High Dynamic Range Externally Time-Gated Photon Counting Optical Time-Domain Reflectometry

Bin Li, Guangwei Deng, Ruiming Zhang, Zhonghua Ou, Heng Zhou, Yun Ling, Yunxiang Wang, You Wang, Kun Qiu, Haizhi Song, and Qiang Zhou

Abstract—Single photon detector (SPD) has a maximum count rate due to its dead time, which results in that the dynamic range of photon counting optical time-domain reflectometry (PC-OTDR) decreases with the length of monitored fiber. To further improve the dynamic range of PC-OTDR, we propose and demonstrate an externally time-gated scheme. The externally time-gated scheme is realized by using a high-speed optical switch, i.e., a Mach-Zehnder interferometer, to modulate the back-propagation optical signal, and to allow that only a certain segment of the fiber under test is monitored by the SPD. The feasibility of proposed scheme is first examined with theoretical analysis and simulation; then we experimentally demonstrate it with our experimental PC-OTDR testbed operating at 850 nm wavelength. In our studies, a dynamic range of 30.0 dB is achieved in a 70 meters long PC-OTDR system with 50 ns external gates, corresponding to an improvement of 11.0 dB in dynamic range comparing with no gating operation. Furthermore, with the improved dynamic range, a successful identification of a 0.37 dB loss event is detected with 30-seconds accumulation, which could not be identified without gating operation. Our scheme paves an avenue for developing PC-OTDR systems with high dynamic range.

Index Terms—Fiber testing, gating operation, optical time-domain reflectometry, photon counting.

I. INTRODUCTION

O PTICAL time-domain reflectometry (OTDR) is a representative distributed fiber optic sensor. Since its first demonstration in 1976 [1], it has been successfully employed in many fields such as optical fiber communication [2], high-voltage transmission lines [3], oil and gas pipelines [4], etc. Most of commercially available OTDR systems are based on linear photon detectors, such as PIN photodiodes or avalanche photodiodes (APDs). Conventional OTDR has great advantages in long distance measurement and has achieved a dynamic range of up to ~50.0 dB with spatial resolution of around one kilometer [5]. However, the improvement of its spatial resolution is still a challenge. This is due to photodetectors under linear regime with large bandwidth and high-sensitivity are too difficult to develop, thus preventing the development of the conventional OTDR system with high spatial resolution and dynamic range [6]–[8].

In 1980, photon-counting OTDR (PC-OTDR) based on the Geiger-mode single photon detector (SPD) was proposed and demonstrated [9]. Compared with the conventional OTDR, PC-OTDR has advantages of higher spatial resolution and larger dynamic range [10] [11]. Especially, with the development of single photon detection technology, Q. Zhao et al. obtained a spatial resolution of 4.0 mm with superconducting nanowire single-photon detectors (SNSPDs) [12], J. Hu et al. demonstrated a dynamic range of 22.0 dB with 6.0 cm spatial resolution at the end of 2.0 km standard single-mode fiber [13], and G.-L. Shentu et al. achieved a dynamic range of 42.2 dB with a spatial resolution of 10.0 cm by using an ultra-low noise up-conversion SPD [14]. Further improvement of the dynamic range of PC-OTDR is limited by parameters of SPD. One key parameter is the so-called dead time, which is the minimum time needed to recover the SPD after a detection event. Therefore, the dead time sets a maximum count rate for SPD [15]. For the PC-OTDR system, the maximum photon counting rate, combining with the noise, i.e., the dark count rate of the SPD, gives the upper limit of the dynamic range or signal to noise ratio (SNR) for PC-OTDR system. In general, the longer the fiber under test (FUT) is, the fewer number of photons from per meter fiber is accumulated. That is to say, the number of photons is fixed by the maximum count rate of the SPD, thus leading to the reduction of the dynamic range of PC-OTDR with increasing the length of FUT. In other words, the dynamic range for PC-OTDR system must not be improved by arbitrarily increasing the back-propagation...
signal, due to the maximum count rate of SPD limited the level of back-propagation signal.

