# Balanced Detection in Single Photon Counting

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Abstract - We demonstrate balanced InGaAs/InP single photon avalanche diodes (SPADs) operated in both pulse-gated mode and sinusoidal gating mode for data transmission rate up to 20 MHz. The photodiode pair is biased in a balanced configuration with only one of the SPADs illuminated. The common-mode signal cancellation realized with the balanced configuration enables detection of small avalanche pulses. Afterpulsing is significantly suppressed due to the capability of detecting small avalanche pulses at high laser repetition rate. For pulse-gated mode operation and laser repletion rate of 20 MHz at 240 K, the dark count probability for photon detection efficiency of 13% is $1.9\times10^{-5}$. The afterpulse probability is 0.3% for 2 ns pulse width, hold off time of 20 ns, and 10% PDE, at 240K. For sinusoidal gating a phase shifter has been incorporated to achieve better synchronization between signals. At laser rate of 20 MHz and 240 K, the dark count probability and photon detection efficiency are $2.8\times10^{-5}$ and 10.8% respectively.

Keywords: photodetector, avalanche photodiode, single-photon detection

## 1. INTRODUCTION

InGaAs/InP avalanche photodiodes have been widely used in infrared detection modules for single photon detection applications [1-3]. These applications include correlated single photon counting[4], infrared remote sensing[5], and quantum information (quantum communication and quantum computing)[6, 7]. For various applications InGaAs/InP single photon avalanche diodes (SPADs) have proven a practical choice due to their high detection efficiency, compactness, high reliability, and low power consumption. The performance of semiconductor SPADs operated in Geiger mode can be adversely affected by long dead times; this is particularly true for InGaAs/InP SPADs. Unlike the Geiger-Muller counter, the dead time of single photon counters is the “hold-off” time before the SPAD can be armed for subsequent detection in order to prevent excess dark counts, i.e., the so-called “afterpulsing effect” [8, 9]. Afterpulsing refers to avalanche events that originate from the emission of carriers that were trapped in deep-level states during previous avalanche events. SPADs are frequently operated in pulse-gated mode to avoid additional dark counts and the aggregated afterpulsing effect. The microsecond-range dead time caused by afterpulsing can limit the gating frequency to several hundred kHz [10].

Recently afterpulsing has been successfully addressed by various biasing and quenching techniques; such as sine-wave gating [2, 3], self-differencing [6, 11], and fast gating with matched delay lines [12, 13]. These techniques are effective in suppressing afterpulsing by reducing the total charge flow during avalanche events [8, 9]. The charge reduction approach, however, encounters challenges in detecting weak avalanche pulses in the presence of transient or common-mode responses. Common-mode and transient cancellation techniques have been demonstrated in various formats. These approaches all employ differential signaling [14]. Examples include self-differencing [6, 11, 15] (using a 50/50 splitter to cancel common-mode signals either optically or electrically), matched delay lines [12, 13] (using terminated delay lines to invert transients), dummy path [1, 16] (using a dummy capacitor to generate the out-of-phase transients) and balanced detection [17-20] (using another photodiode to generate the out-of-phase transients). Recently, pulsed-mode balanced detection has been demonstrated [20] and it is anticipated that further improvements in performance can be achieved through monolithic integration. Sine-wave gating has also been demonstrated using

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balanced detection [17, 18]. This approach has permitted the elimination of the narrow band-stop filters from the conventional sine-wave gating receivers. In addition, balanced detection is also applicable when gating is not periodic.

In this paper we report the design and characterization of a novel balanced single photon receiver that can be operated in both sine-wave and pulsed gating modes without significant afterpulsing up to 20 MHz laser rate. The improved sine-wave gating module incorporates a phase shifter in one of the bias arms, which reduces background noise and has permitted detection of smaller avalanche pulses and, thus, reduced afterpulsing.

## 2. EXPERIMENTAL EVALUATION

The balanced receiver, shown in Fig. 1, is the hybrid circuit reported in Ref. [20], in which low dark count rate and high laser repetition rate were reported for pulse-gated-mode operation. The balanced receiver module was cooled to 240 K. The DC voltages and AC excess bias for the two diodes are complementary in both amplitude and phase. The AC excess bias can be sinusoidal or pulsed. The relative timing of the excess bias signals is of paramount importance for reducing residual background noise. The output signals in the common mode are out of phase except the avalanche signal, which originates from the illuminated diode. The gating frequency was 80 MHz for both sine-wave gating and pulsed gating.

