Novel photon-counting detectors for free-space communication

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ABSTRACT

We present performance data for novel photon-counting detectors for free space optical communication. NASA GSFC is testing the performance of two types of novel photon-counting detectors 1) a 2x8 mercury cadmium telluride (HgCdTe) avalanche array made by DRS Inc., and a 2) a commercial 2880-element silicon avalanche photodiode (APD) array. We present and compare dark count, photon-detection efficiency, wavelength response and communication performance data for these detectors. We successfully measured real-time communication performance using both the 2 detected-photon threshold and AND-gate coincidence methods. Use of these methods allows mitigation of dark count, after-pulsing and background noise effects.

The HgCdTe APD array routinely demonstrated photon detection efficiencies of greater than 50% across 5 arrays, with one array reaching a maximum PDE of 70%. We performed high-resolution pixel-surface spot scans and measured the junction diameters of its diodes. We found that decreasing the junction diameter from 31 μm to 25 μm doubled the e-APD gain from 470 for an array produced in the year 2010 to a gain of 1100 on an array delivered to NASA GSFC recently. The mean single-photon SNR was over 12 and the excess noise factors measurements were 1.2-1.3.

The commercial silicon APD array exhibited a fast output with rise times of 300 ps and pulse widths of 600 ps. On-chip individually filtered signals from the entire array were multiplexed onto a single fast output.

Keywords: Detectors, photon-counting, avalanche photodiodes, optical communication

1. INTRODUCTION

Free-space optical communication technology is advancing rapidly. For example, both direct and coherent detection space-flight systems have been demonstrated recently. For free-space, as with terrestrial communication systems, coherent systems have a great advantage for high data rates. However, adaptive optics or dense multiple-aperture systems are needed for ground-based coherent systems, all of which must operate with atmospheric turbulence. Conversely, for direction detection, cost-effective, commercial, systems using high power lasers operating in the near-infrared, one typically achieves very high sensitivity with photon-counting receivers. The largest commercial advantage for free-space optical communication leverage is typically through the use of long-distance telecommunications optical transceiver components that operate near 1550 nm wavelength. New low-cost 10 Gbps fiber-optic data link transmitter components are also available at 850 nm and 1310 nm. In this paper, we explore possible options for photon-counting detectors that are compatible with at least one of these wavelengths. Our goal is to explore avenues for lower cost photon-counting receiver options while trying to operate at the highest possible receiver data rates.

The highest data rate (2.5 Gbps) photon-counting receiver system demonstrations[1] used superconducting nanowire detectors. In this paper, we demonstrate photon-counting receiver systems that may provide an avenue to much lower cost. A lower-cost single receiver may also provide a path to a lower-cost wavelength division multiplexed (WDM) system for higher data throughput.

Photo-receivers for direct detection high-data-rate free-space optical systems are challenging. For ground-based systems, atmospheric turbulence produces a moving blur spot. Even with a tip/tilt receiver mirror system to eliminate the motion, the detector's area is still an important consideration. Conventional semiconductor single-detector photo-receivers have limited bandwidth due to the capacitance associated with a large area. One of the best conventional semiconductor single-element photodiodes is the near-infrared enhanced linear-mode silicon avalanche photodiode detector (APD). A receiver sensitivity of 23 photons/bit at bit-error ratio (BER) = 10^{-2} was achieved[2] at 1064 nm wavelength (200 MHz detector bandwidth using 10 ns slots). Extending linear-mode silicon APDs to higher data rates comes at the expense of reducing the detector area.

