Cross Effect of Strain and Temperature on Brillouin Frequency Shift in Polymer Optical Fibers

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***Abstract*—The strain–temperature cross-sensitivity effect on the Brillouin frequency shift (BFS) in polymer optical fibers (POFs) is fully investigated. First, we show that the strain coefficient of the BFS is dependent on the temperature. In the strain ranges of 0–1.2% and 4.0–9.0%, the temperature dependence is linear with coefficients of 1.5 and – 0.3 MHz/(%·°C), respectively. We then find that the temperature coefficient of the BFS is linearly dependent on the strain with a coefficient of 1.5 MHz/(%·°C) in the strain range of 0–1.2%. For strains of 4.0–9.0%, the BFS basically decreases with increasing temperature. These results indicate that temperature (and strain) compensation for the strain (and temperature) sensitivity of the BFS is required to correctly detect the magnitudes of the strain and temperature in POF-based Brillouin sensing. For strains >13%, we show that temperature sensing with no sensitivity to strain is potentially feasible using the BFS in POFs. The height of the Brillouin gain spectrum is also evaluated.**

***Index Terms*—Brillouin frequency shift, Brillouin scattering, polymer optical fibers, strain and temperature measurement.**

I. Introduction

FIBER-OPTIC strain and temperature sensing techniques have been extensively studied and used in many application fields including structural health monitoring. Among the various types of fiber-optic sensors, those exploiting Brillouin scattering have attracted a considerable amount of attention owing to their capability of completely distributed measurement based on frequency information [1]–[9]. Their sensor heads are conventionally composed of glass optical fibers, which are easily broken when a strain of only ∼3% is applied. To extend the measurable maximum strain, polymer optical fibers (POFs) have been vigorously studied recently as alternatives to glass fibers because POFs are generally so flexible that they can withstand strains >50% [10]–[19].

Brillouin scattering in POFs was first observed in 2010 [10], and since then, its properties have been evaluated from a variety of aspects. For instance, the Brillouin frequency shift (BFS) dependencies on the strain (a relatively small strain [11] and large strain [12]) and temperature (a relatively narrow range [11] and wide range [13]) have been clarified to be much different from those in silica glass fibers. Other unique features of Brillouin scattering in POFs, such as the BFS hopping phenomenon [14] and the strain and thermal memory functions [20]–[22], have also been investigated, and distributed strain and temperature measurements have been recently demonstrated [15]–[17]. However, no reports have been provided regarding the cross effect of the strain and temperature on the BFS in POFs. As these two parameters generally change simultaneously in practical applications, clarification of this effect is of crucial importance. Although the cross effect has been shown to be negligibly small in the temperature range of 35–83 °C for standard silica single-mode fibers (SMFs) [23], it does not necessarily hold true for POFs with a much lower glass-transition temperature.

In this work, we investigate the strain-temperature cross effect on the BFS in POFs. First, we measure the BFS dependence on the strain at different temperatures and that on the temperature at different strains in the temperature range of 32–60 °C. For strains ranging from 0 to 1.2%, we find that the strain coefficient of the BFS is linearly dependent on the temperature with a coefficient of 1.5 MHz/(%·°C). The temperature coefficient of the BFS is also experimentally confirmed to have a linear strain dependence with a coefficient of 1.5 MHz/(%·°C) (these two values are theoretically identical). For strains ranging from 4.0 to 9.0%, the temperature dependence of the BFS coefficient on the strain is linear with a coefficient of –0.3 MHz/(%·°C). The BFS is found to basically decrease as the temperature increases, and its temperature coefficient is confirmed to be dependent on the strain with a coefficient of –0.3 MHz/(%·°C) (these two values are also theoretically equal). These results indicate that we need temperature (or strain) compensation for the strain (or temperature) sensitivity of the BFS to perform accurate strain and temperature sensing using the BFS. For strains >13%, we show that Brillouin-based temperature sensors with no strain sensitivity can be potentially implemented using POFs. After the BFS measurement, we measure the dependence of the BGS height (i.e., the power difference between the BGS peak and the noise floor) on the strain at different temperatures.

