28th International Conference on Optical Fiber Sensors @ Optica Publishing Group 2023

The following publication H. He, S. Chen, H. Du, Z. Lin, Z. Zhao, L. Wang, D. Huang, S. Fu, and M. Tang, "Sweep-free Brillouin Optical Correlation Domain Analysis Enabled by Multi-core Fiber," in 28th International Conference on Optical Fiber Sensors, Technical Digest Series (Optica Publishing Group, 2023), paper Th2.4 is available at https://dx.doi.org/10.1364/OFS.2023.Th2.4.

Sweep-free Brillouin Optical Correlation Domain Analysis Enabled by Multi-core Fiber

Huan He[1], Shuyan Chen[1], Haoze Du[1], Zhonghong Lin[1], Zhiyong Zhao[1]*, Li Wang[2], Dongmei Huang[2], Songnian Fu[3], Ming Tang[1]
[1] *Wuhan National Laboratory for Optoelectronics (WNLO), Huazhong University of Science and Technology, Wuhan 430074, China*
[2] *Photonics Research Institute, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China;*
[2] *Advanced Institute of Photonics Technology, Guangdong University of Technology, Guangzhou 510006, China*
**Corresponding author: zhiyongzhao@hust.edu.cn*

Abstract: We propose and demonstrate a probe sweep-free Brillouin optical correlation domain analysis sensor based on digital optical frequency comb and multi-core fiber, where acquisitions of Brillouin gain spectrum and Brillouin phase spectrum reach 10 kSa/s. © 2023 The Author(s)

1. Introduction

Brillouin optical correlation domain analysis (BOCDA) has garnered significant research attention in recent years due to its ultra-high spatial resolution and random-access capability. However, conventional BOCDA systems require two time-consuming frequency-scanning processes to interrogate the distributed Brillouin gain spectrum (BGS) of the fiber, which severely limits the system sampling rate [1]. To enable dynamic measurements, a time-divisional pump-probe generation scheme has been employed, allowing single-point position measurements at a sampling rate of 1 kSa/s with slow position shift rate [2]. To achieve higher single position sampling rates, a high-speed lock-in amplifier (LIA) combined with a voltage-controlled oscillator with a short-switch-time can be used [3]. However, the measurement speed is constrained by the operating bandwidth of the LIA. To overcome this limitation, a high-speed measurement of 200 kSa/s has been achieved using an injection locking technique and a subtraction processing scheme. Additionally, by simultaneously shifting the correlation peak instead of sweeping the frequency, the time required for position shifting is eliminated [4]. Nevertheless, the measurement speed is still restricted by the modulation frequency of the laser source due to the low-pass filter for demodulation. The slope-assisted method is reported to avoid frequency sweeping, which extracts information from fixed frequencies on the BGS [5]. However, this method is susceptible to power fluctuations and has a limited dynamic range, hindering its practical application.

Alternatively, digital optical frequency comb (DOFC) technique offers an effective solution for interrogating the BGS in the frequency domain without the need for frequency sweeping, making it suitable for fast measurements with a large dynamic range. DOFC-based systems have the advantages of extending the dynamic range and mitigating measurement errors caused by power fluctuations [6]. However, in high precision measurements based on optical frequency combs, an additional reference fiber path is typically required to ensure accurate demodulation, posing implementation challenges [7]. By utilizing multi-core fiber (MCF) as the sensing fiber, which possesses spatial-division multiplexed transmission capabilities, these challenges can be addressed. In a homogeneous MCF, each core maintains good uniformity, while the off-center cores exhibit high bending dependence. This specific structure of MCF enables the measurement of new parameters such as bending and shape sensing [8].

In this paper, we propose a sweep-free BOCDA system that utilizes DOFC and a 7-core homogeneous MCF. By eliminating the probe frequency-sweeping process, the DOFC enables the interrogation of both the distributed BGS and Brillouin phase shift (BPS) using simple frequency domain processing. The single-position measurement speed of the system only depends on the frequency spacing of the DOFC, indicating the unprecedented potential to achieve MHz-level sampling rates. Demodulation is performed using two cores, one with Brillouin gain and one without, within a single MCF without the need for additional fiber links. The proposed system achieves a single-position sampling rate of 10 kSa/s and a dynamic range of 600 MHz with 10-cm spatial resolution.

