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Distributed acoustic sensing based on pulse-coding phase-sensitive OTDR

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***Abstract*—Phase-sensitive optical time-domain reflectometry (Φ-OTDR), which utilizes the phase information of Rayleigh scattered lightwave inside optical fiber, could turn a fiber cable into a massive sensor array for distributed acoustic sensing (DAS), i. e., an emerging infrastructure for Internet of Things. Given a certain fiber length, there are trade-offs among the sensing bandwidth, the sensitivity and the spatial resolution. In this paper, the concept of linearization and Golay pulse-coding for heterodyne Φ-OTDR are proposed and experimentally verified for the first time. Firstly we gave a full theoretical treatment on how an intensity-coded yet phase-retrieved Φ-OTDR can be built up as a fully linear system, therefore a significant enhancement of signal to noise ratio becomes viable and the sensing bandwidth keeps equal the four-times averaging case. Secondly in the proof-of-concept experiment, submeter gauge length and nano-strain resolution were realized with 10 km sensing range, in other words, more than ten thousand sensitive sensing units were realized along the fiber. This work makes a significant step towards high-performance DAS with orders-of-magnitude performance enhancement.**

Index Terms—Internet of Things, optical fiber sensors, reflectometry, sensor design, acoustic sensors, pulse coding.

I. Introduction

The ultimate goal of the Internet of Things (IoT) is a smarter world [1], where everything could be an IoT device that connects through the IoT to form a huge network. In order to achieve this goal, a large amount of data needs to be transmitted by mobile cellular networks, WiFi or Bluetooth, etc. However, data transmission of the IoT devices is a huge challenge due to the crowded wireless channels. In addition, a large number of sensors need to be laid out which is a time consuming and laborious task. Distributed optical fiber sensing (DOFS) is a promising tool, which is one of the effective ways to overcome this challenge [2]-[6]. Since optical fiber is the most powerful medium for information transmission at present, a large amount of sensing data can be easily transmitted. The sensing unit of DOFS is the optical fiber itself, which can be converted into a massive number of virtual sensors by demodulating the backscattered signal. Therefore, once the fiber is laid, a large number of sensors is deployed at the same time, and there is no need to consider each sensor's power supply. Therefore, the energy efficiency of DOFS is considerably high. Besides, the sensing information of each sensing unit is extracted from the backscattered light, so tens of thousands of sensing units share the same bandwidth. That is to say, comparing with traditional IoT devices, the spectrum efficiency of the DOFS is extremely high. Thanks to the characteristics of optical fiber materials, DOFS is inherently resistant to corrosion and electromagnetic interference. Due to the above features, DOFS is particularly suited for the IoT applications.

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Phase-sensitive optical time-domain reflectometer (Φ-OTDR) is an exemplary type of DOFS. It has attracted a lot of interest due to its unique advantages, such as high sensitivity, instantaneous response property, and the ability of distributed acoustic sensing (DAS) and communication [7]-[13]. A typical application scenario of DAS based on Φ-OTDR is shown in Figure 1. The Φ-OTDR sends out the probe light into the fiber cable and collects the Rayleigh backscattered light, whose phase is related to the acoustic signals acquired by the fiber cable. As a result, the fiber cable is turned into a large-scale acoustic sensor array, while the size of each sensor is defined by virtual gauge length. The system could acquire acoustic signals from various sources such as automobiles, intruders, UAVs, etc.

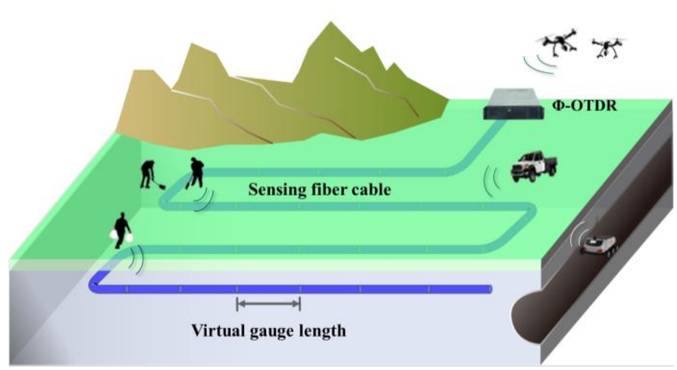

Fig. 1. The typical application scenario of DAS.

