Low-noise single-photon detector for long-distance free-space quantum communication

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Long-distance free-space quantum communications, both terrestrial and space-based, require single-photon detectors (SPDs) with low noise and relatively large photosensitive area. Avalanche photodiodes (APDs) are one of the most practical SPDs for these applications.

We investigate behavior of a common silicon APD (Excelitas C30902SH, 500 μm diameter photosensitive area) at low temperatures down to −100 °C. We measure dark count rate, photon detection efficiency, jitter and afterpulsing with its time constants. The dark count rate drops exponentially with temperature (Fig. 1), leveling off below −90 °C. Although the total afterpulse probability with passively-quenched detection scheme remains low (e.g., about 1% at −100 °C), it notably raises detector noise level for a relatively long period of time after each count. We use an improved time interval analysis allowing to observe and quantify long afterpulse times (Fig. 2). This afterpulsing times become longer at lower temperatures, but then, low noise of the detector can be preserved by discarding afterpulses in post-processing. The optimum temperature and afterpulse discarding time depend on the photon count rate and noise tolerance of a given application. The jitter of our SPD is in the range of 450 to 1500 ps, mainly depending on the bias voltage and slightly on a position of absorbed photon within an APD sensitive area.

Our detector design features a fairly compact package. To achieve temperatures as low as −100 °C, we use 4 and 5-stage thermoelectric coolers (similar to Ref. [1]). The detector package is vacuumed, to improve thermal insulation and to prevent condensation.

As distances of quantum communication increase, low-noise SPDs become increasingly important. For example, the first attempt of 143 km quantum teleportation experiment using commercially available SPDs failed because their dark count rate added too many errors in poor atmospheric conditions. The second attempt in 2012 used our APDs operated at −60 °C with 15 dark counts per second, and resulted in a success [2]. The low temperature APD characterization methods developed in this work are also important for space applications [3], where deep cooling promises to be the main mitigation method for radiation damage to APDs.

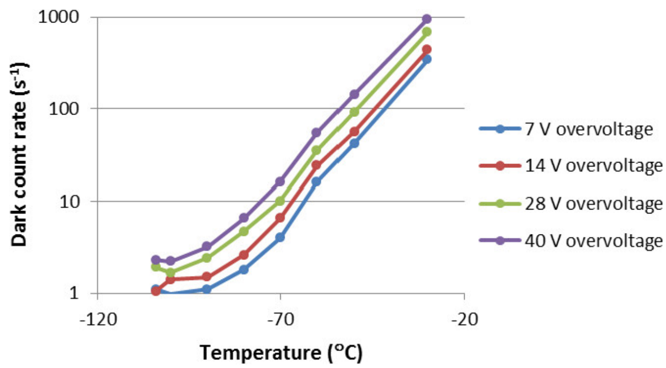

FIG. 1. Dark count rate of Si-APD vs. temperature, at four different voltages above breakdown voltage.

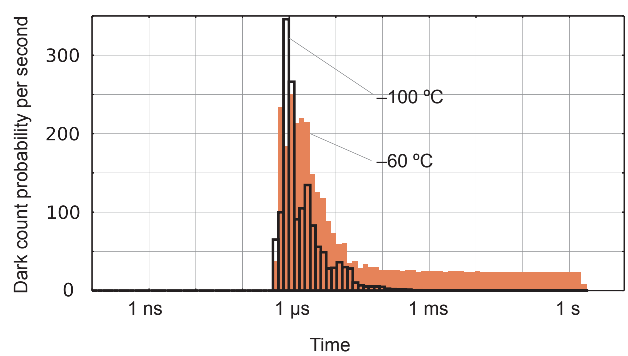

FIG. 2. Dark count probability versus time elapsed since a count, at −60 and −100 °C. The first 0.5 μs is deadtime; the peak is caused by afterpulses; the count probability settles to the dark count rate at long time values.

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