**Practical fast gate rate InGaAs/InP single-photon avalanche photodiodes**

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We present a practical and easy-to-implement method for high-speed near infrared single-photon detection based on InGaAs/InP single-photon avalanche photodiodes (SPADs), combining aspects of both sine gating and self-differencing techniques. At a gating frequency of 921 MHz and temperature of -30 °C we achieve: a detection efficiency of 9.3 %, a dark count probability of 2.8×10⁻⁶ ns⁻¹, while the afterpulse probability is 1.6×10⁻⁴ ns⁻¹, with a 10 ns “count-off time” setting. In principle, the maximum count rate of the SPAD can approach 100 MHz, which can significantly improve the performance for diverse applications.

InGaAs/InP SPADs provide one of the most important approaches for near infrared single-photon detection, especially for practical applications such as quantum key distribution (QKD) [1]. Gated-mode InGaAs/InP SPADs have been well studied and recently this has been extended to free-running mode [2, 3, 4]. However, due to the afterpulsing effect and the need for tens of μs deadtime settings, the gating frequency and the maximum count rate of InGaAs/InP SPADs are both severely limited. On the other hand, the requirements for long-distance and high bit rate QKD systems motivate the development of high-speed near infrared single-photon detectors, of which superconducting single-photon detector (SSPD) [5] and up-conversion detector (UCD) [6] are two common candidates. Unfortunately, the cryogenic requirements of SSPDs and the spurious nonlinear noise of UCDs make them impractical for QKD systems. So far, two types of high-speed InGaAs/InP SPADs have been demonstrated using the techniques of sine gating (SG) [7, 8] and self-differencing (SD) [9, 10], respectively. These new approaches have been demonstrated in QKD [11, 12, 13] and random number generators [14], and have also shown photon-number resolving [15].

The afterpulsing effect is one of the major bottlenecks limiting the performance of InGaAs/InP SPADs. The origin of afterpulsing is due to the trapping of charge carriers by defects in the SPAD’s multiplication layer. Subsequent gates release some of these charges that then create avalanches. The afterpulsing effect is not only attributed to the defect concentration in the multiplication layer, which depends on the impurity and device structure. It is also proportional to the total number of carriers in an avalanche, which depends on the excess bias of the SPAD and the avalanche duration time [3]. In conventional gating, using the relatively long gating time, the avalanche amplitude is large enough to be easily discriminated. However, long deadtime settings are necessary to suppress the afterpulsing.

Conversely, in the case of rapid gating, with gating frequencies \( f_g \) of around 1 GHz, the ultra short gating time ensures that the avalanches are far from saturation and therefore the avalanche currents are quite weak. As such, the afterpulsing effect can be significantly suppressed, although with the disadvantage that the avalanche amplitudes are very faint, normally a few mV, and thus difficult to discriminate. If no avalanche occurs during a gate, the SPAD still outputs a capacitive response, the background signal. In the case of an avalanche the faint avalanche signal is superposed with this background signal. Hence, the central task of rapid gating is minimizing the background level to obtain enough single-to-noise ratio to discriminate the small avalanche.

The SG method [7, 8] uses sine waves to gate a SPAD and band-stop filters (BSFs) to filter out the background frequency response, while SD [9, 10] uses square waves to gate a SPAD and a differencing circuit to subtract the output signals during two consecutive clocks to acquire the weak avalanche signal. Each of the two methods has its own advantages and disadvantages. SG has a simple frequency spectrum and thus can be filtered. However, it is significantly challenging to reduce the sine frequency response to the pure electronic noise level using only filters. Moreover, when the amplitude of background signal is highly attenuated other frequency components, like the harmonics of the fundamental frequency, can encumber the minimization of the background signal. On the other hand, the rejection ratio of the SD circuit is independent of frequency, which facilitates the discrimination of weak avalanches. However, designing a high-bandwidth and high-rejection differencing circuit is also quite challenging. As such, both techniques require complicated and sophisticated electronics, which can prevent their imple-
In this Letter, we report a simple and practical method for rapid gating SPADs that combines aspects of the SG and SD approaches. The overall implementation is easier than each of these previous techniques independently as the requirements for each technique are relatively unsophisticated.

