One-End-Access High-Speed Distributed Strain Measurement with 13-mm Spatial Resolution Based on Brillouin Optical Correlation-Domain Reflectometry

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***Abstract*—We demonstrate a one-end-access high-speed distributed strain sensing with high spatial resolution in optical fibers based on Brillouin optical correlation-domain reflectometry. In this work, Brillouin frequency shifts (BFSs) of a 3-cm fiber section are measured with 13-mm spatial resolution and 50-Hz sampling rate. To our knowledge, this spatial resolution is the best result ever reported in Brillouin scattering-based reflectometers, and is superior to that obtained in Brillouin optical time-domain analyzers, though the signal-to-noise ratio is deteriorated. Data processing to find the peak in the Brillouin spectrum is newly introduced to show directly the BFS with a sampling rate of 19 Hz, and the measurement of vibrated strains at frequencies of up to 4 Hz is presented under 22-cm resolution.**

***Index Terms*—Brillouin scattering, correlation, distributed measurement, modulation, nonlinear optics, real-time systems, reflectometry, signal resolution.**

I. Introduction

OPTICAL fiber sensors based on Brillouin scattering have attracted much attention due to the capability to measure the distribution of strain and/or temperature in structures and materials [1]–[13]. They are classified into two types: "reflectometers" [5]–[8], in which a light beam is injected into one end of the fiber under test (FUT), and "analyzers" [9]–[13], in which two light beams are injected into both ends of the FUT. A Brillouin optical correlation-domain reflectometer (BOCDR), which has been recently proposed by the authors [8], is one of the former sensors. Though analyzers can obtain relatively high signal-to-noise (S/N) ratio and short acquisition time due to utilizing the stimulated Brillouin scattering, they cannot work completely when the FUT has even one breakage point. For some practical applications, one-end access reflectometers are more favorable than analyzers. In conventional pulse-based Brillouin optical time-domain reflectometers (BOTDRs) [5]–[7], the measurement range is as long as several tens of kilometers, but the best spatial resolution is typically 1 m [6], though some progress has been made toward further enhancement [7]. This is because there is a trade-off between the spatial resolution and the Brillouin frequency shift (BFS) resolution [6]. Moreover, the signal reflected from one optical pulse is so small that a large number of pulses have to be integrated for observable read-out. Therefore, the measurement time of BOTDR becomes as long as several minutes, which is insufficient for such applications as real-time health monitoring of various structures.

Recently, we have proposed a BOCDR [8] to measure the strain and/or temperature distribution along an FUT by controlling the interference of continuous lightwaves. The BOCDR system is based on spontaneous Brillouin scattering, and shows unique features such as random access to measuring positions, high spatial resolution, and high-speed measurement, though it has a trade-off relation between the spatial resolution and the measurement range. In our previous preliminary experiment, 40-cm spatial resolution was obtained, where the sampling rate was 50 Hz corresponding to the sweep rate of an electrical spectrum analyzer (ESA) used to detect the signal [8].

In this letter, we challenge the limitation of the spatial resolution in BOCDR, and demonstrate a distributed strain measurement on a fiber section as small as 3 cm with 13-mm resolution. To the best of our knowledge, this is the highest spatial resolution that has ever been reported in spontaneous Brillouin scattering-based strain-sensing reflectometers, and is even superior to that obtained in stimulated Brillouin scattering-based Brillouin optical time-domain analyzers (BOTDAs) [9] (the highest resolution reported so far was 20 mm by dark-pulse BOTDA [10]), though the S/N ratio is deteriorated. In addition, to confirm the dynamic measurement capability of BOCDR, we also introduce the data processing to show directly the BFS, and demonstrate the detection of vibrated strains at frequencies of up to 4 Hz under 22-cm resolution.

II. Principle

When a light beam is injected into an optical fiber, backscattered light (Stokes light) is generated through the interaction with acoustic phonons. This phenomenon is called spontaneous Brillouin scattering [14]. The spectrum of the Stokes light, also known as the Brillouin gain spectrum (BGS), takes the shape of Lorentzian function. The frequency at which the peak power is obtained in the BGS is about 11-GHz down-shifted

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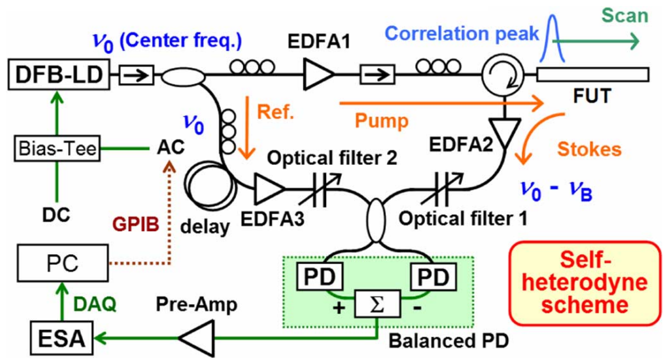

Fig. 1. Experimental setup of the BOCDR system. AC: alternating current; DAQ: data acquisition; DC: direct current; DFB-LD: distributed-feedback LD; GPIB: general-purpose interface bus; PC: personal computer; PD: photodiode.

from the incident light frequency when the incident light wavelength is 1.55 μm. This amount of frequency shift is called the BFS ν_B, and it varies in proportion to the applied tensile strain (0.05 MHz/$\mu\varepsilon$ = 500 MHz/%) or temperature change (1 MHz/K) [1].

