IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 11, Number 1, February 2019

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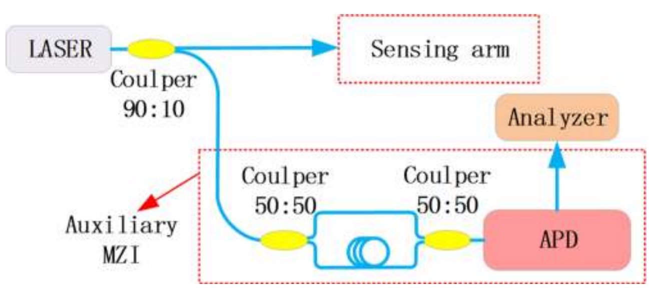

DOI: 10.1109/JPHOT.2018.2884659

Using an Auxiliary Mach–Zehnder Interferometer to Compensate for the Influence of Laser-Frequency-Drift in Φ-OTDR

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DOI:10.1109/JPHOT.2018.2884659

Manuscript received October 15, 2018; revised November 23, 2018; accepted November 29, 2018. Date of publication December 3, 2018; date of current version December 28, 2018. This work was supported in part by the National Natural Science Foundation of China under Grant 61627816, in part by the Key Research and Development Program of Jiangsu Province under Grant BE2018047, and in part by the Fundamental Research Funds for the Central Universities under Grant 021314380116. Corresponding author: Feng Wang (e-mail: wangfeng@nju.edu.cn).

Abstract: In phase-sensitive optical time-domain reflectometry (Φ-OTDR), the frequency drift of the laser source induces the fluctuation of signal, which limits the measurement capacity of Φ-OTDR for low frequency severely. In this paper, we propose a method to compensate for the influence of the frequency drift by using an auxiliary Mach–Zehnder interferometer (MZI). In this method, the signal of the auxiliary MZI is received to monitor the frequency drift continuously, and then, to correct the signal obtained from the sensing path. In the experiment, a vibration with a 0.1-Hz frequency on a 6-km sensing fiber is detected with a 10-m spatial resolution and the sensitivity is estimated to be 5.9 nε. This method will expand the scope of application of Φ-OTDR in the fields that require high sensitivity and low frequency response.

Index Terms: Optical fiber sensor, frequency-drift, phase-sensitive optical time domain reflectometry, vibration measurement.

1. Introduction

Distributed fiber optical vibration sensors have wide-ranging applications in the geophysical research, the health monitoring of civil infrastructures, the perimeter intrusion detection, [1]–[5]. As one of such techniques, phase sensitive optical time domain reflectometry (Φ-OTDR) attracts many attentions because of its superior features such as long sensing range, high sensitivity, fast response speed, immunity to electromagnetic interference and so on [6], [7].

Φ-OTDR utilizes the coherent effect of the Rayleigh backscattering to realize the distributed sensing. A coherent light source in Φ-OTDR injects optical probe pulses into a fiber under test (FUT). Then the backscattering signal exhibits a distributed speckle pattern due to the coherent effect of the Rayleigh backscattering [8]–[14]. A local disturbance on the FUT causes a change in the optical path length of the light passing through it, which in turn changes the intensity and phase of the backscattering signal. Thus by demodulating the intensity evolution or phase evolution of the received signal for each position, distributed measurement of perturbations along the FUT can be achieved.

Ideally, the Rayleigh backscattering returned from the FUT shows a stable speckle pattern in time-domain when there is no perturbation on the FUT. However, because the optical phase at a certain position is related to the frequency of lightwave, the frequency variation of laser source will change the phase difference between two points, resulting in the change of the speckle pattern of the backscattering signal [7]. F. Zhu *et al.* has shown that a commercial laser always has slow frequency-drift which induces significant noise in low frequency domain, restricting the capacity of Φ-OTDR measuring low frequency events [15]. Actually, quasi-static measurement on low-frequency events is essential to certain applications such as earthquake wavefield monitoring, galloping monitoring of power transmission line and suspension bridge, whose vibration frequency ranges from Hz to sub-Hz level [16]. In order to reduce the influence of frequency-drift, a few methods have been proposed [17]. Differential method is a simple and commonly used method, by calculating the difference of demodulated phases between two points on the FUT, and repeating the operation to all the signals along the FUT with a fixed spatial interval, most noises induced by the frequency-drift can be eliminated [18], [19]. F. Zhu has proposed an active compensation method for Φ-OTDR. In this method, the backscattering signal at different laser frequency is pre-measured at first. Then the laser-frequency-drift is tracked and compensated from the cross-correlation between the real-time signals the pre-measured signal [15]. However, the requirement for pre-measurement of the backscattering signal makes the method lack of practicality in many cases.

