

Nonlinearity Mitigation in SPAD-Based PC-OTDR Using Gated Detection With Dynamic Power Control

Zhechun Ding, Xizi Sun, Zheng Wang, Yidong Huang, and Wei Zhang

Abstract—Photon-counting optical time-domain reflectometry (PC-OTDR) based on InGaAs/InP single-photon avalanche photodiodes (SPADs) for long-distance fiber measurement is limited by the long detector dead time, which induces a nonlinear distortion on OTDR trace. Although SPADs are commonly operated with weak optical pulse powers and narrow gate widths to maintain the detector within the linear regime and suppress such distortion, the underlying mechanism of this nonlinear distortion has not been thoroughly investigated, and such operation often suffers from the consumption of measurement time. This work investigates the nonlinear response of SPADs from the count-rate response and the temporal evolution of photon-count traces under both free-running and gated operation. An optimized gated measurement scheme with dynamic control of Rayleigh backscattered optical power incident on the SPAD is proposed, where the operating parameters are optimized by comprehensively considering nonlinear distortion mitigation and signal-to-noise ratio (SNR) performance. Experiment results demonstrate the proposed method and its robustness for loss and reflection events. These results improve the practicality of SPAD-based PC-OTDR for long-distance fiber measurements.

Index Terms—Optical time-domain reflectometry (OTDR), photon counting, nonlinearity, single-photon avalanche photodiode (SPAD)

I. INTRODUCTION

OPTICAL time-domain reflectometry (OTDR) is a widely used techniques for optical fiber testing and sensing [1], [2], [3]. In typical implementations, linear detectors such as PIN photodiodes or avalanche photodiodes (APDs) are employed [4], [5], [6], [7]. To improve spatial resolution, very short optical pulses are required, which consequently demand a wide detection bandwidth. Increasing the detection bandwidth, however, raises the noise level, reducing detection sensitivity and limiting the sensing range. As a result, it remains difficult for conventional OTDR systems to simultaneously achieve high spatial resolution and long sensing range [8].

To address this limitation, photon-counting OTDR (PC-OTDR) has been proposed [9], [10]. By exploiting the high sensitivity of single-photon detectors (SPDs) and the time-resolved measurement enabled by time-correlated single-photon counting (TCSPC), centimeter-scale spatial resolution can be achieved over tens of kilometers [11], [12], [13]. However, long-distance fiber measurement using PC-OTDR is limited by the recovery time of the SPD, defined as the detector

inactive period introduced after each detection event [14]. Superconducting nanowire single-photon detectors and up-conversion silicon SPDs provide nanosecond-scale recovery time, enabling PC-OTDR measurements over hundreds of kilometers [15], [16], [17], [18], [19], [20], but their practical deployment is limited by the need for cryogenic operation or complex frequency-conversion systems. In comparison, InGaAs/InP single-photon avalanche photodiodes (SPADs) offer acceptable detection efficiency with compact, and easily integrable detection systems [21]. A key challenge is the significant afterpulsing effect, which requires a dead time of several tens of microseconds in free-running mode by adjusting the reverse bias of SPADs [14]. As a result, when the Rayleigh backscattered signal is strong, the detector count rate may approach saturation, leading to distortion in the OTDR trace due to pile-up effect [22]. To overcome this issue, gated scanning schemes have been proposed [23], [24], [25]. By employing weak pulse powers and narrow gate widths of a few nanoseconds, the probability of detecting more than one photon within a gate is minimized, thereby suppressing the pile-up effect and reducing trace distortion. Using such gating schemes, fiber measurements over tens of kilometers with SPADs have been demonstrated [26], [27]. This approach nonetheless suffers from two major limitations: weak pulse powers lead to a lower signal-to-noise ratio (SNR) compared with higher pulse powers, and narrow gate widths require more scans to cover the entire fiber, thus increasing total acquisition time.

In this work, we analyze the nonlinear response induced by the long dead time of SPADs in free-running operation from two perspectives: the average count rate and the temporal evolution of photon counts. The corresponding pile-up effect in OTDR traces is examined to clarify the limitations of free-running SPAD operation for long-distance fiber measurements. A measurement scheme combining gating with dynamic control of Rayleigh backscattered optical power incident on the SPAD is proposed. By dynamically adjusting the variable optical attenuation (VOA) for each gate to maintain a constant average count rate and reconstructing the OTDR trace through post-processing, nonlinear distortion is effectively eliminated while a uniformly high SNR is maintained along the entire fiber. A general parameter optimization strategy for pulse power and gate width is also developed for this scheme to balance nonlinear distortion mitigation and SNR performance. Loss and reflection events with different strengths are experimentally measured and compared with results from a commercial OTDR, demonstrating the robustness of the scheme. A correction strategy for extreme OTDR events is presented and experimentally validated.

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II. NONLINEAR RESPONSE OF SPADS

When a photon is incident on a SPAD, the detector cannot respond to subsequent photons during its dead time leading to a nonlinear response of the SPAD. Under high incident optical power, frequent dead-time triggering therefore constrains the achievable count rate. This relationship is described by Eq. (1) [28].

$$C_{\text{count}} = \frac{\eta C_{\text{imp}}}{1 + \eta C_{\text{imp}} T_d} \quad (1)$$

Here, C_{imp} denotes the average incident count rate at the detector, which is estimated from the incident optical power and the photon energy $h\nu$. C_{count} is the measured output count rate, η is the detection efficiency, and T_d is the dead time of the detector. To evaluate the performance of SPAD as the detector in OTDR system, a commercial SPAD (Micro Photon Devices, PDM-IR) is employed in this work, with a dead time set to $24 \mu\text{s}$ (for which the afterpulsing effect is negligible), a detection efficiency of approximately 14% around 1550 nm and a free-running dark count rate (DCR) of approximately 830 cps [29]. Operating the detector in free-running mode, continuous-wave optical signals with different power are directly incident on the detector, and the average count rate is recorded over a measurement time of 5 s. The measured data are fitted using Eq. (1), as shown in Fig. 1(a).