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In DAS, the sensitivity, the sensing bandwidth and the spatial resolution are the most important parameters. The sensitivity is the smallest acoustic signal that the sensing unit can distinguish, and it largely depends on the signal-to-noise ratio (SNR) of the sensing unit; the sensing bandwidth is the maximum frequency of acoustic signal that the sensing unit can measure, and it is limited by the repetition rate of the probe pulse; the spatial resolution refers to the resolvable spatial length for perturbation measurement, and it is bounded by both the pulse width and the virtual gauge length for acquiring the differential phase. There are always trade-offs among them in traditional DAS. Specifically, in order to increase the sensing sensitivity, multiple acquisitions and data averaging are usually used, but it will reduce the sensing bandwidth; for finer spatial resolution, each sensor receives less energy, reducing the strain sensitivity. The key to breaking the above trade-off is to increase the SNR of each sensor without sacrificing other parameters, which also increase the energy efficiency. Several methods have been proposed to somehow break the above trade-offs, for example, distributed amplification for ultra-long sensing range and coarse spatial resolution, or chirped-pulse with matched-filter for moderate sensing range and fine spatial resolution [6], [10], [11]. Since the spatial resolution of the chirped pulse technique is inversely proportional to the sweep frequency range, a complex modulation process is required to achieve high spatial resolution in DAS.

In contrast, the optical pulse coding (OPC) is easy to be generated using the optical communication devices, which has been widely used in intensity-demodulated DOFS systems, such as Brillouin optical time domain analysis (BOTDA) and Raman-based distributed temperature sensor, showing huge signal-to-noise ratio (SNR) enhancement [14]-[17]. In recently, OPC was considered to be implemented in Φ-OTDR. In 2015, Y. Muanenda *et al* proposed an intensity demodulation OPC Φ-OTDR system [18], realizing ~9 dB signal-to-noise ratio (SNR) improvement compared with the single-pulse equivalent. However, this scheme cannot measure the external disturbance quantitatively, because this system can only detect the intensity information of Rayleigh scattered (RS) light which is nonlinear with external disturbance.

In phase-demodulated systems, no high-performance OPC Φ-OTDR has been demonstrated yet. The major reason is that Φ-OTDR is not a naturally linear system, therefore OPC technology cannot be directly applied. In 2016, H. F. Martins *et al* proposed a phase-demodulated phase-shift keying (PSK) pulse coding Φ-OTDR system, 2.5cm spatial resolution in over 500m sensing range is demonstrated. This is a meaningful work towards pulse-coding DAS [19]. However, no high-performance dynamic sensing was demonstrated in that work, indicating the limitation of the proposed scheme.

In this work, firstly, we theoretically derived the linearization approach for phase-demodulated OPC Φ-OTDR. Then a proof of concept experiment was implemented to verify that the proposed scheme has the ability to improve the SNR. Finally, an Φ-OTDR system with sub-meter spatial resolution and nano-strain resolution was demonstrated. Thanks to the advantages of newly designed system, the spectrum efficiency and energy efficiency are both extremely high compared with traditional point sensors. Therefore, in future this technology could be widely used in the IoT field.

II. Principles

A. Linearization of coherent detection Φ-OTDR

In a typical Φ-OTDR with coherent detection, an ultra-narrow linewidth pulse light is injected into the fiber, resulting in RS light due to the fluctuated refractive index distribution along the fiber. The RS signal caused by single-pulse can be seen as the vector sum of the scattered light from a large number of the scattering elements in the fiber, which can be expressed as

$$R(t)=A_s(t)\exp\left[i\omega_s t+i\varphi_s+i\varphi(t)\right] \tag{1}$$

where $A_s(t)$ and $\varphi(t)$ are the amplitude and the phase term of the backscattered signal respectively; ω_s is the angular frequency of the pulse light; φ_s is the phase of the pulse light when it was injected into the fiber; *i* is the imaginary unit. Due to the strong coherence of the optical pulses used, $A_s(t)$ and $\varphi(t)$ become Rayleigh distributions and uniformly distributed random variables [20], respectively. The value of $A_s(t)$ and $\varphi(t)$ are related to the fiber under test (FUT), and they are extremely sensitive to temperature and strain. In other words, the external disturbance information can be extracted by demodulating $A_s(t)$ and $\varphi(t)$ using coherent detection [20]-[25]. The local oscillator (LO) of coherent detection can be described as

