Experimental study of Brillouin scattering in perfluorinated polymer optical fiber at telecommunication wavelength

Yosuke Mizuno[a)] and Kentaro Nakamura
Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

(Received 4 June 2010; accepted 20 June 2010; published online 13 July 2010)

Brillouin scattering properties in a perfluorinated graded-index polymer optical fiber (POF) with 120 μm core diameter were experimentally investigated using a laser with an operating wavelength of 1.55 μm. The Brillouin frequency shift and the Brillouin bandwidth were 2.83 GHz and 105 MHz, respectively. The calculated Brillouin gain coefficient of 3.09×10^{-11} m/W was comparable to that of fused silica fibers. The Brillouin threshold power of the 100 m POF was estimated to be 24 W, which we believe can be reduced by employing POFs with smaller cores. © *2010 American Institute of Physics*. [doi:10.1063/1.3463038]

Polymer optical fibers (POFs) (Refs. 1 and 2) offer extremely easy and low-cost connection compared to other standard glass fibers. They are also so flexible that strain of over 40% can be applied.[3] Therefore, in spite of their higher loss than that of silica fibers, POFs have been used both in medium-range communication applications such as home networks and automobiles,[4] and in high-strain monitoring applications.[3,5] On the other hand, Brillouin scattering[6,7] is one of the most important nonlinear effects in optical fibers, and has been extensively studied. It has many useful applications, such as optical amplification,[7] lasing,[7,8] optical comb generation,[8] microwave signal processing,[9] slow light generation,[10] phase conjugation,[11] tunable delay generation,[12] and strain/temperature sensing.[13–15] So far, Brillouin scattering has been investigated not only for silica fibers but also for some specialty fibers including tellurite glass fibers,[16,17] As_2Se_3 chalcogenide fibers,[18,19] bismuth-oxide fibers,[20,21] and photonic crystal fibers.[22,23] However, the observation of Brillouin scattering in POFs has not been reported yet, which is expected to add various advantages of POFs to the conventional Brillouin application field.

In this letter, we report on the observation of Brillouin scattering in a POF in the 1.55 μm wavelength region. The Brillouin frequency shift (BFS) of 2.83 GHz and the Brillouin linewidth of 105 MHz were measured. The Brillouin gain coefficient g_B of the POF was calculated to be 3.09×10^{-11} m/W, which is close to that of fused silica fibers. The Brillouin threshold power was estimated to be as high as 24 W, which is in agreement with the theoretical predictions reported so far.

A standard POF based on polymethyl methacrylate (PMMA) (Refs. 1 and 2) is optimized for transmission at 650 nm, with a propagation loss of $\sim$200 dB/km. Its loss at telecommunication wavelength, however, is so high ($\geqslant 1\times10^5$ dB/km) that the Brillouin signal cannot be detected. Meanwhile, in order to observe Brillouin scattering in a PMMA-based POF at 650 nm, we need to prepare all the necessary optical devices at this wavelength, which are quite difficult or expensive to prepare. Therefore, we employed a 100 m perfluorinated graded-index POF (PFGI-POF) (Ref. 24) instead of a PMMA-based POF. It has a numerical aperture (NA) of 0.185, a core diameter of 120 μm, a core refractive index of 1.35, and a relatively low loss ($\sim$150 dB/km) even at 1.55 μm.

The experimental setup to study the Brillouin scattering in the PFGI-POF is depicted in Fig. 1. In order to measure the BFS with a high resolution, self-heterodyne detection[15] was used. All the optical paths except the POF were composed of silica single-mode fibers (SMFs). A distributed-feedback laser diode (DFB-LD) at 1552 nm with 10 MHz linewidth was used as a light source, and its output was divided into two light beams with a coupler. One of the beams was directly used as the reference light of the heterodyne detection, after passing a polarization controller (PC). The other beam was amplified with an erbium-doped fiber amplifier (EDFA) and injected into the POF as the pump light. Then, the optical beat signal between the backscattered Stokes light and the reference light was converted to an electrical signal with a photodetector (PD). Finally, the signal was amplified by 23 dB with an electrical preamplifier, and monitored with an electrical spectrum analyzer (ESA). The measurement data were transferred to a personal computer. In this setup, the coupling between the silica SMF and the POF was implemented using so-called butt coupling.[25] Considering the difference between the core diameters (8 μm of SMF versus 120 μm of POF), a large optical loss is expected when light travels from the POF into the SMF, which contributes only to the attenuation of the Stokes light once

