# Digital coherent detection research on Brillouin optical time domain reflectometry with simplex pulse codes*

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(Received 22 March 2014; revised manuscript received 26 May 2014; published online 24 September 2014)

The digital coherent detection technique has been investigated without any frequency-scanning device in the Brillouin optical time domain reflectometry (BOTDR), where the simplex pulse codes are applied in the sensing system. The time domain signal of every code sequence is collected by the data acquisition card (DAQ). A shift-averaging technique is applied in the frequency domain for the reason that the local oscillator (LO) in the coherent detection is fix-frequency deviated from the primary source. With the 31-bit simplex code, the signal-to-noise ratio (SNR) has 3.5-dB enhancement with the same single pulse traces, accordant with the theoretical analysis. The frequency fluctuation for simplex codes is 14.01 MHz less than that for a single pulse as to 4-m spatial resolution. The results are believed to be beneficial for the BOTDR performance improvement.

**Keywords:** Brillouin optical time domain reflectometry, digital coherent detection, simplex pulse codes, signal-to-noise ratio

**PACS:** 07.60.Vg, 07.05.Hd **DOI:** 10.1088/1674-1056/23/11/110703

## 1. Introduction

Recently, a number of studies have focused on the long-distance distributed fiber sensors with spontaneous Brillouin scattering in the optical fiber, which is called Brillouin optical time domain reflectometry (BOTDR),[1–3] for its potential applications of monitoring temperature and strain. The power spectrum of Brillouin backscattering usually includes the strain and temperature information along the whole sensing fiber. In the BOTDR sensing system, the frequency-shift and amplitude variation of the power spectrum are proportional to the changes of strain and temperature.

High SNR power spectrum for spontaneous Brillouin scattering (SpBS) will decrease the peak-power frequency measurement error and it may improve the spatial resolution or increase the sensing distance.[4] Enhancing the SNR for the same launched pulse width is one of the effective solutions to improve the peak-power frequency measurement accuracy without worsening the spatial resolution. Amplification techniques are usually used to increase the sensing distance with the same spatial resolution, but the SNR of the Brillouin signal itself has not been improved.[5,6] Pulse code technology has been proved to be an effective method to improve the SNR.[7–10] Compared to the correlated code technique,[7,8] the linear pulse codes are much more attractive[9,10] for the reason that: simplex codes are generated easily as shift register sequences; and the frequency and amplitude information could also be demodulated correctly, even if the pulse codes that are launched into the sensing fiber have different amplitudes. Simplex pulse code technology[11,12] has been applied into the BOTDR sensing system firstly, and the SNR was improved 7 dB with a 127-bit code.

In the process of applying the simplex code technique, the pulse coding is simple by driving the acoustic–optic modulator (AOM) or electro–optic modulator (EOM) according to the simplex codes; but the decoded scheme with the simplex technique is the key problem in the coherent detection. Generally, with scanning the local oscillator frequency, a series of many consecutive backscattered traces (the amplitude distribution) at every frequency could be obtained,[13,14] and then a three-dimensional Brillouin power spectrum could be constructed. With wide-bandwidth oscilloscope (zero-span mode), Soto *et al.* scanned the amplitude distribution along the sensing fiber every 3 MHz.[15] The above frequency scanning scheme mentioned needing both the frequency-scanning device and the splicing amplitude, extracting the central frequency in every spatial resolution.

In this paper, we experimentally investigate the digital coherent detection for the BOTDR sensing system with simplex

*Project supported by the National High Technology Research and Development Program of China (Grant No. 2012AA041203), the National Natural Science Foundation of China (Grant Nos. 61377062 and 31201377), the Program of Shanghai Excellent Technical Leaders, China (Grant No. 13XD1425400), and the Doctorial Fund of Zhengzhou University of Light Industry, China (Grant No. 2013BSJJ012).

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pulse codes, without any frequency-scanning device, realizing the frequency and amplitude measurement along the sensing fiber. All the time-domain signals are gathered by a high-speed DAQ, and then the data processing mainly focuses on the frequency-domain analysis. With the 31-bit simplex pulse code, the SNR is 3.5 dB larger than the same traces for a single pulse, accordant with the theoretical calculation; correspondingly, the frequency fluctuation is 14.01 MHz smaller for the 4-m spatial resolution. We believe that our study will be helpful to the decoded process, frequency extraction, frequency resolution or sensing distance improvement in BOTDR sensing systems.

