Brillouin Gain Spectrum Characterization in Perfluorinated Graded-Index Polymer Optical Fiber With 62.5-μm Core Diameter

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***Abstract*—We characterize the Brillouin gain spectra (BGS) in perfluorinated graded-index polymer optical fibers (PFGI-POFs) with 62.5-μm core diameter. First, we show that the Stokes power is extremely high compared to that of a standard PFGI-POF with 120-μm core, and discuss the Brillouin threshold power. Then, we demonstrate that the PFGI-POF length has little influence on the BGS when the length is longer than 50 m. We also predict that, at 1.55-μm wavelength, it is difficult to reduce the Brillouin threshold power of PFGI-POFs below that of long silica single-mode fibers even if their core diameter is sufficiently reduced to satisfy the single-mode condition. Finally, we confirm the Brillouin linewidth narrowing effect.**

***Index Terms*—Brillouin gain spectrum, Brillouin linewidth, Brillouin scattering, nonlinear optics, polymer optical fiber (POF).**

I. Introduction

BRILLOUIN scattering in silica-based optical fibers has attracted a great deal of attention [1], [2] and applied to a number of systems, such as lasers [2], signal processors [3], slow light generators [4], and strain/temperature sensors [5]–[9]. These systems have been improved in performance by exploiting Brillouin scattering in various specialty fibers, including tellurite glass fibers [10], chalcogenide fibers [11], bismuth-oxide fibers [12], and photonic crystal fibers [13]. Recently, we have succeeded in observing spontaneous Brillouin scattering (SpBS) at 1.55 μm in polymer optical fibers (POFs) [14], which offer extremely high flexibility, low-cost and easy connection, and high safety compared to other standard glass fibers [15]. The POFs used in the experiment were standard perfluorinated graded-index (PFGI-) POFs with 120-μm core diameter. The estimated Brillouin gain coefficient of 3.09×10^{-11} m/W was almost the same as that of a silica single-mode fiber (SMF), which indicates that Brillouin scattering in PFGI-POFs is applicable to various practical systems in the same way as Brillouin scattering in silica fibers. We have also investigated the dependences of the Brillouin frequency shift (BFS) on strain and temperature in a PFGI-POF at 1.55 μm, and found that SpBS in PFGI-POFs can be potentially utilized to develop high-accuracy temperature sensors with low strain sensitivity [16].

However, the power of the SpBS Stokes light generated in the PFGI-POFs with 120-μm core diameter was quite low due to their multimode nature, and it needs to be enhanced for detailed investigations of the Brillouin gain spectra (BGS) [17]–[19] including the linewidth narrowing effect. One method is to induce stimulated Brillouin scattering (SBS) with low threshold power using so-called pump-probe technique [18], where two light beams are launched from both ends of the PFGI-POF. We have so far obtained extremely large Stokes signal in this scheme [20]. However, since the BGS observed with this technique is easily influenced by the time constant of lock-in detection, detailed evaluation of its linewidth was not feasible. Another approach to enhance the Stokes signal is to make use of PFGI-POFs with core diameters smaller than 120 μm. Although PFGI-POFs with 62.5-μm core diameter have become commercially available very recently (product ID: ID062, Sekisui Chemical Co., Ltd., 2011), no study has been reported on their Brillouin scattering properties.

In this letter, we characterize the BGS in PFGI-POFs with 62.5-μm core diameter. First, using 5-m PFGI-POFs, we show that extremely high Stokes power can be obtained compared to that of a PFGI-POF with 120-μm core, and estimate the Brillouin threshold power to be 53.3 W. Then, we experimentally show that using a PFGI-POF longer than $\sim$ 50 m is not an effective way to enhance the Stokes signal. We also theoretically predict that it is difficult to decrease the Brillouin threshold power of PFGI-POFs at 1.55-μm wavelength down to that of km-order-long silica SMFs even when their core diameter is sufficiently reduced to satisfy the single-mode condition. Finally, we investigate the Brillouin linewidth as a function of pump power, and confirm the linewidth narrowing effect.

II. Experiments and Discussion

A. Experimental Setup

Regardless of the length and the core diameter, PFGI-POFs used in the experiment had a numerical aperture (NA) of 0.185, a core refractive index of $\sim$ 1.35, and a propagation loss of ~ 250 dB/km at 1.55 μm. The experimental setup was basically the same as that previously reported in [14], where the BGS can be observed with high resolution by heterodyne detection. A distributed-feedback laser diode (DFB-LD) at 1547 nm was

