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High Performance Interrogation by a Composite-Double-Probe-Pulse for Ultra-weak FBG Array

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ABSTRACT

We propose and experimentally demonstrate a technique using a composite-double-probe-pulse (CDPP) to eliminate the effect of polarization fading for phase-sensitive optical time-domain reflectometry (Φ-OTDR) based on ultra-weak FBG (UWFBG) array. The CDPP is composed of two optical pulses whose spatial interval is equal to twice the spatial interval of adjacent UWFBGs in the UWFBG array. One optical pulse is a long optical pulse, and the other optical pulse is composed of two continuous short optical pulses, whose polarization states are orthogonal to each other. The width of the short pulse is equal to half of the width of the normal pulse and their frequencies are different from the long pulse. By using such a method to perform the sensing for the UWFBG array, distributed quantitative measurement can be realized with only direct detection scheme and the influence of polarization fading in the demodulation of signal is thoroughly eliminated.

Keywords: Optical fiber sensors, ultra-weak FBG array, polarization fading, phase demodulation.

1. INTRODUCTION

The phase-sensitive optical time domain reflectometry (ϕ-OTDR) was first proposed by Lee and Taylor in 1993 [1]. It was primarily developed for dynamic detection and precision positioning. With the help of the interference phenomenon among Rayleigh backscattering light, the ϕ-OTDR is sensitive to vibrations and can be used for security applications, pipeline monitoring, and interpretation of seismic measurements [2]. However, a few problems are associated with this interference phenomenon, and one of them is known as polarization fading, which restrict the performance of ϕ-OTDR severely.

Several approaches have been used to overcome the affection of polarization fading, including manual or automatic polarization controllers in the arms of the fiber interferometer [3-4], input polarization control/modulation-based approaches [5-6], and polarization diversity detection schemes [7-8]. These methods can solve the problem of the polarization mismatching between the reference lightwave and the scattering optical signal, however, they cannot eliminate the polarization fading during the generation of the scattering optical signal which is a comprehensive coherent result by massive scattered pulses with different polarization states. An obvious alternative approach is to construct the interferometer using polarization-maintaining (PM) fiber [9] which can resolve the polarization fading thoroughly.

Recently, ultra-weak FBG (UWFBG) array based ϕ-OTDR have been proposed for the usage of high performance distributed vibration sensing[10-14]. In this technique, the UWFBG array embedded in the fiber is used as a set of “weak mirrors” to provide a stable and controllable reflected light signal in the specified location of the fiber. These reflected light signals replace spontaneous Rayleigh scattering in the fiber to significantly improve the signal-to-noise ratio (SNR). By demodulating information on the phase or intensity of the interference, external perturbations on the fiber can be detected. Compared with the traditional ϕ-OTDR system, the reflected light signal obtained by the UWFBG array is more stable and has higher sensitivity, showing great potential in the field of distributed vibration sensing. In order to demodulate the signal in UWFBG array to realize distributed sensing, many methods have been proposed, including long-single-pulse method, double-pulse method, three ports coupler method, coherent detection method, et al. [11,12, 14] However,

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none of these methods can avoid the influence of polarization fading during the superimposes between the optical signals reflected from adjacent UWFBGs or between the reflected light signal and the reference lightwave, because the SOP of the lightwave in the UWFBG array is uncontrollable. As a result, the visibility of the interference drops sharply, leading to detection dead zone.

Based on the particularity of the UWFBG array in generating the optical signal compared with a traditional ϕ-OTDR, we propose a method by using a composite-double-probe-pulse (CDPP) to eliminate the influence of polarization fading in UWFBG array based ϕ-OTDR. The CDPP is composed of two optical pulses with different frequencies and one of the optical pulse is composed of two continuous short-pulses whose SOPs are orthogonal to each other. By properly demodulating the signal generated by the CDPP, the influence of polarization fading is eliminated thoroughly.

