Improved sinusoidal gating with balanced InGaAs/InP Single Photon Avalanche Diodes

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Abstract: We report balanced InGaAs/InP single photon avalanche diodes (SPADs) operated in sinusoidal gating mode with a tunable phase shifter to reduce common mode noise. This technique enables detection of small avalanche pulses, which results in reduced afterpulsing. For laser repletion rate of 20 MHz at 240 K, the dark count rate for photon detection efficiency of 10% is 8.9 kHz.

OCIS codes: (230.0250) Optoelectronics; (230.0040) Detectors; (250.1345) Avalanche photodiodes (APDs).

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1. Introduction

InGaAs/InP avalanche photodiodes have been widely employed in infrared detection modules for single photon detection [1–5]. These applications include quantum key distribution [2, 6], semiconductor device characterization [7], eye-safe laser ranging (LIDAR) [8], and biological imaging [9]. 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" [10, 11]. Afterpulsing refers to avalanche events that originate from the emission of carriers that were trapped in deep-levels during previous avalanche events. SPADs are frequently operated in 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 [12].

Afterpulsing has been successfully addressed by various biasing and quenching techniques; such as sine-wave gating [2, 3], self-differencing [6, 13], and fast gating with matched delay lines [14, 15]. These techniques are effective in suppressing afterpulsing by reducing the total charge flow during avalanche events [10, 11]. 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 [16]. Examples include self-differencing [6, 13, 17] (using a 50/50 splitter to cancel common-mode signals either optically or electrically), matched delay lines [14, 15] (using terminated delay lines to invert transients), dummy path [1, 18] (using a dummy capacitor to generate the out-of-phase transients) and balanced detection [19–21] (using another photodiode to generate the out-of-phase transients). Recently, pulsed-mode balanced detection has been demonstrated [22] and it is anticipated that further improvements in performance can be achieved through monolithic integration, for instance improved performance, simplicity of measurement apparatus, and more compact size. Sine-wave gating has also been demonstrated using balanced detection [19, 20]. 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 to operations with non-periodic gating.

In this letter we report the design and characterization of a novel balanced single photon receiver that incorporates a phase shifter in one of the bias arms. This has resulted in reduced background noise, which has permitted detection of smaller avalanche pulses and, thus, reduced afterpulsing.

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2. Counting electronics

Two nominally identical avalanche photodiodes were configured in a balanced receiver module that was cooled to 240 K (Fig. 1). The DC voltages and AC excess bias for diodes #1 and #2 are complementary in both amplitude and phase. 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 #1.

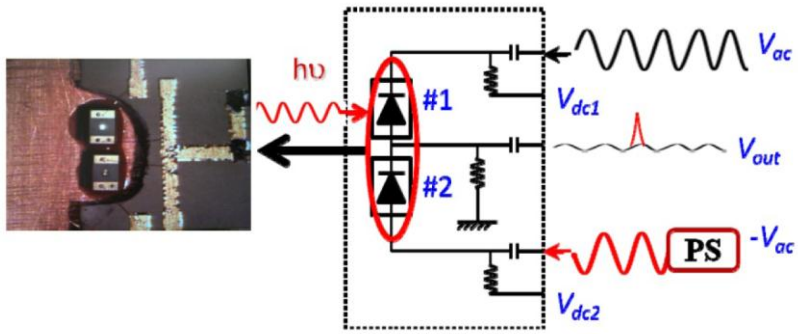

Fig. 1. Balanced receiver layout. Dashed line indicates the circuit board hosting two diodes and other elements. Insert picture shows the actual layout of the two photodiodes. PS: Phase shifter.

Low background noise is essential in order to detect the small avalanche signals that are associated with small charge flow and reduced afterpulsing [13]. In a previous version of a balanced receiver [19, 20], a significant component of the residual background noise was caused by imperfect phase matching of the two sine-wave signals. In this paper, 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. In Figs. 2 (a) and 2 (b) two graphs show the residual background noise with the phase shifter for balanced pulsed-mode and sine-wave [22] 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).

