Photon counting detectors for future laser time transfer missions

Ivan Prochazka, Josef Blazej
Czech Technical University in Prague, Czech Republic
prochazk@fjfi.cvut.cz /Fax +420 224 922 822,

Abstract

We are reporting on research, development and indoor tests of the photon counting detectors that are being developed in our lab for future space missions related to precise time transfer by laser pulses. The detectors are optimized for an on-board detection and precision time tagging of an incoming laser pulse. The key parameters of the detectors are: detection delay stability, broad operation temperature range, capability to operate under high background photon flux, radiation tolerance, mass and power consumption and overall ruggedness. The timing resolution, detection quantum efficiency and the dark count rate are of lower importance. The most challenging requirements are the detection delay stability of the order of units to tens of picoseconds within the temperature range of -30 to +50 C and the detection delay stability under the conditions of extremely high background photon flux well exceeding 10^8 photons per second hitting the detector active area. The detectors are based on the K14 SPAD chips. The new active quenching and gating electronics has been developed, it enables the operation in both gated and non gated modes. In a gated mode the detector is capable to operate – detect individual photons – under the condition of background photon flux exceeding 10^9 (!) photons per second.

Detector space application

One of the many attractive applications for solid state photon counters [1-3] in space is the technique of the time transfer by means of laser pulses. Two projects of time transfer by the laser pulses are in preparation. The Time Transfer by the Laser Light (T2L2) project has been completed by the French group [4]. The Laser Time Transfer (LTT) project was prepared by the Academy of Sciences of China [6]. The project is a spin-off of the existing projects of laser ranging of artificial Earth satellites [9]. The range is determined on the basis of the measured picosecond laser pulse propagation time toward the target satellite and back again. The epoch of transmission of laser pulse is monitored with respect to the local clock for each range measurement. For the time transfer by the laser light the existing satellite laser ranging ground stations will be employed, and new satellites have to be constructed and launched. The satellites are be equipped with retro reflectors and with an optical detector of laser pulses. The satellite range is measured by laser ranging to the on board retroreflectors. In addition the arrival time of the laser pulse to the satellite is recorded by stable on board clock and the recorded time tags will be transmitted to ground via satellite telemetry channel. Once the range and time tagging measurements have been received from several ground stations, combining the laser pulse emission times, propagation delays and satellite arrival time differences, the local clocks at the stations may be compared. The satellite laser ranging (SLR) technique has been well developed in recent years, ranging and epoch timing precision of the order of 1×10^{-11} seconds may be achieved. The range is related to time interval via the speed of light, one millimeter range corresponds to 6.7 picoseconds of two way propagation time. The accuracy of the range measurements is limited mainly by the atmospheric propagation delay model. Its accuracy is high, the absolute error expected to be well below

4×10^{-11} seconds. This accuracy is at least one order of magnitude better in the optical region than in the radio frequency wavelength region [9]. This is the main reason time transfer by laser light technique has been selected for the accurate comparison of time scales [4].

The average optical signal intensity on the LTT satellite is 1 photo-electron per event. The photon counting approach to the optical detection greatly simplifies the optical detector design – the analogue components of the detection chain are completely avoided. The incoming optical signal is selected in wavelength using blocking grass only. The effective optical band pass filter width is 10 nm. This setup results in both detector simplicity and its long term stability. Omitting the collecting optics simplifies the device design and its optical alignment, reduces the device mass and radiation damage problems associated with the optical components in space. The background photon flux conditions vary by several orders of magnitude. The relatively broad field of view of 28 degrees and the optical band pass filter required represent a challenge for signal to noise ratio of the entire experiment. In the very rare situations, when the satellite is moving in the Earth's shadow and when in the detector field of view is the non illuminated Earth's surface only, the background photon flux is well below $1*10^5$ photons per second. For the situation, when the detector is pointing toward illuminated Earth's surface, the background photon flux may reach $3*10^8$ photons per second. In the case when the Sun is within the detector field of view, what is quite common situation, the background photon flux exceeds $5*10^{10}$ photons per second. That is why the photon counting detector is required to operate under extremely high background photon flux conditions.