At near-infrared wavelengths, photomultipliers (PMTs) have low quantum-efficiency and limited bandwidth (despite avoiding the capacitance issue). PMTs were successful in the European ground station in the Lunar Laser Communication Demonstration (LLCD), achieving[3] a receiver sensitivity of 16 photons/bit (0.8 detected-photons/bit) using 39 Mbps 16-ary PPM at 1550 nm. The alternative to a large monolithic single-element detector is to use an array comprising multiple individual detector elements (pixels). Large capacitance issues are avoided by using a number of small pixels. For Geiger-mode devices the dynamic range is directly proportional to the number of pixels. For free-space communication through the atmosphere a minimum of 20 dB dynamic range is a goal. An interleaved array of superconducting nanowires single photon detectors (SNSPD) were used at the White Sands Ground Station in LLCD. With the SNSPD array, LLCD achieved[3] a receiver sensitivity of 1.5 photons/bit at 39 Mbps and 3.5 photons/bit at 622 Mbps with 16-ary PPM at 1550 nm. An asynchronous array of Geiger-mode InGaAsP avalanche photodiodes with a custom read-out integrated circuit was proposed and tested for the Mars Laser Communication Demonstration. This system achieved[4] 1 detected-photon/bit at 14 Mbps at 1064 nm wavelength. We note that having a large number of pixels mitigates issues due to detector post-detection dead time for Geiger-mode APD arrays.

2. PHOTON-COUNTING THEORY

The theoretical quantum limit for the bit error rate (BER) for on-off keying (OOK) is:

$$BER = \frac{1}{2}e^{-\lambda} \qquad (1)$$

where λ is the average photon rate for the asserted signal – K1, (K1 = 1). Some single-photon sensitive detectors can nearly achieve this quantum limit. However, dead-time, dark counts, after-pulsing and excess noise are challenges for many photon-sensitive detectors. To mitigate these effects, we compared two methods. In Method 1 we set the detection threshold at the 2-photon level. In Method 2 we use 2-arrays with a high-speed AND-gate for coincidence detection. The calculated BER for Method 1 (Set threshold at the 2-photon level) is:

$$BER = \frac{1}{2}\left(1+\lambda\right)e^{-\lambda} \qquad (2)$$

The calculated BER for Method 2 (Use 2-arrays with AND-gate and coincidence detection) is given by:

$$BER = e^{-\lambda/2} - \frac{1}{2}e^{-\lambda} \qquad (3)$$

In the next Section we compare the experimental and theoretical performance for these methods.

3. FREE-SPACE OPTICAL COMMUNICATION BENCH EXPERIMENTS

3.1 Silicon Geiger-mode avalanche photodiode array

We present a simple method to greatly reduce dark-count and after-pulsing noise to allow high-rate free-running photon-counting receivers. The method is applicable to any photon-counting array technology. The method uses three key ideas that individually (or in pairs) have been used previously – but to our knowledge not all three together. The key ideas are: 1) use an array of photon-counting elements wired together as a single detector 2) use a high pass filter, ideally on each array element[5] (or on the array output to only preserve the information-bearing portion of the waveform), and 3) depending on the photon-counting element excess noise, use either a "two-photon" intensity threshold level or an AND-gate with coincidence detection.

At 850 nm, the commercial fiber data link transceivers are extremely low-cost (< $1k). 20 Gbaud rates were recently demonstrated[6] using an 850 nm Vertical Cavity Surface Emitting Laser (VCSEL) transmitter and a GaAs PIN diode 22 GHz photoreceiver. Commercial tapered amplifiers are available[7] with average powers up to 3 W and quasi-CW peak power to 56 W[8]. For free-space optical communication, atmospheric transmission is slightly lower at 850 nm. The key system component on which free-space communication depends is a high-sensitivity high-bandwidth receiver.

