Photon Counting OTDR: Advantages and Limitations

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Abstract—In this paper, we provide a detailed insight into photon-counting optical time-domain reflectometer (ν-OTDR) operation, ranging from Geiger-mode operation of avalanche photodiodes (APD), analysis of different APD bias schemes, to the discussion of OTDR perspectives. Our results demonstrate that an InGaAs/InP APD-based ν-OTDR has the potential of outperforming the dynamic range of a conventional state-of-the-art OTDR by 10 dB, as well as the two-point resolution by a factor of 20. Considering the trace acquisition speed of ν-OTDRs, we find that a combination of rapid gating for high photon flux and free running mode for low photon flux is the most efficient solution. Concerning dead zones, our results are less promising. Without additional measures, e.g., an optical shutter, the photon counting approach is not competitive.

Index Terms—Distributed detection, fiber metrology, optical time-domain reflectometry, photon counting.

I. INTRODUCTION

OPTICAL TIME-DOMAIN REFLECTOMETRY [1] is a well-known technique for fiber-link characterization. Most of today’s commercially available optical time-domain reflectometers (OTDRs) are based on linear photon detectors, such as p-i-n or avalanche photodiodes (APDs). Although single-photon detection features unmatched sensitivity, OTDRs based on this technique (ν-OTDR) [2] have reached the market only in niches [3].

Several single-photon detection techniques are possible [4]–[9], but only few of them are suitable for in-field measurements. Geiger-mode-operated InGaAs/InP APDs (for telecom wavelengths) [5], [10], [11] are the most promising candidates, due to their robustness and manageable cooling.

In this paper, we discuss the advantages and limitations of these devices, when used in a ν-OTDR. We concentrate, in particular, on the dynamic range, two-point resolution, measurement time, and dead zone. All ν-OTDR measurements are supplemented by measurements using a conventional state-of-the-art OTDR (Exfo FTB7600). This makes it easier to evaluate the ν-OTDR performance. Our discussion also contains the possible yield of newly emerged gating techniques like rapid gating [12]–[14].

We note that some years ago, ν-OTDRs based on silicon APDs, suitable for C-band operation, were demonstrated [15], [16]. Although silicon APDs show superior behavior, concerning afterpulsing and timing jitter, the upconversion of telecom photons to the visible regime demands more expensive optics and more sophisticated alignment. Therefore, we believe that they are less suitable when robustness is required.

This paper is organized as follows. In Section II, we provide information about Geiger-mode operation of InGaAs/InP APDs and discuss its major impairment, the afterpulsing effect. Section III focusses on ν-OTDR operation and performance (dynamic range, two-point resolution, measurement time, and dead zone), and compares it with the performance of a conventional state-of-the-art long haul OTDR (Exfo FTB7600). Section IV considers time-efficient bias schemes (rapid gating, free running), and finally, we summarize our results in Section V.

II. GEIGER-MODE APD

A. Basic Operation

In Geiger-mode, the APD is biased beyond its breakdown voltage, typically by a few percent. This provides a sufficiently large gain (order of $10^6$) to detect a single incident photon (with detection efficiency η). In contrast to a linear-mode APD, the output signal is no longer proportional to the number of primary charges. Whenever an avalanche occurs and the current reaches a certain discrimination level, a detection is counted, independent of how many primary charges caused or were created during the avalanche.

To reset the APD for the next detection, the avalanche needs to be quenched. This is typically done by lowering the bias voltage, either actively or passively [17].

An APD based on InGaAs/InP is particularly well suited for use with the principal telecom wavelength bands. Although the dark count rate is higher than in silicon-based APDs, high sensitivity can be regained by cooling, typically around $-50\,\text{°C}$ (see also Section II-B).

There are different ways of applying the overbias ($V_{\text{bias}} > V_{\text{bd}}$ (breakdown voltage)) to the diode. The most common ones are the gated mode and the free-running mode [18]. In gated mode, the overbias is applied only during a short time Δ$t_{\text{gate}}$ (called gate), in a repetitive manner with frequency $f_{\text{gate}}$ (respecting $f_{\text{gate}} < 1/\Delta t_{\text{gate}}$). Typically, $\Delta t_{\text{gate}} \in [2\,\text{ns},\,20\,\mu\text{s}]$ and $f_{\text{gate}} \in [100\,\text{Hz},\,10\,\text{MHz}]$. In free-running mode, the overbias is applied until a photon or noise initiates an avalanche.

While the gated mode achieves high SNR ratios when a synchronized signal is being detected, the free-running mode is

1A detection that was not initiated by a signal photon, but by thermal excitation or tunneling.
most suited when the photon arrival time is not known (e.g., in OTDR).

More recent developments, summarized by the name rapid gating [12]–[14], apply very short gates (≈200 ps) in order to severely limit avalanche evolution and reduce afterpulsing (see Section II-C). The technical challenge consists in discriminating the rather small avalanche signal from the capacitive response to overbias of the diode itself. In “classical gating,” described in the previous paragraph, one usually waits until the avalanche signal is easy to discriminate. Typical gating frequencies in rapid gating are of the order of 1 GHz.

In Section IV, we will discuss pros and cons of these different approaches, in particular, concerning their applicability for ν-OTDRs.

B. Detection Sensitivity

A figure of merit for the sensitivity of a detector is its noise equivalent power (NEP). For example, the bandwidth-normalized NEP norm of a linear photodetector is given by [21], [22]

\[ \text{NEP}_{\text{norm}} = \frac{\Delta I_{\text{noise}}}{SG} \left[ \frac{\text{W}}{\sqrt{\text{Hz}}} \right] \]

where \( \Delta I_{\text{noise}} [\text{A}/\sqrt{\text{Hz}}] \) is the standard deviation of the total noise current (thermal, dark, signal shot, and, in case of gain, also gain noise), normalized with respect to the bandwidth of the detector, \( S [\text{A}/\text{W}] \) is the detector photosensitivity, and \( G \) is the gain of the diode (p-i-n diode: \( G = 1 \), linear APD (typically): \( G = 10 \sim 100 \)).

APDs are superior to p-i-n diodes in the circuit-noise-limited regime [23], but lose their advantage when the gain noise becomes important, i.e., at stronger signal powers. The minimal detectable power \( \text{NEP}_{\text{norm},0} [\text{W}/\sqrt{\text{Hz}}] \) is obtained by setting the signal power, and thus, the signal-shot noise equal to zero. \( \text{NEP}_{\text{norm},0} \) can usually be found in the data sheet of the diode, typically \( 10^{-15} \sim 10^{-13} [\text{W}/\sqrt{\text{Hz}}] \) for InGaAs APDs at 25 °C.

