected value of T:

$$E(T) = P_1 \cdot a_{\text{int}} \cdot t_s + P_2 \cdot (a_{\text{int}} + 1) \cdot t_s = a \cdot t_s \quad (11)$$

Therefore, according to the law involving large numbers, when one repeatedly measures T, its arithmetic mean will almost certainly converge to the expected value $E(T)$. Finally, the average value is used to calculate the value of a, and deduce the fiber length L through (5). Without considering any optical loss, the fiber loop can output an infinite pulse sequence signal with a single input optical pulse. In the dual pulse method, we only consider the time interval between the first and the second pulses. We set the sampling interval of the oscilloscope to 38.4 ns and inserted a nominal length of 20 km optical fiber into the system for 50000 measurements. The results are shown in Table I. The experimental results are consistent with our inference, with only two values that differ from 38.4 ns. We used an effective index of 1.463 for fiber length calculation, and the results are 20151.95 m and 20159.82 m. Finally, based on the proposed method, we can obtain more accurate results for 20152.31 m.

The dual-pulse measurement method is an improved method on the TOF method, where the sampling rate of the oscilloscope determines the lower limit of measurement accuracy of this system. On this basis, we use half of the maximum amplitude of the pulse signal collected by the oscilloscope as the positioning point for the pulse, and combine our algorithm to obtain higher accuracy results. Therefore, the accuracy of voltage measurement by the oscilloscope determines the upper limit of our method's accuracy, which is mainly limited by the stability of the laser source, the noise of electronic devices and the voltage resolution of the oscilloscope.

IV. Dual-Pulse Experiment Results

The first optical pulse is the input optical pulse that does not pass through the fiber loop, while the second optical pulse is the same input optical pulse that experiences a delayed arrival due to the fiber loop. After the FUT is inserted into the fiber loop (cleave middle section then splice the fiber ends), the second optical pulse will be further attenuated, and the amplitude of the optical pulse is smaller than that without the FUT.

As shown in Fig. 3, four groups of pulses with different amplitudes were measured with the oscilloscope. Each group was measured 32 times to study the repeatability. When a lunching optical pulses of the same width, a variable optical attenuator (VOA) in the fiber loop serves to change the amplitude of the second pulse. It was observed that through VOA-adjusted increase in the amplitude of the second pulse, its pulse width and the interval between the two pulses also increases. The pulse width of the first pulse was measured as a reference in Fig. 3(a), and that the pulse width measurement result is very stable, due to no adjustment to the pulse amplitude. The change in pulse parameters is caused by the different proportion of the signal amplitude relative to the voltage range selected by the oscilloscope, it is caused by the oscilloscope rather than an actual physical change. Therefore, direct measurement will lead to measurement errors, thus the amplitude of the second

TABLE II
MEASUREMENT RESULTS FOR DIFFERENT LENGTHS OF OPTICAL FIBER, AND COMPARE WITH OFDR AND OTDR

Fiber Length	OFDR	OTDR	Our method	Max difference
0.2 m	0.2268 m	------	0.2473 m	+2.05 cm
0.5 m	0.5235 m	------	0.5807 m	+5.72 cm
1 m	1.0901 m	------	1.0691 m	-2.10 cm
2 m	2.0704 m	------	2.0510 m	-2.94 cm
5 m	5.0859 m	------	5.0542 m	-3.17 cm
20 m	20.2195 m	20.2 m	20.2652 m	+4.57 cm/+6.52 cm
100 m	------	105.0 m	105.1000 m	+0.1 m
1 km	------	1.0221 km	1.0210 km	-1.1 m
10 km	------	10.4353 km	10.4357 km	+0.4 m
20 km	------	20.1530 km	20.1534 km	+0.4 m
50 km	------	50.6606 km	50.6603 km	-0.3 m

pulse measured before and after two measurements must be maintained at the same level. This was not reported in previous work by others, and plays a crucial role in both the dual-pulse and multi-pulse measurement methods.

To solve this problem, Fig. 1 shows that two VOAs in total are employed in the experiment setup. The first attenuator is used to adjust the overall optical pulse amplitude, while the second is used to adjust the amplitude of the second optical pulse to compensate for insertion loss of the FUT that will otherwise lead to slight pulse distortion when measured by the oscilloscope. Two VOAs allow simpler timing (one constant and another with fixed period).

