# Distributed temperature sensing based on slope-assisted Brillouin optical correlation-domain reflectometry with over 10 km measurement range

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The authors demonstrate distributed temperature sensing based on slope-assisted Brillouin optical correlation-domain reflectometry (BOCDR) with a long measurement range of >10 km. They find that to achieve such a long-range measurement, a delay line in a reference path needs to be at least four times longer than the sensing fibre. In addition, they show that the use of such a long delay line induces forward-propagating Brillouin-scattered light in the reference path, which deteriorates the signal-to-noise ratio (SNR) of the system and should be suppressed. Finally, by exploiting a beyond-nominal-resolution effect of the slope-assisted BOCDR, they detect a 3-m-long heated section in a 13-km-long silica fibre in a distributed manner; the reason for its low SNR is also discussed.

*Introduction:* Brillouin scattering in optical fibres has been widely used to develop strain and temperature sensors because of its distributed measurement capability. Several spatially resolving techniques – time-, frequency-, and correlation-domain techniques – have been implemented [1–6]. Among them, Brillouin optical correlation-domain reflectometry (BOCDR) is the only technique that has unique advantages such as single-end accessibility, random accessibility, high-spatial resolution, and cost efficiency [5, 7]. One of the general disadvantages of BOCDR is, however, its long measurement time caused by frequency sweeping for the acquisition of Brillouin gain spectra (BGSs). This shortcoming has now been mitigated by two types of frequency-sweeping-free configurations: phase-detected BOCDR [8] and slope-assisted BOCDR [9]; we focus on the latter configuration in this study.

Slope-assisted BOCDR has been proved to have unique features [10–12]; one of them is its beyond-nominal-resolution effect, with which a strained or heated section with a length shorter than nominal spatial resolution can be detected [10, 12]. For instance, a 2-mm-long strained section of a 2-m-long silica fibre was successfully detected when the nominal spatial resolution was 0.11 m [12]. Meanwhile, almost all the previously reported demonstrations of BOCDR had measurement ranges shorter than ~1.5 km [13] (only one exception is referred to in the conclusion). If we exploit the beyond-nominal-resolution effect, it may be feasible to detect a metre-order-long strained/heated section along a long fibre under test (FUT) even without the use of special configurations for extending measurement range, such as temporal gating [13] and double modulation schemes [14].

In this work, the operation of slope-assisted BOCDR with a long measurement range of >10 km is demonstrated. First, we show that a delay line in a reference path should be at least four times longer than the sensing fibre to achieve such a long measurement range. We also show that the use of such a long delay line inevitably accompanies forward-propagating Brillouin-scattered light in the reference path, which leads to a deteriorated signal-to-noise ratio (SNR) and thus should be filtered out. Then, based on the beyond-nominal-resolution effect, we demonstrate the detection of a 3-m-long heated section in a 13-km-long FUT. We also discuss the reason for the low SNR of the long-range measurement.

*Principle:* BOCDR resolves to sense positions using a correlation peak generated in a FUT by sinusoidally modulating the frequency of the laser output [5, 7]. By sweeping the modulation frequency, the location of the correlation peak can be scanned along the FUT for distributed measurement. The nominal spatial resolution and measurement range are determined by the modulation frequency and amplitude [5, 7]. In standard BOCDR, the information on strain and temperature at a certain sensing position is determined from a peak frequency (i.e. Brillouin frequency shift (BFS)) after the acquisition of the whole BGS, which requires relatively long measurement time. In contrast, in slope-assisted BOCDR [9–12], the information on strain etc. is derived not from the BFS itself but from the spectral power at a constant frequency on the BGS slope, enabling high-speed measurement. The final output of the system is a power-change distribution along a FUT, which is not completely identical to the BFS distribution [9]. By making the most of this discrepancy, a strained/heated section which is much shorter than the nominal spatial resolution can be detected (beyond-nominal resolution effect) [10, 12].

*Setup:* The experimental setup of slope-assisted BOCDR with a long measurement range is depicted in Fig. 1*a*. The output from a frequency-modulated laser (linewidth: ~1 MHz) was divided into pump light and reference light. The pump light was amplified to 10 dBm using an erbium-doped fibre amplifier (EDFA) and injected into a 13-km-long FUT (see below for details). The polarisation state was scrambled. Here, it is notable that the incident power should not be too high, because the Brillouin threshold power of a long FUT is generally low and, even when the frequency is modulated, most of the high-power incident light does not reach the end of the FUT by stimulated Brillouin scattering [15]. What is also unique to long-range measurement is the structure of the reference path; unlike in standard BOCDR, a long delay line and an optical narrowband-pass filter (3-dB bandwidth: ~10 GHz) were employed. One of the new findings is that the length of the delay line should be at least four times longer than the FUT. In this experiment, a 60-km-long delay line was employed; otherwise, the first-order correlation peak cannot be scanned along the entire length of the FUT (the use of a higher-order correlation peak requires an even longer delay line, which is not ideal considering its cost and propagation loss). Another finding is that, when the delay line is extremely long, in addition to the carrier at laser frequency, forward-propagating Brillouin-scattered light, both Stokes and anti-Stokes, is induced and appears as sidebands in the optical spectrum. This results from the back reflection of spontaneous Brillouin scattered components etc. These unintended Brillouin components in the reference path cause considerable noise in the final system output if they interfere with the Rayleigh-scattered light from the FUT. Therefore, the optical filter was newly employed in the reference path to suppress the Brillouin components. The Brillouin-scattered light was amplified and heterodyned with the reference light. Then it was converted into an electrical signal using a photodetector (PD); its spectral power at 10.87 GHz (on the BGS slope) was output using a zero-span mode of an electrical spectrum analyser (ESA) and monitored using an oscilloscope (OSC). The video bandwidth and resolution bandwidth of the ESA were 10 kHz and 10 MHz, respectively. Averaging was performed 128 times on the OSC.

