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

Elena Anisimova,[1,*] Rupert Ursin,[2] Thomas Jennewein,[1] and Vadim Makarov[1]

[1] *Institute for Quantum Computing, University of Waterloo, 200 University Ave. West, Waterloo, ON, N2L 3G1 Canada*

[2] *Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria.*

We report development of low-noise Si avalanche photodiode single-photon detectors (SPDs) for long-distance free-space quantum communications. This application requires relatively large photosensitive area (e.g., ⌀0.5 mm) and very low dark count rate. Cooling avalanche photodiodes is a common technique, allowing to decrese dark counts, but at the same time increasing afterpulsing time. We consider a trade-off between dark counts and afterpulses of SPD cooled down to -60 to $-100\,^{\circ}$C. We describe thermal design needed to achive these temperatures in a compact package. Also, we investigate jitter as a function of bias voltage, discriminator threshold and beam position within the photosensitive area.

Quantum computers and quantum cryptography systems are fast developing area nowadays, and quantum key distribution (QKD) systems are already available on the market. Channels for quantum communications can be optical fibers, with their distance limitations caused by losses in fibers, or free space, where the main losses are caused by atmospherical turbulence and absorption. While distance limitation of fiber can in principle be overcome by quantum repeaters, they are not practical yet. Another way to extend quantum communications to global distances is to use a satellite as communication relay. Quantum communication in terrestrial free-space channels up to 143 km long has been demonstrated [1]. Attenuation in the quantum channel at such distances approximately corresponds to the attenuation of ground to low Earth orbit (LEO) satellite channel, because the atmospheric turbulence mainly occurs in the lowest 20 km layer of the Earth atmosphere. So, a world-wide satellite-based quantum communication network looks to be a realistic goal on the way of quantum communication development.

Detailed analysis and simulations for several types of quantum communications between the ground and LEO satellite are available [2]. Despite such achivements in long distance quantum communication, there are several challenges left. A beam of photons passing through atmosphere and undergoing atmospheric turbulence is widely spread and polluted with stray light. The errors caused by the stray light can be significantly decreased by spectral and temporal filtering. However, the key component of quantum communication scheme, single-photon detector (SPD), has its own intrinsic noise. SPDs always have some non-zero level of dark counts that cause false detections and introduce errors. Thus an SPD should have low dark count rate, and at the same time relatively large sensitive area to collect photons from an angle-spread beam. For example, the 143 km quantum teleportation experiment required detectors with a sensitive area of 0.5 mm diameter, and dark count rate of 10–20 Hz [1].

Most practical detectors used for quantum communications now are detectors based on avalanche photodiodes (APDs). Dark counts in APDs arise via two main mechanisms. Thermally excited carriers in the APD junction cause avalanches indistinguishable from photon-exited ones. During the avalanche, some carriers get trapped, and afterwards they are spontaneously released, causing a new avalanche, named afterpulse. Thermally excited avalanches and afterpulses together cause the intrinsic noise of the APD. Probability of thermal excitation increases exponentially with temperature. Usually to get low dark count rate, APDs are cooled down below $0\,^{\circ}$C. However, at low temperatures car-

* anisimovaa@gmail.com

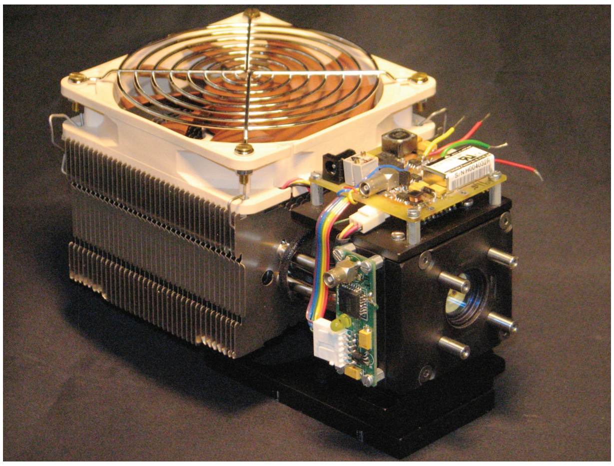

FIG. 1. SPD built for the 143 km quantum teleportation experiment [1].

