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► **To cite this version:**

Jean-Marc Merolla, Dylan Le Gac, Loic Jacquinot, Akram Achoura, Frederic Patois, et al.. A new GHz high-speed near-infrared uncooled single photon detector. 2024. hal-04790524

HAL Id: hal-04790524

<https://hal.science/hal-04790524v1>

Preprint submitted on 19 Nov 2024

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A new GHz high-speed near-infrared uncooled single photon detector

Dylan Le Gac^{*a}, Loic Jacquinet^a, Akram Achour^a, Frederic Patois^a, Johann Cussey^a, Jérôme Prieur^a,
Jean-Marc Merolla^b, Emmanuel Fretel^a

^aAUREA Technology SAS, 18 rue Alain Savary, 25000 Besançon, FRANCE

^bInstitut FEMTO-ST, 15B avenue des Montboucons, 25000 Besançon, FRANCE

ABSTRACT

This paper presents a high-speed Near-infrared single-photon detector developed under the frame of the TeQuantS project (Technological development for space-based Quantum Source distribution, ESA ARTES C&G Programme). Based on a GHz-gated avalanche photodiode operating in Geiger mode, the detector offers compactness, Peltier-cooling capability, maintenance-free operation, and high-speed single photon detection performances. These high performances make it well-suited for extremely low light-level detection applications, such as space-borne quantum communications, satellite laser ranging, orbiting space debris optical tracking, and long-range LIDAR. The paper details the system's architecture and performance metrics, covering quantum efficiency, dark count rate, time jitter, maximum count rate, temporal window width, and afterpulsing probability. Substantial enhancements are demonstrated when using pulsed light compared to free-running or MHz-gated Single Photon Avalanche Diodes (SPADs).

Keywords: Single-Photon Detector, Avalanche Photodiode, Near-Infrared, SPAD, Gating, Quantum communications, GHz, Satellite communications

1. INTRODUCTION

Near-infrared single-photon detectors are essential for various applications that require extremely low light level detection [1]. These applications include quantum communications networks such as Quantum Key Distribution (QKD) [2], Quantum Information Networks (QIN) [3], atmospheric Light Detection and Ranging (LIDAR) [4], satellite laser ranging [5], orbiting space debris optical tracking [6], and fiber sensing such as Optical Time Domain Reflectometry (OTDR) [7]. InGaAs/InP Single Photon Avalanche Diodes (SPADs) operating in Geiger mode offer a practical and reliable solution for these applications at a reasonable cost compared to any current cryogenic solutions. This well-established cryogenic-free photon detection technology provides several advantages, including a small footprint, fiber coupling, maintenance-free operation, low power consumption, Peltier cooling, and high-efficient photon detection performance. In contrast, Superconducting Nanowire Single Photon Detectors (SNSPDs) very high photon detection efficiency but require bulky cryogenic cooling, making their deployment extremely challenging or just impossible on an industrial scale [8].

The InGaAs/InP SPADs have a sensitivity range from 900 nm to 1700 nm, which makes them suitable for telecom (O, S, C, and L bands) and space applications due to their compatibility with the operating wavelength of commercially available photonic devices, such as laser diodes, entangled photon sources [2], filters, modulators, switches, circulators, single-mode and polarization maintaining optical fibers, and photodiodes. This telecom wavelength range also aligns with space-qualified photonic components conforming to the European Space Components Coordination (ESCC), to the rising of the new space economy [9][10][11][12], and to the atmospheric transparency windows. However, commercial InGaAs/InP single-photon avalanche diodes (SPADs) still encounter a significant limitation in the counting rate mainly due to the undesired afterpulsing effect. This effect occurs when previous detections lead to the generation of avalanches. During this process, some charges get trapped and released, resulting in fake detections and increased noise. Consequently, the readout photon count rate of commercially available InGaAs/InP SPAD photon detectors is typically limited to tens of MHz.