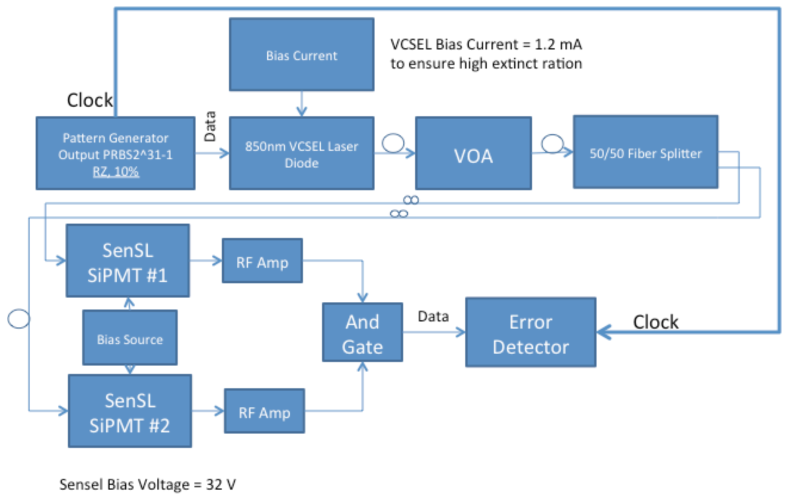

Figure 1. Free-space optical communication bench test diagram for the Sensl APD arrays using coincidence detection. VOA = Variable Optical Attenuator.

Figure 1 shows our free-space optical communication experimental set-up for the Sensl APD arrays using coincidence detection. In our experiment, we used an inexpensive Finisar 850nm VCSEL transmitter and silicon avalanche photodiode array detector (Sensl Model MicroFC-SMA-10010). The binary data stream from a Pattern Generator was a Pseudo-Random-Bit-Sequence (PRBS) of length 2^{31} -1. We calibrated the detected-photon rate (λ) by fitting the experimental intensity histograms (detected-photon number data) in Figure 2 to the Poisson theory. We used a narrow Return-to Zero (RZ) transmitter pulse format (10% duty cycle) to reduce temporal jitter with this and other photon-counting receivers. We could not close the link using the real-time BER Test set (BERT) when we set the detection threshold at the one detected-photon ("1p") level. However, we successfully measured real-time communication performance using both the 2 detected-photon ("2p") and AND-gate coincidence methods. Use of these methods also improves the performance in the presence of background noise. The bit-error ratio vs. number of detected-photons is shown in Figure 3 for a 100 Mbps pseudo-random RZ data with no background noise.

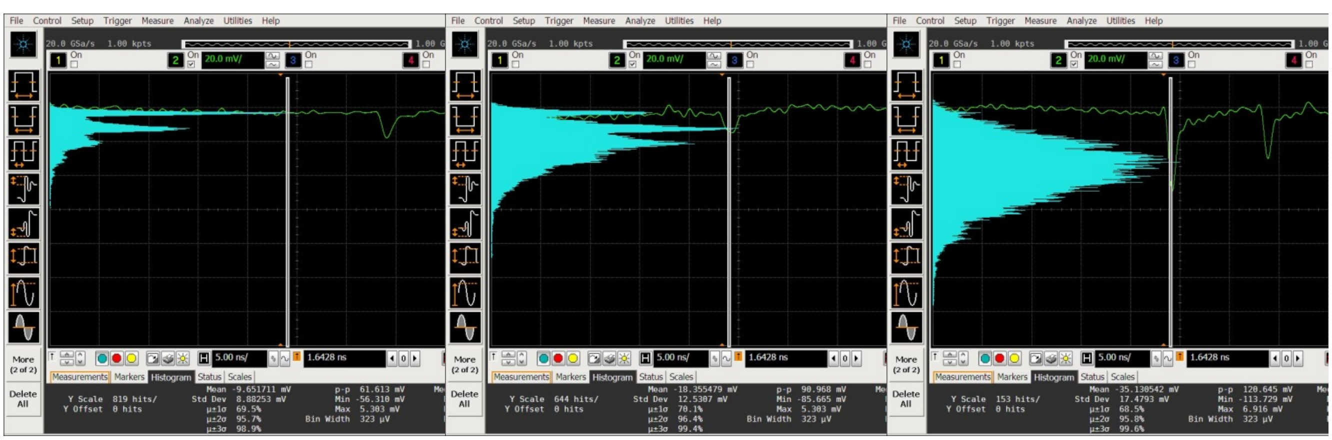

Figure 2. Sensl silicon APD photon number discrimination for a) λ = 0.8 b) λ = 1.7 and c) λ = 3.2

The Sensl detector jitter was measured using a 100 ps laser pulse from Picoquant at 1030 nm wavelength. 5000 pulses were accumulated for each jitter measurement. We measured 120 ps rms jitter for the Sensl detector.