As the incident optical power increases, the detector count rate no longer scales proportionally and gradually approaches saturation. This behavior is defined as the nonlinear response of the detector. In TCSPC measurements, this nonlinearity manifests as a pile-up effect [22], since the counts in each time bin are influenced by all preceding detections within the dead time ($24 \mu\text{s}$). At high optical power ($\text{CR} \approx 37 \text{ kcps}$), corresponding to the near-saturation regime in Fig. 1(a), pronounced pile-up effects are observed, as exemplified in Fig. 1(b). Ideally, under continuous-wave illumination, the recorded counts are expected to remain temporally stable. However, detection events of earlier photons suppress subsequent responses, leading to a rapid drop in the recorded counts. During this low-count interval, the reduced number of detections weakens the suppression exerted on later photons, allowing the count rate to recover. This alternating process gives rise to oscillations. Under low optical power ($\text{CR} \approx 7 \text{ kcps}$), corresponding to the initial linear regime in Fig. 1(a), the pile-up effect is reduced, as exemplified in Fig. 1(c). The count distribution becomes more stable; nevertheless, because pile-up effects cannot be completely eliminated in free-running mode with long dead time, the signal toward the trailing region remains suppressed and deviates from the expected steady level. To investigate the impact of detector nonlinearity in free-running mode on OTDR measurements, the experimental setup shown in Fig. 1(d) is used. A non-coherent laser source is used to generate continuous-wave light at 1550 nm. Optical pulses with a duration of 100 ns (corresponding to a spatial resolution of 10 m) are generated using an acousto-optic modulator (AOM). Pulses with a peak power of -18.7 dBm are sent into a 20 km fiber under test (FUT) via a circulator. The backscattered signal is then detected by the SPAD, which operates in free-running mode with

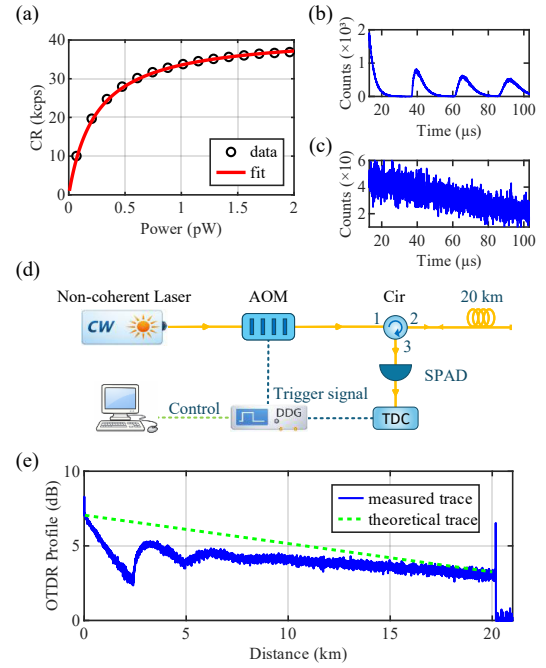


Fig. 1. (a) Count-rate versus input power of the free-running mode SPAD with $T_d = 24 \mu\text{s}$. Representative temporal evolution of photon counts under (b) high optical power ($\text{CR} \approx 37 \text{ kcps}$) and (c) low optical power ($\text{CR} \approx 7 \text{ kcps}$). (d) Experimental setup of the OTDR measurement with the SPAD operating in free-running mode. (e) Measured OTDR profile with an average count rate of 20 kcps and an acquisition time of 1 min.

same parameters used in Fig. 1(a). The output of the SPAD is sent to a TCSPC system (Swabian Instruments, Time Tagger Ultra), which operates in histogram mode with a specified time-bin width and measurement duration. The TCSPC system is periodically triggered by a digital delay generator (Stanford Research Systems, DG645), which is synchronized with the trigger signal of the pulsed light source. The measured OTDR trace is shown in Fig. 1(e), where the average count rate is approximately 20 kcps, making the free-running DCR of approximately 830 cps negligible. The dashed line represents the theoretical trace corresponding to a fiber attenuation of 0.19 dB/km. At the beginning of the fiber, the backscattered optical power is relatively high. Pronounced pile-up effects therefore induce nonlinear distortions in the first half of the measured trace, resembling the near-saturation behavior shown in Fig. 1(b). As the optical power decreases along the fiber due to attenuation, the trace gradually approaches the low-power regime illustrated in Fig. 1(c), becoming more stable but remains lower than the theoretical expectation.

In long-distance OTDR measurements, relatively high pulse power is often required to ensure sufficient dynamic range, likely leading to distortions similar to Fig. 1(e). These observations indicate that long-distance fiber measurements using InGaAs/InP SPADs in free-running mode are significantly limited by long dead time. To solve this issue, an optimized gating scheme is proposed in the following section, and its effectiveness in mitigating detector nonlinearity is demonstrated.

III. GATED SCHEME WITH DYNAMIC POWER CONTROL AND EXPERIMENTAL DEMONSTRATION

The gating scheme employed in this work is implemented by regulating the built-in bias voltage of the SPAD. When the gate is ON, the reverse bias of the APD is set above the breakdown voltage, and the detector operates in Geiger mode with single-photon sensitivity. When the gate is OFF, the bias voltage is reduced below breakdown, and the APD operates in the conventional linear regime with strongly reduced sensitivity. In this state, it is incapable of single-photon detection and cannot respond to backscattered photons.

