Characterization of Stimulated Brillouin Scattering in Polymer Optical Fibers Based on Lock-in-Free Pump–Probe Technique

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***Abstract*—We observe stimulated Brillouin scattering (SBS) in polymer optical fibers (POFs) using a pump–probe technique without lock-in detection, and fully investigate the dependences of the Brillouin gain spectrum on the POF length, pump power, probe power, and temperature. Since the POF has relatively high propagation loss of 250 dB/km at 1.55 μm, an optimal POF length exists for SBS observation, which is found to be approximately 3.8 m with 21.1-dBm pump and 22.2-dBm probe waves. As the probe and pump powers are increased, the Stokes power is also raised but nonlinearly. The temperature dependence of the Brillouin frequency shift is –4.02 MHz/K, which agrees well with the previous report. These results indicate that the Brillouin signal in POFs observed with this technique can be directly applied to the development of POF-based Brillouin optical time-domain analysis systems for high-precision temperature sensing.**

***Index Terms*—Brillouin optical time-domain analysis (BOTDA), distributed measurement, optical fiber sensing, polymer optical fibers, stimulated Brillouin scattering.**

I. Introduction

FOR the past several decades, increasing attention has been directed toward Brillouin scattering in optical fibers [1], which can be applied to a variety of devices and systems, such as lasers [1], microwave signal processors [2], optical memories [3], phase conjugators [4], slow light generators [5], and distributed strain/temperature sensors [6]–[10]. Brillouin properties in many specialty fibers have been investigated to improve their performances, including tellurite glass fibers, chalcogenide glass fibers, bismuth-oxide glass fibers, photonic crystal fibers, and rare-earth-doped glass fibers [11]. All of these glass optical fibers (GOFs) are, however, fragile and require careful handling; in addition, in sensing applications, they cannot be used to measure large strain of over several tens of percentage. Recently, we have put forward a new approach for resolving these problems by exploiting Brillouin scattering in polymer optical fibers (POFs) with extremely high flexibility, which can withstand >50% strain. Especially for sensing applications, some spontaneous Brillouin properties of perfluorinated graded-index (PFGI-) POFs have been investigated at 1.55 μm, and their Brillouin gain coefficient [12], Brillouin threshold power [12], Brillouin frequency shift (BFS) [12], and BFS dependences on strain and temperature [13], [14] have been clarified. These results show that Brillouin scattering in POFs is potentially applicable both to high-precision temperature sensing [13] and to large-strain sensing [14].

Candidate techniques for adding distributed measurement capability to strain/temperature sensors based on Brillouin scattering in POFs include Brillouin optical time-domain reflectometry (BOTDR) [6], Brillouin optical correlation-domain reflectometry (BOCDR) [7], Brillouin optical time-domain analysis (BOTDA) [8], Brillouin optical frequency-domain analysis (BOFDA) [9], and Brillouin optical correlation-domain analysis (BOCDA) [10]. Considering the relatively small Brillouin signal in POFs because of their large core diameter and multimode nature, stimulated Brillouin scattering (SBS)-based analysis systems are preferable to spontaneous Brillouin scattering (SpBS)-based reflectometers. Although each analysis system has its own advantages and disadvantages, here we focus on BOTDA, which is most widely used in the world. SBS in POFs was already observed with so-called pump–probe technique [15], but, since the experimental setup included a lock-in detector, it was not directly applicable to standard BOTDA systems. As is well known, lock-in detection enables us to measure very small ac signals based on a technique known as phase-sensitive detection to single out the component of the signal at a specific reference frequency and phase. The reason for the difficulty in observing SBS in POFs without lock-in detection has been clarified to originate not from their structural problems (large core diameter, etc.) but from their physical problems (high propagation loss, etc.) [16]. Here, we should note that researchers have tried to detect SBS signals using a 100-m-long PFGI-POF, but to no effect [16].

