Long-distance OTDR using photon counting and large detection gates at telecom wavelength

François Scholder*, Jean-Daniel Gautier, Mark Wegmüller, Nicolas Gisin

GAP-Optique, University of Geneva, Ecole-de-Medecine 20, 1211 Geneva 4, Switzerland

Received 1 May 2002; received in revised form 16 September 2002; accepted 28 September 2002

Abstract

Photon-counting OTDRs are typically used in a mode with spatial resolutions in the centimeter range. Here we demonstrate that their sensitivity and dynamic range can be enlarged using lower resolutions. A 44-dB dynamic range was experimentally obtained at a wavelength of 1550 nm. This represents a 4-dB increase compared to state-of-the-art long-haul classical OTDRs having the same spatial resolution, and could even be extended to 6.5 dB when using a source with +13-dBm peak power. Furthermore we demonstrate an original solution to suppress perturbing dead-zones.

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Photon counting; Optical time-domain reflectometry

1. Introduction

Optical time-domain reflectometry (OTDR) is the most widely used fiber-test technique. It can measure fibers of lengths up to about 200 km. The corresponding dynamic range is limited by the detection sensitivity. The latter can be somewhat increased by using smaller bandwidth detectors [1], which has the disadvantage to reduce the spatial resolution. State-of-the-art conventional OTDRs have a dynamic range of up to ~40 dB with spatial resolutions in the kilometer range [2]. On the other hand, an OTDR based on photon counting (v-OTDR) has spatial resolutions that can be as small as a few centimeters, independently of the detection bandwidth [1,3]. However, as for conventional OTDRs, the sensitivity of a v-OTDR is shown to depend on the spatial resolution. If we reduce this resolution from the centimeter range to the hectometer range, we can drastically increase the detection sensitivity.

The paper is organized as follows. In Section 2, after some general remarks on photon counting, we calculate how to extract the net signal from the measurement. Using this signal correction, the noise equivalent power (NEP) is calculated, allowing to predict the dynamic range of our v-OTDR. This result is experimentally confirmed in Section 3. Then in Section 4 we demonstrate a solution to suppress perturbing dead-zones, which
can arise from photon counting, and finally conclude the paper in Section 5.

2. Dynamic range

To detect single photons at a telecom wavelength of 1.55 μm, we are using an InGaAs avalanche photodiode (APD), cooled by Peltier elements. This APD is used in the so-called “gated Geiger mode”, with the detector being active only during a given time slot (“gate”) [4,5]. During this period, a single photon falling on the APD can trigger an avalanche, which is then detected by discriminator electronics. This process is then repeated many times, and from the number of counts for a certain position of the gate, the reflectivity at the corresponding location in the fiber is obtained. Obviously, in order to extract the real signal, the detector has to be operated below saturation. In the present experiments, the probability for a count within one gate has to be smaller than 40% in order to remain in the linear regime. On the other hand, it has to be large enough to be distinguishable from the noise. In order to go beyond these two restrictions, one can use an appropriate data correction, which is now derived.

First, the probability to have a count due to the signal is given by

\[ p_s = 1 - e^{-\eta \mu}, \]

where we have exploited the fact that the number of photons per gate follows a Poisson distribution with a mean number of photons per gate \( \mu \), and that each photon has the same probability \( \eta \) to be detected. If we define \( p_n \) as the probability for a noise count within one gate, the overall probability (signal + noise) to have a count in a gate is given by the complementary probability to have neither a noise nor a signal count

\[ p = 1 - (1 - p_n) \cdot e^{-\eta \mu}. \]

Solving this equation for \( \mu \), the mean number of photons per gate, we have

\[ \mu = \frac{1}{\eta} \cdot \ln \left( \frac{1 - p_n}{1 - p} \right). \]

Hence – knowing the noise count probability \( p_n \) – this equation will be used to obtain the net signal power from the corresponding overall count probability \( p \), and thus correct our v-OTDR trace (cf. Section 3). This correction is especially useful when \( p \) is close either to saturation or to the noise level.