Figure 3 shows a plot comparing these theories to experimental data using the silicon APD array (Sensl).

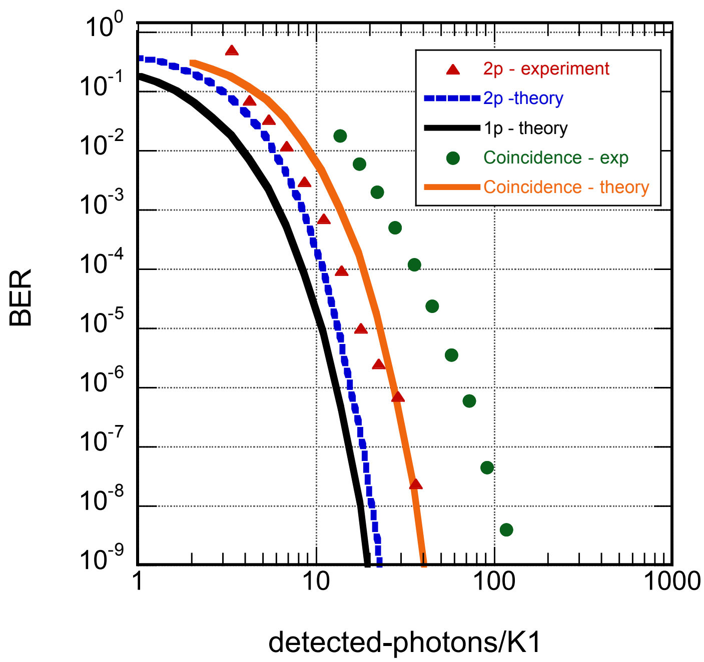

Figure 3. Bit Error Ratio (BER) vs. number of detected-photons per asserted signal for Sensl silicon APD array experimental data with AND-gate coincidence, 2 detected-photon (2p) and quantum limit (1p) threshold theories.

The experimental bit error ratio of two Sensl silicon APD arrays with AND-gate coincidence detection (and 85 kcps background noise) is shown in Figure 4 for several data rates.

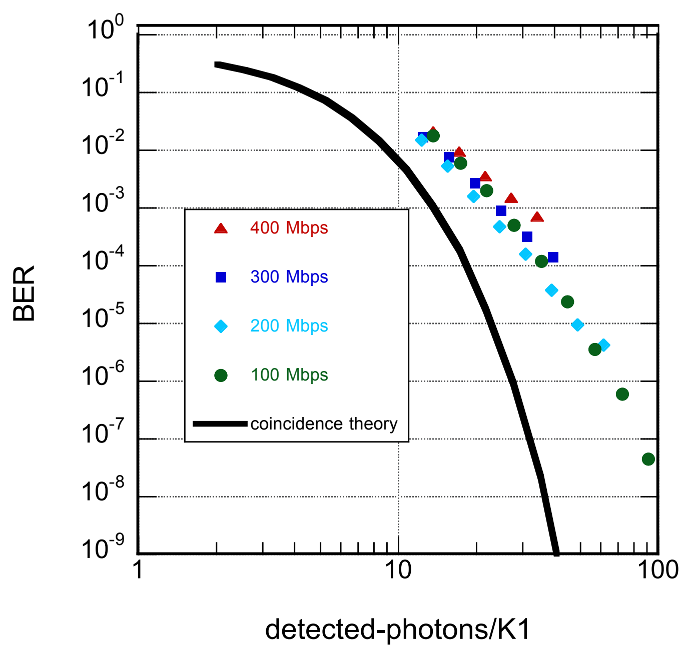

Figure 4. Experimental bit error rate using two Sensl silicon APD arrays with AND-gate coincidence detection (and 85 kcps background noise) at several data rates.

