Brillouin optical time-domain analysis at a high sampling rate (invited)

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Abstract. In the modern industry, a distributed ultra-fast measurement for obtaining environment information (e.g. strain and temperature) is required. Brillouin optical time-domain analysis (BOTDA), one of widely used optical fiber sensing, is usually employed to measure the distributed Brillouin frequency shift over fiber under test via a time-consuming frequency-sweeping process which limits the sampling rate of BOTDA. Several fast BOTDA schemes proposed by our team are summarised and are classified into three categories: frequency-agile technique, slope-assisted methods and optical chirp chain technique.

1. Introduction

The widely used Brillouin optical time-domain analysis (BOTDA) is based the “Pump-probe” scheme [1, 2] that two optical waves (i.e. pump wave and probe wave) with a frequency difference near the Brillouin frequency shift (BFS) of the fiber under test (FUT) are launched into the FUT at opposite direction. The amplified Brillouin backward scattering signal is obtained because the energy transfer from the high-power pump wave to the probe wave occurs due to the stimulated Brillouin scattering (SBS), when the frequency difference is close to the BFS. The pump wave is intensity-modulated into optical pulse resulting a distributed measurement. Finally, the Brillouin gain spectrum (BGS) can be measured by frequency-sweeping the probe wave and then its BFS, which has a linear relationship to the strain or temperature, can be demodulated by Lorentzian or Gaussian fitting the BGS. The maximum sampling rate of strain vibration for the BOTDA scheme can be given[3]

\[ f_{\text{sa}} = \frac{1}{(2nL/e + T_{\text{switch}}) \cdot N_{\text{ave}} \cdot N_f} \]  

where \( c \) is light speed in a vacuum, \( L \) is the FUT length, \( n \) is the refractive index of FUT, \( T_{\text{switch}} \) is the frequency switching time of the optical wave, \( N_{\text{ave}} \) is the averaging time and \( N_f \) is the frequency-sweeping number.

In practice, the sampling rate of the BOTDA for dynamic strain measurement is severely limited by the finite frequency-sweeping time, so that the BOTDA is just suitable for the static or slowly varying strain or temperature measurement. Recently, some fast BOTDA schemes are proposed to reduce the frequency switching time and frequency-sweeping number, which can be classified as frequency-agile technique, slope-assisted method, optical chirp chain technique.
2. Improvement of fast BOTDA schemes

2.1. Frequency-agile technique
To decrease the frequency-sweeping time, a fast BOTDA system has been proposed by using an electrical digital arbitrary waveform generator (AWG) [4] to generate a frequency-agile microwave signal which is connected by 100 microwave signals segments with equal frequency interval in “head-tail”. In this case, the AWG with a bandwidth higher than 11GHz close to the BFS of FUT is required, which will increase the cost of this BOTDA system.

To decrease the bandwidth requirement of AWG, we have demonstrated an improved fast BOTDA [5] based on second-order sideband of modulation as shown in Figure 1(a) and differential pulse pair. The probe wave is frequency-switched by an AWG whose bandwidth requirement is decreased by half to ~5.5 GHz based on the second-order sideband modulation (the black solid curve) in comparison to the first-order sideband modulation (the red dashed curve). A high-spatial-resolution of 20 cm is measured by employing a 52/50 ns differential pulse pair over a 50-m Panda-type PMF while a distributed vibration measurement with the vibration frequency of up to 50 Hz is demonstrated resulting a strain standard deviation of 14 με. Recently, a dual-modulation [6] of fast BOTDA is proposed, in which the frequency-agile modulation is replaced by the combination of a single-frequency modulation with a fixed high frequency of ∼10 GHz and a low bandwidth frequency-agile modulation. As a result, the bandwidth requirement for the AWG is reduced to 700 MHz in experiment.

![Figure 1](image1.png)

**Figure 1.** (a) The second-order sideband modulation (the solid curve) and the first-order sideband modulation (the dashed curve). (b) Schematic illustration of the frequency-agile based on dual-modulation.