## 2. Experimental setup and digital coherent detection

Simplex codes are obtained from the normalized Hadamard matrix of order $L+1$ by omitting the first row and column and substituting 0 for $-1$, and the simplex codes are the rows of the $L \times L$ matrix. The SNR enhancement provided by simplex pulse coding is quantified by code gain $G_{\text{simplex}}$, defined as the ratio of SNR when using the simplex pulse code with the respect to SNR with a single pulse (for the same traces). The simplex codes are obtained as[16]

$$G_{\text{simplex}} = \frac{L+1}{2\sqrt{L}},$$

where $L$ is the code length, $L = 2^n - 1$, and $n$ is an integral number.

A BOTDR sensing system, which is used to test effects of the simplex pulse codes, is illustrated in Fig. 1. A short-cavity stable single-frequency linear-polarization fiber-laser at 1548.976 nm[17] is used as the primary light source for the sensing system. Part of the laser beam is amplitude modulated by an acousto–optic modulator (AOM, Model MT160-IIR10-FIO, AA Inc.) to generate a pulse code sequence (single pulse width, 40 ns; repetition rate, 4 kHz) according to every row in the simplex matrix. The modulated pulse is properly amplified (avoiding stimulated Brillouin scattering in the fiber) by an Erbium doped fiber amplifier (EDFA), as shown in Figs. 2(a) and 2(b) (1st and 16th rows), where the amplified pulse code is uniform compared with the single pulse, as shown in Fig. 2(c); and then launched into the long sensing fiber to generate the backscattering spontaneous Brillouin signal. The backward spontaneous Brillouin scattering (SpBS), carrying local information of temperature and strain along the sensing fiber, can be sensed through the coherent heterodyne detection. The LO used in the BOTDR sensing system is a Brillouin fiber laser (BFL), with 10.8-GHz fixed frequency-deviation from the primary laser.[18] The beat signal between local oscillator (LO) and SpBS is injected into a double balanced photo detector (DB-PD, New Focus 1617-AC, Newport) through a 1:1 coupler and then amplified by a microwave amplifier (MWA, ALPHALAS). All the time domain data are collected with a high-speed data-acquisition card (DAQ, Gage, Model CS82G, 3GS/s sample rate), where the data acquisition is synchronous with the coded signal generation of AOM. The acquisition and analysis of the sensing signal are processed in real time by a home-built LabVIEW-based program.

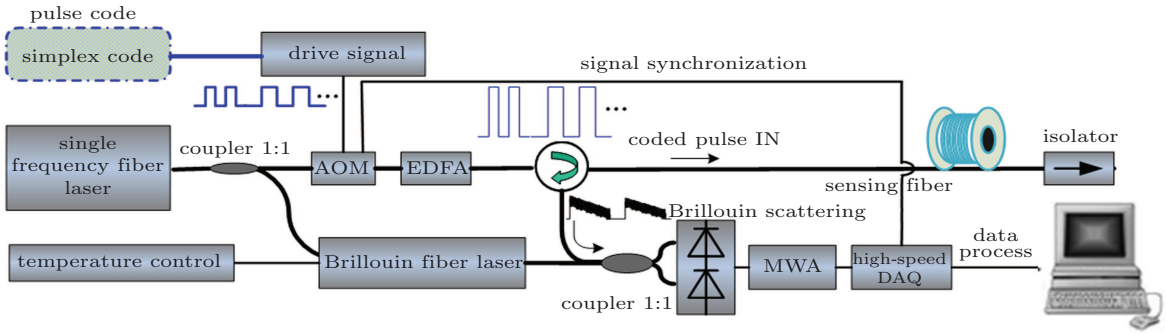



**Fig. 1.** (color online) Configuration of the coded BOTDR sensing system.

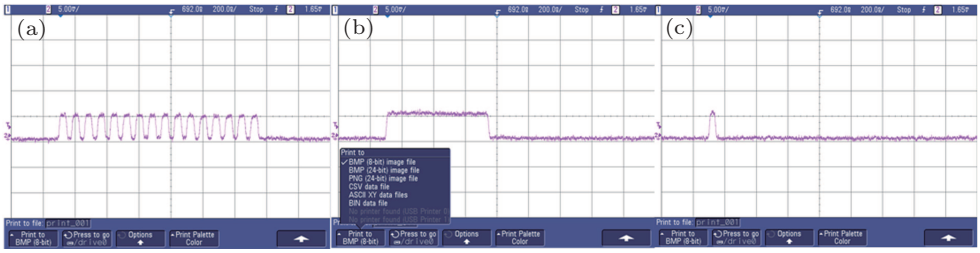



**Fig. 2.** (color online) The simplex code amplification: (a) the 1st row pulse code; (b) the 16th row pulse code; (c) the single pulse.