Several methods have been investigated to enhance the counting rate of the SPAD. These methods include using a balanced detection configuration with a dummy SPAD [13], employing the self-differencing method [14], and implementing harmonic subtraction [15] to mitigate capacitive APD response. While these techniques show promise, they are challenging to implement in an industrial process. For example, fabricating dual avalanche photodiodes with similar characteristics on the same chip is complex, and as a result no commercial products are currently available. The self-differencing method requires extremely high accuracy for the delay line adjustment and suffers from stability issue. An alternative approach

involves implementing sinusoidal fast gating in the GHz frequency range [16][17]. This approach is more straightforward, even if it requires high-performance rejection filtering. In addition, operating at GHz frequency allows the use of standard telecom fiber-optic components such as diode lasers, modulators, photodiodes and Mach-Zehnder interferometers, which are frequently space-qualified or Telcordia-certified, promoting further developments in space applications.

In this article, we present the implementation, and a comprehensive performance study of a fibered Near-Infrared single-photon avalanche diode module gated with a 1 GHz sine wave. Developing such a module is crucial for the European sovereignty of future space photonics infrastructures.

The paper is structured as follows: Section 2 introduces the principle and overall architecture of the GHz-gated single-photon avalanche photodiode module and its features, section 3 presents the process to design and manufacture the filters needed to recover the signal originating from a photon detection, section 4 details the experimental test bed and the metrology tools employed to characterize the performances of the high-speed single-photon detector module and section 5 presents the results achieved. The module's performances have been measured at 10%, 20%, and 30% quantum efficiencies (QE) by using an attenuated laser pulse source operating at 1550 nm.

2. SINGLE PHOTON DETECTOR DESIGN

The architecture of the high-speed Near-infrared single photon detector is based on a fast quenching produced by a 1 GHz sine wave gating signal, as mentioned previously. The GHz sine wave signal is applied to a DC-biased avalanche photodiode. The total voltage applied exceeds the avalanche breakdown voltage during a few hundred picoseconds, enabling a single photon to be detected. To retrieve the electrical signal produced by the detection process, a custom high-rejection multi-notch filter has been designed to reject the fundamental gating frequency and its harmonics coming from the APD nonlinear response.

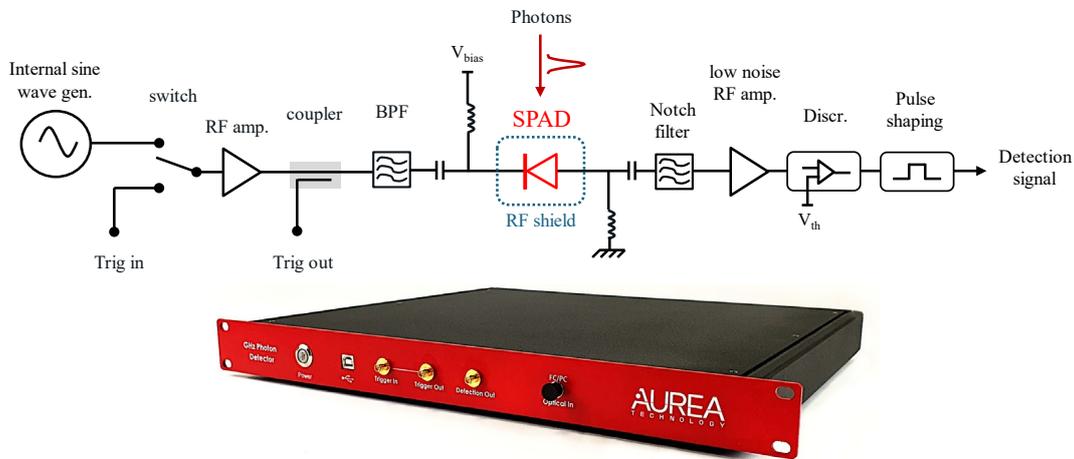


Figure 1: Top: Internal overall architecture of the high-speed single photon detector. A microcontroller (not shown on the figure) sets the parameters of the high-speed single photon detector. Trig: Trigger, Discr.: Discriminator, Amp.: Amplifier, gen.: Generator, BPF: Band Pass Filter, RF: Radio Frequency. Bottom: picture of the high-speed single photon detector module integrated in a 1U 19" telecom rack. A single mode, a polarization maintaining, or a multimode optical fiber can be connected to the FC/PC optical input of the module. SMA connectors are used for the RF signals. A USB interface is used for communication with a CPU and the control with the Graphical User Interface.

