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An Investigation of Fidelity Regions in the Dual-pulse ϕ-OTDR Systems

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Abstract: The dual-pulse interrogation enables the phase extraction from the intensity of the back-reflection signal in ϕ-OTDR systems. We investigate the high and low fidelity regions in the back-reflected signal by analyzing the system response to external disturbances.

1. Introduction

Phase-sensitive optical time-domain reflectometers (ϕ-OTDR) can measure acoustic disturbances around a sensing fiber, by interrogation with highly coherent short pulses [1]. Despite the simplicity of the direct-detection method and its success in the event localization, it does not provide a linear relationship between the magnitude of the disturbance and the intensity measured by the back-reflected light [2]. Better linearity in the reflectometry can be obtained by dual-pulse interrogation. In this method, frequency difference and temporal delay between the pulses are introduced. Then the beat signal can be used to demodulate the linear phase between the two regions of the fiber to retrieve the acoustic information [3,4]. Owing to the fading phenomena [5] and the dynamic behavior of the scattering centers in the fiber [6], this scheme may fail to provide an ideal response. In this paper, we analyze the fidelities of the signals retrieved in the vicinity of an acoustic disturbance.

2. Experimental results

The experimental set-up for the dual-pulse ϕ-OTDR system is shown in Fig. 1. A continuous-wave light at 1550 nm from a narrow linewidth laser is amplified by an erbium-doped fiber amplifier (EDFA). The amplified light is split into two paths, each having an acousto-optic modulator (AOM) that generates the interrogation pulses. The pulse parameters such as the width, frequency, and delay time are introduced by RF input signals synthesized from a data acquisition (DAQ) card. Two paths are, then, recombined to produce pulse pairs and injected into a test fiber via a circulator. The back-reflected light, passing through the same circulator, is pre-amplified and filtered before photodetection. The signal from the photodetector is sampled with the DAQ card at a sampling rate of 256 MS/s.

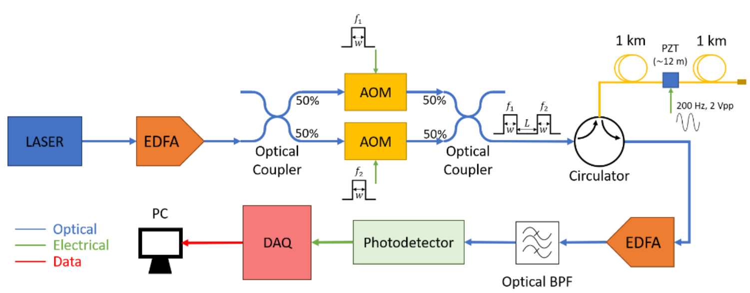

Fig. 1. Experimental set-up for the dual-pulse ϕ-OTDR system. PZT: Piezoelectric transducer; BPF: Bandpass filter; PC: Personal computer (Other acronyms are explained in the text.)

At the photodetector, the current is proportional to the back-reflected intensity, $I = (E_1 + E_2)^*(E_1 + E_2)$, where

$$E_{1,2}(t) = E_{1,2}(0) \sum_{m=j(t)}^{k(t)} r_m \exp(-2\alpha z_m + i(2\pi v t + \phi_m(t))). \quad (1)$$

In equation (1) z_m and r_m are the location and the complex scattering coefficient of the mth scattering center, respectively. α and v are the attenuation coefficient and the optical frequency, respectively. The time-dependent phase of each center, $\phi_m(t)$ is modified by external disturbances to the fiber. For a periodic intrusion, the obtained phase retraces itself only when the complex scattering coefficients and the number of terms in the summation formula, i.e. equation (1), are constant. This suggests that, in the dual-pulse ϕ-OTDR, a high-fidelity response can be obtained when the intrusion event takes place between the pulses. In other words, if the intrusion is distributed over a region longer than the pulse separation, the fidelity worsens as the number of electric fields interfering at the detector is no longer constant in time. To confirm this statement, a 2-km-fiber with a piezoelectric transducer (PZT) at 1 km is interrogated by a dual-pulse ϕ-OTDR at 2000 Hz repetition rate. The PZT is driven with a 200 Hz, 2 Vpp sinusoidal signal, and the backscattering signal is collected to investigate the system response. The phase for each channel is demodulated and the root-mean-square (rms) of the phase is calculated for 50 ms. Finally, the histograms of the phase rms values are obtained for each 1000 cycles.