The sampling interval of the oscilloscope was set to 38.4 ns (26.041667 MS/s) for measuring different fiber lengths. At the same time, OTDR (Anritsu MT9085B) and OFDR (Luna OBR4600) are used to measure the same optical fiber for comparison, and an effective index of 1.463 is chosen. In the data report, the accuracy of OTDR is $\pm 1 + 3 \times L \times 10^{-5}$ m, and the accuracy of OFDR is ± 0.1 mm. The experimental results are shown in the Table II, where it is evident when the fiber length is less than 20 m the results of our method is in excellent agreement with that of OFDR. In the case of more than 20 km, the fiber length measured by our method remains within the accuracy range of OTDR. In general, our method produces

The effective index of the single-mode fiber used was measured as a demonstration using this method, using an oscilloscope with a sampling frequency of 1.25 GS/s. First, a short fiber length of 1.090 m was accurately measured using a physical-visual method. Then, the pulse time intervals before and after adding the fiber was compared and subtracted, yielding a time difference of 5.3466 ns. Finally, according to (5) and (11), the effective index of the fiber is calculated to be 1.4705 RIU @ 1550 nm. While it shows a small discrepancy to the value (1.467 RIU @ 1550 nm) provided by the fiber manufacturer, the RIU error can be minimized by using a PD with lower noise-equivalent power or narrow electrical bandwidth, signal generator (AOM) with lower noise, laser source with lower intensity noise, higher sampling rate of the oscilloscope, and more accurate fiber length measuring tool.

V. MULTI-PULSE PRINCIPLES

In the second method, additional pulses (fast time) are analyzed in the optical recirculation rather than relying on repeated measurements (slow time) to calculate the time of flight. This is similar to ring-down spectroscopy, though the timing of pulses is of interest rather than the peak intensity. Starting from theory, it will be proved that the measurement results converge to the true value as the number of pulse cycles increases. Finally, by synthesizing the measurement data of all pulses, an accurate measurement result for the fiber length can be obtained.

The derivation process is similar to the first method. On the basis of the original method, the 0.5 V position of the rising edge of the $N + 1^{th}$ pulse is set as $t(N)$, and the time difference between $t(0)$ and $t(N)$ is equal to the transit time of N cycles of the optical pulse in the fiber loop.

$$t(N) - t(0) = t(N) = \frac{N \cdot L \cdot n_{eff}}{c} \tag{12}$$

The position of the first oscilloscope sampling point after point $t(N)$ is denoted as t_N, and the value of t_N can be derived:

$$t_N = \left\lceil \frac{N \cdot L \cdot n_{eff}}{c \cdot t_s} - rand \right\rceil \cdot t_s + t_s \cdot rand \tag{13}$$

In this way, the transit time T_N corresponding to the fiber length in the ring device can be expressed by dividing the time difference between the first pulse and the $N + 1$ pulse measured

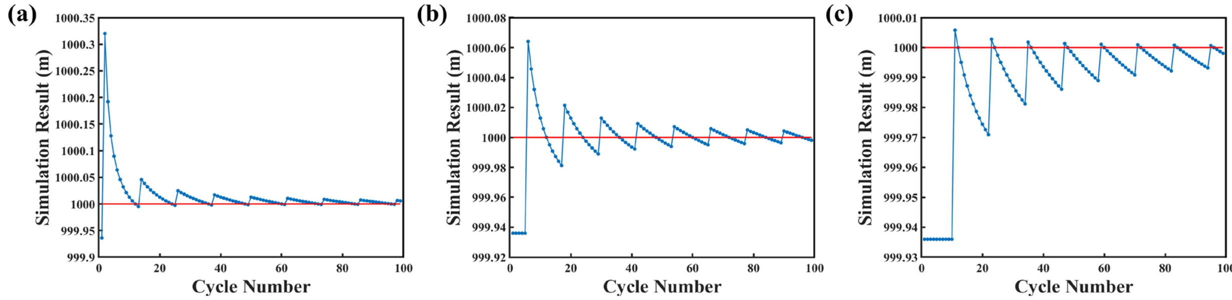

Fig. 4. Three different types of simulation results for (14). (a) Lower-bound convergence; (b) central convergence; (c) upper-bound convergence.

with the oscilloscope by the number of pulses N:

$$T_N = \frac{t_N - t(0)}{N} = \frac{\lceil N \cdot a - b \rceil}{N} \cdot t_s \tag{14}$$