The overall circuit architecture is shown in Figure 1. The 1 GHz, 20 dBm gating signal is generated by an internal sine wave generator (PLL) followed by a low-noise and high-power RF amplifier. An additional coupler allows for the monitoring and the sampling to synchronize external devices. A 45 dB, 50 MHz wide Band-Pass Filter (BPF) centered at 1 GHz removes the disruptive harmonics generated by previous electronic components. This 1 GHz signal is combined to a DC voltage using a Bias Tee and is applied to a fibered InGaAs/InP SPAD cooled with a multistage thermoelectric Peltier module. The heat dissipation of the module is managed by using fans and heat sinks. Under these operating conditions, the SPAD enables single-photon detections by producing electrical pulses after each detection. The detector quantum efficiency is adjusted by tuning the DC bias voltage V_{bias} . A metallic-based RF shield protects the extremely sensitive SPAD against external interfering perturbations. The electrical signal then passes through a custom multi-notch filter. This

notch filter has a 70 dB rejection, a 100 MHz bandwidth and precisely centered at 1 GHz. It rejects the fundamental gating carrier and its second and third harmonics at 2 and 3 GHz, allowing the electrical pulse signal issued from the photon detection to be retrieved. Finally, this filtered signal is amplified using an RF low-noise amplifier, compared to a threshold voltage (V_{th}) with a discriminator, and pulse-shaped to produce standard TTL or PECL output signals.

The high-speed photon detector includes a custom integrated controller and its embedded software to set up all the operating values. These setting values include the photodiode temperature, the DC bias voltage (V_{bias}) controlling the quantum efficiency ranging from 10% to 30% of the photodiode, the detection threshold voltage (V_{th}), and the internal clock RF frequency. Additionally, a Graphical User Interface (GUI) allows for the adjustment of selected parameters such as the quantum efficiency, the fine-tuning of the PLL frequency, and the dead time. The photodiode and case temperatures, as well as the RF power, are monitored and displayed on the GUI. A watchdog ensures the photodiode reaches the desired temperature before starting a measurement. An electrical switch controlled by the microcontroller and the GUI allows selecting either the internal or external 1 GHz gating clock.

Finally, the optical interface consists of a FC/PC fiber input connector on the front panel of the module. This connector is compatible with standard multimode, single mode and polarization maintaining optical fibers.

3. SINGLE PHOTON SIGNAL RETRIEVAL

This section describes the process used to design the notch filter, which enables recovery of the single photon electrical pulse from the APD-generated signal.

Figure 2.a. shows the APD-generated electric signal of a single photon pulse. This APD-generated electrical signal includes the single photon electrical pulse, the residual carrier 1 GHz gating frequency, and its second harmonic. Direct detection of the electrical single photon pulse with a threshold comparator is impossible; hence, filtering is needed. A custom multi-Notch filter (see Figure 2.c.) allows the recovery of the single-photon electrical pulse (see Figure 2.b.). The amplified photon pulse has an amplitude of approximately 15 mV ensuring a sufficient signal-to-noise ratio. Once filtered and amplified, the electric pulse is easily detected by a threshold comparator.