The experimental setup is shown in Fig. 1. The sine waves from the synthesized signal generator (MG3601A, Anritsu) are split by a 6-dB power divider. One part drives the laser diode (LD: PicoQuant PDL 800-B, 30 ps FWHM, max. 80 MHz repetition frequency) for the optical characterization. The other part is amplified by an amplifier (amp1, ZHL-42W, Mini-Circuits) and then coupled to the anode of the SPAD via a 1 nF capacitor. The gate signal typically consists of a DC voltage ($V_{dc}$) of ~55 V and a $V_{pp}$ of ~12 V. The output from the cathode of the SPAD is filtered by home-made BSFs, rejecting the fundamental frequency ($f_g$) and harmonics, especially $2f_g$ and $4f_g$, which are produced mainly due to the non-linear frequency response of the SPAD. After the BSFs, the background amplitude is normally less than 40 mV depending on the BSF adjustment. The BSFs can contribute over 30 dB of attenuation with the remaining attenuation due to the voltage distribution by resistance. Furthermore, the background signal can be suppressed down to the electronic noise level by a self-differencing circuit. A power divider first splits each pulse into two pulses. The inverted pulse is then recombined with the preceding pulse delayed by one clock. Finally, the background level is less than 1 mV while the avalanche level is around 2 mV, see Fig. 2(a). The difference between the cases without and with photon illumination (mean photon number per pulse $\mu \sim 1$, laser frequency $f_p=f_g/12$), shown in Fig. 2(b), clearly illustrates the single-photon counting capability of our scheme.

We measure the parameters of two different SPADs, #1 SPAD (JDSU0131E6739) and #2 SPAD (JDSU0131E6738) cooled to -30°C. A 10 ns “count-off time” is also applied, which means that once an avalanche is triggered the avalanches during the following 10 ns won’t be counted. This allows us to reduce the afterpulse probability and false electronic counts following an avalanche. The effective gating width ($\Delta t$), shown in Fig. 3 is 154 ps, corresponding to a duty cycle of 14.2%.

In Fig. 3 the efficiency ($\eta$) is calculated by,

$$\eta = 1 / \mu \times \ln((1 - R_{dc}/f_g)/(1 - R_{dc}/f_p)),$$

where $\eta$ is the efficiency, $\mu$ is the detection efficiency, $R_{dc}$ is the dark count rate, $f_g$ is the repetition frequency of the gate signal, and $f_p$ is the repetition frequency of the pulse signal. The gate signal typically consists of a DC voltage ($V_{dc}$) of ~55 V and a $V_{pp}$ of ~12 V. The output from the cathode of the SPAD is filtered by home-made BSFs, rejecting the fundamental frequency ($f_g$) and harmonics, especially $2f_g$ and $4f_g$, which are produced mainly due to the non-linear frequency response of the SPAD. After the BSFs, the background amplitude is normally less than 40 mV depending on the BSF adjustment. The BSFs can contribute over 30 dB of attenuation with the remaining attenuation due to the voltage distribution by resistance. Furthermore, the background signal can be suppressed down to the electronic noise level by a self-differencing circuit. A power divider first splits each pulse into two pulses. The inverted pulse is then recombined with the preceding pulse delayed by one clock. Finally, the background level is less than 1 mV while the avalanche level is around 2 mV, see Fig. 2(a). The difference between the cases without and with photon illumination (mean photon number per pulse $\mu \sim 1$, laser frequency $f_p=f_g/12$), shown in Fig. 2(b), clearly illustrates the single-photon counting capability of our scheme.

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In Fig. 3 the efficiency ($\eta$) is calculated by,

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considering a Poisson photon number distribution. $R_{dc}$ is the dark count rate and $R_{dc}^c$ is the coincidence rate between detection and laser pulses. The dark count per ns ($P_{dc}^{ns}$) is calculated by $P_{dc}^{ns} = R_{dc}/(f_g \Delta t)$, neglecting the afterpulsing of dark counts. As shown in Table. I at $f_g=921$ MHz and $\eta=9.3\%$, $P_{dc}^{ns}$ is $2.8 \times 10^{-6}$ ns$^{-1}$ for #1 SPAD, or $4.3 \times 10^{-7}$ per gate, which is very close to the parameter, $2.5 \times 10^{-6}$ ns$^{-1}$, measured at $10\%$ efficiency and $-30^\circ C$ in the conventional gating with the same SPAD.

