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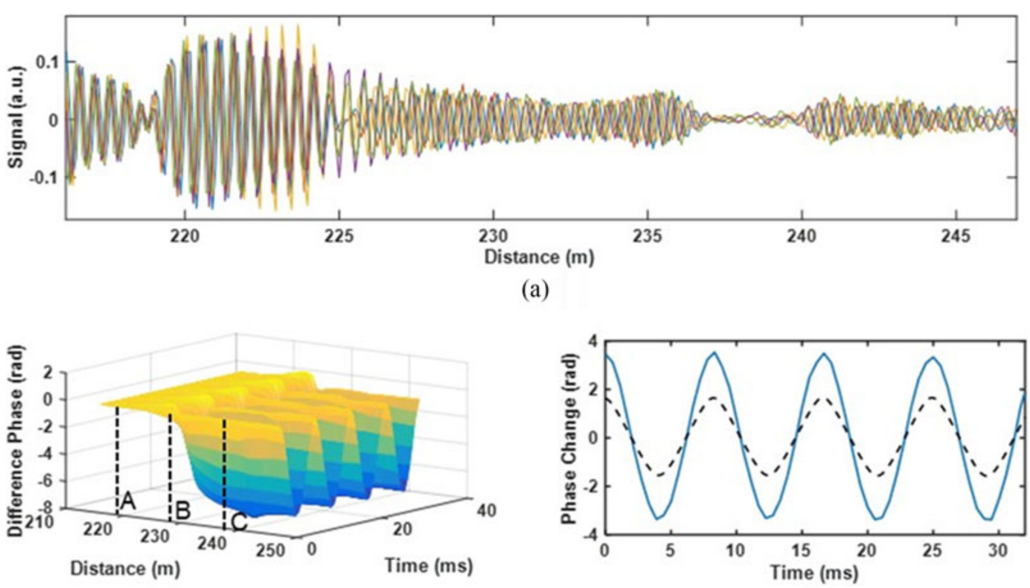
Huanhuan Liu, *Member, IEEE*
Fufei Pang
Longbao Lv
Xuanwei Mei
Yingxiong Song
Jian Chen
Tingyun Wang



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Huanhuan Liu, *Member, IEEE*, Fufei Pang, Longbao Lv, Xuanwei Mei, Yingxiong Song, Jian Chen, and Tingyun Wang

Key laboratory of Specialty Fiber Optics and Optical Access Networks, Joint International Research Laboratory of Specialty Fiber Optics and Advanced Communication, Shanghai Institute for Advanced Communication and Data Science, Shanghai University, Shanghai 200444, China

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Abstract: We demonstrate a method to truly measure the phase change originated from external vibration by heterodyne phase-sensitive optical time-domain reflectometer (φ-OTDR). The method of differential phase between sections of a sensing fiber is explored. In order to truly measure the phase change induced by external vibration, we point out that such sections of the fiber to calculate differential phase must cover at least the whole vibration region together with a section of fiber spaced by a pulse duration. The resultant differential phase is theoretically found to be twice the value of the real phase induced by external vibration. We further experimentally investigate a distributed sensor with a sensing fiber of 41.2 km based on φ-OTDR system. The experimental results are well consistent with the simulation results, which provides a general guidance for quantitative phase measurement of the external excitation such as slow variations based on heterodyne φ-OTDR technique.

Index Terms: Fiber optics sensors, optical domain reflectometry, Rayleigh scattering.

1. Introduction

Optical fiber distributed vibration sensors are widely explored in many areas due to the advantages of long-distance monitoring, immunity to electromagnetic field, robustness, and high sensitivity [1]. Recently, the all-fiber optical time domain reflectometers (OTDRs) based on Rayleigh backscattered light have been developed rapidly as a fully distributed vibration sensor technology [2]–[8]. Compared with conventional OTDRs that can only monitor optical intensity variation along a sensing fiber, the phase-sensitive OTDR (φ-OTDR) is capable of retrieving the phase information of backscattered light induced by external vibration. By retrieving the phase of backscattered light, not only the vibration location but also the information of the type of vibration source can be acquired. Therefore, the fascinating application of a φ-OTDR technique has been extended to the fields of intrusion alarm and location systems, abnormal vibration detection along railways or oil/gas pipes, and distributed acoustic testing for well logging [9], [10]. Generally, highly coherent pulses are adopted as probe pulses, and coherent detection is applied to retrieve the phase information of backscattered light in φ-OTDR systems. However, due to the unavoidable interference with the random distribution along the optical fiber, the received backscattered light could exhibit great variation in amplitude that is called signal fading [11]–[13]. As a result, it is difficult to retrieve accurately the real phase information of external vibration by the amplitude that will be affected by such fading and random noises [14].

