Demonstration of polarization optical-time-domain reflectometer for monitoring of optical fiber lines

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***Abstract*—Monitoring of optical signal polarization state in optical fiber networks can provide a variety of information for infrastructure owners. There is a rather limited choice of available techniques for monitoring the change in a polarization state of an optical signal over the transmission line. Mostly, as the typical measurement, the total optical line polarization mode dispersion (PMD) is determined, or the instantaneous change in polarization state at the line input or output is measured. But that does not allow determining the location and cause of sudden polarization changes in an optical fiber. The authors propose a polarization monitoring technique using a traditional commercially-used optical time-domain reflectometer (OTDR) with additional circuitry to generate polarization-dependent measurement traces. Such a technique can potentially be used for continuously tracking a physical impact on an optical fiber link.**

Keywords — polarization monitoring, polarization optical time-domain reflectometer (POTDR).

I. INTRODUCTION

In general, optical pulses propagating through an optical fiber do not preserve the state of polarization (SOP) due to its birefringence. Despite this being a well-known phenomenon, it is still one of the data transmission throughput limiting factors for single-mode optical fibers [1, 2]. These random changes in polarization cause the polarization mode dispersion (PMD), which can be observed as a delay-time difference between the orthogonally polarized components of an optical signal. The most of optical components - splitters, filters, attenuators, isolators, etc. – also have the polarization-dependent loss (PDL) parameter. On the other hand, light polarization property is used in different applications. For example, signal multiplexing known as polarization-division multiplexing (PDM).

Polarization optical time-domain reflectometry (POTDR) has multiple advantages over other polarization monitoring techniques. It is relatively simple, fast response, single-ended fault location measurement, long-distance monitoring, etc. The most straightforward realization of POTDR is based on the use of a traditional optical time domain reflectometer (OTDR) and additional polarization-sensitive optical circuitry. So far, different variations of this technique have been described in relation to optical fiber PMD measurements [2 - 5]. However, the POTDR method also has the potential to be used for fiber-based sensor solutions [6, 7]. Change in temperature, external vibrations, and different mechanical influences affect an optical fiber birefringence that results in change of light polarisation. Accordingly, an optical fiber cable acts as a sensor and have the potential for various security and monitoring-related applications.

In this paper authors present results of excessive external deformation detection using traditional OTDR and an additional polarizer connected at the input/output port of the OTDR. The paper is organized as follows. We first review the principle of the POTDR in section II, considering that changes in polarization state reflect the change of signal amplitude. Section III presents experimental results from two validated single-mode optical fiber length scenarios: 1.6 km and 21.6 km. Finally, section IV concludes this paper.

II. POTDR MEASUREMENT PRINCIPLE

Currently, if PMD exceeds the limit values of the ITU-T recommendations due to excessive external mechanical influence, it is hard to determine the influencing cause or its location. This drawback can be overcomed by applying the proposed high-precision POTDR technique and measured data time-amplitude analysis.

In this research, we constructed the POTDR setup (see Fig. 1) similar to [5], where the authors used it for fiber optical cable PMD measurements. The operating principle of the POTDR setup is based on the analysis of the reflected optical signal amplitude fluctuations depending on the distance of the fiber under test. OTDR generates polarized probe pulses, receives reflected light, processes measurements, and shows distance versus reflective events trace. The output of OTDR is connected to the launch cable (300 m in length) to reduce dead zone impact on OTDR traces. The output of the launch cable is connected to the polarizer using two optical circulators. This configuration separates forward and backward propagating probe pulse paths (shown in Fig. 1 with semi-transparent arrows). Such a configuration reduces optical path loss for forward propagating probe pulse and accordingly increase the measurement range. The common port of the second circulator is connected to the optical fiber under test. Here we use multiple interconnected sections of different length single-mode optical fibers. Connection points are used to simulate external mechanical vibration impact on a fiber link.

