# Low-cost Brillouin optical correlation-domain reflectometry involving merely one fibre amplifier

Y. Mizuno✉, G. Han, K. Noda, H. Lee and K. Nakamura

Brillouin optical correlation-domain reflectometry (BOCDR) is one of the fibre-optic distributed strain and temperature sensing systems. Conventionally, BOCDR has been implemented using three erbium-doped fibre amplifiers (EDFAs) to enhance the signal-to-noise ratio (SNR) of the measurement. However, the use of multiple EDFAs has restricted the size and cost efficiency of the system. In this work, the authors show that, among the three EDFAs previously employed, the one in the Stokes path plays the most important role in enhancing the SNR. Subsequently, they implement BOCDR using only one EDFA and demonstrate distributed strain sensing. The measurement error is also investigated as a function of the output power of a light source.

*Introduction:* Brillouin scattering in optical fibres has been extensively studied and exploited to develop distributed strain and temperature sensors [1]. A number of configurations including time-, frequency-, and correlation-domain reflectometry (or analysis) have been reported thus far [2–7]. Here we focus on Brillouin optical correlation-domain reflectometry (BOCDR), which is the only technique that can simultaneously achieve operation by single-end light injection, random accessibility to sensing positions, high spatial resolution, and cost efficiency [6, 8]. Unlike two-end-access analysis based on stimulated Brillouin scattering, BOCDR is based on relatively weak spontaneous Brillouin scattering, resulting in a lower signal-to-noise ratio (SNR). To improve the SNR, conventional setups of BOCDR involved multiple – typically three – erbium-doped fibre amplifiers (EDFAs) in the reference path, pump path, and Stokes path (defined in the next section); in addition, in most cases, the EDFA inserted in the pump path was designed for high-power use (>20 dBm) [6, 8–12]. However, the employment of multiple EDFAs including a high-power type has limited the size and the cost efficiency of the whole system. Thus, it is crucial for practical applications to reduce the number of EDFAs used in the BOCDR setup.

In this work, first, we experimentally clarify that, of all the three EDFAs conventionally used in the BOCDR, the EDFA in the Stokes path plays the most important part in increasing the SNR of the system. Then, we implement the BOCDR setup excluding the other two EDFAs and prove that distributed strain sensing can be performed even by use of a single EDFA if the output power of the light source is sufficiently high. The measurement error is also evaluated.

*Principle:* Brillouin sensing generally exploits the dependence of the Brillouin frequency shift (BFS) on strain and temperature. BOCDR is one of the distributed Brillouin sensors and operates based on the synthesis of optical coherence functions. By sinusoidally modulating the output frequency of the light source, what is called a correlation peak (i.e. sensing position) is generated in a fibre under test (FUT) [6, 8]. As the location of the correlation peak can be arbitrarily set in the FUT by adjusting the modulation frequency $f_m$, distributed sensing is feasible by sweeping $f_m$. The measurement range is simply determined by $f_m$ as the interval of neighbouring correlation peaks. In contrast, the nominal spatial resolution is determined not only by $f_m$ but also by the modulation amplitude $\Delta f$ [6, 8].

A typical setup of standard BOCDR is depicted in Fig. 1. The laser output is divided into two; one is pump light injected into an FUT, and the other is reference light. The Brillouin-scattered Stokes light is heterodyned with the reference light, and their optical beat signal is converted into an electrical signal using a photodiode and observed using an electrical spectrum analyser (ESA). A delay line is inserted in the reference path to control the order of the correlation peak; it is difficult to use the 0th correlation peak to perform distributed measurement [6, 8]. What is notable here is that, in this conventional setup, three EDFAs (referred to as EDFA-ref, EDFA-pump, and EDFA-Stk) are inserted in the reference, pump, and Stokes paths, respectively, to enhance the SNR of the measurement. However, the number of EDFAs should be minimised from the viewpoint of the system size and cost efficiency. To date, no reports have been provided regarding the performance of distributed measurement when some (or all) of these EDFAs are removed.