In this paper, we propose to use an auxiliary Mach-Zehnder Interferometer (MZI) to compensate for the laser-frequency-drift in Φ-OTDR. So the noise induced by the laser-frequency-drift is reduced and the ability of measuring slow and tiny external vibrations is improved.

2. Principle

The phase of the backscattering signal in Φ-OTDR is an equivalent phase which is the comprehensive result of massive individual back scattered pulses generated from different backscattering centers. So we use a symbol $\theta_R(f, z)$ to represent the equivalent phase of the scattering signal. And in order to demodulate the phase of the signal, heterodyne detection is a popular method to receive the signal. In this method a small portion of lightwave, serving as reference lightwave, is split from the laser source to mix with the backscattering. Since there is a frequency difference between the reference lightwave and the backscattering signal, the detector will catch a beat signal which can be expressed as:

$$I(z, t) \propto Q(f) \cos\left[\frac{4\pi n}{c} f(t) z - 2\pi f_{AOM} t + \varphi(t) + \theta_R(f(t), z)\right] \quad (1)$$

where $Q(f)$ is the amplitude of the signal, n is the refractive index, c is the velocity of lightwave in vacuum, $f(t)$ is the frequency of laser, z is the position under consideration, f_{AOM} is the frequency of the beat signal, and $\varphi(t)$ is the phase modulated by external perturbation.

Researchers have proposed several methods which can extract the phase of the oscillation term in Eq. (1) [20]–[22]. In order to demodulate the phase changes induced by external perturbations, a differential operation is needed. In this operation, the phase of one position A is subtracted from the phase of another position B, so the phase difference of these two positions is obtained. When A and B are located on each side of the perturbation region, the phase change induced by the perturbation can be obtained. It is noteworthy that the length D_{AB} between the two positions A and B should be larger than the length of fiber under perturbation and the spatial resolution, so the phase change induced by the perturbation can be measured accurately. With the differential operation, the phase at a certain moment can be expressed as:

$$\Delta\Phi_{AB}(t) = \frac{4\pi n}{c} D_{AB} f(t) + \varphi(t) + \theta_R(f(t), z_B) - \theta_R(f(t), z_A). \quad (2)$$

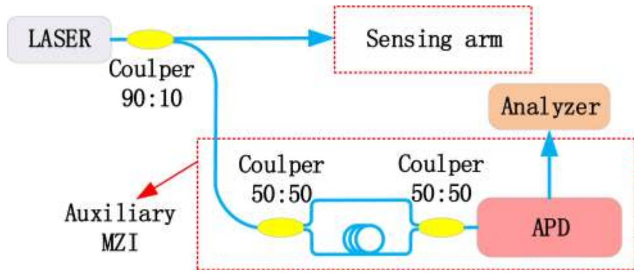

Fig. 1. The scheme of auxiliary MZI in Φ-OTDR.

If there is no laser-frequency-drift, then $f(t)$ keeps constant. In this circumstance, the change of $\varphi(t)$ equals to the change of $\Delta\Phi_{AB}(t)$. So the external perturbation which is linearly proportional to the change of $\varphi(t)$ can be measured qualitatively. Unfortunately, due to the frequency-drift of the laser source, $f(t)$ changes with time. So when using the change of $\Delta\Phi_{AB}(t)$ to represent the change of $\varphi(t)$, the phase term $\frac{4\pi n}{c} D_{AB} f(t) + \theta_R(f(t), z_B) - \theta_R(f(t), z_A)$ in $\Delta\Phi_{AB}(t)$ would induce a noise floor, which limits the performance of Φ-OTDR. It will be shown in the experiment that the noise induced by the laser-frequency-drift is mainly a low frequency noise which influences Φ-OTDR measuring small and low frequency perturbations. So we propose to use an auxiliary MZI to reduce the influence of laser-frequency-drift, which can improve the performance of Φ-OTDR further.

