Observation of stimulated Brillouin scattering in polymer optical fiber with pump–probe technique

Yosuke Mizuno,[1,*] Masato Kishi,[2] Kazuo Hotate,[2] Takaaki Ishigure,[3] and Kentaro Nakamura[1]

[1]*Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan*

[2]*Department of Electrical Engineering and Information Systems, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

[3]*Department of Applied Physics and Physico-Informatics, Keio University, 3-14-1, Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan*

**Corresponding author: ymizuno@sonic.pi.titech.ac.jp*

Received April 20, 2011; accepted May 17, 2011; posted May 18, 2011 (Doc. ID 146210); published June 15, 2011

Stimulated Brillouin scattering (SBS) in a perfluorinated graded-index polymer optical fiber (POF) with $120\,\mu$m core diameter was experimentally observed for the first time, to the best of our knowledge, at $1.55\,\mu$m wavelength with the pump–probe technique. Compared to spontaneous Brillouin scattering previously reported, the Brillouin gain spectrum (BGS) was detected with an extremely high signal-to-noise ratio, even with a short POF (1 m) and scrambled polarization state. We also investigated the BGS dependences on probe power and temperature, which indicate that SBS in a POF measured with this technique can be utilized to develop high-accuracy temperature sensing systems.

OCIS codes: 130.5460, 290.5830.

Brillouin scattering in silica-based optical fibers has been extensively studied [1,2] and applied to a large number of useful devices and systems, such as lasers [2,3], optical comb generators [3], microwave signal processors [4], slow light generators [5], phase conjugators [6], and strain/temperature sensors [7–11]. To improve the performance of these systems, Brillouin scattering in various specialty fibers, including tellurite glass fibers [12,13], chalcogenide fibers [14,15], bismuth-oxide fibers [16,17], and photonic crystal fibers [18,19] has been investigated so far. Recently, we have characterized the spontaneous Brillouin scattering (SpBS) at $1.55\,\mu$m in polymer optical fibers (POFs) [20], which offer extremely high flexibility, easy and low-cost connection, and high safety compared to other standard glass fibers [21]. The estimated Brillouin gain coefficient of 3.09×10^{-11} m/W was comparable to that of a silica single-mode fiber (SMF), indicating that Brillouin scattering in POFs can be applied to a variety of practical devices and 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 POF at $1.55\,\mu$m and found that SpBS in POFs can be potentially used to develop strain-insensitive high-accuracy temperature sensors [22].

The Brillouin scattering in POFs observed in the previous experimental setup [20,22] was not stimulated but spontaneous because the Brillouin threshold of POFs was estimated to be as high as 24 W due to their multimode nature [20]. Consequently, the power of the reflected Stokes light was so low that the following four problems arose: (1) a POF longer than several meters was needed, (2) the polarization state had to be optimized, (3) averaging of the spectral data had to be performed several tens of times, and (4) the signal-to-noise (S/N) ratio of the Brillouin gain spectrum (BGS) was very low, even when (1), (2), and (3) were cleared. In order to implement practical Brillouin sensors and other systems using POFs, these problems need to be resolved.

In this Letter, we report on the observation of stimulated Brillouin scattering (SBS) in a POF with $120\,\mu$m core diameter at $1.55\,\mu$m wavelength with the pump–probe technique. The BGS is detected with an extremely high S/N ratio, even with a 1 m POF, scrambled polarization state, and no averaging. We also investigate the BGS dependences on probe power and temperature and confirm that SBS in a POF measured with this technique can be utilized to develop high-accuracy temperature sensors.

When pump light is injected into one end of a fiber under test (FUT), weak reflected light, called Stokes light, is generated due to SpBS with the center frequency downshifted by the BFS of several gigahertz [1,2]. If the power of the pump light is higher than the Brillouin threshold, the Stokes light caused by SpBS acts as a seed of stimulated scattering, and there occurs a transition from SpBS to SBS. As a result, the power of the Stokes light is drastically enhanced [2]. On the other hand, when probe light at the same frequency as the Stokes light is also injected into the other end of the FUT, SBS is induced even when the power of the pump light is much lower than the Brillouin threshold because the probe light itself acts as a seed of stimulated scattering [23]. This "pump–probe" technique has been used to develop Brillouin systems with a high S/N ratio [9].