In order to detect the location and frequency response of the external vibration, Y. Lu *et al.* have reported a distributed vibration sensor by using heterodyne detection and signal processing of moving averaging and moving differential to reduce the amplitude fluctuation in Rayleigh signal traces [15]. But the detected cut-off frequency decreases when moving averaging times increase. Moreover, the phase change due to the external vibration is not qualitatively measured. In 2011, Z. Pan *et al.* have proposed the digital coherent detection method that serves as an effective tool to rebuild the instantaneous electric field of Rayleigh scattered light and verified the feasibility of acquiring both amplitude and phase by φ-OTDR system [16]. Nevertheless, since the signal fading is randomly occurred, the phase information recovered from amplitude variation or moving averaging and moving differential may not be the accurate phase of the real external vibration. Furthermore, as the external vibration mostly takes place across a distance, it is not straightforward to find which location of a single point that reflects the phase of real external vibration. In 2015, G. Tu *et al.* have shown the measurement uncertainty of phase information due to external vibration can be suppressed by calculating the differential phase in an interrogated fiber separation in φ-OTDR system [17]. Moreover, Y. Dong *et al.* have also demonstrated the differential phase to achieve quantitative measurement of phase by subtracting two phases between two certain positions [18]. Recently, Gabai *et al.* report that the cell separation to take the differential phase for "effective sensor" could be chosen based on the assumption that the noise components of cells are uncorrelated, but the criteria for the minimum of cell separation to take the differential phase have not yet been figured out clearly [19]. Overall, the interrogated fiber sections in above differential phase method only involve the fiber falling into the vibration region [17]–[20]. Indeed, once the leading edge of the probe pulse enters the vibration region, it alters the phase of the forward propagating probe pulse and thus affects the phase of the backscattered light [21]. In other words, the phase change of backscattered light occurs at the position earlier than the vibration region. So the accuracy of above differential phase method for quantitative vibration measurement is not reliable without consideration of the fiber section ahead the vibration region.

In this paper, we propose an effective method to retrieve the true phase change induced by external vibration based on heterodyne φ-OTDR technique. The differential phase between sections of a sensing fiber is explored. For the first time, we point out that the section for differential phase calculation must cover at least the whole vibration region together with a section of fiber spaced by a pulse duration. The true phase information of external vibration is theoretically found to be a half of the differential phase. As a proof of the concept, a φ-OTDR system with sensing fiber of 41.2 km is experimentally investigated. The experimental results verify the feasibility of the method with phase information acquired, showing potential applications in abnormal vibration detection along railways or oil/gas pipes, and distributed acoustic testing for well logging.

2. Theoretical Investigation

In a φ-OTDR system, light pulses with narrow linewidth are launched into a sensing fiber, and the Rayleigh backscattered light reflected from numbers of scattering centers forms the signal light, which is plot of optical power versus time [18]. The coherent detection can be seen as the signal light beating with the local light. The signal light can be expressed as:

$$e_s(t) = E_R \exp\left(j(2\pi(f + \Delta f)t + \varphi(t) + \varphi_1)\right) \tag{1}$$

$$e_{LO}(t) = E_{LO} \exp\left(j(2\pi f t + \varphi_2)\right) \tag{2}$$

where E_R and E_{LO} are the amplitudes of the signal light the local light, f is the frequency of quasi-monochromatic light, and Δf is the frequency shift of the signal light. $\varphi(t)$ is the phase change term

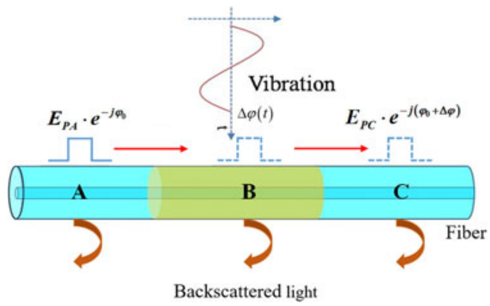

Fig. 1. Schematic diagram of a probe pulse passing through a sensing fiber at different time: before the vibration region (labeled as region A); the leading edge of the pulse enters the vibration region (labeled as region B), the pulse entirely leaves the vibration region (labeled as region C).

