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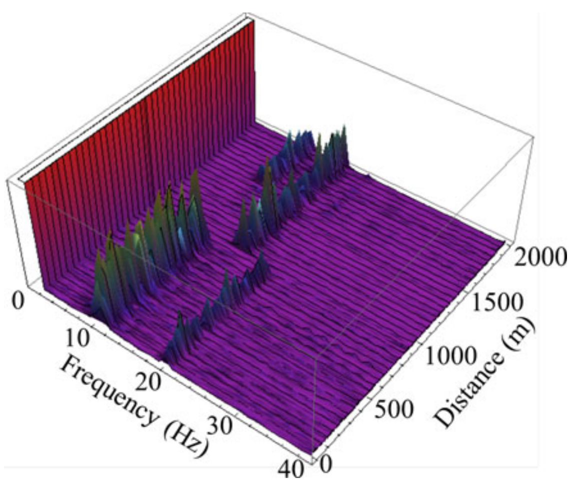

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Development of a Multiperimeter Sensing System Based on POTDR

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Abstract: Polarization optical time-domain reflectometry (POTDR) is sensitive to perturbations on any point of the fiber under test (FUT). However, restricted by the sensing principle, the signal of the front perturbation would mask the signals of the rear ones. Thus, in practical applications, a perturbation on the lead fiber between a POTDR and the FUT would generate unnecessary signal which hinders POTDR from distinguishing the valid signal. In this paper, a new POTDR scheme which is robust to perturbations on the lead fiber is proposed. So only the perturbations on the FUT can generate signals. The principle is explained in detail and experiments demonstrate the validity of this scheme. By using the proposed scheme, multiple perimeters are monitored independently at one time, and distributed sensing is realized for each perimeter.

Index Terms: Optical time domain reflectometry, polarization-OTDR, perimeter monitoring.

1. Introduction

Perimeter monitoring is one of important applications of optical fiber sensor (OFS). Many kinds of OFSs, including interferometer-based techniques [1], [2], optical time domain reflectometry (OTDR)-based techniques [3], [4], have been developed to focus on this application. Polarization optical time-domain reflectometry (POTDR), one of the OTDR-based sensors, realizes distributed sensing by detecting the state of polarization (SOP) of Rayleigh backscattering (RBS) along a fiber. It has advantages of good sensitivity, simple configuration, low cost, etc. So it has attracted much attention [4]–[7].

A typical POTDR has the similar configuration as an OTDR, except for inserting a polarizer before the detector [4]. So the SOP change of the RBS is transformed into the change of intensity via the polarizer and is then detected by the detector. Since the SOP of the RBS is sensitive to the perturbation of fiber, POTDR is capable of realizing distributed perturbation measurement.

The SOP of lightwave at a position is correlated with that before it. This feature makes it very easy for POTDR to detect the first perturbation (nearest to the input end) on a fiber under test (FUT) because even if the perturbation is on a very short length, all the signals after the perturbation point change together [8]. So when used for perimeter monitoring, POTDR can not only detect an intrusion quickly, but can also locate it accurately. However, this feature also results in that the polarization signal induced by the first perturbation may mask the signals of other perturbations.

In practical applications, there is always a distance between the POTDR equipment and the FUT in the perimeter, thus one has to connect the POTDR equipment and the FUT in the perimeter with a lead fiber. However, when the lead fiber is disturbed, unnecessary signal will be generated, which may mask the real signal in the FUT, influencing the monitoring of the perimeter.

Several methods which can extract multiple perturbations with POTDR have been proposed. Zhang *et al*. have proposed a frequency spectrum analyzing method [9] and Wu *et al*. have proposed a 2-D image processing and statistical clustering method [10], both of which can detect multi-vibration events when they have different frequencies. Tong *et al*. have achieved multi-event detection by employing a polarization maintaining fiber (PMF) as the distributed pressure sensor [11]. Linze *et al*. have proposed a method of detecting multi-vibration events by using FBG pairs [12]. Wang *et al*. have proposed a method for detecting two identical frequency vibrations by distinguishing their phase relationship [13]. All the above methods have been proved to be effective. However, they can only detect limited number of perturbations. In theory, a fully POTDR can measure unlimited number of events by analyzing the SOP of the backscattering signal [14]. However, this technique requires a Stokes analyzer which increases the cost dramatically. So when using a normal POTDR for perimeter monitoring, it is critical to isolate the lead fiber from environment, which is very difficult and costly in practice.

