ADVANCED InGaAs/InP SINGLE PHOTON DETECTOR OPTIMIZED FOR SLR AND SPACE DEBRIS OPTICAL TRACKING AT 1 μm WAVELENGTH

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ABSTRACT

The newly optimized version of a single photon detector package based on commercially available InGaAs/InP was developed and tested for space applications including satellite laser ranging and orbiting space debris optical tracking. The detection chip can register photons in the wavelength range from 950 to 1100 nm, making the detector attractive for laser ranging at 1064 nm. The detector key parameters are detection delay, detection probability and timing resolution. All of these parameters remain stable up to 10 μs after the detector is gated. The timing resolution reaches below values of 60 ps rms. The long-term stability of the detector is better than 200 fs for averaging times of hours. This current detector version is suitable for space applications (namely SLR and space debris optical tracking) due to its sub-picosecond long-term detection delay stability and its single-shot precision of 1 cm in laser ranging.

Keywords: Single Photon Detection; Space Debris; Laser Ranging; InGaAs/InP SPAD.

1. INTRODUCTION

Solid-state single photon detectors are well established devices in many fields including space geodesy [1, 2], laser time transfer [3] and many others. This contribution reports on development and testing of a detector which can provide exceptional performance in laser ranging of space objects [4]. The Single Photon Avalanche Diode (SPAD) based on InGaAs/InP structure allows for optical tracking at the wavelength of 1064 nm. This wavelength is especially attractive for laser ranging of space objects due to several reasons [5, 6]. The available laser transmitters provide higher energy per pulse at this wavelength versus laser sources operating at visible range of wavelengths. The atmospheric transmission at 1064 nm is higher in comparison to the visible range. The use of InGaAs/InP photon counting detectors was a key factor of extremely efficient laser ranging of various retroreflectors located on the Moon [7, 8].

There are two sets of single-photon detectors designed by CTU for laser ranging purposes. One version combines the passive quenching principle, the other version is based on the active quenching principle. The emphasis is put on photon detection efficiency, detection timing jitter and long-term stability of detection delay for both detector versions [9].

2. SINGLE PHOTON COUNTING DETECTOR

2.1. Detection Diode

The PGA-200-1064 chip by RMY Electronics is an InGaAs/InP SPAD convenient for photon counting applications [10]. It has an active area of 80 μm in diameter and is back-illuminated. It uses a standard three-stage thermoelectric cooler to cool the chip to temperatures as low as -50 °C. The device can detect single photons in the wavelength range of 950 to 1100 nm, thanks to an antireflection layer on the input window. With a detection efficiency of over 20% at 1064 nm [11], it is a reliable device to be used at the specified wavelength. However, the manufacturer advises not to exceed a bias voltage of 10 V above the chip breakdown voltage to avoid permanent damage. All experiments were conducted in accordance with the diode maximum ratings.

2.2. Passive Quenching Circuit

The AGPQ circuit design is a control circuit that was optimized for use with the InGaAs/InP SPAD detector, and is based on a previously developed detector for laser ranging of orbiting space debris [12]. The circuit function and the passive quenching principle are described in [13] in more detail. A simplified electrical block scheme of the described circuit is in Fig. 1.

2.3. Active Quenching Circuit

The Active Gating Active Quenching (AGAQ) circuit is based on an active quenching circuit described in [14].

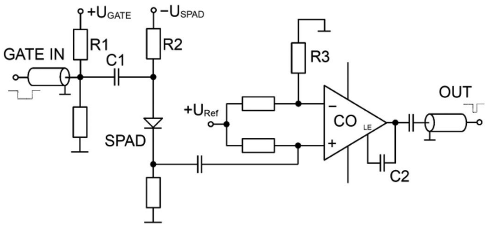

Figure 1. Block scheme of the passive quenching control circuit with InGaAs/InP SPAD [12].

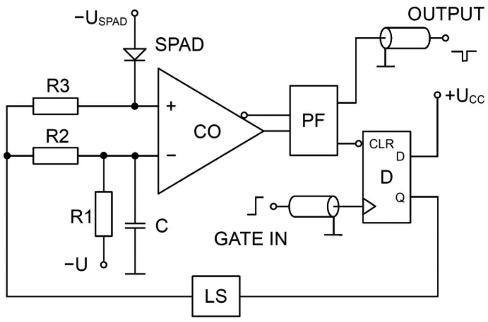

Figure 2. Block scheme of the active quenching control circuit with InGaAs/InP SPAD [14].