T_N meets the following conditions:

$$\frac{(N \cdot a - b) \cdot t_s}{N} \leq T_N \leq \frac{(N \cdot a - b + 1) \cdot t_s}{N}$$

Hence:

$$\lim_{N \to \infty} \frac{(N \cdot a - b) \cdot t_s}{N} = a \cdot t_s \tag{15}$$

$$\lim_{N \to \infty} \frac{(N \cdot a - b + 1) \cdot t_s}{N} = a \cdot t_s \tag{16}$$

According to the Squeeze Theorem, when N tends to positive infinity, T_N will converge to $a \cdot t_s$. Thus, if sufficient recirculation is achieved, the results become more accurate. MATLAB was used to simulate a 1 km length of optical fiber, and the relationship between the measured result T_N and the number of roundtrips varies depending on the parameter b. Overall, there are 3 trends for convergence, as shown in Fig. 4. The red line represents the length of optical fiber set by simulation, and the blue line denotes T_N measured by the oscilloscope. The measurement results do not satisfy monotonic convergence, instead approaches the true value through a series of damped fluctuations. In the experiment, due to significant optical loss along the optical path, the optical power of the pulse after many roundtrips in the fiber loop becomes too weak for it to be detected by the photodetector and oscilloscope. Therefore, an appropriate data fitting method can be used to suit (14) and obtain the value of parameter a, by collecting data of the finite recirculating pulse sequence. Then, the length of the FUT can be calculated according to (5). For the purpose of simplicity, a more convenient method is used to obtain the value of parameter a. According to (14), it is possible to comprehensively measure the maximum and minimum values of T_N, and yield the range of a:

$$\frac{T_{\min}}{t_s} - 1 \leq a \leq \frac{T_{\max}}{t_s} + 1$$

The range of parameter b is given by the nature of random number in (6):

$$0 \leq b < 1$$

Uniformly select n points from the range of a and b to obtain:

$$a_i = \frac{T_{\min}}{t_s} - 1 + \left(\frac{T_{\max} - T_{\min}}{t_s} + 2\right) \cdot \frac{i-1}{n-1},$$
$$i = 1, 2, 3 \ldots, n \tag{17}$$

$$b_j = \frac{j-1}{n-1}, \quad j = 1, 2, 3, \ldots, n. \tag{18}$$

Bring a_i and b_i into (14):

$$T_N(a_i, b_j) = \frac{\lceil N \cdot a_i - b_j \rceil \cdot t_s}{N} \tag{19}$$

Thus:

$$\sigma(a_i, b_j) = \frac{1}{N} \sum_{k=1}^{N} \left[T_k(a_i, b_j) - T_k\right]^2 \tag{20}$$

Finally, the group (a_i, b_i) with the smallest σ was selected as the final measurement result, which is used to calculate the fiber length according to (5). With this method, the more data points, the more time it takes to calculate, and the higher the accuracy of the results. In the experiment, the noise factor in the system should be taken into account for the accuracy, and the number of decimal points selected should be reasonable according to the system hardware and target accuracy.

The multi-pulse measurement method also uses voltage to determine the position of pulses, so it is subject to the same limitations as the dual pulse method. However, as long as we use a sufficiently large N in (20), this limitation will be greatly reduced. In (20), the total number of $\sigma(a_i, b_j)$ required is N^2, therefore increasing N will increase the computation complexity, and the number of summations for each $\sigma(a_i, b_j)$ calculation will also increase. Therefore, while satisfying the number of pulse cycles, the computation complexity is the main limitation of the measurement accuracy of this method.

VI. Multi-Pulse Experiment Results

In the multi-pulse measurement experiment, the power of the laser pulse is continuously attenuated when recirculating in the ring-down structure, resulting in a continuously dampened pulse sequence. However, due to weak power, the signal cannot be detected accurately by the oscilloscope. The pulse signal generated after multiple cycles cannot be detected by the oscilloscope due to two main limitations: first, the optical power