II. Principles

Incident light into an optical fiber interacts with acoustic phonons and generates backscattered light accompanying a frequency downshift of several gigahertz (called the BFS). This phenomenon is Brillouin scattering [24], and the spectrum of

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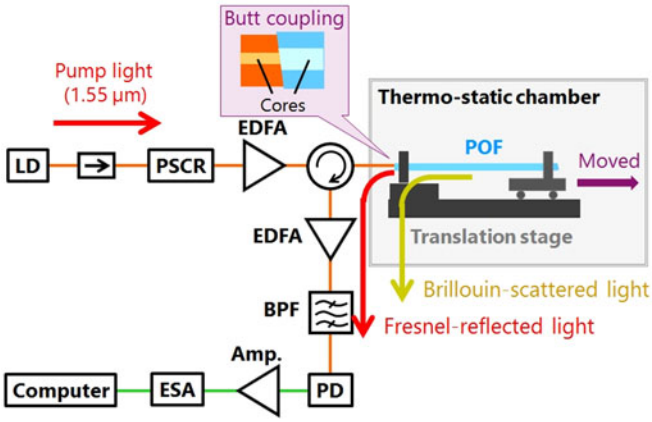

Fig. 1. Experimental setup for measuring the BFS dependence on the strain (or temperature) at different temperatures (or strains). BPF, band-pass filter; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; LD, laser diode; PD, photodetector; PSCR, polarization scrambler. The orange and green lines indicate silica SMFs and electrical cables, respectively.

the backscattered light is known as the Brillouin gain spectrum (BGS). The BFS is expressed by [1], [24], [25]

$$BFS = \frac{2nv_a}{\lambda_p} = \frac{2n}{\lambda_p}\sqrt{\frac{1-\sigma}{(1-2\sigma)(1+\sigma)}\frac{E}{\rho}}, \quad (1)$$

where n is the refractive index, v_a is the acoustic velocity, σ is the Poisson's ratio, E is the Young's modulus, ρ is the density of the core material, and λ_p is the wavelength of the incident light. As all of these parameters excluding λ_p are dependent on the strain and temperature [26]–[34], the BFS also shows strain and temperature dependencies, which serve as the fundamental principle of Brillouin-based sensing. In perfluorinated graded-index (PFGI) POFs (the only POFs in which Brillouin scattering has been experimentally observed) [10], [35], the BFS dependence on the strain at room temperature is reported to be nonmonotonic, i.e., its coefficient varies, including the sign, depending on the strain (for a strain less than 1.0%, the coefficient is constantly −121 MHz/%) [11]. Moreover, the BFS dependence on the temperature in PFGI-POFs is reported to be monotonic but not completely linear (in the limited temperature range from –160 to ∼85 °C at 0% strain, the coefficient is constantly –3.2 MHz/°C) [13].

III. Experimental Procedures

We used ∼440-mm-long PFGI-POF samples (FONTEX, Asahi Glass Co. Ltd.) with a core diameter of 50 μm, a cladding diameter of 70 μm, an overcladding diameter of 490 μm, a core refractive index of ∼1.35, and a propagation loss of ∼250 dB/ km at 1.55 μm. The experimental setup for measuring the BFS dependence on the strain (or temperature) at different temperatures (or strains) is depicted in Fig. 1. A Fresnel-assisted self-heterodyne technique was exploited to acquire the BGS with a high signal-to-noise ratio (SNR) [36]. First, the continuous-wave output from a laser diode (LD) with a central wavelength of 1.55 μm and a bandwidth of ∼1 MHz was guided to a polarization scrambler (PSCR) to randomize its polarization state and thus suppress the polarization-dependent

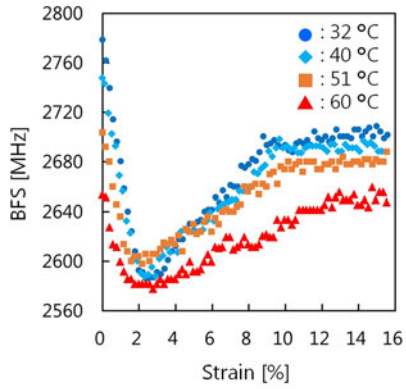

Fig. 2. BFS dependence on the strain at four different temperatures.

fluctuations in the signal. The light was then boosted to 30 dBm using an erbium-doped fiber amplifier (EDFA) and, via an optical circulator, injected into a POF sample fixed on an automatic translation stage in a thermostatic chamber. Both ends of the POF were polished to an angle (8°) using a polishing disc, which was optimally designed so that the angled surfaces of a POF and a silica SMF become parallel when they are connected. One of the POF ends (SC connector) was connected to an SMF (FC connector; the port 2 of the circulator) using an SC-FC adaptor; thus, the Fresnel reflection at the open end of the POF was suppressed. The Brillouin-scattered light from the POF, along with the Fresnel-reflected light from the SMF-to-POF boundary, was amplified again to a total power of approximately –4.5 dBm using another EDFA, the amplified spontaneous emission noise of which was suppressed by an optical band-pass filter (BPF). The light was then guided to a photodetector (PD), which generated an electrical Brillouin signal because of the beating between the Brillouin-scattered light and the Fresnel-reflected light. The Brillouin signal was amplified by 20 dB, observed as a BGS using an electrical spectrum analyzer (ESA), and sent to a computer for data processing. By fitting the BGS with a Lorentzian curve [10], [13], the relevant parameters (the BFS, peak power, and noise floor) were extracted. By changing the strain from 0% to 16% using an automatic translation stage with a speed of 100 μm/s, the strain dependencies of each parameter were measured. Furthermore, this procedure was repeated at different temperatures of 32, 40, 51, and 60 °C, and the temperature (and strain) dependencies of the strain (and temperature) coefficients of each parameter were derived.