$$E_{LO}(t)=A_l\exp\left(i\omega_l t+i\varphi_l\right) \tag{2}$$

where A_l, ω_l and φ_l are the amplitude, the angular frequency and the initial phase of the LO, respectively. After removing the DC component and digitally down-converted into baseband, the beating signal can be described as

$$I(t)=rA_s(t)A_l\cos\left[\varphi_d+\varphi(t)\right] \tag{3}$$

Where *r* is the response factor, $\varphi_d=\varphi_s-\varphi_l$, $A_s(t)$ and $\varphi(t)$ can be obtained using the relations below:

$$\begin{cases} A_s(t)\propto\sqrt{I^2(t)+Q^2(t)} \\ \varphi(t)\approx angle\left[I(t)+jQ(t)\right]-\varphi_d \end{cases} \tag{4}$$

where $Q(t)$ is the quadrature signal of $I(t)$, and it can be obtained by optical 90° hybrid, Hilbert transform, etc [20]-[25].

Actually, the RS signal is slowly changing over time, because the environment around the fiber and the operating state of the laser change over time. However, in the dynamic measurement, the single measurement time is much less than the timescale of significant changes in ambient or laser condition [26]. Therefore, Φ-OTDR in dynamic measurement mode can be considered as a natural time-invariant system.

For OPC Φ-OTDR, it is necessary to use a series of pulse sequences instead of standalone pulses injected into the fiber.

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We assume the coding sequence is $C=\left[C_1,C_2,\cdots,C_{M+1}\right]$, so the M+1 bits optical pulse sequence could be represented by

$$\hat{C}=\sum_{p=1}^{M} C_p \exp\left(i\omega_s p\tau\right) rect\left(t-p\tau\right) \tag{5}$$

where C_p indicates the amplitude of the p-th pulse and τ is the rising-edge interval between two adjacent pulses inside a sequence.

The RS signal of the pulse sequence is the sum of the RS signal of each pulse inside the sequence:

$$\begin{aligned} E(t) &= \sum_{p=0}^{M} C_p \exp\left(i\omega_s p\tau\right) R\left(t-p\tau\right) \\ &= \sum_{p=0}^{M} C_p A_s\left(t-p\tau\right)\exp\left[i\omega_s t+i\varphi_s+i\varphi\left(t-p\tau\right)\right] \end{aligned} \tag{6}$$

After coherent detection with LO expressed in Eq. (2), the beating signal after removing the DC component can be described as:

$$\begin{aligned} I_{code}(t) &= \sum_{p=0}^{M} rC_p A_s\left(t-p\tau\right) A_l \cos\left[\Delta\omega t+\varphi_d+\varphi(t-p\tau)\right] \\ &+\sum_{p=0}^{M-1}\sum_{q=p+1}^{M} 2rC_pC_qA_s\left(t-p\tau\right)A_s\left(t-q\tau\right)\cos\left(\varphi_{pq}\right) \end{aligned} \tag{7}$$

where $\Delta\omega=\omega_s-\omega_l$, $\varphi_{pq}=\varphi\left(t-p\tau\right)-\varphi\left(t-q\tau\right)$, r is the response coefficient of the photodetector.

The first term in Eq. (7) represents the beating signal of $E(t)$ and LO, which is the sum of each pulse's response. The second term in Eq. (7) denotes the crosstalk terms caused by the interference inside the pulse sequence. The crosstalk terms are the major reason of the nonlinear response of coherent OPC Φ-OTDR. Although A_s is much smaller than A_l, when the number of coding bits is large enough, the value of the crosstalk term becomes significant. Fortunately, the beat signal and the crosstalk term are in different frequency bands when $\Delta\omega\neq 0$. Thus, it is easy to eliminate the impact of them using heterodyne detection and bandpass filtering. After bandpass filtering and digital down-conversion, the beating signal can be represented as:

$$\begin{aligned} I_{code}(t) &= \sum_{p=0}^{M} rC_p A_s\left(t-p\tau\right) A_l \cos\left[\varphi_d+\varphi(t-p\tau)\right] \\ &= \sum_{p=0}^{M} C_p I\left(t-p\tau\right) \\ &= C * I\left(t\right) \end{aligned} \tag{8}$$

Equation (8) shows that the system response of the coded pulse is the convolution of the coded sequence and the single pulse response. As a result, through the above processes coherent detection Φ-OTDR becomes a linear time-invariant system. Through proper decoding method, the single-pulse response can be demodulated, and then the amplitude and phase of the RS light can be demodulated using Eq. (4).

