[SSC22-WKI-04]

CubeSat single-photon detector module for performing in-orbit laser annealing to heal radiation damage

Nigar Sultana*, Joanna Krynski, Jin Gyu Lim, Vadim Makarov, Thomas Jennewein
University of Waterloo
Waterloo ON, Canada; * +15197297560
* n6sultan@uwaterloo.ca

Logan M. Power**, John Floyd, Michael Lembeck, Paul Kwiat
University of Illinois Urbana-Champaign
Champaign IL, United States;
**lmpower2@illinois.edu

ABSTRACT

Silicon-based single-photon avalanche photodiodes (SPADs), widely considered for satellite-based quantum communications, suffer a constant increase of dark count rate (DCR) from radiation-induced proton displacement damage in their active areas. When this accumulated damage causes the DCR to exceed a certain threshold (for example, 10,000 counts per second), the SPADs become unreliable for quantum communications, limiting mission lifetime. Previous ground experiments showed that radiation-induced DCR of synthetically irradiated SPADs could be significantly improved by high-power laser annealing, a localized heating of SPADs' active areas using a focused laser beam. The next step is therefore to demonstrate real-time laser annealing on constantly irradiated SPADs in actual low-Earth-orbit is viable. To facilitate this study, the University of Waterloo team built a miniaturized software controllable SPAD module as part of the annealing payload on CAPSat (Cool Annealing Payload Satellite), a 3U CubeSat satellite developed by a team from the University of Illinois Urbana-Champaign. We present the concept of in-orbit laser annealing and the electronic platform of the SPAD module containing four detectors supporting thermal and laser annealing and detector characterization. The CAPSat, launched and deployed in a low-Earth orbit at 400 km altitude from the International Space Station in October 2021, was intended to assess the viability of this approach before incorporating SPADs in future quantum satellite missions, especially in quantum receivers.

Introduction

Single-photon detectors are essential for any satellite-based quantum communications.[1–7] The satellite missions widely consider Silicon-based single photon avalanche photodiodes (SPADs) because of their high quantum detection efficiency, low dark count rate (DCR), low timing jitter, and low afterpulsing probability near 800 nm wavelengths associated with good atmospheric transmission.[8,9] They are smaller in size and commercially available with sufficiently high detection efficiency, above 60%, over a wide range of wavelengths ($400 - 1000$ nm). However, Si-SPADs suffer serious displacement damage due to space radiation, particularly the proton radiation, causing a significant increase of DCR over time, around 30 counts per second (cps) per day per detector.[10] The DCR accumulation will soon become sufficiently high as to severely impact or even prevent the implementation of quantum communication protocols, such as quantum key distribution (QKD)[?,11] and quantum teleportation,[12] thereby limiting mission lifetime. Previous ground-based experiments showed laser annealing being effective in improving DCR that heals radiation damage using a focused laser beam on irradiated Si-SPAD active area.[13,14] We now intend to investigate the effectiveness of real-time laser annealing repeatedly performed on constantly irradiated SPADs in real LEO orbits, which effectiveness still remains unknown.

To facilitate this study, we developed a compact, miniaturized SPAD module for an annealing payload on CAPSat (Cool Annealing Payload Satellite),[15] a 3U CubeSat satellite developed by a team from the University of Illinois Urbana-Champaign (UIUC). Our SPAD module, developed at the University of Waterloo, contained four SPADs (two Excelitas C30902SH and two Excelitas SLiK), detector circuitry and active detector temperature control electronics. In this paper, we present the implementation of this module and the concept of in-orbit laser annealing using the novel technique of fibre-coupling the annealing laser to the detectors for full illumination of their active areas. The fully autonomous module satisfied CAPSat mission requirements, with a form factor of $9 \times 9 \times 5.2\,\mathrm{cm}^3$, mass of 250 g, and power consumption less than 2 W. UIUC conducted vacuum thermal performance and vibration testing of the module prior to CAPSat launch and deployment in October 2021 from the International Space Station in a low-Earth orbit at 400 km altitude [1].

Concept of in-orbit laser annealing

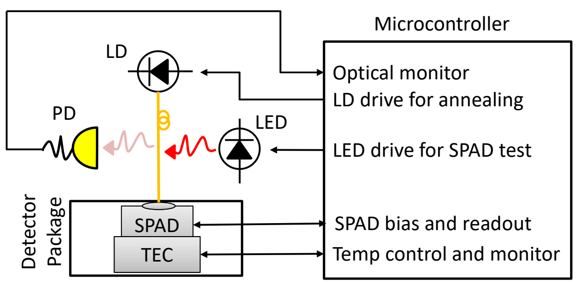

Figure 1: Concept of the in-orbit laser annealing. Laser diode (LD) produces a high-power optical beam used to anneal the SPADs. LD output is guided to the active area of the SPAD through an optical fibre. A light emitting diode (LED) is a reference light source to monitor detectors' photon detection efficiency. Photodiode (PD) monitors the power illuminated to the SPAD. TEC is an integrated thermoelectric cooler with the SPAD.