In this paper, we propose and demonstrate a novel externally time-gated PC-OTDR scheme. Our scheme uses a high-speed optical switch (OSW), i.e., Mach-Zehnder interferometer (MZI) based intensity modulator, to modulate the back-propagation signal, and to allow that only a certain part of the back-propagation signal - defined by the gate - is detected by the following SPD. Alternatively, one can internally gate the SPD by using an electronic gate, such that the detector is active within the gate period [16]. Compared with internally time-gated method, our externally time-gated scheme can eliminate counting spikes at the rising edge of internal gate - see Appendix A for details. A systematic theoretical model is developed to evaluate the performance of our method, which is also experimentally investigated with our PC-OTDR testbed at 850 nm [7]. In our demonstration, by using 50 ns external gates, a dynamic range of 30.0 dB is achieved for a PC-OTDR test of 70-meter long aeronautical fiber, showing an improvement of 11.0 dB in dynamic range comparing with the no gating case. With the improved dynamic range, a successful identification of a 0.37 dB small bend loss event is detected with 30-second accumulation measurement, which is not identified for the no gating case with the same accumulation time. In [17], Herrera et al. also reported their works on PC-OTDR, which achieved a spatial resolution of 2.25 m and a dynamic range of 29.0 dB at distances up to 8.0 kilometers. Our demonstration, by contrast, has a higher spatial resolution of smaller than 0.1 m, and a dynamic range of 30.0 dB. Our scheme paves an avenue for achieving a high dynamic PC-OTDR system.

II. THEORETICAL ANALYSIS FOR EXTERNALLY TIME-GATED PC-OTDR SYSTEM

A. Basic Operation

As shown in Fig. 1, the idea of externally time-gated PC-OTDR is that we divide the OTDR trace into $N$ segments by using an OSW. Each segment is defined by the external gate which controls the OSW. After obtaining $N$ segments of OTDR trace, we can increase the corresponding back-propagation signal to the maximum count rate of the SPD, by improving the intensity of probe signal, thus increasing the signal-level for the PC-OTDR trace. While the noise floor does not change, and is determined by the dark count rate of the SPD. Thus, the dynamic range of the externally time-gated PC-OTDR is improved with the external gating operation. Note that strong Fresnel reflections may take place at connection points along the fiber link, which may saturate the SPD at those places. Fortunately, the Fresnel reflection only happens at a single point, which means that with the proposed externally time-gated scheme these Fresnel reflection points can be skipped by precisely controlling the timing of the external gate, then leaving only the Raleigh scattering is measured along the OTDR trace. Furthermore, locations of all Fresnel reflection points can be automatically located by event location algorithms, such as wavelet transform [18], trend filter [19], etc.

Fig. 1. (a) Schematic diagram of externally time-gated PC-OTDR. (b) Gating signals provided to optical switch (OSW). (c) Simulated OTDR traces of 60 m fiber link using a laser pulse width of 1 ns. The blue curve represents the result of OTDR without gating operation. The peak power of the probe signal is 10 $\mu$W. The result of externally time-gated scheme is represented by the orange curve using an OSW with an extinction ratio of 30.0 dB and a gate width of 150 ns. In order to keep the same count rate from the single photon detector (SPD), the peak power of the probe signal is increased from 10 $\mu$W to 39 $\mu$W in the simulation.

B. Theoretical Model

According to [20], we develop a theoretical model to analyze the feasibility of our proposed scheme. We consider that the FUT is composed of $N_b$ scattering units. For the case without external gating operation, let $P'_{BS}(i)$ be the power of backscatter signal from each scattering unit. The total photon count is then given by the sum of each scattering unit,

$$C_1 = \sum_{i=1}^{N_b} P'_{BS}(i) \times \frac{t_{total}}{h\nu}. \tag{1}$$

where $h\nu$ is the energy per backscattered photon, $t_{total}$ is the measurement time. On the other hand, when we use externally time-gated technique and divide the PC-OTDR trace into $n$ segments by gating, each segment contains $m$ (floor of $N_b/n$) scattering units. Due to the change of input power, the backscatter power for each scattering unit within the gate becomes $P'_{BS}(i)$ and that outside of the gate is $P''_{BS}(i)/\gamma$, where $\gamma = 10^{(E_R/10)}$, $E_R$ is the extinction ratio of the OSW. Hence, for the $k$-th gating signal, the number of photons is calculated as

