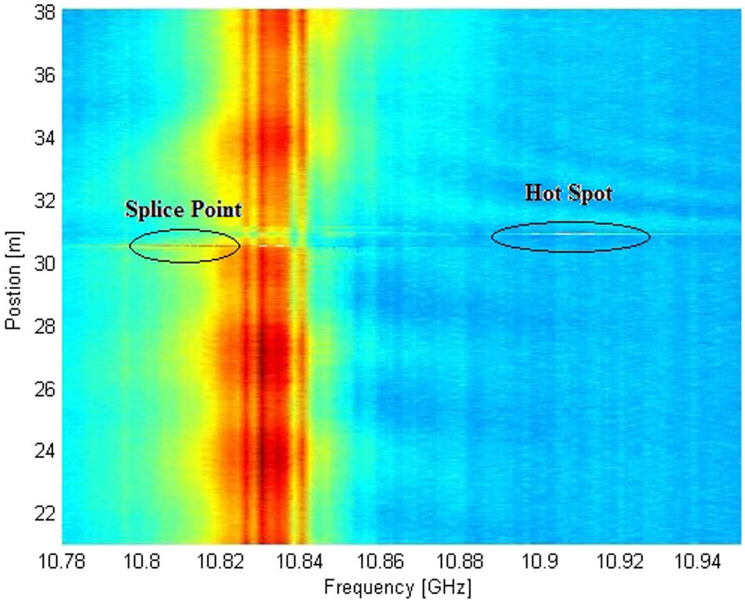
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

1-cm-Spatial-Resolution Brillouin Optical Time-Domain Analysis Based on Bright Pulse Brillouin Gain and Complementary Code

Volume 4, Number 6, December 2012

Y. Mao
N. Guo
K. L. Yu
H. Y. Tam



DOI: 10.1109/JPHOT.2012.2226710

1-cm-Spatial-Resolution Brillouin Optical Time-Domain Analysis Based on Bright Pulse Brillouin Gain and Complementary Code

Y. Mao,[1] N. Guo,[1] K. L. Yu,[1,2] H. Y. Tam,[3] and C. Lu[1]

[1]Department of Electronic and Information Engineering, The Hong Kong Polytechnic University,
Kowloon, Hong Kong SAR, China
[2]Institute of Information Science, Institute of Optical Information, Beijing Jiaotong University,
Beijing 100049, China
[3]Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

DOI: 10.1109/JPHOT.2012.2226710
1943-0655/$31.00 ©2012 IEEE

Manuscript received September 7, 2012; revised October 23, 2012; accepted October 24, 2012. Date of publication October 26, 2012; date of current version December 5, 2012. This work was supported by the Hong Kong Polytechnic University Central Research Grant under Project G-U746. Corresponding author: Y. Mao (e-mail: 07901370r@eie.polyu.edu.hk).

Abstract: We studied the impact of optical pulse coding techniques on Brillouin optical time-domain analysis (BOTDA) systems experimentally. The results show that complementary-coding-based schemes can provide significant enhanced signal-to-noise ratio (SNR) to the BOTDA system. Using complementary coding, the average time can be reduced significantly and so does the measurement time. The complementary-coded pulses with individual pulse duration of 0.1 ns allowed us to realize temperature sensing over 50 m of single-mode fiber with 1-cm spatial resolution.

Index Terms: Brillouin gain spectrum, optic fiber sensors, optical pulse coding, time-domain analysis.

