LATVIAN JOURNAL OF PHYSICS
AND TECHNICAL SCIENCES
2024, N 2

DOI: 10.2478/lpts-2024-0011

ENHANCED-REACH POLARIZATION OPTICAL TIME-DOMAIN REFLECTOMETRY TECHNIQUE FOR FIBRE OPTICAL INFRASTRUCTURE MONITORING

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This interdisciplinary research is focused on constructing and demonstrating enhanced-reach polarization optical time-domain reflectometer (POTDR) for monitoring single-mode fibre optical communication lines. An optical signal state of polarization measurements enables several new possibilities for real-time monitoring solutions in fibre optics. However, there is no commercial equipment available to determine the location in fibre optical cable where the light polarization state changes. The authors present a monitoring technique of an optical signal state of polarization based on reflected signal time-amplitude analysis with improved operation parameters, namely, timing resolution (2 to 3 ps RMS) and amplitude measurement resolution of nanosecond scale pulses (8 to 10 bits) for monitoring of fibre optical communication lines. Additionally, the demonstrated POTDR provides a considerable optical fibre line measurement reach of up to 40 km.

Keywords: *Optical fibres, optical state of polarization, polarization optical time-domain reflectometer (POTDR).*

1. INTRODUCTION

Polarization-related measurements in optical fibre communication lines typically are based on methods that determine only the total polarization mode dispersion (PMD), polarization-dependent loss (PDL) or instantaneous state of polarization (SOP) of optical signal at some specific point. These measurements neither reveal the location or the cause of change in the SOP. Those two aspects are covered in our proposed high-precision time-amplitude analysis method based on time-domain reflectometry. We have tested this technique on localization of outer mechanical impact on fibre causing increased changes in the SOP. However, potentially it can be used to track fibre sections with increased PMD coefficient. This is very essential since PMD is one of the key parameters limiting high-speed signal (>10 Gbps bitrate per data channel) transmission in fibre optical communication systems [1]. Localisation of unusually high SOP changes in the fibre optical network significantly simplifies the detection and elimination of the cause of the problem.

A polarization optical time-domain reflectometer (POTDR) corresponds to a polarization-sensitive optical time-domain reflectometer (OTDR) measurements, which can identify a change in the SOP in a section of the fibre under a test link. In a POTDR setup, a change in the SOP typically is detected as a change of the received signal power, since most of the setups implement an exact SOP as a reference (a change in the SOP from the reference state will cause power penalties). Also, it is essential to mention that by using conventional polarization related measurements, the exact location of the polarization change in an optical fibre line cannot be determined. Instead, it can be detected in an approximate range.

There are different approaches of how to construct a POTDR setup to improve sensitivity, accuracy and measurement range. One of the techniques is to use traditional OTDR and convert it into POTDR using external polarization-sensitive circuitry typically consisting of two 3-port optical circulators and a polarizer as displayed in the measurement setup in Fig. 1 [3], [4], [11]. Accordingly, OTDR trace consists of all reflectivities due to different backscattering mechanisms and additionally also polarization dependent reflected signal amplitude fluctuations, thus identifying changes in the SOP due to specific fibre properties or environmental perturbations. This increases the versatility of the whole monitoring mechanism [3], [4], [11]. POTDR measurements share the same principles as OTDR, including the use of launch cable (typically 300–500 m in length) to reduce a dead zone. Optical circulators are used to separate the transmitted and reflected optical signals. In such measurements, the OTDR must be operated in the real-time mode because averaging of multiple traces hides information about SOP changes. The main disadvantage of real-time mode measurements is the reduced sensitivity of OTDR measurements. As a result, the operating range or reach of this type of POTDR solution is limited to around 20 km [3], [4].

Current research works demonstrate POTDR solutions for PMD measurements in fibre optical communication lines [4]–[6] and distributed fibre optical sensor solutions for strain and vibration monitoring [7]–[13]. POTDR can be used not only in transmission line monitoring but also for a fibre as a sensor system for object perimeter, infrastructure construction, oil and gas pipeline monitoring, etc.

