Demonstration of suitability of avalanche photodiodes for quantum communications in the low-Earth-orbit radiation environment

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Cryptographic techniques that utilize fundamental quantum mechanics, such as quantum key distribution (QKD), are going to be the safest option for secure communication in approaching era of quantum computers. Satellite-based quantum communications will be an important component in achieving world-wide QKD in the near term. For satellites acting as quantum receivers, this will necessitate single photon detectors (SPDs) capable of operating with sufficient fidelity in the space environment. Since long-term cryogenic cooling is difficult to implement in a spacecraft, two suitable technologies not requiring it are photomultiplier tubes (PMTs) and avalanche photodiodes (APDs). The APDs have better characteristics for quantum communications and are better studied in this application in ground-based systems, which makes them the primary candidate. However, space radiation severely impairs APD performance, causing a fast increase of their dark count rate and rapidly making quantum communication impossible. For ground-to-satellite QKD the dark count rate should be $\lesssim$1000 counts per second (cps) [1].

A satellite mission that used Si photon counting APDs (Excelitas SLIK) showed an increase of their dark count rate by $\sim$30 cps per day in orbit [2], which would make them unusable for QKD in at most a few weeks. A single solar storm event could incapacitate these APDs in less than a day. Previous ground-based radiation tests of APDs also demonstrated too high dark count rates reaching $\sim 10^4$ to 10^5 cps [3, 4]. Recent tests used mitigation by cooling to overcome the increased dark count rate, using temperature as low as -20 °C [5]. It is known that the dark count rate of non-irradiated Si APDs can be reduced by deeper cooling, which also increases afterpulsing that may interfere with quantum communication [6, 7]. It is further known that thermal annealing also reduces the dark count rate after irradiation [5]. However no tests have demonstrated a sufficiently low dark count rate for QKD and verified other detector parameters throughout a reasonable lifetime of a quantum receiver satellite (more than 1 year).

Here we show experimentally that effects of radiation doses equivalent to up to 2 years in orbit are successfully mitigated by cooling and thermal annealing, allowing the APDs to be used in the quantum satellite. Afterpulsing, efficiency and jitter of the irradiated SPDs have been characterised and shown to be in the range acceptable for QKD.

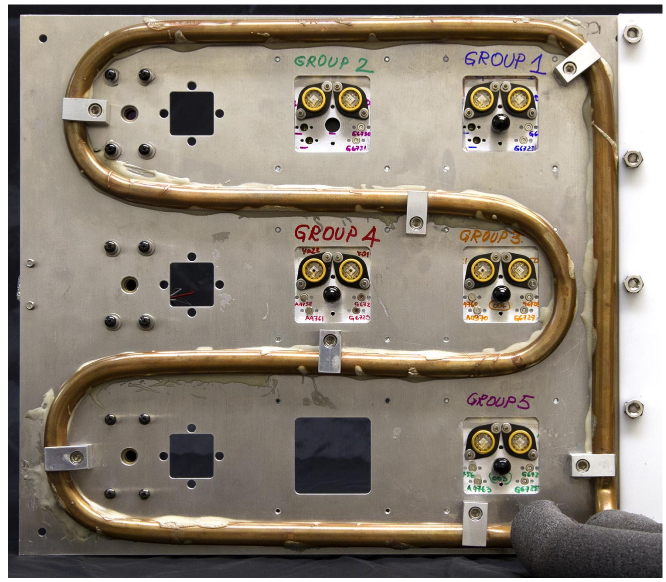

FIG. 1. Test plate with all samples mounted, divided into 8 groups to be exposed to the proton beam separately. The plate was chilled to 0 °C by external liquid cooling, to prevent possible thermal annealing during and after irradiation.