$$C(k) = \frac{1}{\gamma} \sum_{i=1}^{(k-1) \times m} \frac{P'_{BS}(i) \times t_{each}}{h\nu} + \frac{1}{\gamma} \sum_{i=(k-1) \times m+1}^{k \times m} \frac{P''_{BS}(i) \times t_{each}}{h\nu} + \frac{1}{\gamma} \sum_{i=k \times m+1}^{N_b} \frac{P'_{BS}(i) \times t_{each}}{h\nu}. \tag{2}$$

where $t_{each}$ is the time required for each gating test and $t_{each} = t_{total}/n$. The three terms in (2) in order are the count...
generated by the scattering units before, within and after the
gate, respectively. Finally, after recovering the whole trace, we
infer the total photon count of our scheme,

$$C_2 = \sum_{k=1}^{n} C(k).$$

To simplify the analysis, we assume $P_{BS}(i) \cong P_{BS}(1)$ and
$P'_{BS}(i) \cong P'_{BS}(1)$, which is reasonable when the length of FUT
is less than 1 km. And the total photon counts for both cases of
with and without gating operation are the same, i.e., $C_1 = C_2$,
which are determined by the dead time of SPD. Therefore, we
can obtain the improvement of dynamic range for the case with
external gates [20].

$$\Delta D_R = 10 \log \left( \frac{P'_{BS}(1)}{N_{EPO}} \right) - 10 \log \left( \frac{P_{BS}(1)}{N_{EPO}} \right)$$

$$= 10 \log \left( \frac{\gamma N_b}{\gamma m + (N_b - m)} \right),$$

(4)

where $N_{EPO}$ is the minimal detectable power of SPD, $\Delta D_R$ is
the improvement of dynamic range. From (4), one can see that
the dynamic range is improved by using the externally time-
gated scheme, and increases with the increase of extinction ratio
and the decrease of gate width (for details, see Appendix B). If
$\gamma \gg N_b/m$, (4) can be further simplified as,

$$\Delta D_R \cong 10 \log \left( \frac{N_b}{m} \right).$$

(5)

This approximation is valid for OSW with high extinction ratio
($E_R > 30.0$ dB) and less segments. For example, let assume $E_R = 50.0$ dB and $N_b/m = 10$, then the externally time-gated
PC-OTDR achieves a 10.0 dB improvement in dynamic range. Fig. 1(c) shows the simulated OTDR traces of 60 m fiber link
using a laser pulse width of 1 ns. The blue curve represents the
simulated result of OTDR without gating operation. The peak
power of the probe signal is 10 $\mu$W. The result of externally
time-gated scheme is represented by the orange curve using an
OSW with an extinction ratio of 30.0 dB and a gate width of 150
ns. In order to keep the same count rate from the SPD, the peak
power of the probe signal is increased from 10 $\mu$W to 39 $\mu$W in
the simulation. An improvement of a dynamic range of 6.0 dB
is obtained, which corresponds to (5) with $N_b/m = 4$.

III. EXPERIMENTAL DEMONSTRATION AND RESULTS

We experimentally demonstrate our externally time-gated scheme based on our PC-OTDR testbed at 850 nm [7]. Fig. 2
shows the detailed setups of our experiment. Laser pulses at
850 nm output from a vertical cavity surface-emitting laser
(VCSEL) driven by field programmable gate array (FPGA). The
generated laser pulses are launched into the FUT through an
optical circulator. The laser is set at a repetition rate of 1 MHz
and at a pulse width of less than 1 ns, which is equivalent to a
test range of 100 m and a spatial resolution of less than 10 cm.
The back-propagation signal is routed into the third port of the
circulator and then feeds into a MZI, which is the high-speed
OSW in our experiment. The FPGA board creates the electronic
gating signals, i.e., the modulation signals for MZI. The insertion
loss of the MZI is 1.5 dB, and its extinction ratio is 29.0 dB.
Then, the modulated back-propagation signal is detected by the
SPD (Excelitas, SPCM-AQRH-14). The dark count rate of the
SPD is about 100 Hz while the detection efficiency is 45%,
which gives a noise equivalent power (NEP) of about $7.35 \times 10^{-18} \text{ W}/\sqrt{\text{Hz}}$ [20]. The electronic signal from the SPD is
split into two channels by using a T-connector. One feeds to
the time correlated single photon counting (TCSPC, TimeHarp
260) board, and the other to a counter (Agilent, 53131A). The
TCSPC board, working in histogram mode with a time bin width
of 0.1 ns, is triggered by signals from FPGA. Finally, the data
is transmitted to a computer through peripheral component in-
terconnect express (PCIE) interface for processing and analysis.
It is worth noting that the bias point of the MZI drifts with its
temperature. To stabilize its bias point, a data acquisition card
(DAQ, Texas Instruments USB6002) is used to monitor the count
rate from the SPD and to stabilize the bias of MZI in real time.

