Brillouin Optical Correlation Domain Analysis System with a Switch Array Based Delay Line

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Abstract *We propose and experimentally validate a Brillouin optical correlation domain analysis (BOCDA) system with an opto-mechanical optical switch array for tuning sensing positions. This approach helps to reduce the measurement position error caused by ambient temperature changes due to long-delay fiber in the BOCDA system.*

Introduction

Among many distributed fiber optic sensors (DFOS), Brillouin optical correlation domain analysis (BOCDA) stands out for its ability to achieve high spatial resolution on the sub-centimeter scale and its unique characteristic of being randomly accessible to sensing points along the fiber [1-4]. As a result, BOCDA has become an attractive option for a wide range of applications that require high spatial resolution sensing.

However, a conventional BOCDA system uses only single CP in a sensing fiber to avoid position ambiguity, so the measurement range is limited and also the total measurement time is long. Our group introduced a time domain data processing to the ordinary BOCDA, where the pump wave was additionally modulated as a pulse to temporally separate signals from different CP's and thus the system could effectively interrogate multiple CPs, extend the measurement range and reduce the overall measurement time [5]. Additionally combined with Raman amplification, by interrogating 5037 CPs, over 2.5 million sensing points was obtained in about 50 km measurement range [6, 7]. In the above BOCDA system, a delay fiber which is several times longer than the measurement range must be included due to the following two reasons. Firstly, the 0_{th} CP must be located in the outside of the FUT since it cannot be moved by changing the modulation frequency as shown in Fig. 1 (a). Second, if we use a short delay fiber, there can be significant differences in the amount of movement of the CPs depending on the order of correlation when they are moved.

There still remains an issue such as the use of a very long delay fiber for the control of sensing position which requires the control of ambient temperature with high stability [5, 8]. To solve this issue, a program-based optical delay line (PODL) is introduced [9, 10]. However, the PODL is expensive and has a limited delay range.

In this paper, we propose and experimentally demonstrate a variable length of delay line assisted BOCDA system by using an array of 10 (dual 1x2 mini) opto-mechanical switches. By constructing a delay line that can access a total of 1024 optical paths, we were able to equalize the scanning steps of all correlation points, and also mitigate measurement errors caused by ambient temperature changes in the long delay line thanks to the reduction of delay fiber more than thousand times (from 250 km to 200 m).

For experimental verification, we conducted experiments by splicing 5 cm and 10 cm long dispersion-shifted fibers (DSF) to a 51 km test fiber (SMF). We then compared the results obtained using our switch-based delay line with those obtained using a traditional 250 km delay fiber.

Principle

In the BOCDA system, pump wave and probe wave are frequency-modulated in the form of a sine wave and each half cycle makes a SBS induced points where the frequency difference is constant with Brillouin frequency (ν_B), and it called a CP. The position of CPs and its rate of change can be respectively expressed as [5].

$$z_q = \frac{1}{2}(l + l_d) - \frac{1}{2f_m} \cdot \frac{c}{n} \cdot q \qquad (1)$$

$$\Delta z_q = \frac{c}{2nf_m^2} \cdot q \cdot \Delta f_m \qquad (2)$$

z_q and q are the position of CPs and order of CPs, respectively. l and l_d are the length of the sensing fiber and delay fiber of the system, respectively. f_m is frequency of the sine wave modulation and *c, n* are the speed of light in