of signal light, and φ_1 and φ_2 are the initial phase of the signal light and local light, respectively. At the receiver of the φ-OTDR system, the signal light is mixed with the local light, and followed by a balanced detection. The AC component is obtained by using heterodyne detection. The detected optical power (P_{BPD}) is given by:

$$P_{\mathrm{BPD}} \propto 2E_R E_{LO} \sin(2\pi\Delta f t + \varphi(t) + \varphi_1 - \varphi_2) \tag{3}$$

By exploring the orthogonal demodulation method [22] and phase unwrap technique [17], the amplitude (E_R) and phase ($\varphi(t)$) of the Rayleigh scattering light can be expressed by [18]:

$$\begin{cases} I = \langle P_{\mathrm{BPD}}\cos(2\pi\Delta f t)\rangle \propto E_R E_{LO}\sin(\varphi(t)) \\ Q = \langle P_{\mathrm{BPD}}\sin(2\pi\Delta f t)\rangle \propto E_R E_{LO}\cos(\varphi(t)) \end{cases} \tag{4}$$

$$\begin{cases} E_R \propto \sqrt{I^2 + Q^2} \\ \varphi(t) = \tan^{-1}(I/Q) + 2k\pi \end{cases} \tag{5}$$

where k is an integer, and the phase unwrap technique extends the demodulated phase from negative infinite to positive infinite. Therefore, the phase information along the sensing fiber can be accurately demodulated by (5).

In the case that a certain region of the sensing fiber experiences an external vibration, it causes the refractive index and (or) length of the fiber to change, resulting in a localized phase change in the propagation light and the backscattered light. Subsequently, the phase demodulated by (5) could be added by a phase change of $\Delta\varphi(t)$ due to the external vibration. Note that different sections of the sensing fiber will experience different $\Delta\varphi(t)$. As shown in Fig. 1, in the vicinity of the vibration along the sensing fiber, three different regions are considered. Region A refers to the region before the vibration; region B represents the region in the vibration; region C corresponds to the region behind the vibration. We assume the amplitude of the probe pulse to be E_{PA} in region A. When the leading edge of probe pulse enters region B, a phase change will be picked up by the backscattered light due to the external vibration. The total phase change of the external vibration applied on region B is assumed to be $\Delta\varphi_B(t)$. When passing through region B, the forward probe pulse picks up this phase change of $\Delta\varphi_B(t)$ induced by the external vibration. When the probe pulse reaches region C, the backscattered light needs to travel back through region B where the vibration still exists. Due to the fact that the external vibration is a relatively slow change, the backscattered light from region B is considered to be almost at the same time to the backscattered light from region C in speed of light. Taking into account of the phase change induced by the external vibration in region B that adds to the forward probe pulse as well as the backscattered light, the real phase change of the backscattered light from region C is predicted to be twice the value of phase induced by external vibration $\Delta\varphi_c(t) = 2\Delta\varphi_B(t)$.