The feasibility of proposed scheme on improving the dynamic
range is verified and shown in Fig. 3. First, we take the MZI out
from the experimental setups, i.e., PC-OTDR without external
gates. After a 420 seconds measurement, we obtain a curve for
the 70 meters long FUT with a connector located at 20 meters
from the beginning. The curve is in blue and given in Fig. 3(a).
From this curve, a dynamic range of 19.0 dB at the end of the
curve can be obtained. Then, we test the performance of externally
time-gated PC-OTDR system. The MZI is acting as a high-speed
OSW with an extinction ratio of 29.0 dB. The 50 ns
gating signals are generated by the FPGA. In order to make a fair
comparison, the total count rate in the first 50 ns gating period is
set as the same as the total count rate without gating operation,
which is $4.69 \times 10^6 \text{ Hz}$ in our experiment. This is achieved by
improving the power injected into the FUT. By adjusting
the delay of the gating signal, we can measure the OTDR trace
for each segment and reconstruct the whole OTDR curve. The
orange curve as shown in Fig. 3(a) is the recovered PC-OTDR.
trace with external gates. The fiber length of each segment is 5 meters. Fourteen segments are obtained in the experiment. Each segment is obtained with a measurement time of 30 seconds corresponding to a total measurement time of 420 seconds - the time consumption for adjusting the delay of gates is negligible in our system. Again, from the orange curve, a dynamic range of 30.0 dB is observed in our experiment.

As shown in Fig. 3(a), the dynamic range for the case with external gating operation has a 11.0 dB improvement comparing with the case without gating. The improvement in dynamic range is very close to the ideal case, which should be 11.5 dB according to (5) (determined by the number of segments of the FUT divided into, i.e., 14 segments in our demonstration) - the 0.5 dB decline is caused by the limited extinction ratio of the MZI, i.e., 29.0 dB in our experiment. Furthermore, Fig. 3(b) and (c) are the results of those dynamic ranges change with different extinction ratios and gate widths, respectively.

Firstly, we fix the gate width at 50 ns, and measure the improvement of the dynamic range with different extinction ratios of the MZI for 70 meters optical fiber. The change of extinction ratio is realized by varying the amplitude of the electronic gating signal feeding to MZI in our experiment. The theoretical prediction based on (4) is obtained, with $N_b \sim 7000, m \sim 500$. The result is the solid line shown in Fig. 3(b). It is obvious that the dynamic range increases with the increase of extinction ratio until it tends to be stable with extinction ratio greater than 25.0 dB. Then we fix the extinction ratio at the maximum value of 29.0 dB, and measure the improvement of the dynamic range with different gate widths varied from 5 ns to 400 ns. Similarly, we draw the theoretical prediction curve according to (5) as a comparison, for $N_b \sim 7000, E_R \sim 29.0$ dB. The results are shown in Fig. 3(c). It is easy to obtain the inverse proportion relationship between the change of dynamic range and gate width.

