Interrogation of Ultra-weak FBG Array using Double-pulse and Heterodyne Detection

Tao Liu, Feng Wang, Xuping Zhang, Quan Yuan, Jihui Niu, Lin Zhang and Tao Wei

Abstract—A high performance interrogation method for ultra-weak FBG (UWFBG) using double-pulse and heterodyne detection method is proposed. The perturbation along the UWFBG array is located quickly through the use of double-pulsed optical input waveform. Then the perturbation of fiber is quantified precisely by demodulating the phase of differential signals from a heterodyne configuration. The efficiency of measuring the perturbation is improved by more than 20 times than that of using single probe pulse. In comparison with conventional Rayleigh scattering based approach, the proposed method is supreme in signal-to-noise ratio (SNR), approximately 18 dB higher. The use of differential signaling method can effectively remove the influence from frequency drift of the laser source, making this proposed method capable of measuring low frequency vibration. In our experiment, perturbations with both sinusoidal and triangle waveform were generated to quantitatively evaluate the performance of the proposed method. The minimum detectable fiber length variation is 14.85 nm, and the sensing frequency can be as low as 0.2 Hz.

Keywords—Dynamic vibration measurement; Optical fiber interference; Optical fiber sensors; Optical time domain reflectometry; Ultra-weak FBG

I. INTRODUCTION

PHASE-SENSITIVE optical time domain reflectometry (Φ-OTDR) is one of the more popular modalities in distributed optical fiber sensing family. Its superior properties include high sensitivity, fast response speed, long sensing distance, etc. [1-4] Over the past decade, research efforts have been made to develop a series of techniques all towards improvement the performance of Φ-OTDR technology [5-7]. However, the very weak Rayleigh back scattering signal is fundamentally limiting the performance of all Φ-OTDR

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technologies. Recently, ultra-weak Fiber Bragg grating (UWFBG) array is proposed. A large number of FBGs with ultralow reflectivity are inscribed along an optical fiber with identical nominal wavelength and constant spacing between neighboring FBGs. The UWFBG array has much stronger reflection than the Rayleigh backing scattering, making it a preferred choice for many quasi-distributed and distributed fiber sensing applications. C. Wang, P. Han and L. Ma et al. have demonstrated various sensing network using UWFBG to perform distributed sensing [8-10].

In general, the phase change of reflected lightwave contains the information of the change of fiber. It is linearly proportional with the perturbation of the optical fiber, in other words, the alternation of the optical path difference, generated by external perturbation [11]. Thus, precisely demodulating the phase of the reflected lightwave is the key to solve for the distributed perturbation along an optical fiber. A number of demodulation methods have been proposed in the past [12-17]. A. Masoudi and M. Belal used a 3×3 coupler to measure multiple dynamic perturbations along a 1 km fiber [16]. Y. Dong proposed a quantitative measurement system using I/Q demodulation method [13]. G. Yang developed a vibration sensing technique based on Φ-OTDR using Hilbert transform, which is able to measure dynamic strain at a frequency as low as 30 Hz [14].

In this paper, the phase demodulation method, i.e. perturbation measurement method, was inspired by Hilbert transform. The system is based on an UWFBG array assisted Φ-OTDR, and a double-pulse waveform is used as probe signal. The physical spacing between neighboring UWFBGs and the time duration between two pulses are carefully designed, that the reflected optical signal of the front probe pulse overlaps with the reflected optical signal of the rear probe pulse from an adjacent UWFBG. Thus, the two reflected pulses interfere with each other at the receiving side, containing the phase information between two neighboring UWFBGs. So a perturbation on fiber induces the variation of the interference signal from corresponding position. However, due to the fact that the intensity of the interference signal is related to the optical phase change via a trigonometric function, it is hard to demodulate the vibration from the intensity variation of the interference signal as stated in our previous paper [18]. Therefore, a coherent detection scheme is employed in this paper. On the other hand, single probe pulse combined with heterodyne coherent detection cannot locate the perturbation directly from the intensity variation of the signal, because it does not change with the perturbation in this circumstance.