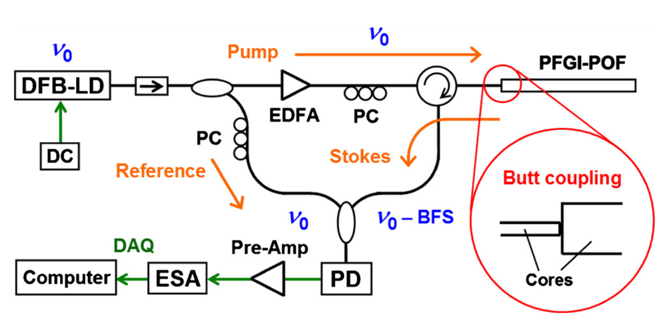

FIG. 1. (Color online) Experimental setup for observing Brillouin scattering in the PFGI-POF: DAQ, data acquisition; dc, direct current; DFB-LD, distributed-feedback laser diode; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; PC, polarization controller; and PD, photodetector.

a)Electronic mail: ymizuno@sonic.pi.titech.ac.jp.

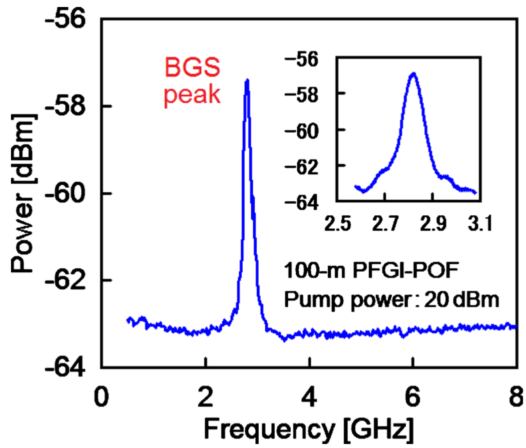

FIG. 2. (Color online) Measured BGS in the PFGI-POF at the pump power of 20 dBm. The inset shows the magnified view around the BGS peak.

generated in the POF. It was measured to be approximately 12 dB, which will be improved by developing an optical lens system. On the other hand, the loss was less than 0.2 dB when light travels from the SMF into the POF. This is sufficiently low to characterize the Brillouin scattering in the POF.

Figure 2 shows the measured Brillouin gain spectrum (BGS) when the 100 m PFGI-POF was pumped with 20 dBm light. The peak corresponding to the BFS was observed at 2.83 GHz, about four times lower than that of standard silica fibers, which allows the use of a PD and an ESA that are cheaper with lower bandwidth. The acoustic velocity v_A is given by the BFS ν_B as[7]

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

where n is the refractive index (1.35) and λ_p is the wavelength of the pump light (1552 nm). So v_A in this POF can be calculated to be 1627 m/s, which is much lower than that of standard bulk PMMA, ~2700 m/s.[26] By fitting the BGS with a Lorentzian curve, the 3 dB Brillouin linewidth $\Delta\nu_B$ was measured to be 105 MHz, which is three to five times broader than that of silica fibers.[27]

Figure 3 shows the relative Stokes gain as a function of pump power. In general, the Stokes gain begins to grow exponentially at the Brillouin threshold power P_{th} and then reaches saturation, which indicates the transition from spontaneous to stimulated Brillouin scattering. Though a rough estimation of P_{th} is often performed using this kind of figure,[7,16,18,27,28] the saturation of the Stokes gain was not observed in Fig. 3. Therefore, P_{th} of this POF seems to be higher than 30 dBm (=1 W). The detailed estimation of P_{th} will be given later in this paper.

