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SINGLE-PHOTON SYSTEMS APPLICATION NOTE

Single-photon OTDR

The extreme performance of the ID230 single-photon detector (DCR<25Hz, <80ps timing) allows scientists and engineers to characterize optical fibers and networks with an accuracy unachievable by traditional means. Defects are visible on the centimeter scale, fiber spans of 200 km can be characterized, as well as multimode devices and connectors.

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Introduction

Optical fibers are at the forefront of several advanced technologies, such as fast communication networks, powerful lasers and accurate sensors. As scientists and engineers push the limits of these technologies, accurate and innovative methods for fiber characterization are required. Single-photon detectors offer a unique advantage as they combine ultimate sensitivity with excellent timing accuracy (<100ps), resulting in high tolerance to loss and high spatial resolution (1 cm).

In this application note, we will give an overview of how these technologies may be used to build a custom optical time-domain reflectometers from benchtop instruments. Adapting the OTDR system to the user's desired measurement, as well as an appropriate choice of detector, will result in significantly higher performance than what can be obtained with commercial OTDRs.

Setup

A typical OTDR setup is shown in Figure 1. A pulsed laser (ID300) generates a short light pulse (<300ps) which is injected into the fiber under test (FUT) through a 50:50 beamsplitter. This beamsplitter directs 50% of any backscattered light towards a fast single-photon detector (ID230). The time delay between the laser pulse and the photon return is recorded using an ID900 time-controller (TDC function), and displayed as a histogram on a computer. A pulse generator (e.g. SRS DG535) can be used to adapt the experiments' repetition rate to the length of the FUT, by ensuring than only one pulse propagates down the fiber at any one time.

For the purpose of this application note, the FUT consists of two multimode (MMF-62.5µm) fibers, the first 2m long, and the second 1m long. The coupler and detector used were also MMF-62.5.

This setup illustrates some of the challenges encountered due to the high reflectivity of MMF connectors, as well as the characterization of short fiber assemblies.

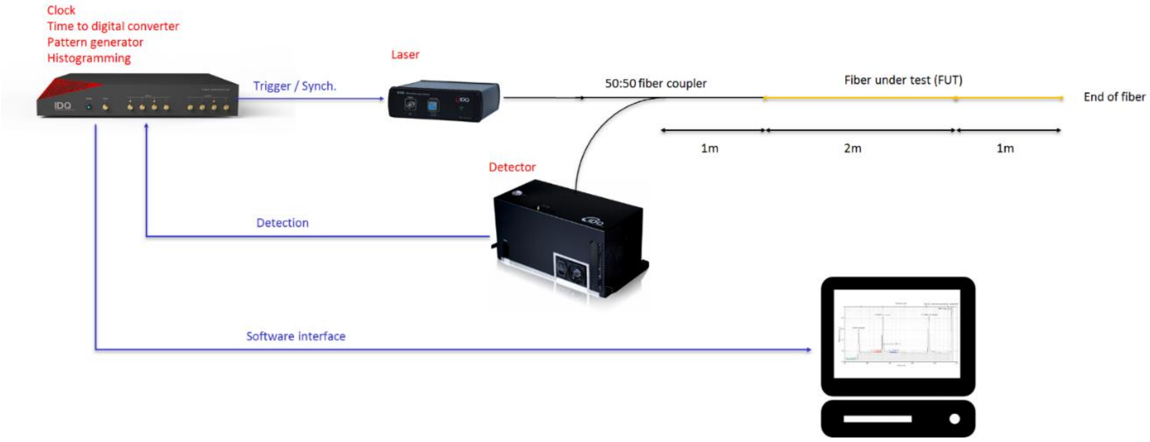

Figure 1 typical OTDR setup: a laser pulse is injected into the fiber under test (FUT) via a 50:50 fiber coupler (beamsplitter). Fiber defects will result in strong reflections. The beamsplitter directs 50% of light coming back from the fiber towards a single-photon detector. The time interval between the pulse generation and return is captured by a time-to-digital converter to 81ps accuracy, corresponding to ~1cm of fiber length. Losses within the fiber can be evaluated by looking at the Rayleigh backscatter.

Measurement

The laser repetition rate was set to 100 kHz, and best performance from the ID230 detector was achieved with the highest efficiency setting (25%). The dead-time on the ID230 was set to 10µs, which significantly reduces afterpulsing. The average light power injected in the system was 6.69nW, this is high and results in the strong reflection from the fiber end saturating the ID230 (always resulting in a click). At this high power, however, Rayleigh backscatter is well beyond the detector's noise background, which allows for an estimation of connector losses.

To accurately measure the amplitude of the reflected light at the peaks, a complementary measurement, performed with lower laser power, and that does not saturate the detector, would be required.

