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Analysis of Avalanche Signal Recovery in Sinewave Gated High Speed Single Photon Detectors

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Abstract—A Single Photon Avalanche Diode (SPAD) can detect a single-photon if the reverse bias is greater than the breakdown voltage. In a time-gated SPAD the bias rises above the breakdown voltage only when a photon is expected. The frequency of the gating signal can be configured depending on the detection speed requirement. The benefits of time-gated operation include faster detector response times and low afterpulsing effect. However, this mode of operation also requires to recover the avalanche signal that can be lost in the capacitive response of the SPAD. Numerous techniques have been developed in the past to solve this issue, in this paper we present the impact of the recovery techniques on the avalanche signal in a sinewave gated high speed SPAD. The measurement results show that Chebyshev low-pass filter distorts the avalanche pulse, whereas the signal remains undistorted when using destructive interference.

Index Terms—Photon, Single Photon Avalanche Diode (SPAD), Avalanche signal, Low-pass filter.

I. INTRODUCTION

According to the quantum theory, light is composed of light quanta known as photons. The energy of each quantised particle is related to the wavelength (λ) and the frequency (f) of the electromagnetic radiation [1]:

$$E = h \frac{c}{\lambda} = hf, \quad (1)$$

where h is the Planck's constant ($6.62607015 \times 10^{-34}$ J.s) and c the speed of light in vacuum (3×10^8 m/s). Optical light in the telecom spectrum range show photon energy of ~ 0.8 eV (1.28×10^{-19} J) which is significantly higher than thermal (0.025 eV) energy. Cooled detectors with low energy absorption have been developed with amplification suitable to detect single photon. Initially vacuum based detectors, such as Photomultiplier Tubes (PMTs), were used for photon counting [2]. The high voltage across the vacuum tube provides the required high multiplication gain. PMTs have large active area and low noise characteristics. The main disadvantages of PMTs are high operating voltage, large size, limited scalability, and susceptibility to external magnetic field effect. Cryogenic-temperature based photodetectors such as superconducting nanowire single-photon detectors (SNSPDs) are alternative technologies to the PMT. The SNSPD offers best performance in terms of detection efficiency and dark count. The cryogenic operating temperature is a major

drawback of the SNSPD [3]. Solid state photo devices such as Single Photon Avalanche Diode (SPADs) are another photodetectors used for photon counting [4]. The SPAD operates in reverse bias above the breakdown voltage. The high reverse bias voltage increases the electric field across the depletion region and the device breaks down on absorbing a single photon, making the detector highly sensitive to weak light. The SPAD has the advantage of smaller size, and higher operating temperature and lower voltage requirements.

II. OVERVIEW OF SINGLE PHOTON AVALANCHE PHOTODIODE

Numerous research have been undertaken in the past to improve the capacity of light sensing/detecting devices in the near infrared spectrum range. Single-photon avalanche diodes (SPADs) have received considerable research attention. These are p-n junction photodetectors designed to work in reverse breakdown region. The schematics of SPAD equivalent circuit is shown in Fig. 1. The bias voltage is applied at the cathode terminal, as a result the diode develops an internal junction capacitance (C_j). The photodiode has also resistance (R_d) given by the series combination of space-charge resistance of the avalanche junction and of the ohmic resistance of the neutral semiconductor [4]. In a high speed gated mode of operation, the circuit includes stray capacitance (C_s) and lead inductance (L_s) due to the pin connectors.

The reverse bias voltage increases the electric field in the depletion region of the photodiode. A single photon with a sufficient energy creates a charge carrier in the depletion layer of the photodiode. The charge carrier gains energy in the high electric field and initiates a self-sustaining multiplication (avalanche) in the process known as impact ionisation [5]. This process internally multiplies the charge carrier which creates sufficient electric current to detect the incident photon. Once the photon is detected successfully, the avalanche should be interrupted/quenched, so the photodetector will be ready for the next detection. To meet this requirement, the detection systems include additional circuitry, such as passive and active quenching circuits. In the former case, the SPAD is biased above the breakdown voltage through a large resistor (R_q) connected in series

with its cathode terminal. After the photon arrival event, the voltage decreases exponentially with time constant τ (2). The avalanche stops when the voltage decreases below the SPAD's breakdown voltage.

$$\tau = C_p(R_q || R_s) \quad (2)$$

The main problem with this scheme is the delay due to the long time constant τ . Active quenching circuits have improved time response compared to the aforementioned scheme, however the quenching speed of these circuits may not be suitable for high speed single photon detection. Gated quenching is widely used in synchronous high speed single-photon detection applications. The gating signal changes in such a way that the bias shifts below and above the breakdown voltage - the bias will be higher than the breakdown voltage during the photon arrival time only. The schematic of a gated SPAD is shown in Figure 1.