1. Introduction

Optic fiber sensors based on Brillouin scattering enable distributed strain and temperature measurement over moderate range with high spatial resolution. The Brillouin frequency shift or Brillouin gain peak frequency of a fiber is a function of temperature and strain. Due to its backscattered nature, one can resolve the temperature and strain distribution along the fiber by analyzing the frequency shift of the scattering light. A commonly used distributed Brillouin sensing technique is Brillouin optical time-domain analysis (BOTDA). It was first proposed to measure optical fiber attenuation in 1989 [1]. It was subsequently used for distributed strain sensing in 1990 [2]. Significant performance improvement of the BOTDA system was achieved by Bao *et al.* in 1993 by reporting a spatial resolution of 10 m and temperature resolution of 1 K over a total sensing length of 22 km [3], and later, this result was further improved to 5-m resolution with measurement range extended to 32 km [4]. Subsequent work by Horiguchi *et al.* achieved 1-m spatial resolution over 11-km fiber in 1994 [5]. For many years, it was believed that the spatial resolution was limited to 1 m since the Brillouin gain spectrum is the convolution between the pump pulse spectrum and the natural Brillouin spectrum, and the phonon lifetime in an optical fibers is $\sim$10 ns. However, it was observed by Bao *et al.* that pre-excitation of the acoustic phonons through a continuous background pump enables the realization of a spatial resolution shorter than the length corresponding to the phonon lifetime, i.e., 1 m [7]. Based on this, Brown *et al.* presented a new scheme using dark-pulse pump signal, which allows strong acoustic field excitation even when ultrashort dark-pulse width is used. Using dark pulses, they realized a sensor system with a spatial resolution of 20 mm [8]. Alternative approach using short-pulse phase modulation of the pump was proposed to further improve the spatial resolution of a BOTDA system. It can cause the same Brillouin loss as a dark pulse but with a magnitude twice as large, thus much more efficient realization [9]. By using differential pulsewidth pairs, Li *et al.* demonstrated a BOTDA system with 10-cm spatial resolution [10].

In a BOTDA system, large number of averages are typically needed for each frequency step in order to realize good measurement accuracy. Coding was proposed to enhance the signal-to-noise ratio (SNR) significantly, and simplex code was used by Soto *et al.* to achieve 120-km total sensing length with 3.1 °C/60-$\mu\varepsilon$ sensing resolution and 3-m spatial resolution [12]. In this paper, using complementary code, we demonstrate experimentally for the first time a spatial resolution of 1 cm over 50-m fiber. High-speed pulse modulation at 10 GHz reduces the spectral width of the pump signal, thus allowing a high spatial resolution to be realized. Using pulse-coded modulation, SNR was significantly improved, and this leads to a reduced measurement time.

2. Coding and Decoding of the Complementary Code

When a pump pulse is launched into the sensing fiber of the BOTDA system, the detected signal $r(t)$ at each given time point represents the amplified probe signal from a particular spatial point along the fiber. The signal is the impulse response of the sensing system. When coded sequence is employed to modulate the pump, the acquired signal through the oscilloscope is the convolution of the coded pulse with the impulse response of the system, which can be expressed as $C(t) \otimes r(t)$, where $C(t)$ is the code words and $r(t)$ is the impulse response of the system. The impulse response is directly related to the spatial resolution of the sensor system. A decoding process is required to recover the impulse response of the system in order to obtain the distributed sensing information (strain or temperature) along the fiber.

Complementary code was first introduced by Golay in 1961 [13] and used to enhance the performance of the OTDR system by Nazarathy *et al.* in 1989 [14]. Recently, this coding technology was also used to enhance the performance of the BOTDA system by Zan *et al.* [15], [16]. A number of iterative constructions to generate complementary codes are derived by Golay [13]. One method is known as appending. The rule is to use N-length code pairs to generate a 2N-length code pairs

$$\left\{\begin{matrix} \mathrm{A} \\ \mathrm{B} \end{matrix}\right\} \rightarrow \left\{\begin{matrix} \mathrm{A}|\mathrm{B} \\ \mathrm{A}|\bar{\mathrm{B}} \end{matrix}\right\} \tag{1}$$

where $\bar{\mathrm{B}}$ denotes swapping the 1's and -1's in B.

According to the calculation, the complementary codes have a very good correlation behavior

$$\mathrm{A}_k * \mathrm{A}_k + \mathrm{B}_k * \mathrm{B}_k = \begin{cases} 2N, & \text{for } k = 0 \\ 0, & \text{for } k \neq 0 \end{cases} \tag{2}$$

where $*$ denotes the cross-correlation of two sequences.

