Range Elongation of Distributed Discrimination of Strain and Temperature in Brillouin Optical Correlation-Domain Analysis Based on Dual Frequency Modulations

Weiwen Zou, *Member, IEEE*, Zuyuan He, *Senior Member, IEEE*, and Kazuo Hotate, *Fellow, IEEE*

***Abstract*— A scheme of dual frequency modulations are proposed for one-laser Brillouin optical correlation-domain distributed discrimination of strain and temperature. A lower frequency modulation is additionally applied to the laser source, which is originally modulated by a higher one for distributed generation and detection of Brillouin dynamic grating. This scheme can suppress the unwanted correlation peaks due to the higher frequency modulation so as to elongate the measurement range with keeping the high spatial resolution. In this experiment, the measurement range is increased from ~5 to 34 m with the spatial resolution maintained to be 10 cm.**

***Index Terms*— Brillouin fiber-optic sensor, strain-temperature discrimination, distributed sensing.**

I. INTRODUCTION

FIBER-OPTIC distributed sensors based on Brillouin scattering have been intensively studied for decades because they have great potential applications in smart materials and smart structures [1], [2]. Recently, we demonstrated a solution to completely discriminate the strain and temperature responses by use of a polarization maintaining optical fiber (PMF) [3], where a concept of Brillouin dynamic grating (BDG) [4] associated with stimulated Brillouin scattering (SBS) was utilized to precisely detect the strain- and temperature-induced changes of the birefringence and the Brillouin frequency shift. A correlation-domain continuous-wave technique [5] and a time-domain pulse-based technique [6] were developed for distributed measurement of Brillouin dynamic grating spectrum (DGS) in a PMF, respectively. Distributed discrimination of strain and temperature with 10-cm spatial resolution was achieved based on the correlation-domain technique [7]; later, a similar performance was also realized based on the time-domain technique [8].

Most recently, to overcome the frequency fluctuation between/among the multiple laser sources required in the DGS distribution measurement systems in [5]–[8], we proposed a one-laser-based system where light waves for BDG writing and reading were inherently coherent [9]. The one-laser-based system ensures precise distributed discrimination of strain and temperature without any time-consuming averaging. However, commonly in the Brillouin optical correlation-domain analysis or reflectometry (BOCDA or BOCDR) systems, the measurement range is limited to the interval between neighboring correlation peaks due to the frequency modulation to the laser source [5], [10]. Furthermore, the measurement range is in a trade-off relation with the spatial resolution [5]. It was proved that applying dual frequency modulations to the laser source is effective to extend the measurement range of BOCDA or BOCDR system [11], [12].

In this paper, we demonstrate a new scheme to elongate the measurement range of the one-laser-based optical correlation-domain distributed discrimination system introducing dual frequency modulations to the single laser source. The measurement range of the distributed Brillouin gain spectrum (BGS) and DGS measurement (i.e., distributed discrimination of strain and temperature) is determined by the second lower frequency modulation, which is experimentally improved by about 7 times (from ~5 m to ~34 m). The spatial resolution decided by the first higher frequency modulation is kept to be 10 cm.

II. PRINCIPLE AND EXPERIMENTAL SETUP

Figure 1 illustrates the principle and experimental setup of the new scheme. As shown in Fig. 1(a), a 1550-nm distributed-feedback laser diode (DFB-LD) is used as the laser source, which is intensity-modulated by a high-speed intensity modulator (IM1) driven by a microwave synthesizer (RF1, ν_1) [9].

Manuscript received June 17, 2013; accepted August 11, 2013. Date of publication September 20, 2013; date of current version November 5, 2013. This work was supported in part by the "Grant-in-Aid for Scientific Research (S)" and the "Global Center of Excellence Program" from the Ministry of Education, Culture, Sports, Science and Technology, Japan, in part by the National Natural Science Foundation of China under Grants 61007052 and 61275097, in part by the International Cooperation Project from the Ministry of Science and Technology of China under Grant 2011FDA11780, in part by the Shanghai Pujiang Program from STCSM under Grant 12PJ1405600, and in part by the "SMC Young Star" Scientist Program of Shanghai Jiao Tong University. The experimental study was finished at the University of Tokyo. The associate editor coordinating the review of this paper and approving it for publication was Dr. David Hecht.