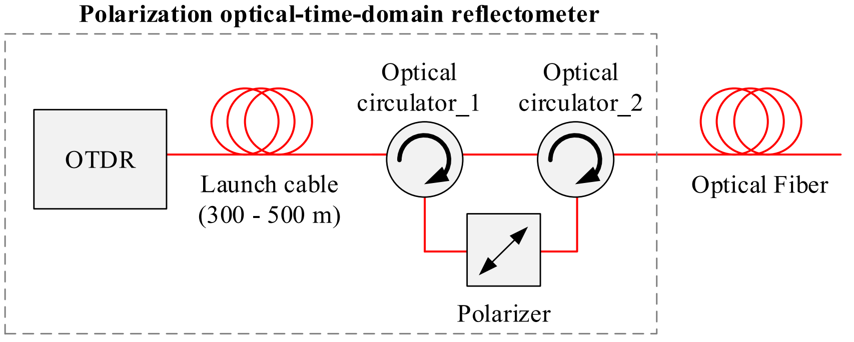

Fig. 1. POTDR measurement setup based on traditional OTDR.

The typical realization of the POTDR measurement setup as demonstrated in [7], [10] is shown in Fig. 2. The pulsed laser source generates POTDR probe pulses. Pulse width and amplitude are adjusted depending on the length of the monitored optical fibre line and its attenuation. The output of the pulsed laser is connected to optical polarizer_1 to attain completely polarized probe pulses. The output of polarizer_1 is connected to the input of the optical circulator, which is used to separate forward travelling and backward reflected optical flows. The common port of the circulator is connected to the launch cable, which, in turn, is connected to the fibre under test. The signal reflected from the optical fibre communication line passes the optical circulator and is therefore directed to Polarizer_2, which converts the changes in the SOP into changes of power. An avalanche photodiode (APD) converts the optical signal into an electrical signal, fed to the signal processor (SP) for further processing.

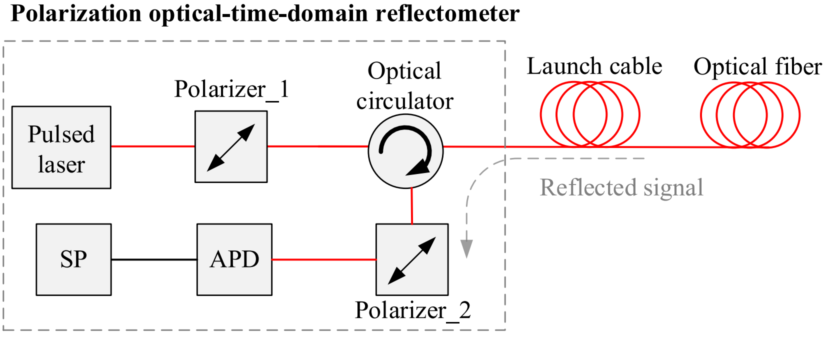

Fig. 2. Typical POTDR block diagram.

Polarization-based effects are stochastic and sensitive to environmental changes (such as temperature, external mechanical impact or even optical fibre vibrations) [1], [3]. Current scientific works [3], [4], [7] report that the operating range of the known POTDR solutions is limited to around 20 km, which is a significant drawback for these measurements. Therefore, it is necessary to develop extended-reach high-accuracy POTDR solutions.

2. POTDR MONITORING SYSTEM

In this research, we demonstrate the setup of an extended reach (up to 40 km) high-accuracy real-time POTDR monitoring system solution (see Fig. 3). Directly-modulated distributed-feedback (DFB) laser is used as the POTDR probe pulse source. The electrical drive signal is generated by a probe pulse generator and fed to the DFB laser RF input. Probe pulse parameters were adjusted depending on the fibre under test length. The typical amplitude (Vpp), frequency (kHz) and pulse width (%) values for 40 km long fibre testing are the following: 2.6 Vpp, 1 kHz, 0.4 %. Since the modulated DFB laser has low output power, an erbium-doped fibre amplifier (EDFA) is used to amplify optical signal up to 4 dBm before launching in the fibre. The use of an optical amplifier increases the power budget and gives the extended measurement range. This approach has not been used widely so far in relation to POTDRs. In [10], it was demonstrated that EDFA extended the reach up to 30 km. Here, we use EDFA in the fixed pump current mode to avoid undesirable gain fluctuations.