The basic idea of this method is monitoring the laser frequency in real time. Once the frequency is known, the phase change induced by the frequency-drift can be deduced. By subtracting this phase change from the demodulated phase, the actual phase change induced by the perturbation can be obtained.

X. Zhong has proposed to use a MZI to measure the laser frequency [7]. In this paper, we use such a scheme to construct an auxiliary interferometer. The laser-frequency-drift compensation system based on the auxiliary MZI is shown in Fig. 1.

The auxiliary MZI consists of two arms which have a length difference of D_{MZI} by inserting a delay fiber in one of the arms. Then the output lightwave from the MZI is:

$$I_{MZI}(t) = P_1 + P_2 \cos\left[2\pi n D_{MZI} f(t)/c\right] \tag{3}$$

where P_1 is the DC component of the interference signal and P_2 is the amplitude of AC component, both of which can be obtained in a pre-measurement. For a specific MZI, the values of P_1, P_2 and D_{MZI} are constant, so the intensity of the lightwave in Eq. (3) is directly correlated with the laser frequency $f(t)$. Thus the phase in the auxiliary MZI can be obtained:

$$\Phi_{MZI}(t) = unwrap\left\{\arctan\left(\frac{Hilbert\left[I_{MZI}(t) - P_1\right]}{I_{MZI}(t) - P_1}\right)\right\} = 2\pi n D_{MZI} f(t)/c \tag{4}$$

The symbol $unwrap\{\}$ represents the unwrapping operation, and $Hilbert[]$ represents the Hilbert transform. Thus the variation of laser frequency for different measurement times t_1 and t_2 can be obtained:

$$\Delta f(t_2, t_1) = f(t_2) - f(t_1) = \left[\Phi_{MZI}(t_2) - \Phi_{MZI}(t_1)\right] c/2\pi n D_{MZI} \tag{5}$$

From Eqs. (2) and (5), the following result is obtained:

$$\begin{aligned}
&\Delta\Phi_{AB}(t_2) - \Delta\Phi_{AB}(t_1) - \frac{2^{*}D_{AB}}{D_{MZI}}\left[\Phi_{MZI}(t_2) - \Phi_{MZI}(t_1)\right] \\
&= \varphi(t_2) - \varphi(t_1) + \left[\theta_R(f(t_2), z_B) - \theta_R(f(t_1), z_B)\right] - \left[\theta_R(f(t_2), z_A) - \theta_R(f(t_1), z_A)\right] \\
&= \Delta\varphi(t_2, t_1) + \left[\theta_R(f(t_2), z_B) - \theta_R(f(t_1), z_B)\right] - \left[\theta_R(f(t_2), z_A) - \theta_R(f(t_1), z_A)\right]
\end{aligned} \tag{6}$$

In Eq. (6), $\Delta\varphi(t_2, t_1)$ is the valid phase change induced by external perturbation. However, due to the unpredictable equivalent phase of the scattering signal, the term $[\theta_R(f(t_2), z_B) - \theta_R(f(t_1), z_B)] -$

TABLE 1
Parameters in the Simulation

Symbol	Parameter	Value
λ_0	Wavelength of the laser source	1550nm
n	Effective refractive index of fiber	1.5
D	Density of the backscatters	1000/m
L_S	Spatial resolution	10m
r	Backscattering coefficient	μ(0,1)
κ	Frequency-drift speed	10 MHz/s
t	Measurement time duration	10 s

μ(0,1) is the random variable with a uniform distribution between 0 and 1.

$[\theta_R(f(t_2), z_A) - \theta_R(f(t_1), z_A)]$ cannot be eliminated. So we cannot purely obtain the phase change even with the assistance of auxiliary MZI.