2. Operation principle

To generate stimulated Brillouin scattering (SBS) interaction and achieve distributed localization, the traditional sinusoidal frequency-modulated BOCDA system utilizes a sinusoidally modulated optical source as the probe, along with counter-propagating pump light. By controlling the modulation frequency, this system produces narrow-band periodic correlation peaks that enable accessing specific points along the sensing fiber randomly. The measurement range is inversely proportional to the modulation frequency, while the spatial resolution depends on both the modulation frequency and amplitude.

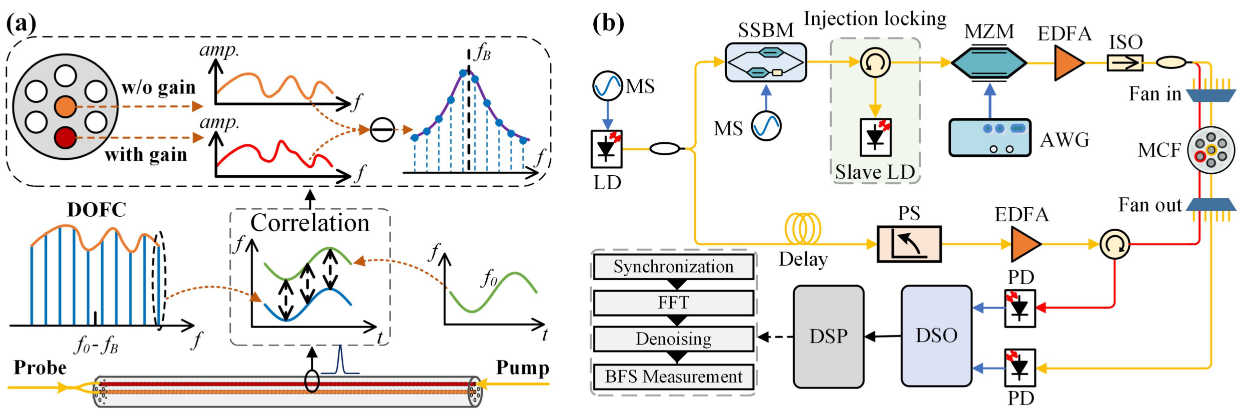

Fig. 1: (a) Principle of sweep-free BOTDA utilizing MCF, (b) experiment setup, MS: microwave source; SSBM: single-sideband modulator; MZM: Mach-Zehnder; AWG: arbitrary waveform generator; EDFA: erbium-doped fiber amplifier; ISO: optical isolator; PS: polarization scrambler; PD: photodetector; DSO: digital storage oscilloscope; DSP: digital signal processing.

In the proposed sweep-free scheme depicted in Figure 1(a), a 7-core MCF is employed for BGS extraction. Instead of using single-frequency light, a wideband DOFC probe is used to interact with the pump light in one of the outer cores, enabling the sweep-free process. At the correlation peak position, each tone of the DOFC probe interacts with the single-frequency pump, resulting in frequency-selective Brillouin amplification. The DOFC probe contains multiple-tone signals around the Brillouin frequency shift (BFS) of the fiber, allowing interrogation of the BGS without the need for frequency sweeping. Therefore, the BFS at a specific position can be located by detecting the output DOFC and demodulating it in the frequency domain. Furthermore, the DOFC provides an effective solution for simultaneous measurement of the BGS and BPS, which is crucial for accurate BFS extraction in BOCDA systems. To obtain the distribution of the BGS along the fiber, consecutive sampled DOFC frames carry gain information for different sensing positions by scanning the modulation frequency to move the correlation peak. The length of the DOFC frame is inversely proportional to the frequency spacing, determining the single-position measurement time of the system. With a typical MHz-level frequency spacing, a MHz-level sampling rate can be achieved, significantly improving the measurement speed without compromising the resolution.

