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ABSTRACT

Satellite Laser Ranging (SLR) is a well established space geodetic technique measuring the satellite distance, which implements time of flight. Up to now, second harmonic Nd:YAG laser pulses have been frequently used for range measurement, since the silicon detector technology allows us to detect single photon echoes reflected from satellites with required high detection probability, millimeter precision, and an acceptable dark count rate. On the other hand, the fundamental wavelength (1064 nm) provides a significantly better overall energy budget, but there were no suitable detectors available. More recently, the use of InGaAs/InP became feasible for developing single photon avalanche diodes, which exhibit high photon detection probability and acceptable timing resolution. Both these properties are important and allow the SLR measurement at the fundamental wavelength. In this Note, we report on construction and testing of a single photon detector package based on the InGaAs/InP diode optimized for the SLR measurement.

A photon counting approach to space objects laser ranging and similar experiments[1] provides numerous advantages in comparison to a multiphoton approach. The key ones are a low echo signal strength requirement, high stability, and high precision and stability of the order of a few millimeters. Up to now, most of the satellite and lunar laser ranging systems have been operated in a visible wavelength range. One of the reasons for this is a limited availability of photon counting detectors, which provide acceptable photon detection probability and detection timing resolution and operate at near infrared wavelengths. The first satellite laser ranging (SLR) experiments at the near infrared wavelengths of 1064 nm and 1540 nm were completed in the late 1980s and early 1990s. The experimental photon counting detectors based on cryogenically cooled[2] germanium have been used for these experiments. The photon counting probability of these detectors at near infrared wavelengths was limited to units of percent only. The first samples of InGaAs/InP avalanche photodiodes suitable for photon counting applications became available about 20 years ago.[3] They were designed and optimized for quantum key distribution on optical fibers. The new semiconductor material provided a photon counting probability exceeding 20% in the wavelength range of 1064–1540 nm. However, the photon counting timing characteristics—timing resolution and stability—of these detection structures were not suitable for laser ranging applications.

The new InGaAs/InP Single Photon Avalanche Diodes (SPADs) provided by Princeton Lightwave represent a new generation of photon counting structures capable of also meeting good timing performance, suitable for laser ranging to space objects.[4,5] The SPAD structure itself cannot be operated separately. It must be a part of an electronic circuit, which controls its operation. We have developed and tested a compact photon counting detector package based on these detection structures having an active area diameter of 80 μm. It has been optimized for application in laser ranging to space objects with a few millimeters precision and stability at the wavelength of 1064 nm.

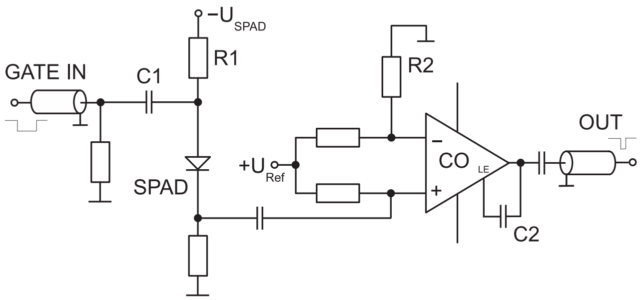

FIG. 1. Simplified block scheme of the detector control circuit.

The SPAD detection chip is operated in a passive quenching and active gating mode. The simplified block scheme of the detector control circuit is depicted in Fig. 1. The passive quenching circuit is formed by resistor *R*1 and capacitor *C*1. The ultrafast comparator *CO* is sensing the detection chip avalanche buildup. The comparator operation is controlled via the Latch Enable *LE* input, which is coupled by capacity *C*2 to the comparator negative output. This setup enables us to generate uniform shape and fixed length output pulses. Their length may be adjusted in a range of units to hundreds of nanoseconds by an appropriate value of the *C*2 capacitor. The non-marked capacitors provide AC coupling, and the non-marked resistors terminate with a value of 50 Ω signal path.

