Measurement error compensation in BOCDR by two-end light injection

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Introduction

For structural health monitoring, distributed strain and temperature sensing techniques based on Brillouin scattering in optical fibers have been extensively studied for the past several decades. Among various schemes, correlation-domain techniques are known to have such advantages as high spatial resolution, high-speed operation, and random accessibility to measuring points. They are classified into two configurations: Brillouin optical correlation-domain reflectometry (BOCDR) [1] and Brillouin optical correlation-domain analysis (BOCDA) [2]. BOCDR operates by light injection to a single end of a fiber under test (FUT), whereas BOCDA requires light injection to both ends of an FUT.

In BOCDR/A, the optical frequency of the laser output is modulated to generate a so-called correlation peak (i.e., sensing position) in the FUT. By scanning the position of the correlation peak along the FUT, Brillouin gain spectrum (BGS) or Brillouin frequency shift (BFS) can be measured in a distributed manner. In most of the BOCDR/A systems, to achieve frequency modulation (FM), the laser driving current is directly modulated. This method is simple and low in cost but suffers from inevitable amplitude modulation (AM). In 2018, Song et al [3] clarified that there exists a phase delay $\Delta\varphi$ between AM and FM in the output of the modulated laser. The AM-FM phase delay has been reported to sometimes cause an error of tens of MHz in BOCDA, which is systematic and cannot be suppressed by data averaging [3]. To date, a new method using injection locking has been developed to compensate such error in BOCDA [4]. However, no trial has been given to mitigate this error in BOCDR.

In this work, to suppress the systematic error caused by the AM-FM phase delay in BOCDR, we propose a new configuration called two-end light injection. Although BOCDR operates by light injection to a single end of the FUT, in this configuration, we intentionally inject light also to the other end, perform the same distributed measurement in both directions, and combine the obtained results to mitigate the error. Here, we reveal the effect of the two-end light injection by simulation. First, considering $\Delta\varphi$, we simulate the measured BGS/BFS distributions in a standard single-end-access BOCDR system and confirm that the results inevitably involve considerable error. Subsequently, we simulate the measured BGS/BFS distributions in BOCDR with two-end light injection and show that the error caused by $\Delta\varphi$ can be significantly suppressed. Finally, the error compensation effect in this configuration when the strain is applied near the fiber end is discussed.

Principle, Setup, and Conditions

The "measured BGS distribution" in BOCDR can be simulated using the fact that it is given by the square of the 2-dimensional convolution of the "beat spectrum" and the "intrinsic BGS distribution"; refer to [1] for details. When $\Delta\varphi$ ($\neq$0°/±180°) is employed, the shape of the beat spectrum is distorted and becomes asymmetric, thus leading to some error in the BGS/BFS measurement. To compensate such asymmetry, we propose a new BOCDR configuration with two-end light injection.

The conceptual setup of the system is shown in Fig. 1, where light is injected into each end of the FUT in turn, controlled by an optical switch. Thus, we can expect the error to be suppressed by averaging the data collected from each end of the FUT.

An imaginary strain was applied to a certain area of the FUT, the length z of which was expressed using a length unit R, which stands for the nominal spatial resolution (~0.97 m). The AM employed was set to 9 dB, defined as the ratio of the maximum power to minimum. The $\Delta\varphi$ was set to 90° (worst case), and z was set to 2R. The strain amplitude was set to cause a target BFS change ν_T of 50 MHz.

Results

The measured and intrinsic BFS distributions in standard BOCDR and two-end light injection BOCDR are shown in Figs. 2(a),(b), respectively. The error caused by $\Delta\varphi$ was clearly compensated by two-end light injection. To give a quantitative comparison, we defined an error evaluation parameter Δh as the value of $\Delta\nu$-ν_T shown in Fig. 2(a), aiming to show the dispersion of the measured BFS.

As shown in Figs. 3(a),(b), the average values of the measured BFS within the strained area using both configurations generally remained close to each other and floated around the target BFS of 10.90 GHz, while the remarkable difference in Δh between the two showed that the two-end light injection can effectively compensate the BFS dispersion caused by $\Delta\varphi$ in BOCDR. However, when the strain was applied near the fiber end (Figs. 4(a),(b)), although the two-end injection BOCDR was still able to suppress the BFS dispersion, the average measured BFS became ~25 MHz lower than the target, leading to considerable inaccuracy. This error may be compensated by some advanced signal processing, but further study is required on this point.

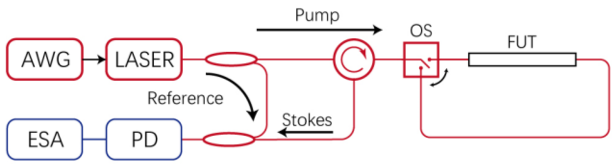

Fig. 1 Conceptual setup of BOCDR with two-end light injection. AWG: arbitrary waveform generator, ESA: electrical spectrum analyzer, FUT: fiber under test, OS: optical switch, PD: photo diode.

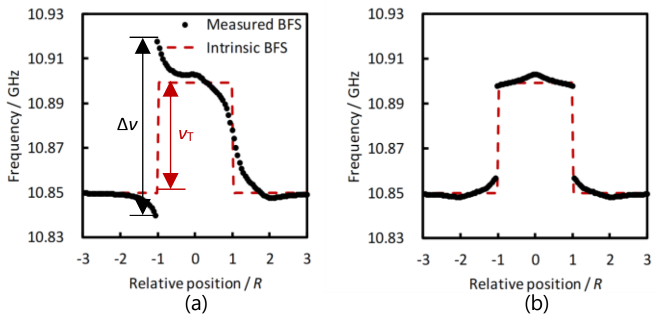

Fig. 2 Measured and intrinsic BFS distributions in (a) standard BOCDR and (b) two-end light injection BOCDR.

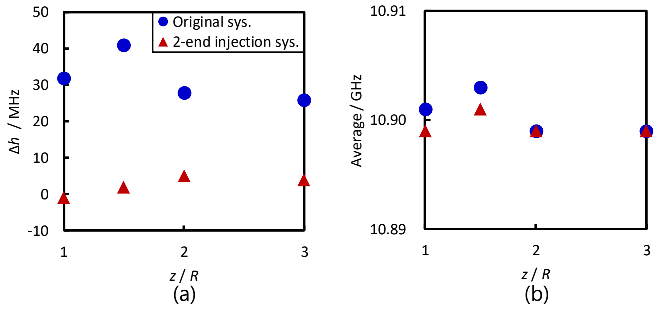

Fig. 3 Error evaluation parameters *vs.* strained length. (a) Δh and (b) average value of the measured BFS within the strained area.

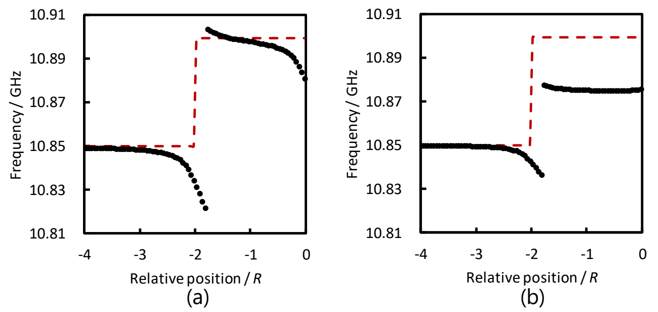

Fig. 4 Measured and intrinsic BFS distributions in (a) standard BOCDR and (b) two-end injection BOCDR. Strain was applied near the fiber end.

References

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