A similar expression can be derived for Geiger-mode APDs (see Appendix B, (21))

\[ \text{NEP}_{\text{norm}} = \frac{h\nu}{\eta} \sqrt{2\rho_{\text{noise}}} \left[ \frac{\text{W}}{\sqrt{\text{Hz}}} \right] \]

where \( \eta \) is the detection efficiency and \( \rho_{\text{noise}} \) is the noise detection probability per gate (including signal and dark count shot noise), normalized with respect to the gate width \( \tau_{\text{gate}} \) in seconds. Again, setting the input optical power equal to zero, we infer the minimal detectable power (Appendix B, (21)) as

\[ \text{NEP}_{\text{norm},0} = h\nu \eta \sqrt{2\rho_{\text{noise}}} \left[ \frac{\text{W}}{\sqrt{\text{Hz}}} \right] \]

where \( \rho_{\text{noise}} \) denotes the dark count probability per gate, normalized with respect to the gate width \( \tau_{\text{gate}} \) in seconds. Inserting the parameters of the Geiger-mode APD used in our experiments (\( \rho_{\text{noise}} = 200 \text{ s}^{-1}, \eta = 10\% \), and \( T = -50 \text{ °C} \), see Section III-A), we estimate \( \text{NEP}_{\text{norm},0} \approx 10^{-16} [\text{W}/\sqrt{\text{Hz}}] \).

In Fig. 1, we see the evolution of \( \text{NEP}_{\text{norm},0} \) as function of temperature. We observe that when approaching ambient temperatures, we almost reach the regime of the best linear-mode diodes. Conversely, one might be tempted to cool linear diodes to \(-50 \text{ °C} \) to reach the NEP of Geiger-mode APDs. Even if this might be, in general, achievable, one should not forget that the output signal still needs to be amplified. Even at ambient temperatures, the NEP is increased by almost a factor of 10 with respect to the usual operating temperature of \(-50 \text{ °C} \).

C. Afterpulsing

One of the major impairments of InGaAs/InP APDs is the afterpulsing effect. Imperfections and impurities in the semiconductor material are responsible for intermediate energy levels (also called trap levels), located between the valence band and the conduction band. During an avalanche, these levels get overpopulated with respect to the thermal equilibrium population. If the APD gets reactivated right after the quenching of an avalanche, the probability of thermal excitation or tunneling of one of these charges into the conduction band and the subsequent initiation of an afterpulse avalanche, is high.

Although fundamentally the improvement of semiconductor purity, and thus, the reduction of the number of trap levels is preferable, different mitigation measures can be carried out:

a) Dead Time: A purely passive measure is the introduction of a dead time. The trap population decreases exponentially with time, due to thermal diffusion. Finally, the thermal equilibrium configuration is restored. The impact of afterpulsing can therefore be mitigated by maintaining the bias voltage below breakdown, i.e., the application of a dead time \( \tau \), after a detection takes place. Dead times severely limit the maximum achievable detection rate.

b) Heating: An increased temperature accelerates the diffusion of trapped charges. However, at the same time, charge excitation from the valence into the conduction band increases, leading to globally increased noise, which eventually reduces the detector sensitivity. Thus, one cannot achieve low afterpulsing and high sensitivity at the same time. It is necessary to find a tradeoff depending on the particular application.

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Footnote:
3Circuit noise results, for example, from thermal motion of charges in resistors or charge fluctuation in transistors in the receiver amplifier.
c) Quenching Technique: As soon as the avalanche has gained enough strength such that the current pulse can be detected, it needs to be quenched. The quenching speed is crucial to limiting the number of secondary charges that can populate trap levels. Here, fully integrated active-quenching circuits yield much better results than nonintegrated ones [19]. Another approach is rapid gating (see Section II-A). Avalanche evolution is terminated by short gate durations (200 ps) and the number of secondary charges is kept low.

In Fig. 2, we plot an example of afterpulse probability as function of dead time $\tau$, using a fully integrated application-specific integrated circuit (ASIC) based active quenching circuit [19]. Whenever a detection takes place, we activate a second gate of width $\Delta t_{\text{gate}} = 10$ ns with a temporal delay of $\tau$. In this second gate, no incident photons are present. If there is a detection, it is either a dark count or an afterpulse. Since for large $\tau$ only the actual dark counts remain, we can subtract it from the total count rate and obtain the pure afterpulsing probability (Fig. 2). During larger gates, the afterpulse probability sums up and afterpulsing increases. One can easily calculate the afterpulse probability of a gate of width $\Delta t_{\text{gate}} (\leq 10 \mu s)$ by

$$\text{PAP}_{\Delta t_{\text{gate}}} (\tau) = 1 - (1 - \text{PAP}_{10 \text{ ns}} (\tau))^m$$

where $\text{PAP}_{10 \text{ ns}} (\tau)$ is the afterpulse probability in a gate of 10 ns width and $m = \Delta t_{\text{gate}}/10$ ns.

We note that if no afterpulse occurs in the first activated gate after a detection, it can also happen in any succeeding gate. However, the probability decreases due to trap charge diffusion. To get the total afterpulse probability, or rather the signal to afterpulse ratio, one needs to account for this summing effect as well. The lower the signal detection rate, the more the summing-up takes place. Thus, a higher signal detection rate improves the signal to afterpulse ratio.

In Fig. 3, we illustrate the impact afterpulsing can have in a $\nu$-OTDR measurement. First, and most importantly, we must consider dead zones (see Section III-D for definition, not to be confused with dead time). Whenever an important loss (at 25 km) or a reflection (at 36 km) occurs, it is followed by a tail that prevents the detection of the Rayleigh backscatter directly behind it. Second, the backscatter trace is shifted to higher values, since more detections than in the pure signal case occur (pile-up effect). Third, the slope of the trace is flatter than it should be.

How much afterpulsing can be tolerated, generally depends on the particular measurement. For instance, in a coarse measurement on a long span of fiber, where only peak positions or large loss events are of interest, one can tolerate a fairly high afterpulsing contribution. On the other hand, in the case of short links, where high precision for fiber attenuation measurement and dead zone minimization is desired, afterpulsing must be kept to a few percent or even lower, depending on required precision of the measurement. Numerical afterpulse correction methods were also analyzed [20], but it was found that for high precision measurements, the algorithm lacks robustness due to possible variations in the afterpulse probability. It should, therefore, be used only when the requirements on precision are not stringent.

III. PHOTON COUNTING VERSUS CONVENTIONAL OTDR

Although this section is mainly concerned with the $\nu$-OTDR technique, we also perform measurements using a state-of-the-art conventional $3$ OTDR (FTB-7600, EXFO), a product especially designed for long-haul applications (up to 50 dB dynamic range). This makes it easier for us to highlight the advantages and drawbacks of the photon counting approach. The experimental setup and a detailed explanation is given in Fig. 4.