Based on this gating operation, a basic gated OTDR scheme is first considered, building upon the approach reported by ref. [26]. Within each pulse period, a single gate probes the corresponding fiber segment. By adjusting the temporal delay between the optical pulse and the gate signal, the entire fiber is sequentially interrogated. In the following experiment, the detector dead time T_d is maintained at $24 \mu s$. Since the FUT is 20 km long, the pulse period T , which also serves as the gate repetition period in each measurement, is set to $230 \mu s$. The gate width t_{on} is varied within the range of $2 - 12 \mu s$. Under this gated operation, the dead time triggered within one gate does not affect subsequent gates because $T \gg T_d$, and each gate can register at most one photon since $t_{on} < T_d$. The detection process is therefore no longer governed by dead-time effects but instead becomes a binary single-photon sampling process in which each gate records either zero or one photon detection. If the average incident count rate from a given fiber segment is C_{imp} , the expected number of signal detections within one gate is $\eta C_{imp} t_{on}$, and the incident photon number follows a Poisson distribution. Because only the first detection event within a gate is registered, the detection probability—corresponding to at least one photon entering the detector—is given by $1 - P(0)$, as expressed in Eq. (2) [14], where $P(0)$ denotes the probability of zero photons in the Poisson distribution.

$$1 - P(0) = 1 - e^{-\eta C_{imp} t_{on}} \quad (2)$$

To quantitatively compare detector nonlinearity under gated and free-running operation, the average count rate of the gated SPAD is measured as a function of incident optical power for two representative gate widths ($2.9 \mu s$ and $5.79 \mu s$) and fitted using Eq. (2). The results are compared with the free-running nonlinearity curve in Fig. 1(a), as shown in Fig. 2(a). The gated mode exhibits an improved linear relationship between photon count rate and incident optical power, with a narrower gate width yielding higher linearity. However, as the optical power increases, linearity still gradually deteriorates. With microsecond-level gate widths, the probability of multiple photons entering a single gate becomes non-negligible at high power. Since only the first detection event is registered, subsequent photons are effectively suppressed, and pile-up effects still occur, resulting in trace distortion. However, if the backscattered optical power injected into SPAD—or equivalently the average count rate—can be maintained at the same level for all fiber segments, and this level is chosen within the region of good linearity, distortion in the reconstructed OTDR trace can be effectively reduced.

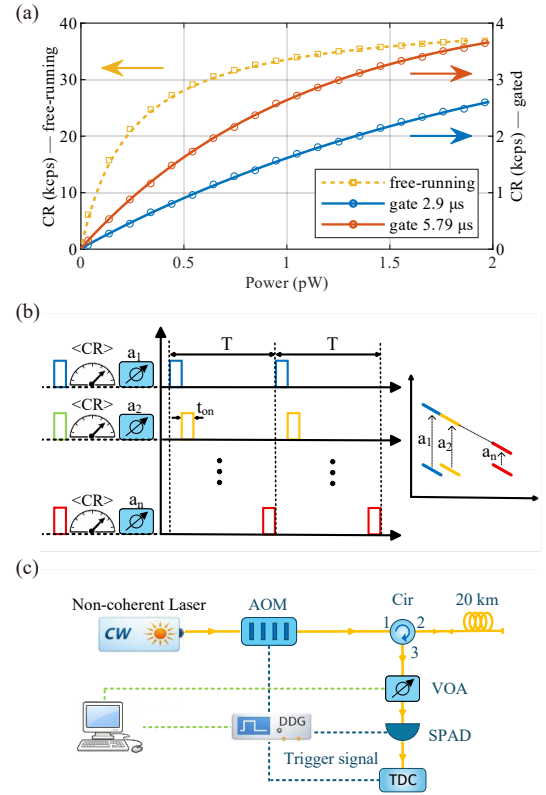


Fig. 2. (a) Comparison of the count-rate nonlinearity of the SPAD under free-running and gated operation with different gate widths. (b) Measurement timing diagram of the proposed scheme. (c) Experimental OTDR setup of the proposed scheme, where the SPAD operates in gated mode.

Motivated by this observation, a gated scanning scheme combined with dynamic optical power regulation via VOA is developed. The timing diagram and the data reconstruction process are illustrated in Fig. 2(b). The original gating strategy is preserved. Before each gate measurement, the count rate is monitored, and the VOA attenuation is dynamically adjusted according to the calibrated relationship between the incident optical power and the count rate for the selected gate width (e.g., the red and blue curves in Fig. 2(a)) until the count rate converges to a predefined target level. The details are provided in the Appendix B. The resulting attenuation is recorded, after which the measurement is performed. This procedure is repeated for each gate, ensuring a consistent average count rate across all gates, hereafter defined as the count-rate working point C_{wp} . During post-processing, individual gated segments are concatenated and their amplitudes are rescaled according to the applied attenuation values, enabling reconstruction of the complete OTDR trace. The experimental setup is illustrated in Fig. 2(c). Compared with the free-running configuration in Fig. 1(d), the detector operates in gated mode and is externally driven by the digital delay generator, while the VOA is dynamically controlled by a computer according to the measured average count rate.

In gated OTDR measurements, improved linearity reduces trace distortion, making narrower gate widths desirable. However, measuring the entire fiber with a smaller t_{on} requires

a larger number of scans and therefore increases the total acquisition time. Alternatively, under a fixed acquisition duration, a smaller t_{on} reduces the integration time allocated to each gate, which in turn degrades the SNR. The measurement parameters—including gate width, the selected count rate to maintain, and the total acquisition time—must therefore be jointly optimized to achieve high SNR while avoiding trace distortion. For simplicity, the total acquisition time is fixed at 20 min. It is worth noting that the input optical power of the SPAD is controlled by attenuation of the VOA to achieve a specific C_{wp} under a specific t_{on} . In the experiment, we set the VOA to achieve a C_{wp} of 354 cps under $t_{\text{on}} = 2 \mu\text{s}$, then normalize input optical powers of the SPAD under other measurement conditions by that under this condition. In this way, a normalized optical power P_{nor} is defined, which is exactly the attenuation difference of the VOA between the case of the current measurement and that under the condition of $C_{\text{wp}} = 354$ cps and $t_{\text{on}} = 2 \mu\text{s}$. In the experiment, the gate width t_{on} and the normalized optical power P_{nor} are varied as independent parameters. A 20 km fiber is measured under each parameter combination. Figs. 3(a) and 3(b) present the SNR and inter-gate discontinuity as functions of t_{on} and P_{nor} . The SNR is calculated from the mean and standard deviation of 20 adjacent sampling points within each gate, and therefore inherently includes the noise introduced by the DCR. Under the gated operating conditions, the DCR is approximately 8 cps for a gate width of $2 \mu\text{s}$ and scales linearly with the gate width. The inter-gate discontinuity is defined as the ratio between the averages of ten data points immediately before and after each gate boundary.

