Proposal of Brillouin optical time domain collider for dynamic strain measurement

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Abstract: The dynamic strain sampling rate of Brillouin-based distributed sensors is limited by fiber length. For breaking this limit, a Brillouin optical time domain collider is proposed. A 10-times enhancement on sampling rate is experimentally demonstrated.

OCIS codes: (060.2370) Fiber optics sensors; (120.7280) Vibration analysis; (290.5900) Scattering, stimulated Brillouin.

1. Introduction

Distributed dynamic strain measurement is an important task in various applications, such as bridge and high-speed railway. As one of the distributed dynamic strain fiber sensors, Brillouin optical time domain analysis (BOTDA) has been widely studied due to its high accuracy and wide-strain dynamic range. Presently, lots of studies have been done to improve the sampling rate of the BOTDA to the dynamic strain [1, 2]. For instance, the use of slope-assisted schemes [3] or optical chirp-chain method [4] can avoid time-consuming frequency-sweeping process in the conventional BOTDA. By using optical pulse coding method, signal-to-noise (SNR) can be significantly enhanced and thus reducing averaging time [5]. Foreseeably, by combining these advanced techniques, the dynamic strain sampling rate of the sensor can be largely enhanced and ultimately limited by fiber length [6].

Theoretically, to avoid crosstalk of sensing information related to two adjacent pump pulses, the pulse interval must be larger than the round-trip time of flight in the fiber [6]. This means that, with the increase of fiber length, the pulse interval has to be increased and the maximal sampling rate of the sensor has to be decreased accordingly. Meanwhile, since the maximal power of the pump and probe is limited by various detrimental nonlinear and non-local effects [7], the SNR is restrained. As a result, for an acceptable measurement accuracy, longer sensing fiber needs more averaging time. Further, the sampling rate of the sensor is degraded [6]. Accordingly, it is expected that a Brillouin-based long-distance dynamic sensor should be able to break the fiber length-limited sampling rate, meanwhile be *robust* to the detrimental effects.

In this work, based on the BOTDA, a new Brillouin optical time domain collider (BOTDC) is proposed and experimentally demonstrated to break through the limit of fiber length on the dynamic strain sampling rate (pulse repetition rate). In the BOTDC, both pump and probe lights are frequency-hopping optical signals and the frequency relationships between the pump and probe are delicately designed, which makes that each pump pulse with a specific frequency only interacts with a relevant-frequency probe wave section through the stimulated Brillouin scattering (SBS). In this way, the sampling rate can be improved without sensing information-crosstalk. Meanwhile, the reduced SBS interaction length can alleviate pump depletion and thus reduce the non-local effects. Moreover, by using frequency-hopping probe, the sensing information can be acquired by employing the direct-detection and low sample-rate data acquisition card, which leads to low data volume and thus potentially high real-time capability. A 4- and 10-times enhancement on the sampling rate are experimentally demonstrated.

2. Principle

In the conventional BOTDA, the energy transfer between a pulsed pump and a continuous-wave (CW) probe through the SBS will happen when their frequency offset falls within the Brillouin gain spectrum (BGS) [1]. In order to avoid the crosstalk of sensing information between two adjacent pump pulses, the pulse interval (T_p, equivalent to the dynamic strain sampling interval (T_{sample})) must be larger than the round-trip time of flight in the fiber ($T_{round\text{-}trip}$), as described in Eq. 1 [6]:

$$T_p > T_{round-trip} (= \frac{2nL}{c}) \tag{1}$$

where n, L and c denotes the refractive index, fiber length and speed of light in vacuum, respectively. It can be seen that, with the increasing fiber length, the maximal sampling rate ($1/T_p$) of the sensor is decreased accordingly. Meanwhile, when a longer fiber is employed, the probe power decreasing is an effective way to avoid the non-local effect [7], which confines the SNR and thus results in longer averaging time (lower sampling rate).

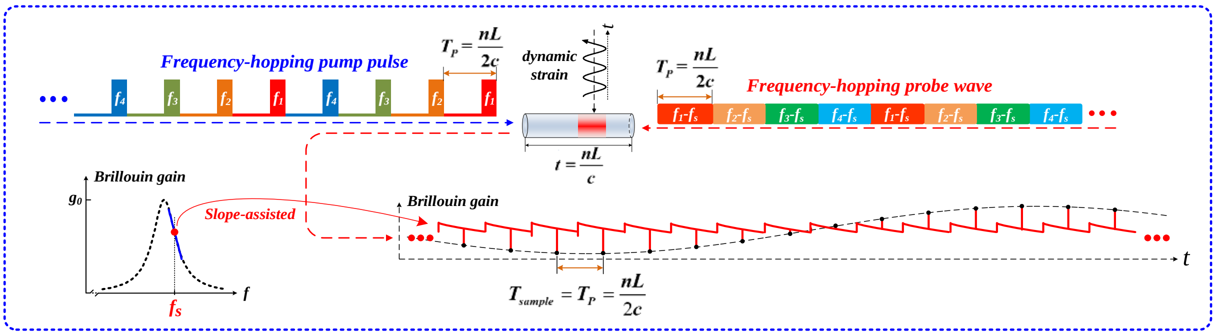

Fig. 1. Schematic diagram of a 4-frequency BOTDC sensor.