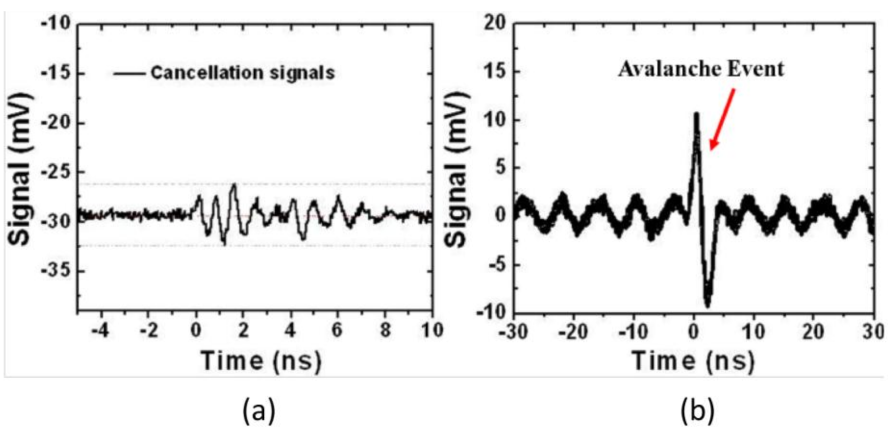

Fig. 2. Cancellation effect for pulsed gating (a) and sine-wave gating (b); (b) also shows an avalanche pulse at gating frequency of 80 MHz. The signals were captured with an oscilloscope without amplification.

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These results were achieved using an 80 MHz gating frequency without band-stop filters. The photon counts were recorded as the delay time of the laser pulse was varied relative to the gating signal of the SPADs. The temporal distribution of the photon counts is plotted in Fig. 3. Assuming a Gaussian distribution, the full width at half maximum (FWHM) was 2.7 ns.

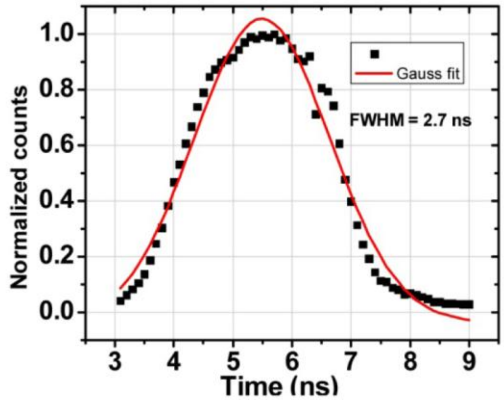

Fig. 3. Effective pulse width of 80 MHz gating rate with laser pulse width of 40 ps for balanced diodes at 240 K.

3. Counting performance

The balanced single photon counting receiver was characterized with 40 ps laser pulses at 1310 nm wavelength. The laser repetition rates were submultiples of the gating rate, ranging from 1 to 20 MHz. The laser repetition rate is limited by the pulse laser driver, which has a maximum pulse rate of 25 MHz. The light intensity was attenuated to 0.1 photons/pulse. During the measurement, the DC bias was constant and the AC bias was varied to obtain different dark count rate (DCR) and photon detection efficiency (PDE). The result depends on excess bias and does not show close relation to whether the bias is varied through the DC or AC sources. Equations (1) and (2) were used to calculate the DCR and PDE [23]. Compared to dark count probability, DCR is the normalized dark counts measured only when the devices are armed. P_d is dark count probability, P_t is total count probability, and n is the mean photon number per pulse (0.1). Dark count probability is the measured dark counts per second divided by the gating frequency, while the total count probability is calculated by dividing the total count per second by the gating frequency. The effective pulse width (τ_e) was determined by measuring the full width at half maximum of the temporal distribution of the photon counts, which is plotted in Fig. 3.

$$DCR \times \tau_e = -\ln(1 - P_d) \tag{1}$$

$$\text{PDE} = \frac{1}{n}\ln(\frac{1-P_d}{1-P_t}) \tag{2}$$

Similar to the self-differencing technique, phase matching is crucial to improve the performance of the counting system [13, 24]. As a result of the high residual background noise of the previous version of the sine-wave balanced receiver acceptable detection efficiencies could only be achieved with avalanche pulses greater than 20 mV. By incorporating phase matching into one of the bias arms, the detectable avalanche pulse level has been reduced to less than 10 mV (Fig. 2). The lower noise floor enables a lower threshold level, which is beneficial for reducing both afterpulsing and timing jitter [1].