2.2. Slope-assisted method
To achieve the real-time measurement, a slope-assisted BOTDA [4, 7] is proposed by utilizing the slope of BGS as a linear segment and choosing the frequency of the probe wave to be at the middle of the slope. As a result, the BFS change has a linear relationship with the intensity of the Brillouin signal. However, the dynamic strain range is limited by the BGS linewidth of ~30MHz.

![Figure 2](image2.png)

**Figure 2.** (a) the measured BGS (blue scatter), BPPS (magenta scatter) and KS (red scatter). (b) the sketch map of the multi-slope assisted BOTDA based on vector SBS.
To enlarge the dynamic range, we define a dimensionless coefficient $K$ as the ratio of Brillouin phase-shift to gain. Compared to the BGS (blue scatter) and Brillouin phase-shift spectrum (BPSS, magenta scatter) in figure 2(a), the K spectrum (KS, red scatter) shows a wide monotonous slope which can make full use of the SBS region.

Figure 3. (a) the measured dynamic strain over time based on FAT for BGS (black scatter) and KS (blue scatter) and multi-slope-assisted methods for KS (red line) at the frequency interval of 160MHz (b) their power spectrum.

Then, to further extend the dynamic strain range, a multi-slope assisted BOTDA [2, 8] scheme is assembled in Figure 2(b). As the pump pulse train is frequency-modulated by the FAT, several KS are located around the frequency of probe wave. These K values can be demodulated by the heterodyne detection between probe wave and reference wave (Ref) and the IQ demodulation algorithm. Then, the BFS can be calculated by using the K value which is near zero. The available dynamic range of KS can reach up to 200 MHz at the case of a 30-ns pump pulse, which is larger than fourfold of 48-MHz linewidth of BGS. As shown in Figure 3 (a), a dynamic strain measurement with wide dynamic range of 5372.9 με is demodulated by setting the frequency interval of 160MHz (red line), which is also in good agreement with the measured results based on FAT for BGS (black scatter) and KS (blue scatter). The strain vibration with frequency components of 5.58 Hz and 11.14 Hz is obtained with the sampling rate of 1 kHz. It is noted that the sampling rate has an inverse proportional relationship with the dynamic range (corresponding to the frequency-sweeping number).

2.3. Optical chirp chain technique.
To maintain the high sampling rate and the wide dynamic range, we have proposed a single-shot BOTDA scheme [9] by using the optical chirp chain (OCC) probe wave instead of traditional single-tone continuous wave. As shown in Figure 4(a), the optical probe wave is frequency-modulated into an optical chirp segment with the frequency from $\nu_1$ to $\nu_N$ and a few tens of nanosecond. Then, several optical chirp segments are connected as the OCC-probe wave. Therefore, the distributed BGS can be illustrated along the OCC probe wave by just launching single pump pulse, if the frequency difference between the pump pulse and the OCC-probe wave covers the BFS of the FUT as shown in Figure 4(b).

Figure 4. The operation principle of the OCC-BTODA. (a) Time domain relationship and (b) frequency domain relationship.
In the experiment, two wide dynamic ranges (corresponding to the frequency-changing range of 300 MHz and 400 MHz) are achieved, which is much larger than the slope of BGS, BPSS and KS. As shown in Figure 5, three different types of dynamic strain, i.e., periodic mechanical vibration in Figure 5(a), mechanical shock in Figure 5(b) and switch event in Figure 5(c), are captured with the high sampling rates of 25kHz, 2.5MHz and 6.25MHz, respectively. To the best of our knowledge, this is the first demonstration of a distributed Brillouin strain sensor with sampling rate up to the MHz range and wide dynamic range.

![Figure 5](image_url)  
**Figure 5.** The dynamic strain measurement of the OCC-BTODA. (a) Periodic mechanical vibration, (b) mechanical shock and (c) switch event.

3. Conclusions
By analysing the limitation factors of sampling rate for distributed dynamic strain measurements in fast BOTDA system, several schemes have been developed in our team. The bandwidth requirement of AWG in fast BOTDA scheme can be significantly reduced by using the second-sideband modulation or dual modulation. Then, the dynamic strain range can be effectively extended by combining the KS and multi-assisted method. Finally, ultra-fast distributed strain measurements with high sampling rate up to ~MHz and wide dynamic range are achieved by using the OCC-probe wave.

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5. References
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