With improved dynamic range of the externally time-gated scheme, we can detect loss event which is drowned out by the noise in the case without gating. To verify, we perform a single gate test at the specified location. In this measurement, the FUT consists of two pieces of 20 meters long multimode fibers. A small bend loss is introduced at around 32.5 meters place along the FUT. To measure the small bend loss, a 50 ns gating signal is generated and delayed to cover it. The results are shown in Fig. 4. The blue curve is a reference curve indicating the result without external gate. Note that the residual three peaks out of the 50 ns gate are due to that the MZI employed in our experiment has a limited extinction ratio. The orange curve is the result for the case with external gate. In the two measurements, the accumulating time (30 seconds) and total count rate ($6.47 \times 10^3$ Hz) from the SPD are keeping the same. As shown in Fig. 4, it can be seen that a small loss event is observed in the case with external gate, while the curve is almost flat for the case without gating. To show it clear, we fit the two curves by using an adaptive filtering algorithm [19], as shown in the inset of Fig. 4. A loss event of 0.37 dB caused by the small bend is obtained due to the increase of dynamic range, while such a loss event is not observed in the case without gating. Note that the 0.37 dB loss is also observed by using a power meter to monitor the output port of the FUT. Hence, our externally time-gated PC-OTDR is very effective to observe small bend loss along the FUT with high spatial resolution, i.e., less than 10 cm in our PC-OTDR testbed.

### IV. DISCUSSION

One may think about that the dynamic range can be further improved by dividing the PC-OTDR curve into more numbers of segments in our scheme. In theory this thought is true, while for implementation we need to think about the speed of the optical switch and the pulse width of electronic gating signal. On one hand, by using cost-effective FPGA to generate electronic gating signal, the minimum gating width could be around 1 ns. On the other hand, the idea for the external gating scheme is that one can increase the photon counting number within the gating period by increasing the power of probe signal. However, this maximum power is limited by the “pile-up” effect as discussed in Appendix B. Furthermore, the spatial resolution in the
experiment is 10 cm, which is mainly determined by the total effect of the pulse width of laser, the time jitter of SPD and the time resolution of TCSPC circuit. For the state of the art, the pulse width of gain-switched laser is limited to ~50 ps [21], which means that the spatial resolution would be further shortened to ~0.5 cm; the time resolution of the TCSPC circuit currently would reach to 4 ps [22], which would not affect the spatial resolution heavily; the time jitter of the SPD has been lowered to ~50 ps [23], which again gives a spatial resolution of ~0.5 cm. Hence, the best spatial resolution for PC-OTDR could reach 1.0 cm. In addition, in order to improve dynamic range by increasing the pulse intensity to the saturation limit, the calibration of the launched peak power is important, both to compensate for fiber loss and to preclude 2-photon events.

In our proof of principle demonstration, the length of FUT is only 70 meters. This is not the longest FUT for our method. In principle, the length of FUT is limited by the dynamic range and the loss of fiber. In our experiment, the dynamic range at the end of the measured OTDR curve is 30.0 dB. This means an extra 30.0 dB loss can be tolerated in our method. Considering that the loss of fiber at 850 nm is ~3 dB/km, the total length of FUT could be extended to ~10 km. Note that in our demonstration, we focus on the test of optical cable on airplane, which means the length of FUT could be less than 1.0 km. It is worth noting that the total light backscattered depends on the total length of the fiber being measured. This impacts the amount of light to be rejected by the MZI gate so that the dynamic range improvement for longer fibers would be smaller. For example, assuming that the optical fiber loss is ~3.5 dB/km at 850 nm, when the gate width and the incident peak power remain unchanged, the backscattered power from 1.0 km long fiber is 6.6 times of that from the 100 meters long one, that is, an increase of ~8.0 dB. Therefore, the extinction ratio of MZI needs to be increased by ~8.0 dB to suppress more signals outside the gate for an equivalent improvement in dynamic range.

Additionally, for PC-OTDR without gating operation, the acquisition time necessary to reveal small losses depends very strongly on the total length of fiber being measured. While this is not the case for externally time-gated PC-OTDR scheme. More precisely, the acquisition time necessary to reveal small losses, is linear proportion to the backscattered photon rate from per meter fiber. For the case without external gating operation, the longer the fiber is, the smaller backscattered photon rate from per meter is obtained. Thus, the dynamic range or SNR decreases with the length, which will increase the time to reveal small losses and even prevent the revealing. While for our externally time-gated PC-OTDR scheme, we can always increase the power of probe signal to keep the backscattered photon rate from per meter fiber the same, i.e., the maximum rate allowed by the SPD, thus keeping the ability to reveal small losses for long distance PC-OTDR and also making that the acquisition time for such revealing is independent with the length of the FUT.