W. Zou and Z. He are with the State Key Laboratory Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: wzou@sjtu.edu.cn; zuyuanhe@sjtu.edu.cn).

K. Hotate is with the Department of Electrical Engineering and Information Systems, The University of Tokyo, Tokyo 113-0033, Japan (e-mail: hotate@sagnac.t.u-toky.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/JSEN.2013.2282639

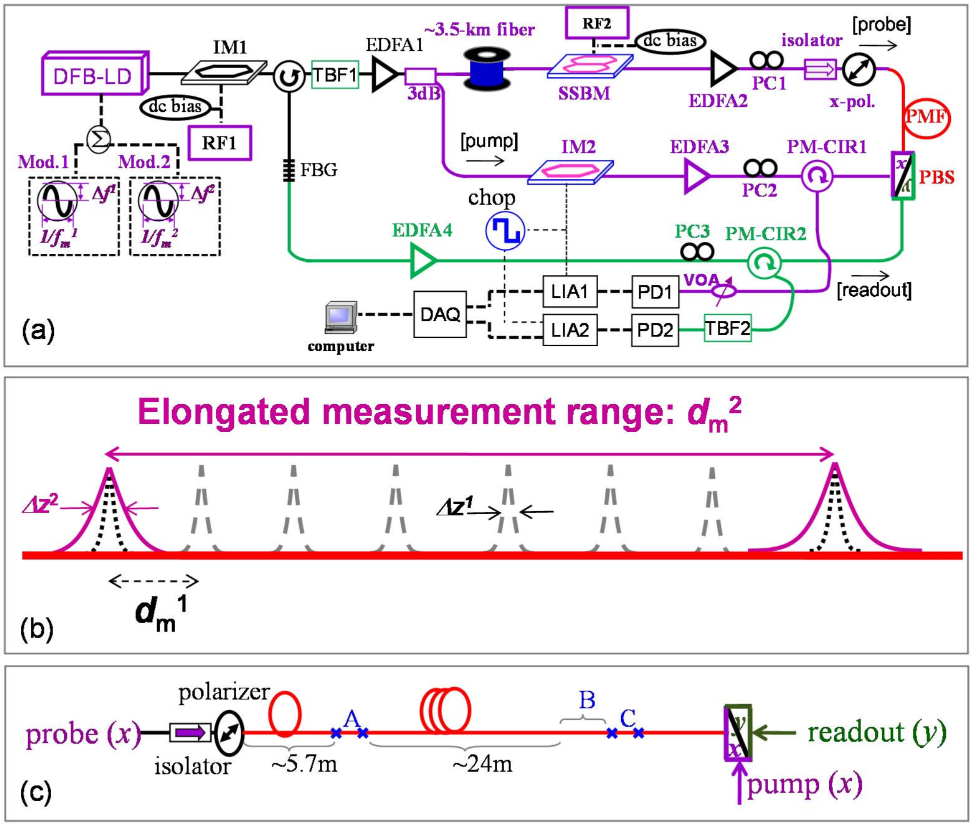


Fig. 1. (a) Experimental setup and (b) principle of one-laser-based distributed discrimination system to elongate measurement range assisted by dual frequency modulations. (c) Configuration of the PMF under test.

The BDG writing and reading waves, which should have about 40 GHz frequency difference with each other, are generated as the upper and the lower side bands by the intensity modulation to the laser source. The writing and reading waves are separated by a fiber Bragg grating (FBG) and a tunable bandpass filter (TBF1). For the BGS measurement as well as BDG generation, the pump-probe frequency offset was precisely controlled by another microwave synthesizer (RF2, ν_2) through a single sideband modulator (SSBM).

For the DGS detection, the pump-readout frequency offset, which is twice as large as RF1 ($2\nu_1$), is accurately tuned and ramp-swept. A low-speed IM2 is used to chop the power of the pump wave for synchronous detection of BGS and DGS in the PMF under test using lock-in amplifiers (LIAs). A set of polarization controller (PC) and polarizer (or polarization-maintaining circulator, PM-CIR) is used to ensure all pump/probe and readout waves to be linearly polarized. A polarization beam splitter (PBS) is used to combine (or divide) the orthogonally polarized waves into (or out from) the PMF. An additional tunable filter TBF2 is placed after PM-CIR2 to filter out the leaked probe wave due to the PMF's crosstalk. The BGS and DGS measurements are recorded by a multi-channel data acquisition card (DAQ), respectively.