In this paper, we observe SBS in POFs, for the first time, using the pump–probe technique without lock-in detection, and fully investigate the dependences of the Brillouin gain spectrum (BGS) on POF length, pump power, probe power, and temperature. The optimal POF length for SBS observation is found to be ~3.8 m when the probe and pump powers are 21.1 dBm and 22.2 dBm, respectively. The Stokes power is raised

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nonlinearly with increasing probe and pump powers. The temperature dependence of the BGS is also measured. These results will be significant information in developing POF-based BOTDA systems.

II. Principle

When a pump wave is injected into an optical fiber, backscattered Stokes light is generated due to SpBS. The Stokes wave spectrum is called the BGS [1]. The center frequency of the Stokes wave is known to be lower than that of the pump wave. The amount of this frequency shift is called the BFS, which is, at 1.55 μm, typically ~10.8 GHz for silica single-mode fibers (SMFs) [1] and ~2.8 GHz for PFGI-POFs [12]. In general, the Stokes power is raised with increasing pump power. When the pump power becomes higher than a certain power called Brillouin threshold power $P_{\rm th}$, the Stokes power begins to drastically increase due to the transition from SpBS to SBS. For sensing applications, the Brillouin Stokes power should be as high as possible, because it leads to high spatial resolution, long measurement range, short measurement time, etc. However, since $P_{\rm th}$ of POFs is extremely high (~53.8 dBm for a 10-m-long PFGI-POF [17]), observing large SBS signal is not easy.

One effective method to generate SBS irrespective of the high $P_{\rm th}$ is a so-called pump–probe technique. The main idea is to provide the SBS seed artificially by using probe wave at the same frequency as the Stokes wave, which is additionally injected into the other end of the fiber. Thus, SBS can be induced at much lower pump power. This scheme has been exploited in developing silica SMF-based BOTDA [6], [18] and BOCDA systems [9], [19]. Although many researchers have attempted to induce SBS in POFs, hardly any experimental results have been reported thus far. In the only successful report, a complicated setup based on lock-in detection was utilized [15], which cannot be directly applied to standard BOTDA systems. The difficulty in observing SBS in POFs with this technique has been shown to consist in the physical problems including their high propagation loss [16]. One solution is to optimize the POF length and the pump/probe powers; when the length is too long, the pump and the probe waves are highly attenuated and do not interact efficiently with each other.

III. Experimental Setup

We employed nine kinds of PFGI-POFs with the lengths ranging from 0.3 to 50 m as fiber under tests (FUTs), all of which had numerical aperture (NA) of 0.185, core diameter of 50 μm, cladding diameter of 750 μm, core refractive index of ~1.35, and propagation loss of ~250 dB/km at 1.55 μm. Both ends of the FUTs were connected to silica SMFs with a multimode fiber (MMF)-assisted coupling technique [20], which can mitigate the damage or burning at the POF/SMF interfaces. Two 1-m-long silica MMFs with BFS of ~10.4 GHz [16] at room temperature were inserted, which have practically no influence on the observation of the BGS in the POFs.

The experimental setup for observing SBS with the pump–probe technique is schematically shown in Fig. 1. Two laser diodes (LDs) at 1.55 μm were used as light sources; one (Santec, TSL-210) was for providing a pump wave, and the other (NEC, NX8562LB) was for a probe wave. The center frequency of the pump wave was swept from ν_0 – 1.3 GHz to ν_0 + 1.3 GHz by modulating the LD driving current with a sawtooth waveform at 80 Hz (ν_0 is the center frequency with no modulation appied) provided by a function generator (NF Electronic Instruments, 1930A). The center frequency of the probe wave was fixed at ν_0 – BFS. Small fractions (10%) of the pump and probe waves were coupled, and their beat signal was divided equally and monitored with an optical spectrum analyzer (OSA) (Anritsu, MS9710A) and after the signal was converted into an electrical signal with a photodetector (PD) (Discovery Semiconductors, DSCR 402; bandwidth, 10 GHz; saturation power, 7 dBm), an electrical spectrum analyzer (ESA) (Anritsu, MS2663C) for rough and precise adjustment of their relative frequency, respectively. The pump wave was amplified with an erbium-doped fiber amplifier (EDFA) (Luxpert, LXI 2000), polarization-adjusted with a polarization controllor (PC), and injected into one end of the FUT. The probe wave was also amplified, polarization-adjusted, and injected into the other end of the FUT. The Stokes wave was directed through an optical circulator to a PD (New Focus, 2053; bandwidth, 10 MHz; saturation power, 10 mW), converted into an electrical signal, and monitored as a BGS with an oscilloscope (OSC) (Tektronix, TDS 3014B) triggered by the LD current modulation.