V. CONCLUSION

In this paper, an externally time-gated PC-OTDR based on high-speed optical switch has been proposed and experimentally demonstrated. Our externally time-gated scheme improves the dynamic range of PC-OTDR, which is limited due to the maximum count rates of SPDs caused by dead time. We first carry out the theoretical analysis and simulation. It shows that the dynamic range of the externally time-gated system increases with the extinction ratio of the MZI, and decreases with the increase of the gate width - the one without gating operation corresponding to the lowest dynamic range. In our experimental investigation, the dynamic range of externally time-gated PC-OTDR is improved by 11.0 dB, which corresponds to dividing the whole OTDR curve into 14 segments by using external gates. More important, thanks to the improvement of the dynamic range with external gating operation, a small bend loss event with a loss of 0.37 dB has been observed in the experiment. Such a bend event has been previously submerged in the noise for the case without external time-gates. Our results show that the proposed scheme paves an avenue for achieving a high dynamic PC-OTDR system.

APPENDIX A
DEFECT OF INTERNAL GATING OPERATION

We show the defect of the internal gating operation. The SPD (Excelitas Technologies, SPCM-AQRH) can work under so-called internally gated mode. One could think about developing a gated PC-OTDR with internally time-gated SPD, i.e., turning on the SPD at a certain period with an electronic gating signal and scanning the whole OTDR trace by moving the gate. We test this method in our experiment and the results are shown in Fig. 5(a). However, the gate only turns the output circuit of the SPD on or off, while it does not turn the Si-APD on or off, which means that the Si-APD still works under free running mode. Thus, the SPD keeps suffering from the saturation count rate under the internally gated mode. Furthermore, as shown in Fig. 5(a), a fake count event has been observed at the rising edge of the gate, which degrades the performance of PC-OTDR. It may be caused by the electrical (or photo) luminescence effect of the semiconductor material itself [24], i.e., the SPD operating under the internally gated mode may cause photon radiation phenomenon. To compare, Fig. 5(b) is the results of our scheme, in which the gating signal is applied to the OSW. Fig. 5 clearly shows the advantages of our proposed scheme: on one hand there is no fake peaks; on the other hand, the dynamic range is much higher than the case without gating operation.
Fig. 6. Simulation results of PC-OTDR traces with extinction ratios of (a) 40.0 dB, (b) 20.0 dB, (c) 5.0 dB, respectively. The blue curve represents the result of PC-OTDR without gating operation. The result of externally time-gated scheme is represented by the orange curve using an optical switch with a gate width of 150 ns. (d) Peak power of probe signal varies with the extinction ratios.

APPENDIX B
SIMULATION PLATFORM OF EXTERNALLY TIME-GATED PC-OTDR

Based on our theoretical model, an externally time-gated PC-OTDR simulation platform is established. It is mainly composed of three parts: Rayleigh scattering module [25], Fresnel reflection module [26] and single-photon detection module [27].

In our simulation, the dark count and dead time of the SPD are set as 200 Hz and 20 ns respectively, at the meanwhile the time jitter is not considered. In order to shorten the simulation time, the fiber length is set to 60 m. Fig. 6 shows the simulated PC-OTDR traces with different extinction ratios, while the width of the gates is kept the same as 150 ns. From Fig. 6(a)–(c), when the extinction ratio is 40.0 dB, 20.0 dB and 5.0 dB, the increases of dynamic range are 6.03 dB, 6.00 dB and 5.63 dB, respectively. This is in good agreement with (4) in the main text. We can conclude that with the decrease of extinction ratio, the suppression of the signal outside of the gate becomes smaller, and the proportion of photon counts contributed from the Fresnel reflections increases, thereby reducing the dynamic range.

One important feature for PC-OTDR system is that the maximum count rate is determined by dead time of SPD. This means that for a given width of gate, the peak power of the probe signal increases with the extinction ratio of the OSW. We analyze this phenomenon with our theoretical model, and the results are shown in Fig. 6(d). In our simulation, the pulse width of the probe signal is 1 ns. It shows that the higher the extinction ratio of the OSW is, the greater the peak power of the probe signal is needed. When that the extinction ratio is larger than 25.0 dB, the peak power of the probe signal is almost unchanged. In conclusion, the larger the extinction ratio the higher the dynamic range is.

