Rapid temperature measurement BOTDR technology based on frequency agility technology

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***Abstract*—We propose a scheme of high-speed Brillouin optical time-domain reflectometer (BOTDR) for dynamic strain measurements, which implements by frequency-agile techniques. The spontaneous Brillouin gain spectrum can be demodulated online in the time domain using band-pass filters and envelope detection for truly distributed, single-ended access and dynamic strain measurements. The proposed sensor achieves a strain sampling rate of 62.5 Hz with 100 sweeps and 64 averages over 172 m of single-mode fiber. The vibration frequencies of 6.82 Hz and 14.77 Hz are measured in the experiment with a spatial resolution of 2 m and a dynamic range of 4000 με. The measurement accuracy is ±30 με, calculated by the standard deviation of the static fiber Brillouin frequency shift.**

Keywords—Brillouin optical time-domain reflectometry, dynamic strain measurement, frequency-agile technique, spontaneous Brillouin scattering

I. INTRODUCTION

Distributed Brillouin optical time-domain fiber-optic sensors have gained significant attention in the last decades due to the feasibility of strain and temperature measurements[1-2]. Spontaneous Brillouin scattering (SpBS) based sensors are competitive for structural health monitoring and fire alarms. Compared with the Brillouin scattering (SBS) based sensors, the SpBS based sensors have unique advantage of single point access, which can offer still working at the breakpoints[3]. The Brillouin optical time-domain reflectometry (BOTDR) is one of the most widely used schemes among the SpBS based sensors. This paper focuses on high-speed BOTDR with high sampling rate for dynamic strain measurement. For the conventional BOTDR scheme, the spontaneous Brillouin signal is mixed with a reference wave to produce a beat signal, which is then converted to an electrical signal by a high-bandwidth photodetector (PD). Through a microwave oscillator and a band-pass filter, the frequency components of the beat signal can be extracted. For mapping the Brillouin gain spectrum (BGS), the frequency of the microwave oscillator gets swept over the expected dynamic range of strain and temperature variations. Therefore the frequency sweeping process is time-consuming, the coherent detection BOTDR is only suitable for static or slowly changing strain and temperature measurements. In this paper, a high-speed BOTDR scheme for dynamic strain measurements has been proposed, which implements by frequency-agile techniques. The reference wave is swept between 10.4 and 10.796 GHz in fast frequency steps of 4 MHz, which enables an accurate mapping of the spontaneous BGS in the time domain and provides a wide dynamic strain range. The fiber length, the averaging time and the number of sweeps limit the measurement time. The frequency switching time can be ignored here, which is a dominant factor for short sensing lengths. The vibration frequencies of 6.82 Hz and 14.77 Hz were measured at a strain sampling rate of 62.5 Hz in the experiment, and a spatial resolution of 2 m was obtained by using a pump pulse of 20 ns. Moreover, the measurement accuracy was ±30 με at 64 averaging times.

II. PRINCIPLE

A. Selecting a Template

In the proposed scheme, the optical frequency modulation technique is utilized to provide a swept frequency reference wave, which implements by an electro-optical modulator (EOM) biased at the minimum transmission for double sideband modulation. Through the fiber Bragg grating (FBG) to choose one sideband. Figure 1 illustrates the operating principle of the high-speed spontaneous BGS online demodulation, which implements by a frequency-agile modulated reference wave. To begin with, the backscattered signal from the pump pulse contains fiber Brillouin information in the frequency domain, which contains two components the Stokes and anti-Stokes signals with the down or up shifted frequencies by 11 GHz respect to the pump wave, respectively. Then the Stokes component is extracted by mixing with a down-shifted frequency-agile modulated reference wave, the heterodyne signal is converted to an electrical signals by a low-bandwidth PD. Next, the spontaneous BGS is converted from the frequency domain to the time domain, implementing by band-pass filters and envelope detection. To be more specific, the reference wave is frequency swept in the range of a few hundred MHz, causing the spontaneous BGS to be taken in the frequency domain. Therefore, the time required to complete the spontaneous BGS reconstruction is T_{mea}, which contains the averaging times N_{ave}, the number of sweeping frequencies M_{fre}, the lasting time of each frequency T_{fre}. Meanwhile, between two frequency-agile temporal frames, the time interval is T_{in} and the frequency-switching time can be ignored. The relationship is given by

