Stable Entire-Length Measurement of Fiber Strain Distribution by Brillouin Optical Correlation-Domain Reflectometry with Polarization Scrambling and Noise-Floor Compensation

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We performed a stable high-speed entire-length measurement of strain distribution by suppressing the signal fluctuations automatically using polarization scrambling. Strain distribution along the entire length of a 100-m fiber was successfully measured with 40-cm spatial resolution and 19-Hz sampling rate. We also demonstrated a signal-to-noise ratio improvement by compensating the noise-floor of the electrical spectrum analyzer.

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Brillouin scattering-based fiber-optic sensors can determine the distribution of strain and/or temperature along an optical fiber, and have been vigorously studied as a promising technology for monitoring conditions in various materials and structures.[1–4] Recently, we have proposed Brillouin optical correlation-domain reflectometry (BOCDR)[5] to measure the strain distribution along a fiber under test (FUT) from a single end of the fiber. Compared to pulse-based conventional Brillouin optical time-domain reflectometry (BOTDR)[6] with the typical spatial resolution of 1 m[7] and the measurement time of several minutes, BOCDR shows unique features by controlling the interference of continuous lightwaves, such as random access to measuring positions, high spatial resolution, and high-speed measurement. In our previous experiment, 13-mm spatial resolution was obtained with 50-Hz sampling rate (excluding data processing time).[8]

It has been also demonstrated that BOCDR can be applied to a distributed measurement of polarization beat length.[9] This measurement is based on the fact that the Brillouin-scattered signal obtained in BOCDR is sensitive to the state of polarization (SOP). However, due to this polarization dependence, frequent SOP optimization by manually adjusting polarization controllers (PCs) was needed for a distributed strain/temperature measurement along a long FUT, and consequently, the measurement time became long in practice. In order to accomplish a stable high-speed distributed measurement along a long FUT, the polarization effect needs to be suppressed automatically. Several techniques have thus far been proposed to mitigate the polarization dependence, including adaptive polarization controllers,[10] polarization diversity,[11,12] Faraday rotation,[13] and polarization scrambling.[14,15] Among them, polarization scrambling is advantageous over the others on the point that it can avoid the need of continuous actuation and the use of extra devices, and doesn't deteriorate the sampling rate. Polarization scrambling has already been used to solve polarization-originated problems, such as polarization mismatch in coherent detection[14] or polarization-dependent gain in optically-amplified fiber communication systems.[15] In BOCDR, the scrambler changes the SOP of the light much faster than the sampling rate, and therefore the measurement becomes independent of the instantaneous SOP mismatch between the reference light and the Stokes light.

In this paper, we perform a stable high-speed entire-length measurement of strain distribution by suppressing the signal fluctuations with polarization scrambling. In the experiment, we demonstrate a stable distributed strain measurement along the entire length of a 100-m FUT with 40-cm spatial resolution and 19-Hz sampling rate. In addition, we develop a new method to improve the signal-to-noise (S/N) ratio of the system by compensating the noise-floor of the electrical spectrum analyzer (ESA).

The basic principle of BOCDR is to select the state of spontaneous Brillouin scattering over one specific point from the FUT by applying the same frequency modulation to the reference and the back-scattered Stokes light.[5] The spatial resolution Δz and the measurement range (i.e., interval between correlation peaks) d_m are given as

$$\Delta z = \frac{V_g \Delta\nu_B}{2\pi f_m \Delta f}, \tag{1}$$

$$d_m = \frac{V_g}{2 f_m}, \tag{2}$$

where V_g is the group velocity of light in the fiber, $\Delta\nu_B$ the intrinsic linewidth of Brillouin gain spectrum (BGS), f_m the laser modulation frequency, and Δf the modulation amplitude, which is limited to a half of the Brillouin frequency shift (BFS), i.e., about 5.4 GHz when standard single-mode fibers (SMFs) are used at 1550-nm wavelength.