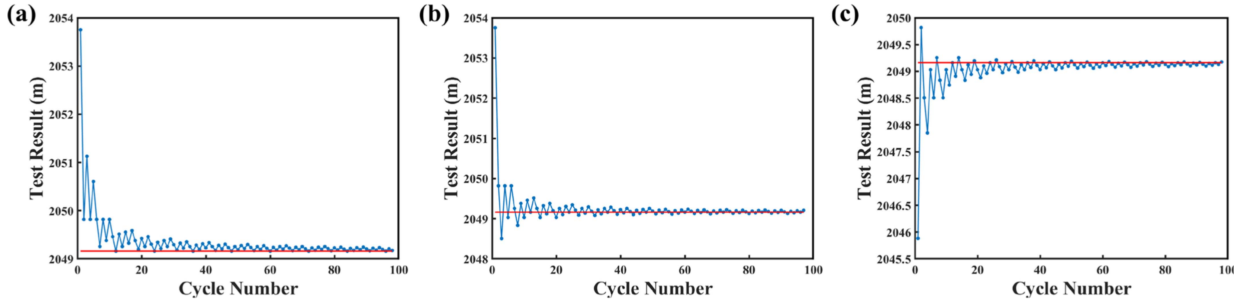

Fig. 5. Three different types of measurement results tested at different times. (a) Lower-bound convergence; (b) central convergence; (c) upper-bound convergence.

TABLE III
TEST RESULT OF MULTI PULSE METHOD

Pulse frequency	Equivalent fiber length	Measurement result	Absolute error	Relative error
5 MHz	40.98324 m	40.98062 m	−2.62 mm	-6.39e-5
1 MHz	204.91623 m	204.91571 m	−0.52 mm	-2.53e-5
500 kHz	409.83247 m	409.82810 m	−4.37 mm	-1.06e-5
100 kHz	2,049.16239 m	2,049.16414 m	+1.75 mm	+8.54e-7
50 kHz	4,098.32478 m	4,098.31866 m	−6.12 mm	-1.49e-6
10 kHz	20,491.62392 m	20,491.61780 m	−6.12 mm	-2.99e-6
1 kHz	204,916.23923 m	204916.28382 m	+44.59 mm	+2.176e-7

is too weak, and PD cannot detect the optical signal; second, the optical power is adequate to be detected by PD, but the voltage range of the oscilloscope to be large enough to receive the pulse signal at the front end of the pulse sequence, and the pulse signal at the back end of the pulse sequence is relatively weak, making it impossible to measure small signals correctly without adjusting the voltage range of the oscilloscope. So not only do we need to ensure that the laser power meets the requirements, but there are also requirements for the dynamic range of the oscilloscope. Hence, relying on current experimental conditions cannot obtain enough pulses to improve accuracy. To address this issue, there are two proposed solutions: (1) Place an AOM before the PD to attenuate the optical power of pulses. The earlier the pulse is received, the higher the set attenuation, and thus pulses are kept at the same voltage level for oscilloscope acquisition. Experiments were conducted based on this scheme and up to 15 pulses were collected. The main limitation is that the adjustable attenuation range of AOM is limited and cannot cover sufficient number pulses. (2) Amplify the optical pulse during each cycle to counter the attenuation, which has not been verified yet due to the lack of suitable devices. Therefore, we temporarily use a signal generator to generate pulse signals of a fixed frequency to mimic a multi-pulse sequence generated by optical recirculation, and directly connect the output signal to the oscilloscope to verify our scheme. The reciprocal value of the set pulse frequency represents the difference between the transit time in the fiber loop of adjacent optical pulses. The fiber length corresponding to the pulse frequency can be expressed as:

$$L = \frac{c}{n_{eff}} \cdot \Delta t = \frac{c}{n_{eff} \cdot f} \tag{21}$$

The experimental results obtained from the multi pulse scheme using a 26.041667 MS/s oscilloscope are shown in the Fig. 5, where measurements taken at different time instances lead to different times of convergence for the fiber length. The measured curve shown in Fig. 5 is like to the simulated results shown in Fig. 4. The detailed data is shown in Table III. In the test of 5 MHz$\sim$10 kHz, the absolute error obtained from the measurement is similar. The error generated by 1 kHz may be caused by the error of the signal generator itself.