The local birefringence of a typical single-mode fiber (SMF) distributes randomly. Therefore, the SOP of the Rayleigh backscattering evolves randomly along the fiber. The SOP of Rayleigh backscattering returning from each position of fiber is fixed until the fiber experiences external mechanical impact [8]. Changes of optical signal`s SOP can be converted into signal`s amplitude or power changes using optical polarizer (see Fig. 2). However, there are several limitations to this technique. This technique is not suited if: (i) reflected signal SOP is orthogonal to the polarizer axis leading to temporary loss of signal; (ii) reflected signal SOP matches polarizer`s axis despite that there has been an external impact on the fiber. A more complex POTDR technique can reduce the negative impact of these exemptions. For example, in [8], the authors have used a multiwavelength laser and three polarizers with orthogonal directions on the Poincaré sphere to detect the change of any SOP in any direction to eliminate the signal fading in POTDR. However, in the case of locating a random outer mechanical influence on an optical cable we don`t expect this aspect to be critical versus more complex optical circuitry.

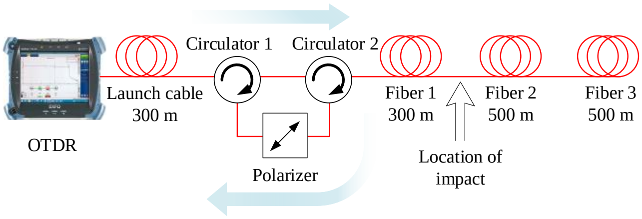

Figure 1. Experimental POTDR measurement setup based on the use of commercial OTDR and optical signal polarizer.

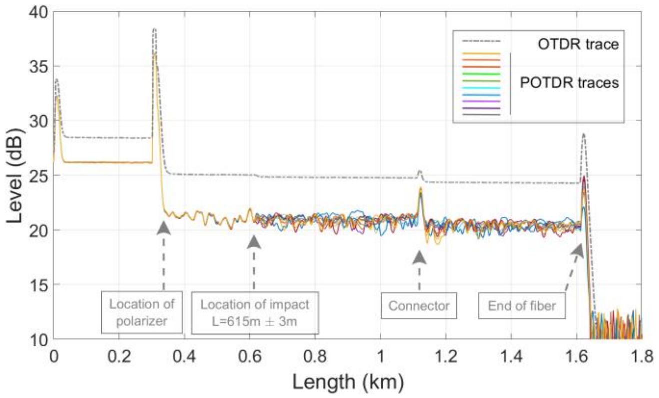

Figure 2. OTDR trace vs. captured POTDR traces. Reflected pulse SOP changes appear as amplitude fluctuations. 10 POTDR traces are shown (each represented by a different color).

A comparison of OTDR traces versus POTDR traces is given in figure 2. Amplitude level difference is due to additional losses in two optical circulators and polarizer in the case of POTDR. The first flat section of the trace is the launch optical cable, followed by a highly reflective event generated by circulators and polarizer. The location of optical components and connectors can be identified in both cases using OTDR and POTDR traces. Amplitude fluctuations in POTDR traces appear only after the polarizer. In this case (Fig. 2) the location of random mechanical vibrations is after 615 m (including the launch cable). As it can be seen after this point, reflections become random. All POTDR traces are measured in the so-called real-time mode. This means that OTDR is not performing averaging of multiple measurements since it completely hides amplitude fluctuations location. The main drawback of the real-time measurement mode is that it significantly reduces OTDR measurement sensitivity (higher noise level). It can be compensated by using longer probe pulses at the expense of lower OTDR resolution. In all experiments, we use 100 ns probe pulses. According to manufacturer specification, this corresponds to a measurement uncertainty of ±3.0 m for the total fiber optical line length of 1.6 km.

