IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 6, Number 3, June 2014

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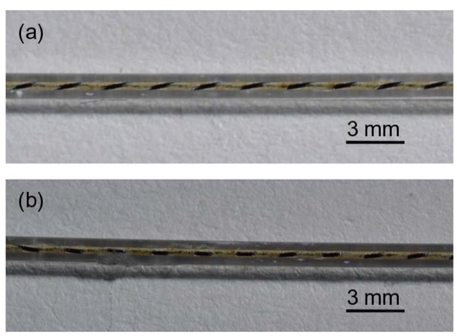

DOI: 10.1109/JPHOT.2014.2323301
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Spiral Propagation of Polymer Optical Fiber Fuse Accompanied by Spontaneous Burst and Its Real-Time Monitoring Using Brillouin Scattering

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DOI: 10.1109/JPHOT.2014.2323301

Manuscript received April 14, 2014; revised May 8, 2014; accepted May 8, 2014. Date of publication May 13, 2014; date of current version May 21, 2014. This work was supported in part by a Grant-in-Aid for Young Scientists (A) under Grant 25709032 from the Japan Society for the Promotion of Science (JSPS) and in part by research grants from the General Sekiyu Foundation, the Iwatani Naoji Foundation, and the SCAT Foundation. The work of N. Hayashi was supported by a Grant-in-Aid for JSPS Fellows under Grant 25007652. Corresponding author: Y. Mizuno (e-mail: ymizuno@sonic.pi.titech.ac.jp).

Abstract: We study the propagation behavior of the polymer optical fiber (POF) fuse at a power density up to several tens of kW/cm^2 (corresponding to subwatt power). The propagation velocity is raised in proportion to the power density, reaching 41 mm/s at 67 kW/cm^2. We also observe spiral oscillation and spontaneous termination of the fuse propagation, with the latter accompanied by a burst. We then develop a new method of detecting the location of the propagating POF fuse remotely and nonvisually in real time using Brillouin scattering, which can be clearly observed at such a high power density. This method requires neither additional light injection nor signal integration, and it could be used to monitor the propagating fuse in glass fibers.

Index Terms: Polymer optical fibers, fiber fuse, Brillouin scattering, remote sensing, real-time monitoring, nonlinear optics.

1. Introduction

Despite their higher loss than that of silica single-mode fibers (SMFs), polymer (or plastic) optical fibers (POFs) [1], [2] provide various advantages such as easy and cost-efficient connection, safety, and extremely high flexibility, leading to medium-range applications [3] and large-strain monitoring applications [4]. Since the first observation of Brillouin scattering [5]—one of the most important nonlinear effects—in POFs in 2010 [6], its properties have been extensively studied, especially for sensing applications [7]–[11]; and recently, distributed Brillouin sensing of strain and temperature in POFs has been successfully demonstrated [12], [13], proving its high-precision temperature sensing capability [7] as well as large-strain sensing capability [8]. The signal-to-noise ratio (SNR) of the system is, however, not sufficiently high when the spatial resolution is set to centimeter-order [13], because of the low Brillouin-scattered power in POFs resulting from their relatively large core diameters and multimode nature [6]. One solution is, as a previous study predicts [9], simply to boost the incident power; but recent reports have clarified that such high-power light injection into POFs causes not merely burning or damage at the POF-to-SMF interfaces [10] but also a continuous self-destruction process of the POFs, i.e., fiber fuse.

A fiber fuse [14]–[18] occurs when high-power light propagating along the fiber locally heats the fiber material and initiates an optical discharge, which is then trapped in the fiber core and propagates back toward the light source, while consuming the optical energy and leaving damage. As the fiber is no longer usable after the fuse passage, this phenomenon is generally considered to be one of the critical factors that limit the maximal optical power to be delivered [19]. Thus, it is of great importance to thoroughly investigate the fuse properties in order that all possible measures are taken to avoid this effect.