$$T_{mea} = N_{ave} \times (M_{fre} \times T_{fre} + T_{in}) \tag{1}$$

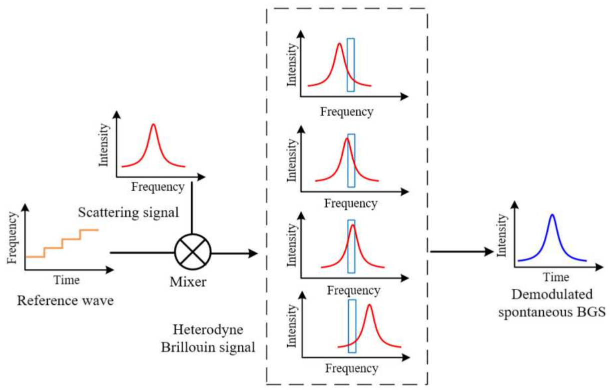

Fig. 1. Operating principle of high-speed spontaneous BGS online demodulation based on frequency-agile technique.

III. Setup

To experimentally demonstrate the proposed fast BOTDR and its performance on dynamic strain measurements, the scheme of Figure 2 was carried out. This is essentially a classical BOTDR setup, in which the reference wave is rapidly scanned by a low bandwidth AWG and an up converter. The laser at 1532 nm was separated into two branches using a 3-dB coupler. The EOM1 is used to generate pump pulses in the upper branch, which is driven by a train of 100 electrical pulses. The driving signal is given by channel 1 (CH1) of the AWG with a repetition rate of 4 kHz. For the pulse, each has the width of 20 ns and the adjacent two have the time interval of 2 μs, corresponding to the 2 m spatial resolution and 200 m sensing range, respectively. Then, the pump pulse is amplified using an erbium-doped fiber amplifier (EDFA) with an output power of about 600 mW. Finally, through a circulator, the pump pulse is injected into the fiber under test (FUT), while the backscattered signal is also captured.

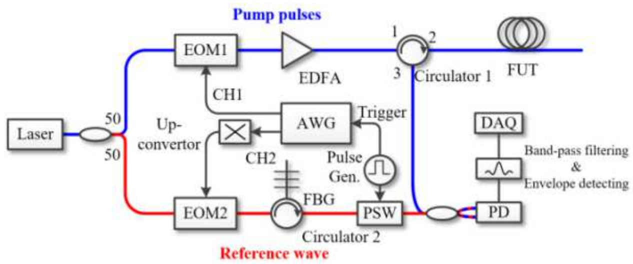

Fig. 2. Experimental setup of the high-speed BOTDR scheme based on the frequency agility techniques.

The EOM2 is used in the lower branch to generate frequency-agile modulated reference waves driven by microwave signals from 10.4 to 10.796 GHz in frequency steps of 4 MHz. In addition, the microwave up-converter was used to reduce the bandwidth requirements of the AWG. The frequency-agile microwave is at a fixed frequency up-conversion of 10.3 GHz, and just swept from 100 to 496 MHz, which is provided by the CH2 of the AWG. The duration of each frequency is also 2 μs to match the backward scattering signal from the corresponding pump pulse. Then through the FBG, the lower-sideband of the frequency-agile modulated light was chosen, whose polarization state was switched by an orthogonal polarization switch (PSW). With the addition of two polarization signals, it can eliminate the signal power fluctuations caused by polarization. By a 2×2 coupler, the backscattered SpBS and the reference wave are mixed, then the beat signal is received with a balanced PD at 350 MHz. To perform spontaneous BGS reconstruction in the time domain, the heterodyne Brillouin signal is swept across 396 MHz in the frequency domain, and then the fixed frequency components are extracted using a band-pass filter and envelope detection. The bandpass filter is with a 300 MHz center frequency and a 100 MHz bandwidth. At the end, the demodulation output is recorded by a data collector (DAQ).

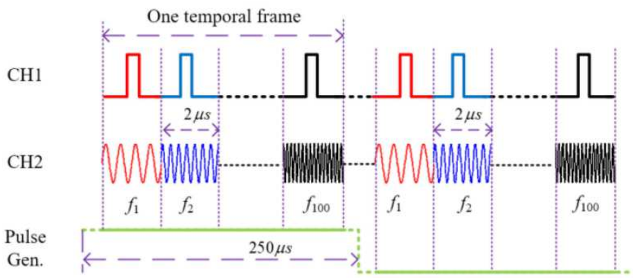

Fig. 3. the synchronization relationship of the three driving signals: electric pulses for pumping waves, frequency modulated signals for reference waves, the electric square waveform for the orthogonal polarization modulation.

