Brillouin frequency shift hopping in polymer optical fiber

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We investigated the Brillouin gain spectrum dependence on large strain of up to 60% in a polymer optical fiber (POF) at 1.55 μm, and found that the Brillouin frequency shift (BFS) abruptly changes from ~2.7 GHz to ~3.2 GHz. We named this phenomenon "BFS hopping," and found it to originate from the varied acoustic velocity induced by the stepwise change in the core diameter of the POF. This is because of the yielding of the overcladding layer composed of polycarbonate. After the occurrence of BFS hopping phenomenon, the BFS dependence coefficients on strain and temperature in the POF were measured to be −65.6 MHz/% and −4.04 MHz/K respectively. These values indicate that, compared to an unstrained POF, further higher-precision temperature sensing with lower strain sensitivity is feasible. © *2014 AIP Publishing LLC*.
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For the past several decades, Brillouin scattering in optical fibers have been intensively studied.[1,2] Its applications include lasers,[2] optical memories,[3] phase conjugators,[4] slow-light generators,[5] and distributed strain/temperature sensors.[6–10] To date, glass optical fibers are mainly used as the sensing heads of Brillouin sensors,[6–13] however, they can withstand only small strain and cannot be applied for large-strain sensing. To resolve this limitation, we propose a unique approach to employ polymer optical fibers (POFs)[14,15] as the Brillouin sensing heads.

POFs have various advantages over glass fibers, such as high flexibility (endurable for several tens of percent), low-cost connection, ease of handling, high safety, and a so-called memory effect.[16] Two types of commercially available POFs are poly(methyl methacrylate) (PMMA)-based POFs[14] and perfluorinated graded-index (PFGI)-POFs.[15] The former basically transmit only visible light at ~650 nm, while the latter can transmit light at telecommunication wavelength of up to 1.55 μm in addition to visible light. So far, we have succeeded in observing Brillouin scattering in PFGI-POFs at 1.55 μm, and studied its fundamental properties including Brillouin frequency shift (BFS), Brillouin linewidth, and Brillouin gain coefficient.[17] We have also investigated the BFS dependence on strain and temperature in PFGI-POFs, and showed their applicability to high-precision temperature sensing with reduced strain sensitivity.[18,19] Besides, we have recently measured the Brillouin gain spectrum (BGS) dependence on large strain of up to 20%,[20] and found that at ~10% strain, the Brillouin Stokes power starts to decrease. We attributed the reason for this behavior to an increased propagation loss leading to a shortened effective length.[20] However, the drastic decrease (~60%) in the Stokes power at 20% strain is not fully explained by only ~30% reduction of the effective length.

In this work, we investigate the BGS dependence on even larger strain of up to 60% in a PFGI-POF at 1.55 μm, and find that the BFS abruptly changes from ~2.7 GHz to ~3.2 GHz. This provides a reasonable explanation for the phenomenon described above. We name this "BFS hopping," the origin of which is shown to be the varied acoustic velocity induced by the stepwise change in the core diameter. Further, from our measurements, we found the strain- and temperature-dependence coefficients of the BFS in the slimmed-down POF (after the BFS hopping) to be −65.6 MHz/% and −4.04 MHz/K, respectively, indicating that with lower strain sensitivity, higher-precision temperature sensing can be achieved.

A beam of light when incident on an optical fiber interacts with the acoustic phonons generating backscattered Stokes light, which propagates in the direction opposite to the incident light. This phenomenon is called spontaneous Brillouin scattering.[1,2] The Stokes light spectrum, referred to as BGS, generally has a Lorentzian shape and the central frequency of the BGS shifts down relative to the incident frequency. The amount of this frequency shift is called BFS, which is ~10.8 GHz and ~2.8 GHz in a silica single-mode fiber (SMF)[2] and PFGI-POF,[17] respectively, at 1.55 μm wavelength. When a temperature change (or strain) is applied to the fiber, the BFS shifts towards a higher or lower frequency depending on the fiber core material; this is the fundamental operating principle of fiber-optic Brillouin temperature (or strain) sensors. The strain- and temperature-dependence coefficients of the BFS at 1.55 μm are reported to be, respectively, 493 MHz/% (Ref. 21) and 1.00 MHz/K (Ref. 22) for silica SMFs, and 121 MHz/% (Ref. 18) and 3.2 MHz/K (Ref. 23) for PFGI-POFs.

