Distributed fiber temperature sensor using a laser diode modulated by a pseudo-random bit sequence

Jing Chai (柴 晶)[1,2], Mingjiang Zhang (张明江)[1,2,*], Yi Liu (刘 毅)[1,2], Lan Li (李 岚)[1,2], Weipeng Xu (许卫鹏)[1,2], and Yuncai Wang (王云才)[1,2]

[1]*Key Lab of Advanced Transducers and Intelligent Control System, Ministry of Education and Shanxi Province, Taiyuan University of Technology, Taiyuan 030024, China*

[2]*Institute of Optoelectronic Engineering, College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan 030024, China*

**Corresponding author: zhangmingjiang@tyut.edu.cn*

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We propose and demonstrate a scheme to measure the distribution of temperature along an optical fiber based on pseudo-random sequence modulation. In our experimental work, current modulation with a pseudo-random bit sequence (PRBS) is applied to a laser diode that serves as the Brillouin pump light and reference light. Because of the independence of the spatial resolution on the PRBS length, the measurement range can be extended while maintaining high spatial resolution using a long PRBS length. Temperature-induced changes in a Brillouin frequency shift of 250 m fiber sections are clearly observed with 54 cm spatial resolution by this method.

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Optical fiber sensors have been widely studied due to the unique advantages in measuring the strain or temperature along an optical fiber[1–4]. Brillouin-based optical fiber sensors are mainly classified into two types: Brillouin optical time domain systems [Brillouin optical time domain reflectometry (BOTDR) or Brillouin optical time domain analysis (BOTDA)][5–9] and Brillouin optical correlation domain systems [Brillouin optical correlation domain reflectometry (BOCDR) or Brillouin optical correlation domain analysis (BOCDA)][10–13]. In conventional pulse-based Brillouin optical time domain systems, the spatial resolution is restricted to about 1 m[14], which is determined by the acoustic phonon lifetime in the optical fiber. Although several measurement schemes have been proposed to enhance the systems' spatial resolution, such as double-pulse BOTDR[6], differential pulse-width pair BOTDA[8], simplex-coded BOTDA[9], and any more, they increase the complexity of the systems. Compared with time domain techniques, Brillouin optical correlation domain systems can improve the spatial resolution[10,13]. Brillouin optical correlation domain systems are based on the synchronous frequency modulation of constant-magnitude pump light and probe light or reference light by a sine wave[11,12]. In previous experiments, a spatial resolution of 40 cm was experimentally demonstrated with a measurement range of 100 m[11]. In Brillouin optical correlation domain systems, the measurement range d_m and the spatial resolution Δz are given by

$$d_m = \frac{v_g}{2f_m}, \tag{1}$$

$$\Delta z = \frac{v_g \Delta \upsilon_B}{2\pi f_m \Delta f}, \tag{2}$$

where v_g is the group velocity of light in the fiber, $\Delta \upsilon_B$ is the intrinsic linewidth of the Brillouin gain spectrum, and f_m and Δf are the modulation frequency and modulation amplitude, respectively, of the light source. A larger modulation amplitude is required to improve the spatial resolution under the same sensing range. Thus, there is a trade-off between the spatial resolution and the sensing range in those systems. In recent works, two methods are proposed to resolve this trade-off in BOCDA[15,16]. One method is that Brillouin pump and signal waves are phase-modulated by a common binary pseudo-random bit sequence (PRBS)[15]. By this technique, a 40 m unambiguous measurement range can be measured with 1 cm spatial resolution. In the other method, Brillouin pump and signal waves are obtained from the broadband amplified spontaneous emission (ASE) of fiber amplifiers[16], and a spatial resolution of 4 mm can be obtained along 5 cm of a silica single-mode fiber (SMF), i.e., the fiber under test (FUT). Whereas the two technologies require two light beams to be injected into both ends of the FUT, they cannot work completely when the FUT has one breakage point[17].

In this Letter, we propose and demonstrate a novel BOCDR scheme utilizing a PRBS-modulated laser diode (LD) to measure the temperature distribution along the optical fiber, which is based on the correlation technique as the current BOCDR. In principle, this new technique significantly resolves the problem of the trade-off between the spatial resolution and the measurement range in traditional BOCDR systems. Moreover, this scheme is much more simplified than previously proposed systems. A spatial resolution of 54 cm was experimentally demonstrated along a 250 m optical fiber.

Figure 1 depicts the proposed experimental setup based on a pseudo-random sequence modulation scheme.