IV. Experimental Results

A. Brillouin Frequency Shift

Fig. 2 shows the BFS dependence on the strain measured at 32, 40, 51, and 60 °C. Irrespective of the temperature, with increasing strain, the BFS first decreased (for strains from 0 to ∼2%), then increased (for strains from ∼2 to ∼13%), and finally became constant (for strains >13%). This behavior has already been reported at room temperature [12]. We measured the measurement errors (defined here as the standard deviations of tens of data obtained with 30-times averaging) at 60 °C, at which the highest errors are anticipated. The errors in 0–1.2,

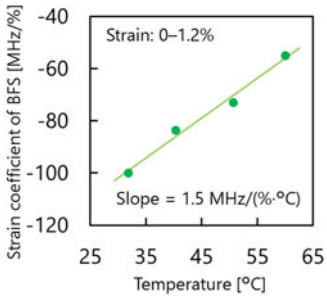

Fig. 3. Temperature dependence of the BFS coefficient on the strain (0–1.2%).

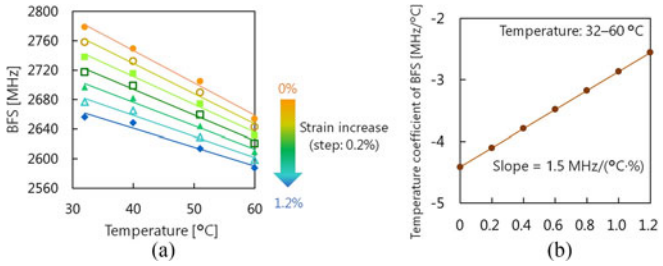

Fig. 4. (a) BFS dependence on the temperature and (b) the temperature coefficient of the BFS for strains of 0–1.2%.

∼2.0–9.0, and ∼9.0–16.0% strains were about ±8, 11, and 10 MHz, respectively, in this experiment. In the following, we analyze the BFS in detail for three strain ranges: 0–1.2%, ∼2.0–9.0%, and ∼9.0–16.0%.

1) Strains of 0–1.2%: The strain dependence was almost linear, and its coefficient was plotted as a function of temperature (see Fig. 3). The strain coefficient was shown to be linearly dependent on the temperature with a coefficient of 1.5 MHz/(%·°C). This indicates that the absolute value of the strain coefficient (which has negative values) becomes smaller with increasing temperature, resulting in a deterioration in the strain sensitivity at higher temperature (the value of –121 MHz/% reported in Ref. [11] was obtained at room temperature lower than 32 °C). Therefore, we clarified that we need to select the specific value of the strain sensitivity depending on temperature to correctly detect the strain magnitude using POF-based Brillouin sensors, especially at higher temperatures. Note that such compensation is not required when standard silica SMFs are used at temperatures less than 83 °C [23].

The temperature dependence of the BFS was linear regardless of the strain [see Fig. 4(a)]. Further, the temperature coefficient of the BFS was linearly dependent on the strain with a coefficient of 1.5 MHz/(%·°C) [see Fig. 4(b)]; it is natural that this value is the same as the temperature coefficient of the strain coefficient mentioned in the preceding paragraph. Note that the value of –3.2 MHz/°C at zero strain reported in Ref. [13] was obtained using another type of PFGI-POF sample (GINOVER, Sekisui Chemical Co. Ltd.); different dopants and their concentration could strongly affect the BFS dependence on temperature [37]. As the absolute value of the coefficient is lowered with increasing strain, the temperature sensitivity of the BFS deteriorates at a larger strain. Thus, we need to use the specific value of the temperature sensitivity depending on the strain to accurately measure the temperature using the BFS.