The experimental setup of BOCDR with polarization scrambling is depicted in Fig. 1. A distributed-feedback laser diode (DFB-LD) at frequency f_0 (1552 nm) was used as a light source, and a sinusoidal frequency modulation was applied to generate a correlation peak within an FUT. The output from the LD was divided into two light beams by a coupler. One of the beams was directly used as the reference light of self-heterodyne detection, after passing a 5-km delay fiber for controlling the order of the correlation peak, a polarization scrambler (PSCR) which can modulate the SOP at 1 MHz[14,15] for suppressing the BGS fluctuations, an Er-doped fiber amplifier (EDFA) for enhancing the heterodyne beat signal, and an optical filter composed of fiber Bragg grating (FBG) with a 3-dB bandwidth of about 10 GHz for suppressing the amplified spontaneous emission (ASE) noise. The other beam was injected into the FUT as the pump light, after being amplified by a high-power EDFA to 28 dBm. The weak Stokes light at frequency $f_0 - f_B$ backscattered from the FUT was amplified again by an EDFA. An optical filter with a 3-dB bandwidth of about 10 GHz was inserted after the EDFA in order to suppress the effects due to the Rayleigh scattering and the Fresnel

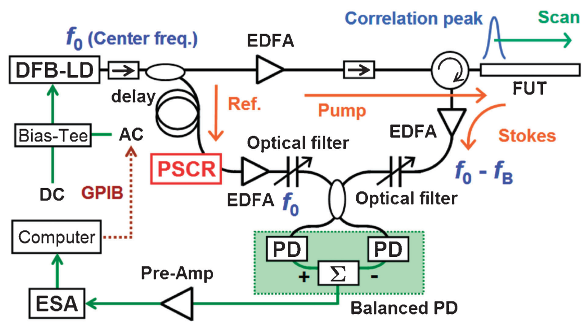

Fig. 1. Experimental setup of BOCDR with polarization scrambling: AC, alternating current; DC, direct current; DFB-LD, distributed-feedback laser diode; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FUT, fiber under test; GPIB, general-purpose interface bus; PD, photo-diode; PSCR, polarization scrambler.

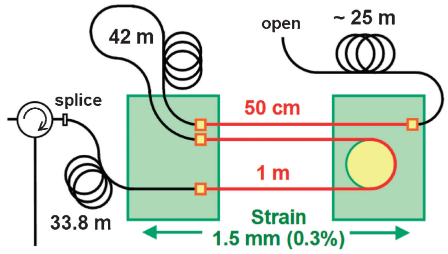

Fig. 2. Structure of the FUT.

reflection from the FUT at frequency f_0. The optical beat signal of the reference light and the Stokes light was converted by balanced photodiodes (PDs) to an electrical signal. After 15-dB amplification from an electrical pre-amplifier, the signal was monitored by an electrical spectrum analyzer (ESA). The measurement data were transferred to a personal computer.

The structure of the FUT is shown in Fig. 2. It was composed of a standard SMF with a length of about 100 m, in which 0.3% strains were applied to a 1-m section (33.8–34.8 m) and a 50-cm section (76.8–77.3 m) fixed on translation stages using epoxy glue. One end of the FUT was spliced to a circulator, and the other end was kept open. The modulation amplitude Δf was set to 3.3 GHz and the modulation frequency f_m was changed from 735.86 to 766.28 kHz, which corresponds to the measurement range d_m of about 140 m and the spatial resolution Δz of about 40 cm from eqs. (1) and (2). The span of the ESA was set to 10.763–11.063 GHz. The overall sampling rate of the BGS measurement for a single position was 19 Hz (including data processing time), and 1001 data were acquired for one BGS. Therefore, the sampling rate of one datum is 19 kHz, which is over 50 times lower than the polarization modulation frequency of 1 MHz. The total measurement time was 40 s, which can be set even shorter if the number of sensing points is reduced (currently, 760 points).