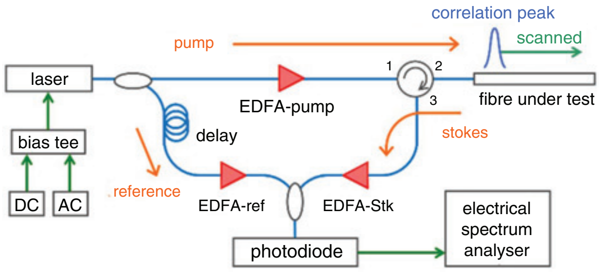


**Fig. 1** *Schematic setup of conventional BOCDR involving three EDFAs. AC, alternating current; DC, direct current*

*Setup:* The first experiment for showing that the EDFA-Stk is the most important of the three EDFAs was performed using the almost the same setup as Fig. 1, except for the following two points. One is that some (or all) of the EDFAs were removed from the setup. The other difference is that the relative polarisation state was scrambled by inserting a polarisation scrambler (PSCR) in the pump path right after an optical coupler to suppress the polarisation-dependent signal fluctuations and to evaluate the observed Brillouin gain spectra (BGSs) fairly. A 1.0-m-long silica single-mode fibre (SMF) was used as the FUT, and the Brillouin signal returned from the whole length of the FUT was observed (i.e. the driving current of the laser was not modulated). The output power of the laser at 1552 nm was 8 dBm. The video bandwidth and the resolution bandwidth of the ESA were 100 kHz and 10 MHz, respectively. Spectral averaging was performed 15 times. The room temperature was 27°C.

The second experiment for demonstrating distributed strain sensing using the EDFA-Stk only was also performed using an almost identical setup as that of the first experiment. One difference is that a polarisation controller was used instead of the PSCR to reduce the system cost. The output power of the EDFA-Stk was 0 dBm. The structure of the FUT is shown in Fig. 2. Strain was applied to a 0.5-m-long section of a 3.9-m-long silica SMF. A bending was applied near the open end of the FUT to suppress the Fresnel reflection. The modulation amplitude $\Delta f$ was ~3.0 GHz, and the modulation frequency $f_m$ was swept from 1.051 to 1.059 MHz. These modulation conditions corresponded to the measurement range of ~97 m and the spatial resolution of ~0.4 m. This resolution is higher than a typical resolution of standard Brillouin optical time-domain reflectometry (~1 m) [3, 13]. The time required to obtain one distributed BFS trace was ~10 s. The other conditions were the same as those of the first experiment.

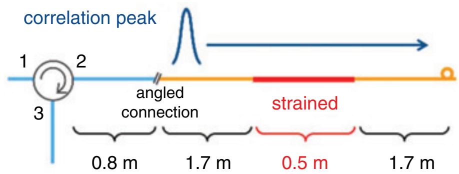


**Fig. 2** *Structure of FUT for distributed measurement*

*Experimental results:* When no EDFAs were employed in the setup, the Brillouin signal returned from the whole length of the 1.0-m-long FUT was not observed. In the same manner, when only the EDFA-ref was used, the Brillouin signal was not observed, either. In contrast, when either the EDFA-pump or the EDFA-Stk was employed, the BGSs were clearly observed as shown in Figs. 3*a* and *b*, respectively. In both cases, as the output power of the EDFA increased, the peak power of the BGS increased. However, the output power of the EDFA-Stk required to obtain the same BGS peak power was >20 dB lower than that of the EDFA-ref. This result indicates that the EDFA-Stk plays the most important role in improving the SNR of the Brillouin measurement and that, if we desire to construct a setup involving merely one EDFA, the most efficient way is to use the EDFA-Stk.

Subsequently, distributed strain sensing was performed using the setup involving only the EDFA-Stk while the output power of the laser was varied. Fig. 4*a* shows the BFS distributions measured when the laser power was 6, 12, and 18 dBm. A 0.25% strain was applied. At 12 and 18 dBm, the BFS along the strained section was upshifted for ∼110 MHz (corresponding well to the 0.25% strain), but the measurement failed at 6 dBm. To evaluate this more quantitatively, the measurement error (defined as the standard deviation of each BFS distribution from its theoretical trend) was calculated and plotted as a function of the laser power (Fig. 4*b*). With increasing laser power, the error initially decreased and then became almost constant. Suppose the measurement error threshold is, for instance, ∼50 MHz (corresponding to ∼0.1%; this requirement differs depending on applications), this results suggests that the laser power of ∼10 dBm or higher is desirable in this experiment. Note that this measurement error can be improved by increasing the number of averaging at the cost of the measurement time.