The annealing payload contains all the necessary resources required to perform laser and thermal annealing and characterize detector parameters such as detection efficiency and dark count rate. Figure 1 illustrates the functional concept of the payload. It contains a high-power laser diode (LD) that focuses an optical beam on the SPAD active area via an optical fiber for laser annealing. A light emitting diode (LED), located close to the optical fiber, is used as a reference light for verifying the photon detection efficiency, lasing LED photons that leaked into the jacked fiber; the LED power itself can be measured using an additional photodiode (PD). A microcontroller (MCU) is used to control these devices, allowing for automatic operation.

The annealing payload is composed of two stacked modules: the Waterloo SPAD module, and the UIUC control module. The SPAD module contains four SPADs and their biasing and temperature control circuitry. The rest of the payload components consisting of two LDs, one LED, one PD, and an MCU are located in the control module. Two LDs are fibre-coupled with two detectors of the SPAD module (One SLiK and one C30902SH) for laser annealing. Other two detectors were kept as control devices that were not intended for laser annealing. Their purpose was to estimate the detectors' cumulative damage due to high-energy space radiation. The SPAD module gets its power supplies and MCU control signals via a PC/104 connector from the control module. The flight version of the payload used an STMicroelectronics STM32L4 microcontroller, however development and testing was performed with a Cypress PSoC3 controller. The MCU is programmed to collect annealing experiment data and send to the CAPSat flight computer; the data consists of DCR and detection efficiency of each detector collected under various conditions, such as different cooling temperatures, with and without annealing, or after various radiation exposures. The flight computer would store the data until downlinked to a ground station.

Overview of the SPAD module

Figure 2 shows the schematic overview of the SPAD module, which is designed to accommodate four SPADs: two Excelitas SLiK and two C03902SH, with active areas of 180 µm and 500 µm, respectively. Each detector package consists of a SPAD, a two-stage thermoelectric cooler (TEC) and a thermistor. The TECs allow precise control of the detector temperature, as measured by the thermistors. While the integrated TECs are primarily used to cool the SPADs, they could also be used to perform thermal annealing by reversing the TEC current direction. The current is controlled to flow through only one TEC at a time, regulated via an optocoupler switching system. In our SPAD module, the detectors are mounted on a separate aluminium plate, which acts like a heatsink, vertically attached to the SPAD PCB. Two SPADs share a high-voltage supply and a detector circuit to bias and process avalanche signals, respectively; SPAD selection is controlled via a solid-state switching system. Each detector is customized to couple with a fiber connector to ensure

[1]Post launch loss of functionality, possibly due to a couple of high solar mass ejections that occurred shortly after deployment.

full illumination of active areas by fiber pigtailed laser beams during annealing. The SPAD operation is fully controllable via software running on the control module. Control signals for the SPADs, as well as the two power supplies, are provided by the control module through the PC/104 stack connector. Power consumption by key components of the SPAD module is given in Table 1 that shows the total consumption is less than 2 W as required. Figure 3 illustrates the flight SPAD module stacked on the other part of the CAPSat annealing payload. CAPSat, however, lost its functionality after launch, in-orbit laser annealing therefore could not be implemented.

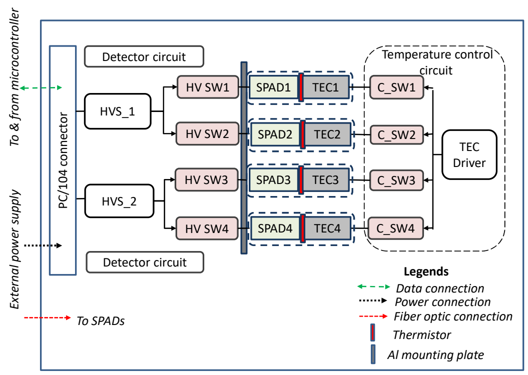

Figure 2: Schematic overview of the SPAD module showing key devices and functional elements.

Table 1: Summary of power consumption of the SPAD module

SPAD module	Power Consumption (mW)
HVS output of 200 V to 485 V	183.5 to 225
Detector circuit	29.5
HV_SW	16.5
C_SW	20
TEC driver	1675

*measurement was taken at −20°C.

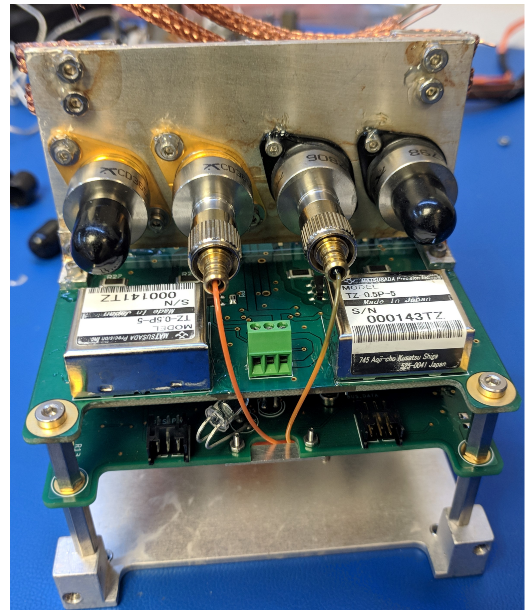

Figure 3: SPAD flight module stacked on control module of the CAPSat annealing payload.

