Dependence of the Brillouin Frequency Shift on Temperature in a Tellurite Glass Fiber and a Bismuth-Oxide Highly-Nonlinear Fiber

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We investigate the temperature-dependences of the Brillouin frequency shift in a tellurite glass fiber and a bismuth-oxide highly-nonlinear fiber using a Brillouin optical correlation-domain reflectometry system for sensing applications. Negative dependences of −1.14 and −0.88 MHz/K are demonstrated, respectively, in contrast to the positive dependence of +1.18 MHz/K in a standard silica fiber.

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We have proposed Brillouin optical correlation-domain reflectometry (BOCDR)[1–3] to measure the distribution of strain and/or temperature along a fiber under test (FUT) from a single end, and obtained 13-mm spatial resolution and 50-Hz sampling rate.[2] This resolution of 13 mm, though the best result ever reported in Brillouin scattering-based reflectometers, was limited by the signal-to-noise (S/N) ratio of the system, which could be enhanced when using a specialty fiber with a large Brillouin gain coefficient as the FUT. Among various specialty fibers, tellurite glass fibers[4,5] and bismuth-oxide highly-nonlinear fibers (Bi-NLFs)[6,7] have been widely studied due to their large Brillouin gain coefficients of 1.7×10^{-10} and 6.43×10^{-11} m/W, respectively, which are about 20 and 8 times as large as that of a standard silica fiber. Compared to the background loss of about 0.0005 dB/m in a silica single-mode fiber (SMF), those of a tellurite fiber and a Bi-NLF are as high as 0.0588 and 0.8 dB/m, respectively. When a long measurement range is not required, however, they can be applied, for realizing a high-resolution measurement due to their high Brillouin gain, not only to BOCDR but also to Brillouin optical correlation-domain analysis (BOCDA).[8,9] For the implementation of such sensing systems using a tellurite fiber or a Bi-NLF, it is imperative to clarify their dependences of the Brillouin frequency shift (BFS) on parameters to be measured.

In this paper, we investigate the dependences of the BFS on temperature in a tellurite fiber and a Bi-NLF using a BOCDR system. It is found that the BFSs in a tellurite fiber and a Bi-NLF shift toward lower frequency with increasing temperature with coefficients of −1.14 and −0.88 MHz/K, respectively. These negative dependences seem to have come from the negative dependences of elastic constants on temperature. Furthermore, we also discuss some potential performances of the BOCDR-based distributed temperature sensing systems with the tellurite fiber or the Bi-NLF employed.

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 the spontaneous Brillouin scattering. Due to the exponential decay of the phonons, the backscattered Brillouin light spectrum, known as the Brillouin gain spectrum (BGS), takes the shape of Lorentzian function.[10] The frequency at which the peak power is obtained in the spectrum is down-shifted by several GHz from the incident light frequency, and the amount of this frequency shift is known as BFS. If tensile strain or temperature change occurs in a standard silica SMF, the BFS varies to higher frequency in proportion to the applied strain (+0.058 MHz/$\mu\varepsilon$)[11] or the temperature change (+1.18 MHz/K).[12] Therefore, by measuring the BFS in the FUT, the strain amplitude or temperature change can be derived.

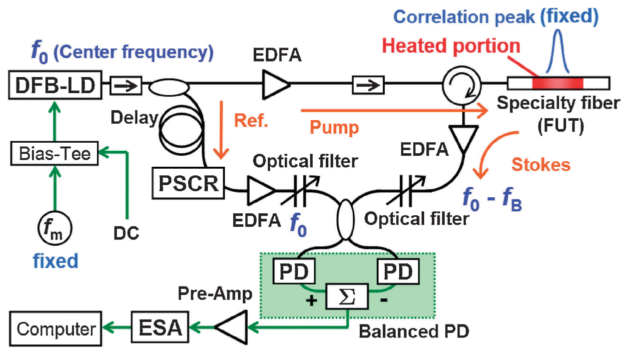

Fig. 1. Experimental setup based on BOCDR for characterizing the temperature dependences of specialty fibers: DC, direct current; DFB-LD, distributed-feedback laser diode; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FUT, fiber under test; PD, photo-diode; PSCR, polarization scrambler.