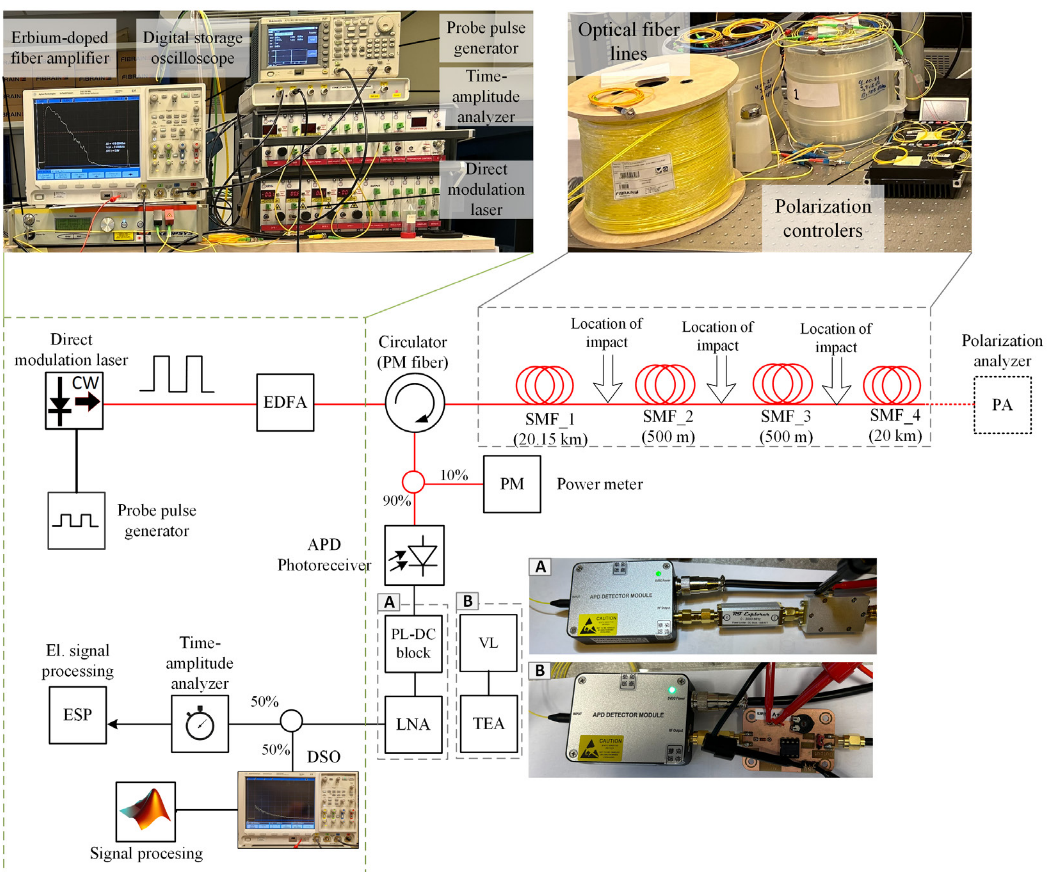

Fig. 3. The developed POTDR measurement setup.

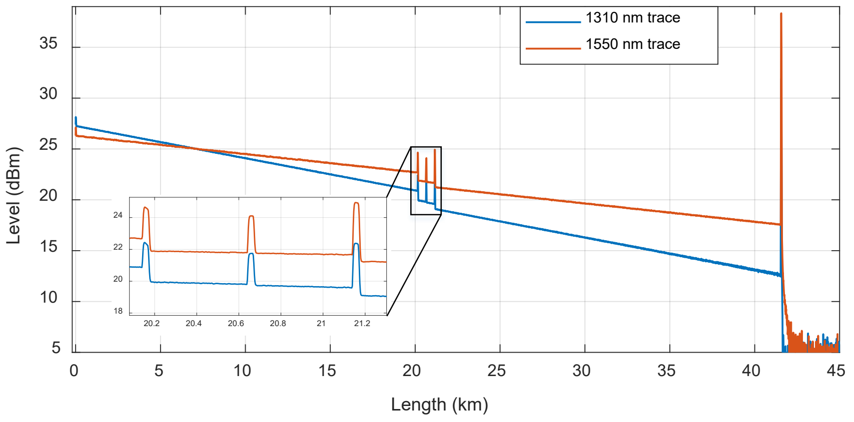

Fig. 4. OTDR trace of the optical fibre under the test line.

As one can see in Fig. 3, the output of the EDFA is connected to a 3-port polarization-maintaining (PM) optical circulator (OC) with an integrated optical polarizer. This type of circulator reduces the need for two optical polarizers (typically being an essential part of POTDR setup (see Fig. 2). This reduces the number of components in the measurement scheme and lowers insertion loss in the probe pulse path. The common port of OC is connected to the optical fibre under the test line consisting of 4 single-mode fibre spans: 20.15 km, 0.5 km, 0.5 km, and 20 km forming the total line length of 41.15 km. Such a number and length of fibre spans are chosen to demonstrate the operation and resolution of the proposed POTDR solution. The measured OTDR trace of this optical line is shown in Fig. 4. The total estimated path loss is 8.77 dB at a reference wavelength of 1550 nm.