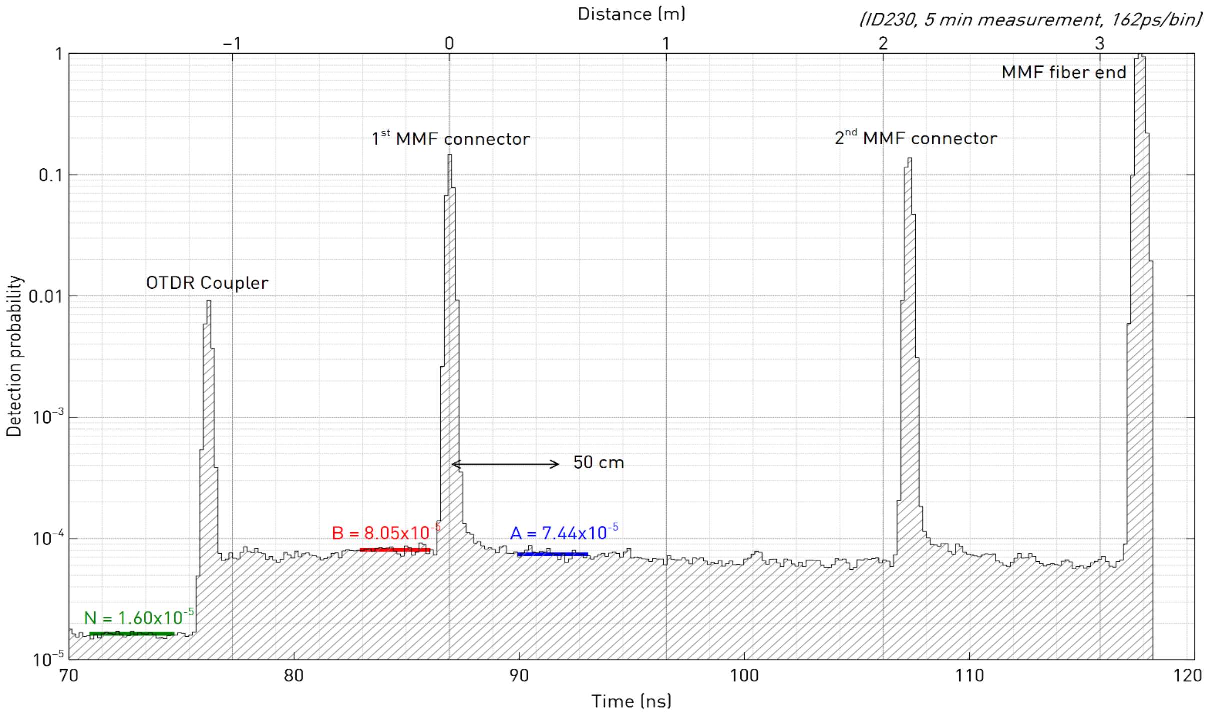

Figure 2: OTDR trace taken with the setup shown in Fig1. This histogram is the result of a 5min integration time. The OTDR 50:50 couple is visible as the first beam, the two subsequent peaks are reflections from the OTDR connector and fiber connector (C1 and C2 in Fig1), while the last peak is the reflection from the fiber end. This peak is saturated and would be 25dB higher if non-saturated. The background after the OTDR coupler is due to Rayleigh backscatter, while the background before the coupler is due to detector noise.

Figure 2 shows the results of a 5-minute measurement. In particular, this plot is the histogram of the probability of the detector clicking at specific time after the laser pulse was injected in the FUT.

The y-axis is logarithmic, so that strong reflections from MMF connectors can be observed at the same time as the Rayleigh backscatter (30dB to 40dB beneath).

The x-axis is plotted both in terms of time-delay (bottom) and distance (top). The distance d in metres corresponds to the time t divided by half the speed of light in the fiber: $d = t/9.63$ (with t in ns).

As the OTDR is a "there-and-back" system, there is a factor of 2x both in the measured time delays and attenuations.

Results

Looking at the OTDR trace qualitatively, the fiber structure is readily observed: at short distances, before the laser light is injected into the fiber, all counts arise solely from noise[1]. The OTDR fiber coupler, 1m before the FUT gives a small reflection peak, 20 dB above the Rayleigh backscatter. The next peak, at d=0 (C1 "1st MMF connector"), is due to the connection between the OTDR output and the FUT. This peak is > 30dB above the Backscatter, and 40dB above the measurement noise floor (N). The FWHM is of 300ps, dominated by the laser pulse, and the peak present a small tail (2ns) at -30dB.

A second connector (C2 "2nd MMF connector") gives another reflection at a 2m distance, before the end of the fiber, which generates a very strong reflection. Note that the very strong reflection coming from the fiber end might contain several photons, and always trigger the detector, "saturating" it. No detections are measured after this point, due to the fact that light does not come back, but also because the detector always enters its "dead-time". A measurement at lower power that does not saturate the detector shows that the fiber end peak is 25dB above the 1st and 2nd connector peaks.