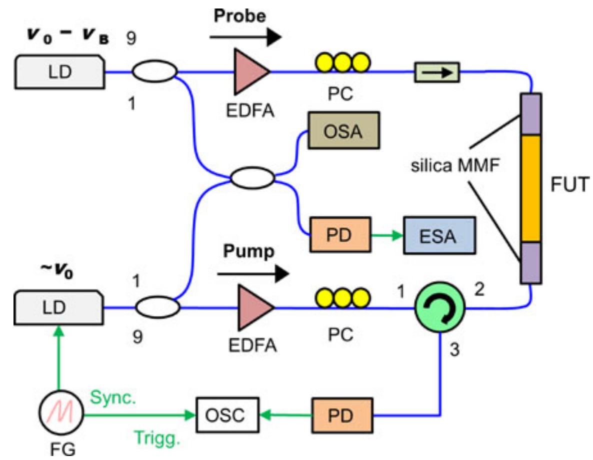

Fig. 1. Experimental setup for observing SBS in POF with pump–probe technique. EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FG, function generator; FUT, fiber under test; LD, laser diode; OSA, optical spectrum analyzer; OSC, oscilloscope; PC, polarization controller; PD, photodetector.

IV. Experimental Results

A. BGS Dependence on POF Length

Fig. 2 shows the measured BGS in a 3.8-m-long POF. The pump and probe powers were 21.1 and 22.2 dBm, respectively. The vertical axis was normalized so that the peak Stokes power was 1.0. Despite the relatively short POF length, a clear BGS was observed even without temporal averaging (sampling rate was 80 Hz in this measurement), which is desirable for future applications to averaging-free BOTDA systems. The BFS was

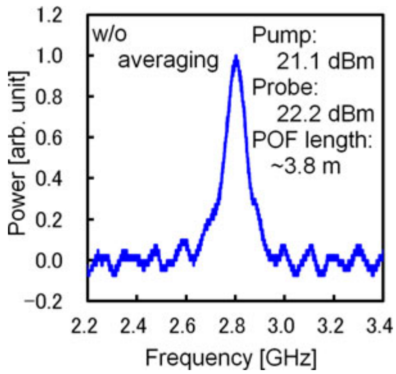

Fig. 2. Measured BGS in 3.8-m-long POF without averaging.

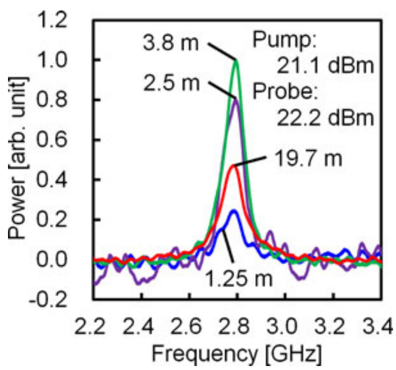

Fig. 3. Measured BGS dependence on POF length.

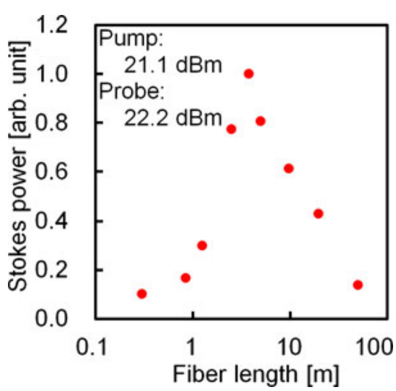

Fig. 4. Stokes power dependence on POF length.