Since, in intensity-modulation-based BOTDA system, only unipolar optical intensity signals are available; in our experiment, four groups of codes A_1, A_2, B_1, and B_2 are used to generate A and B, where

$$\begin{cases} \mathrm{A}_1 = \frac{1}{2}(\mathrm{A} + |\mathrm{A}|) \\ \mathrm{A}_2 = \frac{1}{2}(|\mathrm{A}| - \mathrm{A}) \end{cases} \tag{3}$$

$$\begin{cases} \mathrm{B}_1 = \frac{1}{2}(\mathrm{B} + |\mathrm{B}|) \\ \mathrm{B}_2 = \frac{1}{2}(|\mathrm{B}| - \mathrm{B}). \end{cases} \tag{4}$$

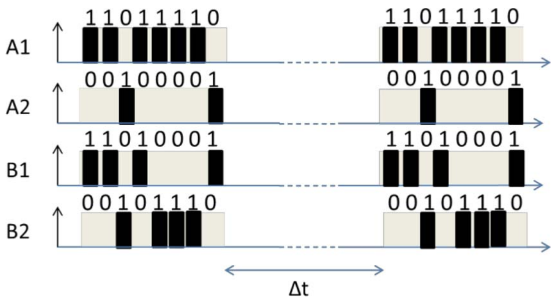


Fig. 1. Eight-bit complementary code used in BOTDA system. Δt is defined by the length of the fiber.

So, we have

$$\begin{cases} \mathrm{A} = \mathrm{A}_1 - \mathrm{A}_2 \\ \mathrm{B} = \mathrm{B}_1 - \mathrm{B}_2. \end{cases} \tag{5}$$

The codes A_1, A_2, B_1, and B_2 of a complementary code used in a BOTDA system is shown in Fig. 1. To make the figure clear, we only show the code with 8 bits. It is zero padded so that there will be only one code inside the fiber at any time. The number of zeros padded to the code depend on the time duration between two pulse sequences Δt, which is decided by the length of the fiber. The total length of the zero paddings should be larger than the roundtrip time of the fiber under test (FUT).

The detected signal can be expressed as the convolution between the code words and the impulse response of the system $R_i(t) = r(t) \otimes C_i(t)$, where $C_i(t)$ is the modulated pump signal. By calculating the cross-correlation between the reflected signal and the original code words for each code and summing them up, the impulse response can be fully recovered. The decoding process can be expressed as in [13]

$$\begin{aligned} R(t) &= \big(R_{\mathrm{A},1}(t) - R_{\mathrm{A},2}(t)\big) * C_{\mathrm{A}}(t) + \big(R_{\mathrm{B},1}(t) - R_{\mathrm{B},2}(t)\big) * C_{\mathrm{B}}(t) \\ &= \big(r(t) \otimes C_{\mathrm{A},1}(t) - r(t) \otimes C_{\mathrm{A},2}(t)\big) * C_{\mathrm{A}}(t) + \big(r(t) \otimes C_{\mathrm{B},1}(t) - r(t) \otimes C_{\mathrm{B},1}(t)\big) * C_{\mathrm{A}}(t) \\ &= (r(t) \otimes C_{\mathrm{A}}(t)) * C_{\mathrm{A}}(t) + (r(t) \otimes C_{\mathrm{B}}(t)) * C_{\mathrm{B}}(t) \\ &= r(t) \otimes (C_{\mathrm{A}}(t) * C_{\mathrm{A}}(t)) + r(t) \otimes (C_{\mathrm{B}}(t) * C_{\mathrm{B}}(t)) \\ &= r(t) \otimes (C_{\mathrm{A}}(t) * C_{\mathrm{A}}(t) + C_{\mathrm{B}}(t) * C_{\mathrm{B}}(t)) = 2N \cdot r(t) \end{aligned} \tag{6}$$

where N denotes the length of the code words.

According to the expression above, the signal processing can be employed to recover fiber impulse response with the spatial resolution of a single bit using the raw signal. The signal power will be increased by a factor of $2N$, and the noise will be increased by a factor of $\sqrt{2N}$. So, the SNR can be improved by a factor of $\sqrt{2N}$ when N-bit complementary code is used.

Besides SNR enhancement, another advantage of using coding techniques is that we can enhance the spatial resolution of the BOTDA system. In a BOTDA system with single pulse, when the width of the pump pulse is very short, the spectral width of the pump pulse is extremely wide. For a pulse shorter than 10 ns to achieve a spatial resolution better than 1 m, its spectral width is much wider than the Brillouin bandwidth. In this case, the efficiency of the Brillouin gain is very low, and the signal is too weak to be detected. By using coding technique, the spectral width of the pump pulse is reduced. Fig. 2 shows the relationship between the bandwidth of the pump pulse train and the length of the codes used. It shows that, although the width of each bit of the code is shorter than 10 ns, the spectral width of the pump pulse train is narrower than the Brillouin Gain spectra. Therefore, by using coding technique, high spatial resolution can be realized. Another way to view this is that the fast changing of the pulse waveform provides a constant dc signal for pre-excitation to allow a high spatial resolution to be realized.