Figure 3 shows the visually the synchronization relationship of the three driving signals. A time frame is determined by the length of a sequence of 100 electrical signals, so that two time frames are measured once. The designed pulse and microwave time frames are pre-written into the AWG and output via CH1 and CH2, respectively. In addition, to ensure the same polarization modulation within a time frame, the AWG is triggered by the pulse generator. In the next frame, the voltage of the pulse generator is switched to produce an orthogonal polarization modulation of the reference wave. One time frame has a duration of about 200 μs thus is triggered at a repetition rate of 4 kHz (250 μs).

Therefore, a time interval of 50 μs is provided between the two time frames to perform polarization switching.

IV. RESULT

In the experiment, a 2.5 m segment of a 172 m single-mode fiber was stretched, which is located between 160 and 162.5 m. To obtained the strain coefficient of the FUT, a static strain measurement is carried out, where the strain was increased from 0 to 4000 με in steps of 400 με. The measured strain coefficient is 0.0496 MHz/με. Moreover, the capability of the proposed scheme that measuring the large strain range is also demonstrated, up to 4000 με. To demonstrate the capability of dynamic strain measurement, two sets of vibrations are employed, with a low-frequency and a high-frequency vibration, respectively. The frequency changing as time of the measured spontaneous BGS are shown in Figure 4. Here, the system strain sampling rate is 62.5 Hz.

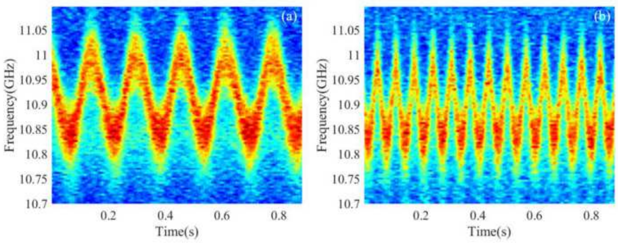

Fig. 4. Frequency changing as time of the measured spontaneous BGS. (a) at low-frequency vibration and (b)at high-frequency vibration.

The demodulated dynamic strain are shown in Figure 5 (a) and (b), which are calculated by the BFS difference and fiber strain coefficient. The fiber with no strain has a BFS of 10.82 GHz. The dynamic strain in the two set of experiment is changing bet 300 ~ 3200 με, and 100 με~ 2600 με, respectively. Through the Fourier transform algorithm, the two vibration frequencies are analyzed and shown in Figure 15(c). The measured low-frequency is 6.82 Hz (blue curve) while the measured high-frequency is 14.77 Hz (red curve) and a second harmonic component of 30.68 Hz is also observed. The standard deviation (SD) of the BFS at the static segment of the FUT is employed to represent the measurement accuracy, which is calculated to about 1.47 MHz (equivalent to an accuracy of ±30 με).

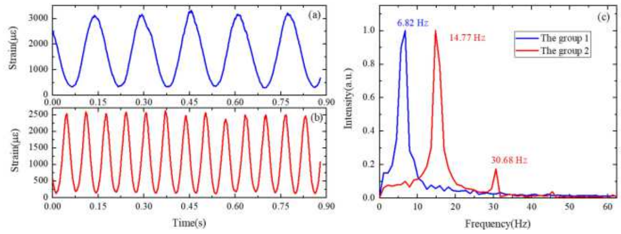

Fig. 5. Demodulated dynamic strain: (a) for Figure 4(a); (b) for Figure 4(b). (c) The vibration frequency results.

V. CONCLUSION

In this work, a high-speed BOTDR scheme based on the frequency-agile technique has been experimentally demonstrated. In the scheme, a frequency-agile modulated reference wave implements the online demodulation of the spontaneous BGS in the time domain. Moreover, the measurement time of the proposed scheme is only limited by the fiber length, averaging times and number of sweeping frequencies, and free from the frequency switching time. The measurement capability has been demonstrated over a 172 m single-mode fiber with a spatial resolution of 2 m. In addition, the measuring strain range was demonstrated up to 4000 με. The sampling rate of the dynamic measurement is up to 500 Hz with 8 times of averaging. The measurement accuracy is ±11.5 με with 256 times of averaging. The proposed high-speed BOTDR is capable of meeting the needs of most engineering applications, both high frequency vibration and good measurement accuracy.

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