B. Selection of the coding type

In order to guarantee time-invariant characteristics and satisfy the requirements of dynamic acoustic sensing, the key factor for selecting the coding type is the measurement time of the system. Golay complementary code is a suitable candidate for this application, which needs bipolar coding. In Φ-OTDR, it is difficult to produce 'negative light', therefore pulse pairs are needed to simulate bipolar coding. There are 4 rows of sequences should be formed, namely C_1, C_2, D_1, and D_2. Where C_1 and C_2, D_1 and D_2 are both pulse pairs used for simulating bipolar coding. The relationship between them is [17]

$$\left(C_1-C_2\right)\otimes\left(C_1-C_2\right)+\left(D_1-D_2\right)\otimes\left(D_1-D_2\right)=2M\delta\left(t\right) \tag{9}$$

where $\otimes$ represents the correlation operation, $\delta\left(t\right)$ is the Dirac function, M is the number of coded bits. Golay complementary sequences can be generated by iterative algorithms [28]. According to Eq. (8), the response of each row is equal to the convolution of the row with the single pulse response of Φ-OTDR:

$$\begin{cases} I_{C_1}(t)=C_1 * I\left(t\right) \\ I_{C_2}(t)=C_2 * I\left(t\right) \\ I_{D_1}(t)=D_1 * I\left(t\right) \\ I_{D_2}(t)=D_2 * I\left(t\right) \end{cases} \tag{10}$$

According to the characteristics of the Golay complementary code shown in Eq. (9), we can get the single pulse response：

$$\left(I_{C_1}-I_{C_2}\right)\otimes\left(C_1-C_2\right)+\left(I_{D_1}-I_{D_2}\right)\otimes\left(D_1-D_2\right)=2MI\left(t\right) \tag{11}$$

It is worth noting that Golay coding requires 4 rows to demodulate the single pulse response, so the Golay coding results need to be compared with the single-pulse results with 4 times averaging. The SNR of the intensity signal is increased by $\sqrt{M}/2$ times [17]. Since the SNR of phase trace is proportional to the SNR of the intensity trace [29], the Golay coding will increase the SNR of the phase-demodulated Φ-OTDR by $\sqrt{M}/2$ times.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. The Comparison between traditional Φ-OTDR and OPC Φ-OTDR

The experimental setup of OPC/single pulse Φ-OTDR is shown in Figure 2. An ultra-narrow linewidth continuous wave (CW) laser is split into two channels with a coupler (OC1). One branch of OC1 is used as the local oscillator (LO), and the other branch of OC1 is modulated by a pulse modulator, which is an acousto-optic modulator (AOM) with 200 MHz frequency shift, generating probe pulses (single or coded) with 40ns duration. The arbitrary waveform generator (AWG) is used to generate an electrical single pulse or Golay coded pulses. The probe pulses are injected into the FUT through a circulator. The RS signal and the LO signal enter the IQ detection module to obtain the in-phase digital signals, and quadrature digital signals are obtained by applying Hilbert transform on in-phase digital signals. The total length of the FUT is 2.2 km. A piezoelectric ceramic transducer (PZT) wrapped with 12.3m fiber is placed

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at 2.1 km. The length of the Golay code sequence is 128, and the peak power of each coded pulse is the same as the single pulse case.

The response of single pulse with averaging case (blue line) and the single pulse response of OPC case (red dashed line) after decoding are shown in Figure 3. The response of entire FUT, the near end of the FUT and the far end of the FUT is shown in Figure 3 (a), Figure 3 (b) and Figure 3 (c), respectively. Figure 3 shows that the trace pattern of the OPC Φ-OTDR is very close to the single-pulse Φ-OTDR case, and the SNR of the OPC Φ-OTDR case is much higher, as can be seen from the trace tail of Figure 3 (a).