Recently, we have reported on the first observation of the fiber fuse in graded-index (GI-) POFs at 1.55 μm [20], and its unique properties have been investigated from various angles [20], [21]. Although its propagation behavior is similar to that of the fuse in silica glass fibers [14]–[18], [22]–[25] from a macroscopic perspective, its velocity is $\sim$20 mm/s [20], which is one to two orders slower. The threshold power density is 6.6 kW/cm^2 [20], which is over 150 times lower than that of silica SMFs. Spectral measurement has clarified that the POF fuse is not a plasma but an optical discharge at a temperature of approximately 3600 K [21]. In addition, microscopic studies have revealed not only that the damage left after the passage of the bright spot looks like a black curve that is slightly oscillatory [20], which can be explained by taking the multimode nature into consideration [21], but also that gas bubbles are sometimes formed simultaneously with the damage [21].

However, these properties have been reported only in the case of a relatively low incident power density ($<$ 13 kW/cm^2; corresponding to a power of 130 mW in the POFs used in Refs. [20], [21]. See Eq. (1) in Ref. [20] for the calculation method), and thus, to clarify the propagation behavior of the POF fuse under a higher power density is an important issue. Another significant task for study is to remotely and nonvisually detect the location of the propagating POF fuse on a real-time basis to minimize the damage extension. As POF-based sensors are often assumed to be used after being embedded in various materials and structures (the POFs can no longer be visually monitored), even though the measurement range is relatively short, a remote-detection method is required. Abedin *et al.* [24] have developed a method of detecting the fuse location in silica SMFs based on optical time-domain reflectometry, but the injection of high-peak-power optical pulses may cause damage at the POF-to-SMF interface; needs for additional light at a different wavelength and for the time-consuming process of signal integration for SNR enhancement are also problematic. Note that Abedin *et al.* [25] have developed another fuse-detecting method based on optical coherence-domain reflectometry, which can rapidly detect the fuse initiation but does not provide its location information.

In this work, we investigate the propagation behavior of the POF fuse at a power density up to several tens of kW/cm^2 (corresponding to a sub-Watt power). The propagation velocity is raised in proportion to the incident power density, reaching 41 mm/s at 67 kW/cm^2. Spiral propagation of damage along with a burst induced by a considerable amount of generated gas is newly observed. We then develop and demonstrate a new method of detecting the location of the propagating POF fuse in real time using Brillouin scattering, in which a continuous wave (CW) is used and neither signal integration nor additional light injection is required.

2. Principle

When propagating in an optical fiber, light is partially returned via spontaneous Brillouin scattering. The backscattered light spectrum is called Brillouin gain spectrum (BGS) [5], and the central frequency of the BGS is downshifted from the incident frequency by the amount called Brillouin frequency shift (BFS). The BFS is known to be $\sim$10.8 GHz for a silica SMF [5] and $\sim$2.8 GHz for a perfluorinated GI-POF [6] at 1.55 μm. According to the theory [5], the Brillouin-scattered power is roughly in proportion to the effective length L_{eff} defined as

$$L_{eff} = \frac{1 - \exp(-\alpha L)}{\alpha} \tag{1}$$

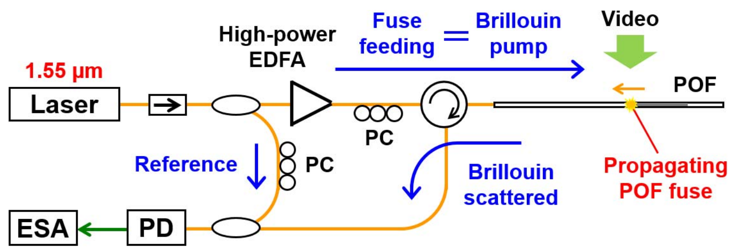

Fig. 1. Schematic setup of Brillouin-based POF-fuse monitoring system. EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; PC, polarization controller; PD, photo detector; POF, polymer optical fiber.

where α is the propagation loss and *L* is the fiber length. The fuse propagation can be regarded as the shortening of *L*, leading to the reduction in the Brillouin signal. Though light can still propagate through a POF after the fuse passage [20], the Brillouin signal from this part is negligibly small.

One may think of an idea of exploiting the Rayleigh-scattered light in the same way, but it is difficult because of its spectral overlap with the Fresnel-reflected light, which is extremely unstable in power. We have also confirmed that the fuse emission is so weak that its direct detection is difficult.