It is important to note that demodulation in the frequency domain requires a reference signal without Brillouin gain as background noise. However, due to the instability of signal modulation and device frequency response, the amplitude jitter of each comb tone can directly affect the gain information as additional noise, greatly impacting the sensing accuracy of the system. Unfortunately, unlike time-domain sensing systems, the BOCDA system cannot easily eliminate dynamic background noise through time-domain modulation of the pump light. To improve the signal-to-noise ratio (SNR), an additional fiber link is introduced as a reference to suppress measurement errors. Thus, a portion of the DOFC probe is launched into the central core to remain unaffected, serving as a reference for denoising. The correct BGS is then calculated by analyzing the gain information from the two probes. Additionally, using two cores helps mitigate power fluctuations caused by fiber loss and frequency modulation of the laser source. It is important to mention that while the proposed working principle is illustrated using a 7-core MCF, the analysis described is also applicable to MCFs with any number of cores.

3. Experimental setup

The experimental setup is depicted in Figure 1(b). A distributed feedback laser diode (DFB-LD) operating at 1550 nm with a 100 kHz linewidth is modulated at a sinusoidal frequency using direct current modulation. The modulation frequency and amplitude are set to 2.9 MHz and 3.46 GHz, respectively, corresponding to a measurement range of 36 m and a nominal spatial resolution of 10 cm. The sinusoidally modulated light source is divided into two paths using a 3-dB optical coupler to serve as the probe and pump signal.

On the probe side, the light passes through a single-sideband modulator (SSBM) driven by an 11.9 GHz down-shifted radio-frequency signal to generate the lower sideband while suppressing other components. To eliminate undesired parasitic intensity modulation caused by the sinusoidal driven current of the LD, an injection-locking technique is employed to maintain high stability of the optical power and purify the useful sideband. Another DFB-LD without internal isolator acts as the slave LD, and the output of the SSBM is injected into the slave LD. By aligning the central wavelengths of the lower sideband and the slave LD, the undesired intensity fluctuation is greatly reduced. Figure 2(a) illustrates the suppression of the undesired sideband and the amplification of the lower sideband. The dual sideband DOFC probe is generated using a Mach-Zehnder modulator driven by an arbitrary waveform generator (AWG) operating at 10 GSa/s, as shown in Figure 2(b). Since separating the two sidebands is challenging in the experiment, the effective dynamic range of the system is determined by one of the sidebands. The DOFC probe consists of 200 frequency comb frames and a short sequence for synchronization. Each frame contains 300 tones with a frequency spacing of 2 MHz, resulting in a single-position measurement time of 0.5 μs. To eliminate beating noise and gain crosstalk from unwanted components, the first tone of each frame is set to 1 GHz. The final measurement range of the BFS is 10.3~10.9 GHz using the upper sideband. Additionally, baseband probes with improved peak-to-average power ratio are obtained by applying quadratic phase coding for enhanced SNR. After amplification by an erbium-doped fiber amplifier (EDFA) to 14.5 dBm, the DOFC probe is split into two parts and launched into the central core and one of the outer cores of a 24-m 7-core MCF using a fan-in coupler.