III. MEASUREMENT RESULTS

A single POTDR trace does not provide information about the location of an external impact. While a comparison of multiple traces reveals discrepancies in amplitude fluctuations. To demonstrate it, we have compared scenarios from 2 up to 10 POTDR traces at 1550 nm and 1625 nm measurement wavelengths to find the optimum measurement conditions for locating external mechanical vibrations applied to fiber optical cable. In all cases, the maximum amplitude difference Δ (dB) versus cable length is obtained (finding local maximum and minimum points) from the POTDR traces (see Fig. 3). Firstly, in the distance up to 300 m, there are small amplitude fluctuations which are primarily attributable to OTDR`s recever noises. After the polarizer, the intensity of amplitude fluctuations increases. It is related to SOP fluctuations in the optical fiber due to PMD. Performance imperfections of other components also should be considered including polarizer. The location of external impact (chaotic vibrations) is identified as a rapid increase in the reflected signal`s amplitude differences on the captured trace. Different approaches can be used to identify the amplitude increase threshold. This study uses the criteria when the amplitude difference exceeds the maximum background fluctuations threshold. Figure 3 shows the case of two POTDR traces being used, and the distance to the impact location is determined to be 621 m. The actual location of impact is believed to be around 615 m ±3.0 m, according to the location of the nearest connector in the OTDR trace. Since we use OTDR in a real-time regime, a set of measurements is performed by collecting up to 10 POTDR traces. Therefore, we can use local minimum and maximum values versus distance from the whole set of traces (further referred as minimum/maximum search technique). Another approach is accumulating (summation) absolute values of amplitude differences from the entire set of POTDR traces. A sample of this technique is shown in figure 4, where 10 POTDR traces are used to calculate the accumulated amplitude differences. Accordingly, we get higher amplitude difference values (y axis). In the case of 10

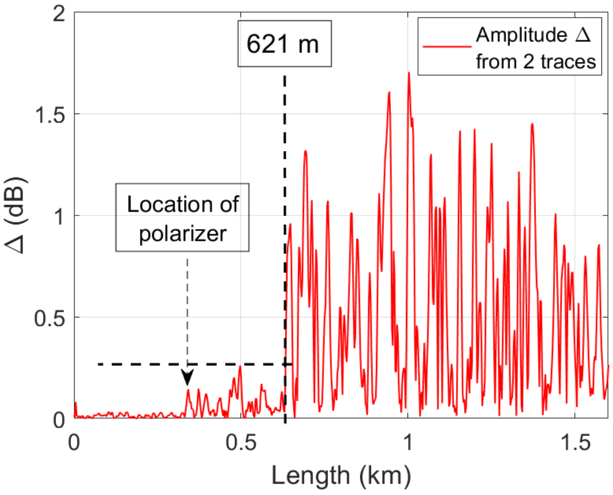

Figure 3. Amplitude difference of 2 real-time POTDR traces at 1550 nm wavelength. Rapid increase in amplitude difference points to external impact location.

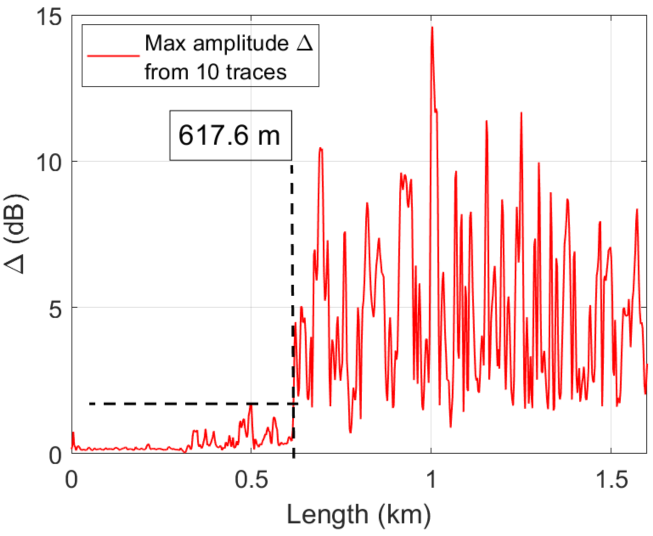

Figure 4. Absolute amplitude difference accumulated from 10 real-time POTDR traces at 1550 nm measurement wavelength.

