Performance enhanced BOTDA sensor using Differential Golay Coding and Deconvolution Algorithm

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Abstract: A novel BOTDA sensor that uses differential Golay coding and deconvolution algorithm is demonstrated utilizing conventional coded BOTDA sensors system, which paves the way to enable both long sensing range and high spatial resolution simultaneously.

1. Introduction

Brillouin optical time-domain analysis (BOTDA) technique was extensively investigated over the last three decades, owing to its outstanding capabilities to monitor large infrastructures by retrieving the temperature and strain information along the sensing fiber. Over the years, a lot of research efforts have been made to enhance the performance of BOTDA sensors, particularly in terms of extending the sensing range and improving the spatial resolution, etc. Various solutions have been proposed to address these issues, e.g. pulse coding and distributed Raman amplification have been demonstrated to be good solutions to allow for considerable sensing range extension [1,2]. On the other hand, as for the enhancement of spatial resolution, several effective techniques have also been proposed, which is enable to achieve sub-meter spatial resolution, e.g. differential pulse pair (DPP) [3], Brillouin echo [4], and pulse pre-pump [5], etc. However, all these approaches can only alleviate one of the problems, i.e. either extending the sensing range or improving the spatial resolution, but not be able to improve both parameters simultaneously. An advanced BOTDA sensor that offers both long sensing range and high spatial resolution using comparable measurement time and complexity with respect to the traditional BOTDA sensors is very useful for many applications. While, sensing range and spatial resolution are contradictory in optical time-domain reflectometry and analysis systems, i.e. on one hand, long pulse duration ensures long sensing distance, but leads to bad spatial resolution. On the contrary, narrow pulse duration allows for high spatial resolution, but results in short sensing distance. Therefore, it turns out that it is very challenging to optimize the two parameters simultaneously.

Recently, a BOTDA sensor that combines Golay coding and differential pulse pair were proposed [6], where a hybrid coding method that combines the features of unipolar Golay coding to get a response equivalent to differential pulses was proposed. The idea shows great potential to enable long sensing range and high spatial resolution simultaneously. However, in order to ensure high spatial resolution, it requires that the durations of the two differential pulses needs to be similar. As a result, the signal-to-noise ratio (SNR) of the differential BOTDA traces will be bad. Therefore, eventually the sensing range is still restricted.

In this work, instead of using DPP technique, we propose to employ deconvolution algorithm post-processing technique to improve the spatial resolution of a differential Golay coded BOTDA sensor. In this way, the pulses that are used for DPP procedure could have large duration difference. As a result, the differential BOTDA traces still have good SNR, which ensures longer sensing range. On the other hand, deconvolution algorithm enables high spatial resolution [7], and thanks to the use of DPP, the Brillouin frequency shift (BFS) distortion issue caused by deconvolution can be prevented [8]. For proof of concept, we demonstrated a performance enhanced BOTDA sensor with 9.63 km sensing distance, 0.5 m spatial resolution using 60/40 ns differential Golay coding and deconvolution algorithm in this work, which paves the way to enable both long sensing range and high spatial resolution simultaneously.

2. Methods

In the hybrid differential Golay coding system, the long pulse sequence and the short pulse sequence can be combined into a mixed sequence. The decoding and DPP procedures can be done at the same time by processing one set of pulse train, i.e. four sets of unipolar Golay codes, as shown in Fig. 1(a) However, it should be noted that the relevant pulse sequence used in decoding should be a differential pulse sequence. Through the optimization of Golay encoding with differential pulse sequences, the required measurement data is reduced by half, and the data processing time is greatly reduced.

