Sweep-free Brillouin Optical Correlation Domain Analysis utilizing Digital Optical Frequency Comb

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Abstract: We propose and demonstrate a probe sweep-free Brillouin optical correlation domain analysis sensor based on digital optical frequency comb, where acquisitions of Brillouin gain spectrum reach 20 kSa/s at arbitrary position with 10-cm spatial resolution. © 2022 The Author(s)

1. Introduction

Distributed fiber sensors based on Brillouin-scattering have been extensively investigated in recent years, among which Brillouin optical correlation domain analysis (BOCDA) technique has stimulated substantial research interests owing to the ultra-high spatial resolution and random accessibility [1]. However, the acquisition of distributed Brillouin gain spectrum (BGS) requires two time-consuming frequency-sweeping process in a conventional BOCDA system, severely restricting the system sampling rate [2]. To speed up the measurement, 1-kSa/s sampling rate for single-position measurement is achieved by using a time-division pump-probe generation scheme, whereas the speed of position shifting is only 0.2 point/s [3]. Though a higher single-position sampling rate can be achieved by using a high-speed lock-in amplifier (LIA) combined with a short-switch-time voltage-controlled oscillator [4], the further improvement of measurement speed is limited by the working bandwidth of the used LIA. To solve this problem, a 200-kSa/s high-speed single-position measurement is demonstrated with the help of injection-locking technique and subtraction processing scheme. What's more, the frequency-sweeping time used for position movement is removed by simultaneously moving the correlation peak, realizing 1-kHz sampling rate for 200 points [5]. Nevertheless, the measurement speed limit is still constrained by the modulation frequency of the laser source due to the low-pass filter. To avoid the frequency-sweeping process of BGS reconstruction, the slope-assisted method is reported to extract the information at a fixed frequency [6]. But this method suffers from power fluctuations and a limited dynamic range, restricting its practical application.

Alternatively, the digital optical frequency comb (DOFC) technique provides an effective solution to interrogate the BGS in the frequency domain without frequency sweeping, which has been verified in the DOFC-based Brillouin optical time domain analysis [7], The sweep-free DOFC-based scheme possesses the outstanding advantages of extending the dynamic range and avoiding the measurement error induced by the power fluctuation, making it suitable for large dynamic range fast measurement.

In this paper, we propose a sweep-free BOCDA by introducing the DOFC technique to further enhance the measurement speed limit. The single-position measurement speed of the system is no longer limited by the device bandwidth and modulation frequency, but depends on the frequency resolution of the used DOFC, which implies the unprecedented potential to reach MHz-level sampling rate. In addition, an injection-locking configuration and quadratic phase coding [8] have been applied to improve the signal-to-noise ratio (SNR). Using a DOFC with 2-MHz frequency resolution and 600-MHz dynamic range, the proposed system achieves a single-position sampling rate of 20 kSa/s and a spatial resolution of 10cm over a measurement range of 36 m.

2. Operation principle

In a sinusoidal frequency-modulated BOCDA, the probe and counter-propagating pump light are sinusoidally modulated to generate stimulated Brillouin scattering interaction at specific points corresponding to narrow-band periodical correlation peaks. The modulation frequency determines the measurement range, which is inversely proportional to the spatial resolution.

The proposed sweep-free scheme is depicted in Fig.1(a). DOFC is used as probe to interrogate the BGS and locate the Brillouin frequency shift (BFS) without frequency sweeping. Containing multi-tone signals around the BFS of fiber with the same frequency spacing, a wideband DOFC probe is launched into the sensing fiber. At the correlation peak position, each tone of DOFC probe interacts with the single-frequency pump to obtain the frequency selective Brillouin amplification. Therefore, the BGS at the position can be directly obtained by detecting the output DOFC and demodulating in the frequency domain. By scanning the modulation frequency of the laser to move the correlation peak, the consecutively sampled DOFC frames are allowed to acquire the BGS distribution along the fiber. The single-position measurement time of the system is dependent on the length of DOFC frame which is inversely proportional to the frequency spacing, indicating a MHz-level sampling rate. Without sacrificing the measurement resolution, the proposed scheme is capable of improving the measurement speed significantly.

