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Distributed incomplete polarization-OTDR based on polarization maintaining fiber for multi-event detection

Youwan Tong [a,b], Hui Dong [b,*], Yixin Wang [b], Wenhui Sun [a], Xin Wang [a], Jinhua Bai [a], Haiqing Yuan [a], Ninghua Zhu [a], Jianguo Liu [a,*]

[a] State Key Laboratory on Integrated Optoelectronics, Institut ute of Semiconductors, Chinese Academy of Sciences, No. A35, QingHua East Road, Haidian District, Beijing 100083, PR China
[b] RF Antenna and Optical Department, Institute for Infocomm Research, 1 Fusionopolis Way, #21-01 Connexis, South Tower, 138632 Singapore, Singapore

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ABSTRACT

A new scheme for the distributed intrusion detection system based on the polarization optical time domain reflectometry (POTDR) for multi-event detection is proposed in this paper. In the scheme, a polarization maintaining fiber is employed as the distributed pressure sensor instead of the single mode fiber. The working principle of the system is described in detail, and an experimental system is set up to confirm the ability to detect several intrusion events happened at the same time along the sensing fiber by measuring the polarization mode coupling coefficient caused by the pressure and three simulated events. And from the final experimental result denoised using wavelet transformation, the three intrusion events can be significantly detected.

1. Introduction

The optical fiber sensors have been widely used in intrusion detection system for security [1] because of their significant advantages over other sensors. The advantages include great sensitivity, reduced size and weight, immunity to electromagnetic interference, reduced cost, versatility, reliability, and compatibility to optical communication and telemetry [2]. An overview of the optical fiber-based intrusion detection sensors can be found in [3]. Such sensors can be mainly divided into the three categories, the interferometer, the fiber Bragg grating (FBG) array, and the polarization optical time domain reflectometry (P-OTDR). The interferometer includes the phase sensitive optical time domain reflectometry (φ -OTDR) [4,5] and the non-distributed interferometer array [6,7]. However, as the detection is based on the phase measurement, they usually have a very high sensitivity, and this can result in a high false alarm rate when they are exposed to harsh and complicated environment. The FBG has also been used in the intrusion detection system [8–10], but the FBG and the fiber grating sensor interrogating system are usually too costly for some application. Beyond that, polarization-based intrusion system has also been developed [11–13] because of its moderate sensitivity and low false alarm rate and it is usually more suitable for the intrusion detection for security.

The P-OTDR includes the completed P-OTDR and incomplete P-OTDR. In the architecture of the completed P-OTDR, as shown in Fig. 1(a), the light in different polarization states is transmitted into the sensing fiber, the back-scattered light is collected and the four Stokes parameters are measured. By using the Stokes parameters of the output light and the input light, the round trip Mueller matrix of the sensing fiber can be calculated [14]. Since the Mueller matrix is the local parameter of the sensing fiber, the multi-event along the fiber can be detected. But the P-OTDR usually has a very complicated structure, low signal noise ratio (SNR), and it is usually costly. In comparison, in the architecture of the incomplete P-OTDR, as shown in Fig. 1(b), the light in a fixed polarization state is transmitted into the sensing fiber, and the back-scattered light is collected, the state of polarization (SOP) of the back-scattered light is measured [1]. The incomplete P-OTDR has the much simpler structure, the higher SNR and it is much more cost-effective. However, because the variation of the SOP is not an isolated incident in the sensing fiber, we can only perceive the first invasion event occuring on the nearest position to the testing place, which implies that multi-events detection cannot be implemented by the incomplete P-OTDR.

In this paper, we proposed a novel kind of the intrusion detection system in which the polarization maintaining fiber (PMF) is

* Corresponding authors.
E-mail addresses: hdong@i2r.a-star.edu.sg (H. Dong), jgliu@semi.ac.cn (J. Liu).

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employed as the sensing fiber. The setup of the system is the same as the structure of the incomplete P-OTDR which can be easily implemented, simple, stable, and cost-effective and has a high SNR. The intrusion detection of the system we proposed is based on measuring the polarization mode coupling of the PMF caused by the perturbation applied to the fiber when intrusion events happen.

This paper is divided as follows: in the first section, what kind of perturbation applied to the sensing fiber can cause polarization mode coupling (PMC) easily is given. In the second section, the architecture of the system is given. In the third section, the result of the experiment which shows how the three intrusion events applied to the fiber are detected and the event location precision is described.