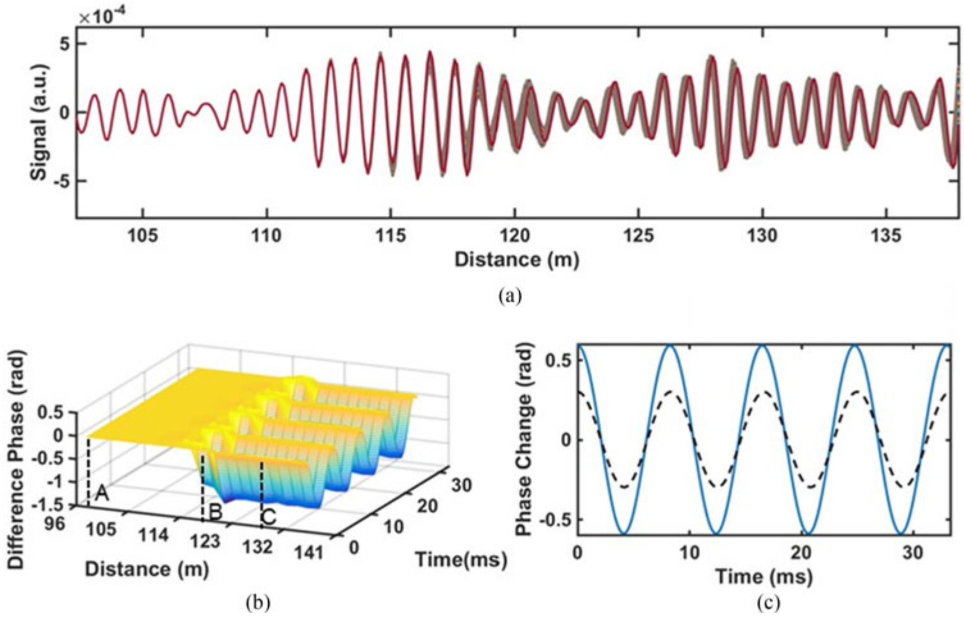

Fig. 2. Simulation results of 200 consecutive superimposed traces: (a) the beat signals and (b) the differential phase of the beat signals near the vibration region; (c) the phase change of applied vibration signal (the black short-dash line) compared with the differential phase by φ-OTDR system at $z2 = 135$ m when $z1 = 100$ m (the blue solid line).

The simulation is conducted to investigate the phase change in different sections of the sensing fiber. The theoretical model of Rayleigh backscattered light is based on the well-known one-dimensional impulse-response model [12]. In the simulation, the vibration region starts from 120 m to 123 m; the length of sensing fiber is 140 m; the pulse duration is 50 ns and the repetition rate of launched pulse is 6 kHz. The center wavelength of pulse is 1550 nm while the frequency shift is 200 MHz. The frequency of the vibration signal is 120 Hz. Fig. 2(a) displays the calculated 200 consecutive superimposed traces of the beat signals, which is originated from the launched pulse sequence. The simulation results show that the beat signals walk off before the location of 120 m. This happens because the locating point of pulse is chosen by the trailing edge. The walking-off point is around 5-m before the vibration region, indicating that the probe pulse enters the vibration region B shown in Fig. 1.

In order to investigate the phase evolution induced by external vibration, the differential phase for single pulse at location $z2$ is defined as:

$$\delta\varphi_{z2}(t) = \varphi_{z2}(t) - \varphi_{z1}(t) \tag{6}$$

Here $\varphi_{z2}(t)$ and $\varphi_{z1}(t)$ refer to the phases demodulated by (5) at the location of $z2$ and $z1$, respectively. The differential phase for single pulse along the sensing fiber is labeled as distance axis, while the pulse sequence is projected into the time axis. So the differential phase for 200 consecutive pulses in vicinity of the vibration region can be calculated.

Fig. 2(b) shows the calculated distance-time map for the differential phase near vibration region. The starting position is set to be $z1 = 100$ m, which is before the vibration region and thus falls in the region A. At distance of 115 m, the differential phase begins to oscillate with time, so that it falls in region B. Beyond 128 m location, the differential phase is kept constant, indicating that the point falls in region C. Fig. 2(c) compares the differential phase at $z2 = 135$ m (when $z1 = 100$ m) and the phase of the original applied signal. We find that the amplitude of the differential phase at 135 m is about 0.6 rad that is twice the value of the phase amplitude of applied vibration signal. Such twice phase relationship is the basic mechanism for an accurate phase measurement in φ-

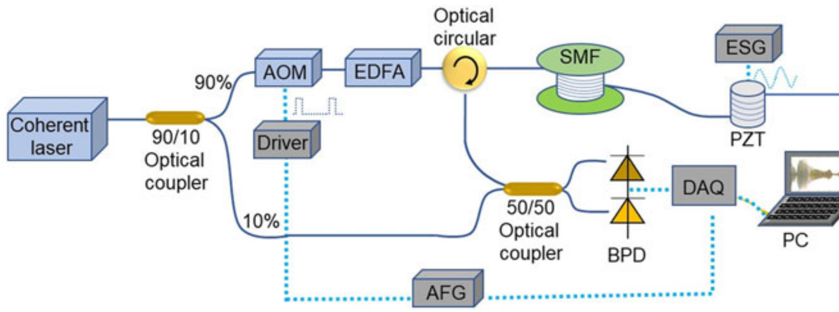

Fig. 3. Experimental setup of a general φ-OTDR sensing system: acoustic-optic modulator (AOM); arbitrary function generator (AFG); erbium-doped fiber amplifier (EDFA); single-mode fiber (SMF); electrical signal generator (ESG); piezo transducer (PZT); balanced photo- detector (BPD); data acquisition (DAQ); and personal computer (PC).