VII. CONCLUSION

For accurate and portable fiber-length and effective-index measurement, we proposed and demonstrated two new measurement methods, dual-pulse and multi-pulse. Many published works on fiber length measurement use the average of multiple measurements as their results, but they do not provide a scientific justification as to whether this approach is reasonable for their system. We have derived the relationship between the time interval of two successive pulses and the fiber in our system, mathematically proved that the arithmetic mean of multiple measurement results gives the true transit time of light in the fiber, and provided experimentally verification. Prior work in the literature only used the time interval between the first and last pulses resulting from optical recirculation for calculating the time of flight, while using the number of cycles to average the measurement error Δ. In the proposed multi-pulse method, the algorithm in (20) was used to utilize the information of each pulse, not only the first and last pulses, to achieve higher measurement accuracy. Both measurement systems are relatively simple, stable and can provide highly accurate real-time results in comparison to commercial tools. With reference to the measurement results of Luna OFDR, the error of the dual-pulse method is within ± 6 cm using an oscilloscope with a sampling frequency of 26.041667 MS/s. Increasing the number of data averages or the sampling frequency will reduce the error. The multi-pulse method is limited in pulse round-trip times due to system hardware limitations, thus the full potential of the measurement method cannot be demonstrated. However, simulations and experiments reveal that even when using a low-end oscilloscope ($\sim$26 MS/s), with a higher-output laser or more sensitive photodetector, it is possible to realize a relative error as low as 8.54×10^{-7} (1.75 mm error for a fiber length of 2.049 km). A single-mode fiber with a reported effective index of 1.467 was characterized using the dual-pulse method, and the measurement result of 1.4705 shows fair agreement with the error attributed to low-spec hardware (demonstrates low-cost approach). Therefore, our new methods combine the qualities of both OTDR (long distance) and OFDR (high accuracy) to provide precise fiber length calibration for distributed fiber-optic sensors, and during the process it can also determine the effective refractive index of the fiber-under-test using a short sample of the optical fiber.

Disclosures: The authors declare no conflicts of interest.

REFERENCES

[1] H. Naruse et al., "Application of a distributed fibre optic strain sensing system to monitoring changes in the state of an underground mine," *Meas. Sci. Technol.*, vol. 18, no. 10, pp. 3202–3210, 2007, doi: 10.1088/0957-0233/18/10/s23.

[2] G. R. McDowell et al., "The use of nanotechnology in the development of a distributed fibre-optic temperature sensor for subsea applications," *J. Phys.: Conf. Ser.*, vol. 450, 2013, Art. no. 012008, doi: 10.1088/1742-6596/450/1/012008.

[3] Z. Wang et al., "Coherent Φ-OTDR based on I/Q demodulation and homodyne detection," *Opt. Exp.*, vol. 24, no. 2, pp. 853–858, 2016, doi: 10.1364/oe.24.000853.

[4] A. Masoudi, M. Belal, and T. P. Newson, "A distributed optical fibre dynamic strain sensor based on phase-OTDR," *Meas. Sci. Technol.*, vol. 24, no. 8, 2013, Art. no. 085204, doi: 10.1088/0957-0233/24/8/085204.

[5] K. Aoyama, K. Nakagawa, and T. Itoh, "Optical-time domain reflectometry in a single-mode fiber," *IEEE J. Quantum Electron.*, vol. 17, no. 6, pp. 862–868, Jun. 1981, doi: 10.1109/jqe.1981.1071237.

[6] Y. Mao et al., "Sensing within the OTDR dead-zone using a two-mode fiber," *Opt. Lett.*, vol. 45, no. 11, pp. 2969–2972, 2020, doi: 10.1364/ol.393539.

[7] H. Zhong et al., "High-spatial-resolution OFDR with single interferometer using self-compensation method," *Opt. Lasers Eng.*, vol. 161, 2023, Art. no. 107341, doi: 10.1016/j.optlaseng.2022.107341.

[8] H. Zhong et al., "Distributed high-temperature sensing based on optical frequency domain reflectometry with a standard single-mode fiber," *Opt. Lett.*, vol. 47, no. 4, pp. 882–885, 2022, doi: 10.1364/ol.449366.

[9] Z. Qin, Y. Hu, Y. Yue, and C. Tan, "A dual-ended 400 km OFDR for vibration detection," *Meas. Sci. Technol.*, vol. 33, no. 4, 2022, Art. no. 045203, doi: 10.1088/1361-6501/ac4ac1.

[10] G. Hao, L. Churui, T. Huang, J. Bo, and W. Chao, "A long-haul and high-accuracy fiber length measurement technology based on Mach–Zehnder and Sagnac hybrid interferometer," *Meas. Sci. Technol.*, vol. 32, no. 11, 2021, Art. no. 115204, doi: 10.1088/1361-6501/ac09b5.

[11] R. Ferriere, J. Cussey, and J. Dudley, "Time-of-flight range detection using low-frequency intensity modulation of a cw laser diode: Application to fiber length measurement," *Proc. SPIE*, vol. 47, no. 9, Sep. 2008, Art. no. 093602, doi: 10.1117/1.2977794.