3.2 Mercury Cadmium Telluride (HgCdTe) linear-mode avalanche photodiode array

DRS Inc. has produced a set of 2x8 pixel Linear-Mode Photon-Counting (LMPC) Focal Plane Arrays[9] capable of detecting single photon events at >60% photon detection efficiency (PDE) at about 150 kcps dark count rates and producing an impulse response of about 8-ns. This HgCdTe APD array has photon detection efficiencies of greater than 50%, as was demonstrated across 5 arrays, with one array reaching a maximum PDE of 70%. High resolution pixel-surface spot scans were performed and the junction diameters of the diodes were measured. The junction diameter was decreased from 31 µm to 25 µm resulting in a 2x increase in e-APD gain from 470 (on an array produced in 2010) to 1100 on the array delivered to NASA GSFC recently. Mean single photon SNR's of over 12 were demonstrated at excess noise factors of 1.2-1.3. Further improvement in the timing performance and noise are expected from the next lot of the devices currently being fabricated. Two proton radiation damage tests have been performed and the results showed the devices can be used in a multi-year Earth orbiting mission. One of these detectors (which was funded by the NASA In-space Validation of Earth Science Technology - InVEST program[10]) will be integrated with a small cryocooler and will fly on a CubeSat in 2016. All of these new LMPC HgCdTe APDs have a much superior cost*performance product vis-à-vis the currently available photodetectors in the SWIR wavelength and are expected to meet a vital need for high speed single photon detectors in MWIR wavelength region.

All of our test data for the HgCdTe APD is taken at an operating temperature of 77K. A surface scan of a single pixel (made of 4 mesas) is shown in Figure 5.

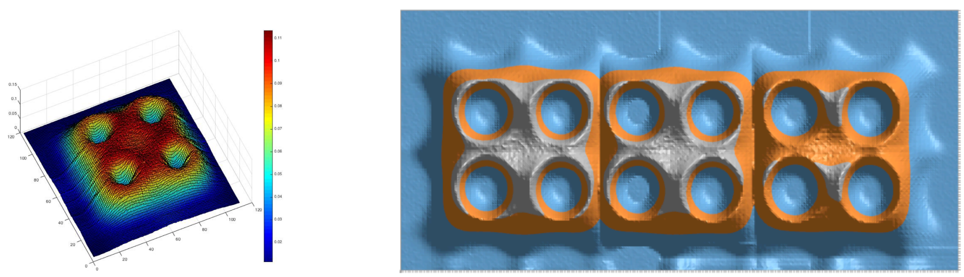

Figure 5. DRS HgCdTe APD surface scan of illuminated a a) single pixel consisting of 4 mesas with 11 V applied b) 3 pixels.

The pulse height distribution for several fixed intensity levels is shown in Figure 6. We calibrated the detected-photon rate by fitting the experimental intensity histograms (detected-photon number data) in Figure 6 to Poisson theory.

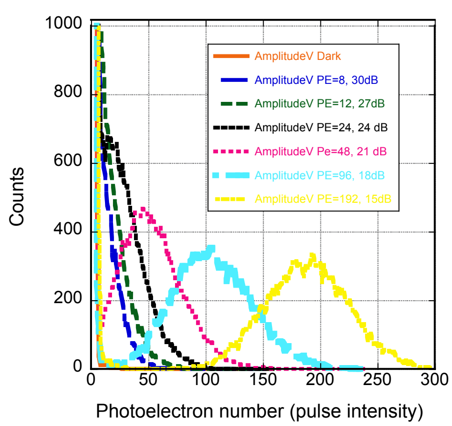

Figure 6. DRS HgCdTe APD pulse height distribution at several intensities.