Using these results, the BFS in this strain range (0–1.2%) and in this temperature range (32–60 °C) can be expressed by the following equation:

$$\begin{aligned} BFS\left(\varepsilon, T\right) &= C_{\varepsilon}\left(T\right)\varepsilon + C_{T}\left(\varepsilon\right)T + BFS\left(0,0\right) \\ &= \left(C_{\varepsilon,\mathrm{T}}T + C_{\varepsilon}\left(0\right)\right)\varepsilon + \left(C_{\mathrm{T},\varepsilon}\varepsilon + C_{T}\left(0\right)\right)T \\ &\quad + BFS\left(0,0\right) \end{aligned} \tag{2}$$

where ε is strain (%), T is temperature (°C), $C_{\varepsilon}(T)$ is the strain coefficient of the BFS (MHz/%) at the temperature T, $C_{\mathrm{T}}(\varepsilon)$ is the temperature coefficient of the BFS (MHz/°C) at the strain ε, $C_{\varepsilon,\mathrm{T}}$ is the temperature coefficient of $C_{\varepsilon}(T)$ (MHz/(%·°C)), $C_{\mathrm{T},\varepsilon}$ is the strain coefficient of $C_{\mathrm{T}}(\varepsilon)$ (MHz/(%·°C)). As mentioned above, the value of $C_{\varepsilon,\mathrm{T}}$ is the same as that of $C_{\mathrm{T},\varepsilon}$. Eq. (2) should be practically used to measure the strain and temperature accurately using the BFS in PFGI-POFs.

2) Strains of ∼2.0–9.0%: In Fig. 2, by exploiting the BFS dependence in this strain range, strain sensing exploiting the so-called strain memory effect with a wider dynamic strain range appears to be feasible [20], [21] unlike strain sensing in the range of 0–1.2%. In that case, we need to apply ∼2% strain beforehand. We calculated the strain coefficients of the BFS at each temperature using the measured data in the range of 4.0–9.0% (where the strain dependence was almost linear irrespective of the temperature) and plotted them as a function of the temperature (see Fig. 5). The strain coefficient (or strain sensitivity) decreased with a coefficient of –0.3 MHz/(%·°C) with increasing temperature, indicating that the temperature compensation of the coefficient is also required for BFS-based strain sensing in this strain range. The absolute values of the coefficients in this range were, regardless of the temperature, $<$1/5 of those for strains of 0–1.2%, resulting in a lower strain sensitivity.

The temperature dependence of the BFS was calculated at different strains [see Fig. 6(a)]. The trends were not completely linear partially due to the thermal instability of the thermostatic chamber. The BFS tended to decrease with increasing temperature. The temperature coefficient, calculated by a rough linear approximation, exhibited a linear strain dependence with a coefficient of –0.3 MHz/(%·°C) [see Fig. 6(b)], which was also the same as the value derived in the preceding paragraph. As the absolute value of the temperature coefficient increased with increasing strain, the temperature sensitivity of the BFS became higher at a larger strain. Therefore, in this strain range, the strain compensation of the BFS coefficient on temperature is also required for accurate temperature sensing. Note that Eq. (2) is still valid because the temperature (and strain) dependencies of the BFS coefficients on the strain (and temperature) were linear.

3) Strains of ∼9.0–16.0%: The BFS slightly increased as the strain increased and became almost independent of the strain. The critical strain at which the BFS became almost constant was plotted as a function of the temperature (see Fig. 7). Such critical strains were calculated as the intersection of (i) the regression line of the strain dependence of the BFS in the range of 4.0–9.0% and (ii) the horizontal line indicating the BFS value averaged for strains $>$13%. The dependence on the temperature

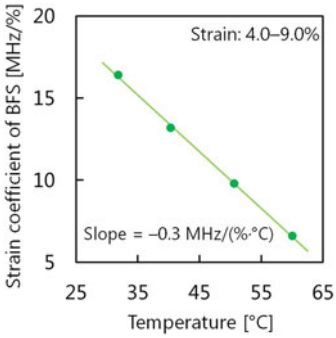

Fig. 5. Temperature dependence of the BFS coefficient on the strain (4.0–9.0%).

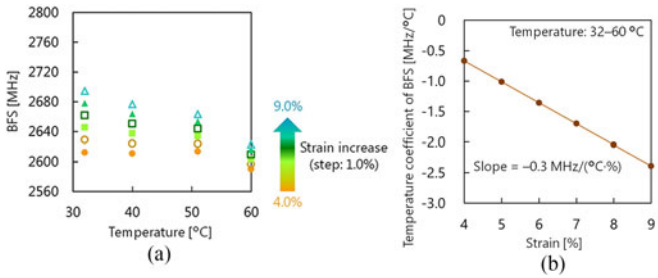

Fig. 6. (a) BFS dependence on the temperature and (b) the temperature coefficient of the BFS for strains of 4.0–9.0%.