To evaluate the dynamic range, we first calculate the noise equivalent power (NEP) of the detector. Due to the specifics of the gated photon-counting technique the total number of noise counts \( N_n \) for a given measurement time \( \Delta t \) follows a binomial statistic \( b(N, p_n) \), where \( N \) is the number of gates (given by the gate frequency \( f \) times \( \Delta t \)) and \( p_n = N_n/N \). After having used Eq. (3) to correct the signal, the mean noise level \( \bar{N}_n \) goes to zero and thus towards minus infinity on the typically employed logarithmic dB-scale. Therefore we will use as NEP the \( \bar{N}_n + \sigma_n \) level, where \( \sigma_n \) is the noise mean fluctuation (i.e., the standard deviation of \( N_n \)). According to the binomial statistic, this fluctuation is given by

\[ \sigma_n = \sqrt{N \cdot p_n \cdot (1 - p_n)}. \]

Theory and measurements both show that for small \( p_n \) (i.e., \( p_n < 10\% \)) the noise probability is proportional to the gate duration \( \tau \) (i.e., \( p_n = \pi_n \cdot \tau \)). The \( \pi_n \) factor was measured to be 30 kHz for the APD used in the present experiments, at a temperature of –57 °C. Note that for a proper signal detection, \( p_n \) has to remain small. This gives a maximum gate duration – e.g. for \( p_n < 10\% \), \( \tau < 3.33 \mu s \). As the spatial resolution is given by a convolution of the gate duration and laser pulse duration, a maximum gate duration leads to a corresponding limit in the spatial resolution – 333 m for the previous example.

According to Eqs. (3) and (4), the NEP level is equivalent to a mean number of photons per gate

\[ \mu_{\text{NEP}} = \frac{1}{\eta} \cdot \ln \left( \frac{1 - p_n}{1 - (N_n + \sigma_n)/N} \right) \]

\[ = \frac{1}{\eta} \cdot \ln \left( 1 + \frac{\sqrt{p_n(1 - p_n)}/N}{1 - p_n - \sqrt{p_n(1 - p_n)/N}} \right) \]

\[ \approx \frac{1}{\eta} \cdot \ln \left( 1 + \sqrt{p_n/N} \right) \]

\[ \approx \frac{1}{\eta} \cdot \sqrt{p_n/N}, \quad \text{if} \ p_n \text{ is small}. \]
Thus, using Eq. (5), the NEP is given by

\[
\text{NEP} = \frac{\hbar c / \lambda}{\tau} \approx \frac{1}{\eta} \sqrt{\frac{\pi n \tau}{f \Delta t}} \cdot \frac{hc / \lambda}{\tau}
\]

\[
= \frac{hc}{\eta \lambda} \sqrt{\frac{\pi n}{f \cdot \Delta t \cdot \tau}}
\]

This simple model shows that the NEP is inversely proportional to the square root of the gate duration \(\tau\) and the total measurement time \(\Delta t\). Therefore measuring for a longer time or with smaller spatial resolution (i.e., a larger gate duration) has the same effect on the sensitivity of the \(\nu\)-OTDR. This behavior is illustrated in Fig. 1. For long measurement times, the NEP – and hence the minimum detectable power – becomes very small indeed. The experimental data are seen to be in good agreement with the theory.

The dynamic range is usually defined as the difference between the initial Rayleigh backscattering (i.e., at the beginning of the fiber) – for a laser source with a pulse length of 10 \(\mu\)s [2] – and the noise level after a 3-min measurement time [1,2]. If using a laser source with a peak power of +8 dBm and 10-\(\mu\)s-long pulses, the Rayleigh backscattering power at the input would be -31 dBm for the Rayleigh backscattering coefficient of -72 dB/m of the fibers used in our experiment. From Eq. (6), a NEP of -121 dBm is obtained for 1-\(\mu\)s-long detection gates, a 3-min measurement time, a detection efficiency of 10\%, and a gate frequency of 400 Hz (allowing to measure distances up to 250 km). Thus the (one-way) dynamic range that could be obtained using our \(\nu\)-OTDR can be estimated to 45 dB, whereas for the same conditions, classical state-of-the-art OTDRs reach 40 dB [2]. Note that for a laser peak power of +13 dBm, we could even increase the dynamic range up to 47.5 dB.

3. Experimental \(\nu\)-OTDR trace

To illustrate the results found in the previous section, we performed a \(\nu\)-OTDR measurement of three FC/PC-connected standard telecom fibers of 10.4-, 16.4-, and 25.3-km length, respectively, using the scheme shown in Fig. 2. A 28-dB loss was added between the first two fibers using an optical attenuator (which simulates a ~140-km-long fiber). For the measurements, 10-\(\mu\)s-long laser pulses, detection gates of \(\tau = 1\ \mu\)s, and a detection efficiency \(\eta = 10\%\) were used. We further employed a gating frequency \(f = 1600\ \text{Hz}\) and a total measurement time \(\Delta t = 45\ s\). Note that we would have to diminish that frequency down to 400 Hz to measure long fibers (up to 250 km), forcing us to use a longer measurement time of 3 min to conserve the same dynamic range. The laser we employed was a +13 dBm DFB laser. Because we are counting single photons, we have to prevent laser emission between the pulses (otherwise these unwanted photons would lead to an increase of the noise level). Therefore the electronics used to drive the laser in a pulsed mode have been adapted for minimal noise. As a consequence, we have a peak power of +8 dBm.