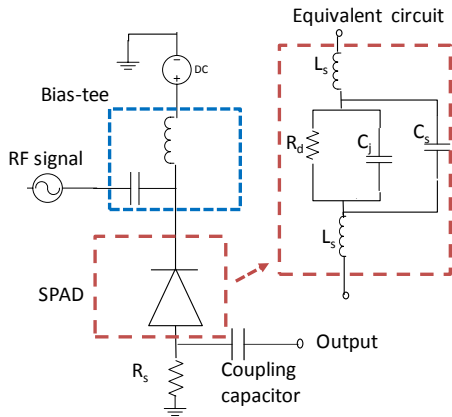


Fig. 1. Sinewave gated SPAD and SPAD equivalent circuit schematics.

The interaction between the diode and the gating signal creates unwanted signal at the output. This effect is attributed to the capacitive response of the diode. The junction capacitance of a reverse biased p-n junction diode is given as:

$$C_j = A \frac{\epsilon_s}{W}, \quad (3)$$

where A , ϵ_s and W denote the area of p-type and n-type regions, the permittivity of the semiconductor, and the width of depletion layer, respectively. An example of SPAD response to a pulse waveform gating signal is shown in Fig. 2. It is required to recover the avalanche signal that was lost in the capacitive response of the SPAD. Photon counting instruments use the avalanche signal to count the arriving photon. These instruments work based on thresholding on the photo-generated pulses, so higher Signal-to-Noise Ratio (SNR) is important. A poorly performing cancellation system leaves a residue that will

significantly degrade the photon counting. As described above, the avalanche charge multiplication increases the current swiftly. The leading edge of the avalanche signal waveform indicates the arrival time of the detected photon.

III. MEASUREMENT SETUP AND TEST PROCEDURE

The proposed scheme was implemented using MPD InGaAs/InP SPAD- SMF28 photodiode. The SPAD is reverse biased through the bias-tee at the input. The breakdown voltage of the detector changes with temperature. In order to ensure consistency, the operating temperature of the detector has been constantly monitored using a temperature controller. The MPD InGaAs/InP SPAD - SMF28 comes with an in-built TE-cooler. Thorlabs TED 200C has been used to control the cooler. The operating temperature of the SPAD was set at 223.15 K (- 50°C) during the measurement. The reverse breakdown voltage of the photodetector at this temperature is 61 V. The fixed DC power supply to the detector was fixed at 1V below the breakdown voltage, and the $5V_{pp}$ gating signal has been used to run the detector in a Geiger mode. The photodiode readily conducts current when it is biased above its breakdown voltage. If no protection is applied, the high current will have a negative impact on the detector. To ensure safe device operation, the current has been limited to $1 \mu A$ using the in-built current limiting feature of the Kelthley 2450 Source Meter. A laser beam taken from Picoquant pulsed laser diode head has been applied to the detector. The schematics and photo of the measurement setup are shown in Fig. 3 and Fig. 4.

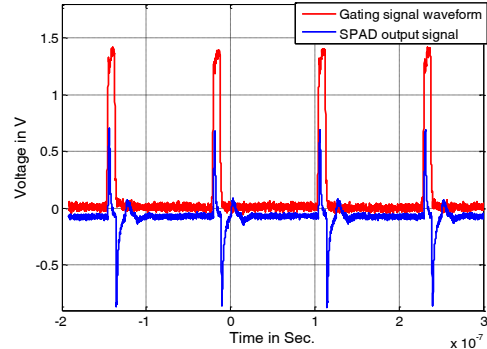


Fig. 2. SPAD response to a pulse waveform gating signal.