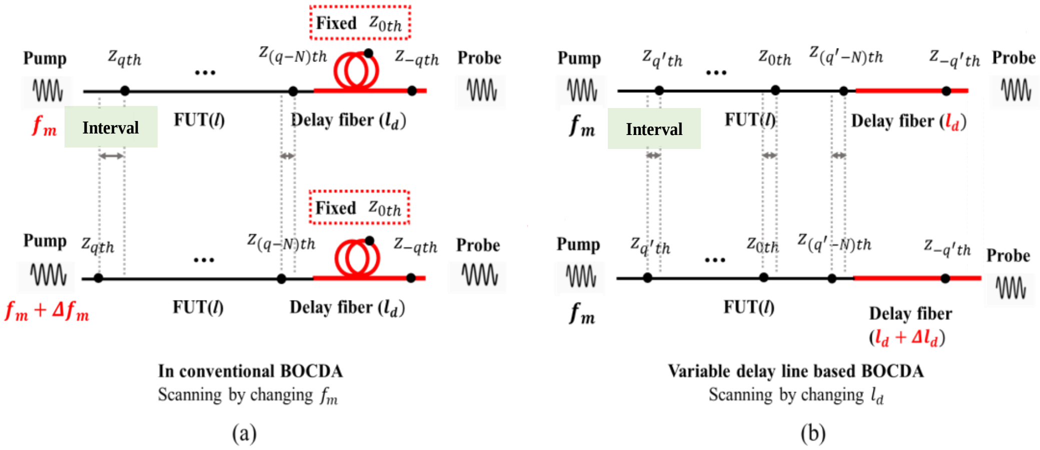

Fig. 1: A schematic diagram of the movement of the CPs in BOCDA system (a) that scans by changing the frequency modulation value and the movement of the CPs in a switch-based variable-length of delay line BOCDA system (b).

vacuum and refractive index of the optical fiber, respectively. When the ambient temperature changes around a long-length delay fiber, it causes a change in refractive index, which ultimately leads to significant changes in the CP position, particularly at high q values. As a result, it is very difficult to perform stable distribution measurements in the BOCDA system with a long delay fiber.

However, in the case of using an optical switch array that can directly change the delay optical fiber length (l_d) with a combination of optical switch connections instead of changing the modulation frequency to move the correlation point, the amount of movement of the CP can be expressed as follows:

$$\Delta z_q = \frac{1}{2} \cdot \Delta l_d \tag{3}$$

Thus, simply by adjusting the combination of optical switch connections, all CPs can be moved same distance, as shown in Fig. 1(b). Moreover, by not requiring the use of higher-order CPs, the length of the delay line affected by ambient temperature changes can be significantly reduced.

An array of opto-mechanical switches consists of N dual 1X2 opto-mechanical bi-directional fiber optic switches. Each optical switch can connect optical channels by redirecting 2 incoming optical signals into 4 output fibers via an electrical control signal. In our configuration, we spliced the L_0 cm and $L_0 + 2^N$ cm optical fibers to first two output channels (blue) and second two output channels (red), respectively as shown in Fig. 2(a). For example, If the connecting state of an optical switch is expressed as 0 and 1, in the [00…00] connecting state, the length of delay line becomes $N \times L_0$ cm. Thus, by adjusting electrical control signals, it is possible to access 2^N optical paths, and a total of $(2^N - 1)\ cm$ distances can be adjusted at 1 cm $(\frac{1}{2} \cdot 2^1\ cm)$ intervals.

Experiment setup and results

Fig. 2. (a) and (b) shows our proposed optical switch array system and experimental setup of the proposed BOCDA system, respectively. A 1548 nm DFB-LD was used as a light source and frequency modulated by the direct current modulation. The modulation frequency (f_m) and modulation amplitude (Δf) were about 10 MHz and 0.97 GHz, respectively. It corresponds to the interval of CPs of 10.07 m and a nominal spatial resolution of 10 cm. The output of the DFB-LD was divided into two arms. The lower arm is modulated by a single sideband modulator (SSBM) to generate the probe wave. The output of SSBM is injection locked by a slave LD to improve the spectral purity and suppress the intensity modulation occurred by direct current modulation of DFB-LD. The injection locked probe wave pass through a proposed optical delay line system which is composed by 10 opto-mechanical switches as shown in Figure. 2 (a). The voltage state of each switch is latched as 0 or 1 according to the set value. Also the Raman pump of 1460 nm is connected with WDM (1460 nm / 1550 nm) to compensate the propagation loss of the pump pulse.

To compare the performance of our proposed system with a previous BOCDA system with a long delay fiber, FUT was composed with a 5 cm SMF, a 5 cm DSF, a 10 cm SMF, and a 10 cm DSF by splicing to both ends of 51.2 km-SMF, as shown in Fig. 3. Thus, 5084 CPs are generated in 51.2 km FUT since the distance between CPs is 10.07 m in Eq. (1). It is worth mentioning that the actual spatial resolution is under 5 cm considering the 30 MHz phase-modulated DM

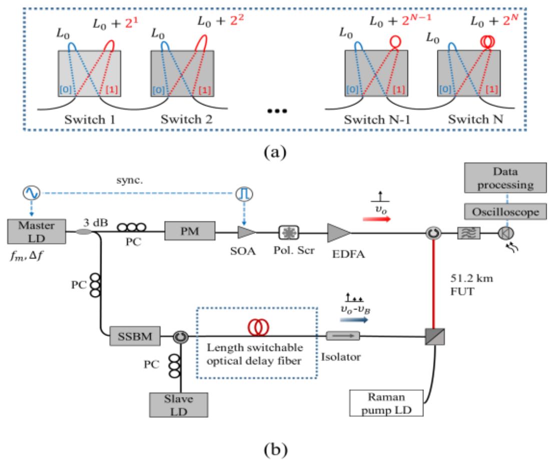

Fig. 2: The structure of N dual 1 x 2 optical switch array (a) and experimental setup of proposed BOCDA system (b).

scheme, which can be confirmed by distribution mapping of ν_B of 5 cm DSF and SMF as shown in Fig. 4. (a) and (b).