For a fixed delay, a number of laser pulses $N_{\text{pulse}}$ (repetition frequency $f_{\text{pulse}}$) are sent and $N_{\text{gate}} (= N_{\text{pulse}})$ gates is activated. A counter records the number of detections. The incident signal power can be inferred from the ratio of detections to activated gates (for details, see Appendix A).

To get information on the backscatter of the entire fiber, the delay needs to be scanned, repeating the procedure explained before for each single delay position. The sampling resolution, i.e., the delay step $\Delta t_{\text{delay}}$ ($t_{\text{delay}} = i \cdot \Delta t_{\text{delay}}, i = 1, 2, 3, \ldots$), needs to be adapted to the requirements of the particular measurement (e.g., zooming or coarse full-trace measurement). The detection bandwidth is given by $B = 1/2\Delta t_{\text{gate}}$.

$3$Based on linear-mode APD detection.
With increasing delay, the backscatter-OTDR measurement, ensuring that OTDR measurements is also shown in C (minimal value). We measure a dark is sent to the APD to apply a detection efficiency adapted to the length for a 10 s gate. The 99% part is launched into the fiber under test (FUT) via a circulator. Backscattered light from the fiber exits the lower port of the circulator and illuminates the InGaAs/InP-APD. The 1% part is used to measure the time of departure of the laser pulse (for synchronization reasons) using a conventional photodiode (Newport, 1 GHz). The output signal is sent to a delay generator. A delayed signal at \( t_0 + t_{	ext{delay}} \) is sent to the APD to apply a detection gate of length \( \Delta t_{	ext{gate}} \) and the backscattered intensity corresponding to the time of departure \( \Delta t_{	ext{delay}} \) is found to be 34.5 dB.

We start measuring the trace with the FTB-7600 for 3 min\(^4\) with a laser pulsewidth of 1 \( \mu \)s. The device acquires 180 s \( \times \) 500 Hz = 9 \( \times \) 10\(^4\) different traces. The final output trace is the numerical average of these single traces (see Fig. 5, light gray curve). For a fair comparison, the detection bandwidth should be equal for the two devices. For the conventional OTDR, it is automatically chosen by the device and not available to us. We infer its value by looking at the noise period at the end of the measurement range. For a pulsewidth of 1 \( \mu \)s, we obtain 4 MHz. Under these conditions, the dynamic range is found to be 34.5 dB.

We then perform the \( \nu \)-OTDR measurement, ensuring that we do not saturate the detector with the backscatter from the beginning of the fiber. Therefore, we insert an additional attenuator in front of the APD to reach the unsaturated regime. We adjust the attenuation to yield a detection rate of about 90% of the gate rate for the first delay position. At each delay position, we count the number of detections within 3 min, which yields the same statistics per sampling point as in the previous case (180 s \( \times \) 500 Hz = 9 \( \times \) 10\(^4\) samplings). We choose \( \Delta t_{	ext{delay}} \) equal to 3 \( \mu \)s (\( \approx \) 300 m sampling point separation in fiber) and \( \Delta t_{	ext{gate}} = \Delta t_{	ext{pulse}} \). With increasing delay, the backscatter power, and thus, the detection rate decreases. When we start to approach the noise level of the detector, we pause the measurement and remove a part of the attenuation (to regain 90% detection rate), reduce the delay for a few kilometers (to get an overlap with the previous part), and resume the measurement. In this way, we obtain several single traces of adjacent parts of the fiber. In the following, we will refer to this as partial trace measurement. By means of the overlaps, the entire trace can be reconstructed. Each partial trace measurement contributes approximately 20 dB to the overall \( \nu \)-OTDR dynamic range. For example, to cover 50 dB of fiber loss, we need to perform three partial trace measurements.\(^5\)

The result of the \( \nu \)-OTDR measurements is also shown in Fig. 5 (blue curve). It is important to note that we adapt the gate width to the laser pulsewidth to obtain the minimal NEP\(_0\) (see Appendix B, (19)) without affecting the two-point resolution (limited by the laser pulsewidth). This means that in the case of Fig. 5, the detection bandwidth of the \( \nu \)-OTDR is \( B = 1/(2\Delta t_{	ext{gate}}) = 500 \text{ kHz}\).\(^6\) To be able to compare the measured results in a representative manner, we average the conventional

Fig. 4. Basic \( \nu \)-OTDR setup. The laser (we use the laser of the FTB-7600, \( P_{\text{peak}} = 400 \text{ mW} \)) emits pulses with a frequency \( f_{\text{pulse}} \) adapted to the length of the fiber under test \( L_{\text{fiber}} \) \((= f_{\text{pulse}} = c/2L_{\text{fiber}})\). The signal is split at a 99/1-coupler. The 99% part is launched into the fiber under test (FUT) via a circulator. Backscattered light from the fiber exits the lower port of the circulator and illuminates the InGaAs/InP-APD. The 1% part is used to measure the time of departure of the laser pulse (for synchronization reasons) using a conventional photodiode (Newport, 1 GHz). The output signal is sent to a delay generator. A delayed signal at \( t_0 + t_{\text{delay}} \) is sent to the APD to apply a detection gate of length \( \Delta t_{\text{gate}} \) and the backscattered intensity corresponding to the time of departure \( \Delta t_{\text{delay}} \) is found to be 34.5 dB.

We note that this is only the most basic version of a photon-counting OTDR. One of the advantages of this system is that due to the low gating frequency, we can totally exclude after-pulse effects (dead time 2 ms). Therefore, we can determine the unadulterated dynamic range and two-point resolution. Nevertheless, data acquisition is very time-consuming. For example, the measurement of the entire 200 km fiber, discussed in the next section (see Fig. 5), took about 6 h. In Section IV, we will see how it can be performed more efficiently.

A. Dynamic Range

To measure the dynamic range of both devices for different laser pulsewidths, we take a 200 km fiber, composed of a 50 km spool and an installed fiber link of 150 km (Swisscom, Geneva-Neuchatel), which itself consists of several fibers. The length of the fiber allows a maximal laser pulse repetition rate of \( f_{\text{laser}} = c/2L_{\text{fiber}} = 500 \text{ kHz} \), where \( c \) is the speed of light in standard optical fiber.

We start measuring the trace with the FTB-7600 for 3 min\(^4\) with a laser pulsewidth of 1 \( \mu \)s. The device acquires 180 s \( \times \) 500 Hz = 9 \( \times \) 10\(^4\) different traces. The final output trace is the numerical average of these single traces (see Fig. 5, light gray curve). For a fair comparison, the detection bandwidth should be equal for the two devices. For the conventional OTDR, it is automatically chosen by the device and not available to us. We infer its value by looking at the noise period at the end of the measurement range. For a pulsewidth of 1 \( \mu \)s, we obtain 4 MHz. Under these conditions, the dynamic range is found to be 34.5 dB.