We employed a 0.6-m-long PFGI-POF with 50 μm core diameter. The core and cladding layers are composed of doped and undoped polyperfluorobutenylvinyl ether (trademark: CYTOP). The refractive index at the center of the core, the numerical aperture, and the propagation loss at 1.55 μm are 1.356, 0.185, and ~250 dB/km, respectively. The polycarbonate reinforcement overcladding layer (diameter of 490 μm) reduces micro-bending losses and increases the load-bearing capability. Instead of the standard experimental setup based on self-heterodyne detection,[17] we used a newly developed Fresnel-assisted setup,[24] which can detect

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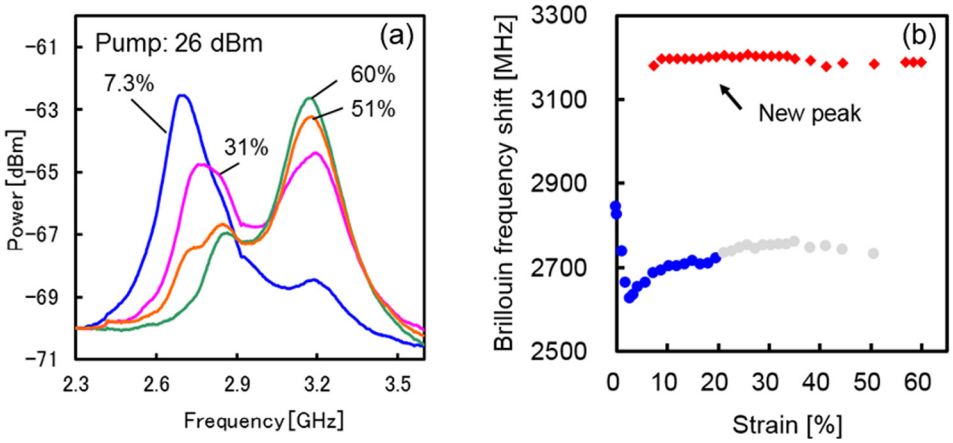

FIG. 1. Measured dependence of BGS (a) and BFS (b) of POF with large strain. In (b), the BFS of the initial peak was not accurately measured with strain >20% (colored in gray).

the BGS in POFs with a higher signal-to-noise ratio. Large strain was applied to the POF with two computer-controlled motorized stages at a room temperature of 20 °C.

First, we measured the BGS dependence on large strain of up to 60% in the POF, as shown in Fig. 1(a). The pump power was 26 dBm, and the strain rate was 200 μm/s. The Brillouin peak observed at ~2.8 GHz in the absence of strain shifted to lower frequency at <2.3% strain, and then shifted to a higher frequency; its peak power gradually reduced with increasing strain (>10%). This behavior has been reported earlier in Ref. 20. However, we first report the appearance of an additional peak at ~3.2 GHz when strain was >7.3% (Fig. 1(a)). At 31% strain, the power of the two peaks is almost the same, and at 60% strain, the initial peak almost disappeared (note that the peak at ~2.85 GHz originated from the ~3-cm-long unstrained POF section near the connector). The BFS of the two peaks were then plotted as functions of strain, as shown in Fig. 1(b). The dependence of the initial peak showed the same non-monotonic behavior as previously reported[20] (>20%, the BFS cannot be accurately measured). The BFS of the newly appeared peak was almost constant, independent of the applied strain in this range.

Next, side views of the POF in the presence of ~7.3% strain are shown in Fig. 2(a). Several sections were slimmed down in a stepwise manner, and with increasing strain, the slimmed sections grew longer (i.e., spread along the POF), while their outer diameter was maintained. This explains the independence of BFS from large strain (>7.3%) described above. The core diameter of the slimmed-down POF was estimated to be 0.84 times of that of the unstrained POF from a cross-sectional view shown in Fig. 2(b). This phenomenon is probably caused by the yielding of the overcladding layer made up of polycarbonate, and not because of the core or cladding layers. The upper yield point of ~8.0% (see Fig. 6 in Ref. 25) agrees with the strain at which the POF was slimmed down (according to the specification sheet, the upper yield point of CYTOP composing the core and cladding layers is approximately 20%). This abrupt change in the core diameter seems to have induced the change in the acoustic velocity, therefore resulting in the BFS hopping. Further, note that the unstable stress-strain curve of the PFGI-POF in the range from ~10% to 60% (see Fig. 1 in Ref. 20) can also be explained by this phenomenon.

