Distributed Brillouin Sensing With Centimeter-Order Spatial Resolution in Polymer Optical Fibers

Neisei Hayashi, Yosuke Mizuno, *Member, IEEE*, and Kentaro Nakamura, *Member, IEEE*

***Abstract*—We present the first demonstration of distributed strain/temperature sensing with a high spatial resolution in plastic optical fibers (POFs) based on Brillouin optical correlation-domain reflectometry. A 50-cm-long strain-applied (or heated) POF section is clearly detected with a theoretical spatial resolution of 34 cm, a high sampling rate of 3.3 Hz (per measured point), and a high signal-to-noise ratio. A 10-cm-long heated POF section is also successfully detected with a theoretical resolution of 7.4 cm. The performance limitation of this system is then discussed.**

***Index Terms*—Brillouin optical correlation-domain reflectometry (BOCDR), Brillouin scattering, polymer optical fibers, distributed measurement, optical fiber sensing.**

I. Introduction

BRILLOUIN scattering in optical fibers has been the subject of extensive research for the past several decades because it provides a means of measuring strain and temperature in a distributed manner [1]–[5]. Up to now, only glass optical fibers have been used for the sensor heads of Brillouin sensors, but they are quite fragile and cannot withstand strains of several percent. One attractive solution to this problem is to make use of plastic optical fibers (POFs), which have such a high flexibility that they can withstand large strains of several tens of percent [6]. Another advantage of POF-based sensors is a unique function called a "memory effect" [7], with which the information on the applied large strain can be stored owing to their plastic deformation. Previous experimental studies on Brillouin scattering in POFs [8]–[10] have revealed its potential applicability to large-strain sensing [9] and to high-precision temperature sensing with less sensitivity to strain [10].

Very recently, Minardo *et al.* [11] have demonstrated low-resolution distributed temperature sensing in a POF based on Brillouin optical frequency-domain analysis (BOFDA) [3]. They detected a 4-m-long heated section—located at one end—of a 20-m-long POF, but the spatial resolution and signal-to-noise ratio (SNR) were not sufficiently high for practical use; relatively high cost of the devices such as a vector network analyzer and a microwave generator is also a problem. Although a 3-cm spatial resolution has been obtained by BOFDA [12] in a silica single-mode fiber (SMF), such a high resolution has not been achieved in a POF not only because of the high propagation loss but also because of the weak Brillouin signal resulting from its large core diameter and multimode nature.

In this work, we report on the first demonstration of distributed strain and temperature sensing with a centimeter-order spatial resolution in a POF based on Brillouin optical correlation-domain reflectometry (BOCDR) [5], which is highly cost-effective. A 10-cm-long heated section—located away from both ends—of a 1.3-m-long POF is successfully detected with a theoretical spatial resolution of 7.4 cm and a sampling rate of 3.3 Hz per measured point (corresponding to a measurement time of ∼1 min, if the number of measured points is 200). We also discuss how the characteristics of POFs (Brillouin frequency shift (BFS), Brillouin bandwidth, propagation loss, etc.) affect the sensing performance of BOCDR.

II. Principle

When light is propagating in an optical fiber, it is partially returned via spontaneous Brillouin scattering. The backscattered Stokes light spectrum is called Brillouin gain spectrum (BGS) [13], and the central frequency of the BGS is downshifted from the incident frequency by the amount called BFS. The BFS is known to be ∼10.8 GHz for a silica SMF [13] and ∼2.8 GHz for a perfluorinated graded-index (PFGI-) POF [8] at 1.55 μm. If temperature change (or strain) is applied to the fiber, the BFS shifts toward higher or lower frequency according to the fiber core material, in which lies the basic principle of Brillouin temperature (or strain) sensing. The temperature dependence coefficient of the BFS is reported to be ∼1.0 MHz/K for a silica SMF [14], and −3.2 MHz/K for a PFGI-POF [15] at 1.55 μm. Considering that the strain dependence coefficient of the BFS in a PFGI-POF is −121.8 MHz/% [10], the absolute value of which is about one fifth of that in a silica SMF, Brillouin scattering in a PFGI-POF has a big potential for high-precision temperature sensing with reduced strain sensitivity [10].