2. Principle

The profile of the proposed CDPP is shown in Fig. 1. The CDPP is composed of two optical pulses. The first optical pulse is a single pulse and the second optical pulse is a composite optical pulse which is composed of two continuous short optical pulses with equal widths and orthogonal SOPs. The two optical pulses have the same peak power. The width of the first probe pulse is equal to the total width of the second composite probe pulse. Meanwhile, the frequencies of the first probe pulse and the second probe pulse are different from each other. When the spatial interval between the first and the second optical pulses is equal to double times the spatial interval of UWFBGs in the UWFBG array, then for two arbitrary adjacent UWFBGs in the fiber, the reflected optical signal of the first optical pulse from the latter UWFBG will completely overlap and interfere with the reflected optical signal of the second optical pulse from the former UWFBG. And the coherent signal oscillates with an intermediate frequency (IF) which equals to the frequency difference between the two optical pulses.

Normally the polarization dependent loss (PDL) of a single mode fiber is very small and the pulse broadening induced by polarization mode dispersion (PMD) is negligible compared with the pulse width of the probe pulse. So because the two short pulses in the second probe pulse undergo the same path in the UWFBG array, their SOPs will keep orthogonal along the fiber and the peak powers of all the optical pulse are nearly the same. So no matter how the SOP of the first reflected optical pulse changes, there is at least one part in the second reflected optical pulse that can generates a good coherent result with the first reflected optical pulse. And then the phase information induced by the external vibration of fiber can be demodulated from the IF signal of this part.

3. Experiment

The experiment setup verifying the proposed method is shown in Fig. 2. The linewidth of the laser source was 100 Hz. Its output was split into two beams by a 1×2 fiber coupler1 (50:50). The two beams were modulated into two optical pulses respectively by the AOM1 and AOM2. The pulse width of the first pulse was 300 ns and the pulse width of the second pulse was 150 ns. The second pulse was firstly divided into two equal pulses by the PC1 and the PBS1. A delay fiber with 30 m length was inserted into one output arm of the PBS1 to induce 150 ns time delay between the two pulses. Then the two pulses were combined together through the PBS2. The PC2 after the delay fiber was used to align the SOP of the optical pulse parallel to the slow axis of the input arm of PBS2. So the optical pulse output from the PBS2 was a composite pulse composed of two successive 150 ns short pulses with orthogonal SOPs. In experiment, the length of the UWFBG array was 4.5 km and the spatial interval of the UWFBGs in the UWFBG array was 50 m, so we set the time

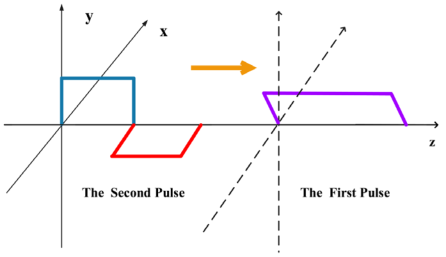

Fig. 1. The profile of the CDPP.

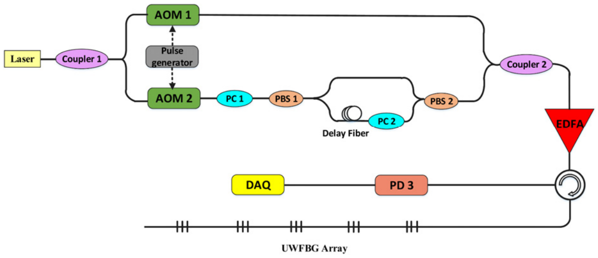

Fig. 2. The experiment setup.

delay between the first and the second optical pulse be 500 ns to make their reflected signal from adjacent FBGs overlap and interfere with each other. The average reflectivity of the UWFBG array was about -40 dB. The insertion loss of the AOM1 and AOM2 were 5 dB and 6 dB respectively, and the additional insertion loss of the two PBSs were 1 dB. So in order to made all the optical pulses in the CDPP have similar peak power, the coupling ratio of the first coupler was chosen to be 30%:70%. The peak power of the CDPP was about 3dBm and was amplified to 18 dBm with an EDFA. Its repetition rate was 10 kHz. The returned coherent signal was received by a photodetector with 350 MHz bandwidth. A data acquisition card (DAQ) with a sampling rate of 500M Sa/s was used to convert the electric signal into digital form and send them to a computer for further processing.