Fig. 2(a) and Fig. 2(b) show the histograms of the root-mean-square (rms) of phases at two different but close locations in the fiber with insets showing rms phases for 1000 cycles against the corresponding channel. In this experiment, the pulse train consists of 150 ns-width pulses with 150 ns delay in between. Similarly, Fig. 2(c) and Fig. 2(d) show the histograms of the rms phases for a pulse train with 190 ns delay in between. The results illustrate that in spite of the PZT signal is sensed in a wide range of channels, the demodulated phase exhibits the least variation at the middle of the channel range, Fig. 2(b-d). In contrast, the phase varies significantly at channels closer to the sides Fig. 2(a-c). However, rms of the phases obtained in 1000 cycles for both regions are similar.

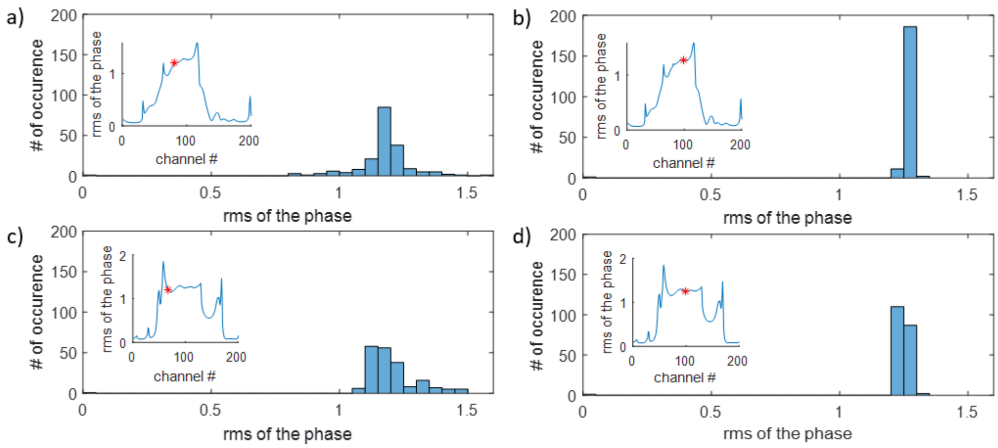

Fig. 2. Histograms of the rms of the phase. For (a) and (b), the delay is 150 ns and for (c) and (d), the delay is 190 ns.

The region where the rms phases exhibit the least variation is the region where the PZT is between the pulses. The channels with large phase variations correspond to the low-fidelity region where the light scatters from defects in the fiber portion affected by the strain induced by the PZT. The PZT used in these experiments consists of ~12 meters of fiber wound around a piezoelectric cylinder. With channels having 0.4 m separation, 12 meters of fiber correspond to 30 channels and pulse separations of 150 ns and 190 ns correspond to 76 and 97 channels, respectively. Excluding the region within the pulse separation occupied by the PZT, there should be 26 and 47 channels where the phase is read linearly, respectively. Experimentally, we found these numbers 24 for 150 ns delay time and 44 for 190 ns delay time.

3. Conclusion

This work demonstrates the different fidelities of the demodulated phase in the dual-pulse ϕ-OTDR. The response exhibits at least two different regions. The location of the intrusion with respect to the pulse train affects the fidelity of the demodulated phase. This result can be used to develop algorithms for better detection of the intrusions along the fiber. Furthermore, it demonstrates the possible strength of dual-pulse ϕ-OTDR in sensing of fixed acoustic sources, such as oil-wells and fault lines.

4. References

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