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The result of the \( \nu \)-OTDR measurements is also shown in Fig. 5 (blue curve). It is important to note that we adapt the gate width to the laser pulsewidth to obtain the minimal NEP\(_0\) (see Appendix B, (19)) without affecting the two-point resolution (limited by the laser pulsewidth). This means that in the case of Fig. 5, the detection bandwidth of the \( \nu \)-OTDR is \( B = 1/(2\Delta t_{\text{gate}}) = 500 \text{ kHz}\).\(^6\) To be able to compare the measured results in a representative manner, we average the conventional

\(^5\)We choose 3 min because this is the time specified in the definition of OTDR dynamic range for conventional OTDRs [24].

\(^6\)The first measurement covers 0–20 dB, the second 15–35 dB, and the third 30–50 dB, respecting the necessary overlap between different partial trace measurements.

\(^5\)The conventional device uses a higher bandwidth, since higher sampling resolution is useful when the position of an event needs to be determined with higher precision.
OTDR can achieve the same dynamic range with a factor of roughly 63–100 smaller than the conventional OTDR. This discussion is postponed to Section IV.

We repeat the measurement for different laser pulsewidths keeping all other parameters unchanged. The final results are shown in Fig. 6. The detection bandwidths were adapted as before. It holds that $B = 1/(2\Delta t_{\text{pulse}})$ for both devices.

For pulsewidths between 30 ns and 1 μs, the dynamic range difference is about 9–10 dB. This is a direct consequence of the smaller NEP$_{\text{norm},0}$ (see Section II-B) of the Geiger-mode APD, since bandwidth and integration time per sampling point were equally chosen. This means that the NEP$_{\text{norm},0}$ of the ν-OTDR is roughly a factor 63–100 smaller than the NEP$_{\text{norm},0}$ of the conventional OTDR (noise dominated by the small-pulse amplifier). However, going to larger laser pulses, we observe increased noise for the ν-OTDR and the advantage gets smaller. We suppose that this happens due to the increased backscatter power from the beginning of the fiber. Although the diode is not active, the charge persistence effect (also called charge subexistence) can have a nonnegligible impact on the noise counts in a subsequently activated gate (for more details, also see Section III-D).

In summary, by adapting sampling statistics and detection bandwidth of both devices, we find an advantage of about 9–10 dB in dynamic range for the ν-OTDR. By increasing the laser pulsewidth, we observe increased detector noise and the effective advantage gets smaller. We uncouple the question of measurement time, since it is highly dependent on the gating technique used in the ν-OTDR. This discussion is postponed to Section IV.

B. Two-Point Resolution

When considering the two-point resolution, one can divide OTDR operation into two regimes: 1) the receiver limited and 2) the laser-power-limited regime. In case 1), the ultimate timing resolution is either given by the amplifier bandwidth or the detector jitter (using fine laser pulses), whereas in case 2), the limited laser peak power makes it necessary to use larger pulsewidths in order to reach high dynamic ranges. In the receiver-limited regime, the advantages of photon counting were already discussed in [20], yielding a maximal two-point resolution of 10 cm for the ν-OTDR and 1 m for the conventional device. In long-haul OTDR applications, we operate in the laser-power-limited regime.

It is easy to see that in this regime, the sensitivity advantage (NEP$_{\text{norm},0}$) of photon counting translates directly into an advantage in two-point resolution.

Example: We consider a reflective event at the end of the dynamic range (with a certain pulsewidth and measurement time) of the FTB-7600 (see Fig. 7).

The ν-OTDR can achieve the same dynamic range with a much smaller pulsewidth (see Fig. 6). According to Appendix D, an advantage of 10 dB in dynamic range corresponds to an advantage in two-point resolution by a factor of 20. In Fig. 8, we see the results of three ν-OTDR measurements focusing on the reflective event at about 102.8 km. With each reduction in pulsewidth, more and more structure is revealed, and we actually find three reflections. The ratio of the peak widths agrees well with the calculated one.

In summary, when the OTDRs are operated in the laser-power-limited regime, the sensitivity advantage of the ν-OTDR translates directly into an advantage in two-point resolution. Its amount is described by (27) in Appendix D.

C. Measurement Time

We start discussing the measurement time by taking a look at the time necessary to obtain a sufficient SNR for a specific delay position in the fiber, from which we receive a backscatter power $P_{\text{opt}}$ (see Appendix E)

$$t = \frac{1}{f_{\text{pulse}}} \left( \frac{\text{SNR} \cdot \text{NEP}_{\text{norm},0} \cdot \sqrt{B}}{P_{\text{opt}}} \right)^2$$  \hspace{1cm} (5)

$^7$Respecting the functional dependence between NEP and dynamic range given in (25), using NEP$_{0} \propto \text{NEP}_{\text{norm},0}$.

$^8$By two-point resolution, we mean the minimal distance necessary between two reflective events, in order to be able to recognize them as distinct peaks on the OTDR trace output (e.g., dip between peaks at least 1 dB lower than the peaks themselves).

$^9$Bandwidth normalized.
where NEP$_{\text{norm}}$ [see (20)] is the NEP normalized with respect to detector bandwidth in [W/√Hz]. $B$ is the detector bandwidth in [Hz], and $f_{\text{pulse}}$ is the laser pulse repetition rate in [Hz]. This formula applies to both the Geiger- and linear-mode operation as long as linearity between input and output signal is guaranteed.\(^\text{(10)}\)

While the Geiger mode exhibits linearity only in a relatively restricted domain of $P_{\text{opt}}$, the linear mode is able to cover several orders of magnitude of input power. Therefore, (5) is applicable for a much wider range of optical powers and shows the significant advantage of the linear mode when larger powers need to be measured ($\propto P_{\text{opt}}^{-2}$).

More interesting from the $\nu$-OTDR perspective is the case when (5) applies as well for Geiger mode, i.e., for sufficiently small powers (order $-100$ dBm). We can then easily calculate the ratio of measurement times (assuming $f_{\text{pulse}}, B$, and $P_{\text{opt}}$ to be equal)

\[
\frac{\tau_{\text{conv}}}{\tau_{\text{pc}}} = \left( \frac{\text{NEP}_{\text{conv}}}{\text{NEP}_{\text{pc}}} \right)^2
\]

(6)

where the superscript pc signifies photon counting (i.e., Geiger mode), and $\text{conv}$ represents the conventional detection mode (i.e., linear mode).