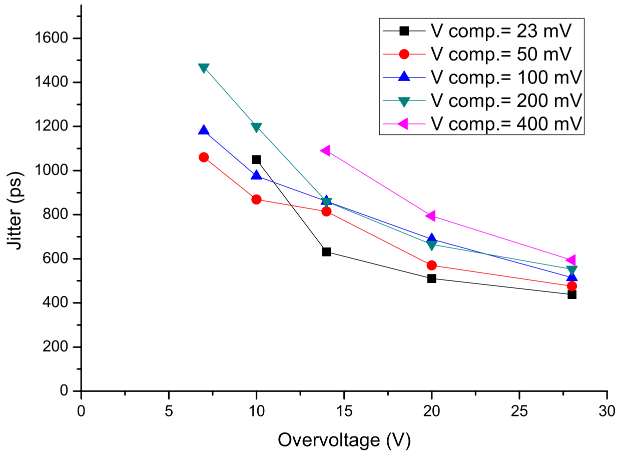

FIG. 2. Jitter of APD vs. overvoltage at different discriminator thresholds. APD was connected to 100 Ω resistor and voltage across the resistor was sensed by a high-speed emitter-coupled logic discriminator with adjustable threshold. Overvoltage is the difference between bias voltage and APD breakdown voltage.

rier trap lifetimes increase. Then, simultaneously with the decrease of the dark count rate, the afterpulsing become more prominent. Afterpulses can be discarded during postprocessing. However extending the time during which counts should be discarded limits the bit rate of quantum communication. Thus, for a given quantum communication link there is an APD temperature that achieves an optimum trade-off between reduction of errors from dark counts and reduction of data rate due to afterpulse discarding time.

To satisfy challenging requirements for experiment [1], we built a compact SPD based on a Si APD (Excelitas C30902SH) cooled with thermoelectric cooler (TEC) (fig. 1) [3]. Its detection efficiency was about 50%, which is good for such type of detectors and sufficient for the quantum communication protocol. Passive quenching scheme was implemented. Dark count rate for this type of SPD approximately halves for every 7 °C decrease of temperature. To achieve dark count rate of 15 Hz, the APDs were cooled down to −60 °C using 3-stage TEC (Thermonamic TEC3-71-31-17-03). The APD and TEC were placed inside an aluminum sealed housing. To prevent ice formation on the detector window, dessicant was placed inside the housing.

Despite the good peformance of the SPD for the teleportation experiment, there is still a room for improvement. The spectral filter width used in the experiment was 8 nm. After this filtering only 100 Hz of stray light remained after temporal filtering (2 ns acceptance window). Postprocessing of afterpulses was not used in this experiment. Newertheless, the experiment produced satisfactory fidelity of quantum teleportation [1]. However it should be possible to achieve successeful quantum communication through a higher-loss channel. Spectral filter bandwidth can be narrowed by 1-2 orders of magnitude to decrease amount of stray light, then dark counts of APD will dominate and limit the channel lengh. Then, we would need to decrese dark count rate further in order to achieve acceptable performance over a higher-loss channel.

To investigate the behaviour of APDs at low temperature we built a new version of the SPD for free-space quantum communication. In a new vacuumed housing APD is cooled down with a 5- or 6-stage TEC to −100 °C. Preliminary measurement of afterpulsing with Si APD (Excelitas C30902SH) has been made at −80 °C, and will be shown on the poster. The measurement shows measurable afterpulsing up to ∼ 300 µs after a detection event. This indicates that additional measurements and careful modeling are required.

Another important parameter of quantum communications is a jitter of APD detection.

Jitter determines timing of quantum communication, a lower jitter lets us use narrower time window and cut out noise and stray light more efficiently. Typical jitter values for such type APDs are about 500 ps. In experiment [1] click acceptance window was 2 ns. Jitter depends on the bias voltage of APD and discriminator threshold voltage. We measured statistical jitter distribution for our SPD at three temperatures: -30, -50, $-60\,^{\circ}$C, as a function of bias voltage and discriminator threshold. In figure 2 you can see the jitter full-width at half-maximum (FWHM) versus bias voltage at $-60\,^{\circ}$C. Also we measured jitter dependence on a position of a focused beam at APD's sensitive area. Jitter difference between the center and the edge of the sensitive area is about 100 ps.

Poster will report the latest results of the study.

---

[1] X.-S. Ma, T. Herbst, T. Scheidl, D. Wang, S. Kropatschek, W. Nailor, B.Wittman, A. Mech, J. Kofler, E. Anisimova, V. Makarov, T. Jennewein, R. Ursin, and A. Zeilinger, Nature **489**, 269 (2012).

[2] J.-P. Bourgoin, E. Meyer-Scott, B. L. Higgins, B. Helou, C. Erven, H. Hübel, B. Kumar, D. Hudson, I. D'Souza, R. Girard, R. Laflamme, and T. Jennewein, New J. Phys. **51**, 023006 (2013).

[3] Y.-S. Kim, Y.-C. Jeong, S. Sauge, and V. Makarov, Rev. Sci. Instr. **82**, 093110 (2011).