

High count rate InGaAs/InP SPAD system with balanced SPAD-dummy approach running up to 1.4 GHz

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ABSTRACT

The capability to achieve high count rates has become an imperative in the most areas where near-infrared single-photon counters are required to detect photons up to 1.7 μm . Hence, afterpulsing mitigation is a dominant theme in recent works concerning systems based on InGaAs/InP SPADs. Given the challenges inherent in reducing the density of defects that give rise to the carrier trapping events causing afterpulsing, the only viable approach is to reduce the potential number of carriers that can be trapped by limiting the charge flow per avalanche event.

In this paper we present a sine-wave gating system based on the balanced detector configuration. The gate frequency is programmable in a wide range (1.0 – 1.6 GHz) for allowing synchronization with an external laser system and for exploring the best trade-off between afterpulsing and photon detection efficiency. The long-term stability can be achieved with a stable cancelation of the gate feedthrough. In this work this is guaranteed by a feedback loop that continuously monitors the residual output power at the gate frequency and adjusts the amplitude and phase of the two sinusoids fed to the SPAD-dummy couple.

Keywords: Single-photon avalanche diode (SPAD), APD, InGaAs/InP, near-infrared, gated mode, sinusoidal gating, afterpulsing, quantum-key distribution, QKD.

1. INTRODUCTION

Single-photon detectors with high count rate (greater than a few Mcount/s), high photon detection efficiency (PDE >30%) at the near-infrared wavelengths (1 μm – 1.7 μm), low noise (few kcount/s), and narrow temporal response (full-width at half maximum – FWHM – lower than 100 ps) are key enabling technologies in many applications (e.g. Quantum Key Distribution – QKD). Currently, many research laboratories exploits superconducting nanowire single-photon detectors (SNSPDs), which withstand high count rates and are operated in free-running mode, but need to be cooled at cryogenic temperature (< 4 K), forcing to use bulky cryostats that impair their applicability at a larger scale. For widespread deployment of QKD systems, InGaAs/InP Single-Photon Avalanche Diodes (SPADs), suitable for compact and reliable single-photon counters, are the only practical solution. The bottleneck for high throughput QKD with InGaAs/InP SPADs is still their strong afterpulsing, which is due to deep levels, present in the InP multiplication region, where charge carriers can be trapped even for few microseconds. Afterpulsing can be reduced either by increasing the hold-off time after each avalanche ignition, though strongly limiting the count rate, or by reducing the charge per avalanche. The latter approach guarantees excellent results in terms of count rate (>100 Mcps).

Short gating techniques exploit sub-ns gate pulses to quench the avalanche during its build-up, thus abruptly reducing the number of charge carriers that can be trapped. However, owing to the capacitive feed-through of gate pulses, the signal at discriminator input includes a small avalanche pulse (whose amplitude is just few millivolts) and a strong disturbance (whose amplitude is orders of magnitude higher than the avalanche pulse). Various solutions have been reported in literature, including: i) self-differencing circuits [1],[2], which require fine-tuned delays; ii) notch filters at the gate frequency and its harmonics [3]. However, hardware changes either on self-differencing delays or notch filters are needed