NEP$_{\text{norm}}$ can be split into a signal-initiated noise contribution NEP$_{\text{norm, sig}}$ and a contribution from signal-independent sources (dark current, dark counts) represented here by NEP$_{\text{norm,0}}$

\[
\text{NEP}_{\text{norm}}^2 = \text{NEP}_{\text{norm, sig}}^2 + \text{NEP}_{\text{norm,0}}^2.
\]

(7)

For sufficiently small input power, NEP$_{\text{norm}}$ becomes NEP$_{\text{norm,0}}$. In Section III-A, we estimated the ratio of the NEP$_{\text{norm,0}}$ of conventional and $\nu$-OTDR to lie within 63 and 100. Thus, the ratio given in (6) approaches a value between 4000 and 10 000. This means that we continuously pass from a huge linear-mode advantage ($P_{\text{opt}}$ large) to a huge Geiger-mode advantage ($P_{\text{opt}}$ small).

We stress at this point that this result applies for the measurement of a specific delay position. OTDR measurements consist of scanning a range of different powers, i.e., the exponentially decreasing backscatter power. In case of the conventional OTDR, the achievement of a sufficient SNR for a certain delay position, e.g., far down the fiber, means that all delays closer to the beginning of the fiber have been scanned at least with the same SNR. Thus, we already obtain the full trace up to that point. How large the actually scanned interval is in the case of photon counting depends on the gating technique. For example, using the basic approach, explained earlier (see Fig. 4), one would scan exactly one position. In Section IV, we discuss how the NEP advantage of photon counting can be used more efficiently.

\section*{D. Dead Zone}

Dead zones are parts of a fiber link where the OTDR trace does not display the actual Rayleigh backscatter, but a signal...
induced by another source. One example that we have already encountered is the afterpulsing effect. If not accounted for, it leads to tails after large loss events or reflections (see Fig. 3). Unfortunately, this is not the only origin of dead zones. If we mitigate the afterpulsing effect by using an appropriate dead time, another effect, very similar to afterpulsing, gets dominant: charge persistence. Even though the APD is not biased beyond breakdown between adjacent gates, there is still a bias that can weakly multiply primary charges created by photons incident during that time. These weak avalanches might, however, lead to increased trap population and increased noise avalanche probability in the next gate ($V_{bkw} > V_{bkw,n}$). This effect, although less severe than afterpulsing, becomes visible under the same circumstances, namely, after large loss events and reflections.

To estimate the impact of this effect on the OTDR output, we perform a measurement on a fiber link containing a large loss event (17 dB), with a reflection ($\approx -45$ dB) just before it. This link simulates a typical situation encountered in passive optical networks, where a splitter of high multiplicity induces a significant loss. Weak reflections right in front can be induced by bad connectors.

We perform a measurement of this particular fiber-link situation using our $\nu$-OTDR in basic mode, which ensures that no afterpulsing effect is present and the charge persistence effect becomes visible. Our results, including the measurement using the conventional OTDR, are shown in Fig. 9. We observe the emergence of a tail approximately 10 dB below the loss edge, which decays by approximately 3.5 dB/km. The lower Rayleigh backscatter level gets visible again after about 2 km ($20 \mu s$).

The result obtained with the conventional OTDR is much better. The emergence of the tail starts on a significantly lower level. Full sensitivity is regained after 1 km. The results found for the $\nu$-OTDR confirm the observations made in [20] and [25]. One possibility to mitigate dead zones, induced by charge persistence, is the use of an optical shutter, as performed in [25]. If the initial backscatter is blocked by the shutter and the gate gets activated, as well as the shutter deactivated right after the loss event, much better results can be obtained.

In summary, concerning dead zones, the conventional OTDR shows superior behavior, when no additional measures are taken in the case of the $\nu$-OTDR, e.g., using an optical shutter.

### IV. Time-Efficient Bias Schemes

The way we implemented the $\nu$-OTDR in Section III is one of the simplest, and trace acquisition is time consuming. It is well suited to study general characteristics, but not for other applications. Its apparent drawback is the wasting of backscattered signal, due to the fact that $f_{gat} = f_{pulse}$, i.e., only one gate per laser pulse is activated.

A more efficient approach is the train of gates scheme [20]. Unlike to the basic mode, the gating frequency is higher than the laser pulse repetition rate and more than one gate gets activated per laser pulse (see Fig. 10). In the ideal case, we could choose a gating frequency $f_{gat}$ in the way that the designated sampling resolution is obtained. Unfortunately, we have to account for the afterpulsing effect, and thus need to apply a dead time $\tau$ (whose length depends on the tolerable afterpulsing). In Appendix F, we discuss the impact of dead time on the detection statistics in detail. To follow the general discussion here, it can be skipped through.

A measure for the acquisition speed is the achievable detection rate $f_{det}$. We state a linearized formula for $f_{det}$, which illustrates the most important relations very well

$$f_{det} = \frac{1}{1/(\eta \mu T) + \tau} \tag{8}$$

where $\eta$ is the detection efficiency, $\mu$ is the incident photon flux (in photons per second), and $\Gamma = f_{gat} \Delta f_{gat}$ is the detection duty cycle $\tau$ is the dead time.

a) **High Flux**: If the photon flux is large, the detection rate is limited by the dead time, i.e., $f_{det,max} = 1/\tau$. In order to increase the detection rate, the dead time needs to be decreased. In

11 As depicted in Fig. 10, we can number each gate in the train of gates, $1, \ldots, n$. In the ideal case (no dead time), each of these gates gets activated for each laser pulse sent into the fiber. In reality, when a dead time needs to be applied, it is not certain that gate $i$ gets activated. It is possible that it falls into the dead time application range (gate 4–7 in Fig. 10).
Section II-C, we have already started to discuss the possibilities of afterpulse mitigation. The quenching technique that yields to date the lowest afterpulsing is rapid gating [12]–[14]. Dead times of the order of 10 ns can be considered realistic. This is approximately a factor 1000 better than the best actively quenched circuits can deliver. To maintain a reasonable duty cycle, gating frequencies of the order of 1 GHz are used ($\Delta t_{\text{gate}} \approx 200$ ps).

b) Low Flux: If the flux is small, the dead time is insignificant and $f_{\text{dead}} = \eta \tau \Gamma$. Here, the most important parameter is the duty cycle $\Gamma$, which should be preferably high. Increasing the duty cycle will finally lead to a situation that is called free-running mode [18] (see Fig. 10). The overbias is applied until a signal photon or a noise effect initiates an avalanche. The photon flux $\mu$ below which the free-running mode yields higher detection rates is roughly $1/\eta \tau$ (also see Appendix F). We see that in this case, improved afterpulsing, and thus, smaller dead times would extend the application range to higher photon fluxes. To date, the best low-afterpulsing solution for the free-running mode is the earlier discussed integrated active quenching approach [19], Fig. 11 illustrates our discussion.

At this point, we want to demonstrate that using the free-running mode in its application regime (low flux), the acquisition speed of the conventional OTDR can be considerably outperformed.