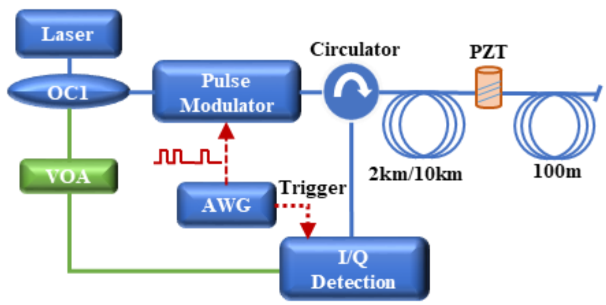

Fig. 2. Experimental setup of OPC/single pulse Φ-OTDR.

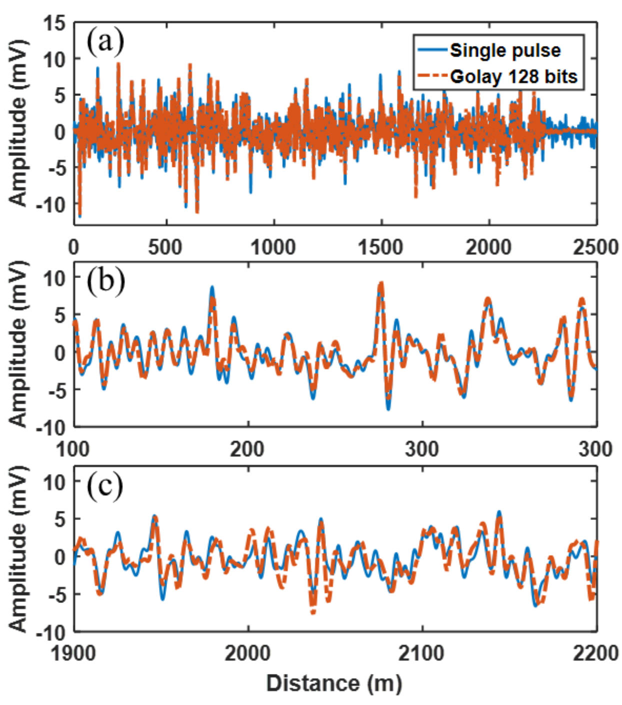

Fig. 3. The single pulse of the OPC/single pulse Φ-OTDR. (a) The entire FUT. (b) The near end of FUT. (b) The far end of FUT.

It can be seen from Eq. (4), the external disturbance can be obtained by demodulating the phase information of the RS signal. In the experiment, 300 Hz sinusoidal disturbance is applied on PZT. Figure 4 shows the demodulation result. Figure 4 (a) is the result of the single pulse, while Figure 4 (b) shows the result of the single pulse with 4 times averaging. Figure 4 (c) is the result of 128-bit Golay coding. Direct trace averaging and Golay coding both can improve the SNR of the demodulated signal, but 128-bit Golay coding shows much better SNR improvement. The noise variance of single pulse, single pulse with 4 times averaging and 128-bit Golay coding is $0.0792/rad^2$, $0.0210/rad^2$ and $0.00009046/rad^2$, respectively. Compared with single pulse with 4 times averaging, the noise variance of Golay 128-bit coding has been compressed by 13.7 dB.