Several distributed measurement techniques based on Brillouin scattering in optical fibers have been proposed so far, which are classified into two categories: "reflectometry" and "analysis." In reflectometry, based on spontaneous Brillouin scattering, a light beam is injected only into one end of the fiber; whereas in analysis, based on stimulated Brillouin scattering (SBS), two light beams are injected into both ends of the fiber. Analysis systems proposed so far include Brillouin optical time-, frequency-, and correlation-domain analysis (BOTDA [1], [16], [17], BOFDA [3], [11], [12], BOCDA [4], [18], [19]),

Manuscript received April 15, 2014; revised July 4, 2014; accepted July 13, 2014. Date of publication July 31, 2014; date of current version September 17, 2014. This work was supported in part by a Grant-in-Aid for Young Scientists (A) (No. 25709032) from the Japan Society for the Promotion of Science (JSPS), and by research grants from the General Sekiyu Foundation, the Iwatani Naoji Foundation, and the SCAT Foundation. The work of N. Hayashi was supported by the Grant-in-Aid for JSPS Fellows (No. 25007652).

The authors are with the Precision and Intelligence Laboratory, Tokyo Institute of Technology, Kanagawa 226-8503, Japan (e-mail: hayashi@sonic.pi.titech.ac.jp; ymizuno@sonic.pi.titech.ac.jp; knakamur@sonic.pi.titech.ac.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JLT.2014.2339361

in which a relatively large signal and thus a high SNR can be obtained. Two-end access is, however, less convenient, because the system does not work completely when the fiber has even one breakage point. Moreover, expensive devices are often required to prepare so-called probe light to induce SBS. In contrast, even though the signal is weak, reflectometry such as Brillouin optical time- and correlation-domain reflectometry (BOTDR [2], [20], [21], BOCDR [5], [22], [23]) can resolve these problems. As the interface between a silica SMF and a POF is easily damaged by injecting short optical pulses with high peak power [24], [25], here we focus on BOCDR.

First proposed in 2008 [5], BOCDR has been used as a promising distributed sensing technique with one-end accessibility, a high spatial resolution, a high sampling rate (i.e., fast measurement speed), and cost efficiency. Its operating principle is based on the correlation control of continuous lightwaves [26]; namely, the pump light and the reference light in a standard self-heterodyne scheme for analyzing Brillouin signals [8] are sinusoidally frequency-modulated at f_m, producing periodical correlation peaks in the fiber to be measured. The measurement range d_m is determined by their interval, which is inversely proportional to f_m as

$$d_m = \frac{c}{2nf_m} \tag{1}$$

where c is the velocity of light in vacuum and n is the refractive index of the fiber core. By sweeping f_m, the correlation peak, i.e., the sensing position, can be scanned along the fiber to acquire BGS or BFS distribution. According to theory [23], when f_m is lower than the Brillouin bandwidth $\Delta\nu_B$, the spatial resolution Δz is given by

$$\Delta z = \frac{c\Delta\nu_B}{2\pi n f_m \Delta f} \tag{2}$$

where Δf is the modulation amplitude of the optical frequency. Considering that f_m higher than $\Delta\nu_B$ does not contribute to the enhancement of Δz [23], and that Δf is practically limited to a half of BFS (ν_B) of the fiber because of the Rayleigh noise [5], [23], the limitation of the spatial resolution $\Delta z_{\min}$ is given by

$$\Delta z_{\min} = \frac{c}{\pi n \nu_B}. \tag{3}$$

The number of effective sensing points N_R, which can be regarded as an evaluation parameter of the system, is given by the ratio of d_m to Δz, as

$$N_R = \frac{d_m}{\Delta z} = \frac{\pi \Delta f}{\Delta\nu_B}. \tag{4}$$

To obtain higher N_R, Δf needs to be raised but it should be lower than $\nu_B/2$; N_R is thus limited to

$$N_{R\max} = \frac{\pi\nu_B}{2\Delta\nu_B}. \tag{5}$$

III. Experimental Setup

POFs employed in the experiment were PFGI-POFs [27] with a numerical aperture of 0.185, a core diameter of 50 μm, a cladding diameter of 100 μm, an overcladding diameter of 500 μm, a core refractive index of ~1.35, and a propagation loss of ~250 dB/km at 1.55 μm. The core/cladding layers and the overcladding layer were composed of amorphous perfluorinated polymer and polycarbonate, respectively.