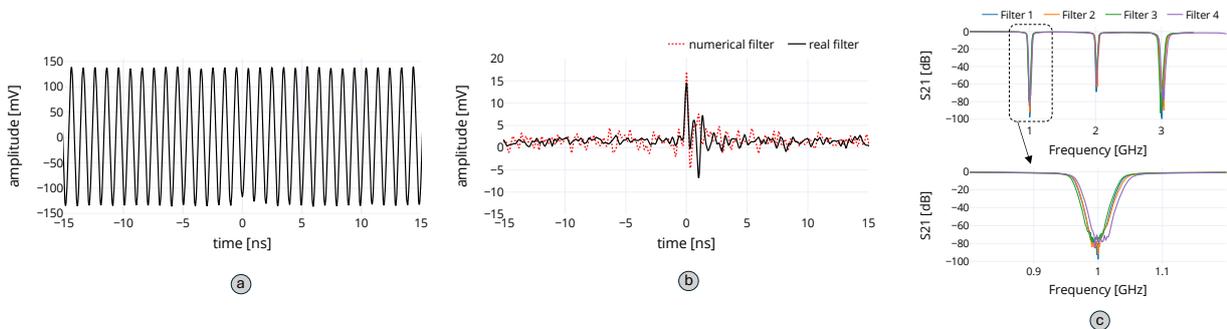


Figure 2:a): temporal signal without notch filtering at 20% QE. The photon pulse signal is undetectable and is interleaved with the 1 GHz carrier and its second harmonic. b): Resulting filtered photon pulse signal using a numerical notch filter (red) and the custom real notch filter (black). After filtering, the measured photon pulse signal-to-noise ratio ensures a sufficient thresholding. c): S-parameter of 4 manufactured notch filters, showing an attenuation higher than 70 dB at 1, 2 and 3 GHz and good reproducibility.

To design the multi-notch filter, the APD-generated electrical signal is first digitized, and then numerically filtered to retrieve the signal shown in Figure 2.b. We have computed that a 70 dB rejection of the 1 GHz signal within a 100 MHz bandwidth and a 40 dB rejection within a 150 MHz bandwidth for the second harmonic is required to properly recover the single photon pulse with a sufficient signal-to-noise ratio (see Figure 2.b.).

The multi-notch filter has been designed using the Finite Element Method. For reproducibility and reliability estimation, we have manufactured and tested 4 of them. Their measured S parameters are shown in Figure 2.c. and compared with our model. A good agreement between the model and experimental data, as well as good reproducibility and center frequency accuracy, has been demonstrated. These good reproducibility and accuracy are crucial for systems employing multiple high-speed single photon detectors and sharing an external clock, as required in quantum communications applications. The 70 dB high-rejection notch filter ensures a sufficient signal-to-noise ratio for efficient thresholding. Figure 2.b. shows the good agreement between the experimental recovery signal and the numerically filtered APD-generated electrical signal.

4. EXPERIMENTAL SETUP

In this section, we present the experimental setup used to assess the performance of the high-speed single photon detector. We used a custom-made, low-intensity 2 GHz fibered diode laser source modulated at frequencies in the tens of MHz. The experimental setup is illustrated in Figure 3.a. The optical pulse width has been measured to be as short as 70 picoseconds (Full Width at Half Maximum - FWHM, refer to Figure 3.b.). This 1550 nm fibered laser diode is attenuated using a Variable Optical Attenuator (VOA) to reach 1 photon per pulse. To detect or count the electrical pulses produced by the high-speed photon detector module, we use a high-resolution time-to-digital converter module with a resolution of less than 13 picoseconds, or a high-speed oscilloscope with a bandwidth of 16 GHz and a sampling rate of 40 GS/s. Furthermore, an external 1 GHz clock is shared between the single photon detector, the pulsed laser source and the time-to-digital converter module or oscilloscope by dividing its frequency to a tens of MHz. By maintaining a pulse rate lower than the gating frequency, the afterpulsing effect has been efficiently measured. A delay line synchronizes the sinusoidal gating signal with the laser pulse repetition rate.