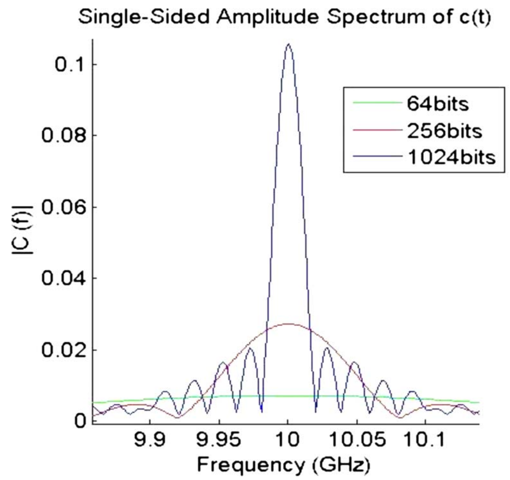


Fig. 2. Dependence of the bandwidth of the pump pulse on the code length.

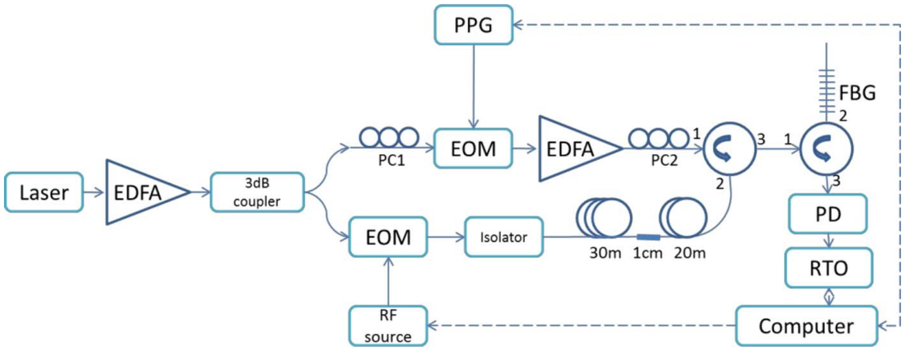


Fig. 3. Configuration of the BOTDA sensing system.

3. Experimental System

The schematic of the experimental setup is shown in Fig. 3. A continuous wave (CW) tunable laser operating at 1550 nm is used. The linewidth of the laser is 100 kHz, which is sufficiently narrower than that of the Brillouin spectral bandwidth. The output of the laser is amplified by an erbium-doped fiber amplifier (EDFA) and then split through a 50/50 coupler to generate both the pump and the probe signals. One beam goes to the upper arm and is modulated by an electrooptic modulator (EOM). The EOM is driven by a pulse pattern generator (PPG), which is controlled by a computer to generate a given length of complementary code. The bias voltage of the EOM is carefully tuned to quadrature point so that the modulator is working at on–off key (OOK) modulation format. In the lower arm, the beam is modulated by another EOM driven by a sinusoidal wave signal generated by a radio frequency (RF) generator. The modulator is biased at the transmission null point, and the frequency of the RF generator is controlled by the computer at a frequency approaching the Brillouin frequency shift of the FUT to generate the Stokes probe signal. Both the pump and the probe signal power are adjusted, respectively, through EDFAs and their states of polarization (SOPs) are adjusted by two polarization controllers (PCs) to obtain maximum Brillouin scattering along the fiber and then injected into the FUT. The Stokes signal is subsequently isolated, detected, and analyzed through a narrow-bandwidth FBG filter ($\sim$2 GHz), a photodetector (PD), and a Tektronix real-time oscilloscope (RTO). The data collected by the RTO are then processed by the computer with a decoding program to recover the spectra along the FUT and to calculate the temperature distribution along the FUT.