The SPAD bias (U_{SPAD}) is adjusted several volts below its breakdown voltage. The active gating applies a uniform negative constant amplitude pulse to the low bias end of capacitor C1. The SPAD avalanche buildup current generates a negative pulse on its grounding resistor. This pulse is AC coupled to the comparator input. Resistor *R*2 sets the comparator trigger level. Its typical value is −20 mV. The entire circuit was designed and built on a multiple layer printed board with dimensions of 30 × 50 mm^2. It enables us to operate various SPAD detection chips having a breakdown voltage of up to 200 V. The detection chip may be actively gated (biased) more than 20 V above its breakdown voltage. The breakdown voltage of the available InGaAs/InP detection chip is 94 V at room temperature and 87 V when thermoelectrically cooled to −30 °C. The SPAD detection chip itself is mounted in a vacuum housing with a three stage thermoelectric cooler and a built-in temperature sensor. It allows us to operate the SPAD chip within a stabilized temperature of −30 ± 0.2 °C. The detection chip together with its control electronics board is mounted in a mechanical housing with dimensions of 50 × 50 × 130 mm^3. The aspheric focusing lens f/D = 0.9 collects the collimated input beam of diameter 12 mm on a detector active area. The detection chip housing window acts as a narrow bandwidth optical filter. It transmits photons in the range of 950–1100 nm only.

The detector package photon counting parameters were tested in a standard Time Correlated Single Photon Counting (TCSPC) experiment. The optical test pulses were generated by a Nd:YAG laser 8 ps long at a wavelength of 1064 nm at a repetition rate of 400 Hz.[5] The detector key parameters were measured for various biases above its breakdown voltage. The SPAD chip supplier declares as absolute maximum rating in gated operation 10 V above the breakdown voltage of the detection chip. For higher biases, there exists a high risk of detection chip irreversible damage. That is why most of the tests were completed for biases in the range of 2–10 V above breakdown. Just one single test series of detection timing resolutions was completed at a bias of 20 V above breakdown for comparison purposes.

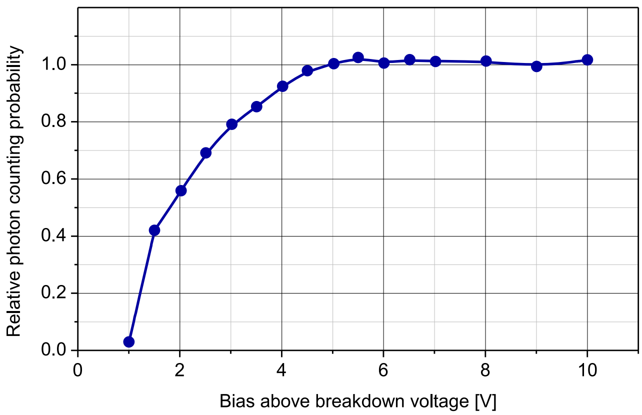

FIG. 2. Photon counting probability in relative units as a function of bias above the breakdown voltage.

The detector photon counting probability as a function of bias above the breakdown voltage is plotted in relative units in Fig. 2. Note the saturation of photon counting probability for biases higher than 5 V above the breakdown voltage. The absolute value of photon counting probability of 20% at 1064 nm is claimed by the chip supplier biasing the chip 3 V above its breakdown. A similar value was also confirmed by the chip users.[4,5]

The photon counting time resolution is illustrated in Fig. 3, where the histograms of TCSPC data are plotted for three different biases 6 V, 10.5 V, and 20 V above the breakdown voltage. The non-standard data distribution and its dependence on the bias above breakdown may be seen. The distribution "tail" is quite common for solid state photon counting devices. Its relative amplitude is in the range of 2% up to 15% with respect to the main detection peak. From Fig. 3, one can conclude that the non-standard distribution is mostly pronounced at bias close to 10 V above the breakdown voltage.

The photon counting time resolution as a function of bias above breakdown is plotted in Fig. 4. The detection time resolution (jitter)

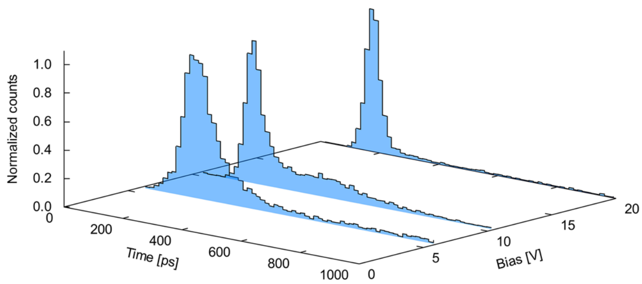

FIG. 3. Histograms of time correlated single photon counting experiment results; note the tail of data distribution. The bin width is 15 ps.