The dual frequency modulations indicated as Mod.1 and Mod.2 in Fig. 1(a) were simultaneously applied to the single laser source. The measurement range ($d_{\mathrm{m}}^{\mathrm{i}}$) for the distributed BGS and DGS measurement is the same, given by

$$d_m^i = \frac{c}{2n_{eff}\, f_m^i}, \tag{1}$$

and the spatial resolutions ($\Delta z_{\mathrm{B}}^{\mathrm{i}}$ for the BGS measurement and $\Delta z_{\mathrm{D}}^{\mathrm{i}}$ for the DGS measurement) are determined by [9]

$$\Delta z_B^i = \frac{c}{2n_{eff}\, f_m^i}\,\frac{\Delta\nu_B}{\pi\,\Delta f^i}, \tag{2}$$

$$\Delta z_D^i = \frac{c}{2n_{eff}\, f_m^i}\,\frac{\Delta f_{yx}}{\pi\,\Delta f^i}, \tag{3}$$

where c is the light speed in vacuum, n_{eff} the effective refractive index ($= \sim 1.446$), $\Delta\nu_{\mathrm{B}}$ the BGS linewidth ($= 30$ MHz), Δf_{yx} the DGS linewidth ($= \sim 300$ MHz), Δf^i the modulation depth and f_m^i the modulation frequency. The superscript $\mathrm{i} = 1$ or 2 corresponds to the Mod.1 or Mod.2, respectively.

As shown in Fig. 1(b), the Mod.1 with higher modulation frequency (${f_m}^1$) and higher modulation depth (Δf^1) produces the first kind of correlation peaks along a PMF under test, which has shorter measurement range of ${d_m}^1$ but narrower spatial resolution of Δz^1. In contrast, the Mod.2 with lower modulation frequency (${f_m}^2 = \sim {f_m}^1/7$) and lower modulation depth (Δf^2) generates the second kind of correlation peaks with longer ${d_m}^2 = \sim 7{d_m}^1$ but broader spatial resolution of $\Delta z^1 < \Delta z^2 < dm^1$. It is noted that due to the cascading effect of the two kinds of correlation peaks only one wanted

TABLE I

STRAIN AND TEMPERATURE APPLIED TO THE PMF UNDER TEST

Fiber positions	***A***	***B***	***C***	***Other***
Length	**16 cm**	**80 cm**	**16 cm**	**~33 m**
Strain (με)	**1500**	**0**	**150**	**0**
Temperature (°C)	**40.5**	**45**	**40.5**	**25**

TABLE II

PARAMETERS OF DUAL FREQUENCY MODULATIONS APPLIED TO THE LASER SOURCE

Mod.	**Spectra**	**f_m^i (kHz)**	**Position**	**Δf^i (GHz)**	**Δz^i (cm)**
1	**BGS**	**20075.8- 20130.2 (64Hz step)**	**0-34m (4cm step)**	**1.0**	**5**
1	**DGS**			**6.0**	**10**
2	**BGS'**	**2945.9-3000.34 (64Hz step)**	**0-34m (4cm step)**	**1.0**	**34**
2	**DGS'**			**1.0**	**340**

correlation peak among the peaks generated by the Mod.1 is selected, while the other unwanted peaks are suppressed by the Mod.2, as shown in Fig. 1(b). Therefore, the measurement range is elongated by about 7 times while the spatial resolution is still determined by the narrower correlation peaks (Δz^1). The BGS and DGS distribution was continuously measured by scanning the modulation frequencies (${f_m}^1$ and ${f_m}^2$) of Mod.1 and Mod.2. It is noticeable that the dual frequency modulations are not necessarily synchronized.

III. EXPERIMENTAL RESULTS

A ~34-m-long PMF under test was configured to comprise three sections (A, B and C) under different strain and/or temperature as schematically depicted in Fig. 1(c). Table I summarizes the setting values of the strain and/or temperature applied to the PMF under test. A spool of optical fiber (3.5 km in length) was inserted in the probe arm to ensure only one higher-order cascaded correlation peak locating in the PMF.