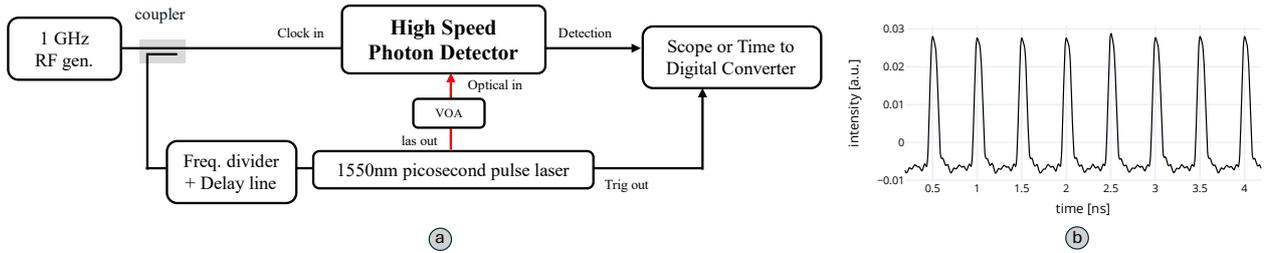


Figure 3: a): performance characterization test bed of the High-Speed Single Photon Detector module. B): 2 GHz repetition rate – 70 ps width laser pulses.

5. PERFORMANCES MEASUREMENT

The sinusoidal fast-gating method improves the performance of Single Photon Avalanche Diodes (SPADs) by enabling a higher photon detection rate. It also reduces dark count rate (DCR), jitter, afterpulsing, dead time, count rate, and detection window width of the SPAD. This section presents the test results for the high-speed single photon detector, which were obtained using the previously described test bed (refer to Figure 3 above).

The high-speed single photon detector module was manufactured and thoroughly tested at three different quantum efficiencies 10%, 20%, and 30% using a 1550 nm wavelength faint laser of 1 photon/pulse. In the tests discussed below, the SPAD temperature was cooled down to -35°C . We provide the measured values for the different performance metrics, which are summarized in Table 1.

Table 1: Measured performances of the high-speed single photon detector, at various quantum efficiencies (10%, 20% and 30%) and a - SPAD temperature value of -35°C .

Quantum efficiency	10%	20%	30%
Dark count rate (counts/s)	171	492	1235
Jitter (ps)	193	144	112
Effective detection width (ps)	230	260	250
Afterpulse probability per gate	$1.1e^{-4}$	$2.7e^{-4}$	$3.7e^{-4}$
Dead time (ns)	5	10	100
Max count rate (MHz)	200	100	10

To compare with commercially available NIR SPAD photon counting detectors, which at 10% QE and 1550 nm typically perform a DCR lower than 700 counts/s, a dead-time of 100 ns, a timing jitter below 350 ps, and an output count rate of 20 MHz. The here described high-speed photon detector counts at a high rate of 200 MHz, which is ten times faster than the commercial NIR SPAD photon detectors, with much better DCR (< 200 counts/s), timing jitter (< 200 ps), and dead time (5 ns) (see Table 1).

The dark count rate, representing the intrinsic noise of the photon detector, has been measured without incoming photons. The timing jitter, which indicates the broadening of the electrical output pulse relative to the incoming single photon source pulse, has been quantified using the FWHM value of the time distribution (see Figure 4.a). The effective detection width, referring to the actual temporal window during which the detector is effectively sensitive to incoming photons, was also measured at the FWHM value (see Figure 4.c.). The afterpulsing probability has been measured by averaging the afterpulse probability of the first 50 gates after the dead time (refer to Figure 4.b.). The period following detection during which further counting events are discarded, known as dead time, is directly related to the afterpulse value. The maximum count rate is deduced as the reverse of the dead time. All the measurements of every single metric are shown in Figure 4. These values are state-of-the-art for such a GHz gated single photon detector, showing a significant improvement compared to free-running or MHz square gating for the single photon detection in high-speed pulsed light operation.