Apparently, if POTDR is insensitive to perturbations on the lead fiber, it will avoid influences of the noises and false signal from the lead fiber, leading to more effective and accurate perimeter monitoring. In this paper, we develop a POTDR which is insensitive to perturbations on the lead fiber for the first time. The principle is analyzed and corresponding experiments are given to demonstrate the validity of the proposed method. Meanwhile, based on the proposed method, we also prove a scheme for monitoring multiple perimeters. The signals from different perimeters do not interfere with each other, so the scheme can monitor multiple perimeters independently at one time.

2. Principle

An intuitive method to avoid the influence of the perturbation on the lead fiber in POTDR may be using a PMF to connect the POTDR and FUT. However, when the RBS from the FUT transmits back, due to its SOP is not parallel to the principle axis of the PMF, its SOP is still sensitive to the perturbation on the PMF, resulting in false signal.

For a POTDR, being insensitive to influences of the lead fiber requires both the intensity and the SOP of the probe optical pulse to keep constant when it is input into the FUT, and the intensity of the returned signal is independent on the state of lead fiber.

Thus, we firstly set a polarizer right before the FUT. So the SOP of the input optical pulse in the FUT is only determined by the polarizer, which guarantees the SOP of the input optical pulse is fixed even if the lead fiber is under perturbation. When the RBS transmits back, the polarizer acts as a polarization analyzer which can transform the change of SOP into the change of intensity. So the proposed scheme is also polarization sensitive for the detection of perturbation on the FUT.

However, a perturbation on the lead fiber would change the SOP of lightwave, resulting in a power variation of the optical pulse after the polarizer. This will induce a power variation of the entire backscattered signal, affecting the detection of the perturbation on the FUT. For this setup, using a PMF to connect the POTDR and polarizer can solve this problem, but the cost of PMF is very much. In this paper, in order to stabilize the power of the probe pulse after the polarizer with a normal lead fiber, we construct a combination of a polarization beam splitters (PBS) and a polarization beam combiner (PBC) after the laser source. The proposed new POTDR scheme is shown in Fig. 1.

The PBS splits the output lightwave of the laser source into two beams equally whose polarization directions are orthogonal to each other. These two beams are coupled into two output arms of the PBS respectively and then are combined together through the PBC. A PM fiber with length of 1 m is inserted into one output arm of the PBS, acting as a delay fiber.

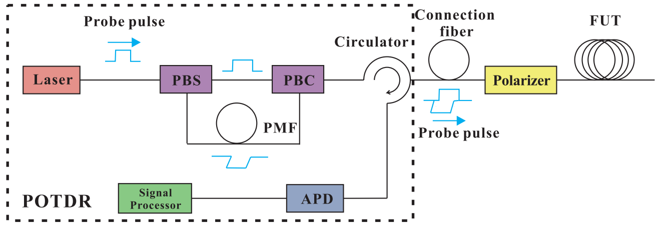

Fig. 1. The proposed new scheme of POTDR.

Provided the intensity of the lightwave output from the laser source is I_0. Then with Jones Matrix representation the two orthogonal optical fields in the two output arms of the PBS are

$$\mathbf{E}_1 = \sqrt{I_0/2}\exp(i2\pi\nu_0 t)\begin{pmatrix}1\\0\end{pmatrix}$$

$$\mathbf{E}_2 = \sqrt{I_0/2}\exp(i2\pi\nu_0 t - \phi_0)\begin{pmatrix}0\\1\end{pmatrix}, \tag{1}$$

where ν_0 is the frequency of the lightwave, and ϕ_0 is the phase difference between the two orthogonal fields. After combined by the PBC, the two optical fields will maintain their polarization states and transmit together in the lead fiber. The lead fiber can be treated as a waveplate, so its transmission matrix is:

$$\mathbf{J_R} = \begin{pmatrix}\cos(\phi/2) + i\sin(\phi/2)cos(2\alpha) & i\sin(\phi/2)\sin(2\alpha)\\ i\sin(\phi/2)sin(2\alpha) & \cos(\phi/2) - i\sin(\phi/2)cos(2\alpha)\end{pmatrix} \tag{2}$$

where ϕ and α are the phase shift of the waveplate and the orientation angle of the waveplate respectively. Meanwhile, the Jones matrix of the polarizer can be expressed as