OTDR system. It should be noted that, in order to truly retrieve the phase of applied vibration signal, the section ($\Delta z = z2 - z1$) for differential phase calculation must cover at least the whole vibration region together with a section of fiber spaced by a pulse duration.

3. Experimental Setup and Results

In order to verify the model and truly measure the phase change induced by external vibrations, the φ-OTDR systems with the vibration sources located near 230 m and 41.07 km are separately investigated in this work. The experimental setup is schematically shown in Fig. 3. Light from a narrow linewidth continuous-wave (CW) laser ($\lambda = 1550.12$ nm, KoherasBasiK E15, line width < 0.1 KHz) is launched into the sensing fiber. A 90:10 optical coupler separates 90% of light as the probe light, and 10% of light as local reference light. An acoustic-optic modulator (AOM, Gooch & Housego T-M200-0.1C2J-3-F2S) driven by an arbitrary function generator (AFG, Tektronix AFG3252C) modulates the probe light into a pulse chain, and introduces 200-MHz optical frequency shift to the pulse train. An erbium-doped fiber amplifier (EDFA) is used to boost up the optical power. External vibration source is simulated by a piezo transducer (PZT) that is coiled with sensing fiber. An electrical signal generator (ESG) drives the PZT. The Rayleigh backscattered traces mixed with the reference light are detected by a balanced photo-detector (BPD). A high-speed data acquisition (DAQ, 8-bit, 1–1.5 GS/s) acquires the beat signal, which is triggered by the AFG for synchronized acquisition. The signal processing is completed in a personal computer (PC) where the calculation of amplitude as well as phase of Rayleigh backscattered light is conducted by the I/Q demodulation according to (4) and (5). In the experiment, the amplitude-based locating technology is explored because the false alarms induced by signal fading can be suppressed by the averaging method [15]. The true phase of external vibration is retrieved based on (6).

For the φ-OTDR system with the vibration locating near 230 m, the external vibration is executed on 5-m-long fiber at the position of 230 m which is driven by a cosine voltage signal with the frequency of 120 Hz. The pulse width and repetition rate of probe pulses are set to be 50 ns and 1.8 kHz, respectively. Fig. 4(a) displays the acquired 60 consecutive superimposed traces of the beat signals. The traces start to walk off at the position of ~222.5 m due to the vibration. By using the demodulation method given by (5), the distance-time map of the demodulated phase can be calculated as plotted in Fig. 4(b). The differential phase is calculated by subtracting the phase at the location beyond 220 m from the demodulated phase at the location 220 m, which falls in region A. Beyond a fixed location of ~222.5 m, the differential phase oscillates with time and thus such location falls in region B. Beyond ~237.5 m, the amplitude of the oscillation tends to be unchanged so that the location falls in region C.

Because the phase response of fiber under test (FUT) can be measured by optical fiber based interferometers, we calibrate the applied phase induced by the PZT using a standard optical fiber