[12] A. Zanobini, G. Iuculano, and A. Ponterio, "Distance scale calibration of optical time-domain reflectometers with the recirculating delay line method," *IEEE Trans. Instrum. Meas.*, vol. 54, no. 6, pp. 2554–2556, Dec. 2005, doi: 10.1109/tim.2005.858106.

[13] K.-H. Yoon, J.-W. Song, and H. D. Kim, "Fiber length measurement technique employing self-seeding laser oscillation of Fabry–Perot laser diode," *Japanese J. Appl. Phys.*, vol. 46, no. 1, pp. 415–416, 2007, doi: 10.1143/jjap.46.415.

[14] Y. L. Hu, L. Zhan, Z. X. Zhang, S. Y. Luo, and Y. X. Xia, "High-resolution measurement of fiber length by using a mode-locked fiber laser configuration," *Opt. Lett.*, vol. 32, no. 12, pp. 1605–1607, Jun. 2007, doi: 10.1364/ol.32.001605.

[15] X. Wang, T. Wang, J. Yu, and X. Wang, "Precise measurement of polarization maintaining fiber length based on sawtooth wave phase modulation," *Optik*, vol. 172, pp. 249–256, 2018, doi: 10.1016/j.ijleo.2018.06.062.

Yuhang Wang received the B.S. degree in optoelectronic information science and engineering from Nanchang Hangkong University, Nanchang, China, in 2020. He is currently working toward the M.S. degree with Shenzhen University, Shenzhen, China. His research focuses on distributed fiber vibration sensors.

Kuan Liu received the B.S. degree in measurement and control technology and instrument from the Hefei University of Technology, Hefei, China, in 2021. He is currently working toward the M.S. degree with Shenzhen University, Shenzhen, China. His research interests focuses on long-range distributed vibration sensing using phase-sensitive forward optical transmission.

Xing Rao received the B.S. degree in optoelectronic information science and engineering from Nanchang Hangkong University, Nanchang, China, in 2020. He is currently working toward the Ph.D. degree with Shenzhen University, Shenzhen, China. His research interests focuses on super long-range distributed vibration sensor based on polarimetric forward transmission of light.

George Y. Chen (Senior Member, IEEE) received the M.Eng. (four-year Bachelor's and Master's joint) degree from Imperial College London, London, U.K., in 2009, in the field of electronics and electrical engineering with computer science, and the Ph.D. degree from the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., in 2013. He was with an Industrial Research Lab, for SPI Lasers Ltd., as a Postdoctoral Research Fellow. From 2013 to 2015. He joined the University of South Australia as a Research Fellow in 2015, and played a critical role in establishing the Laser Physics and Photonic Devices Laboratories and a Joint Research Lab between the University of South Australia and Shandong Academy of Sciences. He was a part of the MinEx CRC. He joined Shenzhen University, Shenzhen, China, as a Professor in 2021, with a focus on the research of long-range distributed vibration sensing technologies. He is a co-inventor of one PCT patent, and he has coauthored a book chapter published by CRC Press. He has authored or coauthored 37 journal papers as first/corresponding author, and Optica.

Yiping Wang (Senior Member, IEEE) was born in Chongqing, China, in 1971. He received the B.Eng. degree in precision instrument engineering from the Xi'an Institute of Technology, China, in 1995, and the M.S. and Ph.D. degrees in optical engineering from Chongqing University, Chongqing, China, in 2000 and 2003, respectively. From 2003 to 2005, he was with Shanghai Jiao Tong University, Shanghai, China, as a Postdoctoral Fellow. From 2005 to 2007, he was with the Hong Kong Polytechnic University, Hong Kong, as a Postdoctoral Fellow. From 2007 to 2009, he was with the Institute of Photonic Technology, Jena, Germany, as a Humboldt Research Fellow. From 2009 to 2011, he was with the Optoelectronics Research Centre, University of Southampton, Southampton, U.K., as a Marie Curie Fellow. Since 2012, he has been with Shenzhen University, Shenzhen, China, as a Distinguished Professor. He has authored or coauthored one book, 21 patent applications, and more than 240 journal and conference papers. His research interests include optical fiber sensors, fiber gratings, and photonic crystal fibers. Prof. Wang is the Optical Society of America, and the Chinese Optical Society.