In our BOTDR system, the frequency shift between the LO and the main optical source is constant, and the frequency of the LO could not be modulated. Lacking the frequency-scanning device, the beat signal including the sensing information could not be obtained through the frequency-scanning technique as mentioned in the references. In this paper, all the time domain signals of every pulse row are collected with the DAQ, and saved in the onboard memory. Digital coherent technology is applied in the data processing. The main algorithmic is as follows. Firstly, the time domain signal of every row is made fast Fourier transformation in a single spatial resolution; and then multi-pulse series of the same row is averaged mathematically; the data corresponding frequency 1 ($f_1 = 300$ MHz) to frequency 2 ($f_2 = 500$ MHz) are extracted every $\Delta f$ (2 MHz). Along the whole sensing fiber, all the data related to $f(f_1 + \Delta f)$ make up a {code bit $\times$ (sensing length/spatial resolution)} matrix. The new matrix is multiplied by the simplex inverse matrix; and finally with the "shift-averaged technique", we could obtain the amplitude distribution for frequency $f$ along the whole sensing fiber. Amplitudes of all frequencies in the focused frequency separation could also make the same calculations. The amplitude data at every frequency and every spatial resolution constitute a three-dimensional graph; by means of Lorentz fitting, the central frequencies of all the spatial resolutions are achieved. The corresponding flow chart is as shown in Fig. 3.

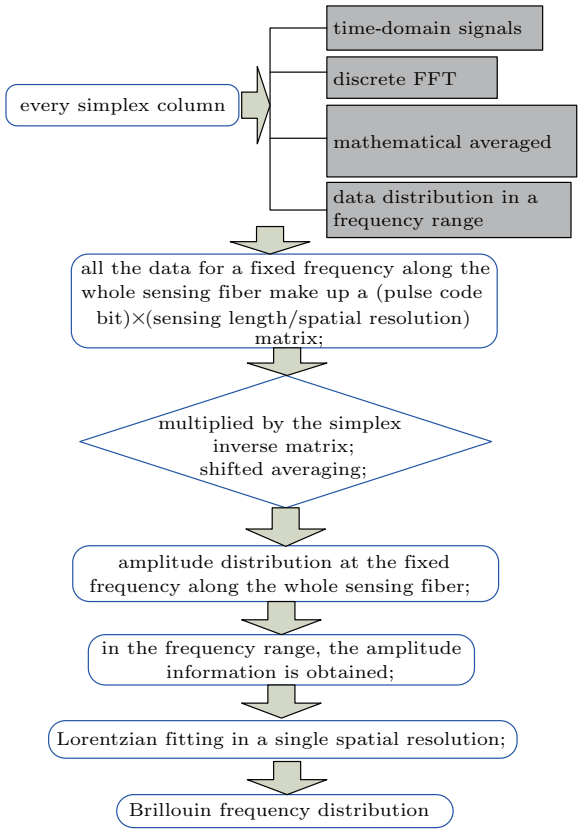



**Fig. 3.** (color online) The flow chart of digital coherent detection.

## 3. Experimental results and discussion

In order to have a reliable comparison between the simplex code and a single pulse, experiments are made for the same traces in both cases. In the experiment, a 31-bit simplex code is applied into the sensing system. According to the data processing mentioned in Section 2, the related time domain signals are analyzed. A comparison is made between the 31-pulse codes, 10 averaging and 310 averaging for a single pulse. The Brillouin scattering spectra are shown in Figs. 4(a) and 4(b), respectively. Amplitude fluctuation results from the polarization effect in the coherent detection.