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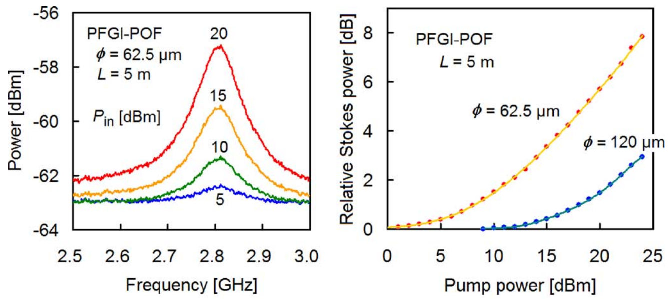
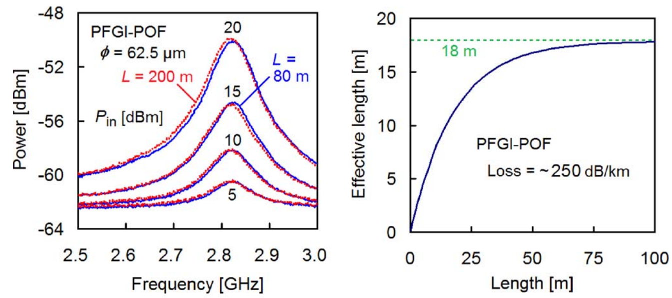


(a) (b)

Fig. 1. (a) BGS dependence on pump power $P_{\rm in}$. (b) Relative Stokes power as a function of pump power; comparison between PFGI-POFs with 62.5- and 120-μm core diameters.



(a) (b)

Fig. 2. (a) BGS dependence on pump power $P_{\rm in}$; comparison between 80-m PFGI-POF (solid line) and 200-m PFGI-POF (dotted line). (b) Effective fiber length versus fiber length.

used as a light source. One end of the PFGI-POF to be measured was optically butt-coupled to the silica SMF, and the other end was kept open.

B. Effects of Small Core Diameter

Fig. 1(a) shows the measured BGS of a 5-m PFGI-POF with 62.5-μm core at pump power $P_{\rm in}$ of 5, 10, 15, and 20 dBm. The polarization state optimized for $P_{\rm in}$ of 20 dBm was employed for all the measurements. The center frequency of the BGS, i.e., the BFS, was approximately 2.81 GHz, which is slightly lower than previously-reported value of 2.83 GHz [14] due to the difference in room temperature [16]. Even when $P_{\rm in}$ was as low as 5 dBm, small but clear BGS was observed. Fig. 1(b) shows the $P_{\rm in}$ dependences of the relative Stokes power, when 5-m PFGI-POFs with core diameters of 62.5 μm and 120 μm (Product ID: Lucina "X", Asahi Glass Co., Ltd., 2009) were employed. The reference power was set to about -63 dBm, which is the Stokes power when $P_{\rm in}$ is sufficiently low. The dependence curve of the PFGI-POF with 62.5-μm core was about 10 dB lower in pump power than that with 120-μm core, which indicates that, even at the same pump power, we can largely enhance the Stokes signal by using a PFGI-POF with a smaller core diameter.

One of the reasons for the 10-dB curve shift is the difference in Brillouin threshold power $P_{\rm th}$. In general, $P_{\rm th}$ is given as [2]

$$P_{\rm th} = \frac{21\, b\, A_{\rm eff}}{K\, g_B\, L_{\rm eff}}, \tag{1}$$

where b is the correction factor for multimode fibers [21], K is the polarization coefficient, and g_B is the Brillouin gain coefficient. $A_{\rm eff}$ is the effective cross-sectional area, which is approximately in proportion to the core diameter for multimode fibers [22], [23]; and $L_{\rm eff}$ is the effective fiber length defined as $L_{\rm eff} = [1 - \exp(-\alpha L)]/\alpha$ (α, propagation loss; L, fiber length) [2]. Using the values of $b = 2$ [21], $K = 0.667$ [2], $g_B = 3.09 \times 10^{-11}$ m/W [14], $\alpha = 0.056$/m ($= 250$ dB/km), and $L = 5$ m, $P_{\rm th}$ of the PFGI-POF with 120-μm core ($A_{\rm eff} = 209\ \mu\text{m}^2$ [24]) was calculated to be 97.7 W. On the other hand, $P_{\rm th}$ of the PFGI-POF with 62.5-μm core ($A_{\rm eff} = 108.9\ \mu\text{m}^2$) was calculated to be 53.3 W, which is lower than 97.7 W by 2.63 dB. Thus, the curve shift observed in Fig. 1(b) can be partially explained by the difference in $P_{\rm th}$, but its amount of 10 dB is much larger than the calculated value.

Another reason for the curve shift is the improvement of optical coupling efficiency at the butt coupling when the Stokes light generated in the PFGI-POF travels back and is injected into the SMF. Due to the unstable core alignment and the rough surface of the PFGI-POF, it is difficult to measure the coupling loss accurately. However, we confirmed that the loss with the PFGI-POF with 62.5-μm core was several dB lower than that with 120-μm core. This fact, along with the difference in internal structure designed by different manufacturers, moderately explains the 10-dB curve shift.