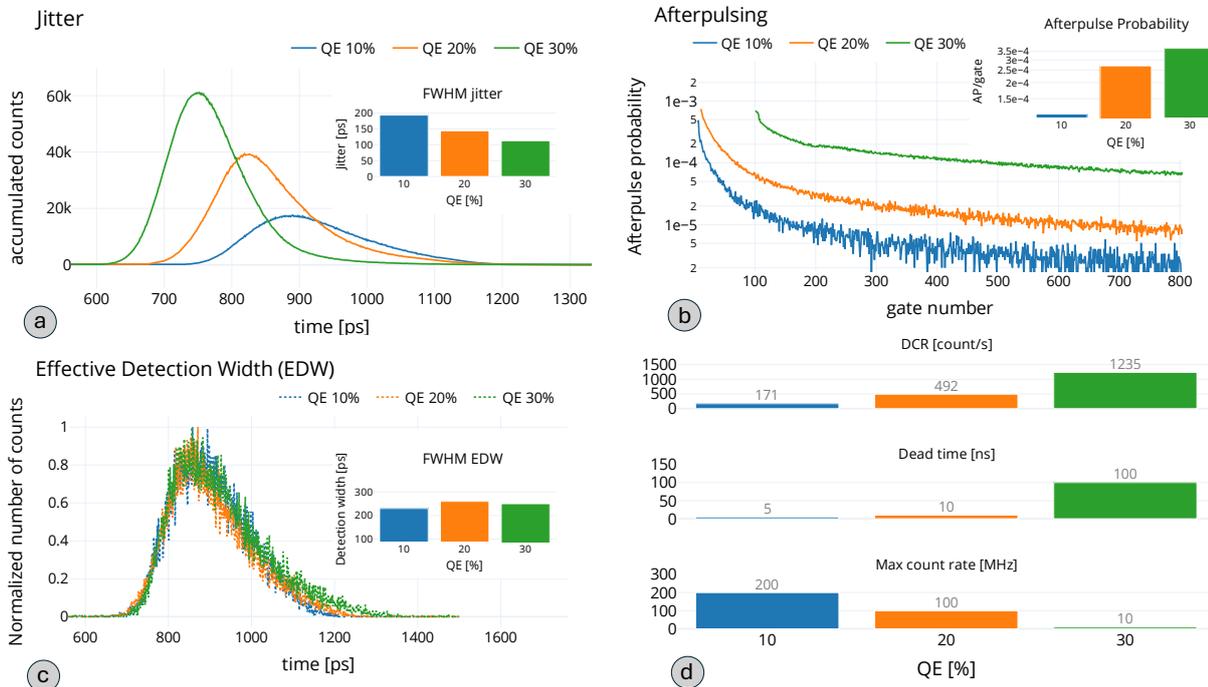


Figure 4: Measured parameters at various QE (10%, 20% and 30%). a): the jitter (FWHM) has been measured to be equal to 193 ps, 144 ps and 112 ps for 10, 20 and 30% QE respectively. b): Afterpulsing Probability per gate vs time. A dead time of 1, 10 and 100 ns are present on the curves, corresponding to a negligible afterpulse probability (about $5 \cdot 10^{-4}$ per gate). c): the Effective Detection width (FWHM) has been measured to be equal to 230 ps, 260 ps and 250 ps for 10, 20 and 30% QE respectively. The Effective Detection width is almost constant with QE. d): The DCR increases with QE. Its value ranges from 171, 492 and 1235 counts/s for 10, 20 and 30% QE respectively. Dead time (and its reverse Maximum Count Rate) has been measured to be equal to 5 ns (200 MHz Maximum Count Rate), 10 ns (100 MHz) and 100 ns (10 MHz) for 10, 20 and 30% QE respectively.

Furthermore, additional investigation has been experimentally conducted about the APD temperature dependency on the performance metrics of the high-speed single photon detector. To be precise, we have measured the evolution of the dark count rate and the afterpulse probability within an APD temperature range between -55 and -16°C at 20% quantum efficiency (see Figure 5). As expected, these two metrics exhibit opposite behaviors, which requires a performance tradeoff depending on the application and system limitations. In the performance measurement mentioned earlier, the photodiode temperature was set at -35°C to achieve a lower dark count rate. By cooling the temperature down to -55°C , the dark count rate can be reduced by a factor of 2, while increasing the afterpulse probability by a factor of 1.6 (refer to Figure 5).