Thus, one has to demodulate all the phases of the optical signal along the fiber to find the vibration, which severely deteriorate the response speed of the system. Double-pulse can help to locate perturbations easily since it generates an intensity variation to the optical signal at the vibration position. Thus, one only needs to demodulate the phases of the optical signals around the vibration position, which can greatly improve the response speed. In addition, a twice-differential method is proposed to eliminate the noise generated from the laser source, so very low frequency signal can be extracted in experiment.

II. PRINCIPLE

The proposed interrogation scheme for UWFBG array is shown in Fig. 1. The UWFBG array has a uniform spatial interval ΔL between adjacent UWFBGs. The output of a narrow linewidth laser (NLL) is split into two paths via a 90/10 coupler. The upper path with higher power is intensity modulated to form the probe signal via an acoustic optical modulator (AOM). The probe signal is composed of two optical pulses with time interval of $2n\Delta L/c$, where n is the refractive index of fiber and c is the velocity of light in vacuum, and each pulse has an angular frequency shift of $\Delta\omega$ introduced by the AOM. Therefore, the reflected optical signals of the double-pulse generated from adjacent UWFBGs overlap with each other. The second path with lower power serves as reference path to hold the lightwave property from NLL. The reflected optical signals of the rear and front probe pulses, as well as the reference signal can be described as:

$$\begin{cases} \mathbf{E}_n = A_n \exp\left[-i\left(\omega t + \phi_n\right)\right] \\ \mathbf{E}_{n+1} = A_{n+1} \exp\left[-i\left(\omega t + \phi_{n+1}\right)\right] \\ \mathbf{E}_{Lo} = A_{Lo} \exp\left[-i\left((\omega+\Delta\omega)t + \phi_{Lo}\right)\right] \end{cases} \quad (1)$$

where A represents the magnitude of electrical field, ω represents the angular frequency of NLL, and ϕ represents the phase. The subscript n denotes the reflected signal of the nth UWFBG, and the subscript Lo denotes the local oscillator signal preserved by the reference path.

Assuming that the reflectivity of the UWFBG array is a constant, when the three signals in (1) are collected and mixed through a 2×1 50/50 coupler, the ac-coupled intermediate frequency (IF) photocurrent can be described as

$$I_{n+1} \propto 2AA_{Lo} \cos(\frac{\Delta\phi_{n+1}}{2}) \cos(\Delta\omega t + \phi_n - \phi_{Lo} + \frac{\Delta\phi_{n+1}}{2}) \quad (2)$$

where $\Delta\phi_{n+1} = \phi_{n+1} - \phi_n$ is the phase difference between the front and rear pulses for the nth and $(n+1)^{\text{th}}$ UWFBGs, which can be named as the $(n+1)^{\text{th}}$ UWFBG pair. When the short fiber section within the $(n+1)^{\text{th}}$ UWFBG pair is disturbed, the phase difference $\Delta\phi_{n+1}$ changes accordingly. From (2) we can see that an external perturbation modulates both phase and amplitude of the ac-coupled IF signal at the receiver, a phase variation $\Delta\phi_{n+1}$ to the IF signal; and the amplitude of the signal via $\cos(\Delta\phi_{n+1}/2)$. Thus, the phase change within the target pair is isolated from other pairs in the array. The perturbation within a specific pair can be resolved simply by demodulating the

amplitude and phase of the IF signal from the target pair, rather than demodulating all IF signals from all reflectors in a single pulse system.