2. Sensor principle

The incomplete P-OTDR has been used to map the PMC location in the PMF in the recent years [15]. If the PMF is well

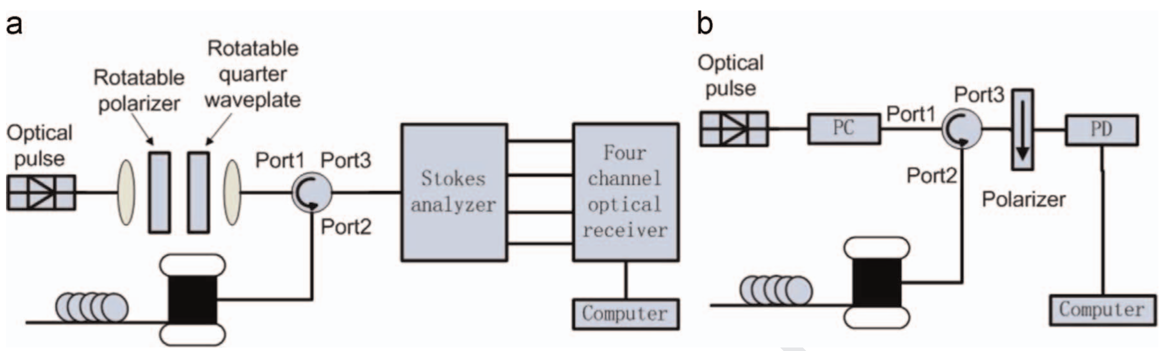

Fig. 1. The architectures of the completed P-OTDR and incomplete P-OTDR (PC: polarization controller; PD: photo-detector).

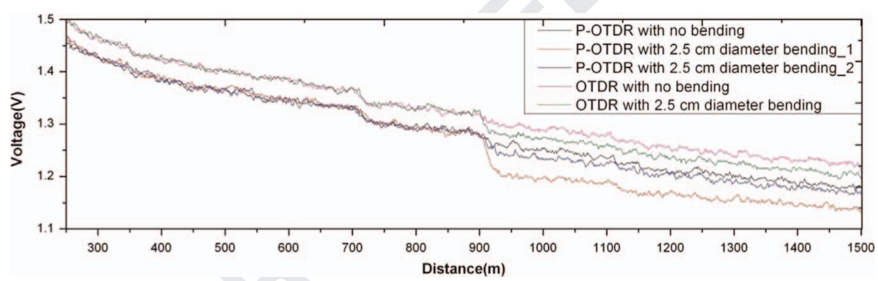

Fig. 2. P-OTDR and OTDR traces as the different forms of bending were applied to the PMF (P-OTDR with no bending & OTDR with no bending: no bending occurred on the sensing fiber; P-OTDR with 2.5 cm diameter bending_1 & OTDR with 2.5 cm diameter bending: 5 circles of bending with the diameter of 2.5 cm were applied to the sensing fiber along an arbitrary direction; P-OTDR with 2.5 cm diameter bending_2: 5 circles of bending with the diameter of 2.5 cm were applied to the sensing fiber along another arbitrary direction which is orthogonal with that of bending_1).

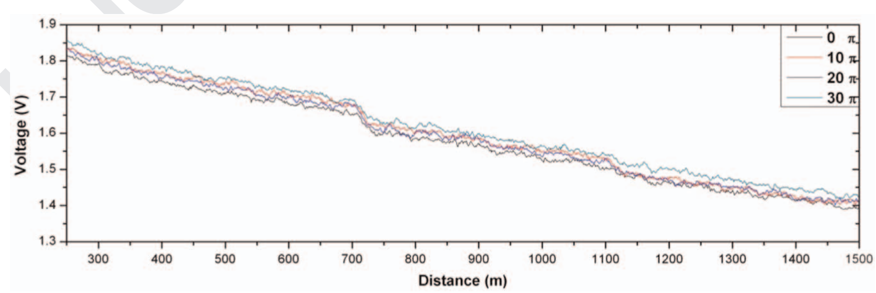

Fig. 3. P-OTDR trace when twisting was applied to the PMF.

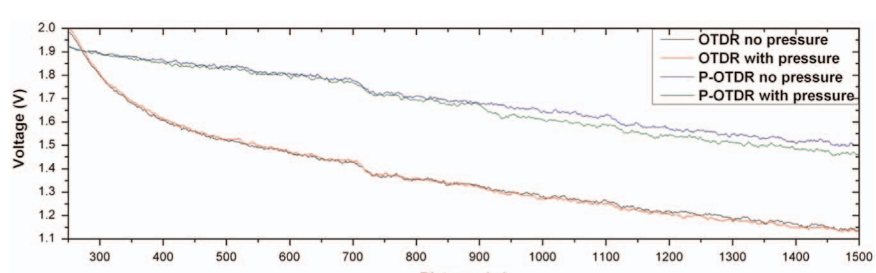

Fig. 4. P-OTDR trace when pressing was applied to the PMF.

manufactured, the PMC is usually caused by the external perturbation applied to the fiber. By measuring the PMC caused by the perturbation, the intrusion event detection can be achieved.