The extra time-varying term $\frac{4\pi n}{c} f(t)z + \theta_R(f(t), z)$ in Eq. (1) is composed of two parts. When the laser frequency changes, the first part $\frac{4\pi n}{c} f(t)z$ stands for the phase variation accumulated in the round-trip of the lightwave from the input end to position z, and the second part $\theta_R(f(t), z)$ stands for the variation of the equivalent phase of the scattering signal of massive individual back scattered pulses. Thus for a certain frequency change, the first part is related to a fiber distance, whereas the second part is related to the scattering characteristics of the massive local scattering centers and the spatial resolution. In order to estimate the effect of the compensation method based on the auxiliary MZI, simulations were made to observe the overall tendency of the phase variation of the second part.

The parameters used in the simulation are listed in Table 1. In the simulation, we assume the backscatters distribute randomly in each unit length. Then the electric filed of the backscattered lightwave from the i-th backscatter is:

$$E_i(t, z) = r_i{}^* \cos\left[2\pi\left(c/\lambda_0 + \kappa t\right)t - 4n\pi\left(c/\lambda_0 + \kappa t\right)\cdot\left(z + l_i\right)/c\right] \tag{7}$$

where l_i is the distance of the backscatter from an arbitrary interested position z. Thus the backscattering signal representing for position z can be expressed by the summation of all the backscattering lightwaves generated in the spatial resolution range:

$$E(t, z) = \sum_{i=1}^{D^* L_S} E_i(t, z) \tag{8}$$

Then the equivalent phase of the backscattering signal for position z can be obtained from the following equation:

$$\Phi(t, z) = unwrap\left\{arc\tan\frac{Hilbert[E(t, z)]}{E(t, z)}\right\}. \tag{9}$$

Here, since the interested object is only the equivalent phase $\theta_R(f(t), z)$, z is set as 0. Fig. 2 shows five simulation results for the evolution of the equivalent phase of the scattering signal induced by the laser-frequency-drift. The backscattering coefficients and the distribution of backscatters are different in each simulation. It can be seen that the overall tendency of the phase change with frequency-drift is monotonous, and the phase change has small random fluctuations because of the scattering signal is a comprehensive result of massive randomly backscattered pulses. Meanwhile, it should be noted that for the term $\frac{4\pi n}{c} f(t)z$ in Eq. (1), the phase change after 10 s for 10 m distance is 62.8 Rad by using the same parameters in Table 1. However, the simulation shows that the phase change of the equivalent phase $\theta_R(f(t), z)$ for the spatial resolution of 10 m is about 15 Rad.

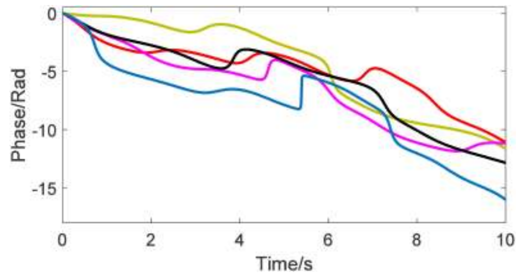

Fig. 2. Five simulation results for the phase variation of the comprehensive backscattering signal induced by the linear frequency drift.

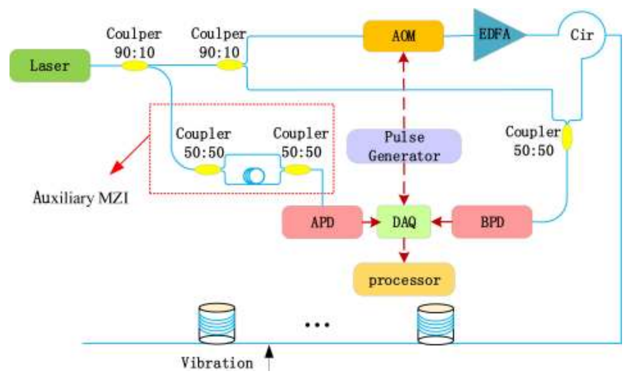

Fig. 3. The scheme of Φ-OTDR with the auxiliary MZI.