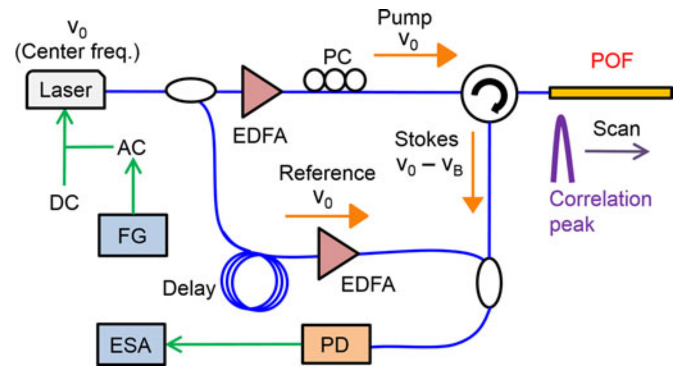

Fig. 1. Schematic setup of BOCDR. EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FG, function generator; PC polarization controller; PD, photo detector.

The schematic setup of BOCDR for distributed measurement in a POF is shown in Fig. 1, which is basically the same as that previously reported in [5]. All the optical paths except the POF were silica SMFs. A distributed-feedback laser diode at 1.55 μm with 1-MHz linewidth was used as a light source, and its output frequency was sinusoidally modulated by direct modulation of the driving current. Its output was divided into two light beams with a coupler. One was directly used as the reference light of heterodyne detection, after passing through a 1-km delay fiber to adjust the correlation peak order, and an erbium-doped fiber amplifier (EDFA) to enhance the beat signal. The other beam was amplified with another EDFA, and injected into the POF as the pump light (incident power: 27 dBm). The optical beat signal between the Stokes light and the reference light was then converted to an electrical signal with a photo detector (PD), which was finally monitored with an electrical spectrum analyzer (ESA) with a 300-kHz frequency resolution. Polarization state was optimized with a polarization controller (PC) at the beginning of each distributed measurement so that the Rayleigh noise was minimal [28].

IV. Experimental Results

A. Distributed Strain and Temperature Measurement With High SNR

First, we demonstrate distributed strain and temperature sensing with a moderate spatial resolution but with a high SNR. The modulation frequency f_m was swept from 11.654 to 11.698 MHz, corresponding to the measurement range d_m of 9.5 m according to Eq. (1). The modulation amplitude Δf was set to 0.9 GHz, resulting in the theoretical spatial resolution Δz of 34 cm from Eq. (2) (the Brillouin bandwidth $\Delta\nu_B$ is ~100 MHz [8] in a POF). Their ratio N_R was 28. The 56th correlation peak was used. The overall sampling rate of single-location measurement was 3.3 Hz.

Fig. 2 shows the structure of a 2-m-long POF to be measured, in which strains of <1.2% (within elastic region [9]) were

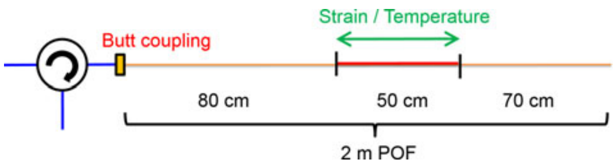

Fig. 2. Structure of POF under test (1).

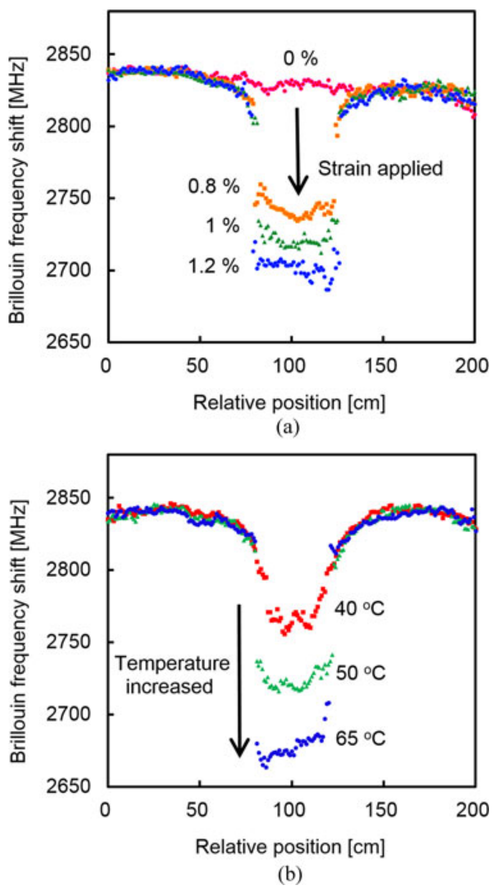

Fig. 3. Measured BFS distributions with a 50-cm-long section (a) strain-applied, and (b) heated.