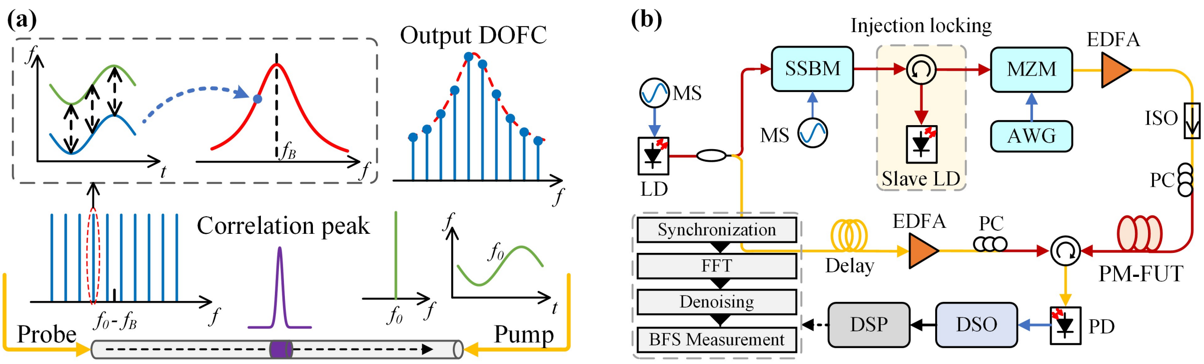

Fig. 1: (a) Principle of sweep-free BOTDA enabled by DOFC, (b) experiment setup, MS: microwave source; MZM: Mach-Zehnder; AWG: arbitrary waveform generator; ISO: optical isolator; PC: polarization controller; PD: photodetector; DSO: digital storage oscilloscope; DSP: digital signal processing.

3. Experiment setup and results

The experimental setup is represented in Fig. 1(b). A distributed feedback laser diode (DFB-LD) operating at 1550 nm with 100 kHz linewidth is modulated at a frequency through a direct current modulation. The modulation frequency and amplitude are 2.85 MHz and 3.42 GHz, respectively, corresponding to a measurement range of 36 m and nominal spatial resolution of 10 cm. The sinusoidal frequency-modulated light source is first split into two parts via a 3-dB optical coupler to serve as probe and pump signal, respectively.

At the probe side, the light is modulated by a single-sideband modulator (SSBM) driven by the 9.1-GHz down-shifted radio-frequency source to generate anti-Stokes sideband while suppressing other components. In order to improve the SNR, an injection-locking configuration is employed to purify and amplify the anti-Stokes sideband. Another DFB-LD without internal isolator is served as the slave LD. After aligning the central wavelengths of the two lasers, the SSBM output is injected into the slave LD through a polarization-maintaining circulator. As shown in Fig. 2(a), the undesired sideband is suppressed while the anti-Stokes sideband is amplified. Then the slave LD output is modulated by a Mach-Zehnder modulator to generate the dual side-band DOFC probe, which is depicted in Fig. 2(b). An arbitrary waveform generator working at 12 GSa/s generates the baseband signal which contains 200 frequency comb frames and a short sequence for synchronization. Each frame has 300 tones and 2-MHz frequency spacing, resulting in a single-position measurement time of 0.5 μs. It is worth noting that the effective dynamic range is half of the total bandwidth of probe. The first tone of the frequency comb is set to 1 GHz to eliminate the beating noise and gain crosstalk from the other useless sideband. The final measurement range of BFS is 10.1~10.7 GHz. Besides, the probe with a flat top are obtained by applying the quadratic phase coding for SNR improvement. To avoid the polarization-dependent gain fluctuation, the 20 m polarization-maintaining fiber is used as the fiber under test (FUT). After being amplified by an erbium-doped fiber amplifier (EDFA) to 13 dBm and adjusted the state of polarization to align with the principle axis, the DOFC probe is launched into the FUT.

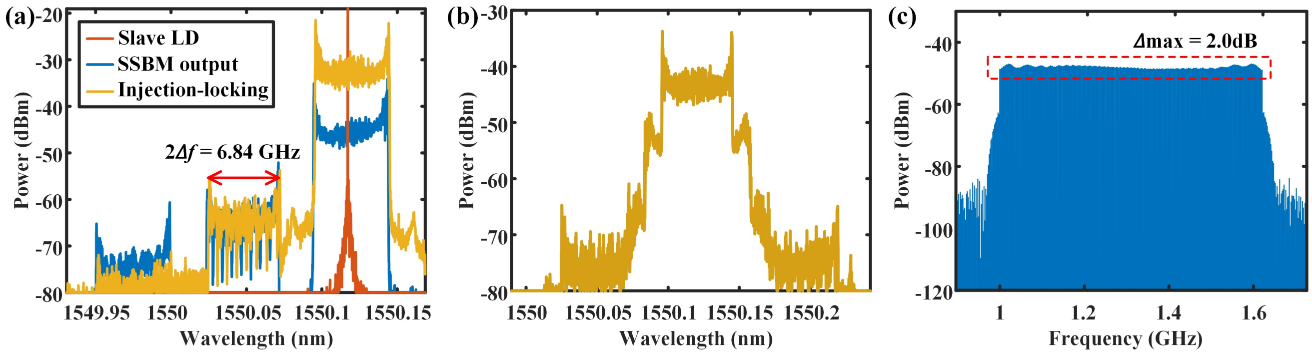

Fig. 2: Optical spectrums of (a) the injection-locking configuration output and (b) DOFC probe, (c) the power spectrum of received frequency comb frames.