POTDR traces, the difference Δ is around 10 times higher compared to minimum/maximum search technique (see Δ (dB) axis in Fig. 3 and Fig. 4). This can be very important when considering longer optical cable lines (sample given at the end of this section).

After the impact location, the remaining trace from 0.615 to 1.6 km (see Fig 3) keeps a similar fluctuations pattern because the reflected light also goes through the externally influenced fiber section. Therefore, it is not possible to locate two or more neighbouring events from a single end measurement.

We have also performed accuracy testing of the proposed POTDR measurement technique. Our approach is to take up to 10 live-mode (non-averaged) POTDR traces and compare how the calculated distance to the point of influence depends on the number of measurements used in the analysis stage. In all cases, one measurement is the reference trace when there is no external influence on the fiber link. Other measurements are taken randomly and are not anyhow synchronized with impact force to the fiber under test. Afterward, we find the absolute amplitude difference of POTDR traces in relation to the reference trace. In the case of multiple data sets, the minimum and maximum deviation (minimum/maximum search technique) is used to identify the point where there is an external influence on the optical fiber link. Figure 5 shows determined external impact distances versus the number of POTDR traces (from 2 to 10) used in calculations for two different wavelength probe pulses 1550 nm and 1625 nm. The dashed blue line is the location reference 615 m, and all the obtained results have the same measurement uncertainty of ±3.0 m represented with error bars.

It is found that for both wavelengths (1550 nm and 1625 nm), the measurement accuracy increases with an increasing number of POTDR traces being used in calculations. However, this dependency is stepwise. At 1550 nm, the measured distance to the point of influence in the case of up to 5 measurements accumulation is 621 m, and starting from the 6th measurement, the obtained impact distance decreases to 617.6 m which is a more accurate reading (assuming that the actual external impact location is around 615 m). Results at 1625 nm wavelength show a similar trend. The measured distance in the case of two POTDR traces is 627.7 m, while for 3 to 6 traces it is 622.6 m, and starting from 7 traces it decreases to 620 m. The difference from 1550 nm is that there are two steps (at 3 traces and 7 traces) and on average, measured location distance is by 2 m larger. This could be related to higher optical fiber attenuation at 1625 nm wavelength as well as slightly different properties of polarizer at 1550 and 1625nm wavelength regions. Despite of lower accuracy at 1625 nm wavelength, this wavelength region is beneficial for live monitoring systems that can work in parallel to fiber optical data transmission systems. Starting from 7 POTDR traces, all error bars partially overlap, and an increase in the number of traces being processed does not influence the result. A more detailed study is going to be done considering the mechanical impact amplitude and frequency to find the sensitivity and accuracy thresholds of this measurement technique.

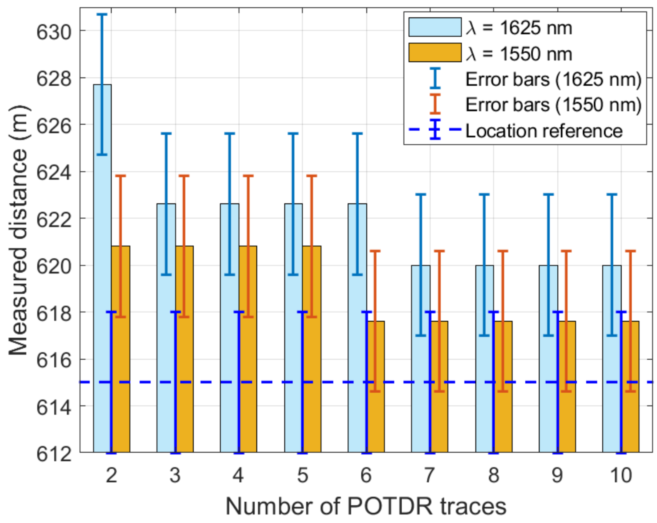

Figure 5. Calculated external impact distance depending on the number of POTDR traces used in the case of 1550 nm and 1625 nm wavelengths. The dashed blue line is the reference distance of 615 m.