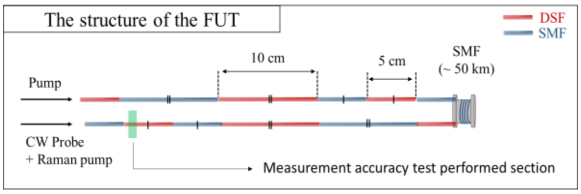

Fig. 3: FUT configuration structured by splicing DSF and SMF

With a 250 km delay fiber (blue line in Figure. 4. (a) and (b)), to move the CPs in the FUT, the modulation frequency needs to be changed. However, the moving distance of each CP is different depending on the order of correlation from Eq. (2). With a change of modulation frequency by 0.944 Hz, the first CP (10168^{th} CP) located in the beginning of the FUT is moved by 1 cm and the last CP (15251^{th} CP) is moved by 1.45 cm as shown in Fig. 4(a) and (b).Therefore, in Fig. 4. (a) (blue line) the 10 cm and 5 cm sections were measured with 10 points and 5 points, whereas in Figure. 4. (b) (blue line) they were measured with 7 points and 3 points. In the case of using a switch-based variable length of delay line, the above problem is solved. We can see that all CPs are moved by same distance as 1 cm in Fig. 4 (a) and (b) (red line).
To compare the measurement error due to the ambient temperature variation for two cases (one is with a long delay fiber and the other is a switch-based variable length of delay line), we measured the Brillouin frequency 100 times at the 5 cm DSF (green box in Fig.3). Figure. 4. (c) shows the result in the case of using a 250 km delay optical fiber without temperature control. We can see that there are frequent incorrect measurements of ν_B (10.65 GHz) of DSF since the location of the CP is moving to the SMF region due to the temperature fluctuation during the measurement. Note that from Eq. (1) the location of CP is dependent on the refractive index, the refractive index is also dependent on the ambient temperature, and the order q is about 15000. Thus, slight temperature variation (about 0.02 °C) leads to several cm movement of the CP.

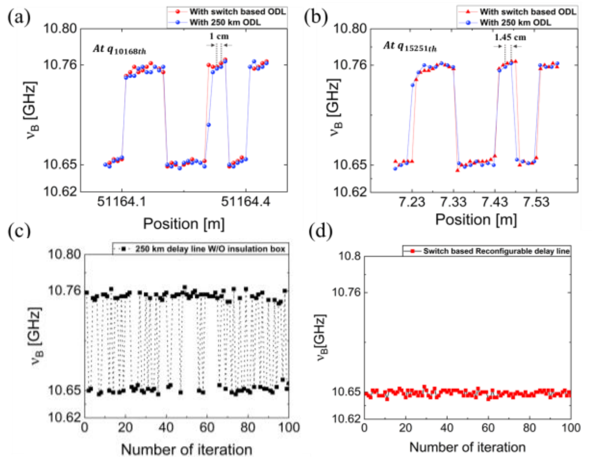

Fig. 4: Comparison of scanning step between the first CP (10168^{th}) (a) and the last CP (15251^{st}) (b) in the FUT when using 250 km delay line (blue dot and line) and when using optical switches based variable length of delay line red dot and line). Comparison of variation of temperature induced measurement error without ambient temperature control of system between using the 250 km delay fiber (c) and using the switch- based variable length of delay line (d).

On the other hand, when we use a switch-based variable length of delay line, there is no measurement inaccuracy as seen in Fig. 4. (d). In this case, the movement of the CP is negligible under environmental temperature fluctuation since the total length of the delay line is thousand times shorter than 250 km long delay fiber.

Conclusions

We have proposed and experimentally demonstrated a variable length of delay line assisted BOCDA system using the array of opto-mechanical switches. Our proposed system provides equal scanning steps to all correlation points and mitigates measurement errors caused by ambient temperature changes in the long delay line. We expect our method provides a cost-effective and practical solution for controlling sensing position and improving measurement accuracy in BOCDA systems.

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