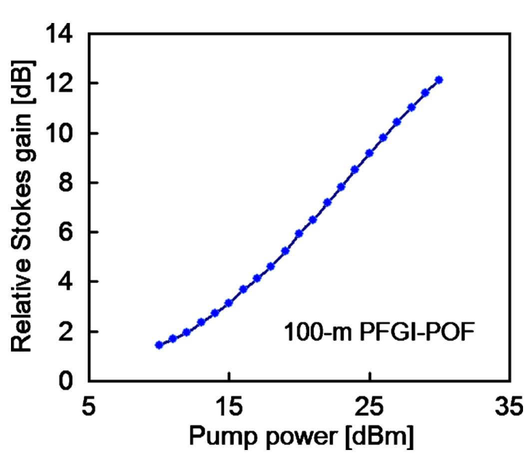

FIG. 3. (Color online) Relative gain of the Stokes light backscattered from 100 m PFGI-POF as a function of pump power.

Next, we estimate the Brillouin gain coefficient g_B. Using the acoustic velocity v_A and the Brillouin linewidth $\Delta\nu_B$, g_B is given by[28]

$$g_B = \frac{2\pi n^7 p_{12}^2}{c\lambda_p^2 \rho v_A \Delta\nu_B}, \tag{2}$$

where p_{12} is the longitudinal elasto-optic coefficient, c the light velocity, and ρ the density. Since the accurate values of p_{12} and ρ are not known for perfluorinated PMMA, we used the values of standard PMMA (Ref. 29) in this calculation. We think further research is needed on this point, but using the measured values of $v_A=1627$ m/s and $\Delta\nu_B=105$ MHz, along with $n=1.35$, $p_{12}=0.297$, $\lambda_p=1552$ nm, and $\rho=1187.5$ kg/m^3, g_B was calculated to be 3.09×10^{-11} m/W, which is almost the same as that of fused silica fibers ($3-5\times10^{-11}$ m/W).[7]

Then, we estimate the Brillouin threshold power P_{th} of the PFGI-POF. An alternative way to calculate g_B is to use the following equation:[30]

$$g_B = \frac{21 b A_{eff}}{K P_{th} L_{eff}}, \tag{3}$$

where A_{eff} is the effective cross-sectional area and L_{eff} is the effective length defined as $L_{eff}=[1-\exp(-\alpha L)]/\alpha$ (α, background loss; L, fiber length). For multimode fibers, a correction factor b is needed,[31] which can be treated as 2 when the NA of the fiber is nearly 0.2. K is a constant that depends on the polarization properties of the fiber,[28,32] which is 1 if the polarization is maintained and 0.667 otherwise. Then, using the values of $g_B=3.09\times10^{-11}$ m/W, $b=2$, $A_{eff}=209$ μm^2,[33] $K=0.667$, $\alpha=0.056$/m, and $L=100$ m, P_{th} can be calculated to be 24 W. This is quite high but valid compared to the theoretically predicted values of ~10 W ($L=300$ m) (Ref. 33) or ~100 W ($L=100$ m) (Ref. 34) reported by other groups. As P_{th} is in proportion to bA_{eff} in Eq. (3), we think P_{th} can be reduced to a moderate power level by employing POFs with smaller cores.

In conclusion, we investigated the Brillouin scattering in the PFGI-POF at 1.55 μm wavelength. The BFS and the Brillouin bandwidth were 2.83 GHz and 105 MHz, respectively. Using these values, the Brillouin coefficient was calculated to be 3.09×10^{-11} m/W, which is close to that of fused silica fibers. This indicates that, as Brillouin scattering in silica fibers has a wide field of application, Brillouin scattering in POFs can also be utilized to develop various practical devices and systems with their low cost, ease of installation, and high flexibility.

This work was partly supported by the Research Fellowships for Young Scientists from the Japan Society for the Promotion of Science (JSPS).

[1]M. G. Kuzyk, *Polymer Fiber Optics: Materials, Physics, and Applications* (CRC, Boca Raton, 2006).
[2]Y. Koike, T. Ishigure, and E. Nihei, J. Lightwave Technol. **13**, 1475 (1995).