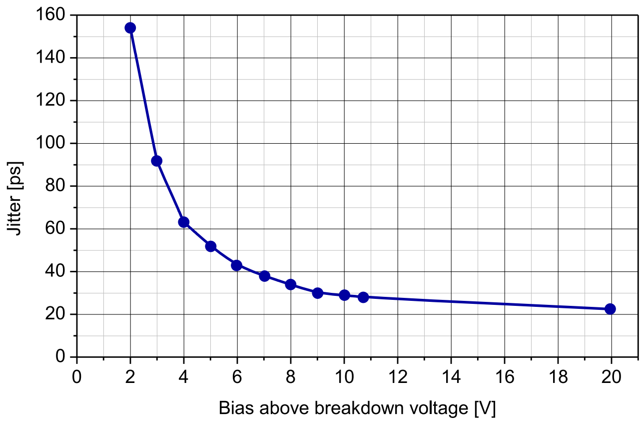

FIG. 4. Detection timing resolution as a function of bias above the breakdown voltage.

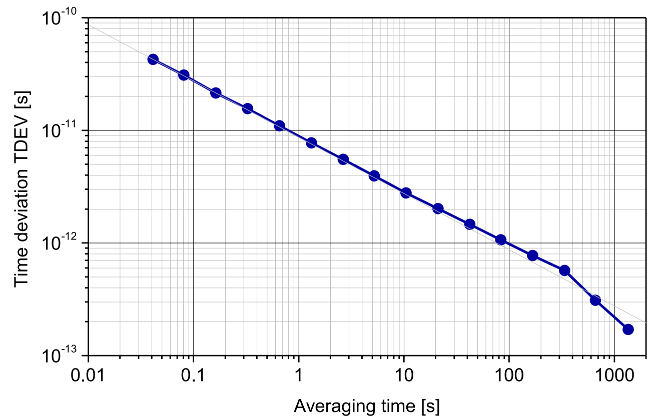

FIG. 5. Photon counting performance tested in a time correlated single photon counting experiment.

is related to the Full Width at Half Maximum (FWHM) of a data distribution by the formula: jitter = FWHM/2.35. Due to the limitations listed above, the detection chip was operated at a bias 10 V above its breakdown voltage in all the other experiments. From Fig. 4, one can conclude that for a bias of 10 V above the breakdown voltage, the timing resolution of the entire TCSPC chain is typically 30 ps root mean square (rms). It corresponds to a single shot range resolution better than 5 mm.

The photon counting detection delay stability is another key parameter in laser ranging applications. For the presented photon counting detector, there exist two main contributors to stability: temperature variations and passive quenching circuit. The most significant contributor to the detection delay variations is the passive quenching and active gating circuit. It provides SPAD biasing above its breakdown. It is formed by *R*1 and *C*1, see Fig. 1. However, due to the non-zero reverse current of the SPAD detection chip, capacitor *C*1 is partially discharged, and its voltage decreases once the gate is applied.

This effect causes the changes of detection chip applied bias within the gate. As the detection delay is dependent on a chip bias, this effect causes the change of detection delay within the gate. For a bias of 10 V above the breakdown, this change was measured to be approximately 30 ps for gate delays 0.1 μs and 1.1 μs. It means that the detection delay will be 30 ps lower in the case when the detector will be gated ON just 0.1 μs before arrival of the photon of interest in comparison to the situation when the detector will be gated 1.1 μs before. One can characterize the detector delay stability as ±15 ps or ±2.3 mm due to this effect. In typical laser ranging of space object applications, the detector is gated ON 0.1–1 μs before arrival of the photon of interest. Hence, the requirement on a few millimeters ranging stability is satisfied. For gates longer than 1.1 μs, the detector key parameters, detection delay, timing resolution, and detection probability degrade considerably. For such type of operation, an active quenching circuit is under development.

The photon counting detection delay temperature dependence is determined by the control electronic circuit only. The SPAD detection chip itself is thermoelectrically cooled, and its temperature is stabilized within a fraction of Celsius. The detector signal is actively processed by a comparator only. Its signal propagation delay temperature dependence was measured in a number of experiments.[6] Its value is well within ±0.3 ps/K in the operational temperature range of −35 °C to 50 °C. As a consequence, the temperature dependence of the detection delay in absolute value is lower than 0.3 ps/K.

The timing performance of the developed detector package was tested in a long term TCSPC experiment, and the results are plotted in a form of Time Deviation (TDEV),[7] see Fig. 5. The experiment repetition rate was 400 Hz. The effective signal strength was 7%. The detector was gated 100 ns before the photon of interest was detected. The operating temperature was stable within ±2 K. The overall system precision expressed in a form of TDEV is better than 0.3 ps for averaging times of 700 s.

We have designed, constructed, and tested a compact field operable photon counting detector package based on the solid state InGaAs/InP avalanche photodiode sensor, which is optimized for laser ranging of space objects at the operation wavelength close to 1 μm. Its single shot detection precision and delay stability are on the millimeter level.

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