The circuit block scheme is shown in Fig. 2. The comparator CO in the circuit senses the avalanche current similarly to the AGPQ circuit. The rest of the control logic is different. The gating logic is controlled by a flip-flop bi-stable circuit type D. The logical D output is level shifted to fit the input common-mode voltage. The detector is activated by the leading edge of the gate signal and deactivated by a breakdown occurrence. The avalanche current is quenched once the avalanche build-up is identified. The detector remains deactivated until the next gate signal is received. The circuit design and construction for InGaAs/InP detection chip control is significantly modified compared to the silicon-based detectors due to the different parameters of the silicon and InGaAs/InP detection chips, such as breakdown voltage, internal resistance, and detection chip capacity. Active quenching circuits can overcome the drawbacks of passive quenching circuits by allowing for a well-defined and short time of quenching (less than 5 ns). However, it is not possible to use the active circuit components with a bias over breakdown voltage higher than 4.5 V. Therefore, it is possible and safe to operate InGaAs/InP SPAD in a range of 0.5 V to 4.5 V above its breakdown voltage.

2.4. Power Supply

Both detector control electronics versions (passive quenching and active quenching variants) are powered by a dedicated power supply. The power supply final setting for experiments with passive quenching detector provides bias over breakdown voltage of 10 V. The power supply final setting for experiments with active quenching detector is biasing the chip 4.2 V above breakdown voltage.

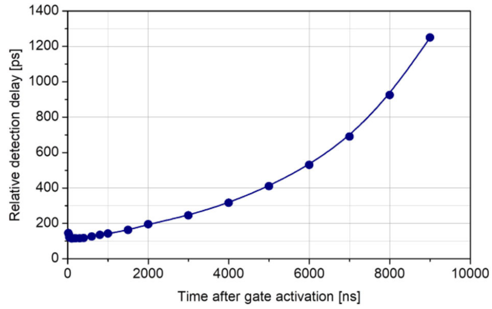

Figure 3. Relative detection delay of passive quenching InGaAs/InP detector. Note the delay when a photon is detected more than 1 μs after the gate window opened [9].

The detection chip may be stabilized at a pre-set temperature between -5 and -40 °C.

3. DETECTOR OPERATIONAL TESTS

In order to compare the devices and to discover their differences, the detector packages were evaluated using standard Time Correlated Single Photon Counting (TCSPC) experiments. The test pulses were generated using a diode laser that emitted 65 ps long pulses at a wavelength of 1064 nm, at a repetition rate of 2.5 kHz.

3.1. Relative Detection Delay

Our findings in [12] showed that there is a strong relationship between the detection delay and the time interval between activating the gate and the detection of the incoming photon, as illustrated in Fig. 3. As the time after gate activation increases, the relative detection delay also increases, which is a main drawback of the use of the passive quenching principle. This makes the passive quenching detector version less suitable for applications that require longer gate windows.

To overcome this limitation, the relative detection delay was tested in the active quenching detector setup. The results, plotted in Fig. 4, show that the detection delay remains stable within a few picoseconds over a long gate window, due to the active quenching principle well-defined bias above the structure breakdown voltage. This detector setup is useful for applications that require stable detection delay over a broad range of gate window.

3.2. Timing Resolution

A crucial aspect of a photon counting detector is its single-shot timing resolution, also known as jitter. The timing resolution of both detector versions were evaluated using TCSPC experiment, by measuring the root

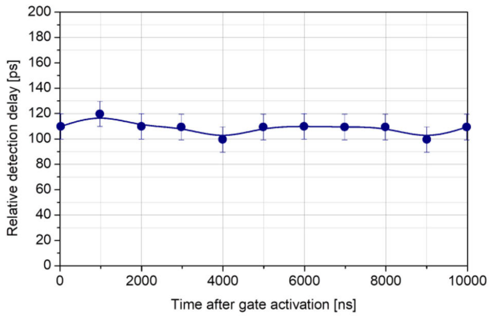

Figure 4. Relative detection delay over time after gate beginning of the active quenching version [9].