For breaking the limit of fiber length to the sampling rate, a new BOTDC is proposed. Compared with the conventional BOTDA, the pump and probe lights are both frequency-hopping optical signals in the BOTDC. Figure 1 illustrates the working principle of a 4-frequency BOTDC. In the time range of 0 to $2nL/c$, four pump pulses with the frequencies of f_1, f_2, f_3, f_4 and four probe sections with the frequencies of f_1-f_s, f_2-f_s, f_3-f_s, f_4-f_s are injected into the fiber simultaneously. Here, $f_1>f_2>f_3>f_4$, and the frequency spacing between two adjacent frequencies (e.g., f_2-f_1) is much larger than the frequency range of the BGS. f_s (~11 GHz) denotes the frequency offset between the pump and probe waves, which makes the Brillouin gain located at the slope of BGS. In this way, after pump-probe colliding at the center of the fiber, each pump pulse with a specific frequency only interacts with the probe wave section which owns the relevant frequency through the SBS. For instance, f_1 pump pulse only interacts with f_1-f_s probe wave section. Consequently, the sampling rate can be improved 4 times without sensing information-crosstalk. It is worth to note that the sampling rate can be further enhanced by increasing the number of frequencies in the same way. Meanwhile, since the SBS interaction length is reduced to be a quarter of the fiber length, the non-local effect is much weaker, and the probe power can be enhanced accordingly [8]. Moreover, a method which can rapidly and flexibly shift the collision area (sensing area) is proposed. This method is mainly based on adjusting the frequency-coding rule and delay of the pump, finally, the relative delay between the pump and probe waves will be changed. For instance, if the coding rules of the pump and probe are [f_1, f_2, f_3, f_4] and [f_1-f_s, f_2-f_s, f_3-f_s, f_4-f_s] respectively, the collision area is from L/2 to 3L/4, as depicted in Fig. 1 (the fiber area marked in red). Moreover, if the coding rules are [f_2, f_3, f_4, f_1] and [f_1-f_s, f_2-f_s, f_3-f_s, f_4-f_s], the collision area is shifted to 3L/4 to L (i.e., the end of the fiber).

3. Experimental setup and results

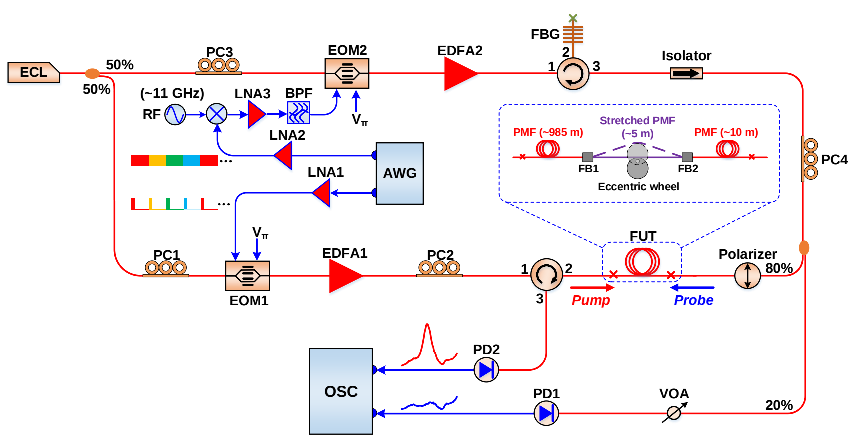

Fig. 2. Experimental setup of the BOTDC.

The experimental setup of the BOTDC is shown in Fig. 2. A CW light from a narrow linewidth (~100 kHz) external cavity laser (ECL) is split into two branches by a 50:50 coupler. In the lower branch, the frequency-hopping pump pulses (30 ns) are generated by a high extinction-ratio (35 dB) electro-optic modulator (EOM1) with the carrier-suppressed mode and driven by frequency-hopping electric pulses. The electric pulses with specific frequencies are sequentially generated by an arbitrary waveform generator (AWG) and amplified by a low-noise amplifier (LNA1). After amplified by an erbium-doped fiber amplifier (EDFA1) and adjusted by a polarization controller (PC2), the pump pulses are injected into the fiber under test (FUT, 1-km polarization-maintaining fiber (PMF)) through a circulator. The stretched section at the end of the fiber is applied the dynamic strain (periodic mechanical vibration) by using an eccentric wheel, as shown in the inset of the Fig. 2. In the upper branch, a carrier-suppressed double-sideband (CS-DSB) frequency-hopping probe wave is generated by the EOM2 driven by a frequency-hopping electric signal. The electric signal with the same frequencies as the electric pulses is firstly generated by the AWG, and then, up-converted by using the combination of frequency mixing and band-pass filtering (BPF). After amplified by the EDFA2, the anti-Stokes component is removed by using a fiber Bragg grating (FBG). Before injecting into the FUT, the probe wave is spilt into two branches by an 80:20 coupler. The 80% of the probe is injected into the FUT and then detected by a 350-MHz photodetector (PD2). Different from the convention BOTDA, the probe light is continuously amplified by the pump pulses in the BOTDC. Therefore, in order to perform logarithmic normalization [5], the 20% of the probe is detected by a 75-MHz PD1 and used as the reference to track the bias of the probe. The sample rate of the oscilloscope (OSC) is 100 MSa/s.