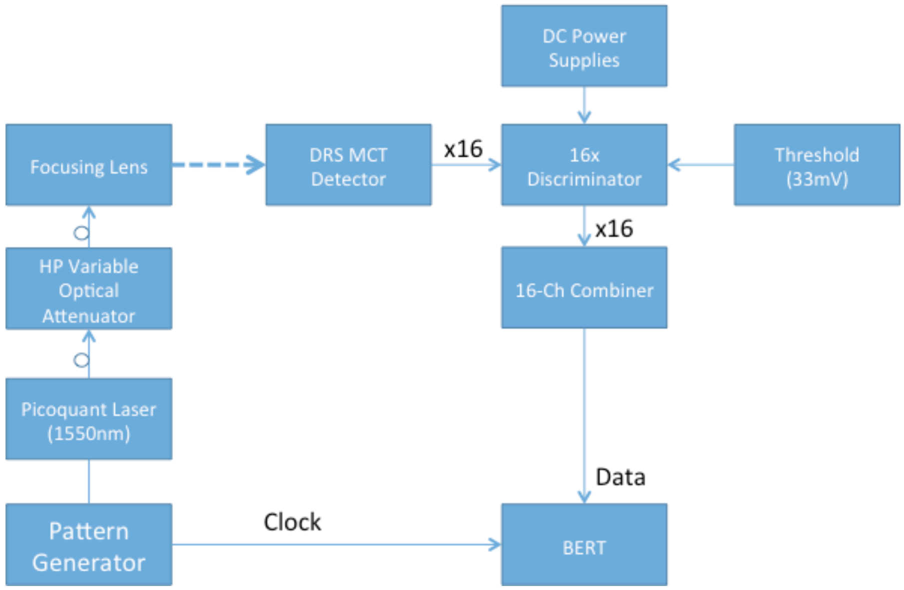

Figure 7. Free-space optical communication bench test diagram for the DRS Mercury Cadmium Telluride (MCT – a.k.a. HgCdTe) APD array.

Our bit error ratio tests of the DRS APD array were conducted at 1550 nm wavelength using an RZ pulse waveform with 10% duty cycle OOK, i.e. RZ-OOK, at a data rate of 50 Mbps. The test set-up block diagram is shown in Figure 7. Figure 8 shows the experimental and theoretical communication performance of a single pixel of the DRS HgCdTe APD array.

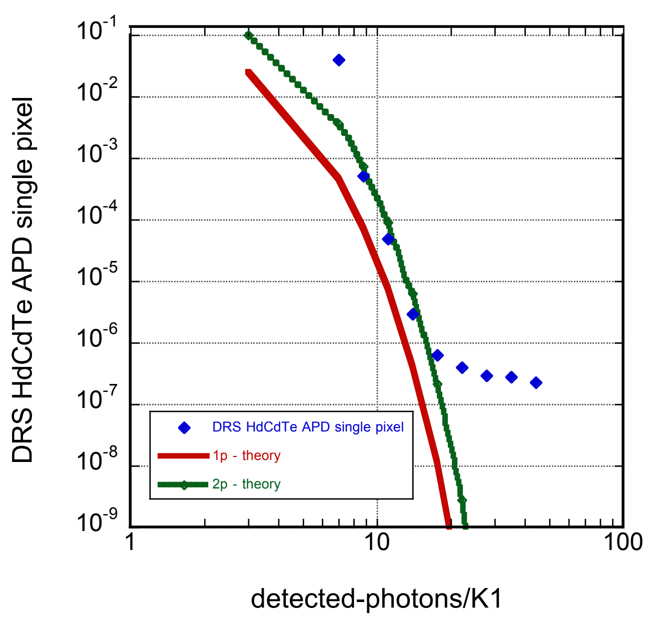

Figure 8. DRS HgCdTe APD experimental BER data with RZ-OOK 50 Mbps data rate with PRBS=2^31-1 from a single pixel compared to 1 and 2 detected-photon threshold theories.

Using a 2x4 subsection of the DRS HgCdTe 2x8 APD array, we added a high-pass filter to each pixel's external output and combined the 8 pixel filtered outputs with an impedance-controlled electrical combiner to demonstrate a real-time communication through the Bit-Error-Ratio Tester at 110 Mbps (RZ-OOK 10% duty cycle) at 8×10^{-8} BER. With this duty cycle (10%), the maximum data rate is limited by the detector timing jitter (measured as ~900 ps). Further improvements are needed in the electrical combiner circuitry to optimize the system.