The perturbation can be mainly divided into the three categories, the bending, twisting, and pressing. In order to investigate the influence of three kinds of perturbation applied to the PM fiber, some experiments were set up. The peak power of the optical pulse was 20 mW. An electrical signal with a width of 200 ns and a repetition period of 1 ms generated by the waveform generator was applied to the light source. All the curves below are the results of 500 times average. All the signal output by the photodetector is sampled by the NI-USB-5133 at the sampling rate of 100 MS/s. When the setup of the experiment is as shown in Fig. 1(b), the P-OTDR trace was obtained, and after removing the polarizer, the OTDR trace was obtained.

Fig. 2 shows the OTDR and P-OTDR curves when 5 circles of bending with the diameter of 2.5 cm were applied to the PM fiber at the distance of 900 m. The directions of the bending of the two P-OTDR curves are orthogonal. From the figure it can be seen that the bending caused a drop both on the OTDR curve and the P-OTDR curve. And the drop of the P-OTDR with 2.5 cm diameter bending_1 is larger than the drop of the P-OTDR with 2.5 cm diameter bending_2. The drop of the P-OTDR curve is resulted from the loss of fiber. Since both the bendings of the fiber are towards different directions, due to the polarization dependent loss (PDL), the drop of one bending P-OTDR curve is smaller than the drop of the OTDR curve and the drop of the other bending P-OTDR curve is larger than the drop of the OTDR curve. But the intrusion event usually cannot cause the bending with such a small diameter; so the drop on the P-OTDR trace cannot be so significant.

Fig. 3 shows the P-OTDR curves when the twisting of 0π, 10π, 20π and 30π was respectively applied to the length of 6 cm of the PM fiber at the distance of 900 m. From the above figure it can be seen that the twisting of the fiber can hardly cause the PMC and the loss of the PM fiber.

The pressure was applied to the fiber as shown in Fig. 5 at the distance of 900 m, and from Fig. 4 we can see that there is no drop on the OTDR curve when the pressure was applied to the PM fiber, therefore the pressure did no cause loss, but the pressure caused a 3.02% drop on the P-OTDR curve. Therefore, the pressure applied to the PM fiber only caused PMC and it was detected by the P-OTDR.

In conclusion, only the pressing applied to the PMF can cause PMC easily, and the intrusion event can be detected by measuring the PMC caused by pressing when the intrusion event happens.

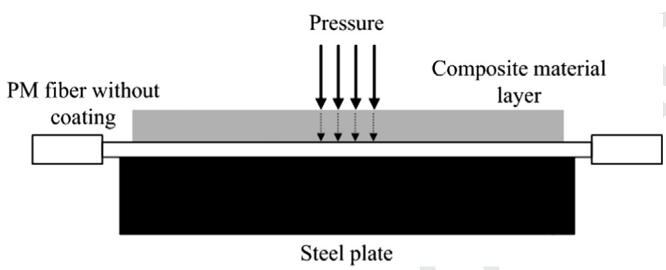

Fig. 5. The fiber with no coating was pressed.

3. Experiment and result

An experiment, as shown in Fig. 6, was set up to demonstrate the performance of the system to detect the multiple intrusion events along the sensing fiber. A directly modulated super-luminescent light emitting diode (SLED) with a bandwidth of 35 nm was chosen as the light source. The peak power of the optical pulse was 20 mW. An electrical signal with a width of 500 ns and a repetition period of 20 μs generated by the waveform generator was applied to the light source. A polarization controller (PC) was used between the light source and the circulator to maximize the output power of the polarizer. The transmitted light went through the circulator and the polarizer and propagated along one optical axis in the 1.2 km PMF. And, the pigtail of the polarizer near the sensing fiber is also PMF. The backscattered light along the input optical axis was collected by the polarizer and circulator and coupled into the avalanche photodiode (APD) photodetector (PD). The output signal of the PD was then sampled at 100 MS/s using

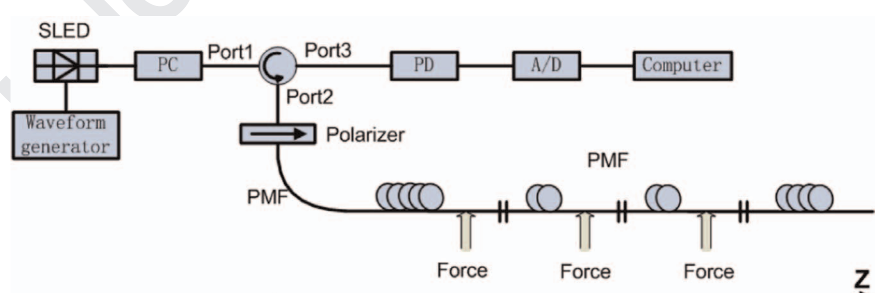

Fig. 6. The architecture of the experiment (SLED: super-luminescent light emitting diode; PC: polarization controller; PD: photo-detector; PMF: polarization maintaining fiber; A/D: analog to digital converter).