Figure 3(a) describes the BGS distribution in the conventional BOTDA. For the 1 km sensing fiber, the time of flight is 10 μs. Thus, the pulse interval must be larger than 10 μs to avoid sensing information-crosstalk. In addition, the strain (the fiber stretching) induced BGS distribution variation at the end of fiber can be clearly observed. Figure 3(b) illustrates the BGS distribution in the 4-frequency BOTDC. It can be seen that the strain is continuously measured by 4 times within 10.2 μs, which means that the sampling rate is enhanced by 4 times. Similarly, a 10 times enhancement on the sampling rate is obtained by adopting a 10-frequency BOTDC, as shown in Fig. 3(c). Figure 3(d) depicts the measured BGSs obtained by different methods. It can be seen that the BGSs are nearly the same, which demonstrates that they have the same responses to the strain.

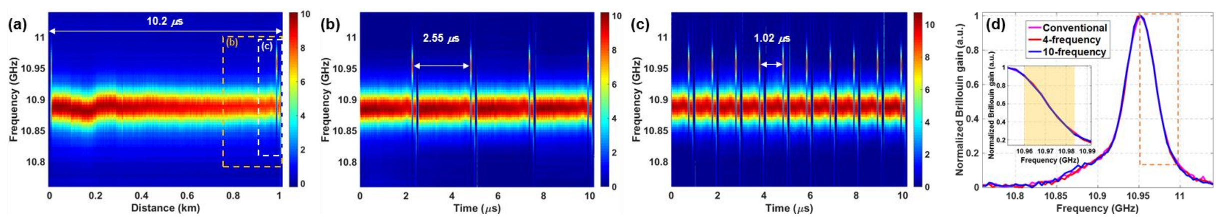

Fig. 3. The BGS distributions in (a) conventional BOTDA, (b) 4-frequency BOTDC and (c) 10-frequency BOTDC. (d) The BGS of the stretched fiber when using different methods.

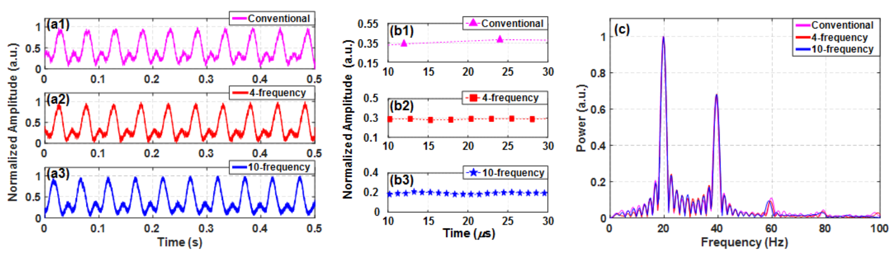

Fig. 4. (a) The measured dynamic strain when employing different methods; (b) The details of the measured dynamic strain from 10 to 30 μs; (c) The corresponding frequency spectrums of the measured dynamic strain.

After verifying the static property of the BOTDC sensor, the measurement of dynamic strain (incorporating with the slope-assisted method) induced by eccentric wheel is performed. Figure 4(a1)-4(a3) illustrate the dynamic strain measured by the conventional BOTDA, 4-frequency BOTDC and 10-frequency BOTDC, respectively. Here, a 20-points moving average is employed. Figure 4(b1)-4(b3) show the details of the Fig. 4(a1)-4(a3) from 10 to 30 μs, respectively. It can be seen that, compared with the conventional BOTDA, the dynamic strain sampling rates are enhanced by 4 and 10 times by using the 4- and 10-frequency BOTDC, respectively. Figure 4(c) illustrates the frequency spectrums of the measured dynamic strain shown in Fig. 4(a1)-4(a3). It can be seen that the spectrums contain a 19.75 Hz fundamental frequency and a 39.49 Hz harmonic frequency.

4. Conclusion

In this work, a new BOTDC sensor is proposed for fast dynamic strain measurement. The 4- and 10-times enhancements on the sampling rate are experimentally demonstrated. Foreseeably, the BOTDC is a potential candidate for high-sampling-rate dynamic strain measurement in key areas over long distance.

5. References

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