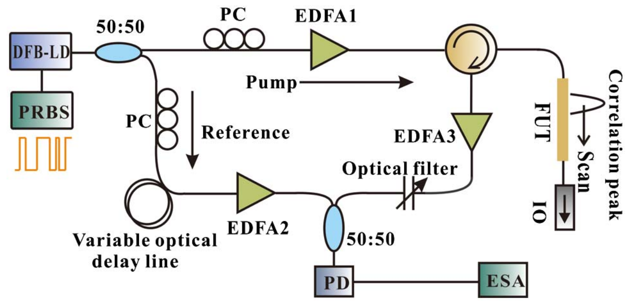

Fig. 1. Experimental setup of BOCDR using a PRBS-modulated LD.

A distributed feedback (DFB)–LD with a wavelength at 1550 nm was used as the light source, which was modulated by a PBRS from a PRBS generator. The modulated light was divided into two light paths by a fiber-optic coupler. After amplification by a high-power erbium-doped fiber amplifier (EDFA) up to 30 dBm, light in the pump path was launched into the FUT via a circulator. When the pump light beam was injected into the optical fiber, Brillouin scattering occurred in the optical fiber, resulting from the interaction between the incident light and the acoustic phonons in the optical fiber. The generated Stokes light propagated in the direction opposite to the incident light. The spectrum of the Stokes light, also known as the Brillouin spectrum, bore the shape of a Lorentzian function[18]. From the Brillouin spectrum, we could obtain the frequency change between the Stokes light and the incident light, which was called the Brillouin frequency shift (BFS) υ_B. By measuring the distribution of the Brillouin spectrum and the BFS along the FUT, the applied temperature change could be derived. The backscattered light from the FUT was amplified again by another EDFA. An optical filter (bandwidth: 6 GHz) was inserted after the EDFA to suppress the ASE noise, the Rayleigh scattering, and the anti-Stokes light from the FUT.

The other branch was used as the reference light of the self-heterodyne detection, and it was amplified by an EDFA in order to enhance the heterodyne beat signal. Moreover, in the reference branch, a variable optical delay line was inserted for locating the measurement point of the optical fiber. The coherence length of the laser modulated by the PRBS is always changing, and only when the optical paths of the pump and the reference light are equal, the coherence length of the pump light is the same as that of the reference light. When the optical path length of the reference branch was adjusted to be equal to that of the measurement point in the FUT, the backscattered Stokes light and the reference light would be in the same coherence length, and then we could obtain a maximum coherence beat signal, which is also called the correlation peak in the FUT[11], as shown in Fig. 1. Our proposed technique utilizes the interference between spontaneous Brillouin radiation and reference light. At the same time, the stimulated Brillouin scattering is suppressed with a PRBS-modulated laser pump such as a chaotic laser pump[19]. The optical beat signal was converted by the photodiode (PD) into electrical signals and monitored by the electrical spectrum analyzer (ESA).

Traditional BOCDR systems apply the sinusoidal modulation to the LD, and serve as the Brillouin pump and the reference light, which can produce a trade-off between the spatial resolution and the sensing range[20]. Unlike the traditional BOCDR, our system modulates the LD with the electrical PRBS corresponding to the modulation both in frequency and amplitude. The separation between adjacent correlation peaks and the width of the correlation peak, corresponding to the maximum measurement range $d_{\max}$ and the spatial resolution (half the coherence length of the source), are given by

$$d_{\max} = \frac{1}{2} M v_g T, \tag{3}$$

$$\Delta z = \frac{v_g}{2\Delta \upsilon}, \tag{4}$$

where v_g is the group velocity of light in the fiber, M is the PRBS length, T is a single coding symbol duration, and $\Delta\upsilon$ is the linewidth of the light source modulated by the PRBS. The linewidth of the modulated light source $\Delta\upsilon$ is influenced by the amplitude and the code rate $1/T$ of the PRBS. By adjusting the PRBS code length M to be sufficiently long, we can ensure only one correlation peak is synthesized at one point within the FUT, as shown in Fig. 1. Thus, the measurement range can be arbitrarily long and the spatial resolution can be high in theory. The position of the single correlation peak between the pump light and reference light could be scanned along the FUT through a variable optical delay line. The PRBS technique provides a simpler method to enhance the measurement range compared with the traditional BOCDR techniques while remaining the high spatial resolution. In our experimental work, the code length was $M = 2^{15} - 1$, the code rate $1/T$ was 1.5 GHz, and the amplitude of the PRBS was 150 mV. Figure 2 shows the time series and power spectrum of the electrical PRBS, which corresponds to an applied code rate of 1.5 GHz. The measured linewidth of the modulated laser is 180 MHz by the means of a delay self-heterodyne. Theoretically, according to

