Performance improvement method of single-ended BOTDA system based on Fresnel reflection*

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To solve the problems of small signal intensity and low signal-to-noise ratio (*SNR*) in single-ended Brillouin optical time domain analysis (BOTDA) system based on Fresnel reflection, we propose and experimentally demonstrate a pulse coding single-ended BOTDA system, which can improve the *SNR* and temperature measurement accuracy. A single-ended BOTDA temperature sensing system using single pulse and pulse coding is designed, and the Brillouin time domain signal and Brillouin frequency shift under different pulse coding bits are measured. The experimental results show that the fluctuations of Brillouin power and Brillouin frequency shift are gradually decreased with the increase of pulse coding bits, and the *SNR* under 32 bit Golay coding offers a 6.18 dB improvement with respect to traditional single pulse system. And the temperature measurement accuracy under 32 bit coding over a 9.35-km-long sensing fiber can be accurately measured as 1.59 °C, while providing a 1.73 °C enhancement when compared to single pulse system.

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Brillouin optical time domain analysis (BOTDA) sensing systems are capable of measuring the temperature and strain changes along the entire fiber[1,2], and can be used for multi-parameter sensing with the characteristics of high accuracy, accurate positioning, long distance up to tens of kilometers, which have been widely applied in various fields such as petrochemical industry, power communication network, submarine optical cable, railways, structure health monitoring and so on[3-5].

In most of the BOTDA systems, a pump wave and a counter propagating probe wave interact through the assistance of an acoustic wave. When the pump-probe frequency offset falls within the Brillouin gain/loss spectrum, the probe wave is amplified/depleted by the pump wave during the stimulated Brillouin scattering (SBS) interaction process. BOTDA systems have the advantages of high signal-to-noise ratio (*SNR*) and long sensing distance. However, due to the use of double-ended structure in BOTDA system, the signal will not be detected if there is a breakpoint in the fiber. Therefore, a single-ended BOTDA system[6] with one light source and one single-ended operation can still detect signals even the optical fiber is broken, which employs the Fresnel reflection as the probe wave. After that, some performance enhancement methods of the single-ended BOTDA systems[7-9] have been proposed and experimentally proved. The probe wave intensity in single-ended BOTDA system is much smaller than that in traditional BOTDA system, which leads to small signal and low *SNR*.

In the single-ended BOTDA system, the increasing of pulse width can improve the *SNR* of the system, but the spatial resolution of the system will be decreased with the increasing of the pulse width. Therefore, the spatial resolution and *SNR* of the system have a mutually restrictive relationship, which is difficult to enhance both of them simultaneously. In 2010, SOTO et al[10] applied Simplex coding in BOTDA to increase the sensing length to 50 km at the spatial resolution of 1 m, which can effectively overcome the mutual restriction between the spatial resolution and *SNR* in the system. Since then, the research on pulse coding technology using complementary sequence[11-13] and linear combination sequence[14] has become a hot spot.

To enhance the signal intensity and the measurement accuracy simultaneously, we propose a pulse coding

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single-ended BOTDA temperature sensing system. The principle of single-ended BOTDA system based on the Fresnel reflection of the fiber end is conducted, the characteristics of the Golay complementary sequence coding are analyzed, and an experimental setup for single-ended BOTDA system using Golay pulse coding is constructed to realize Fresnel reflection based temperature sensing. Finally, the performances of the pulse coding single-ended BOTDA heterodyne detection temperature sensing system with different coding bits are discussed.

A schematic diagram of the single-ended BOTDA system based on Fresnel reflection is shown in Fig.1. In the sensing fiber, the Fresnel reflected wave produced by microwave modulated continuous wave at the end of the fiber acts as the probe wave and the pulsed wave acts as the pump wave. The probe wave experiencing SBS amplification when its frequency lies within the Brillouin gain spectral range, and the maximum Brillouin gain occurs when the optical frequency difference between probe wave and pump wave is equal to the Brillouin frequency shift ν_B. Among them, I_p^0 is the light intensity of the pulsed pump wave at z=0 of the sensing fiber, I_b^0 is the light intensity of the microwave modulated continuous wave at z=0 of the sensing fiber, and I_F is Fresnel reflected wave produced by microwave modulated continuous wave at the end of the fiber.