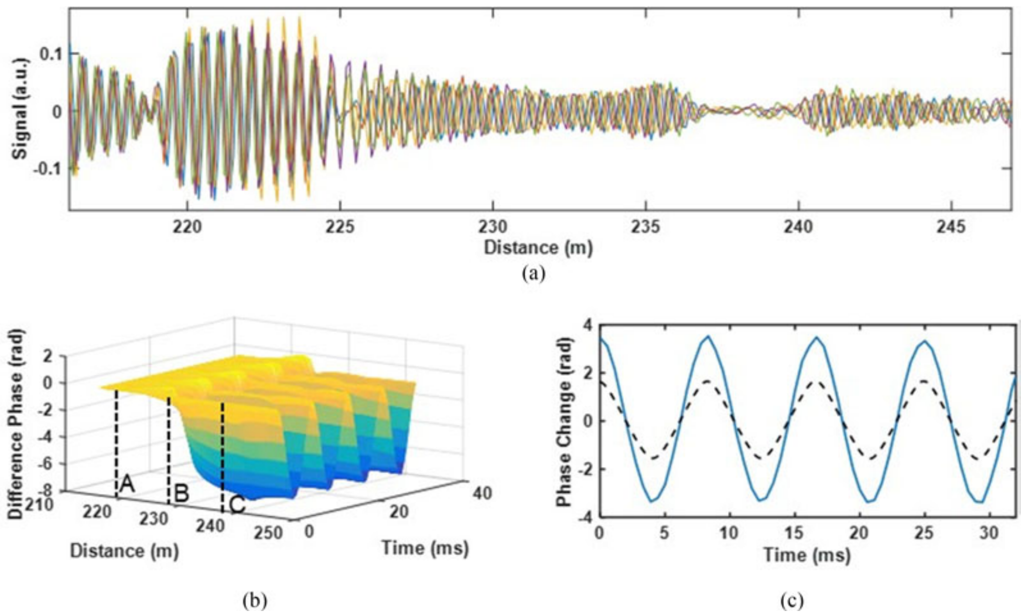

Fig. 4. Experimental results of the consecutive superimposed traces when the vibration locates near 230 m: (a) the beat signals and (b) the differential phase of the beat signals near the vibration region; (c) the phase change of the applied vibration signal (the black short-dash line) compared with the differential phase by φ-OTDR system at the position of $z2 = 240$ m when $z1 = 220$ m (the blue solid line).

Michelson Interferometer (MI). The results of phase measurement by both the MI and the heterodyne φ-OTDR system are shown in Fig. 4(c). The differential phase by the heterodyne φ-OTDR system at the location $z2 = 240$ m (when $z1 = 220$ m) is twice the value of the real vibration phase (the black short-dash line), which is consistent with the simulation result. It also verifies that the section for differential phase calculation must at least cover the whole vibration region together with a section of fiber spaced by a pulse duration. In Fig. 4(b), we notice that the vibration intensity tends to be a non-uniform distribution in the whole vibration region and thus the demodulated phase at the alarm peak of φ-OTDR system will not represent vibration phase change exactly. Therefore, it is meaningful to determine the total phase change of backscattered light in the whole vibration region rather than the exact phase change value at the middle of vibration position.

For the φ-OTDR system with the vibration locating near 41.07 km, the external vibration is executed on 2-m-long fiber at the position of 41.072 km which is driven by a cosine voltage signal with frequency of 150 Hz. The pulse width and repetition rate of probe pulses are set to be 50 ns and 1.8 kHz, respectively. The average power of the probe pulse is measured to be 840.4 μW and thus the peak power of the probe pulse is estimated to be $\sim$9.3 W. Previous report has shown that the threshold power of stimulated Brillouin scattering (SBS) for CW is $\sim$1 mW near 1.55 μm where the effective length is $\sim$20 km because of relatively low losses of optical fibers (0.2 dB/km) at that wavelength [23]. For the given 50-ns, 1.8-kHz quasi-CW, the threshold power of Stocks pulse is calculated to be 11.1 W. Since the peak power of the applied probe pulse is lower than the threshold power of Stocks pulse, the effect of SBS could be neglected in the developed φ-OTDR system.

The amplitude-based technology is explored to locate the external vibration. Fig. 5(a) plots the demodulated amplitude of φ-OTDR traces near 41.07 km based on (5), and the standard deviation (SD) of the amplitude is shown in Fig. 5(b). A significant peak is found near 41.07 km, indicating where the external vibration takes place. Fig. 5(c) shows the distance-time map of demodulated phase. It demonstrates that the differential phase oscillates with time for a fixed location starting from 41.066 km (falls in region B), and the amplitude of the oscillation tends to be unchanged behind 41.078 m (falls in region C). Note that the phase distortion induced by signal fading is