The basic principle of the BOCDR system is to select the state of spontaneous Brillouin scattering over one specific section from the FUT by applying the same frequency modulation to the reference and the Stokes light, producing periodical correlation peaks along the FUT [8], [13]. The spatial resolution Δz and the measurement range (i.e., interval between correlation peaks) d_m are given, by the same equations as those for BOCDA [11], as

$$\Delta z = \frac{v_g \Delta\nu_B}{2\pi f_m \Delta\nu} \quad (1)$$

$$d_m = \frac{v_g}{2 f_m} \quad (2)$$

where v_g is the group velocity of light in the fiber, $\Delta\nu_B$ the intrinsic linewidth of BGS (~30 MHz in fibers), and f_m the modulation frequency of the light source; $\Delta\nu$ is the modulation amplitude, which is limited to a half of the BFS, i.e., about 5.4 GHz in BOCDR [8]. According to (1) and (2), the spatial resolution can be enhanced by increasing f_m further at the cost of the measurement range in principle. However, with the enhanced resolution, the intensity of the Brillouin-scattered signal from the corresponding fiber section is reduced, which leads to decreased S/N ratio in the measurement, because the noise-floor in the electrical region is fixed. Thus, there exists a limitation to the spatial resolution in the BOCDR system.

III. Experiment and Results

The experimental setup of BOCDR is depicted in Fig. 1. A 1552-nm distributed-feedback laser diode (LD) at frequency ν_0 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 2-km delay fiber for controlling the order of the correlation peak, an erbium-doped fiber amplifier (EDFA) for enhancing the heterodyne beat signal, and an optical filter composed of fiber Bragg grating with a 3-dB bandwidth of about 10 GHz for suppressing the amplified spontaneous emission (ASE) noise. The other beam was

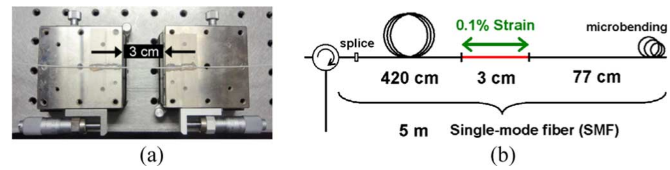

Fig. 2. (a) FUT prepared by fixing an SMF on the translation stage with epoxy glue. (b) Schematic of the structure of the FUT.

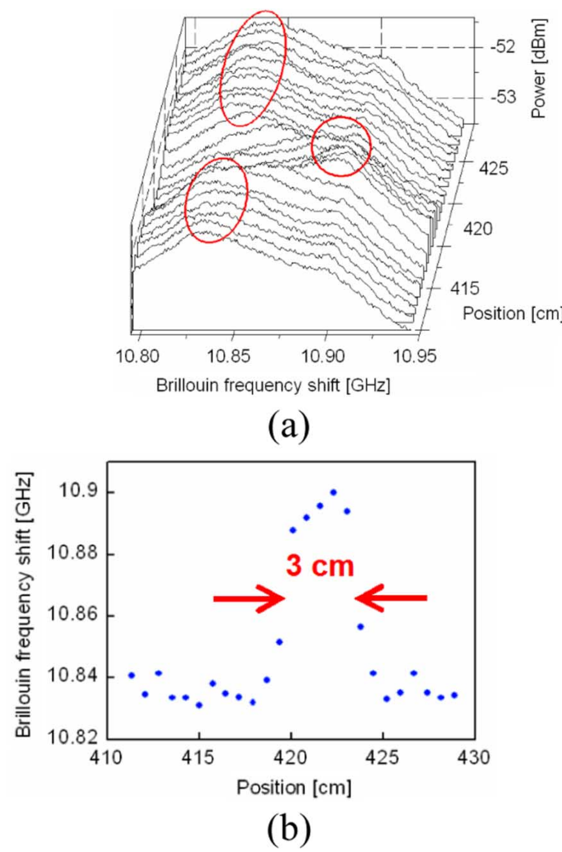

Fig. 3. (a) Distribution of the BGS along the FUT. (b) Distribution of the BFS along the FUT. Spatial resolution better than 3 cm was achieved with 0.02 s/point sampling rate. A resolution of one-half (15 mm) of the marked width is obviously available.