The FUT used in the experiment was a 1 m CYTOP-based perfluorinated graded-index POF [24] with an NA of 0.185, a core diameter of $120\,\mu$m, a core refractive index of ~1.35, and a propagation loss of ~150 dB/km at $1.55\,\mu$m. The experimental setup shown schematically in Fig. 1 is similar to that of Brillouin optical correlation-domain analysis [8,9]. The light beam from a 1550 nm

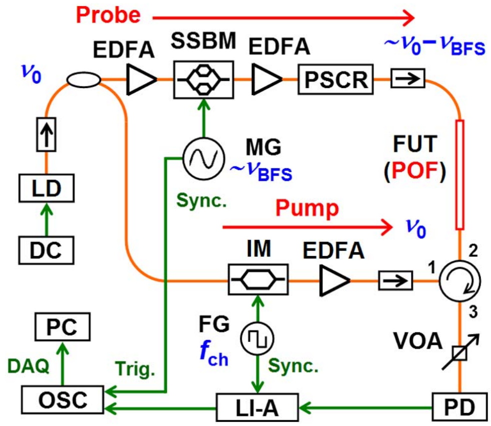

Fig. 1. (Color online) Experimental setup for observing SBS in POF with pump–probe technique. DAQ, data acquisition; DC, direct current; LD, laser diode; EDFA, erbium-doped fiber amplifier; FG, function generator; FUT, fiber under test; IM, intensity modulator; LI-A, lock-in amplifier; MG, microwave generator; OSC, oscilloscope; PC, personal computer; PD, photodetector; POF, polymer optical fiber; PSCR, polarization scrambler; SSBM, single-sideband modulator; VOA, variable optical attenuator.

three-electrode laser diode was divided into two. One was used as the pump light, after being chopped with an intensity modulator for lock-in detection and being amplified with an erbium-doped fiber amplifier (EDFA). The other was used as the probe light, after passing two EDFAs, a single-sideband modulator (SSBM), and a polarization scrambler (PSCR). The SSBM was employed with a microwave generator (MG) and a proper DC bias control to suppress the carrier (pump) and the anti-Stokes component of the two first-order sidebands and to maintain a stable frequency downshift from the pump light [25]. This frequency downshift was swept from 2.5 to 3.5 GHz with a period of 300 ms to obtain the BGS of the POF, which is observed approximately at 2.8 GHz. The suppression ratio of the other frequency components was kept higher than 25 dB, as shown in Fig. 2. The PSCR, which can modulate the polarization state at 1 MHz, was inserted to suppress the polarization-dependent fluctuations of the signal [26]. The POF and the silica SMFs were butt-coupled with the gaps filled with index-matching oil

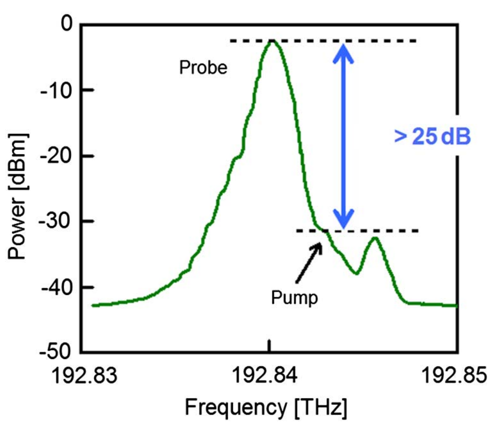

Fig. 2. (Color online) Measured optical spectrum of the SSBM output when the frequency of the MG was set to 2.83 GHz.

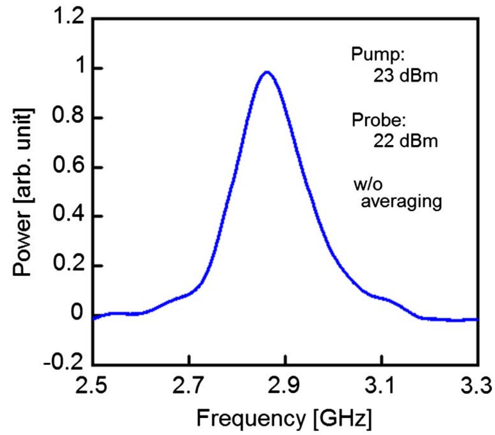

Fig. 3. (Color online) BGS in POF observed without averaging.