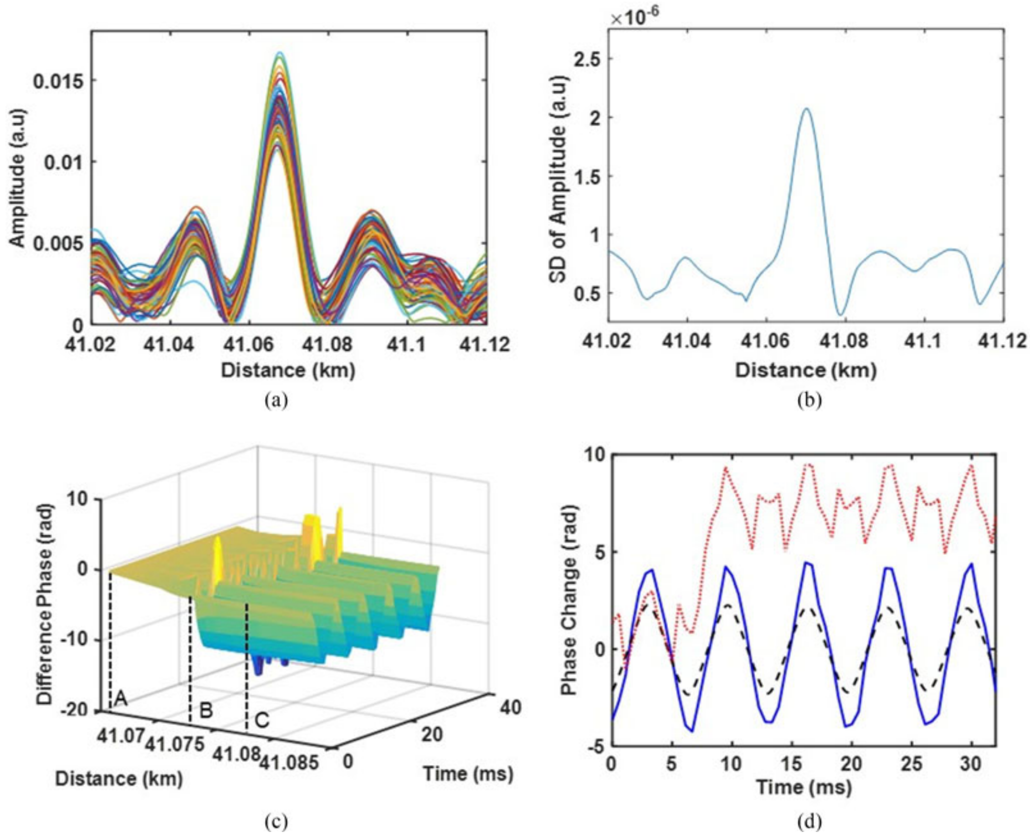

Fig. 5. Experimental results of the consecutive superimposed traces when the vibration locates near 41.07 km: (a) the demodulated amplitude of the beat signals; (b) the locating of external vibration by calculating the standard deviation (SD) of demodulated amplitude; (c) the differential phase of the beat signals near the vibration region, (d) the phase change of applied vibration signal (the black short-dash line) compared with the differential phases by φ-OTDR system at the vibration point of $z2 = 41.072$ km (the red short-dot line) and the point of $z2 = 41.08$ km (the blue solid line) when $z1 = 41.065$ km.

randomly occurred and superimposed on the vibration region near 41.072 km, which makes it difficult to retrieve accurately the phase information at such a fixed location within vibration region. Since only the external vibration can induce an additional phase beyond the vibration region while the signal fading has little influence on the phase beyond its location [21], we can overcome the difficulty in true phase measurement by our proposed differential phase method. Fig. 5(d) plots the differential phase (beyond 41.065 km location) by the heterodyne φ-OTDR system compared with the phase induced by the PZT through a standard optical fiber MI. The differential phase at the location $z2 = 41.08$ km (when $z1 = 41.065$ km) and is twice the value of the PZT real vibration phase (the black short-dash line), which is well consistent with the experimental observation in the φ-OTDR system with the vibration located near 230 m. This further proves that even though the signal fading induced phase distortion exists, the exact phase change induced by external vibration can be easily retrieved by taking the half of the phase change at the location behind the vibration region. Meanwhile, the section for differential phase calculation must cover at least the whole vibration region together with a section of fiber spaced by a pulse duration.