$$\mathbf{J_P} = \begin{pmatrix}\cos^2\beta & \sin\beta\cos\beta\\ \sin\beta\cos\beta & \sin^2\beta\end{pmatrix} \tag{3}$$

where β is the orientation angle of the polarizer. Thus the optical fields after the polarizer can be expressed as

$$\mathbf{E_{out1}} = \mathbf{J_P J_R E_1}$$

$$\mathbf{E_{out2}} = \mathbf{J_P J_R E_2}. \tag{4}$$

Because the coherence length of the probe pulse in POTDR is much shorter than the length of the delay fiber [15], [16], the phases of $\mathbf{E}_1$ and $\mathbf{E}_2$ are irrelative. So the intensity of the output lightwave after the polarizer is

$$I = I_1 + I_2 = \mathbf{E}^{\dagger}_{\mathbf{out1}}\mathbf{E_{out1}} + \mathbf{E}^{\dagger}_{\mathbf{out2}}\mathbf{E_{out2}} = I_0/2 \tag{5}$$

where the superscript † denotes the complex conjugate transpose. Equation (5) shows that with the proposed setup, the intensity of the lightwave after the polarizer has no correlation with the transmission matrix of the lead fiber. Thus no matter how the lead fiber is disturbed, the intensity of the probe pulse after the polarizer keeps constant.

3. Experiments and Discussions

3.1 Single Perimeter Monitoring

So based on the scheme in Fig. 1, we conducted an experiment to verify its validity. Because the output of the laser source was not polarization maintaining in the experiment, a polarization controller was inserted between the laser source and the PBS to equalize the intensities of the

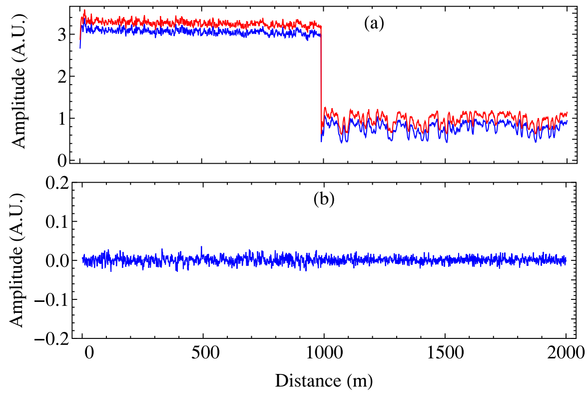

Fig. 2. Signals of the proposed POTDR scheme. (a) Two signals before and after the lead fiber was disturbed. (b) The differential signal of the two signals in (a).

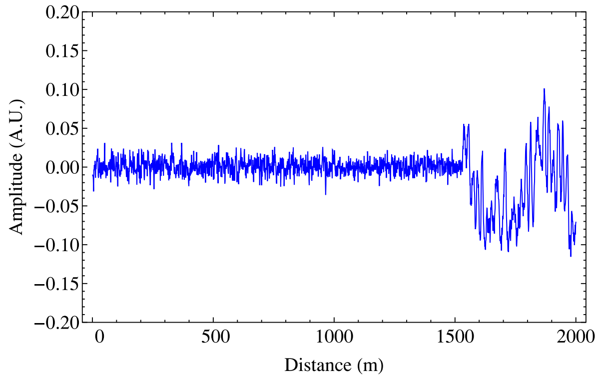

Fig. 3. Differential signal before and after the fiber in the perimeter section was bent slightly.

optical pulses in the two output arms of the PBS. All the devices and components in the dashed rectangle was integrated together as a POTDR equipment, whose output port was the second port of the circulator. The linewidth of the probe pulse was 0.2 nm and the peak power was 16 dBm. The extinction ratio of the polarizer is 23 dB. The gain of the APD is 10^7V/W, and its minimum detectable optical power is -60 dBm. The period of the probe pulse was 50 μs and the pulse width was 40 ns. In order to improve the signal-to-noise ratio (SNR), every 200 POTDR curves were averaged. The length of the lead fiber was about 1 km, simulating a long distance between the POTDR and a faraway FUT in the perimeter.

The POTDR signal is shown in blue in Fig. 2(a). It can be seen that there is no fluctuation in the first 1 km signal, because the polarizer was set at 1 km and the signal before the polarizer was only related to the power of the RBS. In the signal after 1 km, obvious fluctuation can be observed, which is because the RBS was filtered by the polarizer.

