Suppression of systematic error in BOCDR with injection-locked light source

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Introduction

Over recent decades, the demand of health monitoring of infrastructures susceptible to damages from earthquakes, aging, etc., has led to a significant increase in research on optical fiber sensors, which are used to measure the distribution of strain and/or temperature along the fiber attached to the structure under test. Brillouin scattering in optical fibers has been a major tool for developing these sensors. Brillouin-based distributed correlation-domain sensors can be divided into two categories: two-end-access Brillouin optical correlation-domain analysis (BOCDA) [1] and single-end-access Brillouin optical correlation-domain reflectometry (BOCDR) [2]. In addition to the common merits of fiber sensors, such as no need for power sources at sensing parts, resistance to electromagnetic interference, and continuous and long-term operation, these sensors also offer unique merits of relatively high spatial resolution and random accessibility to sensing points.

In 2018, Song et al [3] reported a phenomenon in which the frequency modulation (FM) is delayed from the amplitude modulation (AM) by a phase difference $\Delta\varphi$ in the output of the directly modulated laser, resulting in degraded measurement accuracy in BOCDA and BOCDR. When the AM-FM phase difference is equal to ±90°, errors of up to tens of megahertz can occur, which are systematic and cannot be suppressed by data averaging; while such errors do not occur when $\Delta\varphi$ is 0° or ±180°. To date, a new method using injection locking has been developed to compensate such errors in BOCDA [4]. However, the injection-locking method has not been applied to BOCDR, though another approach has been developed to mitigate these errors [5].

In this work, we demonstrate that the injection-locking method can be effectively used in BOCDR to mitigate the systematic errors caused by the AM-FM phase difference.

Principles

The experimental setup of BOCDR is depicted in Fig. 1. The optical output from a laser diode (LD) is divided into pump and reference light beams. The pump light is injected into a fiber under test (FUT), and the Stokes light is directed into a photodetector. The reference light acts as an optical local oscillator. The electrical beat signal of the two light beams is monitored using an electrical spectrum analyzer (ESA). To resolve the sensing position along the FUT, the frequency of the LD output is modulated in a sinusoidal waveform. We control the modulation frequency to generate only a single correlation peak (i.e. sensing position) within the range of the FUT. In a simple model, the peak frequency observed in the ESA gives the Brillouin frequency shift (BFS) at the correlation peak, which represents the local strain/temperature information. By sweeping the modulation frequency, the position of the correlation peak is scanned along the FUT, allowing the BFS distribution to be obtained.

In standard BOCDR, an LD that is directly modulated by controlling its driving current serves as the light source. However, the direct modulation scheme suffers from systematic errors caused by inevitably induced AM-FM phase difference. Herein, we propose an injection-locked configuration of BOCDR, which modifies the light source in standard BOCDR to suppress these errors. The experimental setup of the injection-locked light source is shown in Fig. 2. A small amount of optical power from a directly modulated master LD is injected to a slave LD through a variable attenuator. The slave LD is a specially manufactured device without an internal isolator, allowing for a high level of injection power. The output of the slave LD replicates the spectrum of the master LD and is then directed to the BOCDR system. Thus, this scheme eliminates the systematic errors by replicating the FM of the master LD while suppressing the AM inevitably induced by direct modulation.

Experiments

We experimentally demonstrate the effectiveness of the injection-locking BOCDR by comparing its performance in distributed measurement with that of the standard BOCDR. First, we implemented the standard BOCDR using the output of the directly

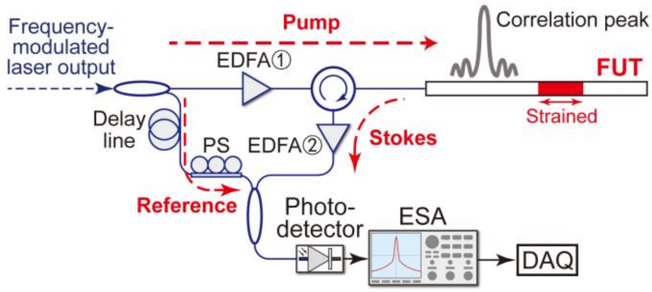

Fig. 1 Experimental setup of BOCDR. DAQ: data acquisition, EDFA: erbium-doped fiber amplifier, ESA: electrical spectrum analyzer, FUT: fiber under test, PS: polarization scrambler.

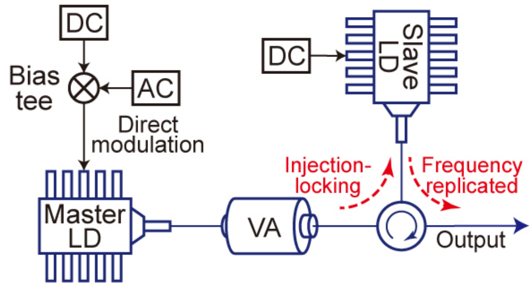

Fig. 2 Implementation of the injection-locked light source under frequency modulation. AC: alternating current, DC: direct current, LD: laser diode, VA, variable attenuator.

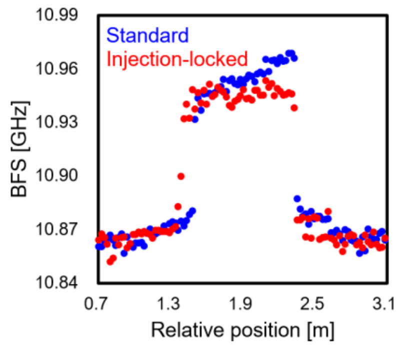

Fig. 3 BFS distributions measured with standard and injection-locked BOCDR configurations.

modulated master LD in Fig. 2 as the light source and performed distributed sensing. The modulation amplitude was 2.86 GHz, and the modulation frequency was swept from 4.95 kHz to 5.03 kHz to perform distributed sensing along a 3.5-m-long FUT. The length of the strained section was 89.6 cm, and strain was applied to cause a target BFS difference of 80 MHz. Subsequently, we used the master LD output, attenuated by 20 dB, as the locking signal and the slave LD output as the light source to implement injection-locking BOCDR. Distributed sensing was performed under the same conditions. The results obtained with the standard and injection-locking BOCDR are shown in Fig. 3. The asymmetric distortion that appeared in the BFS distribution measured by the standard BOCDR conforms to the features of the error caused by the AM-FM phase difference reported in [3,5] and results in a deviation of up to 25 MHz from the target BFS difference. In contrast, the injection-locked light source effectively mitigates such distortion, demonstrating the ability of the injection-locking method to improve the performance of BOCDR.

References

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