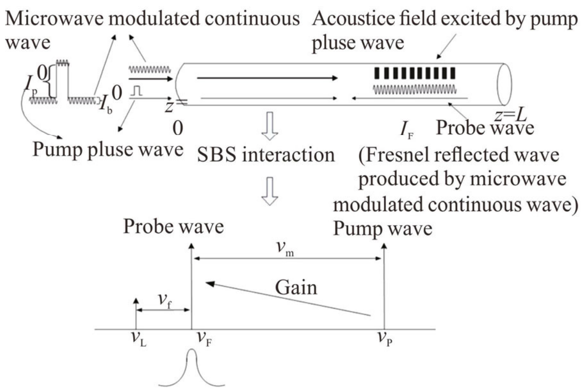


Fig.1 Principle diagram of the heterodyne detection single-ended BOTDA system based on Fresnel reflection

The probe wave and local wave can be described as

$$E_F(t) = E_F \cos[2\pi\nu_F t + \varphi_F(t)]H_{SBS}(\nu, z), \quad (1)$$

$$E_L(t) = E_L \cos[2\pi\nu_L t + \varphi_L(t)], \quad (2)$$

where E_F, ν_F and $\varphi_F(t)$ are the optical field, frequency, and phase of the probe wave, respectively, $H_{SBS}(\nu, z)$ is the transfer function of the SBS interaction, and E_L, ν_L and $\varphi_L(t)$ are the optical field, frequency, and phase of the local light, respectively.

The ac part of the reflected power in the heterodyne detection system can be expressed as

$$i_{ac} \propto R\left|E_F(t)E_L(t)\right|^2 \propto R\sqrt{P_F P_L}H_{SBS}(\nu, z)\cos\left[2\pi\nu_f t + \varphi_F(t) - \varphi_L(t)\right], \quad (3)$$

where R is the responsivity of the photo-detector (PD), P_F is the power of the reflected probe wave, P_L is the power of the local light, and the ν_f *is* the frequency difference between probe wave and local wave.

Suppose A_k and B_k are a pair of Golay complementary sequences with length N. According to the frequency domain characteristics of the complementary sequence, the sum of their autocorrelation functions is an integer multiple of δ function (unit impact function), which can be expressed as[15,16]

$$A_k \otimes A_k + B_k \otimes B_k = 2N\delta_k, \delta_k = \begin{cases} 1, k=0 \\ 0, k \neq 0 \end{cases}, \quad (4)$$

where $\otimes$ is the symbol for correlation operation, and N represents the number of bits of the Golay complementary sequence.

Golay bipolar complementary sequence should be converted to unbipolar sequence in order to transmit in the sensing system. Therefore, A_k and B_k are respectively decomposed into code pulses U_{k1}, U_{k2} and W_{k1}, W_{k2}, which can be expressed as

$$A_k = U_{k1} - U_{k2}, B_k = W_{k1} - W_{k2}, \quad (5)$$

where $U_{k1} = \begin{cases} 1, A_k = 1 \\ 0, A_k = -1 \end{cases}$, $U_{k2} = \begin{cases} 0, A_k = 1 \\ 1, A_k = -1 \end{cases}$, $W_{k1} = \begin{cases} 1, B_k = 1 \\ 0, B_k = -1 \end{cases}$, $W_{k2} = \begin{cases} 0, B_k = 1 \\ 1, B_k = -1 \end{cases}$.

The experimental setup for single-ended BOTDA system with pulse coding based on Fresnel reflection is shown in Fig.2. A continuous wave laser with central wavelength of 1 550.12 nm and linewidth of 1.86 MHz is used as the light source. The output of the light source is divided into two branches by a polarization-maintaining coupler (PMC). The upper branch is pulsed by an electro-optic modulator 1 (EOM1) with an extinction ratio of 40 dB and amplified by an erbium doped fiber amplifier 1 (EDFA1). Then a Bragg grating filter 1 (GF1) with central wavelength of 1 550.064 nm and bandwidth of 0.25 nm is used to filter out the amplified spontaneous emission noise (ASEN) in the pump pulse light. The lower branch is modulated by EOM2 which operates in the suppressed carrier regime and is driven by a microwave generator. The modulated first-order sideband signals are amplified by EDFA2, and a GF2 with central wavelength of 1 550.175 nm and bandwidth of 0.286 nm is used to filter out the anti-Stokes light and ASEN. Then the microwave modulated continuous wave is split into two branches by coupler 2 (CO2). The upper branch and pump pulse light form a synthetic light, and the other branch passing through a 200 MHz down-shifted acousto-optic frequency shifter (AOFS) acts as local light.