[3]I. R. Husdi, K. Nakamura, and S. Ueha, Meas. Sci. Technol. **15**, 1553 (2004).
[4]I. Mollers, D. Jager, R. Gaudino, A. Nocivelli, H. Kragl, O. Ziemann, N. Weber, T. Koonen, C. Lezzi, A. Bluschke, and S. Randel, IEEE Commun. Mag. **47**, 58 (2009).
[5]S. Liehr, P. Lenke, M. Wendt, K. Krebber, M. Seeger, E. Thiele, H. Metschies, B. Gebreselassie, and J. C. Munich, IEEE Sens. J. **9**, 1330 (2009).
[6]E. P. Ippen and R. H. Stolen, Appl. Phys. Lett. **21**, 539 (1972).
[7]G. P. Agrawal, *Nonlinear Fiber Optics* (Academic, California, 1995).
[8]G. J. Cowle, D. Yu, and Y. T. Chieng, J. Lightwave Technol. **15**, 1198 (1997).
[9]S. Norcia, S. Tonda-Goldstein, D. Dolfi, and J.-P. Huignard, Opt. Lett. **28**, 1888 (2003).
[10]K. Y. Song, M. G. Herraez, and L. Thevenaz, Opt. Express **13**, 82 (2005).
[11]E. A. Kuzin, M. P. Petrov, and B. E. Davydenko, Opt. Quantum Electron. **17**, 393 (1985).
[12]W. Zou, Z. He, and K. Hotate, Appl. Phys. Express **3**, 012501 (2010).
[13]T. Horiguchi and M. Tateda, J. Lightwave Technol. **7**, 1170 (1989).
[14]K. Hotate and T. Hasegawa, IEICE Trans. Electron. **E83-C**, 405 (2000).
[15]Y. Mizuno, W. Zou, Z. He, and K. Hotate, Opt. Express **16**, 12148 (2008).
[16]K. S. Abedin, Opt. Express **14**, 11766 (2006).
[17]Y. Mizuno, Z. He, and K. Hotate, Opt. Commun. **283**, 2438 (2010).
[18]K. S. Abedin, Opt. Express **13**, 10266 (2005).
[19]K. Y. Song, K. S. Abedin, K. Hotate, M. G. Herraez, and L. Thevenaz, Opt. Express **14**, 5860 (2006).
[20]J. H. Lee, T. Tanemura, K. Kikuchi, T. Nagashima, T. Hasegawa, S. Ohara, and N. Sugimoto, Opt. Lett. **30**, 1698 (2005).
[21]Y. Mizuno, Z. He, and K. Hotate, Appl. Phys. Express **2**, 112402 (2009).
[22]J. H. Lee, Z. Yusoff, W. Belardi, M. Ibsen, T. M. Monro, and D. J. Richardson, Opt. Lett. **27**, 927 (2002).
[23]J. C. Beugnot, T. Sylvestre, D. Alasia, H. Maillotte, V. Laude, A. Monteville, L. Provino, N. Traynor, S. F. Mafang, and L. Thevenaz, Opt. Express **15**, 15517 (2007).
[24]T. Ishigure, Y. Koike, and J. W. Fleming, J. Lightwave Technol. **18**, 178 (2000).
[25]Y. Sidorin and D. Howe, Opt. Lett. **22**, 802 (1997).
[26]K. Hattori, T. Matsuoka, K. Sakai, and K. Takagi, Jpn. J. Appl. Phys., Part 1 **33**, 3217 (1994).
[27]A. Yeniay, J. M. Delavaux, and J. Toulouse, J. Lightwave Technol. **20**, 1425 (2002).
[28]D. Cotter, Electron. Lett. **18**, 495 (1982).
[29]M. Silva-López, A. Fender, W. N. MacPherson, J. S. Barton, J. D. C. Jones, D. Zhao, H. Dobb, D. J. Webb, L. Zhang, and I. Bennion, Opt. Lett. **30**, 3129 (2005).
[30]R. G. Smith, Appl. Opt. **11**, 2489 (1972).
[31]K. Tei, Y. Tsuruoka, T. Uchiyama, and T. Fujioka, Jpn. J. Appl. Phys. **40**, 3191 (2001).
[32]M. O. van Deventer and A. J. Boot, J. Lightwave Technol. **12**, 585 (1994).
[33]M. Dossou, P. Szriftgiser, and A. Goffin, Proceedings of the 13th Annual Symposium IEEE/LEOS Benelux, University of Twente, Enschede, The Netherlands, November 2008, Chaps. 27–28, p. 175 (www.leosbenelux.org/symposium/Schedule.pdf).
[34]P. Lenke and N. Nother, Proc. SPIE **6582**, 658213 (2007).