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Dependence of Brillouin Frequency Shift on Temperature and Strain in Poly(methyl methacrylate)-Based Polymer Optical Fibers Estimated by Acoustic Velocity Measurement

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We estimated the dependences of Brillouin frequency shift (BFS) on temperature and strain in poly(methyl methacrylate)-based polymer optical fibers using ultrasonic pulse–echo technique at ~10 MHz. The estimated BFS dependence on temperature was linear with a coefficient of approximately −17 MHz/K at 650 nm pump, −34 times larger than that of silica fibers at 650 nm pump. In contrast, its strain dependence was found to be nonlinear, probably originating from the elastic-to-plastic transition.

Optical fiber sensors have a number of attractive features compared with other sensor elements, such as light weight, compactness, low cost, and tolerance to electromagnetic interference. Among them, due to the capability of determining temperature and/or strain distribution along sensing fibers, optical fiber sensors based on Brillouin scattering have been studied as a promising technology for monitoring diverse structures and materials. Up to now, glass optical fibers (GOFs), in particular, silica-based single-mode fibers (SMFs), have been mainly used to develop Brillouin fiber sensors,[1–5] which cannot, however, measure a large strain of >10%. One method to overcome this problem is to implement such Brillouin sensors using polymer optical fibers (POFs), which offer high flexibility, easy connection, low cost, and high safety.[6] A so-called "memory effect" of POF-based distributed strain sensors has also been demonstrated.[7]

Commercially available POFs are classified into two types: poly(methyl methacrylate) (PMMA)-based POFs and perfluorinated graded-index (PFGI)-POFs. We have so far succeeded in observing Brillouin scattering in PFGI-POFs with 120 and 62.5 μm core diameters at 1.55 μm wavelength.[8–10] We have also investigated the dependences of Brillouin frequency shift (BFS) on temperature and strain in the PFGI-POFs, and found that their temperature and strain coefficients are −4.09 MHz/K and −121.8 MHz/% (within the strain range of 0–1%), respectively.[11] PMMA-POFs are, in contrast, much more cost-effective and more widely used in communication applications than PFGI-POFs, and so the observation of Brillouin scattering in PMMA-POFs is important for predicting the performance as sensors but difficult for the following two reasons: (1) the Brillouin signal is extremely small due to their large core diameter (typically 980 μm), and (2) it is not easy to prepare all the optical devices operating at ~650 nm, where the propagation loss of PMMA-POFs becomes lowest. Therefore, we have recently developed a new method of estimating the BFS in POFs from the sound speed measured through ultrasonic pulse–echo technique at much lower frequencies than BFS, and calculated the BFS in PMMA-POFs at 650 nm to be ~13 GHz.[12] In order to evaluate the applicability of the POF samples to distributed temperature and strain sensors based on Brillouin scattering, the dependences of the BFS on temperature and strain in PMMA-POFs need to be clarified.

In this paper, the temperature and strain dependences of the BFS in PMMA-POFs are estimated using the ultrasonic pulse–echo technique. We find that the BFS varies linearly depending on temperature with a coefficient of approximately −17 MHz/K at 650 nm pump. Since this value is −34 times larger than that of silica fibers at 650 nm (0.495 MHz/K), and is even 10 times larger than that of PFGI-POFs at 650 nm (−1.72 MHz/K), we think that PMMA-POFs are potentially applicable to high-precision temperature sensing. We also find that the BFS varies nonlinearly depending on strain, which seems to be caused by the elastic-to-plastic transition of PMMA.