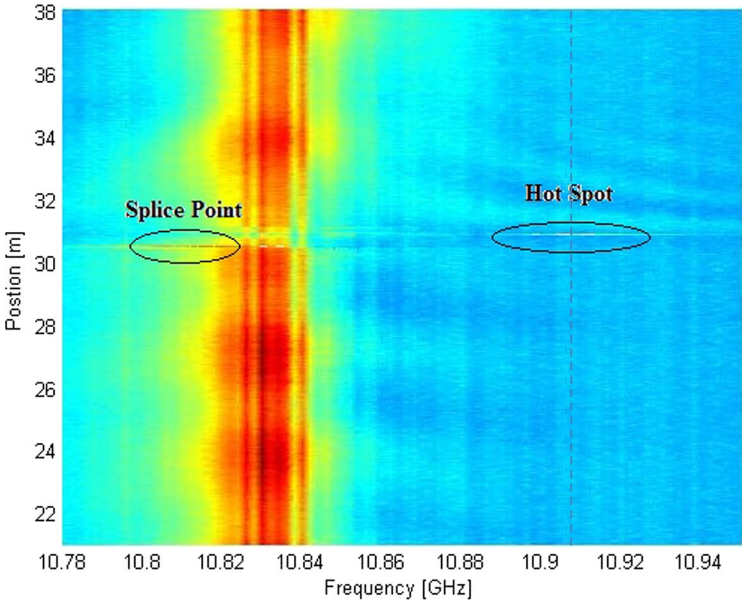


Fig. 4. Experiment result: Spectral distribution along the fiber.

In our experiment, the FUT is a 50-m-long standard single-mode fiber (SMF). A hot spot with a length of 1 cm is introduced to the FUT at the point 30 m away from the start point of FUT. The temperature of the hot spot is controlled by a thermoelectric cooler (TEC).

4. Experimental Results and Discussions

In our experiment, the clock of the PPG is set at 10 GHz. So, the time duration for each bit is 100 ps. After the decoding process, we can recover the impulse response of a single pulse with 100-ps pulsewidth. Theoretically, our system can measure the temperature or strain distribution at a spatial resolution of 1 cm. To verify this 1-cm spatial resolution, we heat 1-cm fiber with a TEC to 82 °C. The hot spot is 30 m away from the start point of the FUT, which has a total length of 50 m. It was put under room temperature of 22 °C. In the measurement, we use a set of complementary code with a code length of 1024. The frequency of the RF generator is controlled by the computer and was scanned from 10.78 GHz to 10.92 GHz with 2-MHz step. For each frequency step, the signal is recorded by the RTO after 100 times of average. After the average process, the results are recorded by the computer, and the decoding process is applied. The spectral distribution along the fiber is plotted and shown in Fig. 4. From Fig. 4, we can clearly see the frequency shift, which is about 80 MHz located 30 m away from the start point of the FUT. The frequency shift coefficient for temperature can be calculated as 1.33 MHz/°C. From this picture, we can also see that a section of fiber has a Brillouin frequency shift slightly smaller. This is due to the strain added by the protection sleeve of the splice point between the 20-m and 30-m fiber. This length of fiber with smaller Brillouin frequency is around 4 cm, as shown in Fig. 4, which goes very well with the length of the protection sleeve that we use. The SNR enhancement is smaller than the theoretical value. This is mainly due to the saturation of the coding gain. Since the power of the pump pulse is limited, the coding gain cannot be infinitely increased. This is also a limitation that we need to take into account when we choose the code length.

To show the spatial resolution of our fiber, we plot the Brillouin signal at the frequency of the hot spot, which is 10.91 GHz in our experiment, as shown in the dashed line in Fig. 4. From the right subplot of Fig. 5, the rising edge of the Brillouin signal from 10% to 90% is 1 cm. This confirms the spatial resolution of 1 cm. The falling edge is longer than the rising edge, which is 1.7 cm.

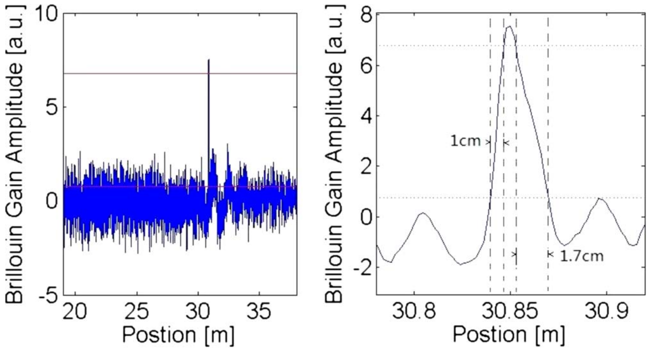


Fig. 5. Brillouin signal at the frequency 10.87 GHz.