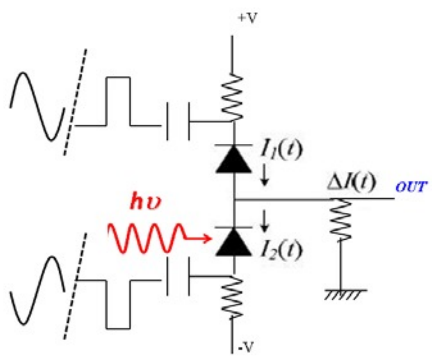
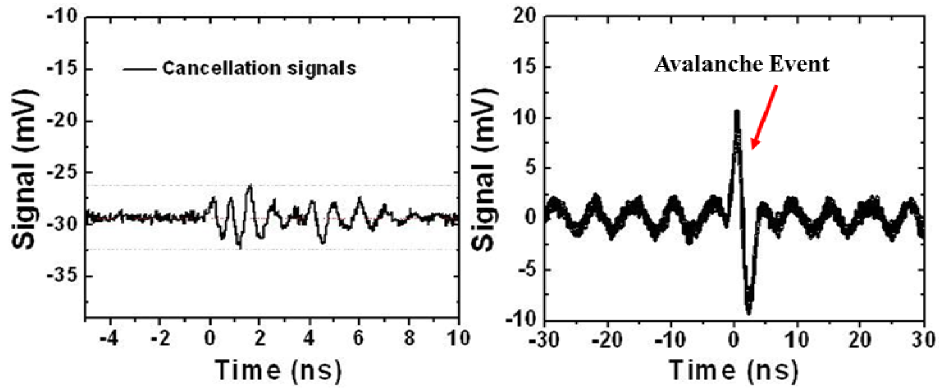



Figure 1. Balanced receiver layout.

Low background noise is essential in order to detect the small avalanche signals that are associated with small charge flow and reduced afterpulsing [11]. In gated-mode, good phase matching was realized by tuning the signal source. In a previous version of a balanced receiver that used sine-wave gating [17, 18], a significant component of the residual background noise was caused by imperfect phase matching of the two sine-wave signals. Better phase matching has been realized by adding a phase shifter (RF-Lambda RVPT0003MAC) to one branch of the sine-wave signal. The adjustability of phase allows greater suppression of the capacitive response with the result that the background noise has been significantly reduced. Figures 2 (a) and 2 (b) show the residual background noise with the phase shifter for balanced pulsed-mode [20] and sine-wave gating, respectively. Both curves demonstrate noise level amplitude less than 3 mV, five times smaller than sine-wave gating without the phase shifter. The residual background noise is well below the avalanche signal in Fig. 2(b).




(a) (b)

Figure 2. Cancellation effect for pulsed gating (a) and sine-wave gating (b); (b) also shows an avalanche pulse at gating frequency of 80 MHz. The signals were captured with an oscilloscope without amplification.

## 3. DARK COUNT RATE AND PHOTON DETECTION EFFICIENCY

Balanced detection enables operation with short bias pulses; the shortest pulse available for this work was 1.4ns. Figure 3 shows dark count probability (DCP) versus photon detection efficiency (PDE) for different laser repetition rates. The laser repetition rate is the same as the gating rate; therefore the clock rate equals the maximum count rate. The pulse width was 1.4 ns for the 10 MHz and 20 MHz measurements and 2.5 ns for 1 MHz. At 20 MHz repetition rate, the dark count probability is $1.9 \times 10^{-5}$ and detection efficiency is 13%. There is no significant increase in DCP for laser rates in the range of 1 MHz to 20 MHz. This indicates significant suppression of afterpulsing owing to the small pulse detection window. On the other hand, sinusoidal gating with balanced detection exhibited an order of magnitude of increase in dark count rate as the repetition rate increased from 1 MHz to 10 MHz [18].

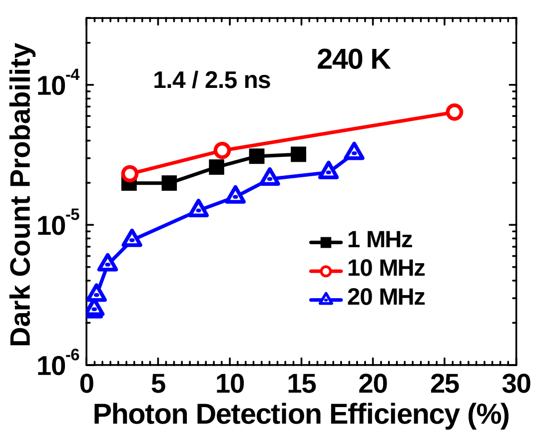



Figure 3. Dark count probability versus photon detection efficiency at 240 K with 1 MHZ, 10 MHz, and 20 MHz laser repetition rates.