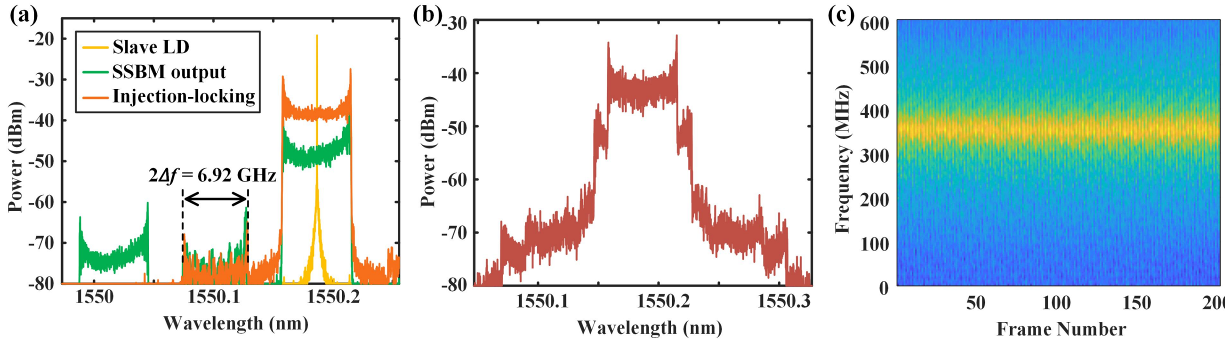

Fig. 2: Optical spectrums of (a) the injection-locking configuration output and (b) DOFC probe, (c) original received BGS for single position.

On the pump side, a 200-m single-mode delay fiber is employed to control the order of the correlation peak without Brillouin gain crosstalk. To mitigate polarization-dependent gain fluctuations, a polarization scrambler rapidly traverses the polarization state. The pump light is then amplified by a high-power EDFA to an average power of 27 dBm. The pump light is launched into the outer core in the opposite direction using a fan-out coupler.

At the receiver end, two paths of DOFC probes, one with and one without the gain information of the fiber under test (FUT), are detected by a photodetector with a bandwidth of 1.6 GHz. The two output electrical signals are digitized by an oscilloscope with a sampling rate of 20 GSa/s for further digital signal processing. To ensure a high SNR, the received frequency comb frames are averaged 200 times to improve the measurement accuracy.

4. Experimental results

After performing synchronization and fast Fourier transform (FFT), the frequency domain analysis yields the amplitude and phase spectrums of 200 individual frequency comb frames with 2-MHz frequency spacing. Fig. 2(c) illustrates the received 200 BGSs at a fixed position, using the frequency comb frames without Brillouin gain from the central core as the background noise. Additionally, Fig. 3(a) displays the simultaneous acquisition of the 200 BPSs. It is worth noting that each tone within a single frame carries amplification information, effectively replacing the conventional point-by-point frequency sweeping technique. The consistency between the BGS and BPS measurements of a specific frequency comb frame is depicted in Fig. 3(b) and Fig. 3(c). By extracting the BFS from either the BGS or BPS measurements, rapid single-point sensing becomes achievable. The measurement time for a single BFS at a specific position amounts to 100 μs (0.5 μs×200), corresponding to a sampling rate of 10-kSa/s.

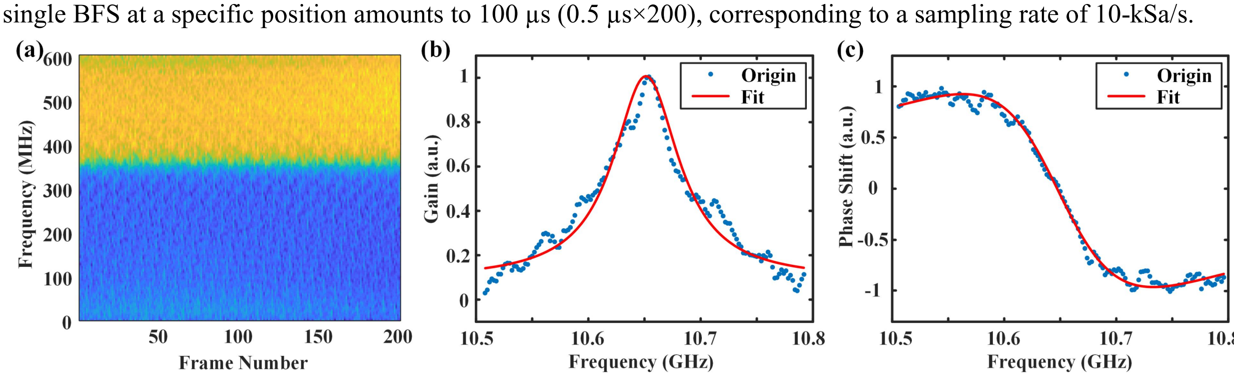

Fig. 3: (a) Original received BPS for single position, Original and fitting (b) BGS and (c) BPS of one frequency comb frame.