The priciple of the deconvolution algorithm is presented in Fig. 1(b). differential pulse sequence $p(t)$ and a continuous light are injected from both ends of the optical fiber under test. Assuming the system response of BOTDA is $h(t)$ and the noise of system is $n(t)$. The stimulated Brillouin signal generated in a BOTDA system can be mathematically represented as a convolution process, and the response $r(t)$ can be expressed by:

$$r(t) = p(t) \otimes h(t) + n(t) \quad (1)$$

The equivalent input pulse becomes a triangular pulse $Tri(t)$ after correlation processing in decoding, as given by

$$Tri(t) = p(t) * p(t) \quad (2)$$

where $*$ represents the correlation calculation. The half-height full width of $Tri(t)$ is the same as the rectangular pulse before encoding and it remains the same spatial resolution [6]. The decoded signal is then processed by deconvolution algorithm in order to improve the spatial resolution. The used deconvolution kernel is the triangular pulse $Tri(t)$. Assuming $\otimes'$ is the deconvolution operator, then the response $r'(t)$ after deconvolution is governed by

$$\begin{aligned} r'(t) &= Tri(t) \otimes h(t) \otimes' Tri(t) + n(t) \otimes' Tri(t) \\ &= \delta(t) \otimes h(t) + n(t) \otimes' Tri(t) \end{aligned} \quad (3)$$

where $\delta(t)$ is the impulse function, which can be regarded as the triangular pulse of the unit sampling point with the current sampling rate, so the spatial resolution can be restored to a very high level. Thanks to the employment of DPP, the BFS distortion issue caused by deconvolution can also be avoided [8].

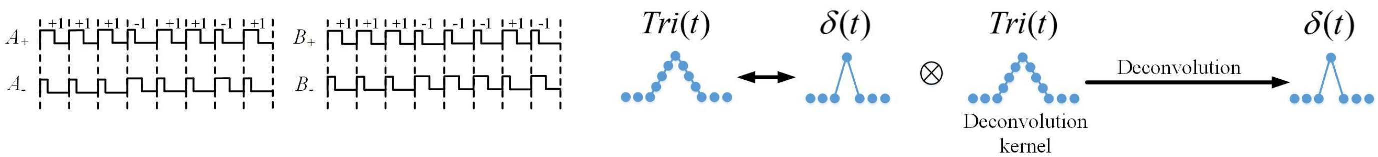

Fig. 1: Schematic diagram of hybrid Golay code and deconvolution algorithm.

3. Experiment setup, results and discussions

The experimental setup is shown in Fig. 2. A 1550 nm narrow linewidth laser with 15 dBm output power is used as the light source, whose output is divided into pump light and probe light through a 60:40 coupler. The upper branch is used to generate probe light through an electro-optic modulator (EOM) with carrier suppressed double-sideband modulation, and the EOM is driven by a microwave source. The probe light is swept near the Brillouin frequency shift. On the other hand, pump light is generated in the lower branch. Four groups of Golay pulse sequences generated in MATLAB are imported into an arbitrary waveform generator (AWG). Then a semiconductor optical amplifier is modulated by the AWG to generate encoded pulse sequences. After passing through the polarization scrambler and circulator, the encoded pulses are launched into the sensing fiber. At the receiver side, a narrowband fiber Bragg grating filter is used to obtain the stokes sideband, which is eventually detected by a photodetector, and an oscilloscope is used for data acquisition with 500 MSa/s sampling rate.

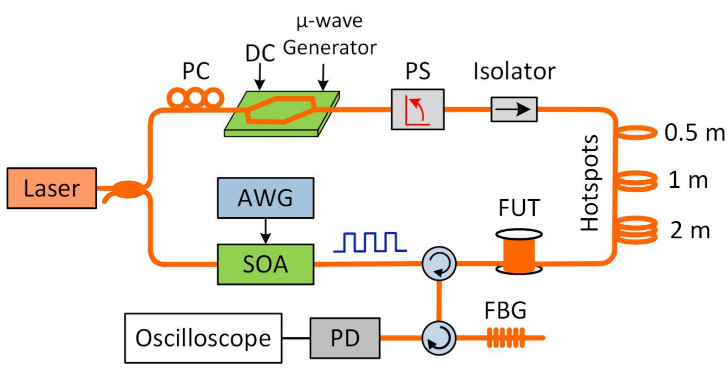

Fig. 2: Experiment setup. PC: polarization controller; MS: microwave source; EOM: electro-optic modulator; SOA: semiconductor optical amplifier; PS: polarization scrambler; FBG: fiber Brag grating; PD: photodetector.