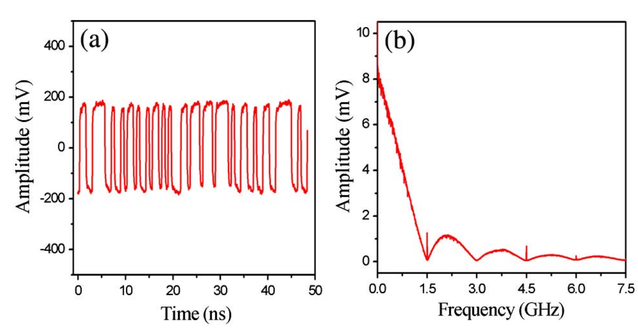

Fig. 2. Electrical PRBS: (a) time series; (b) power spectrum.

Eqs. (3) and (4), the maximum measurement range $d_{\max}$ and the spatial resolution Δz are calculated to be about 2 km and 57 cm.

Figure 3 shows the structure of the FUT, comprised of a standard SMF with a length of about 250 m. The length of fibers in the pump and reference branches were matched such that the reference light could interfere with the Stokes light at the specific point from the FUT. By adjusting the variable optical delay line, the correlation peak was scanned along the FUT to obtain the distribution of the Brillouin spectrum and BFS. In our experimental work, the FUT was placed on a table in the laboratory where the temperature was 24°C, a 1 m section of which was placed in the incubator. Adjusting the length of the reference branch to make it interfere with the Stokes light generated at one point from the 1 m section and changing the temperature of the incubator from 21°C to 51°C, we could obtain the Brillouin spectrum of the specific point at different temperatures. The Brillouin spectra of the point from the FUT at different temperatures are demonstrated in Fig. 4(a). With increasing temperature, the Brillouin spectra shift towards higher frequency. According to these spectra, we can plot the curve of the temperature-dependence of the BFS as shown in Fig. 4(b). From the linear fitting, the measured temperature coefficient is 1.13 MHz/°C and the correlation coefficient is 0.9916.

Then, maintaining the temperature of the incubator at 50°C, we adjusted the length of the variable optical delay line to obtain the correlation peak scanned over the FUT. Figure 5 shows the distribution of the Brillouin spectrum along the FUT with a 1-m-long heated section. A 3D plot of the detected distribution of the Brillouin spectrum is illustrated in Fig. 5, which indicates obvious differences of the BFS of fiber sections inside and outside of the incubator. As mentioned in Ref. [11], if $2\Delta f$ which is larger than the BFS υ_B is applied to the system, the signal-to-noise ratio will decrease drastically, because the measurement is influenced by the Rayleigh spectrum is not completely suppressed. In our experimental work, the linewidth of the modulated laser is about 180 MHz, which is far lower than the BFS, so we can make an estimate that the signal-to-noise ratio of the correlation signal between the Stokes light and reference light is beyond 3 dB as shown in Fig. 5.

Figure 6 shows the distribution of the BFS that we obtained from the data in Fig. 5. In Fig. 6, we can clearly notice a shift of about 29 MHz in the BFS, which agrees well with the applied temperature of the incubator. The accuracy of the measurement at a single position was about ±1.08 MHz, corresponding to a temperature of

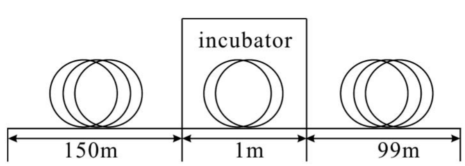

Fig. 3. Structure of the FUT in our experimental work.