C. Effects of Long Fiber Length

According to (1), the use of long PFGI-POFs is another way to reduce $P_{\rm th}$ and to enhance the Stokes signal. Fig. 2(a) shows the measured BGS of 80-m and 200-m PFGI-POFs with 62.5-μm core at $P_{\rm in}$ of 5, 10, 15, and 20 dBm. Much larger Stokes signals (~ 7 dB higher at $P_{\rm in}$ of 20 dBm) than those of the 5-m PFGI-POF shown in Fig. 1(a) were observed.

However, there was hardly any difference between the BGS of the 80-m PFGI-POF and that of the 200-m PFGI-POF, with a very slight discrepancy of the BFS caused by the room- temperature difference. This means that the incident light is considerably attenuated after propagation for 80 m in the PFGI-POF. In order to estimate this effect quantitatively, the effective PFGI-POF length $L_{\rm eff}$ was plotted as a function of actual length L as shown in Fig. 2(b), where $L_{\rm eff}$ gradually approaches 18 m ($P_{\rm th} \sim 13$ W) with the increasing L. Thus, we proved that employing a PFGI-POF longer than ~ 50 m is not an effective way to enhance the Stokes signal.

According to (1), as the core diameter decreases, the Brillouin threshold $P_{\rm th}$ also becomes lower. When $P_{\rm in}$ is higher than $P_{\rm th}$, SBS is induced and consequently the Stokes signal is exponentially enhanced [2]. Here, under the rough assumption that the multimode nature, NA, refractive index, and loss do not change with core diameters, we calculated $P_{\rm th}$ of a 50-m PFGI-POF with 10-μm core diameter ($A_{\rm eff} = 17.4\ \mu\text{m}^2$) to be 2.22 W ($= 33.5$ dBm). This value is more than one order magnitude higher than the pump power of several tens to hundreds of mW commonly used in BGS characterization in silica SMFs [17], [19]. Even when the PFGI-POF is treated as an SMF (i.e., $b = 1$ [2] but $A_{\rm eff}$ becomes larger [23] in (1)), this difference cannot be compensated. Thus, it seems to be difficult to reduce $P_{\rm th}$ of PFGI-POFs down to the same level of that of long silica SMFs

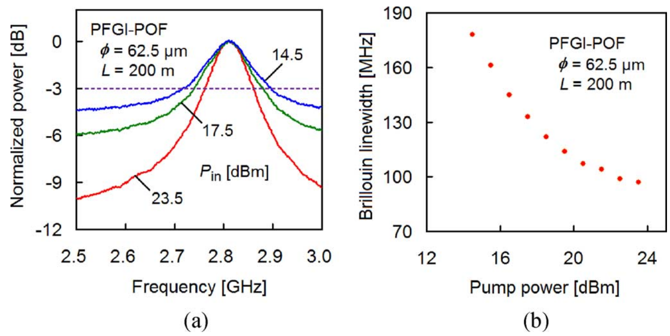


Fig. 3. (a) Normalized BGS at pump power of 14.5, 17.5, and 23.5 dBm. (b) Brillouin linewidth versus pump power.

by decreasing the core diameter, which is due to the limited effective length of 18 m associated with the high propagation loss at 1.55 μm.

D. Brillouin Linewidth Narrowing Effect

The Brillouin linewidth of a PFGI-POF has been reported to be 105 MHz at $P_{\rm in}$ of 20 dBm in [14], but detailed investigation was difficult because the Stokes power was extremely low. Here, by making use of the enhanced Stokes power, we investigated the Brillouin linewidth dependence on $P_{\rm in}$.

Fig. 3(a) shows the measured BGS of the 200-m PFGI-POF with 62.5-μm core at $P_{\rm in}$ of 14.5, 17.5, and 23.5 dBm, where the Stokes power is normalized so that the maximum power is 0 dB. Fig. 3(b) shows the Brillouin linewidth dependence on $P_{\rm in}$. From these figures, we can see that, with the increasing $P_{\rm in}$, the 3-dB linewidth of the BGS decreases, but that its slope gradually becomes small. This behavior agrees well with the experiment and theory of the linewidth narrowing effect in silica-based SMFs [17].

III. Conclusion

The BGS properties of PFGI-POFs with 62.5-μm core diameter were investigated. The Stokes power was extremely high compared to that of a PFGI-POF with 120-μm core, and the Brillouin threshold power for 5-m PFGI-POF was estimated to be 53.3 W. It was also shown that employing a PFGI-POF longer than $\sim$ 50 m is not an effective way to enhance the Stokes signal. In addition, it was theoretically found that it is difficult to reduce the Brillouin threshold power of PFGI-POFs at 1.55-μm wavelength below that of long silica SMFs even if their core diameter is sufficiently decreased to satisfy the single-mode condition. Finally, the Brillouin linewidth narrowing effect was confirmed. We believe these results will be a good guideline for developing practical Brillouin systems using PFGI-POFs as well as for designing new PFGI-POF structures for Brillouin applications in future.

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