As shown in Fig. 4, for a laser repetition rate of 20 MHz at 240 K, the dark count rate for photon detection efficiency of 10% is 8.9 kHz. Fig. 4 also compares the dark count rate

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versus photon detection efficiency (PDE) at 1 MHz and 20 MHz for balanced detectors with and without the phase shifter. We have used the same device and module as in the circuit without phase shifter. For a laser repetition rate of 20 MHz, the dark count rate is significantly lower than that for the circuit without the phase shifter. While 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. In the low efficiency region, we observed slightly higher DCR at 1 MHz than 20 MHz. This is probably due to uncertainties in the measurements.

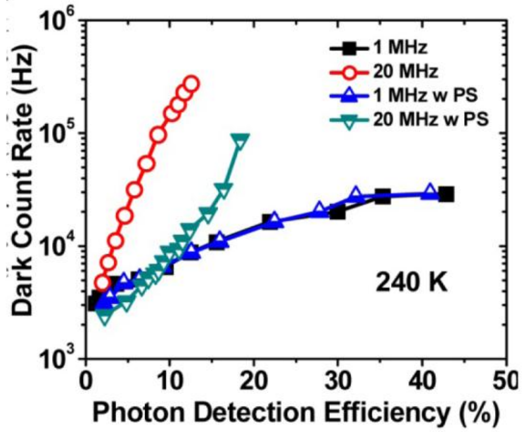

Fig. 4. Comparison of balanced sine-wave gating results with and without phase shifter at 240K. Effective pulse width is 2.7 ns.

Figure 5 compares the DCP with PDE at 240K for both pulsed gating and balanced sine-wave gating at 20 MHz laser repetition rate. For sine-wave gating the phase shifter reduces DCR at 10% PDE by approximately one order of magnitude compared with the original balanced receiver. 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 [20]. On the other hand, pulse width and avalanche charge flow are crucial in terms of reducing dark counts. 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 [13]. 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]. We have compared avalanche charge flow in different gating techniques is included in Table 1. This parameter is closely related to afterpulsing therefore is a good indicator for suppressing afterpulsing.

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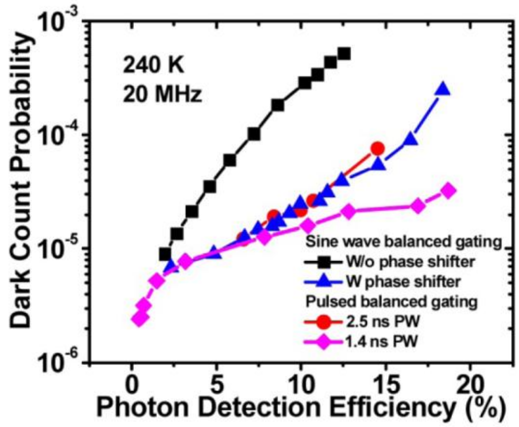

Fig. 5. Photon counting result at 20 MHz counting rate from pulsed gating and sine-wave gating, both gating schemes are realized with balanced detection.

Table 1. Comparison of balanced sine wave gating result with conventional sine wave gating and self-differencing techniques

Quenching Method	Charge Flow (pC)
Conventional Sine-Wave Gating [a]	0.8
Present work	0.16
Self-differencing [b]	0.036
Balanced SPADs Pulse Gating (1.4 ns) [c]	0.09

[a] Ref [20], [b] Ref [5]. and [13], [c] Ref [22].

4. Conclusion

In conclusion, balanced sine-wave gating with phase shifter has demonstrated improved single photon counting performance. At 20 MHz laser repetition rate the background noise has been reduced by a factor of 5 and the dark count probability (2.5×10^{-5} at PDE of 10%) was reduced by an order of magnitude compared with the balanced sine wave gating without the phase shifter. This could lead to a factor of 5 reduction in the quantum bit error rate in QKD applications if ideal optical and temporal alignments in the experiments are assumed.