Finally, we have tested the maximum distance range capability of POTDR measurement technique using a longer fiber optical cable line. For this reason, an additional 20 km fiber section is added between fiber 2 and fiber 3 (see Fig. 1). In this case the mechanical impact location is located after 21.1 km (before the last 500 m section). Results from these measurements are presented in figure 6. A longer fiber optical cable produces significantly higher attenuation of the reflected signal. This leads to a much higher noise level in POTDR traces. The noise level tends to increase with cable length and this also shows up as a gradual increase in amplitude difference fluctuations (indicated in Fig. 6 as a gray line). The minimum/maximum search technique in this case cannot be used since the noise level is too high and SOP change cannot be identified. Therefore, here we use the accumulation of absolute amplitude differences from all 10 traces to increase the amplitude difference resolution. However, the noisiness still masks the point of impact entirely, and the increase in amplitude difference is hard to identify. Therefore, additional moving window averaging is also applied with a window size of 10 OTDR measurement points (see the red line in Fig. 6). From the averaged results, it is possible to identify a slight amplitude difference increase at the end of the POTDR trace. The applied threshold, in this case, is tilted to follow amplitude fluctuations increase.

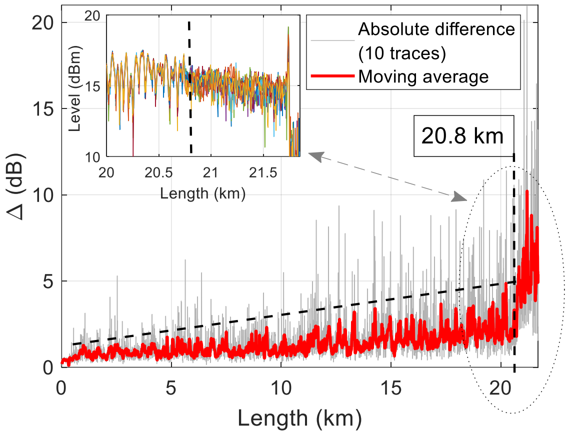

Figure 6. Absolute amplitude difference of 10 POTDR traces at 1550 nm wavelength. Red line is the moving average value for window size of 10 OTDR measurement points. Inset shows the zoomed-in area of 10 overlapping POTDR traces.

The obtained distance is 20.8 km which is approximately 300 m away from the actual impact location (according to connector location in OTDR trace). Of course, this is the worst-case scenario for reflectometry-based measurement, and in practice it can be resolved by performing bi-directional OTDR measurements. The main distance limitation comes from the aspect that POTDR traces are generated without applying the trace averaging function. This significantly reduces dynamic range of the OTDR device and does not reduce the noise generated by the receiver.

IV. CONCLUSIONS

A simple POTDR measurement technique is being developed and experimentally tested for locating external mechanical vibrations on the single-mode fiber optical communication lines. This is obtained by monitoring changes in optical signal SOP versus fiber optical cable distance based on the use of commercial OTDR device and external polarizer circuitry. The developed POTDR model is capable of evaluating both: the reflections coming from optical components and connectors and signal amplitude fluctuations due to light SOP in the fiber optical communication line depending on its distance. It is found that at 1550 nm and 1625 nm wavelength bands, a set of 7 POTDR traces is sufficient to get the distance values that overlap considering the OTDR measurement uncertainty window.

The accuracy of the demonstrated POTDR measurement technique can be incrased via different ways. Our research aims to develop POTDR technology based on time-amplitude analysis of event flows, which has higher timing resolution (2 – 3 ps RMS) and high resolution of nanosecond pulse amplitude measurement (8 – 10 bit), high stability of measurement parameters, and investigate applications of this technology in testing and monitoring of optical communication lines.

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