Detector concept

For the joint project with the Shanghai Observatory, Academy of Sciences of China, we developed the detector package dedicated to the project of synchronizing the hydrogen masers based time scales by laser pulses [12]. The detector key parameters were defined by the Laser Time Transfer project requirements as follows: active quenching, active area 25 μm in diameter, resolution 200 picoseconds FWHM, quantum efficiency 10 % at 532 nm, temperature range –20 … +65 ^{o}C. In comparison to other application of SPADs, the requirements on the detector dark count rate, detection efficiency and timing resolution are modest. Rather high dark count rates of the order of ~ 10^4 counts per second may be tolerated in the real operation, the background photon flux will be anyway substantially higher than the detector dark count rate. A detection efficiency of 10 % is acceptable thanks to the energy balance of the entire experiment and the signal to background noise ratio. The modest timing resolution requirement is a consequence of the existing ground segment parameters. However, the detection delay stability is a key parameter of the detector; the stability must be within +/– 25 picoseconds over the entire operating temperature range. The Single Photon Avalanche Detection (SPAD) chip manufactured using the K14 technology on silicon has been selected [11]. Our experience of previous space applications influenced this selection. The Active Quenching and Gating Circuit (AQGC) based on ECL logic is used. It allows the operation of the detection diode within the range of 0.2 to 1.1 Volts above its break down voltage. For operation in space a bias of 0.7 Volts above the breakdown voltage was used. This voltage above the break down voltage provides the desired timing resolution of 200 picoseconds Full Width Half Maximum (FWHM) and a detection efficiency of 10 % at 532 nanometres. The detector dead time was set in the quenching circuit to 160 nanoseconds.

The detector is successfully operating on-board the Compass M1 – Beidou satellite since its launch April 14, 2007 [13]. However, high background photon flux is strictly limiting data yield, timing resolution and timing biases, as well. That's why, the new concept of the detector and its AQGC was developed. The detector is capable of both gated and not gated operation, switching between both modes does not cause any detection delay change. The block scheme is in Figure 1.

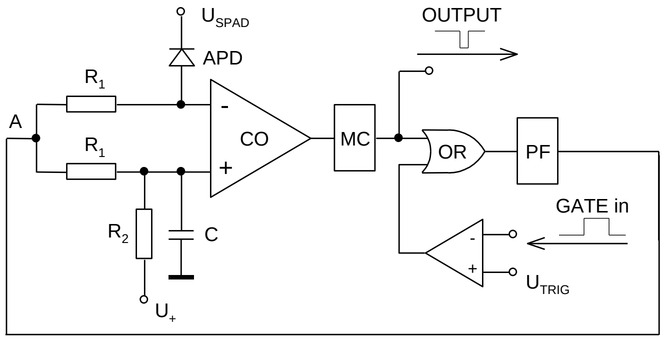

Figure 1. The active quenching and gating circuit block scheme.

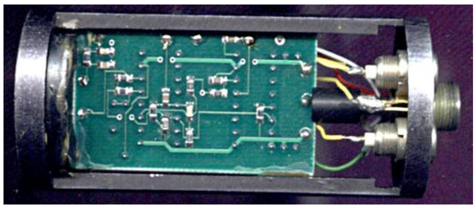

Figure 2. Laboratory sample of the detector package, board is installed in the coaxial holder. The SPAD detection chip is on the left, the SPAD chip is located in the left cylindrical holder.

All the logical components are formed using available space qualified fast ECL comparators. The laboratory sample of the detector with the AQGC is in Figure 2.

Detector basic characteristics tests

The detector has been tested in a conventional scheme of Time Correlated Photon Counting (TCPC). The picosecond laser diode Hamamatsu C4725 providing 42 ps wide pulses at 778 nm has been used as a signal source. The timing chain consisted of an ORTEC Time to Amplitude Converter 566, feeding data to a multi-channel analyser card in a personal computer. The timing resolution of the entire chain is 50 picoseconds Full Width at Half Maximum (FWHM). The timing resolution of the detector is typically < 100 ps FWHM for both operation modes.

