Multi-Event Detection in Polarization-OTDR Based on Principal Depolarization Factors

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Abstract: Principal depolarization factors (PDF) are demonstrated to be the local polarization parameters in single-mode fibers. Based on measurements of PDFs, polarization-OTDR with wider optical pulses has demonstrated multi-event detection for the first time.

1. Introduction

Polarization optical time domain reflectometry (P-OTDR) was proposed in 1981 to measure the field distributions along a single-mode optical fiber (SMF) [1]. With the measurement of the temporal variation of the state of polarization (SOP) along the SMF, P-OTDR has been used to detect the perturbations applied to the SMF that are induced by local events [2]. However, this approach is only capable of detecting the first event because SOP is not the local polarization parameter. By using a complete P-OTDR to measure the round-trip Mueller matrix, the local linear birefringence can be measured to realize the real multi-event detection [3]. The latter approach must use a very narrow optical pulse (≤ 10 ns), which leads to unacceptable signal-to-noise ratio (SNR) when the sensing fiber length is longer than 1 km.

In this paper, we demonstrate that three principal depolarization factors (PDF) are local polarization parameters which can be measured using a complete P-OTDR with wider optical pulse (hundreds of ns). The capability of multi-event detection using the P-OTDR with wider optical pulses is demonstrated for the first time.

2. Principle

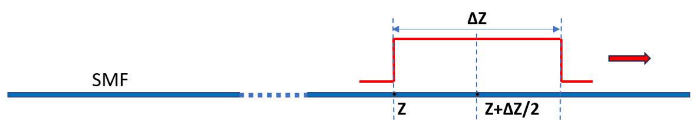

Fig.1 An incoherent optical pulse is propagating along a SMF in z direction. The pulse width is Δz.

As shown in Fig. 1, an incoherent optical pulse, with the pulse width of Δz, propagates in a SMF in z direction. The Mueller matrix, which depicts the polarization properties of the fiber segment from the input end to the length z in the forward direction, is denoted as $\boldsymbol{M}(z)$ and its matrix elements are denoted as $m_{ij}, i, j = 1,2,3,4$. Because commonly used SMFs are purely birefringent, it has $\boldsymbol{M}\boldsymbol{M}^T = \boldsymbol{M}^T\boldsymbol{M} = \boldsymbol{I}$ and $\boldsymbol{M}^T = \boldsymbol{M}^{-1}$. Here, the superscripts "T" and "-1" denote the matrix transpose and the inverse matrix, respectively. $\boldsymbol{I} = diag(1,1,1,1)$ is the identity matrix. The superposed Rayleigh backscattered lights are reflected from z to $z + \Delta z/2$, then the round-trip Mueller matrix $\boldsymbol{M}_B(z)$ is [4]

$$\boldsymbol{M}_B = \boldsymbol{R}\boldsymbol{M}^T\boldsymbol{R}\boldsymbol{M}_{RTS}\boldsymbol{M} \tag{1}$$

where $\boldsymbol{R} = diag(1,1,1,-1)$. The Mueller matrix $\boldsymbol{M}_{RTS}$ depicts the reflection and the superposition of the Rayleigh scatterers in the fiber segment from z to $z + \Delta z/2$, which is [4, 5]

$$\boldsymbol{M}_{RTS} = \boldsymbol{R}\boldsymbol{A} = \boldsymbol{R}\sum_{k=1}^{n} c_k^2 \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-2m_{42k}^2 & -2m_{42k}m_{43k} & -2m_{42k}m_{44k} \\ 0 & -2m_{42}\ m_{43k} & 1-2m_{43k}^2 & -2m_{43k}m_{44k} \\ 0 & -2m_{42k}m_{44k} & -2m_{43k}m_{44k} & 1-2m_{44k}^2 \end{bmatrix} \tag{2}$$

where n is the total number of Rayleigh scatterers in the fiber segment from z to $z + \Delta z/2$, c_k^2 is the Rayleigh backscattering coefficient of the k-th Rayleigh scatterer as the fiber loss is neglected. The round-trip Mueller matrix $\boldsymbol{M}_B(z)$ can be measured using a complete P-OTDR. When the pulse width Δz is tens of meters or larger, $\boldsymbol{M}_B(z)$ will describe both birefringence and depolarization effects. To evaluate the depolarization, the following calculation can be implemented

$$\boldsymbol{M}_B^T\boldsymbol{M}_B = \boldsymbol{M}^T\boldsymbol{M}_{RTS}^T\boldsymbol{M}_{RTS}\boldsymbol{M} = \boldsymbol{M}^{-1}\boldsymbol{A}^2\boldsymbol{M} \tag{3}$$

Here, we used $\boldsymbol{A}^T = \boldsymbol{A}$. Equation (3) means that $\boldsymbol{M}_B^T\boldsymbol{M}_B$ and $\boldsymbol{A}^2$ are two similar matrices. Therefore, they have the same eigenvalues. If the eigenvalues of $\boldsymbol{M}_B^T\boldsymbol{M}_B$ are measured as $\lambda_1^2, \lambda_2^2, \lambda_3^2$, then the absolute values of the eigenvalues of $\boldsymbol{A}$ will be $|\lambda_1|, |\lambda_2|, |\lambda_3|$, which have been called PDFs [6]. It can be demonstrated, by theoretical analysis, that three

PDFs are local parameters depending on only the local birefringence distribution in the fiber segment z to $z + \Delta z/2$. In this paper, we validate this finding with simulation and experimental results.