Brillouin scattering is one of the most important nonlinear phenomena in optical fibers. When pump light is injected into optical fibers, part of the light is reflected due to Brillouin scattering, i.e., the interaction between phonons and acoustic phonons.[13] The frequency of the Brillouin-scattered light is down-shifted by several GHz, and the amount of this frequency shift is called the BFS. In optical fibers, the BFS ν_B is given as[13]

$$\nu_B = \frac{2n v_A}{\lambda_p}, \tag{1}$$

where n is the refractive index, v_A is the acoustic velocity, and λ_p is the wavelength of the incident pump light. Consequently, the BFS in optical fibers can be estimated by using a measured value of v_A. Moreover, it is clear that, if the dependences of v_A on temperature and strain are obtained, the BFS dependences on temperature and strain can also be estimated, if we neglect the temperature and strain dependences of n. Although measuring v_A in SMFs using the ultrasonic pulse–echo technique is extremely difficult due to their small core diameter (~8 μm), we showed that it is feasible for PMMA-POFs with a large core diameter (980 μm).[12]

The experimental setup for acoustic velocity measurement is schematically shown in Fig. 1. An ultrasonic pulse generated with a transducer (Panametrics M316) connected to a pulser-receiver (Panametrics 5900PR) was directed to a POF sample fixed in degassed water, and the reflected waves were detected with the same transducer. The BFS was estimated by substituting the measured acoustic velocity into eq. (1) under the assumption that the acoustic velocity is independent of the frequency. We employed PMMA-POFs with numerical aperture (NA) of 0.5, core diameter of 980 μm, cladding diameter of 1000 μm, core refractive index of ~1.49, propagation loss of ~150 dB/km at 650 nm wavelength, and tolerable temperature range from −55 to 70 °C. The center frequency of the ultrasonic wave was approximately 10 MHz. The POF samples used to measure the strain

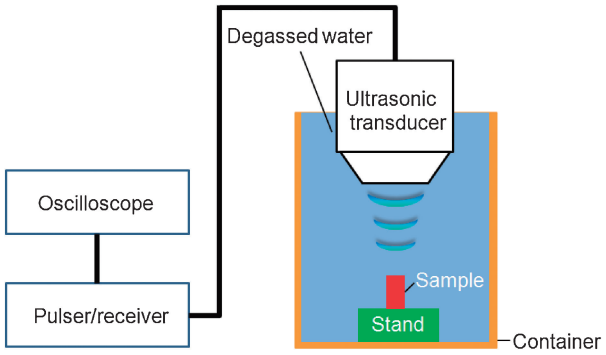

Fig. 1. Schematic setup for measuring the acoustic velocity in POF samples.

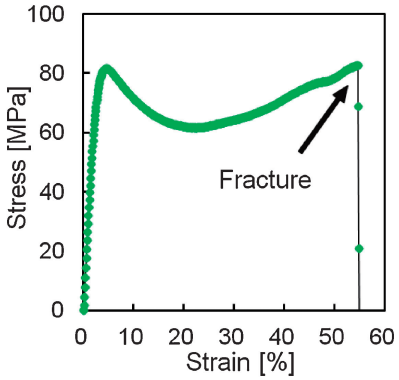

Fig. 3. Stress–strain curve in the PMMA-POF.

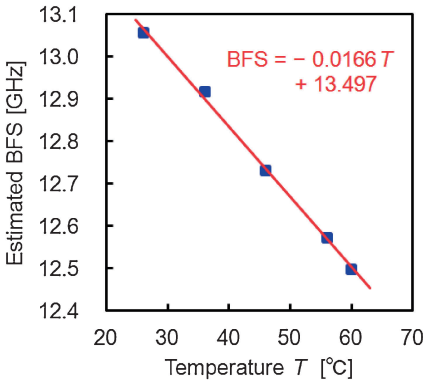

Fig. 2. Estimated BFS dependence on temperature in the PMMA-POF at 650 nm.

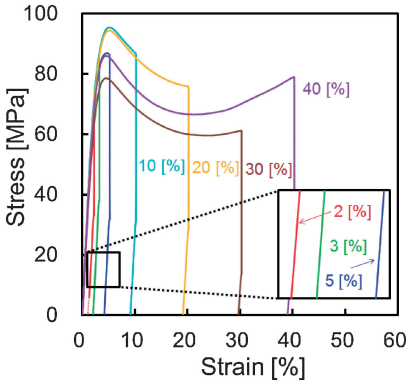

Fig. 4. Stress–strain curve for the fabrication of each POF sample. The inset shows a magnified view.

dependence were fabricated using the following procedure: (1) measure the stress–strain curve of the POFs and obtain their fracture strain ε_f, (2) keep strains of 2–40% ($< \varepsilon_f$) applied to the POFs for 15 min so that they do not relax to the initial length,[7] and (3) cut the elongated POFs into samples of several mm length.