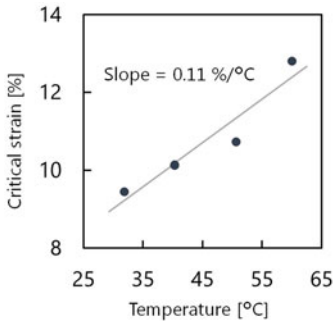

Fig. 7. Critical strain (at which the BFS becomes almost constant) plotted as a function of the temperature.

exhibited a monotonic increase with a roughly linear coefficient of 0.11%/°C. This result indicates that the dynamic strain range for strain sensing (which exploits the BFS dependence in the range of ∼2–9%) is widened at higher temperatures, which is a trade-off with the strain sensitivity (refer to the preceding paragraph). Moreover, as the critical strain corresponds to the strain at which the POF partially starts to slim down [14], this temperature dependence may explain the reason why this slim-down phenomenon does not occur in the case of POF tapering performed at high temperatures [38], [39].

For strains >13%, the BFS became almost constant. The temperature dependence of the BFS (averaged in the range of 13–16%) is shown in Fig. 8. The BFS decreased with increasing temperature, and the rough linear approximation led to a coefficient of –1.8 MHz/°C. By using POFs prestrained at strains >13%, temperature sensors with no sensitivity to strain appear to be implementable.

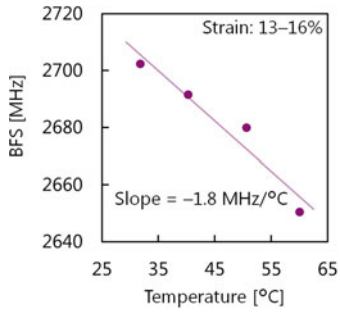

Fig. 8. Temperature dependence of the BFS for strains of 13.0–16.0%.

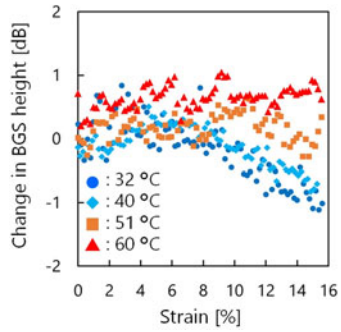

Fig. 9. Strain dependence of the BGS height measured at four different temperatures.

B. BGS Height

Fig. 9 shows the strain dependence of the change in the BGS height measured at 32, 40, 51, and 60 °C. Here, the BGS height was defined as the difference between the peak power and the noise floor. At 32 and 40 °C, the BGS height slightly decreased with increasing strain, and its change reached approximately –1 dB at ∼16% strain. The slopes of the strain dependencies for strains >8% measured at 32 and 40 °C were approximately –0.14 and –0.12 dB/%, respectively. In contrast, when the temperature was greater than 51 °C, the BGS height was almost constant. Thus, strain sensing using the BGS height, which can be potentially used to implement simultaneous strain and temperature sensing [40], appears difficult at temperatures >51 °C (although the SNR is insufficient even at temperatures <40 °C at present).

V. Conclusion

In the temperature range of 32–60 °C and in the strain range of 0–16%, we investigated the BFS and BGS height dependencies on the strain (and temperature) at different temperatures (and strains) in POFs. First, the strain coefficient of the BFS was shown to be linearly dependent on the temperature with a coefficient of 1.5 MHz/(%·°C) for strains of 0–1.2% and –0.3 MHz/(%·°C) for strains of 4.0–9.0%, indicating degraded strain sensitivity at higher temperatures. The absolute value of the strain coefficient for strains of 4.0–9.0% was then found to be <1/5 of that for strains of 0–1.2% at the same temperature. Subsequently, the temperature coefficient of the BFS was found to be linearly dependent on the strain with a coefficient of 1.5 MHz/(%·°C) for strains of 0–1.2%. For strains of 4.0–

9.0%, the BFS tended to decrease with increasing temperature. The temperature coefficient showed a linear strain dependence with a coefficient of –0.3 MHz/(%·°C). In addition, temperature sensing that is not susceptible to the strain was shown to be potentially feasible by using the BFS in POFs prestrained at strains >13%. Further, we found that strain sensing using the BGS height appears to be difficult at least at temperatures >51 °C. The most important finding is that temperature (and strain) compensation for the strain (and temperature) dependence of the BFS needs to be conducted to correctly detect the strain and temperature values in POF-based Brillouin sensing. We hope that this paper will be an important archive in developing distributed strain and temperature sensors based on Brillouin scattering in POFs.

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