($n = 1.46$) to minimize the Fresnel reflection [20]. The Stokes light was adjusted in power with a variable optical attenuator and converted to an electrical signal with a 125 MHz photodetector. After passing a lock-in amplifier (LI-A) with a chopping frequency of 5.018 MHz and a time constant of 10 ms, the electrical signal was observed as a BGS with an oscilloscope synchronized with the frequency sweep of the SSBM.

Figure 3 shows the measured BGS with no averaging when the pump power and the probe power were 23 and 22 dBm, respectively. The power was normalized so that the peak power was 1.0. Although the POF length was only 1 m and the polarization state was scrambled, the BGS was observed with a much higher S/N ratio than that previously reported [22]. The BFS was 2.86 GHz, which is slightly higher than the previously reported value of 2.83 GHz [20]. This discrepancy seems to originate from the difference in temperature and the time constant of the LI-A, which is not short enough. The 3 dB bandwidth of the BGS measured in this experiment was about 160 MHz, but further research is needed on the bandwidth because it is also dependent on the time constant of the LI-A (when the time constant was shorter than 10 ms, the BGS was distorted).

Figure 4 shows the dependence of the BGS on probe power when the pump power was fixed at 23 dBm. The

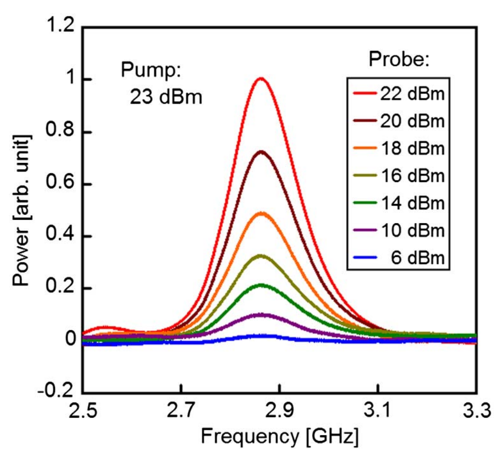

Fig. 4. (Color online) Dependence of BGS on probe power in POF.

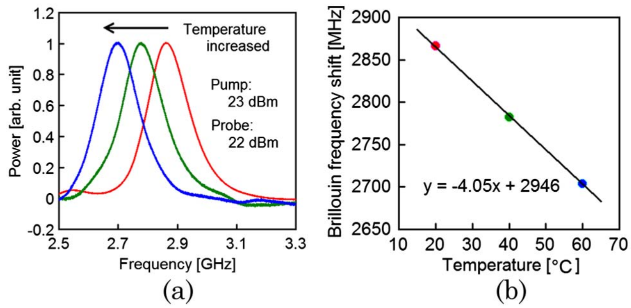

Fig. 5. (Color online) Dependence of (a) BGS and (b) BFS on temperature in POF.

probe power was reduced from 22 to 6 dBm, and averaging was performed 30 times. As the probe power decreased, the Stokes power also decreased, which proves that this BGS is caused by the interaction between the pump light and the probe light, i.e., SBS.

We also measured the dependence of the BGS on temperature as shown in Fig. 5(a). The pump power and the probe power were 23 and 22 dBm, respectively, and averaging was performed 30 times. The temperature was set to 20 °C, 40 °C, and 60 °C. With the increasing temperature, the BGS shifted toward lower frequency. Figure 5(b) shows the temperature dependence of the BFS. The slope of −4.05 MHz/K is in good agreement with the previous report [22], which confirms that the BGS in a POF observed with the pump–probe technique can be applied to high-accuracy temperature sensing.

In conclusion, we observed the SBS in a POF at 1.55 μm with the pump–probe technique. We successfully detected the BGS with an extremely high S/N ratio, even with a 1 m POF, scrambled polarization state, and no averaging. We also investigated the BGS dependence on probe power, which proved that the measured BGS was caused not by SpBS but by SBS. Besides, we measured the BGS dependence on temperature, showing that the BGS in a POF observed with this technique can be applied to temperature sensing with high accuracy. We believe that this work is a significant step toward the development of Brillouin-based distributed temperature/strain sensing systems using POFs.

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

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