Then we slightly bent the lead fiber at about 500 m to change the SOP of the optical pulse. The corresponding POTDR signal is shown in red and is up-shifted by 0.2 in order to be shown clearly in Fig. 2(a). The differential curve between the two blue and red curves is shown in Fig. 2(b). Through the comparison between the two curves, it can be seen that both the pattern and the amplitude of the POTDR signal keep constant under the perturbation. So it demonstrates that the proposed scheme is robust to the perturbation on the lead fiber. In contrast, when we touched the FUT 500 m behind the polarizer and induced a displacement of 5 mm, the fluctuation pattern of the POTDR signal has obvious variation after the bending position, as shown in Fig. 3. The variation of the

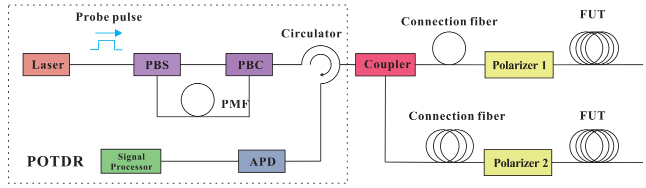

Fig. 4. The POTDR setup for the detection of two perimeters simultaneously.

signal starts at about 1520 m, which indicates that the perturbation is at 520 m of the FUT. So by using the proposed scheme, it is still sensitive to the change of SOP in the FUT and can locate the perturbation. Obviously, because the influence of the lead fiber is eliminated, any perturbation on the lead fiber does not mask the real signal in the FUT. Thus, the proposed scheme is more reliable to detect perturbations of the perimeter.

The ratio of the intensities of the optical pulses output from the two arms of PBS is crucial. Assuming the intensities of the two optical pulses are I_1 and $I_2(I_1 > I_2)$ respectively and $I_1 + I_2 = I_0$, then we can split the intensity of the first optical pulse into two portions. One portion has the same intensity I_2 as the second optical pulse, and the other portion has an intensity $I' = I_1 - I_2$. Apparently, the first portion of the first optical pulse combines orthogonally with the second optical pulse. When passing through the polarizer, their output intensity equals to I_2 according to (5). The second portion of the first optical pulse will also pass through the polarizer. However, its intensity passing through the polarizer depends on its SOP. When the lead fiber is disturbed, the intensity varies accordingly and the variation range is $0 \sim I'$. This will change the total intensity of the probe optical pulse after the polarizer, and thus induce amplitude variations in POTDR signal, leading to false signal.

In the worst case, perturbations on the lead fiber will induce the amplitude of the POTDR signal to change by a proportion of I'/I_2. Thus, a perturbation on the FUT may be masked when its amplitude is too small. As shown in Figs. 2 and 3, the amplitude variation of the POTDR signal induced by the perturbation is about 15% in proportion. Thus, an intensity difference of 7% between the two output arms of the PBS is acceptable in our experiment. If using a PMF to connect the PBS, an angle misalignment of $\pm 4^\circ$ is allowed which can be easily fulfilled by most commercial components.

3.2 Double Perimeters Monitoring

Based on the advantages of the proposed POTDR scheme that it is insensitive to perturbations on the lead fiber, one may set a POTDR scheme which can monitor multiple perimeters independently at one time. As a proof of concept, we set up an experiment configuration which can monitor two perimeters simultaneously. The scheme of the POTDR is shown in Fig. 4. The main configuration was based on that in Fig. 1, and a 3 dB coupler was inserted behind the second port of the circulator. So the POTDR had two equal output ports to connect to two perimeters respectively. In Fig. 4, the lengths of the FUTs for the two paths were both about 1 km. The lengths of the lead fibers in the first path and the second path were about 1 m and 1 km respectively. The lead fiber of the second path was longer than the total length of the first path, so the signals of the two perimeters could be distinguished from distance.