Figure 3(a) shows the measurement results of the distribution of the BFS along the entire length of the FUT, with and without the polarization scrambling. When polarization was not scrambled, at some positions where the SOP was not optimized, the signal level largely fluctuated within the range of the span of the ESA as the measuring position shifted, and consequently, the frequency at which the power became maximal was unstable. Meanwhile, when polarization was scrambled, the fluctuations were suppressed, and the large changes of the BFS were stably detected only at the strain-applied positions. The magnified views around the strain-applied sections are shown in Figs. 3(b) and 3(c). Thus, 1-m and 50-cm strains were successfully detected with 40-s measurement time. The accuracy of the measurement at a single position was about ±10 MHz, which corresponds to the strain of ±0.02% (±200 $\mu\varepsilon$) in this experiment.

Next, we developed a new method to improve the S/N ratio of the system by compensating the noise-floor of the ESA. Since BOCDR is based on weak spontaneous Brillouin scattering, its S/N ratio is low especially when the spatial resolution is high.[8] Noise-floor compensation was performed according to the following procedures: (1) suppress the fluctuations of the BGS by polarization scrambling, (2) acquire the BGS with sufficiently large strain applied, as noise-floor, and (3) after a conventional distributed strain measurement, use the difference calculated by subtracting the noise-floor from the observed BGS, as "net BGS".

First, the effect of the compensation method was experimentally evaluated when the measuring position was fixed. Figures 4(a) and 4(b) show the measured BGS without and with the noise-floor compensation, respectively, when the correlation peak was located at the center of a 1-m strain-applied section. The resolution was set to 80 cm, and the magnitudes of the applied strains were 0, 0.08, 0.16, 0.24, and 0.32%. Averaging was carried out 10 times for one BGS, and the sampling ratio was about 2 Hz. The large strain used for acquiring the noise-floor was 0.5%. When the noise-floor was not compensated, as shown in Fig. 4(a), the width

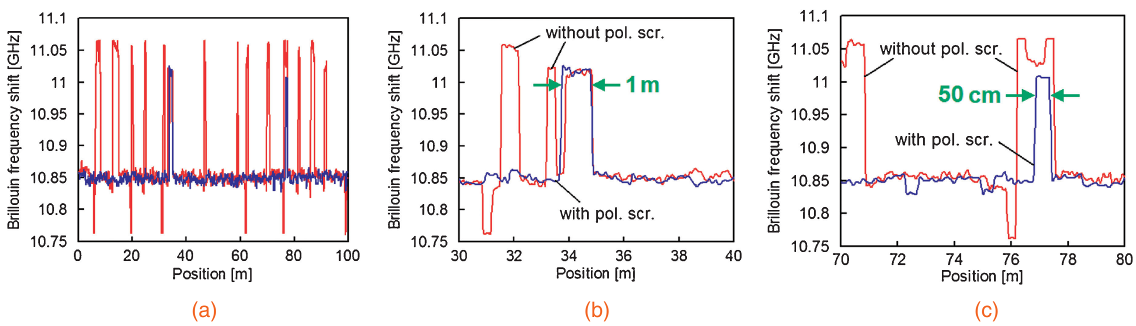

Fig. 3. (a) Measured distribution of the Brillouin frequency shift (BFS) along the entire length of the 100-m FUT with (blue) and without (red) a polarization scrambling, (b) its magnified view with the range of 30–40 m, and (c) that with the range of 70–80 m.

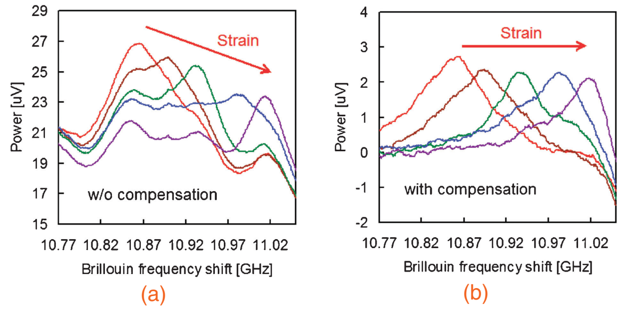

Fig. 4. Measured BGS (a) without and (b) with noise-floor compensation. Strains of 0, 0.08, 0.16, 0.24, and 0.32% were applied.