In order to obtain the correct values for the reflected optical power – especially for values being close to the noise level – Eq. (3) has to be used to remove the counts due to the noise. The so-corrected \(\nu\)-OTDR trace is shown in Fig. 3. The vertical scale is defined as the one-way loss with the initial Rayleigh backscattering level normalized to zero. Therefore the \(N_n + \sigma_n\) level directly gives the dynamic range. We measured 44 dB, which is in excellent agreement with the theoretical value of 45 dB of above, even more so if considering that the extra 1-dB loss due to the optical
circulator was neglected in the calculations. From the Rayleigh backscattering in Fig. 3, standard losses of 0.22, 0.30, and 0.25 dB/km are obtained for each fiber, respectively. Note that for the last fiber – for which the backscattered signal is close to the noise level – the correct loss is only obtained when the signal correction (Eq. (3)) is applied. A loss of 0.047 dB/km is obtained otherwise. We also note that there are hardly any fluctuations in the v-OTDR trace, except when we are close to the NEP. Of course these fluctuations can be reduced when integrating over a longer period of time, hence giving us better statistics.

4. Dead-zones elimination

A striking feature of the v-OTDR trace is the large dead-zone of about 6 km right after the 28-dB attenuation at a distance of 11 km (cf. Fig. 3). This dead-zone is due to charge trapping inside the APD – an effect proper to photon counting. Intense light falling on the APD outside the detection gate period (i.e., when the APD is not active) will create trapped electron–hole pairs that will be subsequently released with exponentially decaying probability [4–6]. If the APD becomes active shortly thereafter, these trap-released carriers will create an unwanted extra avalanche. This phenomenon is particularly noticeable when using high-voltage and large detection gates as the trapped carriers have more energy and time to be freed. Moreover this effect is only seen after a high signal difference on a short distance (here a one-way loss of ~33 dB between the 10.4-km reflection peak and the Rayleigh backscattering level right after the attenuator). Also, a small peak located at a distance of 21 km can be discerned after the dead-zone. This peak however is due to a completely different effect. It is a “ghost peak” caused by a double reflection between the strong initial peak (at 0 km) and the 10.4-km peak. This ghost peak is pretty small and can be seen only because the signal at that position is low.

To eliminate undesired dead-zones, a fast optical shutter can be employed to blind the APD outside the detection gates, thus preventing any
charges from being trapped. This can be realized with an intensity modulator synchronized with the gating electronics and placed between the circulator and the APD, as shown in Fig. 2 (dashed elements). As optical shutter we used a proton-exchange LiNbO$_3$ intensity modulator. Since proton-exchange modulators are polarization-dependent, we used a polarization scrambler to cancel that effect. As a matter of fact only one polarization is guided through the modulator, thus leading to an additional 3-dB loss for non-polarized (or polarization-scrambled) light. Note that in a real application, either a polarization-independent modulator or a polarization-diversity scheme (employing two modulators) should therefore be used. The extinction-ratio of our modulator is 30 dB. Consequently dead-zones are completely removed when the signal drops by less than 15 dB (on the one-way loss scale). This is illustrated in Fig. 4, where we used the same setup as before, but with the attenuation between the first two fibers set to 15 dB. As expected, a big reduction of the dead-zone can be seen. The dead-zone is however not completely removed as the signal-drop between the reflection peak and the Rayleigh level after the attenuator is 20 dB.

5. Conclusions

An investigation of the sensitivity and dynamic range of a v-OTDR was presented. Calculations and measurements showed that the noise equivalent power, and hence the minimum detectable power, scales as the inverse square root of the product of gate duration and total measurement time. Therefore increasing the gate duration, and thus decreasing the spatial resolution, enhances the dynamic range. Setting the spatial resolution to 1 km – as typically used for OTDR characterization – we obtain a 44-dB dynamic range in our experiment, which represents a 4-dB improvement with respect to state-of-the-art conventional OTDRs.

Further, an original solution to suppress disturbing dead-zones is presented. It consists of inserting a fast optical shutter before the detector. The shutter – an optical intensity modulator with 30-dB extinction ratio – allowed to decrease the dead-zone by 15 dB.

Acknowledgements

We would like to thank S. Tanzilli (Laboratoire de Physique de la matière condensée, Université de Nice-Sophia Antipolis) for the intensity modulator. We also thank the Swiss Commission for Technology and Innovation (CTI) for financial support.

References