The dark count rate of the detector in the not gated mode as a function of SPAD detector temperature is in Figure 3.

The operation of the detector under the conditions of extremely hight background photon flux was tested in the TCSPC set-up, see Figure 4. Note the bulb brightness and the fact, that the detection chip is located in the white cylinder in the right without any spatial or frequency filtering and optical attenuation. The laser diode signal was attenuated using a neutral density filters stack (silver rings, left from the bulb) down to the average signal level of single photons on the detection chip aperture.

The set of TCSPC experiments was carried out for various background photon flux level. The resulting main parameters- the data yield, timing resolution and detection delay stability are plotted in Figures 5 and 6 for gated and not gated operation respectively. The measurements in a gated operation mode were arranged in such a way, that the detector was gated ON 30-35 nanoseconds prior to arrival of photon of interest. The data yield was normalized to unity corresponding to the situation of low background photon flux. This situation simulates the best possible gating strategy for the foreseen application – synchronization of the clock in space using laser pulses. The experiment was carried out at rather low repetition rate of 1kHz to simulate low repetition rates of the proposed experiment. The timing resolution in the form of r.m.s. (root mean square) jitter of the detection delay for the gated operation and in the form of Full Width Half Maximum (FWHM) for the not gated one. For normal data distribution, the FWHM value is 2.3 times the r.m.s. value. The detection delay is referred to different origin in the gated and not gated measurement series.

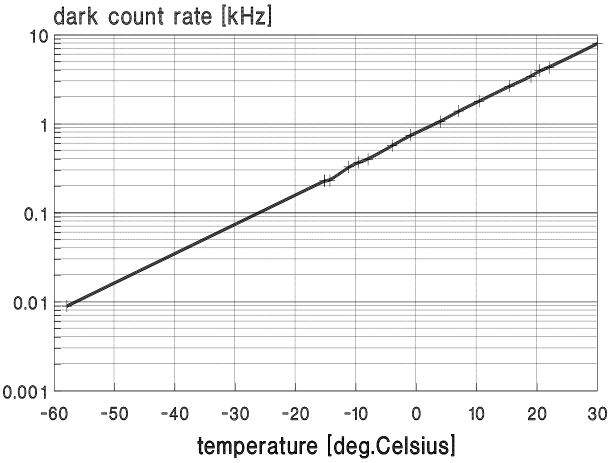

Figure 3. The detector dark count rate as a function of chip temperature, SPAD 25 um in diameter biased 0.7 V above, the slope corresponds to a drop of dark count rate of one decade per 30 K.

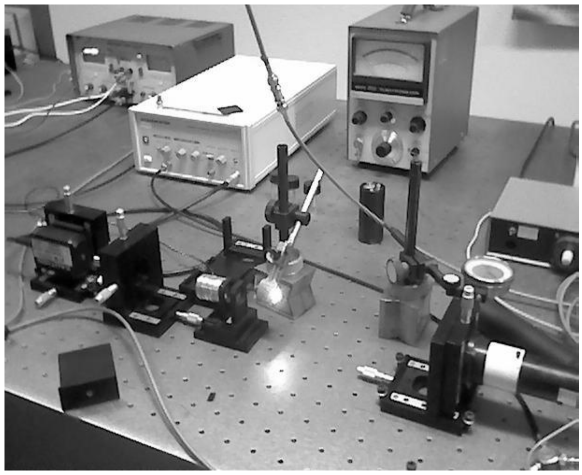

Figure 4. The TCSPC experimental setup. Left to right: laser diode, collimating optics, neutral density filters stack, tungsten bulb, SPAD detector holder on X-Y-Z stage. The tungsten bulb (bright in the middle) is used to generate

Several serious conclusions may be made on the basis of experiments mentioned above:

- the detector is operational in both gated and not gated modes in the presence of a background photon flux exceeding 2 * 10^9 photons per second hitting the active area

- the data yield is dropping down with background photon flux intensity due to photon counting statistics (as expected) and due to after-pulsing effects in the case of not gated operation mode.