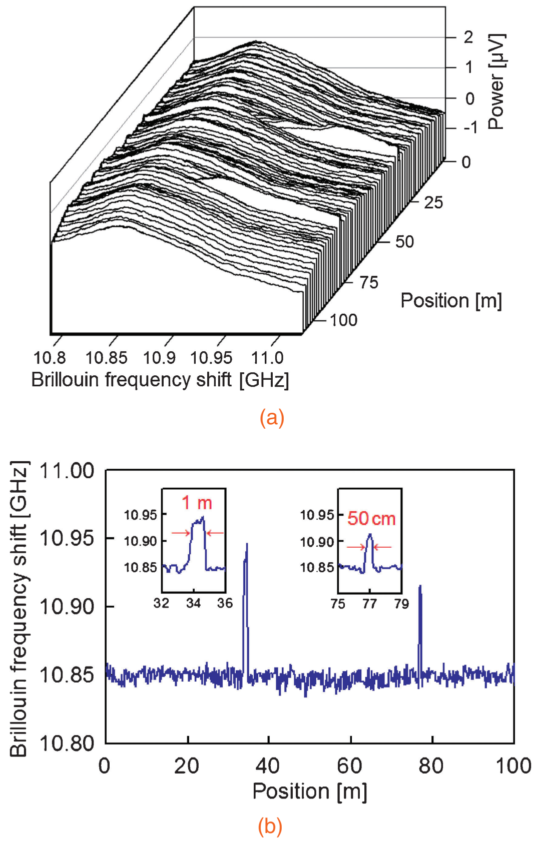

Fig. 5. Measured distributions of (a) BGS and (b) BFS. The insets in (b) show the magnified views around strain-applied positions.

of the BGS changed according to the BFS, i.e., the magnitude of the applied strain. It became large near the frequencies at which the noise-floor had relatively high power (e.g., when 0.24% strain was applied), which leads to the deterioration of the measurement accuracy. Meanwhile, when the noise-floor was compensated, as shown in Fig. 4(b), the width of the BGS was stable, resulting in higher measurement accuracy. The BGS power fluctuations in Fig. 4(a) were larger than that in Fig. 4(b), not only because the noise-floor shape was involved in the power fluctuations but because the SOP was optimized. In Fig. 4(b), the signal power decreased around 11.04 GHz, which can be removed by employing a strain of more than 0.5% as the large strain used to acquire the noise-floor. Thus, this compensation was confirmed to improve the S/N ratio of the system when the measuring position was fixed.

Then, a distributed strain measurement was performed using this method. The FUT was composed of a standard SMF with a length of about 100 m, in which 0.2 and 0.14% strains were applied to a 1-m section (33.8–34.8 m) and a 50-cm section (76.8–77.3 m), respectively. One end of the FUT was spliced to a circulator, and the other end was kept open. The modulation amplitude Δf was set to 5.4 GHz and the modulation frequency f_m was about 750 kHz, which corresponds to the measurement range d_m of about 140 m and the spatial resolution Δz of about 24 cm from eqs. (1) and (2). Averaging was carried out 5 times for one BGS, and the sampling rate was about 4 Hz. The measured distributions of BGS and BFS are shown in Figs. 5(a) and 5(b), respectively. The S/N ratio was drastically improved compared to that of conventional systems,[5,8] and the measurement accuracy at a single position was enhanced to about ±5 MHz, which corresponds to the strain of ±0.01% (±100 $\mu\varepsilon$). This result indicates that the influence of the reflected light from the correlation peak sidelobes is much smaller than the noise-floor of the ESA in BOCDR.

In conclusion, we performed a stable entire-length measurement of strain distribution by suppressing the BGS fluctuations with polarization scrambling. In the experiment, we demonstrated a distributed strain measurement along the entire length of a 100-m FUT with 40-cm spatial resolution and 19-Hz sampling rate. In addition, we developed a new method of compensating the noise-floor of the ESA to improve the S/N ratio of the system.

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