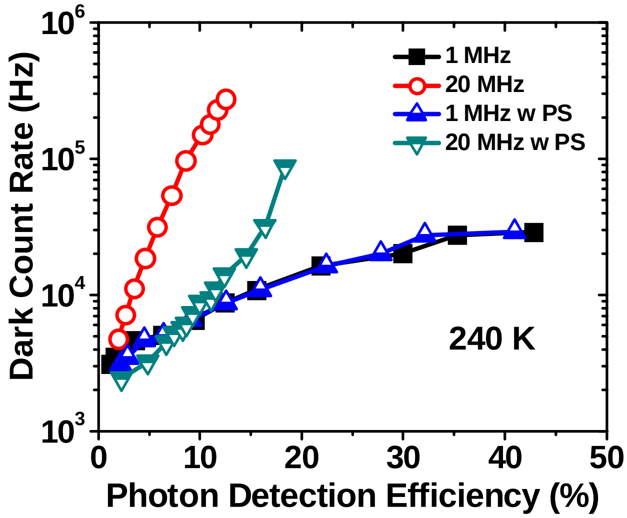



Figure 4 Comparison of balanced sine-wave gating results with and without phase shifter at 240K.

Figure 4 compares sine-wave gating at 1 MHz and 20 MHz with and without the phase shifter. For a laser repetition rate of 20 MHz, the dark count rate for photon detection efficiency of 10% is 8.9 kHz. For a laser repetition rate of 20 MHz, the dark count rate with the phase shifter is significantly lower than that for the circuit without the phase shifter. However at 1MHz, the fact that the phase shifter does not provide a significant reduction in dark count probability (DCP) indicates less severe afterpulsing effect at low frequencies, i.e., a hold–off time of 1 μs is sufficient to effectively release the trapped carriers that cause afterpulsing.

Figure 5 compares the DCP with PDE for both pulsed gating and balanced sine-wave gating at 20 MHz laser repetition rate. For sine-wave gating the phase shifter reduces DCP at 10% PDE by approximately one order of magnitude compared with the receiver with the phase shifter. The pulsed gating result with 2.5 ns pulse width (PW) overlaps that of sine-wave gating with phase shifter. This indicates that for these operating parameters the extra biasing gates in sine-wave gating are not the primary reason for the degraded performance at high laser repetition rate [18]. On the other hand, pulse width and avalanche charge flow are crucial in terms of reducing dark counts [20]. A quantitative study of the total charge flow shows that there is 0.09 pC charge flow during an avalanche pulse with the 80 MHz sine-wave gating frequency. This is very close to the avalanche charge flow that has been reported for self-differencing [11]. Figure 5 shows that the best performance is achieved with the 1.4 ns pulse width. The reason is simply due to the faster quenching and smaller avalanche pulses associated with the narrower gate pulses. This is consistent with the excellent performance achieved with GHz sine-wave gating [2, 3].

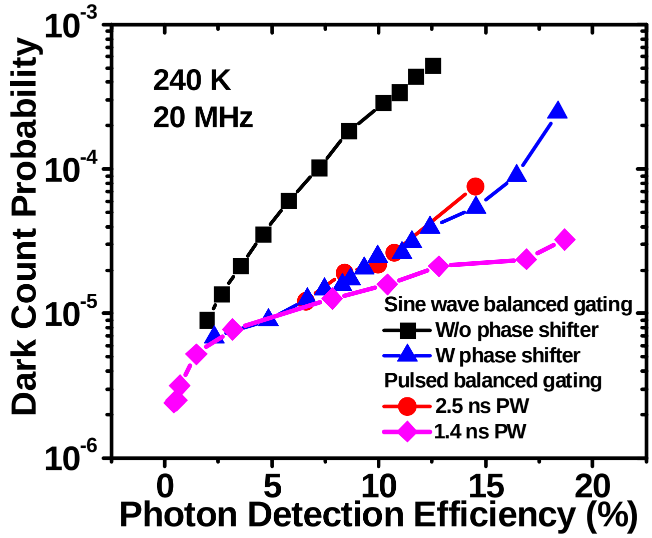



Figure 5 Photon counting result at 20 MHz counting rate from pulsed gating and sine-wave gating, both gating schemes are realized with balanced detection.

## 4. SUMMARY

In this paper, we report balanced detection using InGaAs/InP SPADs. Both pulse-gated mode and sinusoidal gating operation have been carried out at 240K with balanced detection. Pulse gating has yielded better results due to the narrower pulse width compared with sinusoidal gating at 80 MHz. For pulse-gated mode operation and laser repletion rate of 20 MHz, the dark count probability for photon detection efficiency of 13% is $1.9\times10^{-5}$. For sinusoidal gating at 20 MHz gate frequency the dark count probability is $2.8\times10^{-5}$ with a photon detection efficiency of 10.8%.

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