- in the gated operation mode, the detection delay and timing resolution are stable independent on background photon flux within measurement errors.

- from all the studied parameters point of view, the use of gated operation mode is favourable in comparison to the non gated one

To demonstrate the detector capability in the gated mode, the analogical TCSPC experiment was carried out with even stronger background illumination reaching 5 * 10^9 photons per second. Gating the detector 5-6 nanoseconds before the photon of interest arrival the relative data yield of 0.02 was obtained, while the timing resolution and detection delay remained unchanged even for this extremely high background photon flux.

Conclusion

The optimized detector is able to detect single photon events in both gated and not gated operation modes. The timing resolution is 200 psec FWHM, dark count rate is below 10 kHz and the timing stability is of the order of 10 psec. The detector is capable of operation under the conditions of extreme background photon flux conditions reaching 2 * 10^9 photons per second hitting the detector active area in both operating regimes. For background photon flux exceeding 10 millions photons per second, the gated operation mode is preferable. The gated operation mode enables us to operate the detector at the background photon flux exceeding 5 * 10^9 without scarifying the detector timing performance. The detector design and construction is a promising candidate for the next phase of the space project of Laser Time Transfer recently under preparation in China.

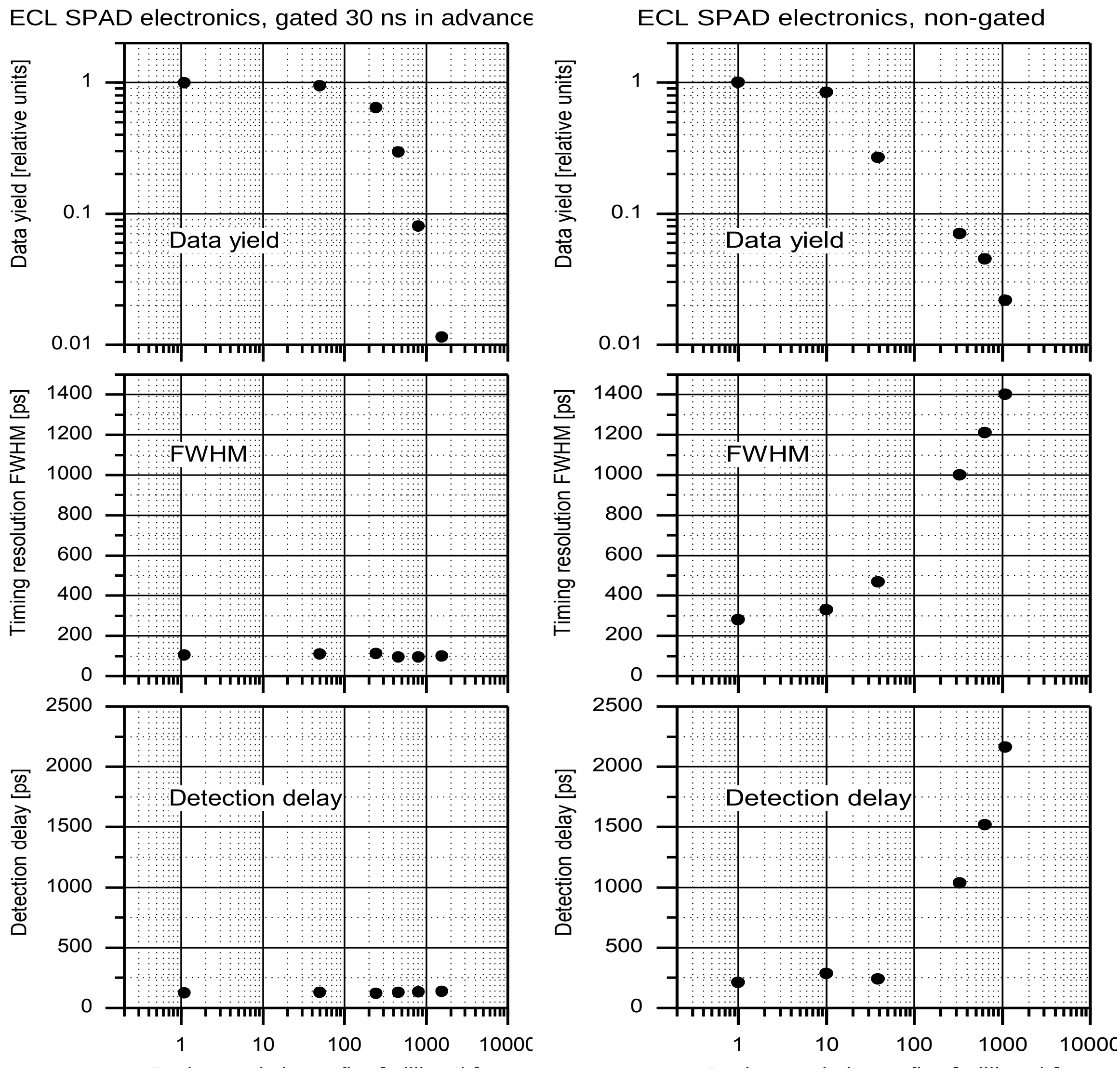

Figure 5 (left). The results summary of TCSPC experiments, SPAD gated 30 ns before arrival of photon of interest, data yield (up), timing resolution r.m.s. and detection delay (bottom) versus background photon flux intensity in millions per second hitting the detector active area.

Figure 6 (right). The results summary of TCSPC experiments, SPAD not gated, data yield (up), timing resolution FWHM and detection delay (bottom) versus background photon flux intensity in millions per second hitting the detector active area.