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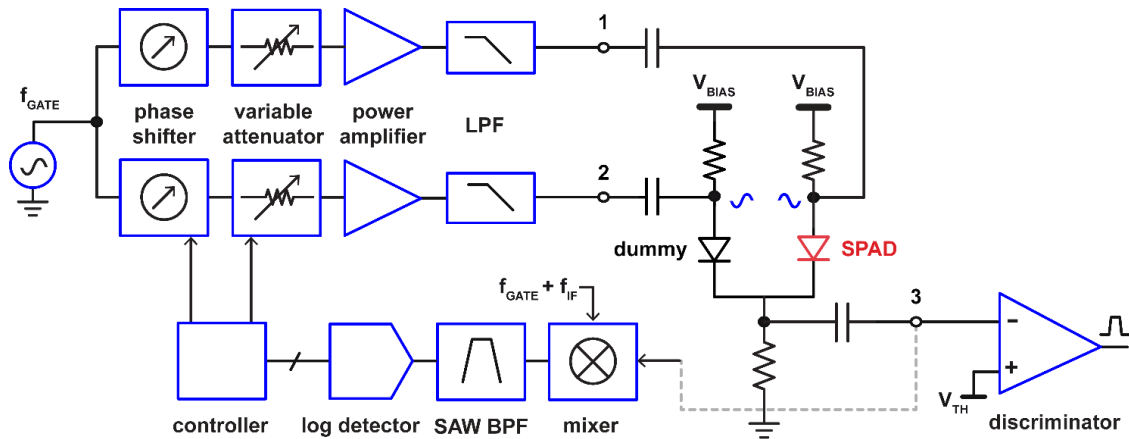


Figure 1. Simplified block diagram of the SPAD-dummy balanced configuration for cancelling the capacitive coupling of the gate at the discriminator input. LPF = low pass filter, SAW BPF = surface acoustic wave band pass filter.

to adjust the gate frequency (e.g. when changing the frequency of the photon source). Conversely, broadband circuit solutions such as the harmonic subtraction technique [4] and the balanced detector configuration [5], which actively synthesize a signal that cancels the gate feedthrough, permit to adjust the gate frequency in a wide range and synchronize it to an external photon source.

In ref. [4] we presented an experimental setup for GHz sinusoidal gating of an InGaAs/InP SPAD that exploits the balanced detector configuration [6] for cancelling the spurious capacitive coupling from the gate driver to the discriminator input. In detail, at a gating frequency of 1.3 GHz, we achieved very low afterpulsing probability ($<1.5\%$), high dynamic range (maximum count rate is 650 Mcount/s), high photon detection efficiency (PDE $>30\%$ at 1550 nm), low and low timing jitter (<70 ps FWHM). Here we describe an improved version of such circuit, capable of operating continuously in real settings thanks to a feedback control loop that guarantees the long-term stability of the gate feedthrough cancellation.

2. BALANCED DETECTOR CONFIGURATION

In the balance detector configuration (Figure 1) the InGaAs/InP SPAD is paired with a “dummy” structure, i.e. a diode that mimics the electrical response of the detector, but it is insensitive to photons. The diodes are both reverse biased at the SPAD breakdown voltage, while two opposite sinusoids are AC coupled to their anodes. The SPAD gate feed-through is balanced with its own anti-phase copy (propagating through the “dummy” path) at the common cathode node, i.e. where the avalanche signal is picked-up. The SPAD is periodically biased above its breakdown voltage by the gate signal, while the “dummy” is always under its breakdown voltage.

The system here described has been characterized with a $25\ \mu\text{m}$ active area diameter InGaAs/InP SPAD developed at Politecnico di Milano [7]. In order to maximize the matching between the SPAD and dummy electrical responses and, eventually, the gate feedthrough cancellation quality, we fabricated both diodes in the same chip. The “dummy” is another p-n junction with breakdown voltage about 10 V higher than that of the SPAD. SPAD and “dummy” diodes have a common cathode contact on the chip backside and separate anode contacts on the chip frontside. Therefore the “dummy” mimics very well the parasitic capacitances and inductances, but no avalanche is triggered in it, since we never apply voltages

exceeding its breakdown level (i.e. the maximum gate amplitude is lower than 10 V). The SPAD-dummy chip is mounted on a three-stage thermoelectric cooler and packaged in a hermetically sealed TO-8 package. Figure 2 compares the transmission responses from the SPAD and dummy anodes to the common-cathode at gate frequencies up to 4 GHz. So, referring to Figure 1, the forward transmission coefficient S_{31} is a measure of the power at port 3 when an RF stimulus is sent to port 1, while port 2 is terminated into $50\ \Omega$. Similarly, S_{32} is the forward transmission coefficient between port 3 and 2, while port 1 is terminated into $50\ \Omega$.