3. Methods

POFs employed in the experiment were perfluorinated GI-POFs [2] with a numerical aperture of 0.185, a core diameter of 55 μm (different from that in Refs. [20], [21]), a cladding diameter of $\sim$100 μm, an overcladding diameter of 750 μm, a core refractive index of $\sim$1.35, and a propagation loss of $\sim$250 dB/km (i.e., $\alpha = 0.056$ /m) at 1.55 μm. The core/cladding layers and the overcladding layer were composed of amorphous perfluorinated polymer and polycarbonate, respectively.

The experimental setup is depicted in Fig. 1. The POF fuse was initiated in the same way as in Refs. [20], [21]. The Brillouin detecting system based on self-heterodyne was essentially the same as that previously reported in Ref. [6]. The high-power light at 1.55 μm, which was boosted with a 1-W-output erbium-doped fiber amplifier (EDFA; HPA-200, Alnair Labs), not only provided energy for the initiation and propagation of the fuse but also served as Brillouin pump light. The polarization state was optimized using polarization controllers (PCs). The fuse propagation was recorded with a video camera to obtain its velocity and location.

4. Experimental Results on Fuse Characterization

The measured dependence of the POF-fuse propagation velocity on the power density is shown in Fig. 2. The power (density) was calculated by taking into consideration the coupling loss at the POF-to-SMF interface, the propagation loss of the POF, and other losses caused in the optical circulator, etc. With increasing power density, the propagation velocity was linearly raised, and reached 41 mm/s at 67 kW/cm^2 (corresponding to $\sim$800 mW). The threshold power density was 8.4 kW/cm^2, which is close to the previous report (6.6 kW/cm^2) [20]. The proportionality constant was 440 mm $\cdot$ s^{-1} MW^{-1} cm^2 in this range, which is $\sim$3.5 times smaller than the previous report (1560 mm $\cdot$ s^{-1} MW^{-1} cm^2) [20]. This discrepancy may be elucidated by Todoroki's [26] theory on fuse propagation modes proposed for silica SMFs; further study is needed on this point.

Microscopic analyses also revealed some unique features. Fig. 3(a) shows a micrograph of the damage left spirally after the fuse passage at 42 kW/cm^2. The period of the spiral oscillation was approximately 1400 μm, which moderately agrees with the theoretical period of the ray propagating in a GI fiber (1204 μm in this POF) [27]. The diameter of the spiral oscillation was $\sim$200 μm (measured by observing the cross section of the damaged POF with a microscope; Fig. 3(a) does not provide correct information on its diameter because of the lens effect of the POF side surface), which is larger than the core/cladding diameter ($\sim$100 μm), indicating that the overcladding layer was thermally damaged at this high power density. The conversion of the spiral direction was also

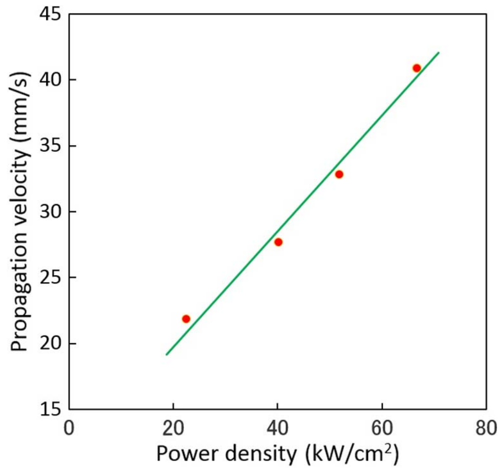

Fig. 2. POF-fuse propagation velocity *vs.* power density. The red circles are measured points, and the green line is a linear fit.

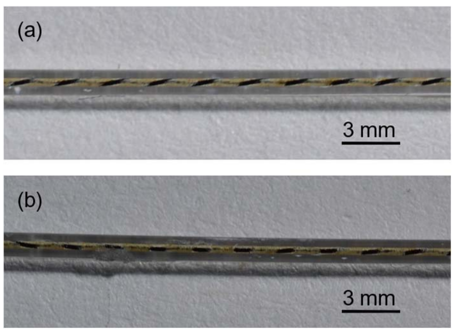

Fig. 3. (a) and (b) Two examples of the paths of the POF fuse at a power density of 42 kW/cm^2.

