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Photon counting detector for space debris laser tracking and lunar laser ranging

Ivan Prochazka [a,*], Jan Kodet [a,b], Josef Blazej [a], Georg Kirchner [c], Franz Koidl [c]

[a] *Czech Technical University in Prague, Brehova 7, 115 19 Prague, Czech Republic*
[b] *Technische Universität München, Fundamental station Wettzell, Sackenrieder Str. 25, 93444 Bad Kötzting, Germany*
[c] *Space Research Institute of the Austrian Academy of Sciences, Lustbuehelstrasse 46, A-8042 Graz, Austria*

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Abstract

We are reporting on a design, construction and performance of solid state photon counting detector package which has been designed for laser tracking of space debris. The detector has been optimized for top photon detection efficiency and detection delay stability. The active area of the commercially available avalanche photodiode manufactured on Si (SAP500 supplied by Laser Components, Inc.) is circular with a diameter of 500 μm. The newly designed control circuit enables to operate the detection sensor at a broad range of biases 5–50 V above its breakdown voltage of 125 V. This permits to select a right trade-off between photon detection efficiency, timing resolution and dark count rate. The photon detection efficiency exceeds 70% at the wavelength of 532 nm. This is the highest photon detection efficiency ever reported for such a device. The timing properties of the detector have been investigated in detail. The timing resolution is better than 80 ps r.m.s, the detection delay is stable within units of picoseconds over several hours of operation. The detection delay stability in a sense of time deviation of 800 fs has been achieved. The temperature change of the detection delay is 0.5 ps/K. The detector has been tested as an echo signal detector in laser tracking of space debris at the satellite laser station in Graz, Austria. Its application in lunar laser ranging is under consideration by several laser stations.

Keywords: Photon counting detector; Laser ranging; Space debris; Lunar laser ranging

1. Introduction

Solid state single photon detectors are getting more and more attention in various areas of space science: optical sensors, communication, quantum cryptography, optical ranging and laser time transfer and many others (Eisaman et al., 2011). The application of solid state detectors in photon counting devices has been pioneered by Cova et al. (1983). This detector is an avalanche photodiode structure prepared using a planar technology on silicon. Single photon sensitivity is achieved by biasing the diode above the junction breakdown voltage. The key parameters of interest are: photon detection efficiency, dark count rate, timing resolution, detection dead time, detection active area, and after – pulsing probability. Various applications put various requirements on the photon counter.

Our main application of interest is laser ranging of space objects. Our group has designed and constructed several solid state photon counters for application in space related projects in the last years (Prochazka et al., 2011). We have been developing and providing photon counting detectors for ground based satellite laser ranging and laser time transfer systems. In these earlier applications the high timing resolution and sub-picosecond detection delay stability were the key requirements (Prochazka et al., 2013). The

* Corresponding author.
E-mail address: prochazk@cesnet.cz (I. Prochazka).

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newly emerging techniques of laser ranging of space debris and Lunar laser ranging require also high photon detection efficiency (Kirchner et al., 2012; Meng et al., 2013). That is why we have developed and tested a new photon counting detector providing a high photon detection efficiency while maintaining high timing resolution and detection delay stability. Considering the existing activities in space debris laser tracking the wavelength of interest is the second harmonic of the Nd:YAG laser namely 532 nm. Photon detection efficiency is defined as a probability that a photon of interest will be detected by a detector.

2. Photon counting detector design and construction

In order to achieve the highest photon detection efficiency the commercially available large area single-photon avalanche diode SAP500 (Laser Components. Inc.) has been used. The structure of the SAP500 detection chip is a typical reach-through back illuminated Single Photon Avalanche Diode (SPAD) (Stipcevic et al., 2010). Its active area diameter is relatively large 0.5 mm, its breakdown voltage is typically 125 V. The capacitance of the SPAD detection chip depends on a reverse bias applied. For biases near the breakdown voltage this capacitance is typically 10 pF. This detection chip has been extensively tested by M. Stipcevic and co-workers mainly for applications in quantum communication and quantum key distribution experiments (Stipcevic et al., 2013). They did measure, among other, the photon detection efficiency of 73% at the wavelength of 540 nm. It has been measured in a setup where the detection chip has been biased 15 V above its breakdown voltage. The timing resolution and the detection delay stability were not critical in these experiments.