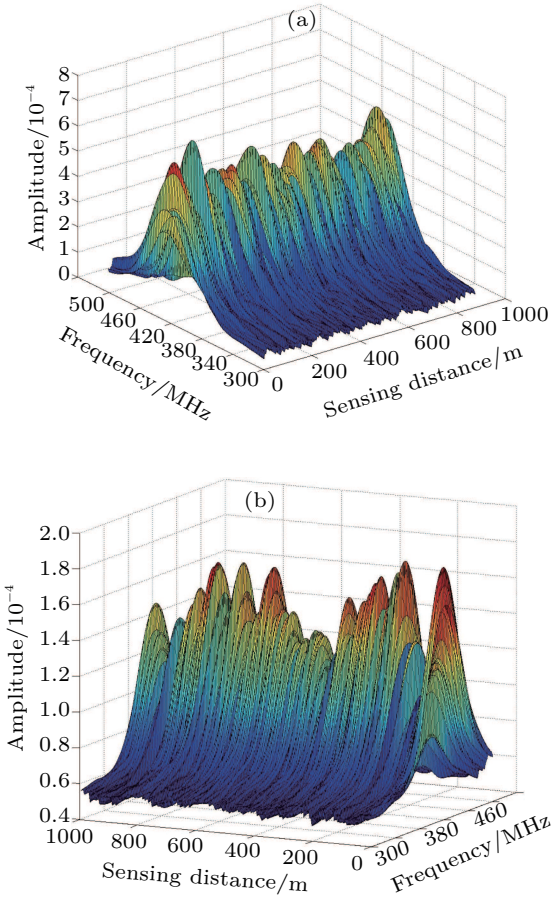



**Fig. 4.** (color online) The Brillouin scattering spectra: (a) 31-bit pulse coding, 10 averaging; (b) single pulse, 310 averaging.

SNR enhancement is the focused issue after digital coherent analysis. For a fixed frequency, the SNR is expressed as the ratio of maximum and the minimum of the Lorentzian fitting curve for all the amplitude data. Therefore, the SNR distribution along the whole sensing fiber is as that in Fig. 5. SNR fluctuation results from the amplitude distribution variability, and the mean value is chosen as the SNR, ignoring the influence of the polarization effect. It can be seen that the SNR gain for 31-bit simplex pulse coding is about 3.5 dB larger than the single pulse averaging for the same traces. According to the theoretical calculation for the 31-bit code, the code gain is 2.87 times larger (about 3.6 dB). Therefore, the experimental results are accordant with the theory calculation. The

SNR enhancement is beneficial to the frequency resolution, as $\delta\nu = \Delta\nu/\sqrt{2}(\mathrm{SNR})^{1/4}$,[19] where $\delta\nu$ is the frequency resolution, and $\Delta\nu$ is the natural linewidth of Brillouin scattering in the $SiO_2$ fiber of 35 MHz. Frequency fluctuation analyses for the two cases are also made, as shown in Fig. 6. It can be obtained that the frequency resolution for the 31-bit simplex pulse code is 9.076 MHz, while it is 23.179 MHz for the same single pulse averaging. Obviously, the frequency resolution is 14.103 MHz higher for the former than the latter. Correspondingly, the sensing resolution for temperature or/and strain could be enhanced through the linear relation between the frequency and the sensing parameter.

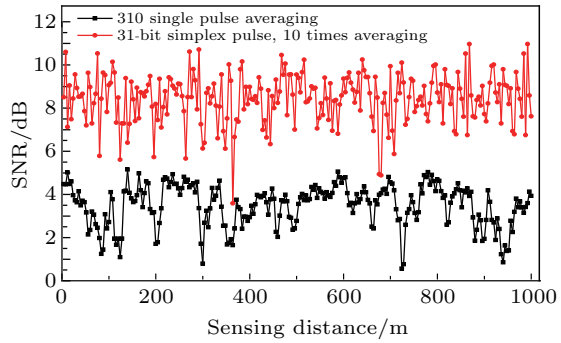



**Fig. 5.** (color online) SNR comparisons between pulse coding and single pulse.

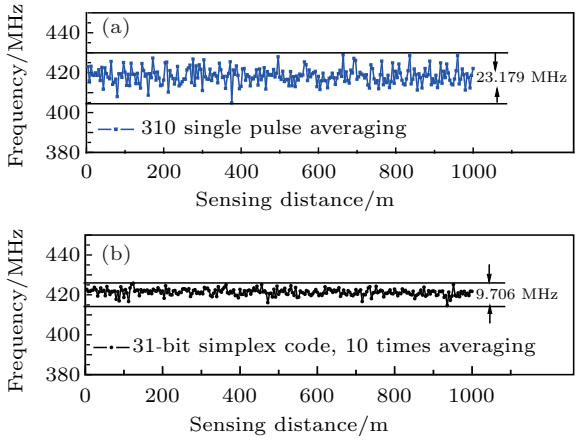



**Fig. 6.** (color online) Comparison of frequency fluctuation for pulse coding and single pulse. The frequency fluctuation range is 23.179 MHz for 310 single pulse averaging (a), and 9.706 MHz for 31-bit simplex and 10 times averaging (b).

## 4. Conclusions

A digital coherent detection technique has been investigated in the Brillouin optical time domain reflectometry with simplex pulse codes. With a 31-bit simplex code, the SNR has a 3.5-dB enhancement with the same single pulse traces, which is accordance with the theoretical analysis. For a 4-m spatial resolution, the frequency fluctuation for the simplex code is 14.01 MHz less than that for the single pulse. Experimental results show that the simplex code and digital coherent detection techniques are beneficial for the BOTDR sensing system performance improvement.

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