The synthetic light enters the sensing fiber via an optical circulator (OC), and the Fresnel reflected light generated at the end of the fiber acts as the probe light.

The polarization scrambler 1 (PS1) and PS2 are used to eliminate polarization dependent noise. The backscattered probe light carrying SBS information and local light are mixed together by CO3 and converted into an electrical signal at a 1 GHz bandwidth PD. The electrical signal output from the PD is collected by an electric spectrum analyzer (ESA) with an 8 MHz resolution bandwidth.

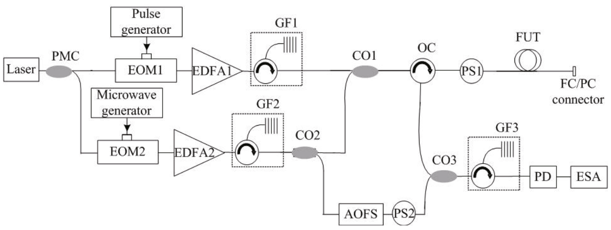


Fig.2 Experimental setup for single-ended BOTDA system with pulse coding based on Fresnel reflection

In the experiment, a 9.35-km-long single mode fiber (SMF) is adopted as the functional unit test (FUT) and a 100-m-long test fiber at the end of FUT is heated with a temperature of 50 °C. The pulse width of the pump wave is 130 ns, the powers of the pump wave, continuous wave and local wave are 100 mW, 1.75 mW and 0.06 mW, respectively. To accomplish the BOTDA signals measurement, a frequency sweep is done from 10.80 GHz to 10.91 GHz with a sweeping step of 5 MHz and 5 000 times average is performed at each sweeping.

The obtained Brillouin power distributions under single pulse, 8 bit coding, 16 bit coding and 32 bit coding at the frequency of 10.85 GHz are shown in Fig.3. The Brillouin power fluctuation with pulse coding is effectively reduced than that with single pulse. And the Brillouin power fluctuation is gradually decreased with the increase of the number of pulse coding bits.

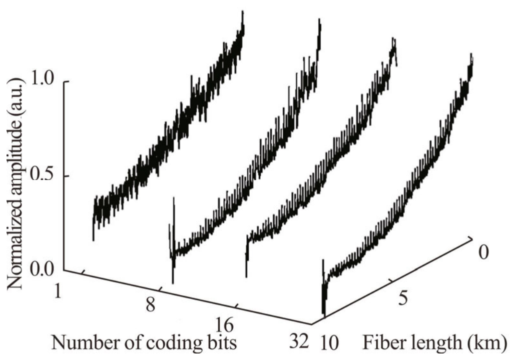
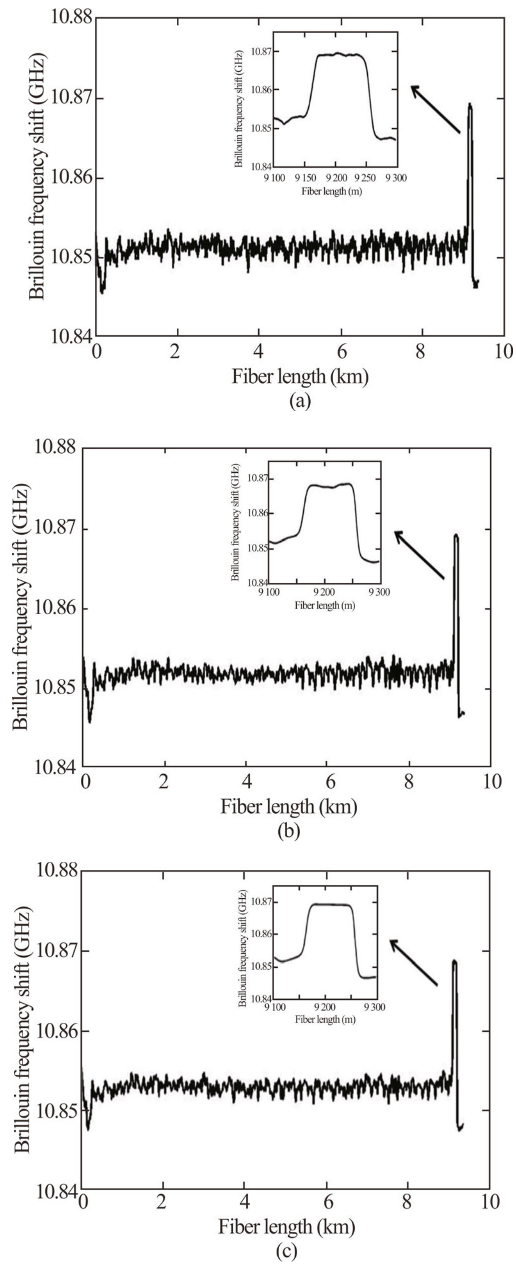
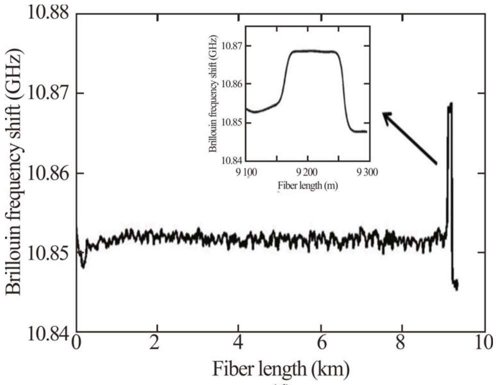