Interconnections between fibre spans are used as known locations where the external impact on the optical line can be applied. Here, we consider the case where a mechanical force is applied to the fibre (random vibrations, bending, and torsion). During the initial phase of tests, a polarimeter was used to evaluate the magnitude and nature of SOP changes in the case of external mechanical impact. For comparison, fibre at idle state was also tested to see the PMD-caused test signal SOP variations.

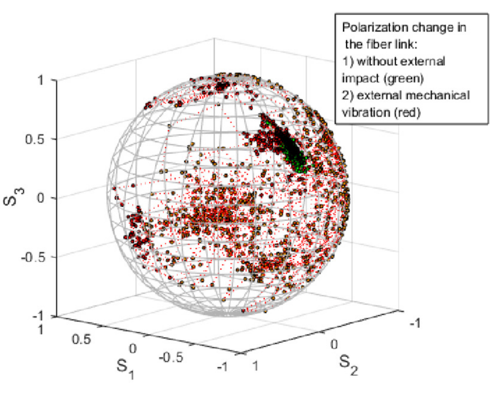

Fig. 5. Poincare sphere with SOP changes in the fibre link:
1) without an external impact (green points); 2) external mechanical vibration applied (red points).

Poincare sphere is used to represent these measurements (see Fig. 5) with and without external impact on optical fibre. Since the fibre vibration/bending causes rather uniform coverage of the Poincare sphere, it was decided to emulate this kind of impact using two motorized polarization controllers (MPCs). Series connection of two quarter waveplate polarizers gives more random SOPs. Figure 6 shows Poincare sphere when MPCs are used. For comparison, green dots represent the case without an external impact.

As one can see in Fig. 3, the reflected optical signal from the optical fibre communication line is transmitted to a non-symmetrical optical power splitter (10/90 %), where the 10 % output port is connected to the optical power meter and the 90 % output port to an APD photodiode with photoreceiver RF bandwidth of 200 MHz (3 dB bandwidth). The optical power meter is only used to monitor the optical power level at the input of the APD.

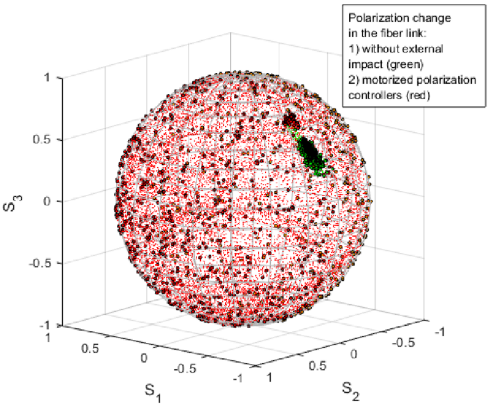

Fig. 6. Poincare sphere with SOP changes in the fibre link:
1) without an external impact (green points); 2) MPC (red points).

The low level optical signal sensitivity of APDs is -47 dBm. Photoreceiver's output electrical signal is, first of all, fed into the amplitude limiter circuitry. Amplitude limiter reduces electrical signal amplifier saturation due to Fresnel reflections from connectors, being much higher than the Rayleigh backscattering. Two electrical signal processing circuit versions are considered in our experimental POTDR measurement setup for signal amplitude limitation and signal amplification:

A. the research team developed voltage limiter (VL) with an adjustable limiting threshold (series positive limiter with bias) and a tunable electrical amplifier (TEA);
B. commercially available power limiter with the direct current block (PL-DC) and fixed 30 dB low noise amplifier (LNA).

The series-positive limiter circuit with bias voltage is presented in Fig. 7. The function of this electronic circuit is to limit the amplitude of an input signal *Vin* considering DC bias offset *VBias*. While the input voltage does not exceed the *VBias*, the diode *D1* will conduct. When the positive *Vin* exceeds *VBias*, the diode becomes reverse biased and limits the positive voltage of the output signal to *VBias*. The reason is that the cathode is positive with respect to the anode, diode *D1* is reverse-biased and will not conduct. The diode *D1* will remain reverse biased until it becomes lower than *VBias*.

The output of the voltage limiter is connected to the operational amplifier (OP-AMP) in voltage repeater mode, also known as a buffer. The buffer divides different stages of the circuit by preventing the input impedance of one stage from loading the output impedance of prior stage, which causes undesirable loss of signal transfer.