The structure of the FUT is depicted in Fig. 1*b*. A 13-km-long silica single-mode fibre (BFS = 10.88 GHz) was employed as a FUT, and a considerable bending loss was artificially applied near its end to suppress the Fresnel reflection. A 3-m-long section (11 km far from the proximal end) was heated from room temperature (23°C) to 70°C. The modulation amplitude was 5 GHz, and the modulation frequency was swept from 4.51 to 7.07 kHz, corresponding to the measurement range of 14.5 km and the nominal spatial resolution from 26.7 to 41.9 m [5, 7]. Note that the variation of the resolution according to the measurement position is striking when the FUT is extremely long.

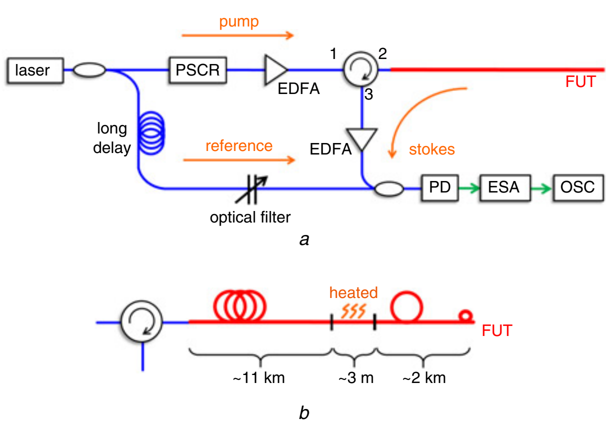


**Fig. 1** *Schematic setup*

*a* Setup of slope-assisted BOCDR with a long measurement range. EDFA: erbium-doped fibre amplifier, ESA: electrical spectrum analyser, FUT: fibre under test, OSC: oscilloscope, PD: photodetector, PSCR: polarisation scrambler
*b* Structure of FUT

*Experimental results:* The normalised power-change distributions near the heated section (23, 50, and 70°C) are shown in Fig. 2*a*. Clear peaks were observed at the heated section. The shape of the waveforms at the heated section is not rectangular, which is valid considering the nature of slope-assisted BOCDR [9]. It is also valid that the peaks were broadened because the nominal spatial resolution at this position is 28.2 m. The SNR was not high in this long-range measurement, because (i) the incident power was much lower than those of shorter-range measurement, (ii) the weak incident power was reduced further during propagation of the long FUT, (iii) the measurement position is far beyond the coherence length of the laser (~100 m) [16], and (iv) the aforementioned noise caused by the Brillouin components in the reference path cannot be completely suppressed. Subsequently, we plotted the maximal power-change at the heated section as a function of temperature (Fig. 2*b*). The dependence was almost linear, indicating that, although the SNR was low, a 3-m-long heated section was properly detected at a >10 km distant position.

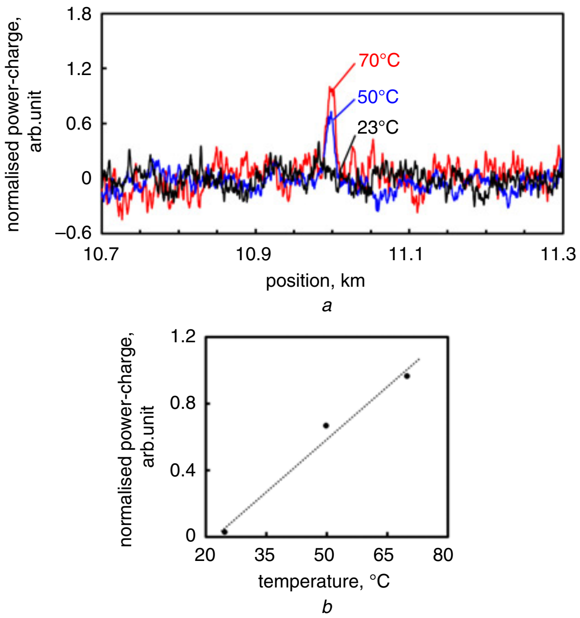


**Fig. 2** *Measured results*

*a* Power-change distributions near 3-m-long heated section
*b* Maximal power-change plotted as a function of temperature. Dotted line is a linear fit

*Conclusion:* We demonstrated the operation of slope-assisted BOCDR with a >10 km measurement range. The experimental setup needed to be modified from a standard short-range setup. We found that a delay line of at least four times the length of the FUT should be inserted in the reference path. We also showed that the long delay line induces forward-propagating Brillouin-scattered light in the reference path and that it should be filtered out to avoid the deterioration of the SNR. Finally, based on the beyond-nominal-resolution effect, a 3-m-long heated section in a 13-km-long FUT was detected. We discussed four reasons why the SNR was relatively low in this measurement.

Although there is a report that BOCDR with such a long measurement range properly operated [17], the temporal gating scheme was employed to extend the measurement range [13] and, in that case, a long delay line did not need to be used. Unlike this report, our study is useful on the point that the influences of the long delay line on the performance of BOCDR have been investigated for the first time to the best of our knowledge. By additionally employing the temporal gating scheme [13] and/or the double modulation scheme [14], we may be able to extend the measurement range further while maintaining the short-hot-spot detectability.

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One or more of the Figures in this Letter are available in colour online.

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