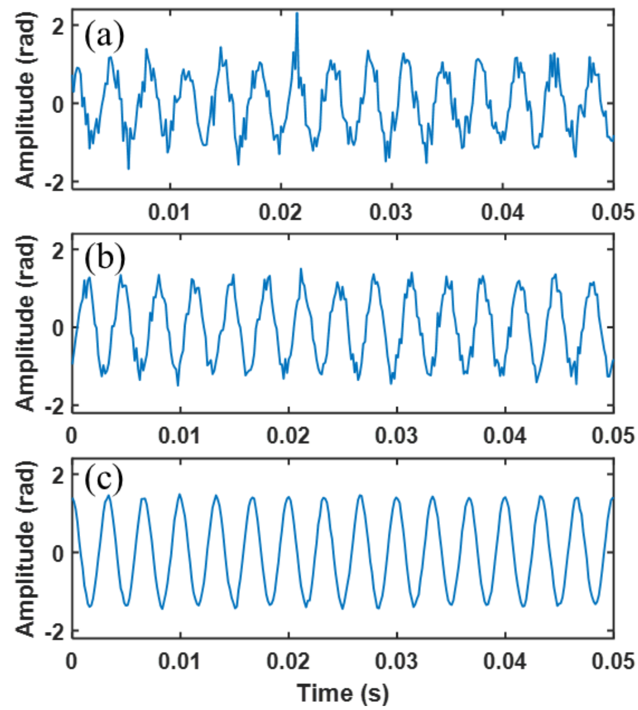

Fig. 4. The demodulation result of external disturbance. (a) The results of the single pulse; (b) the results of the single pulse after averaging 4 times; (c) the results of 128-bit Golay coding.

In order to further demonstrate the performance of OPC Φ-OTDR, we use the waveforms with complex spectrum to perturb the PZT. A triangular wave of 200 Hz and a linear chirp signal sweeping from 100 Hz to 1 kHz are respectively applied to the PZT.

Figure 5 shows the demodulation results with the triangular wave excitation. Figure 5 (a) is the results of single pulse with 4 times averaging and Figure 5 (b) is the results of 128-bit Golay coding, respectively. The demodulated trace in Golay coding case is much smoother, i.e., it has a larger SNR than that in the single pulse case. Figure 6 shows the demodulation results with the linear chirped signal excitation. Figure 6 (a) and (b) shows the time domain signal of the single pulse with 4 times averaging and the results of Golay 128-bit coding, respectively, and Figure 6 (c) and (d) are the short-time Fourier transform (STFT) results of Figure 6 (a) and (b). The demodulation result of 128-bit Golay coding is better than the result of single pulse with 4 times averaging in both time domain and frequency domain.

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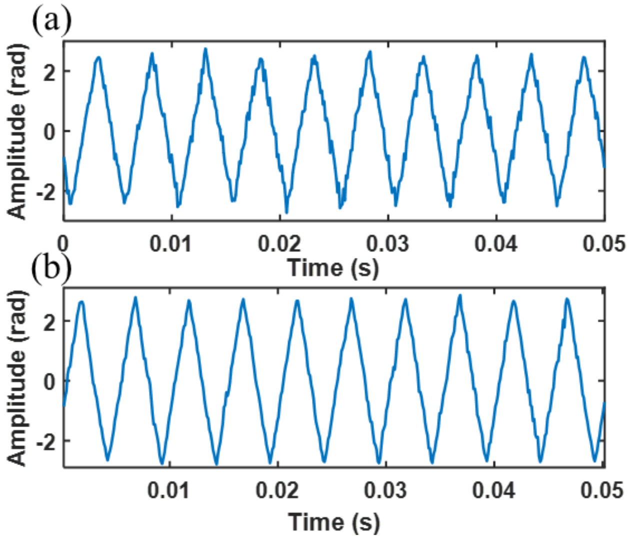

Fig. 5. The demodulation results of the triangular wave.
(a) The results of the single pulse after averaging 4 times; (b) the results of Golay 128-bit coding.