∼2.80 GHz, which is slightly lower than the previously reported value of 2.83 GHz [12], probably due to the difference in room temperature [13]. The ripples on the noise floor are probably caused by the interference of the waves Fresnel-reflected at the POF/MMF and MMF/SMF interfaces.

Since SBS in POFs has been shown to be influenced by their physical properties, including high propagation loss [16], the POF length is one of the most important parameters to be optimized to obtain a large SBS signal. Fig. 3 shows the BGS dependence on the POF length with 32-times averaging. The Stokes power was drastically changed according to the POF length. The Stokes power dependence on the POF length is shown in Fig. 4. The maximum Stokes power was observed at the POF length of 3.8 m. Here, the optimal POF length exists

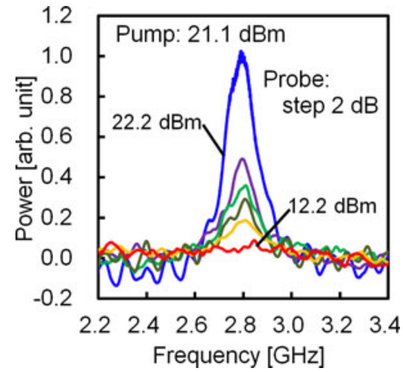

Fig. 5. Measured BGS dependences on probe power.

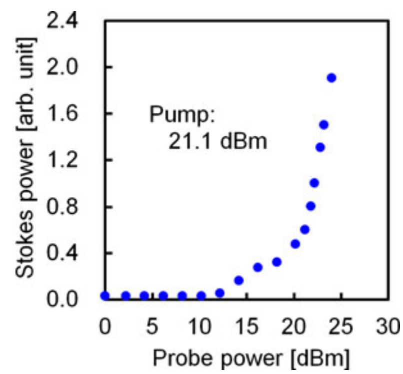

Fig. 6. Stokes power dependence on probe power.

because, as the POF length is longer, the Brillouin effective length also becomes longer (leading to higher Stokes power) but the pump and probe waves suffer from more significant attenuation. We predict that the optimal POF length can be elongated by employing the pump and probe waves with much higher powers.

B. BGS Dependences on Probe and Pump Powers

The BGS dependence on probe power in the 10-m-long POF was measured when the pump power was fixed at 21.1 dBm, as shown in Fig. 5. Averaging was performed 32 times. With increasing probe power, the Stokes power was raised, verifying that this BGS originates from the pump–probe interaction, i.e., SBS. The Stokes power dependence on probe power is shown in Fig. 6. The Stokes power began to increase rapidly at the probe power of approximately 20 dBm; this behavior seems to be due to the pump depletion [1]. The Stokes power was also measured as a function of pump power as shown in Fig. 7, where the vertical axis was normalized so that the Stokes power with 24.8-dBm pump was 1.0. The probe power was fixed at 20.5 dBm. With increasing pump power from 0 dBm, the Stokes power was gradually enhanced; and it also began to increase rapidly when the pump power was higher than ∼20 dBm, which is much lower than the theoretical Brillouin threshold without the pump–probe technique (∼53.8 dBm [15]). These results suggest that the pump and probe waves with the powers of higher than ∼20 dBm should be used to efficiently induce SBS in POFs with this technique.

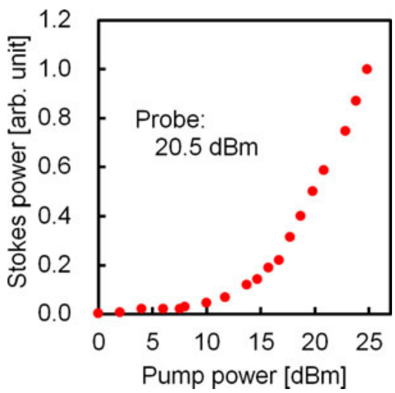

Fig. 7. Stokes power dependence on pump power.