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.[1] The spatial resolution Δz and the measurement range (i.e., interval between correlation peaks) d_m are given by

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

$$d_m = \frac{c}{2 n f_m}, \tag{2}$$

respectively, where c is the velocity of light, n the refractive index, f_m the modulation frequency of the light source, $\Delta \nu_B$ the intrinsic linewidth of BGS, and Δf the modulation amplitude of the light source.

The experimental setup to characterize the temperature-dependences of the specialty fibers is shown in Fig. 1. This is basically the same as that reported previously,[3] where a polarization scrambler (PSCR) was inserted in the reference path to suppress the polarization-dependent fluctuations of the output signal observed by the electrical spectrum analyzer (ESA). The structures of the FUTs comprising a tellurite fiber and a Bi-NLF are shown in Figs. 2(a) and 2(b), respectively. Since it is difficult to directly splice a tellurite

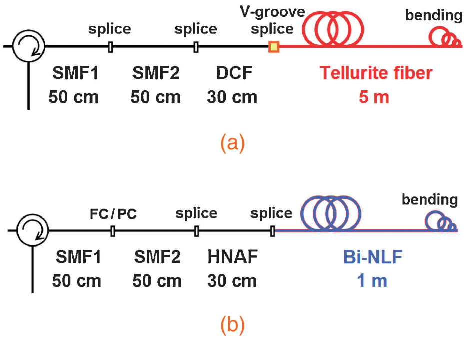

Fig. 2. Structures of the FUTs comprising (a) the tellurite fiber and (b) the Bi-NLF.

fiber (5 m) and a Bi-NLF (1 m) to SMFs, a dispersion–compensation fiber (DCF, 30 cm)[13] and a high-numerical-aperture fiber (HNAF, 30 cm) were employed between them, respectively. Each end of the tellurite fiber and the Bi-NLF was bent to suppress the Fresnel reflection. The measurement was conducted using this BOCDR system with the measurement window (the correlation peak) fixed at a position within the tellurite fiber or the Bi-NLF to select the portion where the temperature is changed and to remove the effects of the other portions.

In the measurement of the tellurite fiber, the power P_{in} of the light beam injected into the FUT was set to 28 dBm. The amplitude Δf and the frequency f_m in the laser modulation were set to 1 GHz and 7.8028 MHz, respectively, which correspond to the measurement range d_m of 9.47 m and the spatial resolution Δz of about 3 cm from eqs. (1) and (2) (the value of $\Delta\nu_B$ is described shortly after). In the measurement of the Bi-NLF, with P_{in} set to 26 dBm, Δf and f_m were set to 2 GHz and 1.0654 MHz, respectively, corresponding to d_m of 63.4 m and Δz of 79.9 cm. In general, the Brillouin gain bandwidth $\Delta\nu_B$ depends on P_{in},[14] and, in our experiment, it was 10 MHz in the tellurite fiber and 79.2 MHz in the Bi-NLF as shown in Figs. 3(a) and 3(b).

Different temperature changes were applied to a 40-cm section of the tellurite fiber and the whole length of the Bi-NLF placed on a hot plate. In both measurements, the position of the correlation peak was set to the middle of the section where temperature changes were applied, and the sampling rate of the BGS acquisition was about 2 Hz including 10-times averaging.

The temperature-dependences of the BGS in the tellurite fiber and the Bi-NLF are shown in Figs. 4(a) and 4(b), respectively. In both cases, the BGS shifted toward lower frequency with increasing temperature. In Fig. 4(b), the BGS peak power was so weak that it changed due to the noise floor of the ESA, which can be suppressed by a noise-floor compensation technique.[3] From these spectra, we can plot the temperature-dependences of the BFS as shown in Figs. 5(a) and 5(b). The error bars are ± 2.5 MHz, corresponding to the BFS fluctuations when temperature was fixed. The dependences are both almost linear, and their coefficients were calculated to be -1.14 and -0.88 MHz/K, respectively. Although the absolute values are close to that of a standard SMF (+1.18 MHz/K[12]), their signs are opposite.