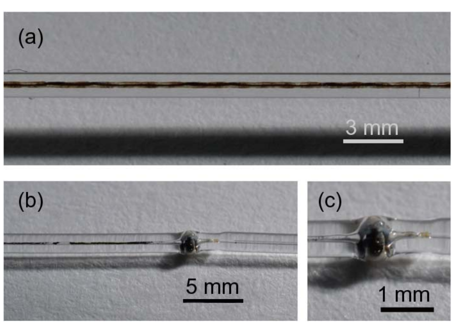

Fig. 4. (a) Path of the POF fuse at a power density of 67 kW/cm^2, (b) that with a burst, and (c) its magnified view.

observed as shown in Fig. 3(b), which suggests the possible change in the fuse propagation mode, supporting the mechanism of the POF fuse propagation reported in Ref. [21], i.e., the bright spot travels only along the optical path of a particular propagating mode (that with the highest energy) that provides it with energy directly.

When the power density was as high as 67 kW/cm^2, not only did the spiral oscillation become less clear (Fig. 4(a)) but the fuse propagation was also sometimes spontaneously ceased

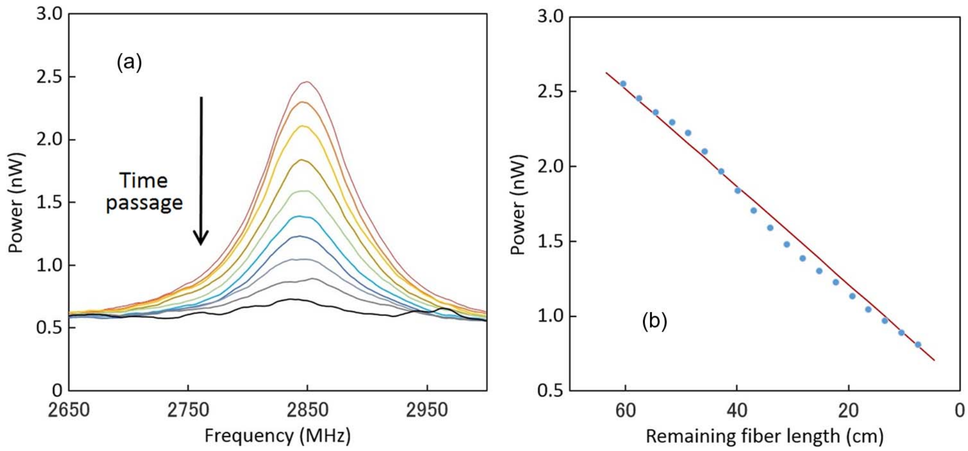

Fig. 5. (a) BGSs in POF measured every 2 s after the fuse initiation. (b) Peak power dependence on the remaining POF length. The blue circles are points measured every 1 s, and the red curve is a theoretical fit.

accompanying a burst, as shown in Fig. 4(b) and (c). This burst appears to have been induced by a considerable amount of generated gas; and the higher the incident power was, the more frequently it was observed. Thus, it is difficult to make the POF fuse propagate for a relatively long distance (longer than several tens of centimeters) at a power density higher than ~100 kW/cm^2 (or at a power higher than ~1 W).