The length of sensing fiber is 9.63 km.256-order hybrid differential Golay codes were used in the experiment, where the long pulse and short pulse are respectively 60 ns and 40 ns, which corresponds to a spatial resolution of 2 m after decoding with DPP. Three hotspots with 2 m, 1 m and 0.5 m were generated at the end of the optical fiber, and the interval between two adjacent hotspots is 3 m. The temperature of the hotspots is 50 °C, and the room temperature is 18 °C. The frequency sweeping range is from 10.65 to 10.75 GHz with the step of 2 MHz.

The acquired data was firstly decoded, and then processed by deconvolution algorithm. A comparison of the obtained 3D

Brillouin gain spectrum (BGS) near the hotspots without and with deconvolution processing is shown in Fig. 3. The 60/40 ns hybrid differential Golay coding offers a spatial resolution of 2 m. Since the hotspots are not longer than 2 m, so it is difficult to identify these events from the original measurement, as shown in Fig. 3(a). However, once the raw data is processed by deconvolution algorithm, the spatial resolution will be enhanced considerably, as presented in Fig. 3(b), where the three hotspots can be easily distinguished.

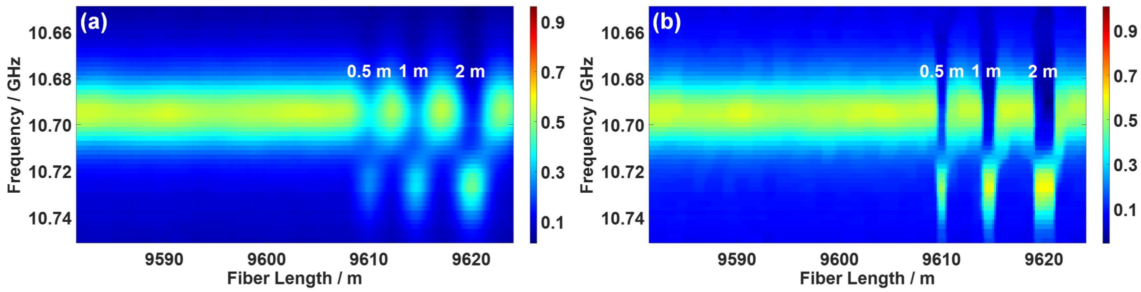

Fig. 3: Comparison of the obtained BGS without and with deconvolution processing.

The fitted BFS curves around the hotspots are presented in Fig. 4(a), where both the BFS of the original 60/40 ns DPP and the deconvolved results are plotted. It indicates that significant spatial resolution improvement can be achieved after deconvolution processing. To determine the restored spatial resolution, a zoom-in view around the 1 m hotspot has been presented in Fig. 4(b). The spatial resolution is estimated to be about 0.5 m by measuring the length of rising edge from 10% to 90% of the BFS variation.

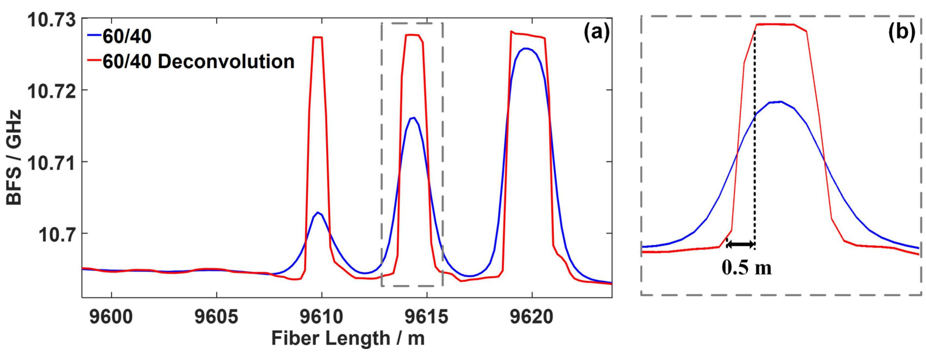

Fig. 4: (a) The fitted BFS curves around the hotspots (b) zoom-in view around the 1 m hotspot.

4. Conclusions

In this work, we proposed a novel BOTDA sensor that combines the hybrid differential Golay coding with deconvolution algorithm, whose feasibility has been experimentally demonstrated. The proposed sensing system paves the way to enable both long sensing range and high spatial resolution simultaneously.

Acknowledgements

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