Example: We want to scan a 10 km interval of a 200 km fiber ($f_{\text{probe}} = 500$ Hz). We assume $\tau = 10$ µs, $\eta = 0.1 \Rightarrow$ the maximal flux is $\mu = 10^6$ photons/s, which corresponds to a power of $P_{\text{start}} = -99$ dBm$^{12}$. At the end of the 10 km interval, the power drops to about $P_{\text{stop}} = -103$ dB-m (assuming regular fiber behavior, attenuation $= 0.2$ dB/km). From $P_{\text{stop}}$, one can infer $\phi_{\text{dc}}$ (22), and using $\phi_{\text{dc}} = 2000$ s$^{-1}$, we obtain $\text{NEP norm} = 3.6 \times 10^{-16}$ W/\text{Hz} [see (20)], which enters into (5) for measurement time calculation. The bandwidth $B$ of the measurement is managed by appropriate averaging of adjacent points after the full data is acquired. Here, we suppose a bandwidth $B$ of 10 MHz (averaging on 50 ns intervals) and a SNR of 4. All together, we compute a measurement time of approximately 20 s.

To obtain the time of the conventional OTDR, we calculate the $\text{NEP norm}$ and the ratio of (6). In the beginning of Section III-C, we stated that the $\text{NEP norm} = 10^{-16}$ W/√Hz. The signal power is low enough to neglect the signal-induced noise contribution, and we simply obtain $\text{NEP norm norm} = 63 \times \text{NEP norm} = 6.3 \times 10^{-15}$ W/√Hz yielding a total measurement time for the conventional device of about 1.5 h, assuming the same detection bandwidth $B$.

We stress that during this time, the conventional device obtains information not only on our 10 km measurement range, but also about the entire range before. The $\nu$-OTDR scans only the designated 10 km, but finishes doing this in around 20 s.

V. CONCLUSION

The huge advantage of Geiger-mode APDs with respect to its linear-mode counterparts is the small core noise equivalent power $\text{NEP norm}$. Our comparison of a state-of-the-art conventional OTDR (based on linear-mode APD) and a photon-counting OTDR (based on Geiger-mode APD) reveals a difference of roughly two orders of magnitude. We demonstrate that this resource has the potential to improve the dynamic range by 10 dB, as well as the two-point resolution by a factor of 20 (in the laser-peak-power-limited regime). The important question is how efficient can it be used in OTDR applications (concerning the measurement time)? To sample the backscatter of a fiber, we have different possibilities at hand, i.e., train of gates (with classical gating), free-running mode, or rapid gating. For sufficiently low backscatter power (order of $-100$ dBm; long fibers), we show that the free-running mode is capable of efficiently using the NEP advantage. For example, measuring a 10 km interval far down the fiber, yielded a measurement time of around 20 s, while the conventional device needs to integrate for about 1.5 h to average out the noise sufficiently. At higher backscatter power, i.e., closer to the beginning of the fiber, we show that rapid gating can largely profit from its reduced afterpulsing, which makes dead times of the order of 10 ns realistic.

We see a combination of rapid gating for the beginning of the fiber and free-running mode for its end part as the currently best $\nu$-OTDR solution. Alternatively, one can also imagine a hybrid of conventional OTDR for high flux and photon counting for low backscatter power, including high-resolution scans with fine laser pulses on short distances.

Concerning dead zones, the conventional OTDR is clearly superior. It is more robust to sudden changes in backscatter power, while the $\nu$-OTDR suffers from the charge persistence effect. This effect can, for example, be mitigated by using an additional optical shutter.
APPENDIX A

POWER MEASUREMENT WITH GATED APD

We consider coherent light, with a mean photon number per second \( \mu \), incident on the diode (detection efficiency \( \eta \)). We apply gates of duration \( \Delta t_{\text{gate}} \), which means that on average \( \mu \times \Delta t_{\text{gate}} \) photons hit the diode during a gate. Due to the limited detection efficiency, not every photon leads to a detection. If our detector would be photon number resolving, the average number of signal detections per gate would be given by \( \eta \mu \Delta t_{\text{gate}} \). Since our APD does not have this ability, all cases where more than one signal detection would occur, results in only one detection output. According to Poissonian statistics, the probability of having no signal detection is given by \( e^{-\eta \mu \Delta t_{\text{gate}}} \); hence, the probability of having an APD signal detection output is given by

\[
p_{\text{sig, gate}} = 1 - e^{-\eta \mu \Delta t_{\text{gate}}}. \tag{9}
\]

\( \mu \) can be expressed by the incident optical power \( P_{\text{opt}} \) as

\[
\mu = \frac{P_{\text{opt}}}{h \nu}, \tag{10}
\]

Solving for \( P_{\text{opt}} \) yields

\[
P_{\text{opt}} = \frac{-h \nu}{\eta \Delta t_{\text{gate}}} \ln(1 - p_{\text{sig, gate}}). \tag{11}
\]

Measuring the ratio of the number of detections \( N_{\text{det}} \) (including signal detections \( N_{\text{sig}} \) and dark counts \( N_{\text{dc}} \)) and the number of activated gates \( N_{\text{gate}} \), yields the signal detection probability per gate

\[
p_{\text{sig, gate}} = \frac{N_{\text{det}} - N_{\text{dc}}}{N_{\text{gate}}} \tag{12}
\]

and finally, the incident optical power \( P_{\text{opt}} \).

If the signal is weak, then it is apparent that first of all the signal needs to be separated from noise by applying a sufficiently large number of gates \( N_{\text{gate}} \) (also see Appendix B). Once this is achieved, one has to consider the precision or statistical error of the result, which also is a function of \( N_{\text{gate}} \). Two examples: 1) \( N_{\text{gates}} = 10, \Delta t_{\text{gate}} = 100 \text{ ns} \), \( p_{\text{dc, gate}} = 2 \times 10^{-4} \), \( p_{\text{sig, gate}} = 0.2 \), the probability of a dark count to appear is negligible, and we obtain \( 2 \pm \sqrt{2} \) signal counts = total counts, from which we can calculate an optical input power lying in [0.7 pW, 5.3 pW]; 2) \( N_{\text{gates}} = 10000 \) and the other parameters like before, we obtain a number of total counts of \( 2002 \pm \sqrt{2002} \) from which \( 2 \pm \sqrt{2} \) are dark counts and \( 2000 \pm \sqrt{2000} \) are signal counts. From the signal counts, we infer an optical input power lying within [2.8 pW, 2.9 pW]. The statistical error of the second measurement is much smaller.

APPENDIX B

NEP OF GEIGER-MODE APD

In the treatment of the APD noise, we mainly consider two contributions, i.e., the shot noise of: 1) the signal counts and 2) the dark counts (assuming that afterpulse contributions can be neglected, for example, by choosing a sufficiently large dead time).