Acknowledgement

This work has been carried out at the Czech Technical University in Prague. Numerous grants were provided by the Czech Grant Agency, Czech Technical University in Prague, the Czech Ministry of Education, and by international agencies. Recently, the research and development of solid state photon counting detectors and their applications is supported MSM6840770015. The contribution of Lukas Kral is acknowledged.

References

[1] S. Cova, IEEE J. Quantum Electron. **19**, pp. 1211–1218 (1983).
[2] I. Prochazka, K. Hamal, B. Sopko, J. Mod. Opt. **51** 9–10, pp. 1289–1313 (2004).
[3] I. Prochazka, K. Hamal, S. Pershin, Proc. SPIE **4546**, pp. 64–65 (2002).
[4] M. Ravet, *et al.*, online at: http://www.roa.es/14workshop-laser/#Presentations (accessed 10th Nov 2005).
[5] E. Samain, Available online ahttp://cddisa.gsfc.nasa.gov/lw13/docs/papers/detect_samain_1m.pdf Y. Fumin, private communication, Shanghai, China (2005).
[6] T. Y. Huang (editor), *Proceedings of the First International ASTROD Symposium on Laser Astrodynamics*, published in Int. J. Mod. Phys. D **11** 7, pp. 1035-1048 (2002).
[7] J.J. Degnan, paper presented at the 12th International Workshop on Laser ranging, Matera, Italy, November 2000; available online at: http://geodaf.mt.asi.it/html/news/iwlr/ J.J. Degnan, in Contribution of Space Geodesy to Geodynamics – Geodynamics Series **25** (American Geophysical Union, Washington, 1993), edited by D.E. Smith and L.Turcotte, pp. 133–162.
[8] X. Sun, *et al.*, J. Mod. Opt. **51** 9–10, pp. 1333–1350 (2004).
[9] I. Prochazka, *et al.*, Inst. of Physics, Series No. 126, Bristol and Philadelphia, pp. 147–149 (1991).
[10] [?? A Prochazka, I., Hamal, K., Kral, L **Journal of Modern Optics,** Vol. 54, No.2-3, p.151-162, 2007
[11] Yang Fumin, et al, http://www.oca.eu/gemini/ecoles_colloq/colloques/ilrs2007/PresentationsPdf/8_Session.pdf/8.2_Fumin_LTTExperiment.pdf [accessed May 20,2008]