The parameters of the dual frequency modulations are given in Table II. The measurement range and the spatial resolutions for each modulation are estimated according to Eqs. (1)-(3), respectively. As explained above, the measurement range ($d_m^2 = \sim 34$ m) is determined by the Mod. 2; the nominal spatial resolutions are decided by the Mod.1, which are ~5 cm and ~10 cm for BGS and DGS measurement, respectively. It is noted that since the spatial resolution of DGS measurement mainly limited by the achievable modulation depth of the DFB-LD is ~10 cm [7], [9], the one of BGS measurement is set to be a comparable value (~5 cm) for distributed discriminative sensing of strain and temperature. For distributed measurement, the modulation frequencies are changed with a small step of 64 Hz, corresponding to a 4 cm sweeping step of the sensing location.

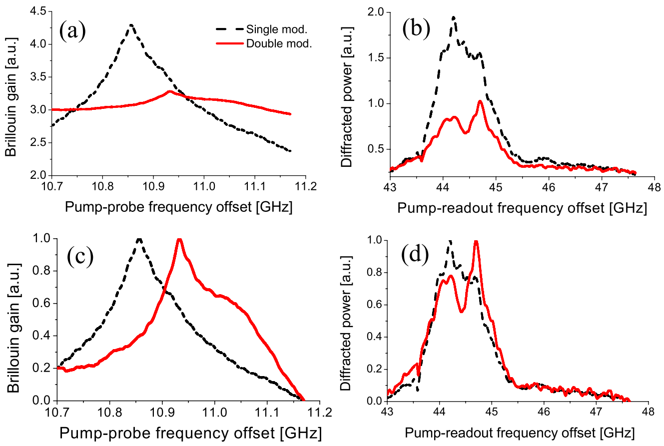


Fig. 2. Local BGS (a) and DGS (b) measured at the A section with 1500 $\mu\varepsilon$ and 40.5 °C ($\Delta T = 15.5$ °C). (c) and (d) are the normalized results to the maximum values of (a) and (d). The dashed or solid curves denote the single or dual modulations to the laser diode, respectively.

First, the modulation frequencies are set to localize the A section, which was heated by $\Delta T = 15.5$ °C. Figure 2(a) and (b) show the local BGS and DGS. The spectra normalized to the maximum values are illustrated in Figs. 2(c) and (d) for clear comparison. As shown by the solid curves when the two modulations were applied simultaneously to the laser source, the local BGS and DGS at the A section were successfully identified, where the spectral peaks were shifted from their original positions by strain and heating. When only the Mod.1 was applied, the local BGS and DGS at the A section were not identified as shown by the dashed curves, because they were covered by BGS and DGS at loctions corresponding to unwanted correlation peaks, where no strain/heating applied. It is noted that the BGS and DGS detected in this dual frequency modulation scheme are weaker compared to those under single frequency modulation [see Figs. 2(a) and (b)]. This is because the output is attributed to all 7 correlation peaks (1 wanted plus 6 unwanted) in the latter case while only one wanted correlation peak in the former case.

Three-dimensional (3-D) distribution of BGS and DGS around the A section is depicted in Figs. 3(a) and 3(b). The distribution of the changes of ν_B and f_{yx} were evaluated by peak-searching of the BGS and DGS distribution, which is summarized in Fig. 3(c). By use of the cross-sensitivity matrix [3], we calculated the strain and temperature distribution. The results are plotted in Fig. 3(d), which are all in good agreement with the setting values shown in Table 1.

Figure 4 illustrates the characterized distribution of the changes of ν_{B} and f_{yx} along the entire PMF. It is clear that three sections under different strain and temperature settings can be distinguished. For example, at the B section, since only temperature was changed from 25 °C to 45 °C, opposite behaviors of ν_{B} and f_{yx} to heating are observed. Again, the strain and temperature distribution around the B and C sections could be evaluated according to the cross-sensitivity matrix [3]. The strain and temperature distribution around the