In general, the temperature coefficient of the normalized BFS is given by

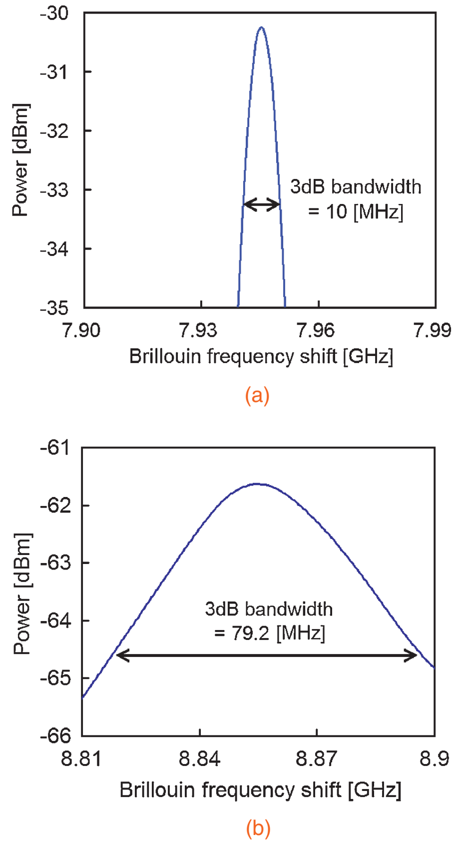

Fig. 3. Measured BGS from (a) the 5-m tellurite fiber with P_{in} of 28 dBm, and (b) the 1-m Bi-NLF with P_{in} of 26 dBm.

$$\begin{aligned}\frac{1}{\nu_B}\frac{\partial \nu_B}{\partial T} &= \frac{1}{n}\frac{\partial n}{\partial T} + \frac{1}{2}\left(\frac{1}{C}\frac{\partial C}{\partial T} - \frac{1}{\rho}\frac{\partial \rho}{\partial T}\right)\\ &= \frac{1}{n}\frac{\partial n}{\partial T} + \frac{1}{2}\left(\frac{1}{C}\frac{\partial C}{\partial T} + \beta\right), \end{aligned} \tag{3}$$

where C is the effective elastic constant (in optical fibers, C is almost the same as the Young's modulus), ρ the density, and β the volume expansion coefficient of a material. For a tellurite crystal, Sonehara *et al.*[15] have reported that the term $(1/C)(\partial C/\partial T)$ becomes dominant and is negative, though the values are slightly different depending on the crystal orientation. From their experimental result, we can estimate the temperature coefficient in the tellurite crystal at around room temperature to be approximately -1.06 MHz/K ($= -0.04 \times 7950$ MHz/300 K), which roughly agrees with the experimental value (-1.14 MHz/K) in the case of the tellurite fiber. The negative dependence of an elastic constant on temperature may also be the origin of the negative temperature-dependence of the BFS in the Bi-NLF, but further research is needed to clarify this point.

Finally, the potential performances of the distributed temperature sensing based on BOCDR using the tellurite fiber or the Bi-NLF are discussed from the aspects of the number of effective sensing points or the ratio between the measurement range and the spatial resolution, and the measurement accuracy. First, the number of effective sensing points N, which can be regarded as the evaluation parameter of the sensing system, is given by the ratio between d_m, eq. (2), and Δz, eq. (1), as