Let \( P_{\text{opt}} \) be the incident optical power on the diode. With the energy per photon \( h \nu \), the detection efficiency \( \eta \) and the gate width \( \Delta t_{\text{gate}} \), we infer the signal detection probability per gate (linearized version of (9), for sufficiently small \( P_{\text{opt}} \)) as

\[
p_{\text{sig, gate}} = \frac{P_{\text{opt}} \Delta t_{\text{gate}}}{h \nu}. \tag{13}
\]

After applying \( N_{\text{gate}} \) gates of the same width, the mean number of signal detections \( N_{\text{sig}} \) is

\[
N_{\text{sig}} = p_{\text{sig, gate}} N_{\text{gate}}. \tag{14}
\]

Assuming Poissonian statistics, we calculate the fluctuation

\[
\Delta N_{\text{sig}} = \sqrt{p_{\text{sig, gate}} N_{\text{gate}}}. \tag{15}
\]

The same derivation holds for the dark counts: we introduce a dark count probability per gate \( p_{\text{dc, gate}} \) (which will be measured directly) leading to

\[
\Delta N_{\text{dc}} = \sqrt{p_{\text{dc, gate}} N_{\text{gate}}}. \tag{16}
\]

The NEP is inferred by calculating the optical power necessary to produce \( \Delta N_{\text{tot}} \) counts when applying \( N_{\text{gate}} \) gates. In order to achieve this, we replace \( P_{\text{opt}} \) by NEP in (12) and multiply by \( N_{\text{gate}} \) as

\[
\Delta N_{\text{tot}} = \frac{\eta}{h \nu} \frac{\Delta t_{\text{gate}}}{N_{\text{gate}}} \tag{17}
\]

Using (14)–(16) and solving for NEP yields

\[
\text{NEP} = \frac{h \nu}{\eta} \sqrt{p_{\text{sig, gate}} + p_{\text{dc, gate}}} \frac{1}{N_{\text{gate}} \Delta t_{\text{gate}}} \] (in W). \tag{18}

The minimal detectable power \( \text{NEP}_0 \) is obtained by setting the signal shot noise contribution equal to zero

\[
\text{NEP}_0 = \frac{h \nu}{\eta} \sqrt{\frac{p_{\text{dc, gate}}}{N_{\text{gate}} \Delta t_{\text{gate}}}} \] (in W). \tag{19}

The existence of \( N_{\text{gate}} \) in these equations represents the iteration of a measurement and is a function of time \((N_{\text{gate}} = f_{\text{probe}}(t))\). The elemental measurement time is represented by \( \Delta t_{\text{gate}} \), the duration of a single gate, which can be interpreted as the detection bandwidth via \( B := 1/(2 \Delta t_{\text{gate}}) \). These formulas are practical when a NEP for a particular measurement needs to be
calculated (see also Appendix C). In order to obtain a formula that makes it easy to compare different detectors, we normalize with respect to \( N_{\text{gate}} \) (which represents nothing else than the measurement time) and bandwidth \( B \)

\[
\text{NEP}_{\text{norm}} = \frac{h \nu}{\eta} \sqrt{2(\hat{p}_{\text{sig}} + \hat{p}_{\text{dc}})} \left[ \frac{W}{\sqrt{Hz}} \right]
\]

and

\[
\text{NEP}_{\text{norm},0} = \frac{h \nu}{\eta} \sqrt{2\hat{p}_{\text{dc}}} \left[ \frac{W}{\sqrt{Hz}} \right]
\]

where

\[
\hat{p}_{\text{dc}} := \frac{\hat{P}_{\text{DC, gate}}}{\Delta t_{\text{gate}}}, \quad \hat{p}_{\text{sig}} := \frac{\hat{P}_{\text{sig, gate}}}{\Delta t_{\text{gate}}}
\]

are the signal and dark count probability per gate, normalized with respect to the gate width in seconds.\(^\text{13}\)

**APPENDIX C**

**DYNAMIC RANGE OF OPTICAL TIME-DOMAIN REFLECTOMETER**

The strongest backscatter signal is observed right after the emission at time \( t_0 = \Delta t_p/c \), coming from the fiber locations within the interval \([0; \Delta t_p/2] \), where \( c \) is the speed of light in the fiber and \( \Delta t_p \) is the width of the laser pulse. The corresponding backscatter power is given by [24]

\[
P_{\text{BS,0}} = SP_{\text{eff}} e^{-2\alpha_s L}(1 - e^{-\alpha_s \Delta t_p})
\]

where \( S \) is the fibers caption ratio, \( P_{\text{eff}} \) is the effective laser peak power corrected for internal component (e.g., circulator) and connector loss, and \( \alpha_s \) the scattering coefficient. If we assume that \( \alpha_s \Delta t_p \ll 1 \), which is true in standard fiber (\( \alpha_s \approx 0.04 \text{ km}^{-1} \)) and \( \Delta t_p < 2 \text{ km} (\Delta t_p < 10 \text{ ms}) \), we can expand the exponential and get

\[
P_{\text{BS,0}} \approx SP_{\text{eff}} \alpha_s \Delta t_p.
\]

The dynamic range is then given by the ratio of \( P_{\text{BS,0}} \) and the minimal detectable power \( \text{NEP}_0 \) [in watts]

\[
\text{SNR} = 5 \log \left( \frac{P_{\text{BS,0}}}{\text{NEP}_0} \right)
\]

where the factor 5 accounts for the round-trip in the fiber. Finally, we obtain

\[
\text{SNR} \approx 5 \log \left( \frac{SP_{\text{eff}} \alpha_s \Delta t_p}{\text{NEP}_0} \right).
\]

We note that \( \text{NEP}_0 \), like the one used here, includes the measurement time and decreases \( \propto \sqrt{t} \) (also see (19) in the case of the \( \nu \)-OTDR, where the measurement time \( t \) is represented by the number of applied gates, \( N_{\text{gate}} = f_{\text{pulse}} t \)).

The operational definition of the dynamic range of an OTDR, given, for example, in [24], contains a measurement time of 3 min. It is apparent that an extended measurement time enhances the \( \text{NEP}_0 \), and thus, the dynamic range. In general, if the measurement time is increased by a factor \( d \), the standard deviation of the noise is lowered by a factor \( \sqrt{d} \), and thus, the \( \text{NEP}_0 \) by the same amount.

**APPENDIX D**

**TWO-POINT RESOLUTION ADVANTAGE OF \( \nu \)-OTDR**

We assume an \( x \) dB \( \nu \)-OTDR advantage in dynamic range (with respect to conventional OTDR, using the same laser pulselength \( \Delta t_p \)). Now, we look for a factor \( \alpha \) such that \( \alpha \Delta t_p \) yields a reduction of the \( \nu \)-OTDR dynamic range by \( x \) dB. Using (26), (19), and \( \Delta t_{\text{gate}} = \Delta t_p/c \) (adapting laser pulselength and gate width), we have to fulfill

\[
5 \log \left( \frac{(\alpha \Delta t_p)^{3/2}}{(\Delta t_p)^{3/2}} \right) = x
\]

yielding

\[
\alpha = 10^{-2x/15}.
\]

For example, \( x = 10 \text{ dB} \rightarrow \alpha = 0.046 \). Thus, the \( \nu \)-OTDR can achieve the same dynamic range with a 20 times smaller pulselength.