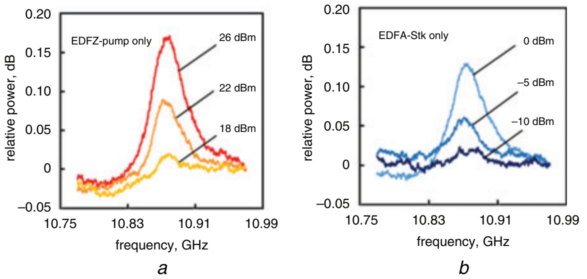


**Fig. 3** *Dependence of the measured BGSs on the output power of the EDFAs*

*a* When only the EDFA-pump was used
*b* When only the EDFA-Stk was used

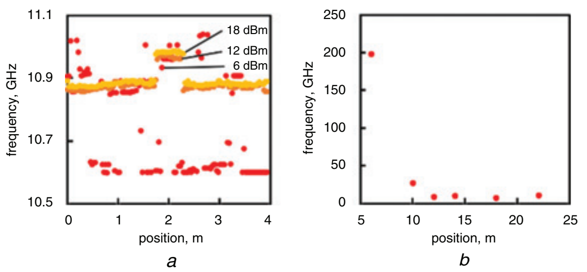


**Fig. 4** *Results of distributed strain measurement (1)*

*a* BFS distributions measured at three different output powers of the laser
*b* Measurement error plotted as a function of the laser output power

Finally, at the laser power of 12 dBm, we measured the BFS distributions when applied strain increased (Fig. 5*a*). The upshift of the BFS at the strained section became larger with increasing strain. Fig. 5*b* shows the BFS (averaged along a 0.3-m-long section around the midpoint of the strained section) plotted as a function of strain. The dependence was almost linear with a coefficient of ∼436 MHz/%, which moderately agreed with the previously reported coefficient [14]. Thus, distributed strain sensing was demonstrated using a low-cost setup of BOCDR involving a single EDFA in the Stokes path.

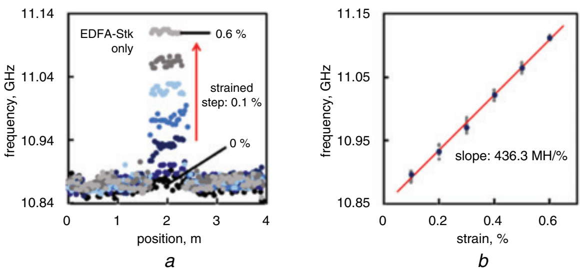


**Fig. 5** *Results of distributed strain measurement (2)*

*a* BFS distributions measured when different strains were applied
*b* BFS versus applied strain. The grey plots are raw data along the strained section, the blue circles are their averages, and the red line is a linear fit

*Conclusion:* We experimentally proved that, of all the three EDFAs used in the conventional BOCDR setup, the EDFA in the Stokes path plays the most important part in increasing the SNR. We then implemented the setup involving a single EDFA in the Stokes path and demonstrated distributed strain measurement with a spatial resolution of 0.4 m. The measurement error was also evaluated with varying the output power of the laser, and the laser power of >10 dBm was shown to be required in this experiment if the error of <0.1% is to be obtained. Note that this power can be obtained without difficulty using inexpensive commercially available lasers. As the reduction in the number of the EDFAs involved in the setup is beneficial from the viewpoints of cost and size, we believe that this study will be a useful contribution to the development of cost-effective/compact BOCDR configurations in the near future.

*Acknowledgments:* This work was supported by JSPS KAKENHI grant numbers 17H04930 and 17J07226.


Submitted: *14 February 2019* E-first: *21 May 2019*
doi: 10.1049/el.2019.0572
One or more of the Figures in this Letter are available in colour online.

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