Fig.3 Brillouin power distributions under different coding bits

In order to further illustrate the performance enhancement of the temperature sensing system, the Brillouin frequency shift distributions under different coding bits are acquired by fitting the measured spectrum with Lorentz curve, as shown in Fig.4. In Fig.4, the largest fluctuation of Brillouin frequency shift in the heating section under single pulse, 8 bit coding, 16 bit coding, and 32 bit coding can be obtained as 1.37 MHz, 0.975 MHz, 0.863 MHz, and 0.463 MHz, respectively, which demonstrates that the noise level of Brillouin frequency shift is continuously reduced when the number of coding bits increases.

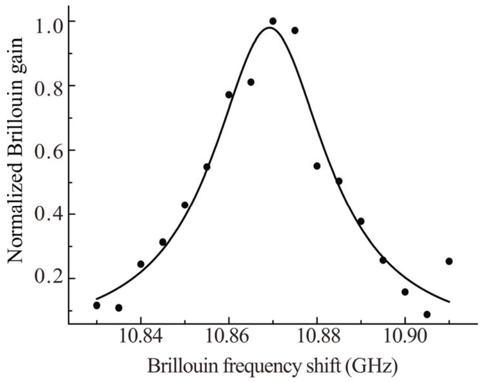
Through the Lorentz fitting of the measured time domain signal in the heating section, the Brillouin gain spectrum and the fitting data under different coding bits are respectively shown in Fig.5 and Tab.1. Taking the root mean square error (*RMSE*) as the noise power, the *SNR* under single pulse, 8 bit coding, 16 bit coding and 32 bit coding can be obtained as 31.27 dB, 34.51 dB, 35.68 dB and 37.45 dB, which indicates that pulse coding can effectively improve the *SNR* and increase the sensing distance.



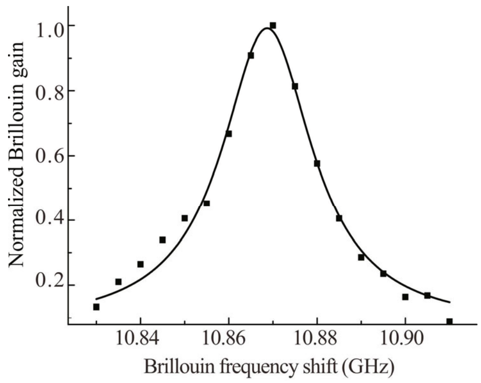


(d)