We further investigate the φ-OTDR system with sensing fiber of 41.2 km when two adjacent vibration events exist. The first vibration event is executed on the sensing fiber at 41.072 km with 2-m long, and the frequency of applied signal is 120 Hz. The second vibration event is executed on the sensing fiber at 41.09 km with 5-m long, and the frequency of applied signal is 150 Hz. By demodulating the amplitudes of the beat signals, two vibration points are found to locate at

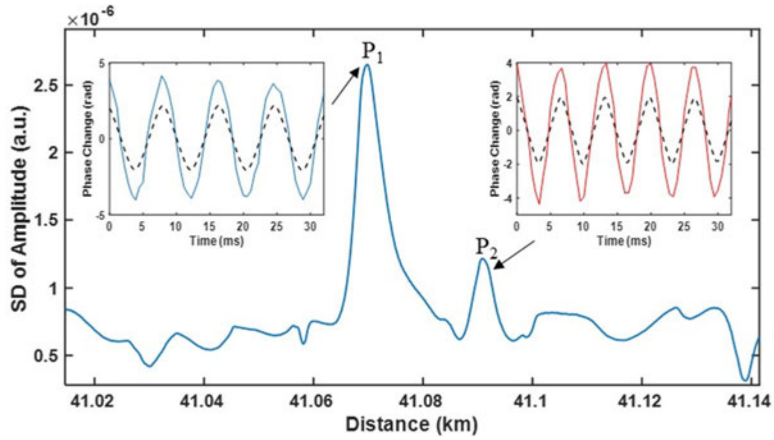

Fig. 6. Experimental results of a φ-OTDR system with two adjacent vibration events locating at 41.072 km and 41.09 km simultaneously. The insets show the corresponding phase change: the applied vibration signal (the short-dash lines) at 41.072 km and 41.09 km and the differential phases by φ-OTDR system (the solid lines) at $z2 = 41.08$ km when $z1 = 41.065$ km (the blue line) and $z2 = 41.10$ km when $z1 = 41.08$ km (the red line).

41.072 km (P_1) and 41.09 km (P_2) as shown in Fig. 6. Although the two vibration events occur simultaneously, we can still demodulate the phase change of backscattered light. As shown in the insets of Fig. 6, the differential phase by the φ-OTDR at $z2 = 41.08$ km (when $z1 = 41.065$ km) is twice the value of phase change of applied signal at 41.072 km. The differential phase by the φ-OTDR at $z2 = 41.10$ km (when $z1 = 41.08$ km) is twice the value of phase change of applied signal at 41.09 km. Therefore, we prove that this method can be extended to detect multiple vibration events along the sensing fiber as well as capture its accurate phase change by the φ-OTDR technique.

As phase noise from the laser source is a significant factor in phase measurements in interferometer system, we also investigate the influence of phase noise from the laser source on the accurate phase measurement. The applied laser (NKT, KoherasBasiK E15) with a linewidth of 0.1 kHz shows the phase noise of $\sim 0.3\,\mu\text{rad}/\sqrt{\text{Hz}}$ at 2.5 kHz from the datasheet of equipment. Here 2.5 kHz corresponds to the time delay of a probe pulse propagating the sensing fiber with length of ~82 km, which is the maximum optical path of the round trip of the pulse. We find that the retrieved phase change due to the external vibration by the proposed differential phase method is almost the same even though Δz is relatively long length of ~500 m. Since the laser phase noise is nearly unchanged during a relatively short period of time, the impact of phase noise can be suppressed effectively through the differential phase method. On the other hand, since the phase noise from the laser source may fluctuate significantly over a very long distance, Δz for differential phase method should be limited in order to support true phase measurement. In the experiment for a single vibration event, when $\Delta z < 500$ m, the signal-to-noise ratio (SNR) of the retrieved phase shows comparable value, while $\Delta z > 500$ m the SNR is dropped. The results indicate that the upper limit of Δz could be extended to ~500 m to support true phase measurement.

4. Conclusion

In conclusion, we have proposed a differential phase method to retrieve the true phase change induced by external vibration based on the heterodyne φ-OTDR system. For the first time, we point out that the fiber sections for calculating the differential phase must cover at least the whole vibration region together with a section of fiber spaced by a pulse duration. The resultant differential phase is theoretically found to be twice the value of the real phase induced by external vibration. Therefore, different from finding the exact location of a single point responding to external vibration, we can directly retrieve the accurate phase information of external vibration by taking half of the differential phase. We further experientially investigate a distributed sensor with a sensing fiber of 41.2 km based on φ-OTDR system. The experimental results verify the feasibility of the method with true phase information acquired, showing potential applications in abnormal vibration detection along railways or oil/gas pipes, and distributed acoustic testing for well logging.

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