applied to a 50-cm-long section fixed on a translation stage, or the same section was heated up to 65 °C (sufficiently lower than glass-transition temperature [29]). One end of the POF was butt-coupled to a silica SMF (second port of the circulator) via an SC connector, and the other end was cut at 8° to suppress the Fresnel reflection. The room temperature was 18 °C.

The measured BFS distribution when strain was applied is shown in Fig. 3(a). The measurement time was approximately 1 min (200 points), which can be set shorter by reducing the measured points. The 50-cm-long strain-applied section was successfully detected. The BFS shifted to lower frequency with increasing strain with a proportionality constant of -115.3 MHz/%, which was moderately consistent with that previously reported (-121.8 MHz/% [10]. The BFS changed even along the strain-free sections by about ± 10 MHz, which indicates that the strain measurement error is $\pm 0.09\%$.

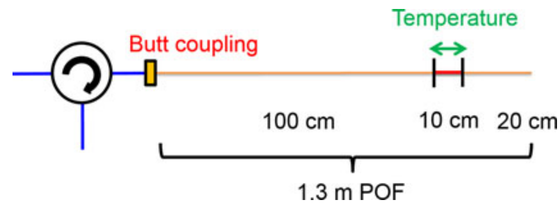

Fig. 4. Structure of POF under test (2).

The measured BFS distribution when temperature was changed is also shown in Fig. 3(b), where the 50-cm-long heated section was clearly detected. The measurement time was also about 1 min. The proportionality constant of temperature dependence was -3.27 MHz/°C, which is in good agreement with previous result (-3.2 MHz/% [15]). The temperature measurement error was evaluated to be 3.1 °C.

B. Distributed Temperature Measurement With High Spatial Resolution

Next, we demonstrate distributed temperature sensing with a centimeter-order spatial resolution. The modulation configurations of the light source were: $f_m = $ 53.321–53.451 MHz and $\Delta f = 0.9$ GHz, corresponding to d_m of 2.1 m and Δz of 7.4 cm ($N_R = 28$). Fig. 4 shows the structure of a 1.3-m-long POF employed, where a 10-cm-long section was heated to 40 °C.

Fig. 5(a) shows the measured distribution of normalized BGS along the POF, and Fig. 5(b) shows the BGS examples at non-heated and heated positions (relative positions of 67 and 104 cm, respectively). Fig. 5(c) shows the BFS distribution corresponding to Fig. 5(a). The measurement time was approximately 40 s (130 points). The BFS clearly downshifted at the 10-cm-long heated section. The amount of the BFS shift was approximately 26 MHz, which agrees well with the actual temperature (40 °C). The gradual BFS changes at the relative positions of ~90 and ~115 cm were probably caused by the overlap of two broad BGSs ($\Delta\nu_B \sim$100 MHz) from the sections with and without temperature changed.

C. Discussion on Sensor Performance

Finally, we compare the performances of POF-based BOCDR with those of silica SMF-based BOCDR. First, according to Eq. (3), the highest spatial resolution $\Delta z_{\min}$ theoretically achievable in POF-based BOCDR ($\nu_B \sim 2.8$ GHz; $n \sim 1.35$) is calculated to be 23 mm, which is approximately 1/4 of that in SMF-based BOCDR ($\nu_B \sim 10.8$ GHz; $n \sim 1.46$). However, a weak Brillouin signal in a POF [8]–[10], leading to a low SNR, practically limits the spatial resolution, as shown in the aforementioned experiment. Next, according to Eq. (5), the maximal number of effective sensing points $N_{R\max}$ of POF-based BOCDR ($\Delta\nu_B$ ~100 MHz) is calculated to be 44, which is ~1/13 of that of SMF-based BOCDR ($\Delta\nu_B \sim 30$ MHz). This problem can be mitigated by employing so-called temporal-gating [30] and double-modulation schemes [31]. Note that the measurement range d_m itself is limited not only by its trade-off relation to Δz but also by the high propagation loss (250 dB/km at 1.55 μm) of