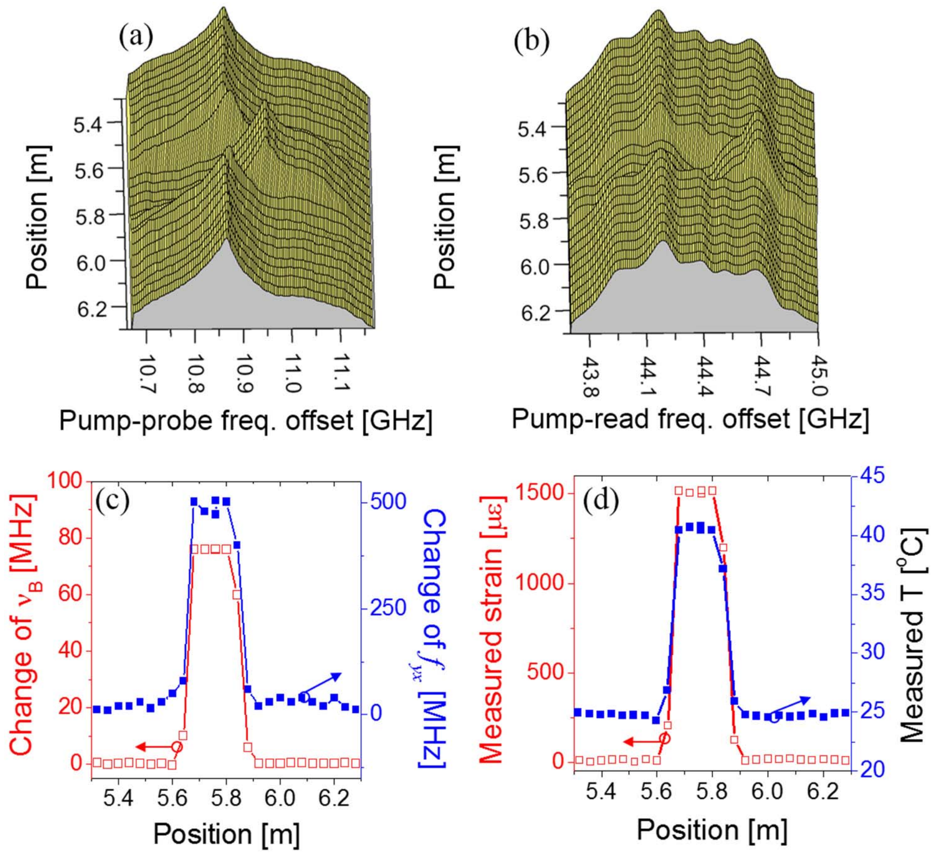


Fig. 3. Measured 3-D distribution of BGS (a) and DGS (b) around the A section. (c) Distribution of the measured changes of ν_{B} or f_{yx}, and (d) distributed discriminative sensing of strain and temperature around the A section.

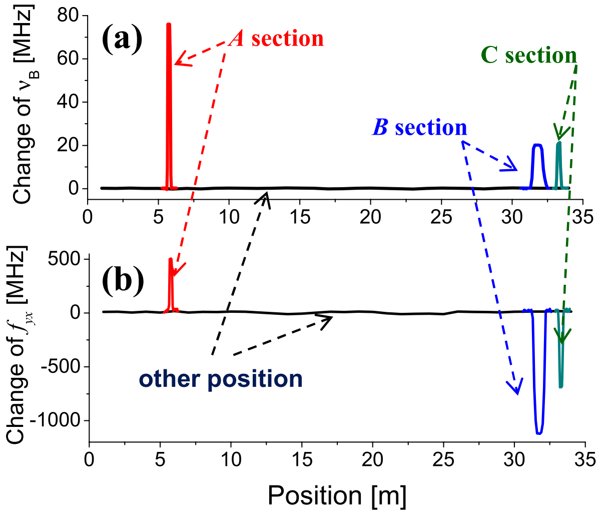


Fig. 4. Distribution of the changes of ν_{B} (a) and f_{yx} (b) along the entire PMF where three sections (A, B and C) are set under different strain/temperature.

B and C sections were also interrogated, which are shown in Fig. 5 and match well with the setting values. The accuracy of distributed discriminative sensing of strain and temperature is about ~0.1 °C and ~5 $\mu\varepsilon$, respectively.

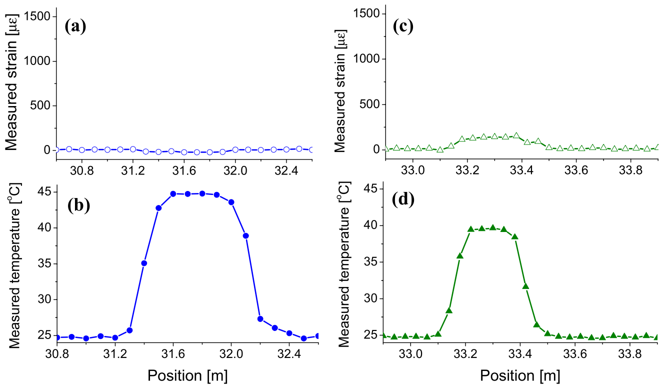


Fig. 5. Distributed discriminative sensing of strain and temperature for the B section (a, b) and the C section (c, d).