With the total acquisition time held fixed, a larger gate width t_{on} requires fewer gate scans to cover the FUT, thereby allocating longer integration time to each gate and improving the SNR. In addition, higher incident optical power further enhances the SNR. However, as shown in Fig. 2(a), higher incident optical power increases the probability of multiple photons entering a gate, thereby aggravating pile-up effects. Photons arriving immediately after gate opening are more likely to trigger detection and suppress subsequent photons, causing distortions like those observed in Fig. 1(c). Increasing integration time by using larger t_{on} further amplifies this effect. Since adjacent gates are statistically independent, suppression at the end of one gate creates a discontinuity when concatenated with the beginning of the next gate, resulting in inter-gate jumps. To illustrate this phenomenon, two representative parameter sets are selected. Fig. 3(c) shows concatenated and rescaled traces of two adjacent gates (distinguished by color), with the dashed line representing the theoretical attenuation of 0.19 dB/km. The upper panel in Fig. 3(c) is obtained using $t_{\text{on}} = 12.11 \mu\text{s}$ and $P_{\text{nor}} = 0$ dB, corresponding to the parameter marked by triangles in Figs. 3(a) and 3(b), under which the SNR reaches 12.58 dB. However, pronounced pile-up effect suppresses the trailing portion of each gate, resulting in evident inter-gate discontinuities. It should be noted that the trace shown has been post-processed according to the applied attenuation for each gate. As observed, the leading portions of the gates, where pile-up is less significant, align well with the theoretical curve, indicating that the inter-gate discontinuities originate

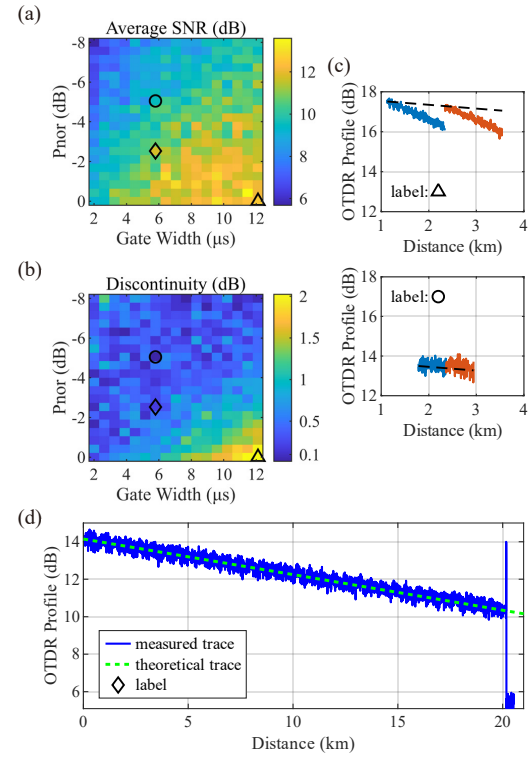


Fig. 3. (a) Average intra-gate SNR and (b) inter-gate discontinuity of the OTDR trace measured under different gate widths (2 – 12 μs) and normalized optical power levels (0 to –8 dB). The symbols (Δ , $\circ$, $\diamond$) indicate the parameter sets corresponding to the traces shown in (c) and (d). (c) Representative OTDR traces illustrating strong (top) and weak (bottom) inter-gate discontinuities, corresponding to $t_{\text{on}} = 12.11 \mu\text{s}$, $P_{\text{nor}} = 0$ dB and $t_{\text{on}} = 5.79 \mu\text{s}$, $P_{\text{nor}} = -5.05$ dB, respectively. (d) Measured OTDR profile of a 20 km fiber obtained with the optimal working parameters ($t_{\text{on}} = 5.79 \mu\text{s}$, $P_{\text{nor}} = -2.53$ dB).

solely from intra-gate signal suppression induced by pile-up effects. In contrast, the lower panel in Fig. 3(c), obtained with $t_{\text{on}} = 5.79 \mu\text{s}$ and $P_{\text{nor}} = -5.05$ dB (corresponding to the parameter marked by circles in Figs. 3(a) and 3(b)), exhibits a smoother trace but the SNR drops to 9.49 dB. These results reveal the intrinsic trade-off between SNR and inter-gate continuity, necessitating balanced parameter selection.

Fig. 3(b) illustrates inter-gate discontinuity trends but does not directly correlate with practical OTDR event detection metrics. Since inter-gate jumps typically appear as signal variations resembling reflection events, a reflection-event decision framework based on Poisson statistics is constructed, inspired by the Neyman–Pearson criterion [30]. This decision framework is applied to the OTDR trace under each parameter set (t_{on} , P_{nor}). With predefined detection performance (P_D^R and P_{FA}^R), the P_D^D and $\Delta\lambda$ are calculated for parameter selection. The definitions of the involved parameters are summarized in Table I, and the detailed modeling and derivation are provided in the Appendix.