To assess the uncertainty of the measured BFS, the standard deviation of the 200 BFSs extracted from the measured BGSs is calculated. To validate the effectiveness of the reference path, Fig. 4(a) presents the BFS uncertainty resulting from 200 experimental measurements conducted under the same environmental conditions. These results indicate that employing the central-core reference path successfully mitigates real-time fluctuations in the background noise, surpassing the use of previous frames without Brillouin gain as a reference.

To enable distributed measurement, the modulation frequency of LD is swept from 2.56 MHz to 3.41 MHz to shift the correlation peak. In order to assess the spatial resolution, a significant strain is applied to the 10-cm section located at the end of the MCF. The resulting distribution of BFS measurements along the FUT, obtained by extracting information from the BGS, is depicted in Fig. 4(b). The small sections at the front and end represent the measurement results of the fan-in/out couplers. Notably, the stretched section is accurately identified without any impact on the adjacent sections, thereby validating the proposed system's spatial resolution of 10 cm.

As a proof of concept, a strain measurement is carried out to validate the performance of the system. Without the unwanted strain generated by twisting the fiber, a 10-cm-long section is stretched by a displacement platform to gradually increase the strain. The measured BFS change with strain variation is represented in Fig. 4(c). The measurement results exhibit good linearity of the system response to strain with strain coefficient of 20.81 με/MHz.

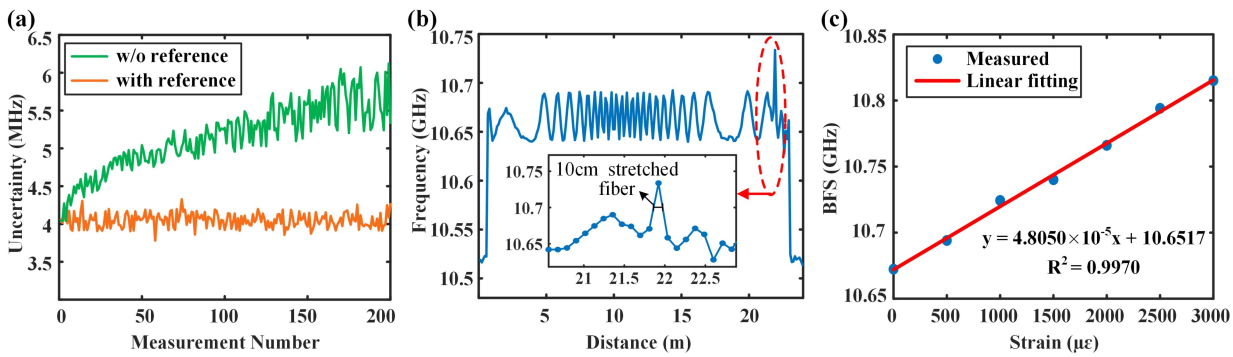

Fig. 4: (a) BFS uncertainty using BGS, (b) distributed BFS extracted from the distributed BGS, (c) strain measurement results.

5. Conclusions

A probe sweep-free BOCDA based on MCF is proposed and demonstrated experimentally. Utilizing DOFC as probe to interrogate the BGS in the frequency domain, the sweep-free scheme avoids traditional frequency scanning process and take the ability to measure BPS. The implementation of 7-core MCF provides extra reference path, thereby mitigating the fluctuation of background noise over time. The proposed system provides a high performance with a single-position sampling rate of 10 kSa/s and a high spatial resolution of 10 cm. With further improvements SNR, the measurement speed is expected to achieve MHz-level sampling rates, showing highly promising for future applications in ultrafast high-resolution distributed bending and shape sensing.

Acknowledgements

National Key Research and Development Program of China (2021YFB2800902); National Natural Science Foundation of China (61931010, 62105111).

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