From the relationship between $R_{dc}^c$ and detection rate ($R_{dc}$), the afterpulse probability ($P_{ap}$) can be deduced as

$$P_{ap} = (R_{dc} - R_{dc}^c - 11/12 \times R_{dc})/R_{dc}^c. \quad (2)$$

This implies that $P_{ap}$ highly depends on $R_{dc}$. In order to quantify and compare $P_{ap}$ under different conditions, we depict the normalized parameters to ns$^{-1}$ as shown in Fig. 1. The best and direct solution for evaluating the afterpulse probability per ns ($P_{ap}^{ns}$) is to use the double-gate method [3]. However, it is quite difficult to directly apply such a method for rapid gating systems. An alternative solution is to divide $P_{ap}$ by the average effective time between detections,

$$P_{ap}^{ns} = P_{ap}/(f_g \Delta t/R_{dc}) \sim P_{ap} f_g \mu \eta/(f_g \Delta t), \quad (3)$$

where the interval time is $\sim \mu$s level for $10\%$ efficiency, see Table. I and therefore the deadtime is negligible. If the interval time is much less than the detrapping lifetime of afterpulses [3], $P_{ap}^{ns}$ can well describe the afterpulsing behaviors, otherwise long interval times or small detection rates will underestimate $P_{ap}^{ns}$. For comparison, we also take the data from Ref. [3] and Ref. [8] and calculate them according to Eq. 3 and list the results in Table. I. In our case, we measure a $P_{ap}$ of $3.4\%$ and calculate a $P_{ap}^{ns}$ of $1.6 \times 10^{-4}$ ns$^{-1}$, which is larger than those in SD and SG, since our value of $R_{dc}$ is much higher than theirs, but still comparable to the value using the active quenching with $15\mu$s deadtime [3]. In general, $P_{ap}^{ns}$ is larger than $P_{ap}^c$, which implies that the afterpulsing still dominates the noise characteristics of SPADs in the rapid gating.

We also characterize the count rate behavior. As $\mu$ rises count rate increases linearly when $\mu < 10$ and finally the count rate is saturated close to $f_p$. The theoretically maximum count rate can approach $100$ MHz due to $10\%$ “count-off time”.

Rapid gating is highly suited for applications requiring high-speed synchronized single-photon detection like short-distance and high rate QKD [11, 12, 13], but for the applications of asynchronous or low photon flux detection, such as the long-distance QKD, the free-running detector, which has low noise characteristic with large deadtime, appears to be a better choice [2, 3].

In summary, we have implemented a simple and practical method for high-speed near infrared single-photon detection based on InGaAs/InP SPADs.

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| Parameter | This Letter | SD [9] | SG [8] | AQ [3] |
|-----------|-------------|--------|--------|--------|
| Temperature ($^\circ C$) | -30 | -30 | -50 | -35 |
| $f_g$ | 921 MHz | 1.25 GHz | 1.5 GHz | 10 kHz |
| $\eta$ (%) | 9.3 | 10.9 | 10.8 | 10.7 |
| $P_{dc}^c$ ($\times 10^{-5}$ ns$^{-1}$) | 0.28 | 1.5 | 0.63 | 0.57 |
| $\Delta t$ | 154 ps | 170 ps | 100 ps | 100 ns |
| $P_{ap}$ (%) | 3.4 | 6.2 | 2.8 | 1.8 |
| $R_{dc}$ (kHz) | 732 | 213 | 108 | 1 |
| $P_{ap}^{ns}$ ($\times 10^{-5}$ ns$^{-1}$) | 16 | 6.3 | 2 | 18.3 |
| Deadtime | 10 ns | 10 ns | 50 ns | 15 $\mu$s |

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