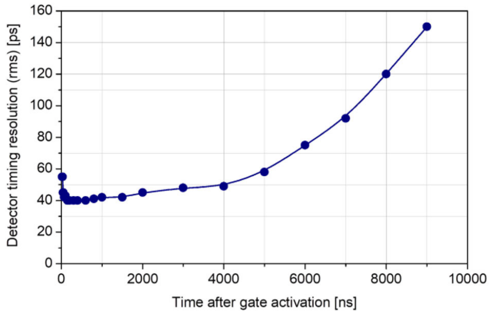

Figure 5. Timing resolution (rms) over time after gate activation, passive quenching detector version. The values include the laser pulse length contribution [9].

mean square (rms). The contribution of the laser pulse length (65 ps) was not removed when creating the plot. The timing resolution of the passive quenching detector is shown in Fig. 5. It can be seen that as the time after the start of the gate window increases, the timing jitter also increases, which is a significant drawback. However, when the bias is set to 10 V above the SPAD breakdown voltage, the timing resolution can be as good as 28 ps rms within the first 500 ns after the gate is on, after removing the contribution of the laser pulse length.

The active quenching detector was also tested in this way. Bias above breakdown voltage was set to 4.2 V. The resulting value corresponds to a timing resolution (rms) of 67 ps after removing the contribution of the laser pulse length. This value corresponds to a single-shot precision of 1 cm in laser ranging.

3.3. Relative Detection Probability

Another characteristic to consider is the relative detection probability, which measures the likelihood of detecting a single photon. The results of an experiment with the passive quenching detector set to a bias of 10 V above breakdown voltage are plotted over time after the beginning of the gate signal in Fig. 6 as filled circle points. The graph suggests that it is highly likely to detect a single photon shortly after the beginning of the gate window. It is possible to exploit this relatively high detection probability

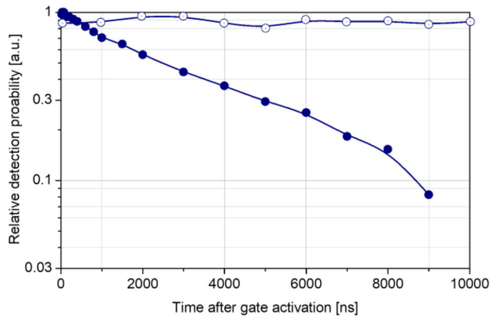

Figure 6. Relative detection probability over time after gate activation, the passive quenching version dependence is plotted as filled circle points, the active one is plotted as empty circle points. The mutual position is absolute [9].

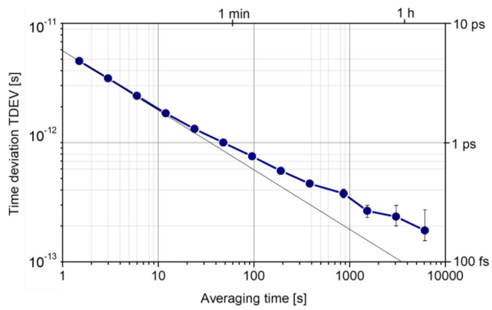

Figure 7. Time stability in a form of TDEV, active quenching version. Note the timing stability of 0.2 ps for averaging times of 5000 s. Diagonally grid line represents ideal $t^{-1/2}$ trend [9].

at various biases above the breakdown voltage. However, for biases higher than 4.5 V above breakdown voltage, the photon counting probability begins to saturate [12]. At a bias of 3 V above breakdown voltage, the absolute value of the photon counting probability reaches 20% at 1064 nm [11].

The active quenching detector was also tested to measure the relative single photon detection probability over time after gate activation (Fig. 6). The results show a uniform relative detection probability up to 10 microseconds after the beginning of the gate.

3.4. Detection Delay Long-Term Stability

To evaluate the active quenching detector timing performance, a long-term TCSPC experiment was performed. The results are presented in terms of Time Deviation (TDEV) [15] in Fig. 7. The experiment repetition rate was set to 2.5 kHz, and the effective signal strength was 10% due to the use of neutral density filters to reduce the laser signal. The gate window opened 200 ns before a single photon was detected. The device temperature was set to -40 °C. The overall timing stability of the experiment in terms of TDEV was better than 0.2 ps for averaging times of 5000 seconds.

4. CONCLUSION

In order to state the difference between two detectors based on passive and active quenching principle, we have designed and constructed two compact versions of photon counting detectors using InGaAs/InP detection chips. Both versions are designed for active gating operations. The passive quenching version has a higher timing resolution and detection probability, but these advantages are only useful in a relatively narrow gate width of 100 to 500 nanoseconds. In contrast, the active quenching circuit provides consistent key detection parameters across a wide gate window of 50 ns to 10 μs. The passive quenching electronics version is optimized for applications that prioritize high timing resolution, while the active quenching electronics is optimized for applications that require sub-picosecond long-term detection delay stability, making the latter more attractive for orbiting space debris optical tracking.

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