5. Experimental Results on Fuse Monitoring

The incident light power was ~450 mW, corresponding to a power density of 38 kW/cm^2. The room temperature was 19 °C. A fuse was initiated at around the open end of a 62-cm-long POF. Fig. 5(a) shows the BGSs measured every 2 s after the fuse initiation, the vertical axis of which is in linear scale. The noise floor was ~0.6 nW. The BFS was ~2850 MHz, which agrees with the previously reported value [6]–[11]; a slight discrepancy was caused by the different room temperature and video bandwidth of an electrical spectrum analyzer (ESA). As the fuse propagated, the peak power of the BGS was continuously reduced. In the weakest BGS presented in Fig. 5(a), an additional peak was observed at approximately 2960 MHz, which originated not from the heated POF but from the noise floor of the ESA, because the BFS in a POF is lowered with increasing temperature [7]. Fig. 5(b) shows the peak power, measured every 1 s (this interval can be even shorter; if BGSs are unnecessary, we need not use an ESA with a relatively low sampling rate to measure the peak power), plotted as a function of the remaining POF length. The red line indicates a fitted curve calculated using the effective length given by Eq. (1), which can be regarded as almost linear with a slope of 0.032 nW/cm in this range (When the POF length is shorter than ~10 m, linear approximation is valid [9]). Thus, the fuse location can be identified using the peak power. The measurement error seems to originate from polarization- and multimode-dependent signal fluctuations. The fuse propagation velocity calculated from Fig. 5(b) was ~29.4 mm/s, which well agrees with the result in Fig. 2. As long as a POF fuse is initiated, the maximum length of the remote detection is, in principle, not limited, because the optical power required for Brillouin observation is much lower than that for fuse initiation [20]. Although demonstrated using the POF fuse, we expect this real-time monitoring method is applicable also to the glass optical fiber fuse.

6. Conclusion

The propagation behavior of the POF fuse at a power density up to several tens of kW/cm^2 (or at a sub-Watt power) was investigated. The propagation velocity was proportional to the power density, and reached 41 mm/s at 67 kW/cm^2. The spiral propagation mode of damage as well as spontaneous termination of the fuse propagation accompanied by a burst was newly observed. A novel method of detecting the location of the propagating POF fuse in real time using Brillouin scattering was also developed. This CW-based method is free from the necessity of injecting additional light and/or integrating signal, and could be implemented also for glass-fiber fuse monitoring. We believe that this work will be useful in developing POF-based systems for high-capacity transmission and distributed Brillouin sensing [28]–[32] in the near future.

Acknowledgment

The authors are grateful to R. Nedelcov (Department of Language Arts, Tokyo University of the Arts) for his English editing.