Ultimately, for each OTDR trace measured under a given pair of working parameters (t_{on} , P_{nor}), the SNR is calculated to characterize the signal quality. A decision system with $P_D^R \geq 80\%$ and $P_{FA}^R = 0.1\%$ is then applied to evaluate P_D^D for each trace, which serves as a quantitative metric

TABLE I
DEFINITION OF KEY PARAMETERS IN THE DECISION FRAMEWORK

Symbol	Definition
P_D^R	Probability of correctly detecting a reflection event
P_{FA}^R	Probability of falsely identifying a reflection event when no event is present
P_{FA}^D	Probability that an inter-gate discontinuity is falsely identified as a reflection event
$\Delta\lambda$	Minimum detectable signal change

of inter-gate smoothness. Based on these two metrics, the optimal parameter set is selected as the one that provides the highest SNR while satisfying the constraint $P_{FA}^D < 5\%$. This selection leads to $P_{\text{nor}} = -2.53$ dB and $t_{\text{on}} = 5.79$ μs , corresponding to $C_{\text{wp}} = 580$ cps. Under this parameter set, an SNR of 11.77 dB with $\Delta\lambda = 0.68$ dB is achieved, while P_{FA}^D is reduced to 4%, satisfying the design constraint. The 20 km measurement obtained with a total acquisition time of 20 min under these conditions (marked by diamonds in Figs. 3(a) and 3(b)) is shown in Fig. 3(d). As observed, the nonlinear distortion illustrated in Fig. 1(e) is effectively eliminated, and the measured OTDR trace closely follows the theoretical trace corresponding to a fiber attenuation of 0.19 dB/km. Compared with conventional gated schemes that employ nanosecond-scale gates and weak optical power to avoid distortion under strong signals—at the cost of reduced SNR for weak signals—the proposed approach dynamically adjusts the VOA during scanning to maintain the detector at the same optimal working point along the entire fiber. This enables the use of wider gates at the microsecond scale together with higher optical power to improve SNR, while simultaneously suppressing nonlinear distortion and preventing the gradual SNR degradation with distance.

IV. ROBUSTNESS TO LOSS AND REFLECTION EVENTS

In practical scenarios, the FUT exhibits loss events caused by fiber bending or loose connectors, as well as Fresnel reflection events originating from imperfect connector interfaces. In gated OTDR measurements, when a loss or reflection event falls within a gate, the count rate can vary sharply in the vicinity of the event. Although the average count rate is regulated around C_{wp} through the VOA, a wide count-rate variation may still exist within a single gate, which can introduce measurement errors. This section evaluates the accuracy of the proposed gating scheme in characterizing loss and reflection events and examines its robustness under different event magnitudes.

For loss-event characterization, a 1 km fiber segment is connected to a 20 km fiber through an attenuator to artificially introduce attenuation with different magnitudes. The optimal working parameters identified in Section III are maintained. Fig. 4(a) shows an OTDR trace near a 5.2 dB loss event, where adjacent gates are distinguished by color. As observed, the gates that do not contain the loss event (blue and green) maintain similarly high SNR, demonstrating stable system performance under uniform conditions. In contrast, the gate

that contains the loss event (red) clearly resolves the step-like attenuation introduced by the event. However, although the average count rate within the gate is regulated around $C_{\text{wp}} = 580$ cps, when the loss is large, the abrupt change in count rate at the loss event still leads to reduced SNR in the region after the attenuation, resulting in degraded signal quality. To further evaluate the robustness of the proposed scheme, the magnitude of loss event is varied by adjusting the attenuator, and the measured loss values are compared with those obtained from a commercial OTDR (Yokogawa, AQ7280), as shown in Fig. 4(b). The results indicate that the PC-OTDR measurements closely match those of the conventional OTDR over a wide range of loss levels. Although local SNR degradation may occur within gates containing large loss events, reliable loss estimation is still achieved, demonstrating the robustness of the approach.

For reflection events, the 1 km and 20 km fiber segments are directly connected using a fiber connector. Different levels of Fresnel reflection are generated by adjusting the connector tightness and the cleanliness of the fiber end face. Fig. 4(c) shows a representative OTDR trace near a reflection event, where the peak-to-background ratio is approximately 5.5 dB. The reflection peak corresponds to a localized and transient increase in count rate, which has little influence on the signal level after the event and therefore only a minor impact on the overall average count rate. As a result, regulating the average count rate through the VOA effectively suppresses distortion while maintaining a uniformly high SNR across the trace. Fig. 4(d) compares the peak-to-background ratio of reflection events measured by the proposed PC-OTDR scheme with those obtained from the commercial OTDR. A systematic deviation of 0.48 dB is observed, which remains within an acceptable range. These representative results for both loss and reflection events, together with the comparison against the commercial OTDR, confirm that the proposed scheme achieves good measurement accuracy while maintaining high robustness under complex measurement conditions.

Furthermore, the detection strategy for extreme events, such as severe loss or very strong reflections, requires special consideration. These events can induce excessively large count-rate variations within a single gate. Even under gated scheme with the average count rate being regulated, the signal may still deviate from the effective linear region of the SPAD, leading to distortion in the reconstructed trace. Therefore, once such event is identified after the initial scan, a dedicated correction strategy for the affected region becomes necessary. To address this issue, the proposed correction strategy is inspired by the two-step measurement method presented in [27]. First, the initial scan with $t_{\text{on}} = 5.79$ μs serves as a coarse scan, which provides accurate measurements for most event magnitudes but may exhibit distortion in the presence of extreme events. Once the gate containing such an event is identified, a second fine scan is performed over the corresponding region covered by that gate. As shown in Fig. 2(a), a narrower gate width offers improved linearity; therefore, the fine scan adopts a gate width close to the spatial resolution to mitigate intra-gate nonlinear effects. The fine scan results are then rescaled and concatenated with the unaffected gates from the coarse scan