The Hilbert transform of (2) can be expressed as:

$$H(I_{n+1}) \propto 2AA_{Lo} \cos(\frac{\Delta\phi_{n+1}}{2}) \sin(\Delta\omega t + \phi_n - \phi_{Lo} + \frac{\Delta\phi_{n+1}}{2}) \quad (3)$$

based on (2) and (3), the phase of the $(n+1)^{\text{th}}$ signal is derived:

$$\Delta\phi_{n+1} = 2(\arctan(\frac{H(I_{n+1})}{I_{n+1}}) + m_{n+1}\pi - \Delta\omega t + \phi_{Lo} - \phi_n) \quad (4)$$

In (4), $m_{n+1}\pi$ (m_{n+1} is an integer) is an item to unwrap the arctan function, and $\phi_{Lo} - \phi_n$ is constant ideally. In practical scenario, however, since the item $\cos(\Delta\phi_{n+1}/2)$ in (2) varies with perturbation, it induces large error to the result obtained with (4) when $\cos(\Delta\phi_{n+1}/2)$ is close to zero. But we can find that $\Delta\phi_r$ is constant for the rth UWFBG pair as long as $r \neq n+1$, thus by rearranging (4), the following equation can be obtained:

$$\phi_{n+2} = \arctan(\frac{H(I_{n+2})}{I_{n+2}}) + m_{n+2}\pi - \Delta\omega t - \frac{\Delta\phi_{n+2}}{2} + \phi_{Lo} \quad (5)$$

Because the item $\Delta\omega t$ changes with time, the value ϕ_{n+2} obtained from (5) is different for different measurement time. This makes it hard to extract the actual phase change induced by external perturbation, so a differential method is implemented. In this method, we also extract the phase $\Delta\phi_n$ of the nth signal by using (5). Subtracting ϕ_n from ϕ_{n+2} leads to the following equation:

$$\Delta\phi'_{n+2,n} = \phi_{n+2} - \phi_n = 2\{\arctan[H(I_{n+2})/I_{n+2}] \\ -\arctan[H(I_n)/I_n] + C\} \quad (6)$$

where $C = (m_{n+2} - m_n)\pi + (\Delta\phi_n - \Delta\phi_{n+2})/2$ is constant. Thus, the phase change induced by the perturbation within the $(n+1)^{\text{th}}$ UWFBG pair is obtained.

III. EXPERIMENT

The configuration of experiment is shown in Fig. 1. The length of the sensing fiber was 4.5 km. The whole fiber was integrated with UWFBG array which had equal spatial interval of 50 m. The length of each UWFBG was about 0.05 mm, the central wavelength of all the UWFBGs was 1550 nm and the bandwidth of the reflective spectrum of the UWFBG was about 5.5 nm. The laser source worked on 1550.12 nm. The output lightwave was split into two paths with a 90:10 optical coupler. The 90% lightwave was modulated into the double-pulse by an acoustic optical modulator (AOM) and the 10% lightwave served as reference lightwave. The pulse width of each optical pulse was 300 ns, and the time interval between the two pulses was 500 ns. So the reflected pulses of the front and rear pulses overlapped together. Meanwhile, the probe pulse had 200 MHz frequency shift, induced by the AOM. Then the probe pulse was launched into the sensing fiber through a circulator, and the reflected signal mixed with the reference lightwave. The heterodyne optical signal was received by a photo diode (PD)
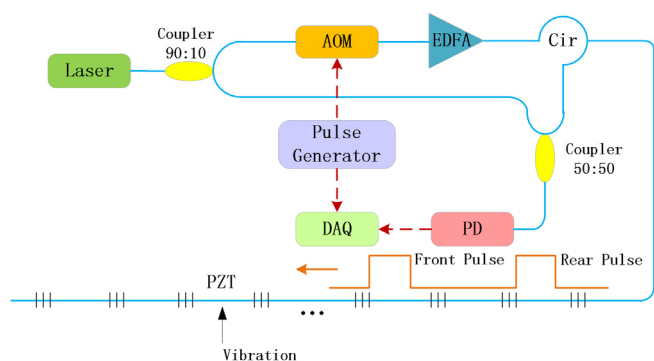
Fig. 1. The experiment setup.

Fig. 3. The comparison of the demodulated phase signal and the driving electric signal.

and its output signal was converted to digital form by a data acquisition card (DAQ) with a sampling rate of 500 MSa/s. A PZT vibration source was set at about 4 km.