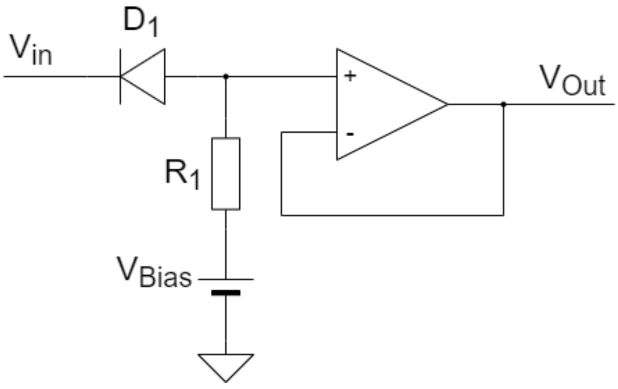

Fig. 7. Series-positive limiter circuit with bias voltage.
R_1 = 1 kΩ, D_1 is 1n4148 silicon diode, LT1013 operational amplifier.

The amplified electrical signal is transmitted to the electrical power splitter (50/50 %), where the signal power is split to the digital storage oscilloscope (DSO) and high-precision time-amplitude analyser (timing resolution: 2 to 3 ps RMS), amplitude measurement resolution of nanosecond pulses: 8 to 10 bit). However, time-amplitude measurement is applicable for time interval measurement to get the overall length of fibre cable line (reflections from connectors are high enough to be detected by the timer receiver). Measured time interval is used for digital storage oscilloscope (DSO) measurement data calibration to achieve higher accuracy for location detection of the external impact on the optical line. Simultaneous amplitude measurement enables continuous monitoring of fibre line to detect changes in the fibre under test. Changes in the reflected signal amplitude from the far end of the cable (last connector) can be used as triggering event to start POTDR trace accumulation for further post-processing. MATLAB software is used to process and visualize the signal received from DSO and the time-amplitude analyser.

3. MEASUREMENT RESULTS

The results obtained by constructed POTDR measurement setup are shown in Figs. 8–12. A single POTDR measurement trace is not enough to locate the external impact from the SOP change since fibre under test does not maintain polarization due to internal birefringence. In fact, multiple traces are needed since the change in amplitude fluctuations can be very tiny depending on the distance and the scale of external impact (here represented using MPCs) as can be seen in Fig. 8. The external impact typically creates a tiny change in signal amplitude (millivolts), so the absolute amplitude difference is used for comparison. The data processing involves the following steps:

- calculating the average trace amplitude from all the accumulated POTDR traces;
- finding the absolute amplitude difference (ΔV) of each POTDR trace versus average value;
- accumulation of all ΔV results versus fiber distance and performing moving average filtering (window size 10 points) to reduce data noisiness.

Accumulation of several tenths of traces gives a notable change in the reflected signal amplitude, which reveals the location of external impact. This is studied in more detail by considering a different number of traces and its impact on event location accuracy in the post-processed POTDR trace.

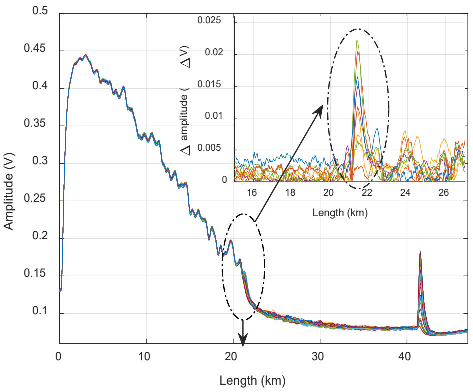

Fig. 8. Delta amplitude calculation and evaluation.

The total absolute amplitude difference accumulated from 5 to 50 real-time POTDR measurement traces at 1550 nm measurement wavelength is considered here (see Fig. 9). As it can be seen, the higher the number of accumulated traces, the more explicit the location of impact. Trace accumulation also raises the total voltage level, thus suppressing the background noise (mainly the EDFA amplified spontaneous emissions and photoreceiver noise) as well as PMD caused power fluctuations. We propose the use of 50 traces; however, finding the optimum number of traces remains a task of further research. The rest of the results (Figs. 10–12) are attained using 50 POTDR trace accumulation.