And since the term $\theta_R(f(t), z)$ has similar overall tendency for different local scattering parameters, the differential term $[\theta_R(f(t_2), z_B) - \theta_R(f(t_1), z_B)]$-$[\theta_R(f(t_2), z_A) - \theta_R(f(t_1), z_A)]$ in Eq. (6) would have a much smaller value (the maximum value is about 5 Rad in Fig. 2) than $\frac{4\pi n}{c} f(t)z$. So the term $\frac{4\pi n}{c} f(t)z$ in Eq. (1) is the main source of the phase noise induced by laser-frequency-drift. In Eq. (6), the term $\frac{4\pi n}{c} f(t)z$ has been thoroughly eliminated. Thus, according to the output of the auxiliary MZI, the noises induced by the laser-frequency-drift can be eliminated and the phase variation induced by external perturbation can be measured in real time.

3. Experiments and Results

Several experiments were carried out to verify the effects of the proposed method. The setup of the Φ-OTDR system based on an auxiliary MZI compensation is shown in Fig. 3. The narrow linewidth laser source ($\Delta\nu = 100$ Hz) worked on 1550.12 nm. Its output lightwave was split into three paths with two 90:10 couplers. The 81% lightwave in the first path was modulated into a probe pulse by an acoustic optical modulator (AOM) which also introduced 40 MHz frequency shift to the lightwave. The pulse width was 100 ns, equaling to 10 m spatial resolution. The 9% lightwave in the second path served as reference lightwave. The probe pulse was launched into the FUT through a circulator after it was amplified by an EDFA. The backscattering signal was mixed with the reference lightwave via a 3 dB coupler and their beat signal was received by a balanced photo detector (BPD). The 10% lightwave in the third path was input into the auxiliary MZI which has a 10 m delay fiber in one of its arms. The auxiliary MZI is put inside a foam box to avoid the influence of external environment. The output lightwave of the auxiliary MZI was received by a photodiode (PD). Both the signals of the sensing path and the auxiliary MZI were converted into digital form by a dual-channel data acquisition (DAQ) card with a sampling rate of 500 MSa/s. The length of the FUT was 6 km and a vibration was applied on the FUT with a PZT (OPTIPHASE PZ2) at about 5 km.

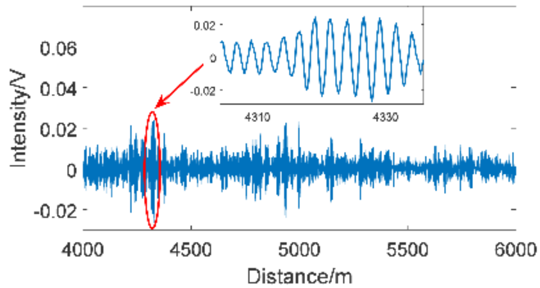

Fig. 4. Time domain signal of Φ-OTDR.

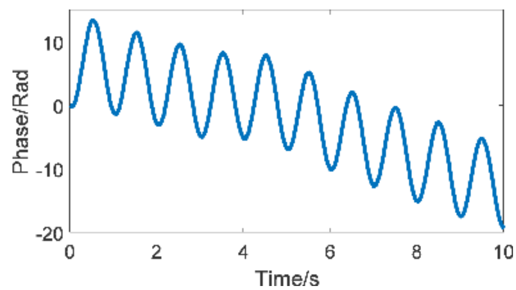

Fig. 5. The variation of phase for the signal at 5.1 km with differential operation.

At first, the PZT was driven by a 1 Hz sinusoidal signal and the repetition rate of the probe pulse was 1 kHz. One of the temporal signal traces from 4 km to 6 km is shown in Fig. 4. From the inset the 40 MHz beat signal can be seen clearly. In experiments, the phase of the beat signal was derived by the IQ demodulation method.

The variation of phase with time for the signal at 5.1 km is shown in Fig. 5. Each phase value at different time was extracted by IQ demodulation and differential operation. In the differential operation, the length D_{AB} between two differential points was setting as 80 m (the length of fiber wounded on the PZT is 60 m). Fig. 5 shows that the 1 Hz driving signal can be obtained clearly. However, the signal also goes downward slowly which induces by low frequency noise and hampers the Φ-OTDR measuring very slow signals.