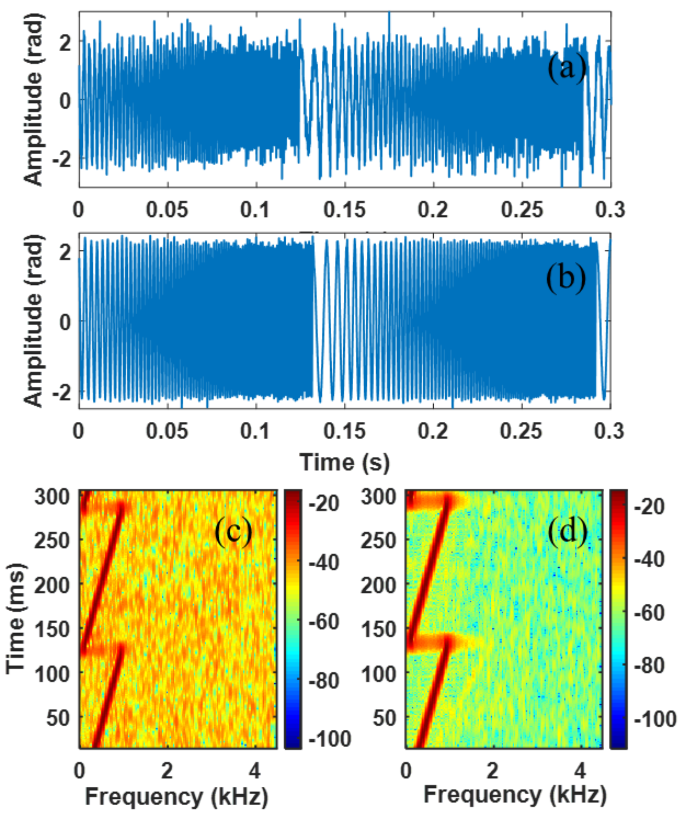

Fig. 6. The demodulation results of linear chirp signal.
(a) The averaging 4 times case; (b) the Golay 128-bit coding case; (c) the STFT results of (a); (d) the STFT results of (b).

B. *OPC Φ-OTDR with longer code length*

In the above experiments, the AOM was used to generate the coded pulse. Due to its limited bandwidth, it is unable to generate a pulse shorter than 10 ns (corresponding spatial resolution is 1m). In order to produce narrower pulses, the AOM is replaced with an electro-optic IQ modulator, generating 2048-bit Golay sequences with 8 ns duration (corresponding 80 cm spatial resolution) and 700 MHz frequency shift. The peak power of each pulse is 15.5 dBm. The FUT is changed from 2.1 km fiber to 10 km fiber. The sinusoidal signal with 3 V amplitude and 50 Hz frequency, is applied on the PZT at the end of the 10 km FUT.

It is worth noting that the spatial resolution of the phase-demodulated Φ-OTDR is the larger one between half of the pulse width and the virtual gauge length for acquiring differential phase. In this experiment, the gauge length is 92 cm and 1/2 pulse width is 82 cm, therefore the spatial resolution is 92 cm. The experimental results of the single pulse with 4 times averaging are shown in Figure 7.

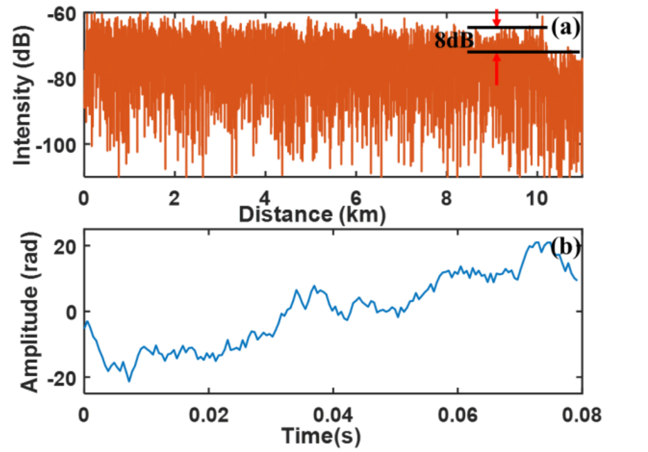

Fig. 7. The experimental results of the single pulse after averaging 4 times.
(a) Intensity trace along the entire FUT; (b) the differential phase signal at the disturbance zone.

Figure 7 (a) and (b) are the intensity trace of the entire fiber and the differential phase signal at the disturbance zone, respectively. It can be seen from Figure 7 that the intensity SNR at the end of the FUT is only 8 dB and the external disturbances cannot be correctly demodulated.

Under the same test conditions, the result of Golay 2048-bit coding is shown in Figure 8. Figure 8 (a), (b) and (c) are the intensity trace of the entire fiber, the differential phase signal at the disturbance zone and the power spectral density (PSD) of the demodulated disturbance signal, respectively. The SNR of the intensity trace at the end of FUT is increased from 8 dB to 16 dB, and the demodulated 50 Hz external disturbance signal can be clearly identified. Form Figure 8 (c), the demodulated signal is 18.3 dB higher than the noise level, and in this case the strain resolution is calculated as 4.2 $n\varepsilon$ [11].

C. *Linearity of the system response*

The linearity of Φ-OTDR's system response to external disturbances is also an important parameter, which is related to the quality of the demodulated signal. In order to verify the response linearity of the OPC Φ-OTDR, we change the voltage of sinusoidal applied on the PZT from 600 mV to 3 V with a step of 200 mV. The relationship between the amplitude of the demodulated phase signal and the voltage amplitude applied to the PZT is shown in Figure 9.