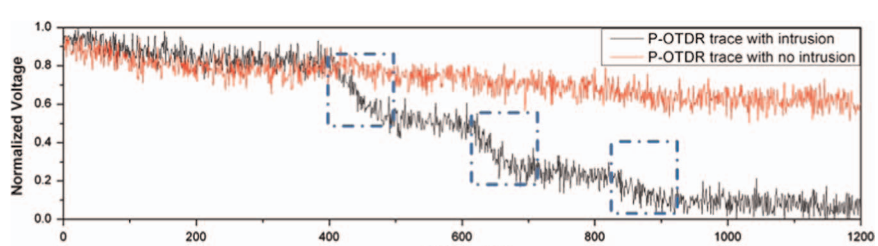

Fig. 7. The result of the experiment.

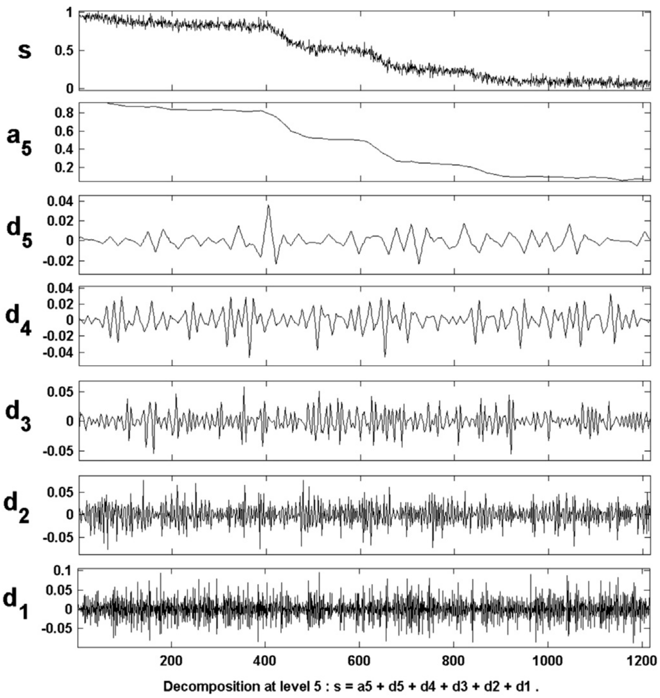

Fig. 8. The wavelet coefficients of the P-OTDR trace with intrusion.

an 8-bit analog-to-digital converter (NI-USB-5133) and then transmitted into a computer.

The steps of the experiment are as follows:

Step 1: Run the program on the computer to acquire data and get the P-OTDR trace as reference.
Step 2: Apply force on the three points on the PMF and repeat Step 1.
Step 3: Compare the two P-OTDR traces and obtain the location of the three events along the sensing fiber.

The experiment results are shown in Fig. 7. We can see that the three intrusion events happened respectively at distances of 400 m, 610 m and 820 m. In order to see the drop caused by the intrusion event evidently, the wavelet analysis was adopt to de-noise the P-OTDR trace with intrusion event as shown in Fig. 8. The P-OTDR trace was decomposed by using 5-level Daubechies-4 wavelet transform, the wavelet coefficients produced by wavelet transform are shown in Fig. 8, here, s is the original signal, and $s = a5 + d5 + d4 + d3 + d2 + d1$. From the wavelet coefficient $a5$, the drop can be distinguished more easily.

The force applied to the fiber caused obvious increase of the PMC, and a part of optical energy was coupled into the other optical axis, which cause a distinct drop on the P-OTDR trace in comparison with the P-OTDR trace with no applied force. In addition, we can also find that, the width of the drop part on the trace is equal to the width of the optical pulse. Therefore, the position of the intrusion point can be located by the point where the trace begins to drop, and the accuracy of intrusion event location can be much higher than the width of the optical pulse adopted in the system. That is to say, in this architecture, a wide optical pulse can be employed without affecting the accuracy of intrusion event location. As a result, the accuracy of intrusion event location is decided by the SNR of the system.

4. Conclusion

In this paper, we achieved multi-event detection along the fiber using simple and cost-effective incomplete P-OTDR structure. In the system, the event location accuracy is decided by the SNR of the system, and it can be much higher than the width of the optical pulse. In addition, wide optical pulse can be used to improve the SNR without decreasing the event location accuracy. Furthermore, wide band optical source was adopted, so the coherent noise was avoided totally. Moreover, the light was transmitted along one optical axis, so the decrease of the degree of polarization (DOP) along the fiber will not affect the dynamic range.

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