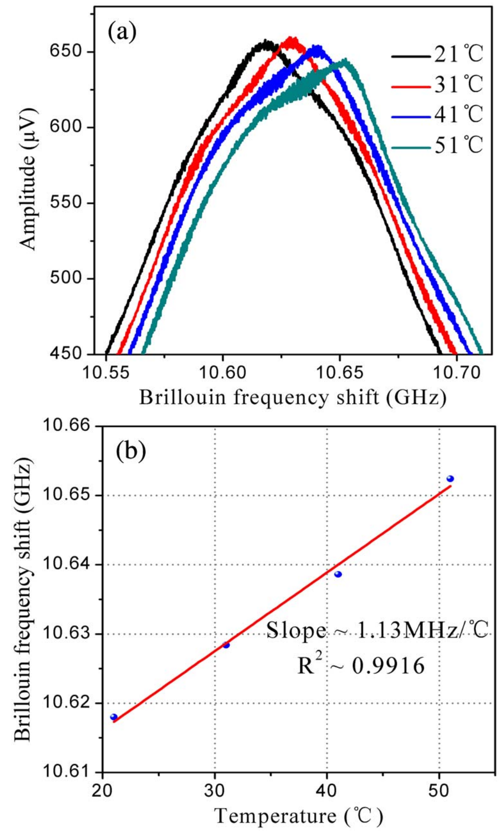

Fig. 4. (a) Measured Brillouin spectra at different temperatures; (b) temperature-dependence of the BFS.

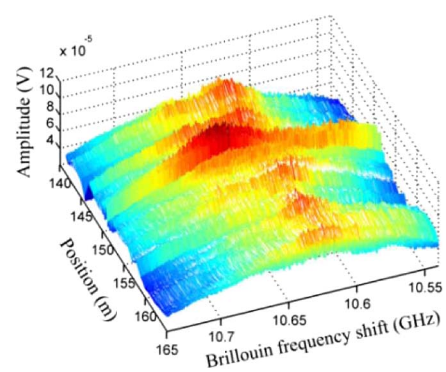

Fig. 5. Distribution of the Brillouin spectrum along the FUT with a 1-m-long heated section.

±0.96°C in our experimental work. From the inset in Fig. 6, we can see that the spatial resolution of this BOCDR system can reach 54 cm, which is consistent with the 57 cm spatial resolution calculated in accordance with Eq. (4).

Regarding the difference between the measured and the calculated spatial resolution, we accounted for this issue by the fact that the coherence length between the Stokes light and the reference light deteriorates after the pump is launched into the FUT, which results from the nonlinear Brillouin scattering in the optical fiber. Moreover, the

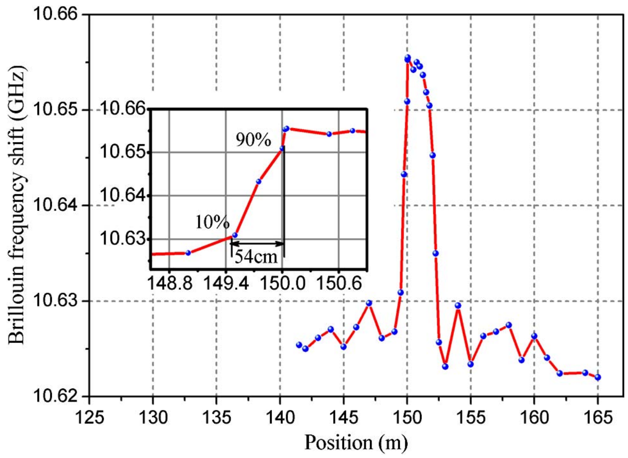

Fig. 6. Fitted BFS as a function of position along the FUT with a 1-m-long section heated to 50°C. Inset, 54 cm resolution can be achieved by this method.

bandwidth of the optical filter inserted into the pump branch also has an influence on the coherence. Thus, half of the coherence length is shorter than the theoretical resolution. Therefore, we can consider that the experimental result agrees well with the theoretical analysis in accordance with the aforementioned spatial resolution equation.

The spatial resolution of the proposed method can be on the millimeter (mm) scale if we use a higher code rate PRBS and a higher amplitude to modulate the LD. Nevertheless, a higher code rate requires a high-rate modulation to the LD. Additionally, mm-scale resolution results in a weak Brillouin scattering signal, which will lead to a low signal-to-noise ratio of the system. Due to the low signal-to-noise ratio, the measurement range is eventually restricted.

A new type of BOCDR sensing technology is proposed and demonstrated to measure the distribution of the temperature along an optical fiber from a single end, based on the frequency modulation with PRBS. This new method utilizes the PRBS to modulate a LD, instead of the sinusoidal waveform in traditional BOCDR systems, which can avoid the limitation of the periodic correlation peaks to the measurement range while remaining a high spatial resolution. A 54 cm resolution and a 250 m measurement range are successfully realized using this method. The proposed scheme is simpler than conventional Brillouin sensing systems. The new method has the potential for high-accuracy distributed temperature measurements, such as for the fiber optic gyros and so on.

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