A 30 Hz triangular signal was given to drive the PZT. The repetition rate of the double-pulse was 2 kHz and 1000 temporal curves were obtained. The signal obtained from the experiment is shown in Fig. 2, including 50 temporal curves obtained successively. Each peak is the interference result between the reflected front and rear pulses. Its length is determined by the probe pulse width. Obviously, the position of the vibration can be easily located with this method, as shown in the red circle in Fig.2. The two insets in Fig.2 show three temporal curves for 100 ms, 200 ms and 300 ms. The left inset shows the signal at the vibration position. As depicted before, the amplitude of the signal also varies with vibration, thus it induces large error to the extraction of phase when the amplitude is close to zero. Thus, as shown in the right inset in Fig. 2, the signal right after the vibration was chosen to extract the phase according to (5).

Then by applying (5) to the signal at the vibration position and that right before it, the phase variation induced by the vibration was obtained. The demodulated result is show in Fig. 3, where the black curve represents the driving signal applied on the PZT and the read and blue ones are the demodulated phase signal with 5 Vpp and 10 Vpp driving voltages respectively. Apparently, the demodulated phase restores the driving signal accurately.

Next, we changed the driving signal to sinusoidal waveform. The demodulated phase result and its spectrum are shown in Fig. 4. Synthesizing Fig. 3 and Fig. 4 we can see that the
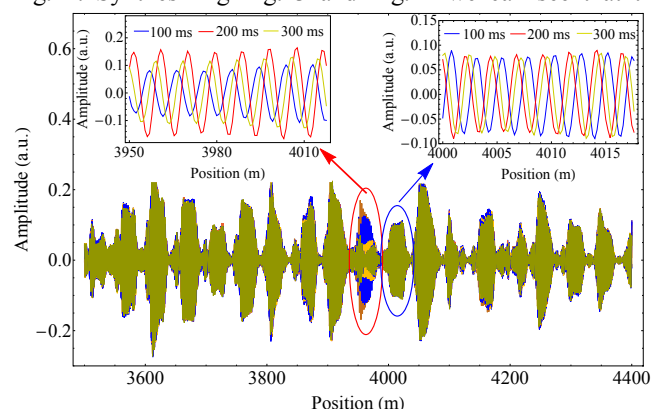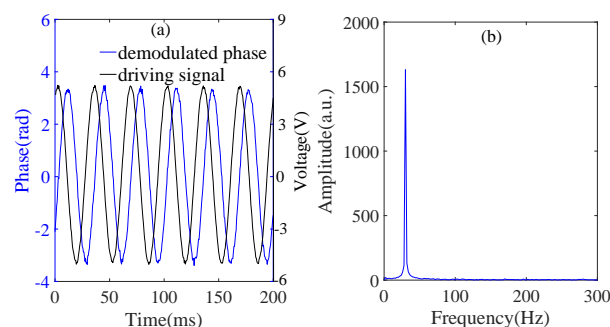

Fig. 4. The demodulated result for (a) sinusoidal driving signal and (b) its frequency spectrum.

method can demodulate different signal waveforms effectively. Then the driving voltage varied from 2 Vpp to 10 Vpp with a step of 0.5 Vpp and the amplitudes of the fundamental frequency in the spectrum were recorded. In this experiment, the signal under each driving voltage was measured ten times. The mean value of the results and the driving voltage are shown in Fig. 6, where a good linear relationship (r^2=0.9998) was observed. The maximum standard deviation of the FFT amplitude for each driving voltage is 17.14, which determines the minimum detectable phase difference is 0.068rad, corresponding to a fiber length variation of 14.85 nm [19].

Furthermore, the ability of measuring very low frequency with the proposed method was also demonstrated. In this experiment, the sinusoidal driving signal was set at 0.2 Hz and 10 Vpp. The repetition rate of the double-pulse was changed to 100 Hz, to match the slow vibration. Then 1000 temporal curves were obtained which would cover two periods of the
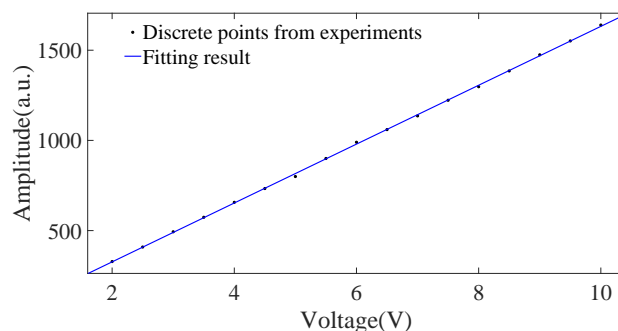

Fig. 2. The temporal signal after the DC component is filtered.