IV. CONCLUSION

We have demonstrated a new scheme to elongate the measurement range with keeping the high spatial resolution in the one-laser Brillouin optical correlation domain distributed temperature/strain discrimination system. Dual frequency modulations were simultaneously applied to the laser source to suppress the unwanted correlation peaks in the PMF under test. A measurement range of ~34 m (improved by 7 times) was preliminarily achieved with a spatial resolution of ~10 cm.

We have recently demonstrated the measurement range of about 500 m by using the temporal gating scheme [13]. However, the spatial resolution was limited around 45 cm in the experiment [13], mainly due to the trade-off relation between the spatial resolution and the correlation peak interval in the BOCDA system with the one frequency modulation scheme. Brillouin optical correlation-domain distributed discrimination of strain and temperature having both a higher spatial resolution (better than 10 cm) and a longer measurement range (better than 1,000 m) is expected to be realized by combining the dual frequency modulation scheme with the temporal gating scheme [13], which is now under study.

REFERENCES

[1] X. Bao, A. Brown, M. DeMerchant, and J. Smith, "Characterization of the Brillouin-loss spectrum of single-mode fibers by use of very short ($<$ 10 ns) pulses," *Opt. Lett.*, vol. 24, no. 8, pp. 510–512, Apr. 1999.

[2] 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, no. 17, pp. 2526–2528, Sep. 2006.

[3] 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, no. 3, pp. 1248–1255, Feb. 2009.

[4] K. Y. Song, W. Zou, Z. He, and K. Hotate, "All-optical dynamic grating generation based on Brillouin scattering in polarization-maintaining fiber," *Opt. Lett.*, vol. 33, no. 9, pp. 197–199, May 2008.

[5] W. Zou, Z. He, K. Y. Song, and K. Hotate, "Correlation-based distributed measurement of dynamic grating spectrum generated in stimulated Brillouin scattering in a polarization-maintaining optical fiber," *Opt. Lett.*, vol. 34, no. 7, pp. 1126–1128, Apr. 2009.

[6] K. Y. Song, W. Zou, Z. He, and K. Hotate, "Optical time-domain measurement of Brillouin dynamic grating spectrum in a polarization maintaining fiber," *Opt. Lett.*, vol. 34, no. 9, pp. 1381–1383, May 2009.

[7] W. Zou, Z. He, and K. Hotate, "Demonstration of Brillouin distributed discrimination of strain and temperature using a polarization-maintaining optical fiber," *IEEE Photon. Technol. Lett.*, vol. 22, no. 8, pp. 526–528, Apr. 15, 2010.

[8] Y. Dong, L. Chen, and X. Bao, "High-spatial-resolution time-domain simultaneous strain and temperature sensor using Brillouin scattering and birefringence in a polarization-maintaining fiber," *IEEE Photon. Technol. Lett.*, vol. 22, no. 18, pp. 1364–1366, Sep. 15, 2010.

[9] W. Zou, Z. He, and K. Hotate, "One-laser-based generation/detection of Brillouin dynamic grating and its application to distributed discrimination of strain and temperature," *Opt. Exp.*, vol. 19, no. 3, pp. 2363–2370, Jan. 2011.

[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, no. 3, pp. 405–412, Mar. 2000.

[11] K. Hotate and M. Tanaka, "Correlation-based continuous wave technique for optical fiber distributed strain measurement using Brillouin scattering with cm order spatial resolution-applications to smart materials," *IEICE Trans. Electron.*, vol. E84-C, no. 12, pp. 1823–1828, Dec. 2001.

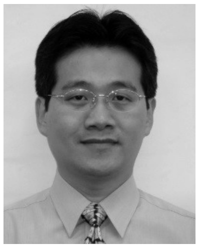
[12] Y. Mizuno, Z. He, and K. Hotate, "Measurement range enlargement in Brillouin optical correlation-domain reflectometry based on double-modulation scheme," *Opt. Exp.*, vol. 18, no. 6, pp. 5926–5933, Mar. 2010.