Finally, after the whole length of the POF was slimmed down at 60% strain, its BGS/BFS dependence on strain and temperature was investigated after the strain was released, and the results are shown in Figs. 3(a)–3(d). Their BFS dependence coefficients were found to be −65.6 MHz/% and −4.04 MHz/K (Figs. 3(b) and 3(d)), which are 0.5 times[18] and 1.3 times[23] the value of an unstrained POF. This result indicates that further higher-precision temperature sensing

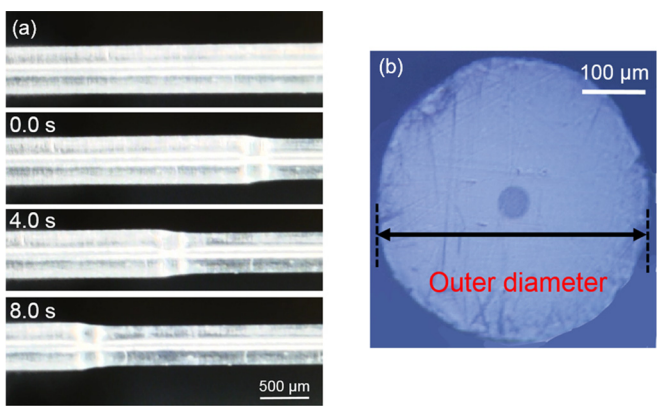

FIG. 2. (a) Side views of the slim-down process of the POF (taken every 4 s), and (b) cross-sectional view of the slimmed-down POF.

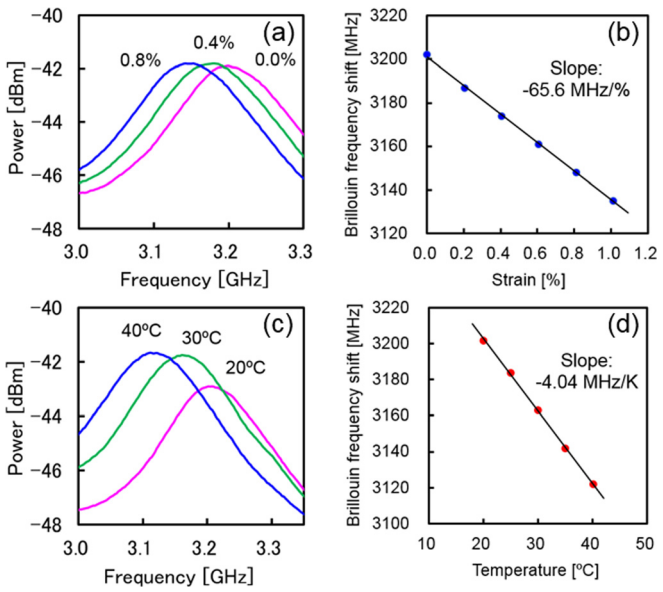

FIG. 3. Measured strain dependence of BGS (a) and BFS (b), and temperature dependence of BGS (c) and BFS (d) of the slimmed-down POF.

with lower strain sensitivity is feasible by exploiting the Brillouin signals in the slimmed-down POFs.

In conclusion, the BGS dependence on large strain of up to 60% in a PFGI-POF was investigated at 1.55 μm, and an abrupt change in BFS from ~2.7 GHz to ~3.2 GHz was observed. We showed that this "BFS hopping" is probably caused by the varied acoustic velocity induced by the stepwise change in the core diameter (because of the yield of polycarbonate-based overcladding layer). The strain- and temperature-dependence coefficients of the BFS in the slimmed-down POF were −65.6 MHz/% and −4.04 MHz/K, respectively, which indicates the possibility of further higher-precision temperature sensing with lower strain sensitivity. We believe that the physical aspects of these results are interesting and will be of great significance in developing POF-based large-strain sensing systems in the near future.

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