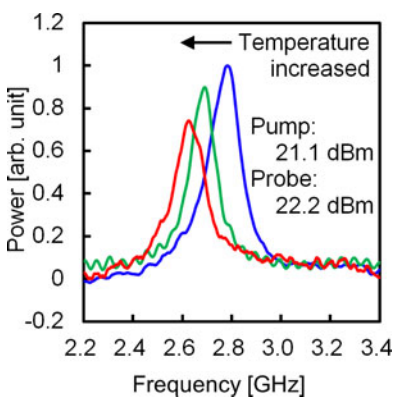

Fig. 8. Measured BGS dependence on temperature.

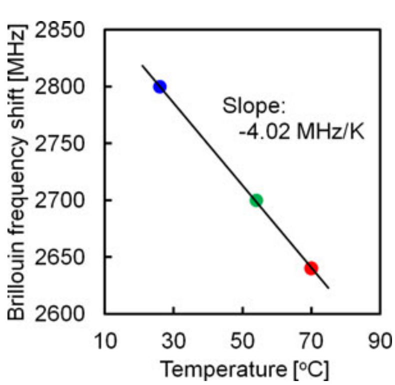

Fig. 9. BFS dependence on temperature.

C. BGS Dependence on Temperature

We also measured the temperature dependence of the BGS in the 10-m-long POF, as shown in Fig. 8. The temperature was set to 25 °C, 55 °C, and 70 °C. Averaging was performed 32 times. With increasing temperature, the BGS shifted toward lower frequency. The Stokes power was decreased probably due to the polarization fluctuations and the nonuniform temperature distribution along the POF. Fig. 9 shows the temperature dependence of the BFS. Note that the dependence is well known to be linear in the range from 20 °C to 80 °C [13], [15]. The slope of –4.02 MHz/K is in good agreement with the previously reported values [13], [15], which means that the BGS in POFs observed with this technique can be directly applied to high-precison temperature sensing.

V. Conclusion

SBS in POFs was observed, for the first time to the best of our knowledge, using the pump–probe technique without lock-in detection, and the dependences of the BGS on POF length, pump/probe powers, and temperature were fully investigated. We clarified that the optimal POF length for SBS observation is 3.8 m when the probe and pump powers are 21.1 dBm and 22.2 dBm, respectively. This length can be, we predict, elongated by the pump and probe waves with much higher powers. We also showed that the Stokes power was raised nonlinearly with increasing probe and pump powers, and that >20-dBm power is required for both pump and probe waves to efficiently induce SBS in POFs. In addition, the BFS dependence on temperature was measured to be –4.02 MHz/K, which was in good agreement with previous experiments. We believe that these results will offer a crucial basis for implementing distributed Brillouin sensors (especially, BOTDA systems) based on POFs with extremely high flexibility.