In the experiment, a PZT was set at about 4.1 km to stretch the fiber by winding fiber on it. The dirving signal was a 30 Hz sinusoidal signal and the driving voltage is 6 V. The obtained signal curve is shown in Fig. 3. It can be seen that there are many peaks in the signal, each of which is a cohenrent superposition between two optical pulses reflected from two adjacent UWFBGs. Due to the two optical pulses in the CDPP have different frequencies, each peak has obvious oscillation whose frequency equals to 160 MHz (the frequency difference between the two optcial pulses). Meanwhile, each peak has two parts which are related to the front part and rear part of the second optical pulse respectively. And the fringes of the two parts are different in different peak. In the insets in Fig. 4, signals are enlarged to show three typical cases: the fringe of the left part is very large and the fringe of the right part is very small, the fringe of the left part is very small and the fringe of the right part is very large, the fringes of the left part and the right part are similar. These signals demostrate that due to the reflected signal of the first probe pulse undergoes an extra round-trip in one more UWFBG pair than that of the second probe pulse, their SOPs may have various different relationships. No matter what SOPs of the first probe pulse and the second probe pusle are given at the input end, as long as each of them has single SOP, the polarization fading may occur for some UWFBG pairs. Then the sensitivities for these positions deteriorate dramastically.

However, as explained in the principle and shown in Fig. 3, when using the CDPP proposed in this paper, at least one part of each peak has obvious interference signal. Since the interference is a beat signal with intermediate frequency, it is easy to demodulate its phase directly by using IQ demodulation method. The final demodulated result is shown in Fig. 4. In Fig. 4 , there are 15 cycles of the signal and the time duration of the signal is 0.5 second. The demodulated signal restores the driving signal accurately.

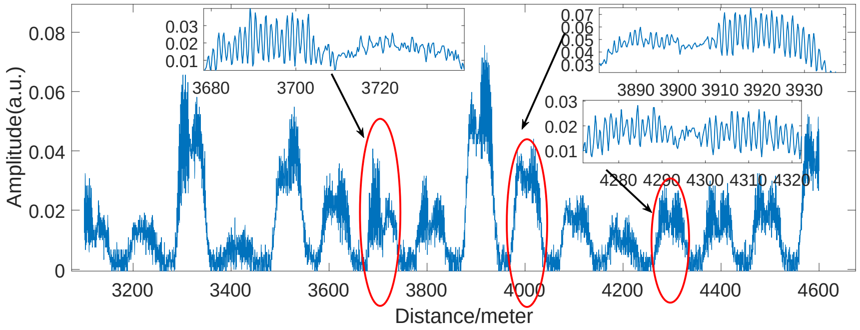

Fig. 3. The detected signal for the UWFBG array with the CDPP.

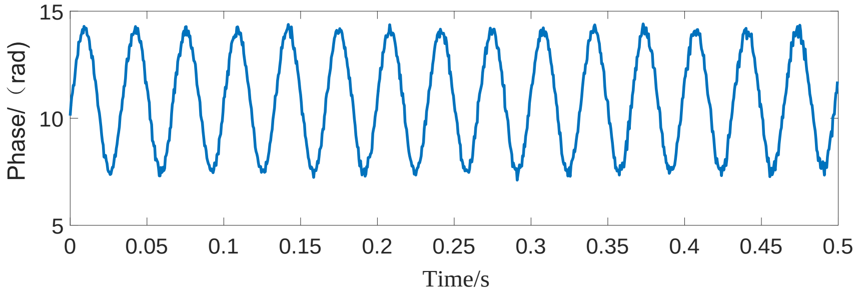

Fig. 4. The demodulated sinusoidal signal with the proposed method.

4. Conclusion

A high performance interrogation method by a composite-double-probe-pulse for UWFBG array is proposed. The CDPP is composed of two optical pulses with different frequencies and one of the optical pulse is composed of two continuous short-pulses whose SOPs are orthogonal to each other. The proposed method is free of polarization fading which deteriorates the performance of ϕ-OTDR severely, and can achieve quantitative measurement with only direct detection. The experiment result shows that this novel method can achieve good performance. The influence of polarization fading is eliminated for all the positions along the UWFBG array. And the disturbance signal applied on the fiber can be accurately demodulated at the same time.

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