5. Conclusion

We have shown the improvement of the performance of BOTDA systems by employing complementary-coded pump pulses. By using complementary-coded pulses with individual pulse duration of 0.1 ns, 1-cm high-resolution BOTDA system based on bright pulse Brillouin gain has been realized. Compared with single-pulse-based system, both spatial resolution and SNR can be significantly enhanced by the coding technique, so we can reduce the average time, which will reduce the measurement time significantly. In our experimental system, 1000 averages per measurement point were used for single-pulse system, and only 100 averages per measurement were necessary for complementary-code-based system. This allows the total measurement time to be reduced by ten times.

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, no. 8, pp. 1170–1176, Aug. 1989.

[2] T. Horiguchi, T. Kurashima, and M. Tateda, “Nondestructive measurement of optical fiber tensile strain distribution based on Brillouin spectroscopy,” *Trans. IEICE Jpn.*, vol. J73-B-I, no. 2, pp. 144–152, 1990.

[3] X. Bao, D. J. Webb, and D. A. Jackson, “22-km distributed temperature sensor using Brillouin gain in an optical fiber,” *Opt. Lett.*, vol. 18, no. 7, pp. 552–554, Apr. 1993.

[4] X. Bao, D. J. Webb, and D. A. Jackson, “32-km distributed temperature sensor using Brillouin gain in an optical fiber,” *Opt. Lett.*, vol. 18, no. 18, pp. 1561–1563, 1993.

[5] T. Horiguchi, T. Kurashima, and Y. Koyamada, “1 m spatial resolution measurement of distributed Brillouin frequency shift in single-mode fibers,” in *Proc. NIST Tech. Dig. Symp. Opt. Fiber Meas.*, 1994, pp. 73–76.

[6] M. Nickles, L. Thevenaz, and P. A. Robert, “Measurement of the distributed-Brillouin-gain spectrum in optical fibers by using a single-laser source,” in *Proc. OFC Tech. Dig.*, 1994, pp. 89–90.

[7] X. Bao, A. Brown, M. De Merchant, 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.

[8] A. W. Brown, B. G. Colpitts, and K. Brown, “Dark-pulse Brillouin optical time-domain sensor with 20-mm spatial resolution,” *J. Lightw. Technol.*, vol. 25, no. 1, pp. 381–386, Jan. 2007.

[9] L. Thevenaz and S. F. Mafang, “Distributed fiber sensing using Brillouin echoes,” in *Proc. 19th Int. Conf. Optic. Fibre Sens.*, Perth, Australia, 2008, pp. 70043N-1–70043N-4.

[10] W. H. Li, X. Bao, Y. Li, and L. Chen, “Differential pulse-width pair BOTDA for high spatial resolution sensing,” *Opt. Exp.*, vol. 16, no. 26, pp. 21 616–21 625, Dec. 2008.

[11] X. Bao and L. Chen, “Recent progress in optical fiber sensors based on Brillouin scattering in Ottawa University,” *Photon. Sens. Rev.*, vol. 1, no. 2, pp. 102–117, Jun. 2011.

[12] M. A. Soto, G. Bolognini, and F. Di Pasquale, “Long-range simplex-coded BOTDA sensor over 120 km distance employing optical preamplification,” *Opt. Lett.*, vol. 36, no. 2, pp. 232–234, Jan. 2011.

[13] M. J. E. Golay, “Complementary series,” *IRE Trans. Inf. Theory*, vol. IT-7, no. 2, pp. 82–87, Apr. 1961.

[14] M. Nazarathy, S. A. Newton, R. P. Giffard, D. S. Moberly, F. Sischka, W. R. Trutna, and S. Foster, “Real-time long range complementary correlation optical time domain reflectometer,” *J. Lightw. Technol.*, vol. 7, no. 1, pp. 24–38, Jan. 1989.

[15] M. S. D. B. Zan, T. Sasaki, T. Horiguchi, and D. Uchiyama, “Phase shift pulse Brillouin optical time domain analysis (PSP-BOTDA) employing dual Golay codes,” in *Proc. ICCCE*, Kuala Lumpur, Malaysia, May 11–13, 2010, pp. 1–6.

[16] M. S. D. B. Zan and T. Horiguchi, “A dual Golay complementary pair of sequences for improving the performance of phase-shift pulse BOTDA fiber sensor,” *J. Lightw. Technol.*, vol. 30, no. 21, pp. 3338–3356, Nov. 2012.