**APPENDIX E**

**SNR AS A FUNCTION OF MEASUREMENT TIME**

We derive a formula for the SNR as a function of time from the photon-counting perspective. However, the final result, after linearization, will not contain any photon-counting specific quantity and is therefore generally applicable.

We define the SNR as the ratio of signal counts \( N_{\text{sig}} \) to the total fluctuation of the counts \( \Delta N_{\text{tot}} \), including fluctuation of signal and dark counts (like defined in Appendix B)

\[
\text{SNR} = \frac{N_{\text{sig}}}{\Delta N_{\text{tot}}} = \frac{P_{\text{sig, gate}} N_{\text{gate}}}{\sqrt{(P_{\text{sig, gate}} + P_{\text{dc, gate}}) N_{\text{gate}}}}
\]

using (13) and (16). Now, we introduce the bandwidth-normalized NEP (20) and use \( N_{\text{gate}} = f_{\text{pulse}} t \), where \( t \) is the measurement time

\[
\Rightarrow \text{SNR} = \frac{\sqrt{2h\nu}}{\eta} \frac{P_{\text{sig, gate}} f_{\text{pulse}} t}{\text{NEP}_{\text{norm}} \sqrt{\Delta t_{\text{gate}}}}
\]

then replacing \( P_{\text{sig, gate}} \) using (9) and (10)

\[
\text{SNR} = \frac{\sqrt{2h\nu}}{\eta} \left( \frac{1 - e^{-\eta \nu f_{\text{gate}}}}{f_{\text{pulse}} t} \right)^{1/2} \frac{1}{\text{NEP}_{\text{norm}} \sqrt{\Delta t_{\text{gate}}}}
\]

\[\text{(28)}\]
If the optical input power is sufficiently small, the signal detection probability increases linearly with the optical power and we can expand the exponential to obtain

\[
\text{SNR} = \frac{P_{\text{opt}} \sqrt{f_{\text{pulse}}} \sqrt{2 \Delta t_{\text{gate}}}}{\text{NEP}_{\text{norm}}} = \frac{P_{\text{opt}} \sqrt{f_{\text{pulse}}} \sqrt{B}}{\text{NEP}_{\text{norm}} \sqrt{B}} \tag{29}
\]

where we used \( B = 1/(2 \Delta t_{\text{gate}}) \), the detection bandwidth.

This final formula is independent of any photon counting quantities and does also apply for the general case, including linear APD detection. In the linear regime, there is even no such severe restrictions as in photon-counting mode, since much higher \( P_{\text{opt}} \) can be processed.

On the other hand, if measurement time needs to be calculated as a function of SNR, we obtain straightforward

\[
t = \frac{1}{f_{\text{pulse}}} \left( \frac{\text{SNR} \cdot \text{NEP}_{\text{norm}} \sqrt{B}}{P_{\text{opt}}} \right)^2. \tag{30}
\]

APPENDIX F

TRAIN OF GATES DISCUSSION

The application of a dead time can have considerable impact on the gate activation statistics. Fig. 12 shows what happens if the product \( f_{\text{gate}} \cdot \tau \) is chosen too large.

If we assume that the probability of detecting a signal photon in the first gate of the train of gates is \( p_{\text{sig, gate1}} \), then gate 2 gets activated with probability \( (1 - p_{\text{sig, gate1}}) \) (otherwise, it falls into the dead time of gate 1). The probability that gate \( i \) gets activated \( (i = f_{\text{gate}} \cdot \tau) \) is then given by

\[
p_{\text{act, gate}i} = (1 - p_{\text{sig, gate1}})^{(i-1)} \tag{31}
\]

where we assume that the signal detection probability is almost constant at the beginning of the fiber. This expression approaches 0 when \( i \) is large. In the worst case, “activation holes” appear in a repetitive manner (see Fig. 12, in the case where the minima of the periodic structure at the beginning touch zero probability), and therefore, detections around these locations are impossible or only possible with very low statistics.

To avoid this, we can define a criteria, which ensures that each gate has a sufficient number of activations. The first minimum plays the role of a bottleneck. When it is above some threshold (to be defined), all the other minima are also above the threshold.

The minimum depends on \( p_{\text{sig, gate1}} \) and \( f_{\text{gate}} \cdot \tau \).

Using (31), we can calculate the maximally suitable gating frequency \( f_{\text{gate, max}} \), depending on a designated threshold (see Fig. 13).

**Example:** Assuming \( \tau = 1 \mu s, p_{\text{sig, gate1}} = 0.25 \), and an activation minimum of 0.4. Then, we infer \( f_{\text{gate, max}} \cdot \tau = 4 \) (see arrows in Fig. 13), and therefore, \( f_{\text{gate, max}} = 4/\tau = 4 \text{ MHz} \). If the maximally suitable gating frequency \( f_{\text{gate, max}} \) is not large enough to obtain the designated sampling resolution, it is necessary to shift the start delay of the train of gates. For instance, if we want a sampling resolution of 5 m, but \( f_{\text{gate, max}} = 4 \text{ MHz} \), yielding only 25 m, we need to delay the train (with respect to the laser pulse departure) four times by 50 ns. This of course increases the total measurement time by a factor 5.

We note that \( f_{\text{gate, max}} \) is in principle bounded by \( 1/\Delta t_{\text{gate}} \).

If the suggested \( f_{\text{gate, max}} \), according to Fig. 13, is larger than \( 1/\Delta t_{\text{gate}} \), we are naturally led to the free-running mode, where the diode stays active until a detection is obtained [18] (see Fig. 10). This happens if

\[
\mu < \frac{b}{\tau} \tag{32}
\]

or equivalently

\[
P_{\text{opt}} < \frac{h \nu b}{\eta \tau} \tag{33}
\]

where \( \mu \) is the photon flux (number of photons per second, cw) and \( P_{\text{opt}} \) the corresponding power, \( \eta \) the detector efficiency, \( \tau \)

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14The reason for this is the fiber loss, which decreases the backscattered signal, and therefore, yields less detections and dead time applications. The dead time effect gets less severe. When the backscatter power is very low, there is almost no difference to the ideal case.
the detector dead time, and \( b \) a constant depending on the activation minimum criteria, explicitly: for an activation minimum of 0.2 (0.4, 0.6, 0.8), one obtains \( b = 1.61(0.92, 0.51, 0.23) \). Due to its superior duty cycle, the free-running mode is the ideal low-power solution.

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