Conclusion

We have described the concept of in-orbit laser annealing inside CAPSat and overviewed the SPAD module designed to operate with low power and low mass environment typical of CubeSats. The annealing on the SPADs was intended to be performed in orbit at 400 km altitude. Such tests would provide us with a better insight into the radiation damage occurring to SPADs in real space and the effectiveness of in-orbit laser annealing to heal real radiation damage, a step forward toward incorporating SPADs in future satellite quantum receivers.

Acknowledgements

The authors wish to thank the funding support from the Canada Foundation for Innovation (CFI), the Canadian Space Agency (CSA) the Ontario Research Fund (ORF), the Natural Sciences and Engineering Research Council of Canada (NSERC), and Industry Canada. The UIUC work is supported by the National Aeronautics and Space Administration.

References

[1] R. Bedington, J.M. Arrazola, and A. Ling. Progress in satellite quantum key distribution. *npj Quantum Information*, 3(1):30, 2017.

[2] S.K. Liao, W.Q. Cai, J. Handsteiner, B. Liu, J. Yin, L. Zhang, D. Rauch, M. Fink, J.G. Ren, W.Y. Liu, et al. Satellite-relayed intercontinental quantum network. *Physical Review Letters*, 120(3):030501, 2018.

[3] H. Takenaka, A. Carrasco-Casado, M. Fujiwara, M. Kitamura, M. Sasaki, and M. Toyoshima. Satellite-to-ground quantum-limited communication using a 50-kg-class microsatellite. *Nature Photonics*, 11(8):502, 2017.

[4] K. Günthner, I. Khan, D. Elser, B. Stiller, Ö. Bayraktar, C.R. Müller, K. Saucke, D. Tröndle, F. Heine, S. Seel, et al. Quantum-limited measurements of optical signals from a geostationary satellite. *Optica*, 4(6):611–616, 2017.

[5] D.KL. Oi, A. Ling, G. Vallone, P. Villoresi, S. Greenland, E. Kerr, M. Macdonald, H. Weinfurter, H. Kuiper, E. Charbon, et al. Cubesat quantum communications mission. *EPJ Quantum Technology*, 4(1):6, 2017.

[6] D.P. Naughton, R. Bedington, S. Barraclough, T. Islam, D. Griffin, B. Smith, J. Kurtz, A.S. Alenin, I.J. Vaughn, A. Ramana, et al. Design considerations for an optical link supporting intersatellite quantum key distribution. *Optical Engineering*, 58(1):016106, 2019.

[7] M. Yang, F. Xu, J.-G. Ren, J. Yin, Y. Li, Y. Cao, Q. Shen, H.-L. Yong, L. Zhang, S.-K. Liao, et al. Spaceborne, low-noise, single-photon detection for satellite-based quantum communications. *Optics Express*, 27(25):36114–36128, 2019.

[8] J.P. Bourgoin, E. Meyer-Scott, B.L. Higgins, B. Helou, C. Erven, H. Huebel, B. Kumar, D Hudson, I. D'Souza, R. Girard, et al. A comprehensive design and performance analysis of low earth orbit satellite quantum communication. *New Journal of Physics*, 15(2):023006, 2013.

[9] J.P. Bourgoin, N. Gigov, B.L. Higgins, Z. Yan, E. Meyer-Scott, A.K. Khandani, N. Lütkenhaus, and T. Jennewein. Experimental quantum key distribution with simulated ground-to-satellite photon losses and processing limitations. *Physical Review A*, 92(5):052339, 2015.

[10] X. Sun, P.L. Jester, J.B. Abshire, and E.S. Chang. Performance of the glas space lidar receiver through its seven-year space mission. In *CLEO: Applications and Technology*, page ATuA2. Optical Society of America, 2011.

[11] A.K. Ekert. Quantum cryptography based on bell's theorem. *Physical Review Letters*, 67(6):661, 1991.

[12] C.H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W.K. Wootters. Teleporting an unknown quantum state via dual classical and einstein-podolsky-rosen channels. *Physical Review Letters*, 70(13):1895, 1993.

[13] A.N. Bugge, S. Sauge, A.M.M. Ghazali, J. Skaar, L. Lydersen, and V. Makarov. Laser damage helps the eavesdropper in quantum cryptography. *Physical Review Letters*, 112(7):070503, 2014.

[14] J.G. Lim, E. Anisimova, B.L. Higgins, J.P. Bourgoin, T. Jennewein, and V. Makarov. Laser annealing heals radiation damage in avalanche photodiodes. *EPJ Quantum Technology*, 4(1):11, 2017.

[15] SivSchwink. `https://physics.illinois.edu/news/CAPSat-in-orbit`, 2021.