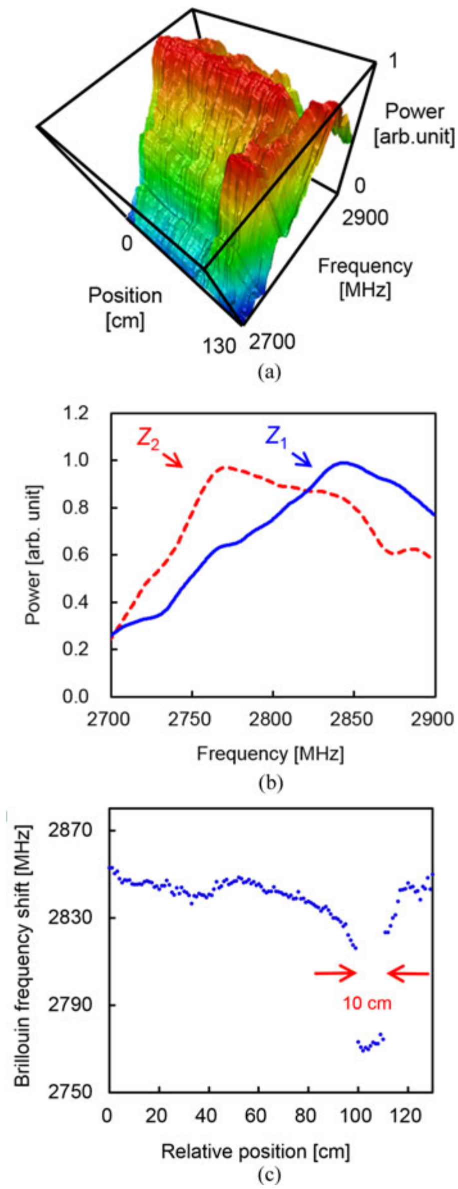

Fig. 5. (a) Normalized BGS distribution. (b) Examples of BGS (Z_1: at 67 cm (room temperature); Z_2: at 104 cm (heated)). (c) BFS distribution measured with cm-order resolution.

the POF. Currently, the practical limitation of d_m is several tens of meters (depending on Δz, incident power, and many other parameters); we believe it can be elongated to several hundreds of meters by using shorter pump wavelengths at which the propagation loss is much lower (for instance, ∼10-dB/km loss is reported at 0.98 μm [27]). As for the sampling rate of single-location measurement, 3.3 Hz demonstrated in the experiment is restricted by the speed of signal acquisition from the ESA via a general-purpose interface bus, which might be further enhanced by use of faster data acquisition methods that have been implemented in SMF-based BOCDR [22] and BOCDA [32]. Highly accurate discriminative sensing of strain and temperature [33] using POFs is another important problem to be tackled.

V. Conclusion

Distributed strain and temperature sensing with a centimeter-order spatial resolution in a POF was demonstrated for the first time using a cost-effective BOCDR technique. A 10-cm-long heated section of a 1.3-m-long POF was successfully detected with a theoretical spatial resolution of 7.4 cm and a sampling rate of 3.3 Hz (per measured point). The limitation of the sensing performances was discussed. We believe that our results have overcome a stereotype of perceiving POF-based Brillouin distributed sensing with a high resolution and/or a high SNR as almost infeasible.

Acknowledgment

The authors are grateful to Profs. K. Hotate and M. Kishi, the University of Tokyo, Japan, for their experimental assistance.