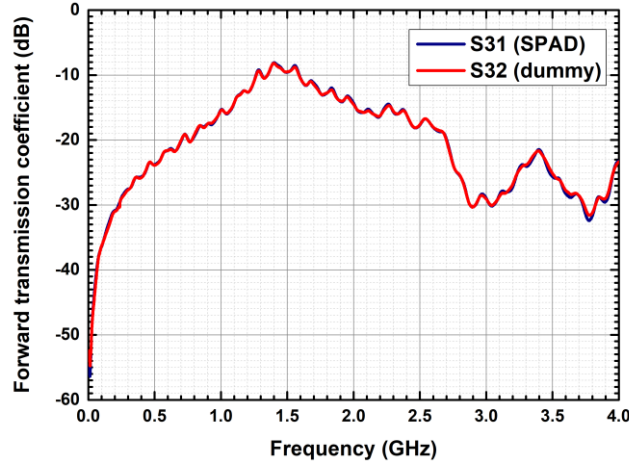


Figure 2. S_{31} : forward transmission coefficient from the SPAD anode port to the common-cathode port (dummy anode port terminated into 50Ω). S_{32} : forward transmission coefficient from the dummy anode port to the common-cathode port (dummy anode port terminated into 50Ω).

Despite the high degree of symmetry between the SPAD and dummy paths shown in Figure 2, component tolerances and temperature drifts may introduce some residual mismatches. Therefore, the relative amplitude and phase of the two sinusoids need to be finely adjusted for achieving a good cancellation.

3. GATE SUPPRESSION FACTOR

In order to avoid missing the small pulses due to avalanches triggered towards the end of the gate signal, a low discriminator threshold (<10 mV) is needed. We introduce a quantity called gate suppression (GS) factor, defined as the ratio between the gate power at the readout node with the dummy sinusoid off and disturbance power with the dummy sinusoid on:

$$GS = 10 \log_{10} \left(\frac{A^2}{2} \right) - 10 \log_{10} \left(\int_0^{\frac{2\pi}{\omega}} V^2(t) dt \right)$$

where A is the gate amplitude attenuated by the forward transmission coefficient S_{31} , $\omega/2\pi$ is the gate frequency and $V(t)$ is the disturbance voltage waveform, i.e. the combination of the two gate sinusoids sent to the SPAD and dummy:

$$V(t) = A \cdot \sin(\omega \cdot t) + A \cdot (1 + \epsilon) \cdot \sin(\omega \cdot t + \pi + \phi)$$

As a reference, we consider an InGaAs/InP SPAD gated with a 14 V peak-to-peak sinusoid (i.e. 27 dBm) at 1.3 GHz and a discrimination threshold of 5 mV (-36 dBm). As shown in Figure 2, at 1.3 GHz the forward transmission coefficient S_{31} is equal to -10 dB. Hence, the gate power at the discriminator input with the dummy sinusoid off would be 17 dBm (i.e. $A = 2.24$ V) and the gate suppression GS must be at least 53 dB. To achieve such a good cancellation, the resolution of the relative amplitude and phase control has to be very tight. If we neglect the amplitude difference (i.e. $\epsilon = 0$), the disturbance amplitude is $2 \cdot A \cdot \sin(0.5\phi)$, whose first term of the Taylor expansion, calculated in $\phi = 0$, is $A\phi$. Hence, for a gate suppression of 53 dB, the phase control resolution must be about 2 mrad (i.e. 0.1°). Similarly, neglecting the phase shift (i.e. $\phi = 0$), the amplitude error must be about 0.2%, i.e. 15 mV.