A. Avalanche signal recovery

The gating signal is generated at 1.72 GHz using ADF4355-2 Analog Devices microwave wideband synthesizer. At the output, the avalanche signal has been recovered using two separate schemes. The first scheme used a Low-Pass Filter (LPF) with cut-off lower than the gating signal frequency. Different types of LPF have been used in order to investigate their impacts on the avalanche

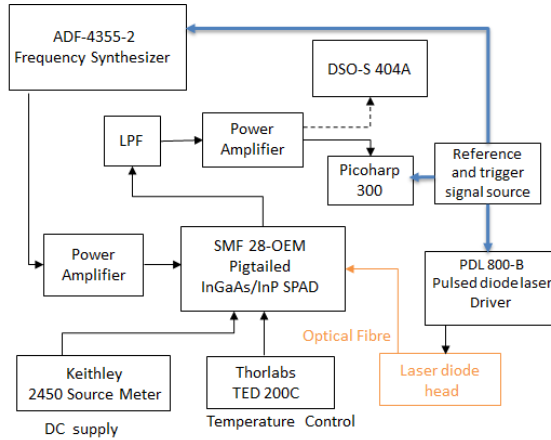


Fig. 3. Measurement setup schematic.

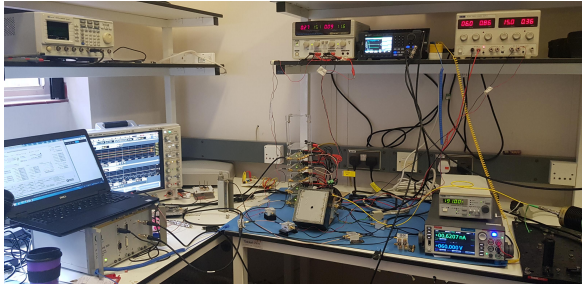


Fig. 4. Photograph of measurement setup.

signal. The test has been carried out using Chebyshev, Butterworth and Bessel-Thomson LPFs. As can be seen in Fig. 5, the Chebyshev LPF has removed the SPAD's capacitive response, but it has changed the shape of the waveform of the avalanche signal. The output signal has shown overshoot, ringing and slow rise time. These effects are relatively low in the Butterworth LPF. The output of Bessel-Thomson LPF did not show any of the problems mentioned above, but it did not help in removing the SPAD's capacitive response due its much slower pass-band to the stop-band transition characteristics. In the second scheme, the desired signal is recovered by adding destructive interference to the SPAD output signal. The cancellation signal was generated at the same frequency as the gating signal from a different ADF4355-2 Analog Devices microwave wideband synthesizer. The synthesizers, laser source and the PicoHarp were locked to a common external reference and trigger source. The cancellation process includes changing the amplitude and the phase of the cancellation signal - the phase is adjusted until it is out-phase with the SPAD's output signal by 180° . The two signals are then combined to recover the desired avalanche signal. This scheme does not affect the shape of the avalanche waveform and does not attenuate the avalanche signal as well. However, its performance is conditional

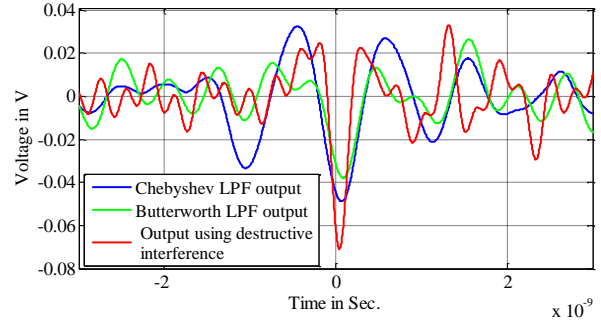


Fig. 5. SPAD output signal using low-pass filter and cancellation using destructive interference.

on the phase and amplitude alignment of the combining signals. Fine resolution is required for variable attenuation. The destructive interference/cancellation signal needs to be finely attenuated, so it will be the same magnitude as the SPAD's output signal.

IV. CONCLUSION

A time-gated SPAD has the advantage of faster detector response times and low afterpulsing effect, but it is necessary to suppress the capacitive response of the SPAD and recover the avalanche signal. Chebyshev low-pass filters distorted the avalanche pulse. This effect was relatively low in the Butterworth LPF. The output of Bessel-Thomson LPF does not affect the shape of the waveform, but it has the disadvantage of slower pass-band to the stop-band transition characteristics. The avalanche signal is recovered by combining the SPAD output with a destructive interference. This has shown less impact on the the avalanche pulse, but requires accurate phase and amplitude cancellation alignment.

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