The error induced by the frequency-drift in each measurement is very small compared with that between two measurements, because the frequency of the probe pulse keeps constant after it is injected into the FUT and the error is only induced by the frequency change of the reference lightwave during the flying time of light over the differential length D_{AB}. So we took the average value of the first 50 data obtained from the auxiliary MZI to track the laser-frequency-drift after each probe pulse was injected into the FUT. Due to the imbalance of optical intensity in the two arms of the auxiliary MZI, the beat signal output from the MZI would have DC components. Thus before formal measurements, a pre-measurement which lasts for 10 s was taken to calibrate the output of the auxiliary MZI. The signal of the auxiliary MZI obtained in the pre-measurement is shown in Fig. 6(a). The variation of intensity with time indicates that the laser frequency was drifting with time. By using Eq. (3) to fit the signal, parameters of P_1 and P_2 could be determined. So in the formal measurement, an intensity variation induced by laser-frequency-drift could be transformed into the phase variation immediately with Eq. (5).

The demodulated phase variation induced by the laser-frequency-drift is shown in Fig. 6(b), from which we can find that it is very consistent with the downward component in Fig. 5. Then by subtracting the phase variation measured with the auxiliary MZI from the demodulated signal, the final result was obtained as shown in Fig. 7. It can be seen that the final result has smaller low frequency noises which is beneficial for improving the sensitivity and measuring low frequency signal.

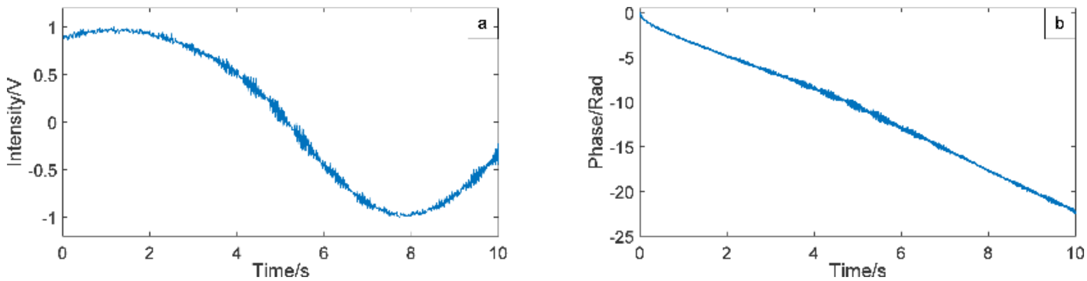

Fig. 6. (a) The output signal of the auxiliary MZI. (b) The deduced phase variation induced by the laser-frequency-drift

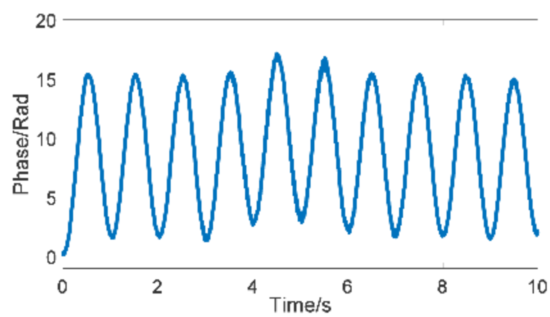

Fig. 7. The final signal after compensation with auxiliary MZI.

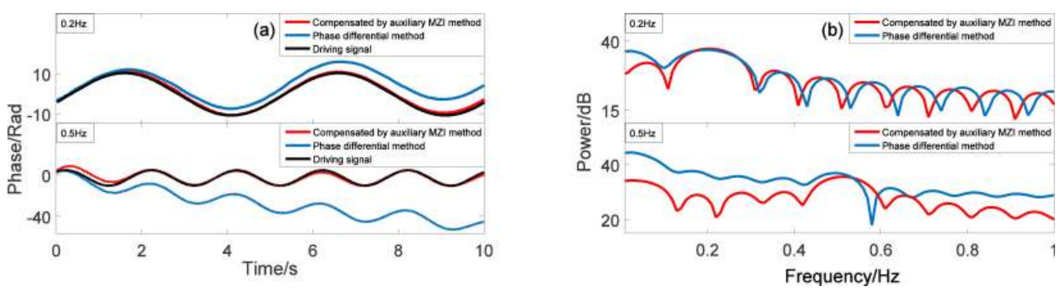

Fig. 8. (a) Waveforms and (b) power spectra before and after compensation with different frequency by auxiliary MZI method.