Figure 3 reports the gate feedthrough power at the common cathode output measured by a spectrum analyzer. At $t = 0$ s two sinusoids of the same amplitude (27 dBm) and frequency ($f_G = 1.3$ GHz), but with a phase difference of $\pi + \phi = 120^\circ$, are fed to the two anodes. It can be demonstrated that in such condition the gate feed-through power is 17 dBm (i.e. $27 \text{ dBm} + S_{31}(f_G) + 10 \log_{10}(2 + 2\cos(120^\circ))$). At $t = 10$ s, the feedback control loop starts minimizing the gate feed-through power by adjusting the relative amplitude and phase of the two sinusoids with progressively smaller step sizes. Once the gate feedthrough has been reduced below the desired avalanche discrimination threshold, the feedback loop keeps monitoring and adjusting the relative amplitude and phase shift to compensate for temperature drifts.

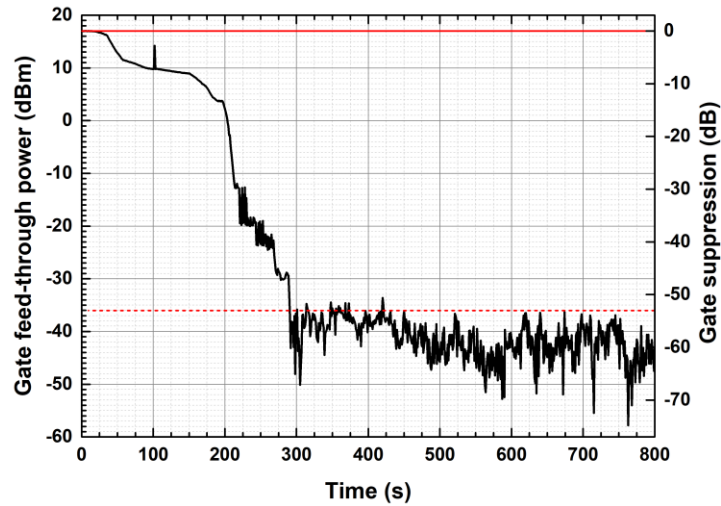


Figure 3. Short-term monitoring of gate feed-through at the readout node. The feedback control loop is turned ON at $t = 10$ s.

4. AVALANCHE SIGNAL

Figure 4 shows a $1 \mu\text{s}$ oscilloscope trace acquired at the discriminator input. Thanks to the very low noise level (below 1 mV), almost all avalanche events are distinguishable from the noise floor. However, the amplitude of the avalanche signals can be seen to vary widely from one avalanche event to another. This distribution has direct bearing on the excess bias that is not constant within the gate, and underscores the importance of a low discrimination threshold for preserving low-jitter temporal response of the detector.

5. CONCLUSIONS

We presented a photon-counting system based on InGaAs/InP SPADs gated by a high frequency sinusoid. The joint use of a balanced detector configuration, with SPAD and “dummy” integrated in the same chip, and proper fine-tuning of the relative amplitude and phase shift guarantees to achieve a good suppression of the gate signal coupling, thus allowing for detecting avalanches with low threshold. Moreover, this configuration allows to adjust the gating frequency in a wide range, from 1 to 1.6 GHz, with the gate sinusoid that can be different from that of the photon source. Finally, a feedback control loop automatically optimizes the gate feed-through suppression in order to have a stable system that can operate continuously in real settings.