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References

[1] G. P. Agrawal, *Nonlinear Fiber Optics*. San Francisco, CA, USA: Academic, 1995.
[2] S. Norcia, S. Tonda-Goldstein, D. Dolfi, and J. P. Huignard, "Efficient single-mode Brillouin fiber laser for low-noise optical carrier reduction of microwave signals," *Opt. Lett.*, vol. 28, pp. 1888–1890, 2003.
[3] Z. Zhu, D. J. Gauthier, and R. W. Boyd, "Stored light in an optical fiber via stimulated Brillouin scattering," *Science*, vol. 318, pp. 1748–1750, 2007.
[4] E. A. Kuzin, M. P. Petrov, and B. E. Davydenko, "Phase conjugation in an optical fibre," *Opt. Quantum Electron.*, vol. 17, pp. 393–397, 1985.
[5] K. Y. Song, M. G. Herraez, and L. Thevenaz, "Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering," *Opt. Exp.*, vol. 13, pp. 82–88, 2005.
[6] T. Kurashima, T. Horiguchi, H. Izumita, S. Furukawa, and Y. Koyamada, "Brillouin optical-fiber time domain reflectometry," *IEICE Trans. Commun.*, vol. E76-B, pp. 382–390, 1993.
[7] Y. Mizuno, W. Zou, Z. He, and K. Hotate, "Proposal of Brillouin optical correlation-domain reflectometry (BOCDR)," *Opt. Exp.*, vol. 16, pp. 12148–12153, 2008.
[8] T. Horiguchi and M. Tateda, "BOTDA—Nondestructive measurement of single-mode optical fiber attenuation characteristics using Brillouin interaction: Theory," *J. Lightw. Technol.*, vol. 7, no. 8, pp. 1170–1176, Aug. 1989.
[9] D. Garus, K. Krebber, F. Schliep, and T. Gogolla, "Distributed sensing technique based on Brillouin optical-fiber frequency-domain analysis," *Opt. Lett.*, vol. 21, pp. 1402–1404, 1996.
[10] K. Hotate and T. Hasegawa, "Measurement of Brillouin gain spectrum distribution along an optical fiber using a correlation-based technique – proposal, experiment and simulation," *IEICE Trans. Electron.*, vol. E83-C, pp. 405–412, 2000.
[11] Y. Mizuno, N. Hayashi, and K. Nakamura, "Dependences of Brillouin frequency shift on strain and temperature in optical fibers doped with rare-earth ions," *J. Appl. Phys.*, vol. 112, p. 043109, 2012.
[12] Y. Mizuno and K. Nakamura, "Experimental study of Brillouin scattering in perfluorinated polymer optical fiber at telecommunication wavelength," *Appl. Phys. Lett.*, vol. 97, p. 021103, 2010.

[13] Y. Mizuno and K. Nakamura, "Potential of Brillouin scattering in polymer optical fiber for strain-insensitive high-accuracy temperature sensing," *Opt. Lett.*, vol. 35, pp. 3985–3987, 2010.
[14] N. Hayashi, Y. Mizuno, and K. Nakamura, "Brillouin gain spectrum dependence on large strain in perfluorinated graded-index polymer optical fiber," *Opt. Exp.*, vol. 20, pp. 21101–21106, 2012.
[15] Y. Mizuno, M. Kishi, K. Hotate, T. Ishigure, and K. Nakamura, "Observation of stimulated Brillouin scattering in polymer optical fiber with pump-probe technique," *Opt. Lett.*, vol. 36, pp. 2378–2380, 2011.
[16] N. Hayashi, Y. Mizuno, and K. Nakamura, "Observation of stimulated Brillouin scattering in silica graded-index multimode optical fibre based on pump-probe technique," *Electron. Lett.*, vol. 49, pp. 366–367, 2013.
[17] Y. Mizuno, T. Ishigure, and K. Nakamura, "Brillouin gain spectrum characterization in perfluorinated graded-index polymer optical fiber with 62.5-μm core diameter," *IEEE Photon. Technol. Lett.*, vol. 23, no. 24, pp. 1863–1865, Dec. 2011.
[18] D. M. Nguyen, B. M. W. Stiller, J. Lee, Beugnot, H. Maillotte, A. Mottet, J. Hauden, and T. Sylvestre, "Distributed Brillouin fiber sensor with enhanced sensitivity based on anti-stokes single-sideband suppressed-carrier modulation," *IEEE Photon. Technol. Lett.*, vol. 25, no. 1, pp. 94–96, Jan. 2013.
[19] K. Y. Song, Z. He, and K. Hotate, "Distributed strain measurement with millimeter-order spatial resolution based on Brillouin optical correlation domain analysis," *Opt. Lett.*, vol. 31, pp. 2526–2528, 2006.
[20] Y. Mizuno, N. Hayashi, and K. Nakamura, "Brillouin scattering signal in polymer optical fiber enhanced by exploiting pulsed pump with multimode-fiber-assisted coupling technique," *Opt. Lett.*, vol. 38, pp. 1467–1469, 2013.

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