Fig. 7. The PC-OTDR simulation results corresponding to different external gate widths, when the extinction ratio of gating signal is 30.0 dB. (a) OTDR traces. (b) Peak power of probe signal with different gate widths. (c) The improvement of dynamic range with different gate widths for 60 m long FUT.

Furthermore, the width of the external gate is an important parameter for PC-OTDR. In our theoretical analysis we keep the extinction ratio as 30.0 dB, and obtained the PC-OTDR results with different gate widths, as shown in Fig. 7. At the meanwhile the total count in each gate keeps the same, i.e., the maximum count rate determined by the dead time of SPD, thus the peak power of the probe signal should be adjusted when changing the gate width. Assuming the power is $P_1$ and $P_2$, which correspond to gate widths of $W_{gate1}$ and $W_{gate2}$, respectively. Based on the (4) and (5) in the main text, we obtain straightforward

$$
\frac{P_1}{P_2} = \frac{W_{gate2}}{W_{gate1}}.
$$

In general, if the gate width is increased by a factor $d$, the peak power of the probe signal is lowered by the same factor. As shown in Fig. 7(b) and (c), the wider the gate width, the smaller the pulse power required and the smaller the improvement of the dynamic range, which is in good agreement with (6) and (5).

Meanwhile, as shown in the inset of Fig. 7(a), the green curve has an anomaly segment with clear negative-slope, i.e., pile-up effect [28]. This effect arises because, in the SPD, only one event is detected at most (also related to the dead time of the SPD), so that the photons appeared at the gate opening time have higher probability of being detected than those scattered at the back end. This effect is negligible when using the wide gate with low incident power, for example pulse widths of 100 ns and 150 ns in the simulation.

We further study the pile-up effect theoretically, by using our theoretical model. First, by fixing the extinction ratio at 30 dB, we obtain a set of curves with different gate widths, and for each gate width the count rate from the SPD is the same. The results are shown in Fig. 8(a). Fig. 8(b) shows the slopes of the curves within the gate, obtained by piecewise-linear-fitting algorithm.
Obviously, the slope is basically unchanged in the process of shortening the gate width from 100 ns to 60 ns. When the gate widths are 50 ns, 40 ns and 30 ns respectively, the slope of the initial segment decreases obviously and decreases with the decrease of the gate width. As the gate width is further reduced, the amount of change in slope becomes larger and larger, that is, the pile-up effect is more serious. This is due to the fact that in our scheme, the reduction in gate width means an increase in the power of the probe signal. Then we verify the change of the pile-up effect when only the peak power of the probe signal is changed. The results are shown in Fig. 8(c), at the meanwhile, the slopes of the curves within the gate are shown in Fig. 8(d), where the gate width and extinction ratio are fixed at 50 ns and 30 dB, respectively. It can be seen that the slope is unchanged at that the peak power equals to 0.02 mW. As the power increases to 1.0 mW, the slope changes suddenly and the slope of the initial segment becomes smaller. After that, the larger the peak power, the more significant of the slope gradient, which means that the pile-up effect is more obvious. In summary, in order to improve the dynamic range, we cannot improve the peak power or shorten the gating time unlimited, otherwise it will cause pile-up effect, resulting in test errors. In actual operation, we can set the gate width larger and adjust the power of the probe signal to make the count rate of SPD nearly saturated; then the optimal gate width can be obtained by continuously reducing the gate width and increasing the power until the obvious pile-up effect is about to appear in the test results. In this case, the reconstructed OTDR curve has the highest dynamic range.

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Bin Li received the B.S. and M.S. degrees from the University of Electronic Science and Technology of China, Chengdu, China, in 2011 and 2014, respectively. He is currently working toward the Ph.D. degree in optical engineering at the University of Electronic Science and Technology of China, Chengdu, China. His research interests include single-photon detection and its application, and optical fiber communication.

Guangwei Deng was born in Sichuan Province, China, in 1987. He received the B.S. and Ph.D. degrees in physics from University of Science and Technology of China, Hefei, China, in 2011 and 2016, respectively. From 2016 to 2018, he was a Research Associate Professor of Physics with the Key Laboratory of Quantum Information, University of Science and Technology of China. Since 2018, he has been a Professor with the Institute of Fundamental and Frontier Sciences, University of Electronic Science and Technology of China, Chengdu, China. He is the author of one chapter of a book and more than 20 articles. His current research interests include quantum optomechanics, defects in diamond or SiC, quantum optics, quantum memory, and quantum applications in 2-D materials. Dr. Deng was a recipient of the 66th Lindau Nobel Laureate Meetings, and he was selected as a youth editorial board of “Defence science and technology.”