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The red dots are the experimental results and the black solid line is the fitting line. The R-square of the fitting line is 0.9988, which shows good linearity.

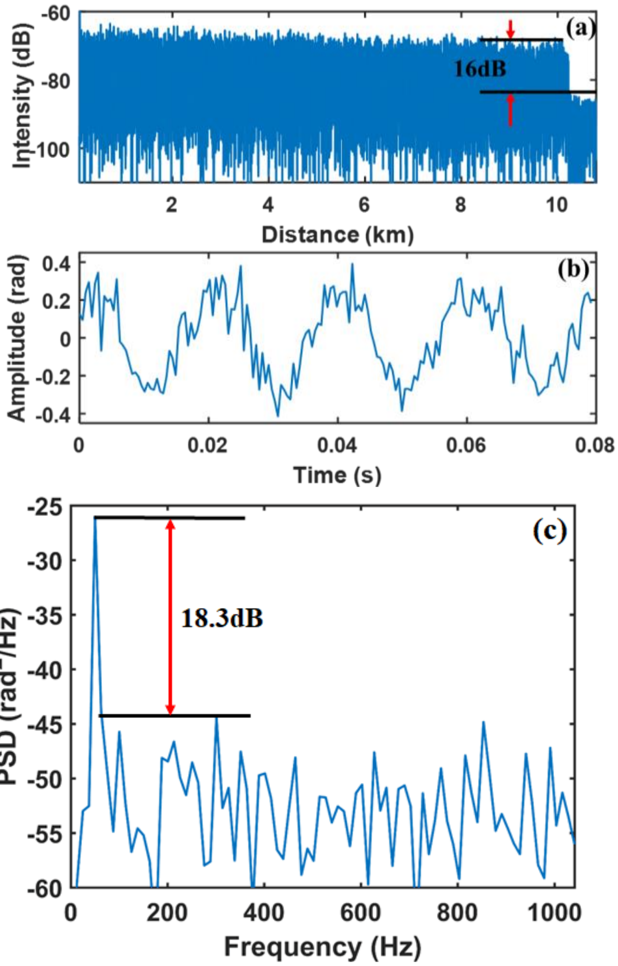

Fig. 8. The result of Golay 2048-bit encoding.
(a) Intensity trace along the entire; (b) the differential phase signal at the disturbance zone; (c) the PSD of the demodulated disturbance signal.

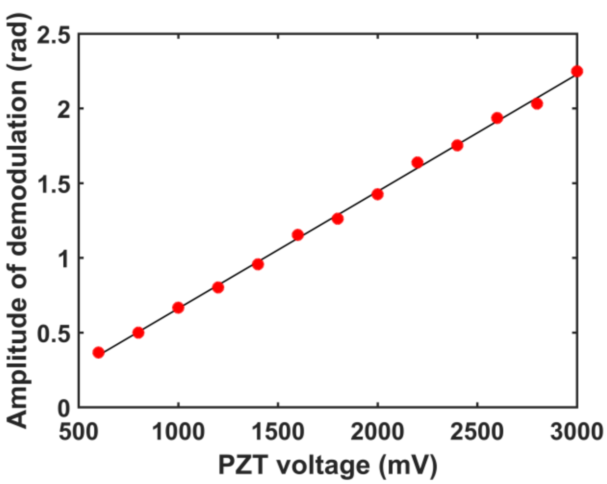

Fig. 9. The amplitude of the phase variation v.s. the voltage amplitude applied to the PZT.

IV. Conclusions

In order to break the inherent trade-off between the key parameters in Φ-OTDR, we present a novel phase-demodulated OPC Φ-OTDR. The linear characteristics of coherent detection Φ-OTDR were analyzed, and the corresponding linearization procedure was presented. The proof-of-concept experiment shows that Golay-coded OPC Φ-OTDR can nicely demodulate single-pulse-response and significantly improve the SNR of the sensing signal. The sensing bandwidth and energy efficiency of sensing fiber can be significantly optimized. It is also worth noting that this method is well compatible with other performance enhancement methods, such as frequency-division multiplexing for further increasing sensing bandwidth and the methods for fading elimination, etc.

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