A polar orbit at 600 km altitude providing global coverage was chosen for our quantum satellite. Predicted radiation doses were calculated by COM DEV, using estimated shielding levels and the online SPENVIS radiation modeling tools. Samples were irradiated by a 100 MeV proton beam at the TRIUMF facility (Vancouver) with doses equivalent to 3 weeks, 6 months, 1 year and 2 years in the orbit. The following samples were tested: Si APDs C30921SH, SLIK (Excelitas), SAP500S2 (Laser Components), photomultiplier tubes H7422P-40 (Hamamatsu). In total 32 APDs and 4 photomultiplier tubes were tested (Fig. 1). We used a passively-quenched detector scheme for all APDs, because it is adequate for QKD satellite applications with relatively low count rates. One group of APDs was operating in photon counting regime under high-voltage bias during the irradiation, and exhibited a higher rate of damage (see

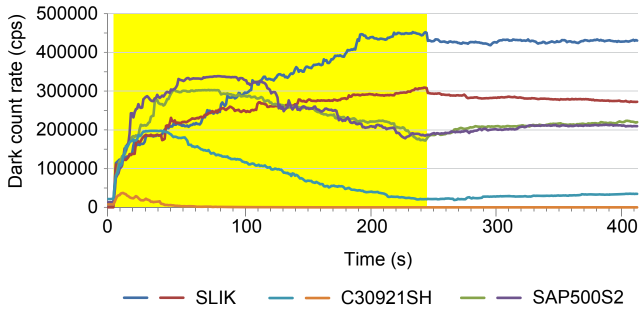

FIG. 2. Real-time recording of dark count rate before, during and after irradiation. Yellow shading denotes the time the radiation source was on. Sample temperature was 0 °C. The decrease of the count rate during irradiation in some of the samples occurred because the avalanche rate reached the peak saturation rate of the passively-quenched detector scheme, and overloaded it [8].

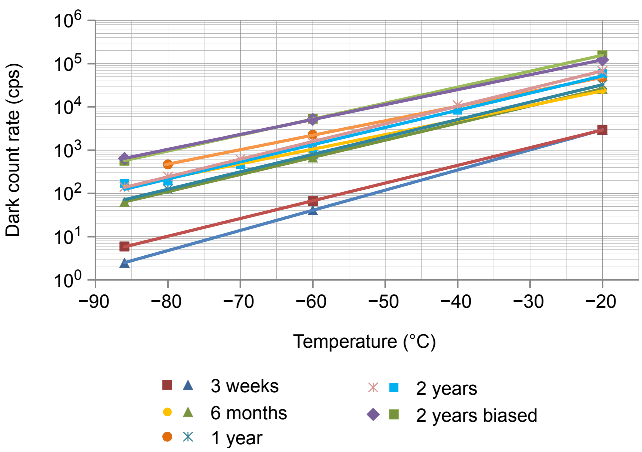

FIG. 3. The cooling effect on the measured dark count rate for SLIK APDs after various levels of irradiation (equivalent radiation time listed), before thermal annealing. Two samples were tested at each radiation level.

Fig. 2 for real-time count rate recording during irradiation). All samples survived the irradiation and remained functional photon detectors, with the only significant effect being the increase of the dark count rate in all APD samples. SLIKs demonstrated the best performance after irradiation. C30921SH showed ∼10 times higher dark count rate increase than SLIK, and SAP500S2 ∼20 times higher. We also observed a small increase of the dark count rate in the PMTs.

The increased dark count rate after irradiation was successfully mitigated by cooling the APDs down to −86 °C. In all SLIK samples, the dark count rate at that temperature was acceptable for satellite QKD (Fig. 3). Thermal annealing at up to +100 °C was then applied. It reduced the dark count rate after irradiation further, by up to a factor of 5.

Afterpulsing probability was calculated by an improved correlation analysis of dark count timing [6]. In all SLIK and C30921SH samples afterpulsing probability at the lowest measured temperature of −86 °C did not exceed 3% (except the one SLIK sample biased under irradiation where the afterpulsing probability was 6.5%). However, SAP500S2 demonstrated a surprisingly high afterpulsing probability of about 30%. Afterpulsing can be reduced by post-processing of raw detection data.

In conclusion, we have demonstrated single-photon counting APD operation with sufficiently good parameters for ground-to-satellite quantum communication, after radiation doses equivalent to 2 years in the low Earth polar orbit. This study paves the way for a straightforward implementation of a compact SPD package for the quantum satellite, using minimal radiation shielding and a mix of radiative and low-power thermoelectric cooling for APDs. Further prototyping for a Canadian quantum satellite is currently in progress.

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