[13] R. K. Yamashita, W. Zou, Z. He, and K. Hotate, "Measurement range elongation based on temporal gating in Brillouin optical correlation domain distributed simultaneous sensing of strain and temperature," *IEEE Photon. Technol. Lett.*, vol. 24, no. 12, pp. 1006–1008, Jun. 15, 2012.

Weiwen Zou (S'05–M'08) received the B.S. degree in physics and the M.S. degree in optics from Shanghai Jiao Tong University, Shanghai, China, in 2002 and 2005, respectively, and the Ph.D. degree in optoelectronics from the University of Tokyo, Tokyo, Japan, in 2008.

He was engaged in research of non-volatile photorefractive-based holography with the University of Electro-Communications, Tokyo, in 2003, as an Exchange Student. Since 2005, he has been involved in Brillouin-scattering-based discriminative sensing of strain and temperature for his doctoral research in electronic engineering, University of Tokyo. From 2008 to 2009, he was a post-doctoral research fellow with the University of Tokyo. In 2009, he became a Project Assistant Professor with the University of Tokyo. In 2010, he joined Shanghai Jiao Tong University as an Associate Professor. His current research interests include fiber-optic distributed sensors, fiber-optic measurement, and optical information processing.

Dr. Zou is a member of the Optical Society of America.



Zuyuan He (M'00) received the B.S. and M.S. degrees in electronic engineering from Shanghai Jiao Tong University, Shanghai, China, in 1984 and 1987, respectively, and the Ph.D. degree in optoelectronics from the University of Tokyo, Tokyo, Japan, in 1999.

He joined the Nanjing University of Science and Technology, Nanjing, China, as a Research Associate, in 1987, and became a Lecturer in 1990, where he was engaged in the research of fiber optic sensors, evaluation and measurement of optical devices, and optical instrumentation. From 1995 to 1996, he was a Research Fellow with the Research Center for Advanced Science and Technology, University of Tokyo, involved in the research on optical information processing. In 1999, he became a Research Associate of the University of Tokyo, on measurement and characterization of fiber optic components and systems, fiber optic reflectometry, fiber optic sensors, and multi-dimensional optical information processing. In 2001, he joined CIENA Corporation, Linthicum, MD, USA, as a Lead Engineer responsible for optical testing and optical process development. He was with the University of Tokyo as a Lecturer in 2003, and became an Associate Professor in 2005. He was a Professor with the Center of Excellence in Electrical and Electronic Engineering, University of Tokyo. Since 2012, he has been with Shanghai Jiao Tong University as a Distinguished Professor. His current research interests include optical fiber sensors, optical fiber measurement, and optical information processing.

Dr. He is a member of the Optical Society of America, and the Institute of Electronics, Information, and Communication Engineers of Japan.

Kazuo Hotate (M'91–SM'98–F'03) was born in Tokyo, Japan, on June 20, 1951. He received the B.E., M.E., and Dr.Eng. degrees in electronic engineering from the University of Tokyo, Tokyo, Japan, in 1974, 1976, and 1979, respectively.

He joined the University of Tokyo as a Lecturer in 1979. He became a Professor with the Research Center for Advanced Science and Technology, University of Tokyo, in 1993. Currently, he is a Professor in the Department of Electrical Engineering and Information Systems, School of Engineering, University of Tokyo. He served as the Dean of Faculty and Graduate School of Engineering, University of Tokyo, in 2008 and 2009. He was engaged in projection-type holography, measurement, and analysis of optical fiber characteristics. He is involved in photonic sensing. He has authored or coauthored several books on optical fibers and optical fiber sensors and more than 370 journal papers and international conference presentations.

Prof. Hotate is a fellow of the Institute of Electronics, Information, and Communication Engineers, the Society of Instrumentation and Control Engineers (SICE), and the Japan Society of Applied Physics. He was a BoG member of the IEEE Photonic Society. He received academic awards such as SPIE DSS Life-Time Achievement Award, Ichimura Prize, and Hasunuma Prize (SICE). He served as Co-Chair for SPIE Fiber Optic Gyros: Twentieth Anniversary Conference in 1996, the Technical Program Committee Chair for 13th International Conference on Optical Fiber Sensors (OFS-13) in 1999, and the General Chair for OFS-16 in 2003.