To verify the effectiveness of the method, several vibrations with different frequencies were measured. Fig. 8(a) shows the results in time domain for two vibrations with frequencies of 0.2 Hz and 0.5 Hz respectively. It shows that the proposed compensation method can compensate for the phase noise induced by the frequency drift properly and the demodulated results are coincident well with the driving signals. Meanwhile, from their power spectra shown in Fig. 8(b), one can see that the noise near the DC band is suppressed significantly. From the power spectrum of the 0.5 Hz signal where the spectrum leakage has smaller influence to the DC band, we can see the low frequency noise is reduced by 10 dB. In Fig. 8, the driving voltages of the signal were all 0.1 V, which corresponding to a strain of 11.8 nε.

To test the limit of the proposed method, many driving sinusoidal signals with different frequencies and amplitudes were applied to the PZT. Fig. 9 shows the measurement results for the driving signal with 0.1 Hz frequency and 0.05 V amplitude which corresponds to a strain of 5.9 nε. From the figure, it can be seen that the slow and small sinusoidal signal can still be detected by the proposed method.

Because the performance of the laser source in the experiments was relatively good, the frequency-drift in the preceding experiments was all unidirectional. In order to study the effect

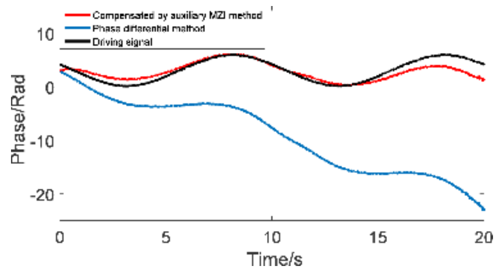

Fig. 9. Sinusoidal waveform with frequency of 0.1 Hz.

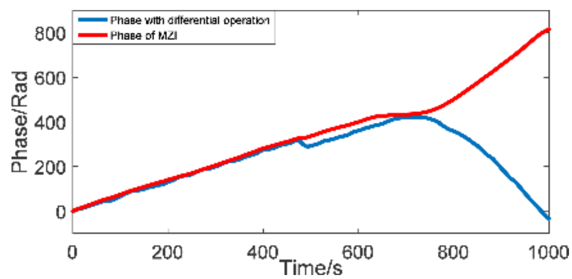

Fig. 10. Comparison between phase variations obtained with MZI and with differential method.

of the proposed method when the direction of the frequency-drift changes, we made a measurement without external perturbations and it lasted for 1000 seconds. Due to the limitation of the DAQ card, the repetition rate of the probe pulse was set to 5 Hz. As shown in Fig. 10, the red curve is the phase variation acquired by MZI, and the blue curve is a differential phase. From the curves we can see that the direction of frequency-drift changes at about 700 seconds. Before the direction of frequency-drift changes, the phase of MZI is in good agreement with the differential phase, whereas when the direction changes, the two curves deviate from each other. Therefore, this method is only valid when the laser-frequency drifts in single direction. However, as shown in Fig. 10, the unidirectional frequency-drift can last for long time. So the proposed method is still effective in most measurements lasting for less than tens of seconds. And searching for a simple method which can completely track the frequency-drift will be studied in our future researches.

4. Conclusion

In conclusion, we adopt an auxiliary Mach-Zehnder Interferometer (MZI) method in a traditional Φ-OTDR system to compensate for the influences of laser-frequency-drift. The frequency-drift is tracked by the auxiliary MZI and then the result is used to correct the phase of the main signal. The method is verified by a series experiments. For a limit test, a vibration with frequency of 0.1 Hz and amplitude of 5.9 nε is successfully detected by the proposed method.

Acknowledgment

The authors would like to thank the anonymous reviewers for their valuable suggestions.

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