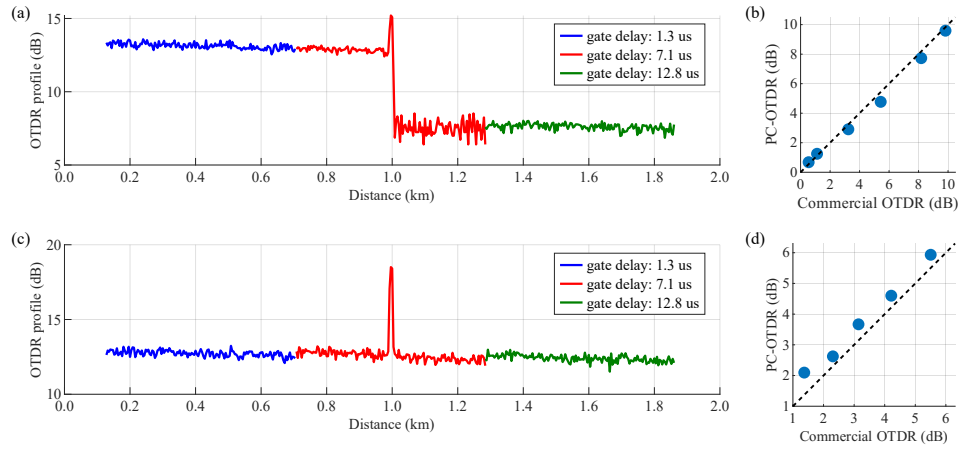


Fig. 4. OTDR traces near (a) a 5.2 dB loss event and (c) a reflection event with a peak-to-background ratio of approximately 5.5 dB, measured with $t_{\text{on}} = 5.79 \mu\text{s}$ and $C_{\text{wp}} = 580$ cps. Comparison of the (b) loss and (d) reflection measurements obtained with the proposed PC-OTDR scheme and a commercial OTDR (Yokogawa, AQ7280) for different event magnitudes.

to reconstruct the complete OTDR trace.

To validate this strategy, a 10 dB loss event is constructed using the same configuration as in Fig. 4(a) and 4(b), where the attenuator introduces approximately 10 dB attenuation between the 1 km and 20 km fiber segments. To maintain the count rate around $C_{\text{wp}} = 580$ cps at such high loss event, the pulse width is increased to $1 \mu\text{s}$ to raise the incident optical energy. The coarse scan, whose result is shown in Fig. 5(a), employs the same working parameters ($t_{\text{on}} = 5.79 \mu\text{s}$, $C_{\text{wp}} = 580$ cps) with the same acquisition time. The fine scan, presented in Fig. 5(b), is applied to the gate region containing the loss event (red), and employs a gate width $t_{\text{on}} = 200$ ns and $C_{\text{wp}}^{(f)} = 20$ cps, which is derived as $580 \text{ cps} \times (200 \text{ ns} / 5.79 \mu\text{s})$ to maintain consistent SNR between coarse and fine scans, while keeping the integration time per gate identical. In Fig. 5(b), the fine-scanned region is displayed in a uniform red color due to the increased number of narrow gates, while the remaining portions of the trace retain the same color convention as in Fig. 5(a).

Fig. 5(a) shows that even though the average count rate is regulated within the linear operating region through the VOA, a 10 dB loss event still drives the signal beyond the appropriate working range. The count rate before the loss remains excessively high, and the suppression of subsequent photons is still significant, so pronounced pile-up effects persist within the gate. As a result, the signal level at the trailing edge of the red gate becomes lower than that at the leading edge of the following green gate, leading to inter-gate discontinuity. More critically, the count rate after the loss drops substantially, resulting in very low SNR, thereby reducing the reliability of the measurement. After performing the fine scan over the affected region and rescaling the result, the reconstructed trace shown in Fig. 5(b) exhibits uniform SNR before and after the loss event and smooth inter-gate continuity without noticeable discontinuities. The measured loss is 9.6 dB, which agrees closely with the value of 9.8 dB obtained from the commercial OTDR. These results demonstrate that localized fine scanning with a narrow gate effectively reconstructs extreme events and

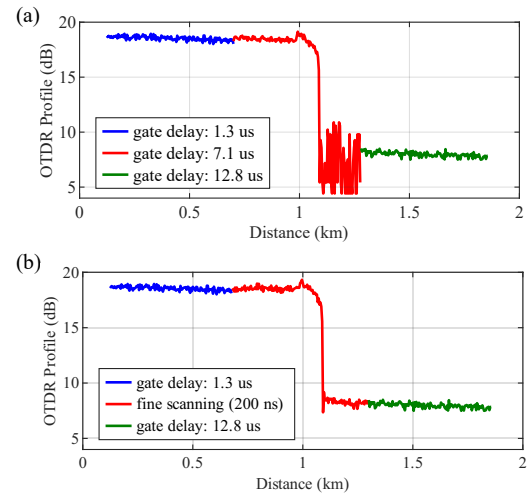


Fig. 5. (a) Coarse scan OTDR trace for a 10 dB loss event measured with $t_{\text{on}} = 5.79 \mu\text{s}$ and $C_{\text{wp}} = 580$ cps. (b) OTDR trace of the same event after fine scanning with $t_{\text{on}} = 200$ ns and $C_{\text{wp}} = 20$ cps (red), concatenated with the unaffected coarse scan gates; the integration time per gate remains unchanged.

extends the applicability of the proposed scheme to nearly all practical fiber sensing scenarios.

V. DISCUSSION

In the current implementation, only one gate is employed per measurement, leading to a relatively long total acquisition time. This limitation can be alleviated by replacing the VOA with an optical modulator capable of continuous intensity modulation. With proper temporal synchronization, multiple gates can be configured within a single measurement. Specifically, the required modulation level for each gate position can be pre-calibrated through count-rate convergence, and the modulation signal can then be aligned with the gating signal during measurement. In this way, multiple valid signal segments can be acquired within one pulse period. Under the same operating conditions in Fig. 3(d), up to six gates can be

accommodated within a single pulse period ($T/(t_{\text{on}} + T_d)$), potentially reducing the total acquisition time to approximately one-sixth.