Fig. 5. The relationship between the driving voltage and the amplitude of the frequency spectrum of the demodulated phase result.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LPT.2018.2811411, IEEE Photonics Technology Letters
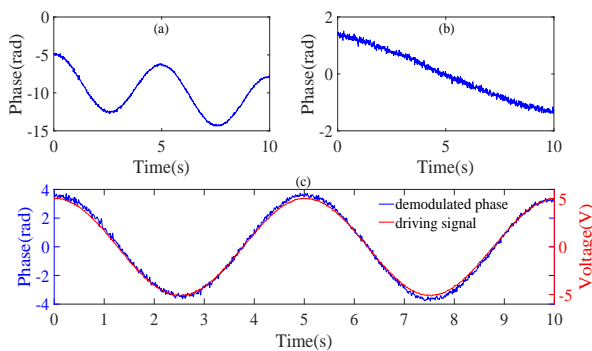
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Fig. 6. The process of demodulating 0.2Hz sinusoidal signal. (a)The primary result mixed with the influence of frequency drift. (b)The phase drift caused by frequency drift obtained through the differential method. (c) The final demodulated result.

vibration. The demodulated result is shown in Fig. 6.

In Fig. 6(a), the 0.2 Hz signal can be observed clearly, but the curve also shows a very slow downward trend with time. We cannot determine whether this is induced by an actual signal or by a noise. Although we had implemented a differential operation between $\Delta\phi_{n+1}$ and $\Delta\phi_n$, which eliminated most common noises before the (n-1)th UWFBG, there is still 100 m fiber length difference between the (n+1)th and (n-1)th UWFBGs. The frequency drift of the laser source on this fiber section is non-negligible during a long measuring time. Thus we proposed a twice-differential method to further reduce the influence of the laser frequency drift. In this method, the differential operation by using (5) was implemented to the signals between another two UWFBG pairs, whose interval was also 100 m and between which there was no perturbation. The result is shown in Fig. 6(b), where also exhibits a downward tread signal. Finally, by subtracting the result in Fig. 6(b) from that of Fig.6(a), the influence of the laser source on the 100 m fiber section can also be removed. The final result is shown in Fig.6(c). By comparing with the driving signal, they are totally coincident.

The reflectivity of the UWFBG used in experiment was about -40 dB. So the power of the reflected signal for a probe pulse with 300 ns pulse width is about 18 dB higher than that of the Rayleigh backscattering. Taking the advantage of high SNR, the sensitivity of the system was very good. According to the preceding signal processing procedure, in order to demodulate the phase of a given position and to eliminate the influence of laser frequency drift, the signals between four UWFBG pairs' phase information were calculated, costing 0.66s in the experiment. If double-pulse was not adopted, however, the vibration position cannot be located directly, so the phase information of all the signals along the fiber should be demodulated. There were total 88 UWFBGs in the fiber of the experiment, it will cost 14.52s to process all the UWFBGs' signal. Therefore, using double-pulse can improve the response speed significantly.

IV. CONCLUSION

In conclusion, we demonstrate a phase demodulation method

based on UWFBG array assisted Φ-OTDR. We use double-pulse to locate the vibration and use heterodyne coherent detection and Hilbert transform to quantitatively demodulate the phase variation of the lightwave induced by vibration. Both sinusoidal signal and triangle signal are demodulated accurately. The demodulated result has a very linear relationship with the amplitude of the driving signal and the minimum detectable fiber length variation is 14.85 nm. Because of the high SNR of the reflected signal and the twice-differential method, very low frequency of vibration can be detected. A 0.2 Hz sinusoidal driving signal is properly detected.

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