References

[1] M. G. Kuzyk, *Polymer Fiber Optics: Materials, Physics, and Applications*. Boca Raton, FL, USA: CRC Press, 2006.
[2] Y. Koike and M. Asai, "The future of plastic optical fiber," *NPG Asia Mater.*, vol. 1, pp. 22–28, 2009.
[3] I. Mollers *et al.,* "Plastic optical fiber technology for reliable home networking: Overview and results of the EU project POF-ALL," *IEEE Commun. Mag.*, vol. 47, no. 8, pp. 58–68, Aug. 2009.
[4] I. R. Husdi, K. Nakamura, and S. Ueha, "Sensing characteristics of plastic optical fibres measured by optical time-domain reflectometry," *Meas. Sci. Technol.*, vol. 15, no. 8, pp. 1553–1559, 2004.
[5] G. P. Agrawal, *Nonlinear Fiber Optics*. San Diego, California, USA: Academic Press, 1995.
[6] Y. Mizuno and K. Nakamura, "Experimental study of Brillouin scattering in perfluorinated polymer optical fiber at telecommunication wavelength," *Appl. Phys. Lett.*, vol. 97, no. 2, pp. 021103-1–021103-3, Jul. 2010.
[7] Y. Mizuno and K. Nakamura, "Potential of Brillouin scattering in polymer optical fiber for strain-insensitive high-accuracy temperature sensing," *Opt. Lett.*, vol. 35, no. 23, pp. 3985–3987, 2010.
[8] 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, no. 19, pp. 21101–21106, 2012.
[9] 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.
[10] 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, no. 9, pp. 1467–1469, May 2013.
[11] N. Hayashi, Y. Mizuno, and K. Nakamura, "Characterization of stimulated Brillouin scattering in polymer optical fibers based on lock-in-free pump-probe technique," *J. Lightwave Technol.*, vol. 31, no. 19, pp. 3162–3166, Oct. 2013.
[12] A. Minardo, R. Bernini, and L. Zeni, "Distributed temperature sensing in polymer optical fiber by BOFDA," *IEEE Photon. Technol. Lett.*, vol. 26, no. 4, pp. 387–390, Feb. 2014.
[13] N. Hayashi, Y. Mizuno, and K. Nakamura, "First demonstration of distributed Brillouin measurement with centimeter-order resolution based on plastic optical fibers," presented at the OptoElectronics Commun. Conf. Australian Conference Optical Fibre Technology (OECC/ACOFT), Melbourne, Australia, Jul. 6–10, 2014, paper 239.00.
[14] R. Kashyap and K. J. Blow, "Observation of catastrophic self-propelled self-focusing in optical fibres," *Electron. Lett.*, vol. 24, no. 1, pp. 47–49, Jan. 1988.
[15] R. Kashyap, "Self-propelled self-focusing damage in optical fibres," in *Proc. 10th Int. Conf. Lasers Appl.*, F. J. Duarte, Ed. McLean, VA: STS Press, 1988, pp. 859–866, Lake Tahoe, NV, USA, Dec. 7–11, 1987.
[16] R. Kashyap, "The fiber fuse—From a curious effect to a critical issue: A 25th year retrospective," *Opt. Exp.*, vol. 21, no. 5, pp. 6422–6441, 2013.
[17] S. Todoroki, "Fiber fuse propagation behaviour," in *Selected Topics on Optical Fiber Technology*. Rijeka, Croatia: InTech, 2012, pp. 551–570.
[18] S. Todoroki, *Fiber Fuse—Light-Induced Continuous Breakdown of Silica Glass Optical Fiber*. Tokyo, Japan: Springer-Verlag, 2014.
[19] T. Morioka *et al.,* "Enhancing optical communications with brand new fibers," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. s31–s42, 2012.
[20] Y. Mizuno, N. Hayashi, H. Tanaka, K. Nakamura, and S. Todoroki, "Observation of polymer optical fiber fuse," *Appl. Phys. Lett.*, vol. 104, no. 4, pp. 043302–043302-4, Jan. 2014.
[21] Y. Mizuno, N. Hayashi, H. Tanaka, K. Nakamura, and S. Todoroki, "Propagation mechanism of polymer optical fiber fuse," *Sci. Rep.*, vol. 4, no. 4800, pp. 1–4, Apr. 2014.
[22] S. Todoroki, "Origin of periodic void formation during fiber fuse," *Opt. Exp.*, vol. 13, no. 17, pp. 6381–6389, 2005.
[23] R. M. Atkins, P. G. Simpkins, and A. D. Yablon, "Track of a fiber fuse: A Rayleigh instability in optical waveguides," *Opt. Lett.*, vol. 28, no. 12, pp. 974–976, 2003.
[24] K. S. Abedin and M. Nakazawa, "Real time monitoring of a fiber fuse using an optical time-domain reflectometer," *Opt. Exp.*, vol. 18, no. 20, pp. 21315–21321, 2010.
[25] K. S. Abedin, M. Nakazawa, and T. Miyazaki, "Backreflected radiation due to a propagating fiber fuse," *Opt. Exp.*, vol. 17, no. 8, pp. 6525–6531, 2009.
[26] S. Todoroki, "Fiber fuse propagation modes in typical single-mode fibers," in *Proc. Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf.*, Anaheim, CA, USA, 2013, pp. JW2A.1–JW2A.11.
[27] G. P. Agrawal, *Fiber-Optic Communication Systems*. Hoboken, NJ, USA: Wiley, 2010.

[28] T. Horiguchi and M. Tateda, “BOTDA—Nondestructive measurement of single-mode optical fiber attenuation characteristics using Brillouin interaction: Theory,” *J. Lightwave Technol.*, vol. 7, no. 8, pp. 1170–1176, Aug. 1989.
[29] T. Kurashima, T. Horiguchi, H. Izumita, and M. Tateda, “Brillouin optical-fiber time domain reflectometry,” *IEICE Trans. Commun.*, vol. E76-B, pp. 382–390, 1993.
[30] 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, no. 3, pp. 405–412, Mar. 2000.
[31] Y. Mizuno, W. Zou, Z. He, and K. Hotate, “Proposal of Brillouin optical correlation-domain reflectometry (BOCDR),” *Opt. Exp.*, vol. 16, no. 16, pp. 12148–12153, Aug. 2008.
[32] D. Garus, K. Krebber, and F. Schliep, “Distributed sensing technique based on Brillouin optical-fiber frequency-domain analysis,” *Opt. Lett.*, vol. 21, no. 17, pp. 1402–1404, Sep. 1996.