Regarding the sensing range, the current system employs a pulse peak power of -18.7 dBm. By introducing an optical amplifier, such as an erbium-doped fiber amplifier, the pulse peak power can be increased to approximately 20 dBm, which is comparable to commercial OTDR systems. For the 20 km measurements shown in Fig. 3(d), a dynamic range of 3.8 dB is demonstrated (calculated using a fiber attenuation coefficient of 0.19 dB/km), and the optimized operating point still retains 2.53 dB of available VOA attenuation. By increasing the pulse peak power from -18.7 dBm to 20 dBm, the dynamic range can therefore be extended to approximately 24.4 dB, calculated as $3.8 + (20 + 18.7 + 2.53)/2 = 24.4$ dB. Furthermore, if sufficient backscattered optical power is ensured, a narrower pulse width can be employed to improve spatial resolution.

VI. CONCLUSION

In summary, this work systematically analyzes the limitations of free-running InGaAs/InP SPADs for long-distance PC-OTDR from two perspectives: the nonlinear count-rate response of the detector and the distortion of temporal evolution of photon counts due to pile-up effect. These effects are further illustrated through a practical PC-OTDR measurement over a 20 km fiber link, which reveals the pronounced distortion introduced by the long dead time under free-running operation. To address this issue, a measurement scheme combining gated detection and dynamic power control is proposed, along with a parameter optimization framework. An optimal parameter set of $t_{\text{on}} = 5.79 \mu\text{s}$ and $C_{\text{wp}} = 580$ cps is identified and used for a 20 km fiber measurement with a total acquisition time of 20 min. Under these conditions, nonlinear distortion is successfully eliminated, achieving a uniform SNR of 11.77 dB, while the false-alarm probability of inter-gate jumps is only $P_{FA}^D = 4\%$. The robustness of the proposed scheme is demonstrated through loss and reflection measurements. The measured loss values agree well with those obtained from a commercial OTDR, while reflection measurements exhibit a systematic deviation of 0.48 dB, which remains within an acceptable range. For extreme events, a dedicated correction strategy is introduced, and the reconstructed result differs by only 0.2 dB from the reference measurement. These results demonstrate an effective methodology for mitigating nonlinear distortion in SPAD-based PC-OTDR, thereby improving its practicality for long-distance fiber measurements.

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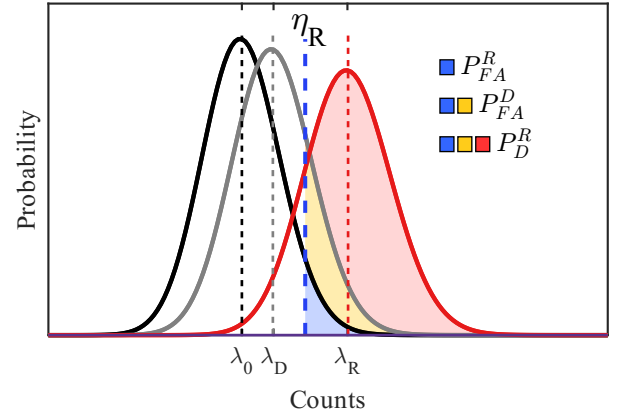


Fig. 6. Schematic illustration of the reflection-event decision framework based on Poisson statistics.

APPENDIX A FALSE-ALARM PROBABILITY OF INTER-GATE DISCONTINUITIES

For parameter optimization, OTDR traces are measured under different combinations of normalized power P_{nor} and gate width t_{on} . Based on these measurements, the intra-gate SNR and the inter-gate discontinuity are calculated (see Figs. 3(a) and 3(b)). To further quantify the impact of inter-gate discontinuities, an event-decision model based on photon-counting Poisson statistics is used. With this decision framework, the probability that photon-count jumps caused by inter-gate discontinuities are falsely identified as reflection events can be evaluated. A schematic illustration of the decision framework is shown in Fig. 6.

In this model, photon counts follow a Poisson distribution with mean values of λ , where λ_0 , λ_R , and λ_D denote the average photon numbers corresponding to the no-event case, reflection events, and the signal level after an inter-gate jump, respectively. The parameter η_R denotes the decision threshold that identify a reflection event. The definition of parameters P_D^R , P_{FA}^R and P_{FA}^D are given in Table I. For a given mean photon number, the detector count fluctuates according to a Poisson distribution, whose expression is given in Eq. (3).

$$P(N = n | \lambda) = \frac{e^{-\lambda} \lambda^n}{n!}, \quad n = 0, 1, 2, \dots \quad (3)$$

where N denotes the random photon count. In the decision system, these fluctuations are regarded as statistical noise. For reflection-event detection, the probabilities P_D^R and P_{FA}^R can be expressed by Eq. (4) and Eq. (5), respectively.

$$P_D^R = P(N \geq \eta_R | \lambda_R) = \sum_{n=\eta_R}^{\infty} \frac{e^{-\lambda_R} \lambda_R^n}{n!} \quad (4)$$

$$P_{FA}^R = P(N \geq \eta_R | \lambda_0) = \sum_{n=\eta_R}^{\infty} \frac{e^{-\lambda_0} \lambda_0^n}{n!} \quad (5)$$

In this work, the decision system is configured to satisfy $P_D^R \geq 80\%$ and $P_{FA}^R = 0.1\%$. For each OTDR trace measured under a given set of working parameters, the average photon count of the last 20 sampling points of the preceding gate (see

Algorithm 1 Quantification of Inter-Gate Discontinuity

Input: gate width sequence t_{on} , normalized power sequence P_{nor} , OTDR traces $Tr(t_{on}, P_{nor})$, required detection performance P_D^R — the probability of correctly detecting a reflection event, and P_{FA}^R — the probability of falsely identifying a reflection event when no event is present.