The signal without perturbation is shown in Fig. 5. It can be seen that the signal along the fiber has obvious fluctuation. The signal for the first 1 km is the summation of the POTDR signal of the FUT in the first path and the RBS of the lead fiber in the second path, and the signal after 1 km is the POTDR signal of the sensing fiber in the second path. As given in (5), because the intensity of the optical pulse in the lead fiber is twice larger than that in the FUT, the RBS is twice larger than the POTDR signal. So there is an obvious step at 1 km in the signal which can help to discriminate the POTDR signals of the first and the second paths. Meanwhile, because the RBS is

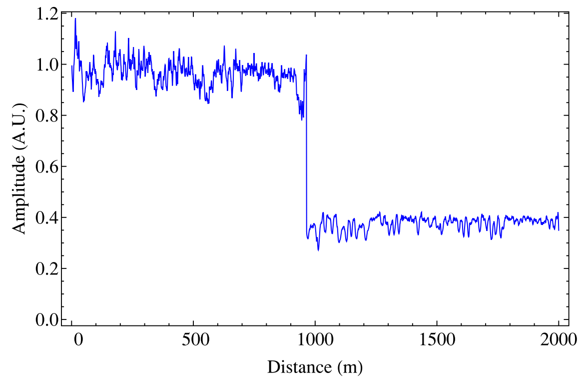

Fig. 5. The signal for monitoring two perimeters simultaneously with the setup in Fig. 4.

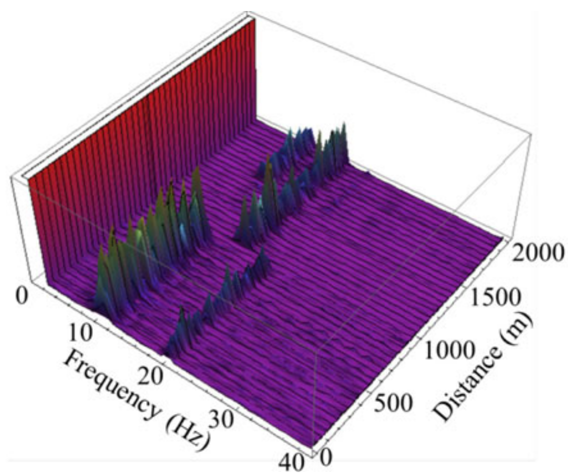

Fig. 6. The frequency spectrum distribution of the vibration signal.

insensitive to perturbations of the lead fiber, it can be easily eliminated with differential method. So it does not influence the sensing of the first path either.

Then we set vibrations on the FUTs in both paths to demonstrate the independent sensing ability for different paths. All the amplitudes of the vibrations were about 5 mm. In the first path one vibration with frequency of 10 Hz was set right after the polarizer1. In the second path, two vibrations were set on the FUT. One vibration with frequency of 15 Hz was set right after the polarizer2, and the other vibration with frequency of 10 Hz was set at 500 m behind the polarizer2. The parameters of the optical pulse were the same as the first experiment. By using the spectrum analyzing method to process the POTDR signals [9], the frequency spectrum distribution of the signal is obtained and is shown in Fig. 6. The signal with 10 Hz frequency nearly starts from 0 m, which indicates that there is a 10 Hz vibration at the beginning of the first path. This signal ends at 1 km which is the end of the first path, because the SOPs of all the optical signal after the vibration position were changed by the vibration. The signal with 20 Hz frequency is the second-order harmonic of the 10 Hz signal, and it also indicates that the signals of the two paths do not interfere with each other. Then the 10 Hz signal starts again at 1500 m, which indicates that there is also a 10 Hz vibration in the second path. By subtracting the length of the lead fiber in the second path, one can easily locate the vibration which is at 500 m. Meanwhile, it can be seen that there is also a signal with frequency of 15 Hz starting from 1000 m, which means that this signal is at the beginning of the second path. Thus, the preceding experiments demonstrate that the proposed POTDR scheme can measure multiple perimeters simultaneously. With the assistances of time division multiplexing and spatial division multiplexing, the signals for different perimeters are independent with each other, and for each perimeter, the scheme can realize distributed measurement as the normal POTDR.

4. Conclusion

In this paper, a new scheme of POTDR is proposed. An output optical pulse composed of two orthogonal optical pulses is generated at the output of the POTDR and a polarizer is set right before the FUT to stabilize the SOP of the probe pulse at the input end of the FUT. Theoretical analysis and experiments demonstrate that the proposed POTDR scheme can avoid the influence of perturbations on the lead fiber. And distributed perturbation measurement can still be realized in the interested perimeter. So the proposed POTDR scheme is more reliable to detect perturbations in the perimeter. With the proposed scheme, independently monitoring for multiple perimeters can be realized at one time. In the experiments, we successfully measured the vibration events for two independent perimeters simultaneously.

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