References

[1] T. Horiguchi and M. Tateda, "BOTDA—Nondestructive measurement of single-mode optical fiber attenuation characteristics using Brillouin interaction: Theory," *J. Lightw. Technol.*, vol. 7, pp. 1170–1176, 1989.
[2] 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.
[3] 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.
[4] 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.
[5] 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.
[6] M. G. Kuzyk, *Polymer Fiber Optics: Materials, Physics, and Applications*. Boca Raton, FL,USA: CRC Press, 2006.
[7] K. Nakamura, I. R. Husdi, and S. Ueha, "A distributed strain sensor with the memory effect based on the POF OTDR," *Proc. SPIE*, vol. 5855, pp. 807–810, 2005.
[8] Y. Mizuno and K. Nakamura, "Experimental study of Brillouin scattering in perfluorinated polymer optical fiber at telecommunication wavelength," *Appl. Phys. Lett.*, vol. 97, pp. 021103-1–021103-3, 2010.
[9] 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.
[10] 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.
[11] 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.
[12] R. Bernini, A. Minardo, and L. Zeni, "Distributed sensing at centimeter-scale spatial resolution by BOFDA: Measurements and signal processing," *IEEE Photon. J.*, vol. 4, no. 1, pp. 48–56, Feb. 2012.
[13] G. P. Agrawal, *Nonlinear Fiber Optics*. CA, USA: Academic Press, 1995.
[14] T. Kurashima, T. Horiguchi, and M. Tateda, "Distributed-temperature sensing using stimulated Brillouin scattering in optical silica fibers," *Opt. Lett.*, vol. 15, pp. 1038–1040, 1990.
[15] K. Minakawa, N. Hayashi, Y. Shinohara, M. Tahara, H. Hosoda, Y. Mizuno, and K. Nakamura, "Wide-range temperature dependences of Brillouin scattering properties in polymer optical fiber," *Jpn. J. Appl. Phys.*, vol. 53, pp. 042502-1–042502-4, 2014.
[16] M. A. Soto, X. Angulo-Vinuesa, S. Martin-Lopez, S.-H. Chin, J. D. Ania-Castanon, P. Corredera, E. Rochat, M. Gonzalez-Herraez, and L. Thevenaz, "Extending the real remoteness of long-range Brillouin optical time-domain fiber analyzers," *J. Lightw. Technol.*, vol. 32, no. 1, pp. 152–162, 2014.
[17] Y. Dong, L. Chen, and X. Bao, "Extending the sensing range of Brillouin optical time-domain analysis combining frequency-division multiplexing

and in-line EDFAs," *J. Lightw. Technol.*, vol. 30, no. 8, pp. 1161–1167, Apr. 2012.

[18] 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.

[19] W. Zou, C. Jin, and J. Chen, "Distributed strain sensing based on combination of Brillouin gain and loss effects in Brillouin optical correlation domain analysis," *Appl. Phys. Exp.*, vol. 5, pp. 082503-1–082503-3, 2012.

[20] Y. Zhao, Y. N. Zhang, B. Han, C. Qin, and Q. Wang, "High sensitive BOTDR demodulation method by using slow-light in fiber grating," *J. Lightw. Technol.*, vol. 31, no. 21, pp. 3345–3351, Nov. 2013.

[21] F. Wang, W. Zhan, X. Zhang, and Y. Lu, "Improvement of spatial resolution for BOTDR by iterative subdivision method," *J. Lightw. Technol.*, vol. 31, no. 23, pp. 3663–3667, Dec. 2013.

[22] Y. Mizuno, Z. He, and K. Hotate, "One-end-access high-speed distributed strain measurement with 13-mm spatial resolution based on Brillouin optical correlation-domain reflectometry," *IEEE Photon. Technol. Lett.*, vol. 21, no. 7, pp. 474–476, Apr. 2009.

[23] Y. Mizuno, W. Zou, Z. He, and K. Hotate, "Operation of Brillouin optical correlation-domain reflectometry: Theoretical analysis and experimental validation," *J. Lightw. Technol.*, vol. 28, no. 22, pp. 3300–3306, Nov. 2010.

[24] 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.

[25] Y. Mizuno, N. Hayashi, H. Tanaka, K. Nakamura, and S. Todoroki, "Observation of polymer optical fiber fuse," *Appl. Phys. Lett.*, vol. 104, pp. 043302-1–043302-4, 2014.

[26] K. Hotate and Z. He, "Synthesis of optical-coherence function and its applications in distributed and multiplexed optical sensing," *J. Lightw. Technol.*, vol. 24, no. 7, pp. 2541–2557, Jul. 2006.

[27] Y. Koike and M. Asai, "The future of plastic optical fiber," *NPG Asia Mater.*, vol. 1, pp. 22–28, 2009.

[28] Y. Mizuno, N. Hayashi, and K. Nakamura, "Polarisation state optimisation in observing Brillouin scattering signal in polymer optical fibres," *Electron. Lett.*, vol. 49, pp. 56–57, 2013.

[29] R. Gravina, G. Testa, and R. Bernini, "Perfluorinated plastic optical fiber tapers for evanescent wave sensing," *Sensors*, vol. 9, pp. 10423–10433, 2009.