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 ν_0–ν_B backscattered from the FUT was amplified again by an EDFA. A precisely adjusted optical filter was inserted after the EDFA in order to suppress the noise associated with the Rayleigh scattering from the FUT at frequency ν_0 [8]. The optical beat signal of the reference light and the Stokes light was converted by balanced photodiodes to an electrical signal. After 15-dB amplification from an electrical preamplifier, the signal was monitored by the ESA. The measurement data were transferred to a personal computer.

The modulation frequency f_m was 13.4624–13.4672 MHz, which corresponds to a measurement range d_m of 7.6 m according to (2). The amplitude of the frequency modulation $\Delta\nu$ was 5.4 GHz, and the nominal spatial resolution Δz was calculated to be about 13 mm from (1). The 128th correlation peak was used. Fig. 2(a) and (b) shows the structure of the FUT comprising a 5-m standard single-mode fiber (SMF), in which a

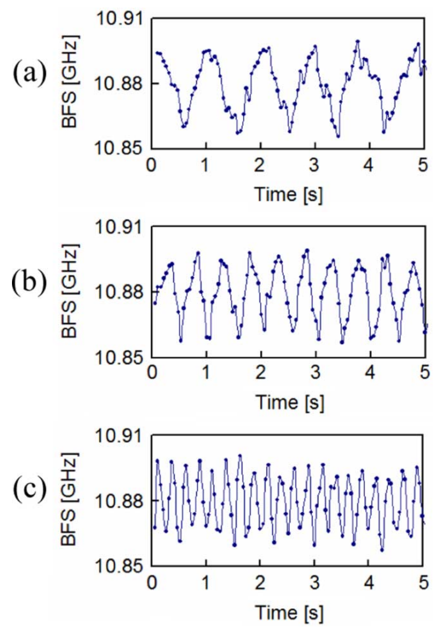

Fig. 4. Results of dynamic strain measurement with sinusoidal driving voltages applied to the PZT at (a) 1 Hz, (b) 2 Hz, and (c) 4 Hz, respectively. Note that the sampling rate is 19 Hz.

0.1% strain was applied to a 3-cm section fixed on a translation stage with epoxy glue. One end of the FUT was spliced to a circulator, and the other end was microbent to suppress the Fresnel reflection. The overall sampling rate of the measurement for a single position was 50 Hz, which is quite high compared with the time-domain techniques.

Fig. 3(a) shows the measurement result of the distribution of the BGS along the FUT. The BGS at the strain-applied section is recognized. Fig. 3(b) shows the distribution of the BFS. We can see that a spatial resolution better than 3 cm is achieved, and a resolution of one-half (15 mm) of the marked width is obviously available. It is in good agreement with the calculated value of 13 mm. The change of the BFS was about 50 MHz, which agrees well with the applied strain of 0.1%. The accuracy of the measurement at a single position was about ±5 MHz, which corresponds to the strain of ±0.01% (±100 $\mu\varepsilon$) in this experiment. However, the S/N ratio for this case was deteriorated, so that the peak of the BGS was mostly buried by the electrical noise floor of the ESA if the resolution was set even higher. As a method to enhance the resolution further, new schemes such as lock-in detection must be developed.

Next, we confirmed the real-time measurement capability of the BOCDR by a dynamic strain sensing experiment. When data processing to find the peak in the Brillouin spectrum was introduced, the maximum sampling rate was 19 Hz. In order to obtain a higher S/N ratio, the modulation frequency f_m and the modulation amplitude $\Delta\nu$ were set to 828.26 kHz and 5.4 GHz, respectively, which correspond to 22-cm spatial resolution and 124.9-m measurement range. A 5-m SMF was used as an FUT, in which dynamic strains were applied to a 28-cm section (420–448 cm) by a piezoelectric transducer (PZT) with the most achievable strain of about ±450 $\mu\varepsilon$ (±22.5 MHz in BFS). Sinusoidally modulated voltages were applied to the PZT at the frequencies of 1, 2, and 4 Hz, respectively. The measurement results are shown in Fig. 4, where the strain oscillations are clearly observed. The amplitude discrepancy seems to have come from the mitigation effect by the fiber jacket. The accuracy of the measurement is limited by the electrical noise of the ESA as well as the instability of polarization state.

IV. Conclusion

We demonstrated a one-end-access distributed strain measurement with 13-mm spatial resolution based on Brillouin optical correlation-domain reflectometry. The BFSs of a 3-cm fiber section were measured, though S/N ratio was deteriorated. Such a high resolution and a high sampling rate have not yet been realized by other Brillouin scattering-based reflectometers as well as two-end-access time-domain analyzers. Data processing to find the peak in the BGS was newly introduced to show directly the BFS with a sampling rate of 19 Hz, and a detection of vibrated strains at frequencies of up to 4 Hz was presented under the resolution of 22 cm.

Although BOCDR has an advantage of one-end accessibility, its performance has not come up to that of BOCDA [11], [12] yet. On this point, we think further improvement is needed.

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