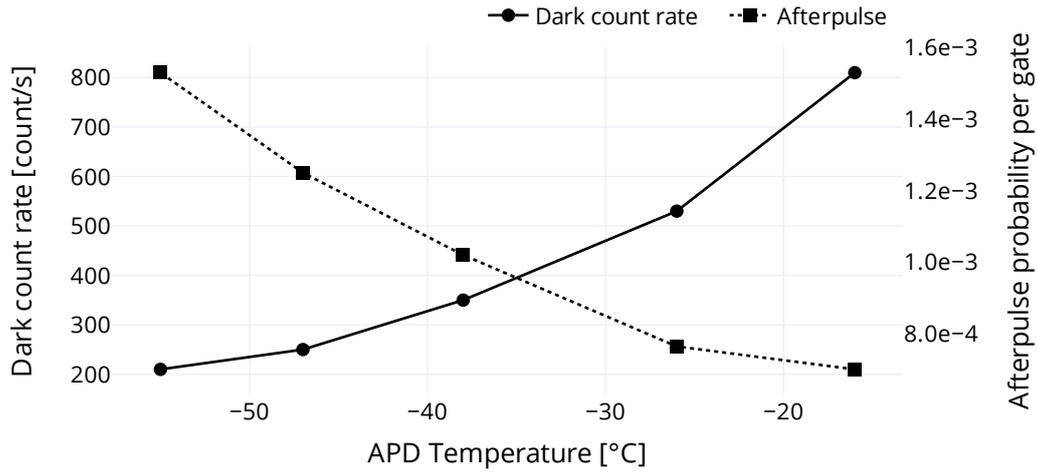


Figure 5: Dark count rate (solid line-left) and after pulse probability (dashed line-right) vs avalanche photodiode temperature at 20% Quantum efficiency.

6. CONCLUSION

The newly designed high-speed NIR SPAD single photon detector, gated at 1 GHz, has been developed, manufactured, and tested at various quantum efficiencies. The test results demonstrate that the high-speed 1 GHz NIR SPAD single photon detector counts ten times faster than currently available NIR SPAD single photon counting detectors.

Moreover, it features extremely low dark count rate < 200 counts/s, an excellent timing jitter < 200 ps, a minimal afterpulsing, and a very-short dead time < 5 ns. It shows state-of-the-art photon detection performances in the NIR, which is considered as a technological breakthrough in the low-level-of-light NIR detection domain. Furthermore, this vacuum-free photon detector does not require additional bulky and hard to maintain water or cryogenic cooling systems, making it suitable for space and industrial applications.

The outstanding performance of this new high-speed NIR SPAD photon detector module proposes the fastest, most energy-efficient, most compact, most reliable, and most cost-efficient photon detector. It is very promising for space applications, including ultra secure quantum communications, long-distances ranging instruments, and very high-resolution optical sensors.

Additional studies are currently being conducted to optimize system performance and further reduce the Size, Weight and Power (SWaP) of the high-speed NIR SPAD single photon detector module.

ACKNOWLEDGEMENTS

The authors thank the French Space Agency CNES and the European Space Agency ESA for the funding of the TeQuantS project (ARTES C&G Programme-ESA Contract 4000140116/22/NL/MM/gm).

We gratefully acknowledge CNES and ESA project officers for their outstanding support, technical guidance and management role during the contract execution. The authors thank Thales Alenia Space in Toulouse, France (Prime Contractor; AUREA-Thales Alenia Space Contract 1550007993) for fruitful discussions and contract execution. Moreover, the authors thank Airbus Defence and Space in Toulouse, France for fruitful discussions and advice.

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