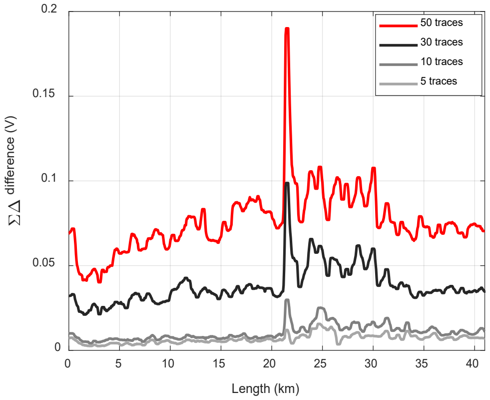

Fig. 9. The number of accumulated POTDR traces versus the absolute amplitude difference in volts.

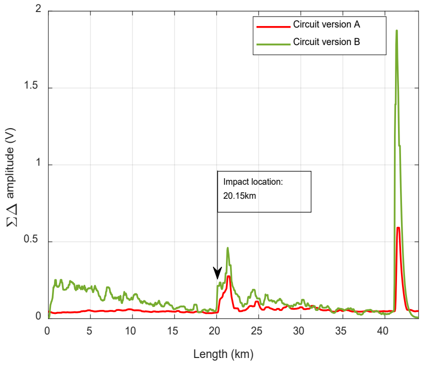

Fig. 10. The accumulated absolute amplitude difference versus fibre length when MPCs are located after the SMF_1 line in the case of electric signal circuitry A and B.

Figures 10 to 12 show results obtained by two electrical signal circuit solutions, where circuit version A uses PL-DC, but B uses AM with an adjustable limiting threshold for amplitude limitation and signal amplification. Figure 10 shows the case when the distance to the location of 2 MPCs is determined to be 20.15 km. Figures 11 and 12 are the cases when the distance to the location of 2 MPCs is determined to be 20.65 km and 21.15 km. All the identified locations correspond to the fibre under the test line with two 500 m spools after 20.15 km.

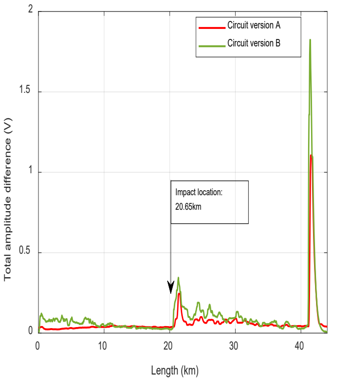

Fig. 11. The accumulated absolute amplitude difference versus fibre length when MPCs are located after the SMF_2 line in the case of electric signal circuitry A and B.

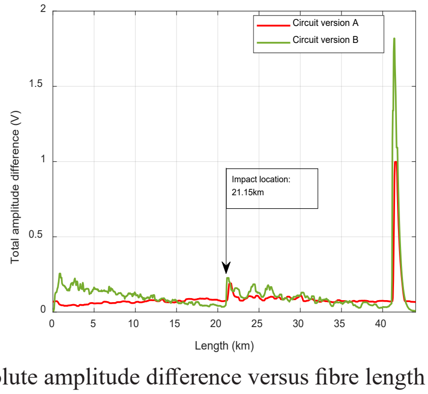

Fig. 12. The accumulated absolute amplitude difference versus fibre length when MPCs are located after the SMF_3 line in the case of electric signal circuitry A and B.

As it can be seen in Figs. 10–12, in all cases it is possible to detect accurately the location of external impact from 2 MPCs using both (A and B) circuit versions. The combination of PL-DC and LNA gives less noisy trace, thus giving more noticeable location of external impact. On the other hand, the VL – TEA version produces higher fluctuations amplitude and more distinct front of the event. As it has been mentioned previously, in all cases the total length of fibre under test (41.38 km) has been determined using time-amplitude analyser with timing resolution of 2 to 3 ps RMS. The total length is afterwards used as the reference for DSO measurements.

4. CONCLUSIONS

In this research, the enhanced-reach POTDR technique was experimentally developed for real-time monitoring of the fibre optical infrastructure. The research presented a monitoring technique of an optical signal state of polarization based on reflected signal time-amplitude analysis with improved operation parameters, namely, timing resolution (2 to 3 ps RMS) and amplitude measurement resolution of nanosecond scale pulses (8 to 10 bits) for monitoring of fibre optical communication lines. This technique can detect the location of external impacts (mechanical vibrations, strain, etc.) on the optical fibre lines. The demonstrated POTDR provides a considerable optical fibre line measurement reach of up to 40 km.

ACKNOWLEDGEMENTS

The research has been funded by the European Regional Development Fund (ERDF) project "Technology for High-Precision Time-Amplitude Analysis of Event Flow (TIME-AMP)", No. 1.1.1.1/20/A/076.

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