At the pump side, a 300-m single-mode delay fiber is employed to control the order of the correlation peak without gain crosstalk. The pump light is amplified by a high-power EDFA to the average power of 27 dBm and aligned with the state of polarization to the principle axis. At the receiver end, the DOFC probe with the gain information of the FUT is detected by a photodetector with 1.6-GHz bandwidth. Then the output electrical signal is digitalized by an oscilloscope with a sampling rate of

20 GSa/s for further digital signal processing. Due to the poor SNR of the direct detection, the received signal is averaged by 100 times to improve the measurement accuracy. The power spectrum of received frequency comb frames is shown in Fig. 2(c), which is ultra-flat within the measurement range.

The frequency comb frames without Brillouin gain are regarded as the background noise. After synchronization and fast Fourier transform (FFT), the denoising BGS at the position is obtained with 2-MHz frequency spacing. Eventually, the single BFS measurement time for single position is 50 μs (0.5 us×100). As show in Fig. 3(a), each tone of single frame carries amplification information, replacing the frequency sweeping point by point. The measured 200 BGSs at a fixed position are obtained by the separated frames, which is shown in Fig. 3(b), corresponding to the sampling rate of 20-kSa/s. By extracting the maximum value of the measured BGS, the change of the single-point BFS can be rapidly observed.

To implement distributed measurement, the modulation frequency of the laser source is swept from 2.65 MHz to 2.88 MHz to move the correlation peak. A large strain is applied to a 10-cm section at the end of the FUT. The measured 200-point BFS distribution along the FUT with 100-Hz repetition rate is shown in Fig. 3(c), and the front small section is the measurement result of the fiber pigtail. It turns out that the stretched section can be accurately identified without affecting adjacent sections, proving that the proposed system has a spatial resolution of 10 cm.

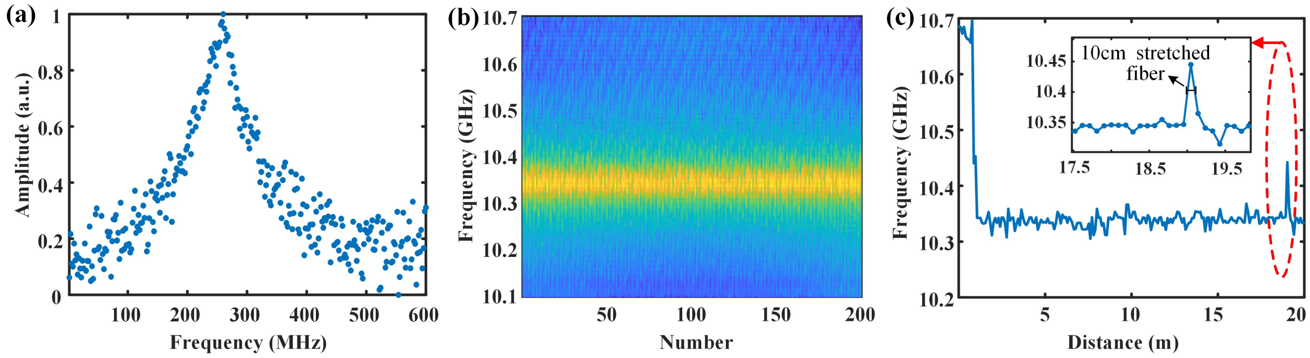

Fig. 3: (a) Original received BGS, (b) measured BGSs for single position, (c) distributed BFS extracted from the distributed BGS.

4. Conclusions

A probe sweep-free BOCDA based on DOFC is proposed and demonstrated experimentally, where the DOFC is used to interrogate the BGS in the frequency domain, thus avoiding the traditional frequency scanning process. The proposed system provides a high performance with a single-position sampling rate of 20 kSa/s and a high spatial resolution of 10 cm. The measurement speed is expected to realize MHz-level sampling rate with further SNR improvement, showing promising dynamic measurement capability in high spatial resolution applications.

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