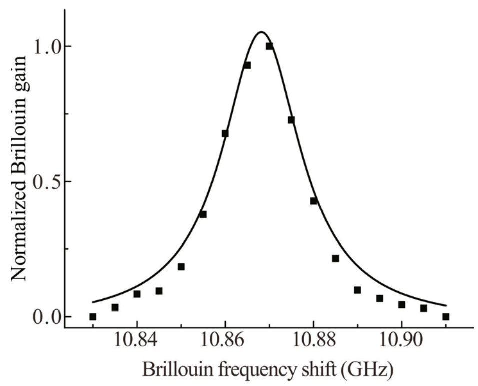
Fig.4 Brillouin frequency shift distributions under different coding bits: (a) Single pulse; (b) 8 bit coding; (c) 16 bit coding; (d) 32 bit coding



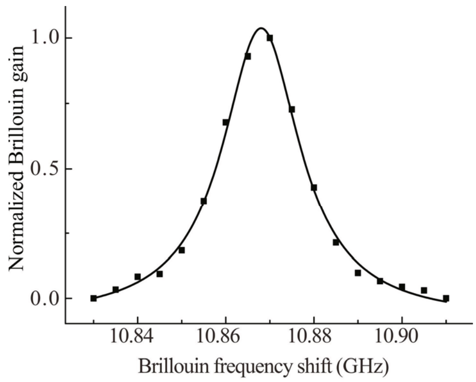
(a)



(b)



(c)



(d)

Fig.5 Brillouin gain spectra with Lorentz fitting under different coding bits: (a) Single pulse; (b) 8 bit coding; (c) 16 bit coding; (d) 32 bit coding

Tab.1 Fitting data with Lorentz curve under different coding bits

Coding bits	Brillouin frequency shift (GHz)	*RMSE*	$\Delta\nu_B$ (MHz)	*SNR*(dB)
Single pulse	10.868 91	0.000 745 8	31.48	31.27
8 bits	10.868 68	0.000 353 7	25.12	34.51
16 bits	10.868 57	0.000 270 4	21.76	35.68
32 bits	10.868 63	0.000 179 7	21.56	37.45

According to the Brillouin frequency shift accuracy formula $\delta\nu_B=\Delta\nu_B/(4SNR)^{1/4}$ in which $\Delta\nu_B$ is the full-width at half- maximum (*FWHM*) of the measured Brillouin gain spectrum, it can be calculated that the Brillouin frequency shift accuracies under different coding bits are 3.679 MHz, 2.436 MHz, 1.972 MHz, and 1.765 MHz, respectively. Further, we can calculated the temperature measurement accuracy through the formula $\Delta T=\delta\nu_B/C_{\nu T}$, in which $C_{\nu T}$=1.109 MHz/°C is the temperature coefficient of Brillouin frequency shift. Thus, the temperature measurement accuracies under single pulse, 8 bit coding, 16 bit coding, and 32 bit coding can be obtained as 3.32 °C, 2.20 °C, 1.78 °C, and 1.59 °C, respectively. It can be clearly obtained that with the increase of the number of coding bits, the accuracy of temperature measurement is continuously improved, which demonstrates that the performance of the single-ended system can be greatly increased by pulse coding.

In this paper, the maximum number of coding bits is 32 bit. However, with the increase of the number of coding bits, the *SNR* and measurement accuracy of the system will tend to be a saturation value. Moreover, in order to obtain the time domain signal, decoding processing should be required, which will increase the system's measurement time. In practical application, the measurement time determines the real-time performance of the system, thus pulse coding technology will obviously reduce the real-time performance of the system. Therefore, we will research the optimal coding bits in the follow-up to further improve the system's performance.

In conclusion, a theoretical and experimental analysis of pulse coding single-ended BOTDA temperature sensing system based on Fresnel reflection has been proposed. Furthermore, the Brillouin power and the Brillouin frequency shift distributions along the 9.35-km-long fiber under single pulse, 8 bit coding, 16 bit coding, and 32 bit coding are analyzed. The experimental results show that the Brillouin power fluctuation with pulse coding is obviously less than that with single pulse, and the temperature measurement accuracy is continuously improved by increasing the number of pulse coding bits. The temperature measurement accuracy under 32 bit coding can be enhanced to 1.59 °C, while providing an overall 6.18 dB *SNR* enhancement when compared to single pulse system. Therefore, the pulse coding technology can effectively improve the performance of single-ended BOTDA system, which will provide theoretical and experimental basis for the realization of single-ended BOTDA long-distance and high-precision sensing.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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