Zonghua Ou was born in Chongqing, China, in 1978. He received the B.S. degree in applied electronics from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2001, and the M.S. and Ph.D. degrees in optics engineering from UESTC in 2004 and 2009, respectively. Since 2011, he has been an Assistant Professor with the School of Opto-Electronic Science and Engineering, UESTC. His research interests include the area of photonics detection and information processing, fiber optics sensing, fiber laser, etc.

Zonghua Ou was born in Chongqing, China, in 1978. He received the B.S. degree in applied physics and the Ph.D. degree in optical engineering from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2002 and 2008, respectively. From 2008 to 2010, he was a Lecturer, and since 2011, he has been an Associate Professor with the School of Information and Communication, UESTC. He is the author of more than 40 articles and more than 20 inventions. His research interests include optical fiber communication, optical signal processing, microwave photonics, and photoelectric detection.

Yunxiang Wang received the B.S. degree in electronic science and technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2003, and the Ph.D. degree in optical engineering from Tsinghua University, Beijing, China, in 2008. He is an Assistant Professor with UESTC, Chengdu, China. His current research interests include solid-state laser technology and coherent optical communication.

You Wang was born in China, in 1966. He received the B.S. degree in laser technology from Zhejiang University, Hangzhou, China, in 1986, and the M.Sc. degree in optics from the Chinese Academy of Science (registered in Hefei University of Technology), Hefei, China, in 1991. He received the Ph.D. degree in electronics/communication from Tohoku University, Sendai, Japan, in 1997. After that, he was with Tohoku University as an Assistant Professor, a Researcher of the major institutes of RICOH Co. Ltd, and a Laser Scientist of both the Center Laboratory of HPK Co. Ltd and Institute of Physical and Chemical Research of Japan (RIKEN) for more than 15 years.

Kun Qiu received the M.S. and Ph.D. degrees from Tsinghua University, Beijing, China, in 1987 and 1990, respectively. He is currently a Full Professor and a Ph.D. Supervisor of optical communications with the University of Electronic Science and Technology of China, Chengdu, China. He is the author/coauthor of more than 200 scientific papers (reviews) in the scientific journals and academic conferences. He has more than 100 articles and more than 25 inventions. His research interests include quantum optomechanics, microlaser processing, special waveguides, and optoelectronic technology.

Haiyong Liu was born in Shanxi Province, China, in 1968. He received the B.S. degree in semiconductor physics from Nanjing University, Nanjing, China, in 1990 and the Ph.D. degree in condensed-matter physics from Peking University, Beijing, China, in 1995. From 1995 to 1998, he did postdoctoral work at Nanjing University, China and Katholieke Universiteit Leuven, Belgium. From 1998 to 2001, he was a Research Associate with the University of Tsukuba, Japan. In 2001, he joined Fujitsu Laboratories Limited, Japan to be a Researcher. From 2012 to 2014, he was a Senior Researcher with the University of Tokyo, Japan. Since 2014, he has been a Professor with the Southwest Institute of Technical Physics, Chengdu, China. In 2015, he joined University of Electronic Science and Technology of China as a Professor. He is an author/coauthor of more than 100 articles and more than 25 articles. His research interests include semiconductor optoelectronics, quantum information, and nano-photonic devices.

Qiang Zhou received the B.Sc. degree in optoelectronic information from the University of Electronic Science and Technology (UESTC), Chengdu, China, in 2002, and the Ph.D. degree in electronic science and technology from Tsinghua University, Beijing, China, in 2011. From 2014 to 2017, he was a Postdoctoral Fellow with the Department of Physics and Astronomy, Institute for Quantum Science and Technology, University of Calgary, Calgary, AB, Canada. He is currently an Associate Professor with UESTC. His current research interests include quantum information technologies, quantum photonics, communication systems, nonlinear optics, fiber optics, nanophotonics, and electronics.