If strong reflections are present in the system, a gated detector, such as the ID210 must be used, so that it can be turned off during the strong reflections to prevent saturation and dead-time.

In some instances, it is also possible to quantitatively measure connector loss. This is done by obtaining a value for the backscatter before and after the connector (B and A respectively) and the noise floor N.

Characterizing this for C1 we obtain: $B = 8.05 \times 10^{-5}, A = 7.44 \times 10^{-5}, N = 1.60 \times 10^{-5}$ per 162 ps bin. These results were obtained by averaging over 40cm of fiber, and ensuring that the "After" measurement does not include the "tail" of the connector's reflection.

Loss is then calculated as $L = \sqrt{\frac{A-N}{B-N}}$, where the square-root accounts for the fact that the loss happens twice in the OTDR, as it is a "there-and-back" measurement. In decibels, $L_{dB} = 10 \log_{10} L$.

The uncertainty in L can be calculated starting from the uncertainties in A, B: σ_A, σ_B.

$$\sigma_L = \frac{L}{2}\sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2}$$

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[1] The ID230 detector is very low noise (<25 cps, corresponding to a noise probability of 4×10^{-9} per 162 ps bin. In this measurement, noise is dominated by environment noise (e.g. room lighting) and afterpulsing. Nevertheless, in this setup, noise is negligible with respect to the signal strength.

In decibels, $\sigma_{LdB} = \left|\frac{10\sigma_L}{L\ln 10}\right|$.

For this test, it was possible to compare the results obtained with the OTDR with actual loss measured with a powermeter (PM). The amount of light was measured at the fiber end and at C1 to be 6.34 nW and 6.69 nW respectively. Results are shown in the table below.

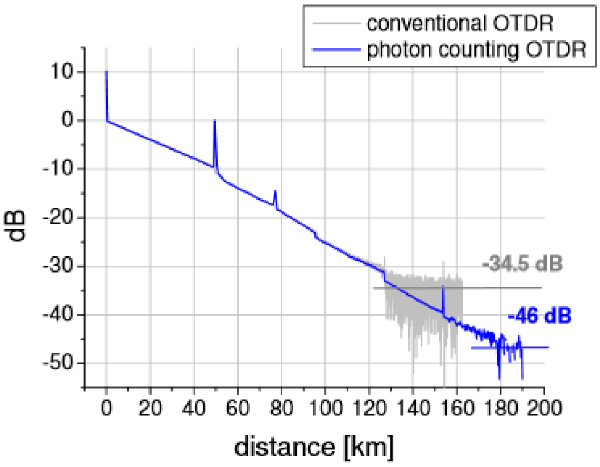

Figure 3 : long-range single-photon OTDR measurement, as reported in [1].

	Measurement (P/10^5)	Uncertainty	PM measurement (nW)
Mean det prob 1 (A)	8.05	0.09	6.34
Mean det prob 2 (B)	7.44	0.08	6.69
Background (N)	1.6		
Attenuation	0.952	0.02	0.948
Attenuation (dB)	-0.22	0.09	-0.23

The above measurement shows that loss can be measured quantitatively even for connectors between short fibers (<1m in length). The very high sensitivity of photon counters also enables long distance OTDR measurements (up to 200km), as described in detail in the scientific publication [1], from which Figure 3 is borrowed.

Which detector to choose?

The choice of detector will influence the OTDR measurement. In cases where strong reflections are present, the "free-gating" capability of the ID210 can be used to turn the detector off during the brief reflection time. On the other hand, if very long distance measurements are to be made, an ultralow noise detector, such as the ID230 will be suitable. The ID230 also offers the highest timing accuracy, with effective sub-centimeter resolution.

The ID281 superconducting detector offers extreme performance, in terms of noise, speed, repetition rate and timing resolution but is only available for single-mode fiber. The ID220 works sufficiently well in many situations and can easily be mounted as an OEM component for a complete system.

	ID230	**ID220**	**ID210**	**ID281**
Coupling	SM or MM fiber up to 100 µm diameter	SM or MM fiber up to 100 µm diameter	SM or MM fiber up to 100 µm diameter	SM / MM fiber
Operation	Free-running	Free-running	Gated	Free-running
Detection efficiency	>25%	>20%	>25%	>80%
Dark count rate	<25 /s	<1000 /s	<10'000 /s	100 /s down to < 1/s (on request)
Maximum count rate	500 kHz	1 MHz	5 MHz	15 MHz
Timing resolution	<80 ps	160 ps	250 ps	50 ps down to 30 ps (on request)

References

[1] http://arxiv.org/pdf/1001.0694.pdf