4. FUTURE WORK

Under a lidar receiver program, we are developing a resonant-cavity silicon APD array[11] optimized for use at 1030 nm wavelength. For optical communications, a similar device optimized for use at 850 nm wavelength is promising. At 1550 nm wavelength, we hope to pursue an array of InGaAs Negative-Feedback-Avalanche-Diodes[12] (NFAD). We believe that >1 Gbps with a single array (in InGaAs) and multi-Gbps with WDM should be viable. We plan to improve the electrical combiner circuitry for the HgCdTe APD. Including this circuitry as part of a Read-Out-Integrated Circuit (ROIC) would be ideal. The HgCdTe APD timing jitter can be improved by incorporating an external electric field into the device design.

5. SUMMARY

We demonstrated high-data-rate (up to 400 Mbps) free-space optical communication with a photon-counting receiver using three ideas: 1) use an array of photon-counting elements wired together as a single detector 2) use a high pass filter, ideally on each array element (or on the array output to only preserve the information-bearing portion of the waveform) and 3) depending on the photon-counting element excess noise, use either a "two-photon" intensity threshold level or an AND-gate with coincidence detection. Use of these methods allows mitigation of dark count, after-pulsing and background noise effects. Commercial 850 nm VCSEL transmitters and silicon APD Geiger-mode arrays provide a viable path to low-cost high-rate (500 Mbps) free-space optical communication links. We achieved excellent communication performance at 50 Mbps @1550 nm with single-pixel HgCdTe APD and demonstrated external filtering and multi-pixel array combining to achieve 110 Mbps data rate.

REFERENCES

[1] Robinson, BS et al. "Demonstration of Gigabit-per-second and higher data rates at extremely high efficiency using superconducting nanowire single photon detectors" Proc. SPIE 6709, 67090Z (2007).

[2] Biswas, A. et al. "Ground detectors for optical communications from deep space" Proc. SPIE 4635, 72-83 (2002)

[3] Grein, M. E. et al. "An optical receiver for the Lunar Laser Communication Demonstration based on photon-counting superconducting nanowires" Proc. SPIE 9492, Advanced Photon Counting Techniques IX, 949208 (2015)

[4] Hopman, P. I. et al. "An end-to-end demonstration of a receiver array based free-space photon counting communications link" Proc. SPIE 6304, 63040H doi:10.1117/12.682845 (2006)

[5] Pavlov, N. "Silicon Photomultiplier and Readout Method" USPTO Patent Application Publication, No. US2013/0099100 A1 (2013).

[6] Szczerba, K. et. al. "70 Gbps 4-PAM and 56 Gbps 8-PAM Using an 850 nm VCSEL" Journal of Lightwave Technology, 33(7), 1395-1401 (2015).

[7] http://www.toptica.com/products/laser_diodes/tapered_amplifier_chips.html

[8] Wang, X. "56W optical output power at 970nm from a truncated tapered semiconductor optical amplifier" 2011 IEEE Photonics Conference, 577-578 (2011).

[9] J. D. Beck et al., “Linear mode photon counting with the noiseless gain HgCdTe e-avalanche photodiode,” Optical Engineering, 53, pp. 081905-1 to -10, (2014).

[10] R. Fields et al., “A linear mode photon-counting (LMPC) detector array in a CubeSat to enable earth science lidar measurements,” 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), FR2.B1.5. (2015).

[11] Vasile, S. et al. , “Near-infrared silicon, resonant cavity RC-GPD, and ROIC arrays” Proc. SPIE 8385, Sensors and Systems for Space Applications V, 838508 (2012).

[12] Jiang , X. et al. , “InGaAs/InP negative-feedback avalanche diodes (NFADs) and solid state photomultipliers (SSPMs)” Proc. SPIE 8375, Advanced Photon Counting Techniques VI, 83750U (2012)