The estimated BFS dependence on temperature in the PMMA-POF at 650 nm pump is shown in Fig. 2. The temperature was increased from 26 to 60 °C. We did not take into account the refractive-index dependence on temperature, because its coefficient in bulk PMMA is reported to be as small as $-1.2 \times 10^{-4}\,K^{-1}$.[14] The BFS was estimated to vary linearly depending on temperature with a coefficient of −17 MHz/K within this temperature range. This value agrees well with that of bulk PMMA,[12] which is −34 times larger than that of silica fibers at 650 nm (0.495 MHz/K)[15] and is even 10 times larger than that of PFGI-POFs at 650 nm (−1.72 MHz/K).[11] Therefore, compared with silica fibers and PFGI-POFs, PMMA-POFs can be potentially applied to high-precision temperature sensing.

Figure 3 shows the stress–strain curve of one of the PMMA-POFs. Upper and lower yield points were observed at 4.5 and 22%, respectively, and the fracture strain was 55%. This stress–strain curve indicates that the elastic-plastic transition of the PMMA-POF is induced at several % strain. Such stress–strain curves were also measured while each POF sample was being fabricated, as shown in Fig. 4. It is clear that, for each POF sample, residual strain exists even after it is released. Since the residual strain is slightly lower than the target strain, we define, for clarity, the residual strain as the "applied strain" in the next experiment. Figure 5 shows the estimated BFS dependence on applied strain in the PMMA-POFs at 650 nm pump. The refractive index n was assumed to be constant (1.49), and the temperature was kept at 19 °C. The BFS dependence on applied strain showed a nonlinear behavior; its coefficient was positive within the strain ranges of 0 to ∼10 and ∼20 to ∼40%, but was negative within the range of ∼10 to ∼20%. This feature is similar to that of the stress–strain curve shown in Fig. 3, probably originating from the transition of PMMA from the elastic to the plastic regime. Further study is, however, needed to clarify this point. While the sign of the strain coefficient of the PMMA-POFs around 0% applied strain was positive, that of PFGI-POFs is reported to be negative.[11] This difference indicates that the strain coefficient of POFs for small strain can be controlled, including its sign, by fluorine doping; thus, we can expect that high-precision temperature sensing with zero strain sensitivity can be achieved by optimizing the fluorine doping concentration.

In conclusion, the BFS dependences on temperature and strain in PMMA-POFs were estimated using ultrasonic pulse–echo technique. We found that the BFS varies linearly depending on temperature with a coefficient of approximately −17 MHz/K at 650 nm pump. Since this value is −34 times larger than that of silica fibers at 650 nm, and is

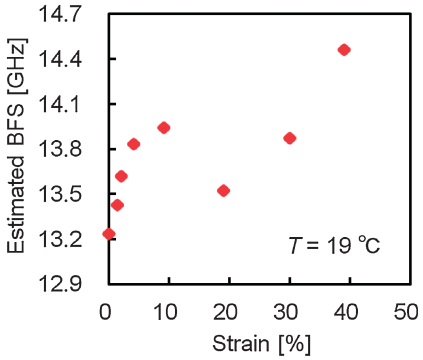

Fig. 5. Estimated BFS dependence on strain in the PMMA-POF at 650 nm.

even 10 times larger than that of PFGI-POFs at 650 nm, PMMA-POFs appear to be a good candidate for Brillouin-based temperature sensing with high precision. We also found that, in contrast, the BFS varied nonlinearly depending on applied strain, which seems to be related to the elastic-to-plastic transition of PMMA. More accurate estimation will be feasible by taking the refractive-index dependence on strain into consideration. We believe that this information will be useful in developing temperature/strain sensors based on Brillouin scattering in POFs with high flexibility, low cost, easy connection, high safety, and memory effect.

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