In our detector design we have used this detection chip providing top detection efficiency and we have developed a new electronic circuit of the detector. The requirements on a photon counting detector package for laser ranging are quite different from that ones for optical communication. In laser ranging experiments the detector has to be activated for relatively short time windows of fractions to tens of microseconds at a repetition rate of 10 Hz to 1 kHz only. The detection is activated – gated – shortly before an arrival of photon of interest. It is de-activated as soon as a signal or noise photon has been detected or the“ time window” of interest has expired. That is why a new active gating and quenching circuit has been designed and tested. The concept of a control circuit determines to a large extent the property of the entire detector package. This circuit is sensing the avalanche it is quenching it and provides active gating. In addition it is generating a uniform output pulse synchronously to the avalanche build up. The active quenching and gating circuit block scheme is in Fig. 1.

The SPAD detection chip avalanche current buildup is sensed by the comparator *CO*, its output is driving the detector output. The detection chip is biased by the voltage U_{SPAD} several volts below its breakdown voltage. It is activated – gated – by applying the additional voltage step U_{GATE} via a capacitor *C1*, the gating is controlled by an external pulse *GATE*. Once the avalanche is triggered by an incoming photon or by a dark event the avalanche current is quenched by a serial resistor *R1*. Then the detector remains de-activated until the next gate signal is applied. The comparator *CO* trigger threshold is fine tuned by a resistor *R2*, the SPAD capacitance is compensated by a capacitor *C2*. The comparator inputs are biased at the voltage of U_{Ref} within the input differential voltage range. The feedback formed by a capacitor *C3* between the comparator output and its Latch Enable (*LE*) input is used to determine the output pulse length. The output pulse is a uniform shape AC coupled negative pulse compatible with the NIM signals used for timing electronics. The passive avalanche quenching is simple and represents no limitation in a foreseen application. As an advantage this gating circuit enables to operate the detection chip in a broad range of biases of 2 V up to 50 V above its breakdown voltage. The voltage above the breakdown determines the detector dark count rate, timing resolution and detection efficiency.

The circuit is constructed on a multiple layer printed circuit board 32 × 50 mm. The circuit total power consumption is below 0.2 W. The temperature sensor is installed close to the comparator to enable the device temperature

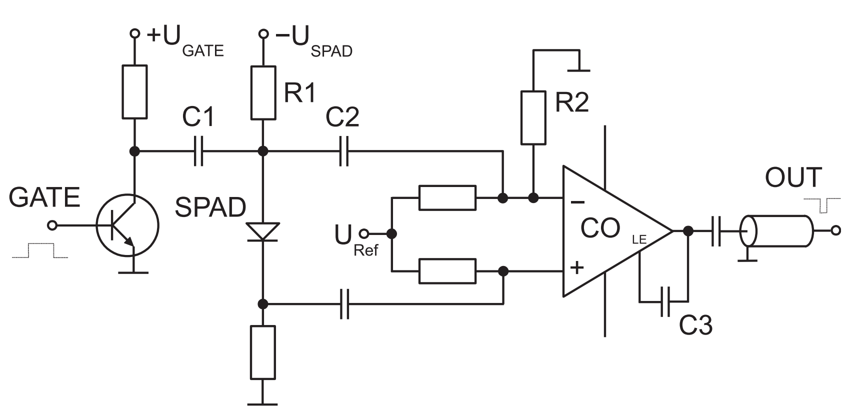

Fig. 1. Block scheme of the active gating and quenching circuit of the photon counting detector.