3. Simulation and Experimental Results

Simulations are performed by using an adopted wave-plate model as described in [7]. The simulated SMF length is 200 meters, and the optical pulse width is 10 meters (50 ns). The number of the Rayleigh scatterers is set as 100 per meter. In the first step, three PDFs along the SMF are calculated as the benchmark before perturbation. In the second step, the birefringence distributions of 1 m-long fiber are altered around three fiber length points of approximately 50 m, 100 m, and 150 m to simulate three independent local perturbation events. In the third step, three PDFs along the altered SMF are calculated again. The simulation results are plotted in Fig. 2, which show that only the local PDFs around approximately 50 m, 100 m, and 150 m have been changed by three corresponding independent events.

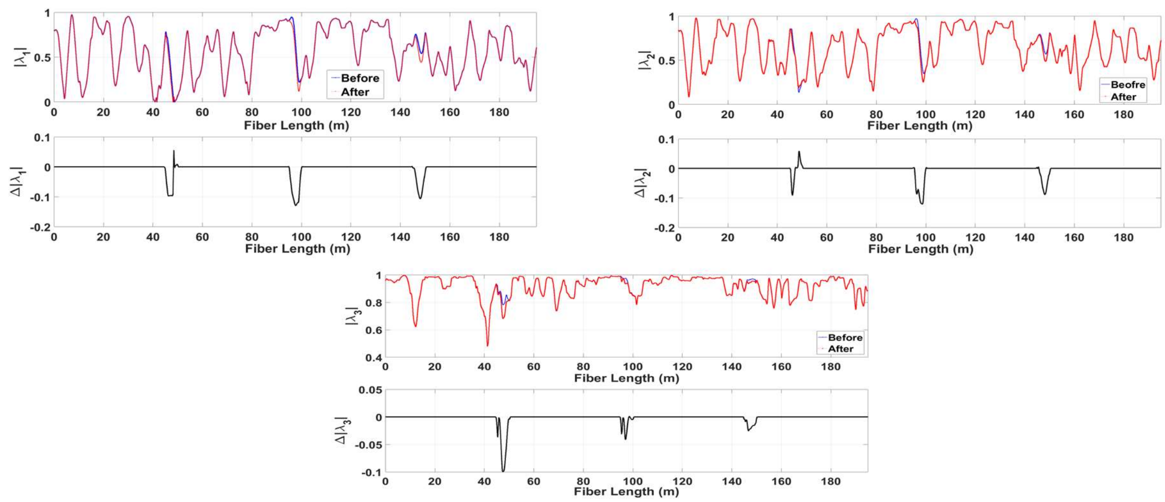

Fig.2 The simulation results of three PDFs versus fiber length before (blue) and after (red) perturbation at approximately 50 m, 100 m, and 150 m. The differences between PDFs before and after perturbations are also shown in black.

A preliminary experiment is also performed to further confirm the finding. The experimental setup is illustrated in the left figure of Fig. 3. The used pulse width is 500 ns (100 meters). The experiment also involves three identical steps as those employed in the simulation. In the experiment, only one perturbation is introduced by using a polarization controller (PC2) at the fiber length of 2.3 km. In Fig. 3, the difference between the sums of three PDFs, $D = |\lambda_1| + |\lambda_2| + |\lambda_3|$, before and after perturbation, is shown. This outcome reaffirms that three PDFs serve as local parameters capable of enabling multi-event detection in P-OTDR.

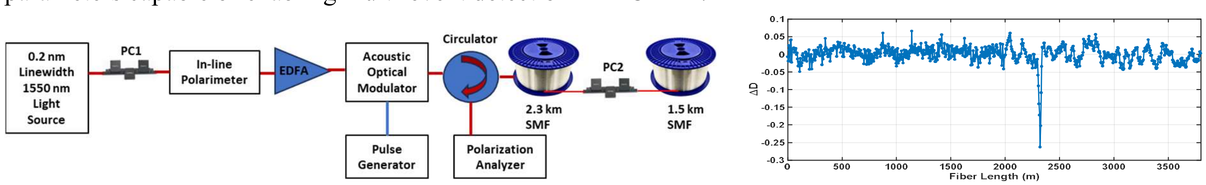

Fig. 3 The experimental setup (left) and the difference between the sums of three PDFs before and after perturbation at 2.3 km (right).

4. Conclusions

We demonstrate that three PDFs are local polarization parameters along a SMF. They can be measured using a complete P-OTDR to realize the multi-event detection without the restriction of pulse width. Consequently, these measurements contribute to an improved SNR, thereby extending the sensing fiber length to several kilometers or even longer distances.

5. Acknowledgements

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6. References

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