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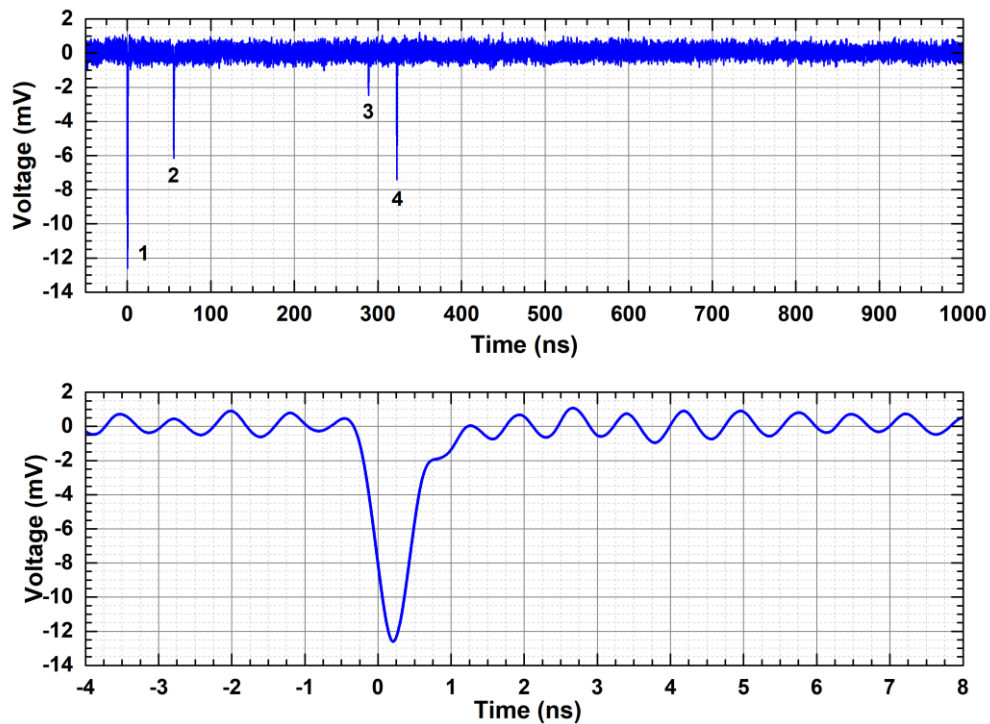


Figure 4. Output signals after gate feed-through cancellation. The second plot shows avalanche “1” on faster time-scale.

REFERENCES

- [1] Yuan, Z. L., Kardynal, B. E., Sharpe, A. W. and Shields, A. J., “High speed single photon detection in the near infrared,” *Appl. Phys. Lett.* 91(4), 41114 (2007).
- [2] Restelli, A., Bienfang, J. C. and Migdall, A. L., “Time-domain measurements of afterpulsing in InGaAs/InP SPAD gated with sub-nanosecond pulses,” *J. Mod. Opt.* 59(17), 1465–1471 (2012).
- [3] Namekata, N., Adachi, S. and Inoue, S., “Ultra-Low-Noise Sinusoidally Gated Avalanche Photodiode for High-Speed Single-Photon Detection at Telecommunication Wavelengths,” *IEEE Photonics Technol. Lett.* 22(8), 529–531 (2010).
- [4] Restelli, A., Bienfang, J. C. and Migdall, A. L., “Single-photon detection efficiency up to 50% at 1310 nm with an InGaAs/InP avalanche diode gated at 1.25 GHz,” *Appl. Phys. Lett.* 102(14), 141104 (2013).
- [5] Scarcella, C., Boso, G., Ruggeri, A. and Tosi, A., “InGaAs/InP single-photon detector gated at 1.3 GHz with 1.5 % afterpulsing,” *IEEE J. Sel. Top. Quantum Electron.* 21(3), 17–22 (2015).
- [6] Campbell, J. C., Sun, W., Lu, Z., Itzler, M. A. and Jiang, X., “Common-Mode Cancellation in Sinusoidal Gating With Balanced InGaAs/InP Single Photon Avalanche Diodes,” *IEEE J. Quantum Electron.* 48(12), 1505–1511 (2012).
- [7] Tosi, A., Calandri, N., Sanzaro, M. and Acerbi, F., “Low-Noise, Low-Jitter, High Detection Efficiency InGaAs/InP Single-Photon Avalanche Diode,” *IEEE J. Sel. Top. Quantum Electron.* 20(6), 192–197 (2014).