Output: false-alarm probability P_{FA}^D , minimum detectable signal change $\Delta\lambda$

```

for  $i \in t_{on}, j \in P_{nor}$ 
     $Tr_{ij} \leftarrow Tr(t_{on,i}, P_{nor,j})$ 
    Split  $Tr_{ij}$  into preceding-gate segment  $G^-$  and
    following-gate segment  $G^+$ 
     $\lambda_0 \leftarrow \text{Mean}(G^-(\text{end} - 19 : \text{end}))$ 
     $\lambda_D \leftarrow \text{Mean}(G^+(1 : 20))$ 
     $\eta_R \leftarrow \text{Quantile}(\lambda_0, P_{FA}^R)$  (using Eq. (6))
     $\Delta\lambda \leftarrow \text{Sensitivity}(\eta_R, P_{FA}^R, \lambda_0)$  (using Eq. (7) and
    Eq. (8))
     $P_{FA}^D(i, j) \leftarrow \text{Poisson\_tail}(\eta_R, \lambda_D)$  (using Eq. (9))
end

```

blue curve in Fig. 3(c)) is taken as λ_0 . Based on Eq. (6), the corresponding decision threshold η_R that satisfies the required P_{FA}^R is calculated according to:

$$\eta_R = \min \{ \eta \mid P(N \geq \eta \mid \lambda_0) \leq P_{FA}^R \} \quad (6)$$

Using this threshold η_R together with the specified P_D^R , the minimum detectable reflection-event photon count λ_R of the system is obtained according to Eq. (7):

$$\lambda_R = \min \{ \lambda \mid P(N \geq \eta_R \mid \lambda) \geq P_D^R \} \quad (7)$$

To provide a physically meaningful metric for signal detection, the minimum detectable signal variation is defined relative to the no-event photon count λ_0 . Specifically, the minimum detectable signal change $\Delta\lambda$ is given by:

$$\Delta\lambda = 5 \log_{10} \left(\frac{\lambda_R}{\lambda_0} \right) \quad (8)$$

Finally, the average photon count of the first 20 sampling points of the following gate (see red curve in Fig. 3(c)) is taken as λ_D , and the corresponding Poisson distribution is constructed. Based on the previously determined threshold η_R , the probability P_{FA}^D —that a signal jump induced by an inter-gate discontinuity is falsely identified as a reflection event—can be calculated, as expressed in Eq. (9):

$$P_{FA}^D = P(N \geq \eta_R \mid \lambda_D) = \sum_{n=\eta_R}^{\infty} \frac{e^{-\lambda_D} \lambda_D^n}{n!} \quad (9)$$

In the parameter-optimization analysis, the SNR presented in Fig. 3(a) characterizes the signal quality within individual gates, whereas P_{FA}^D , related to the inter-gate discontinuities shown in Fig. 3(b), provides a quantitative measure of distortion between adjacent gates. The optimal working parameters therefore require a balance between high SNR and low distortion induced by the gated measurement scheme, while also

maintaining sufficient sensitivity for event detection (i.e., a small minimum detectable signal change $\Delta\lambda$).

Based on the above derivation, the evaluation procedure is summarized in Algorithm 1.

APPENDIX B CONVERGENCE PROCEDURE FOR DYNAMIC VOA ADJUSTMENT

Once the gate width is determined, the detector is first calibrated in the gated mode, as represented by the red and blue curves in Fig. 2(a). These calibration curves characterize the relationship between the count rate (CR) and the incident optical power, and serve as the reference for subsequent VOA adjustment. For a given detector, this calibration generally remains valid over a long period and does not need to be repeated.

The convergence procedure is illustrated in Fig. 7. After the gate delay is set or updated, a 2 s CR measurement is first performed. The measured CR is then mapped to the corresponding optical power using the calibration curve, and the VOA attenuation is adjusted according to the difference between this optical power and that corresponding to C_{wp} . Since the detector response gradually approaches saturation at high optical powers and exhibits poor linearity, a single adjustment may not place the operating point sufficiently close to C_{wp} . Therefore, a CR verification step is introduced before the formal measurement.

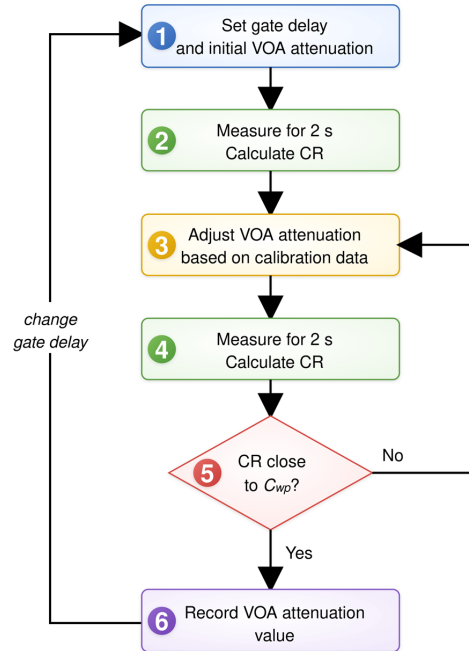


Fig. 7. Flowchart of the count-rate convergence procedure for a fixed gate width using the calibration data.

The convergence criterion is defined as the measured count rate falling within $C_{wp} \pm \text{std}(C_{wp})$, where std is the standard

deviation of the measured CR, such that the deviation of the operating point is smaller than the intrinsic statistical fluctuation of the photon counts. Since photon counts follow Poisson statistics, the standard deviation is equal to the square root of the mean count. For the 20 km measurements, C_{wp} is set to 580 cps, resulting in a tolerance band of 580 ± 24 cps. In practice, no more than two measurement–adjustment iterations are typically required to satisfy this criterion. In practice, no more than two measurement–adjustment iterations are typically required to satisfy this criterion.

In the experiments, the VOA attenuation for all gates is fully determined through the above convergence procedure before the formal OTDR measurement is started. Therefore, the reported acquisition time of 20 min does not include the convergence process. For the 20 km measurement presented in this work, the convergence process requires approximately 185 s in total for 37 gates ($t_{on} = 5.79 \mu s$). The VOA used in our experiments, Santec OVA-100, has a response time on the order of milliseconds. A faster convergence strategy may be developed in the future by using improved control algorithms, thereby further reducing the convergence time.

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