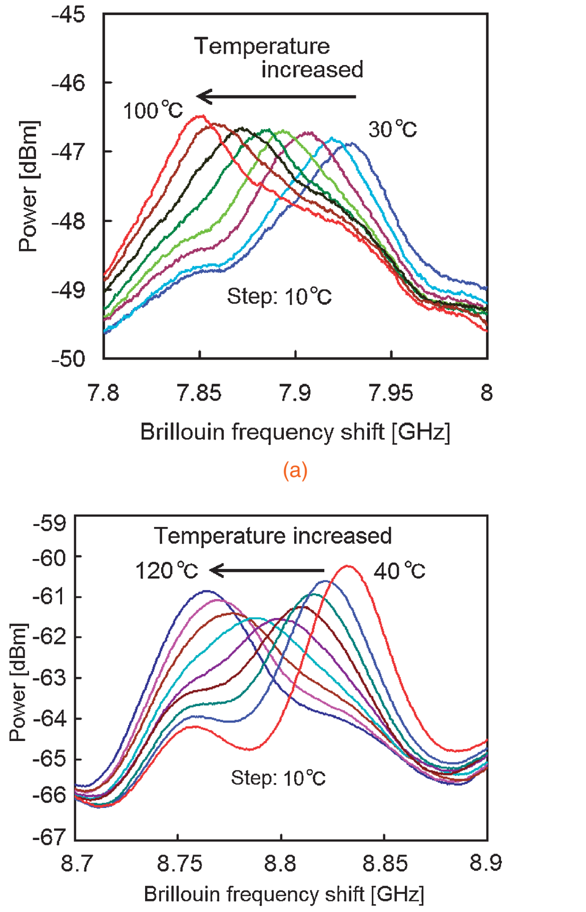

Fig. 4. Temperature-dependences of the BGS in (a) the tellurite fiber and (b) the Bi-NLF.

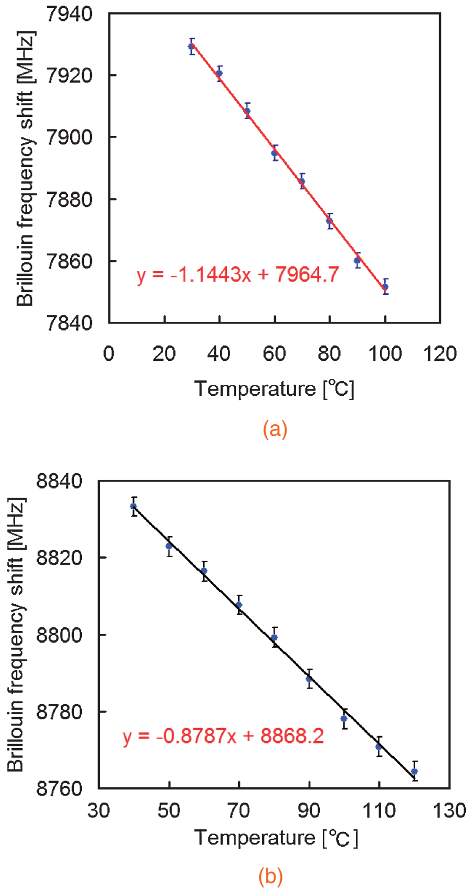

Fig. 5. Temperature-dependences of the BFS in (a) the tellurite fiber and (b) the Bi-NLF.

$$N = \frac{d_{\mathrm{m}}}{\Delta z} = \frac{\pi \Delta f}{\Delta \nu_{\mathrm{B}}} < \frac{\pi\,\mathrm{BFS}}{2\Delta \nu_{\mathrm{B}}}. \tag{4}$$

Here, the inequality holds true, because Δf must be lower than a half of the BFS of the FUT due to the Rayleigh scattering-induced noise.[1)] While N is about 570 in a silica fiber,[1,2)] it can be enhanced to 1250 by using the tellurite fiber ($\Delta\nu_{\mathrm{B}} = 10\,\mathrm{MHz}$), but is reduced to 175 by using the Bi-NLF ($\Delta\nu_{\mathrm{B}} = 79.2\,\mathrm{MHz}$). Second, the measurement accuracy of BOCDR using the Bi-NLF is worse than that using the tellurite fiber or a silica fiber, because the absolute value of the temperature coefficient of BFS in the Bi-NLF (0.88 MHz/K) is lower than that in the tellurite fiber (1.14 MHz/K) or a silica fiber (1.18 MHz/K). For example, the BFS fluctuations of ±2.5 MHz in the Bi-NLF, the tellurite fiber, and a silica fiber, correspond to the measurement accuracy of ±2.84, ±2.19, and ±2.12 K, respectively. Thus, from the viewpoint not only of the Brillouin gain and the optical loss, but also of the number of effective sensing points and the measurement accuracy, the tellurite fiber is thought to be more favorable than the Bi-NLF as a specialty fiber employed to enhance the performance of the BOCDR system.

In conclusion, we investigated the temperature-dependences of the BFS in a tellurite glass fiber and a Bi-NLF for sensing applications. In both fibers, the BFS shifted toward lower frequency with increasing temperature with coefficients of −1.14 and −0.88 MHz/K, respectively. These negative dependences seem to be caused by the negative dependences of the elastic constants on temperature. We consider the tellurite fiber is more suitable as the FUT in the BOCDR-based distributed temperature sensing systems than the Bi-NLF.

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