[30] Y. Mizuno, Z. He, and K. Hotate, "Measurement range enlargement in Brillouin optical correlation-domain reflectometry based on temporal gating scheme," *Opt. Exp.*, vol. 17, pp. 9040–9046, 2009.

[31] Y. Mizuno, Z. He, and K. Hotate, "Measurement range enlargement in Brillouin optical correlation-domain reflectometry based on double-modulation scheme," *Opt. Exp.*, vol. 18, pp. 5926–5933, 2010.

[32] K. Y. Song and K. Hotate, "Distributed fiber strain sensor with 1-kHz sampling rate based on Brillouin optical correlation domain analysis," *IEEE Photon. Technol. Lett.*, vol. 19, no. 23, pp. 1928–1930, Dec. 2007.

[33] W. Zou, Z. He, and K. Hotate, "Complete discrimination of strain and temperature using Brillouin frequency shift and birefringence in a polarization-maintaining fiber," *Opt. Exp.*, vol. 17, pp.1248–1255, 2009.

Neisei Hayashi was born in Gunma, Japan, on April 13, 1988. He received the B.E. degree in advanced production from the Gunma National College Technology (GNCT), Gunma, Japan, in 2011, and the M.E. degree in electronic engineering from Tokyo Institute of Technology, Tokyo, Japan, in 2013.

From 2008 to 2010, he studied a ring-wandering phenomenon for the Bachelor's degree at the GNCT. From 2011 to 2013, he worked on nonlinear optics in polymers for the Master's degree at Tokyo Institute of Technology. In 2013, he became a Research Fellow (DC1) of the Japan Society for the Promotion of Science, and, since then, he has been continuing to study polymer optics for the Dr. Eng. degree at Tokyo Institute of Technology. His research interests include fiber-optic sensors, polymer optics, and ultrasonics.

Mr. Hayashi is the Winner of the TELECOM System Technology Award for Student 2012. He is a Member of the Japanese Society of Applied Physics, and the Institute of Electronics, Information, and Communication Engineers of Japan.

Yosuke Mizuno was born in Hyogo, Japan, on October 13, 1982. He received the B.E., M.E., and Dr. Eng. degrees in electronic engineering from the University of Tokyo, Tokyo, Japan, in 2005, 2007, and 2010, respectively. From 2007 to 2010, he was engaged in Brillouin optical correlation-domain reflectometry for the Dr. Eng. degree at the University of Tokyo.

From 2007 to 2010, he was a Research Fellow of the Japan Society for the Promotion of Science. From 2010 to 2012, as a Research Fellow of JSPS, he worked on polymer optics at Tokyo Institute of Technology, Japan. In 2011, he stayed at BAM Federal Institute for Materials Research and Testing, Germany, as a Visiting Research Associate. Since 2012, he has been an Assistant Professor at the Precision and Intelligence Laboratory, Tokyo Institute of Technology, where he is active in fiber-optic sensing, polymer optics, and ultrasonics.

Dr. Mizuno received the Funai Research Award 2010, the Ando Incentive Prize for the Study of Electronics 2011, the NF Foundation R&D Encouragement Award 2012, and the Kenjiro Nakamura Prize 2012. He is a Member of the Japanese Society of Applied Physics, and the Institute of Electronics, Information, and Communication Engineers of Japan.

Kentaro Nakamura (M'00) was born in Tokyo, Japan, on July 3, 1963. He received the B.E., M.E., and Dr. Eng. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 1987, 1989, and 1992, respectively.

Since 2010, he has been a Professor at the Precision and Intelligence Laboratory, Tokyo Institute of Technology. His research field is the applications of ultrasonic waves, measurement of vibration and sound using optical methods, and fiber-optic sensing.

Prof. Nakamura is the Winner of the Awaya Kiyoshi Award for encouragement of research from the Acoustical Society of Japan in 1996, and the Best Paper Award from the Institute of Electronics, Information and Communication Engineers in 1998, and from the Symposium on Ultrasonic Electronics in 2007 and 2011, respectively. He also received the Japanese Journal of Applied Physics Editorial Contribution Award from the Japan Society of Applied Physics in 2007. He is a Member of the ASJ, the JSAP, the IEICE, and the Institute of Electrical Engineers of Japan.