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Optical to electrical detection delay in avalanche photodiode based detector and its interpretation

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Josef Blažej[1]
Czech Technical University in Prague
Břehová 7, 115 19 Prague 1, Czech Republic
E-mail: blazej@fjfi.cvut.cz

Ivan Procházka
Czech Technical University in Prague
Břehová 7, 115 19 Prague 1, Czech Republic

Jan Kodet
Czech Technical University in Prague
Břehová 7, 115 19 Prague 1, Czech Republic
Technical University in Munich
FSG, 80290 Munich, Germany

A measurement process to determinate the optical to electrical delay of the photon counting detector is presented. The absolute value of the time interval between the time of arrival of the signal photon onto the detector input aperture and the time when the electrical output signal is exceeding the predefined level have to be determined. Also results showing a temporal relation between the optical input and the electrical output of a photodiode are presented to describe an effect used device bandwidth. The presented results are a byproduct of the more complex experiment which aims to identify the absolute delay contributors in picosecond time-resolved single photon detection technique.

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[1] Speaker

1. Introduction

The laser time transfer link is under construction for the European Space Agency for its application in the experiment Atomic Clock Ensemble in Space (ACES). The device is expected to be launched towards the International Space Station in 2015. The objective of this laser time transfer is the synchronization of the ground based clocks and the clock on board the space station with precision of a few picoseconds and the accuracy of 50 picoseconds [1, 2]. The project is a spin-off of the existing projects of laser ranging to artificial Earth satellites (SLR) [3]. The on-board hardware consists of a comer cube retro-reflector (CCR), a co-located optical receiver based on a single-photon avalanche diode (SPAD) and an event timing device connected to the local time scale. The ultra short laser pulses fired towards the satellite by a ground laser ranging station will be time tagged with respect to the ground time scale. They will be detected in space and time-tagged in the local time scale. At the same time, the CCR will re-direct the laser pulse towards the ground station providing precise ranging information and hence providing the information about the ground-to-space signal propagation delay. This procedure will provide, among others, the time transfer ground to space with precision and accuracy outperforming the microwave techniques.

The photon counting detection modules designed in our labs have been used for laser time transfer ground-to-space in previous years [4]. However, for the prepared ACES mission the requirements put on the detector performance [2] are significantly higher from the point of view of time resolution and detection delay stability. And in addition, the analysis of individual delay contributors has been required [5]. One of them is the contribution of SPAD.

2. Experimental setup

2.1 Complete ELT delay measurement

The optical to electrical delay of the entire ELT photon counting device consists of roughly contributors as described in figure 1.

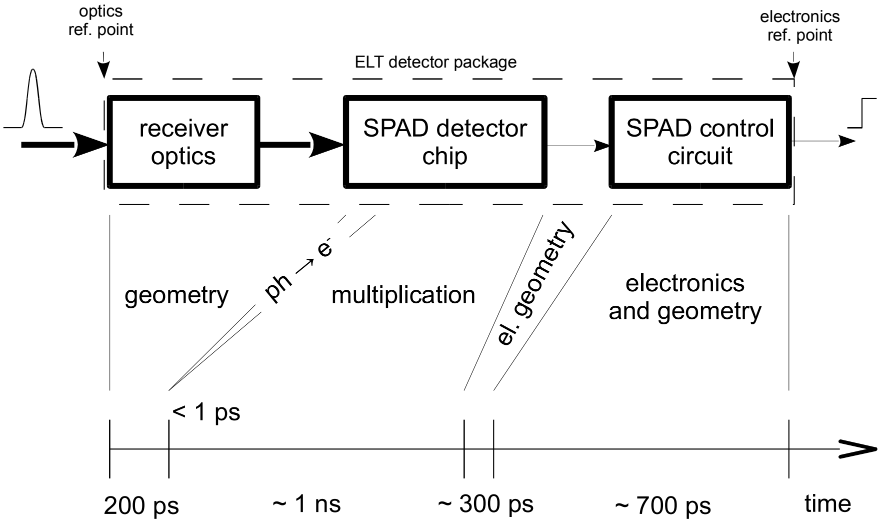

Figure 1: A rough estimation of delays.

The following optical scheme was used to measure the photon counting delay: as the photon counting is a quantum mechanics process, the event of arrival of the photon of interest on the detector input may be determined only indirectly, see figure 2. The ultrashort laser pulse was collimated and split by an optical beam splitter. One part of the optical signal consisting of many photons was directed to a fast photodiode PD. The second part of the optical signal was attenuated down to the signal level of single photon and was directed to the photon counting detector under test. The optical attenuation was adjusted to the level when only about 5 % of laser pulses caused photon counting detector response. This setting assured the single photon signals on the photon counting detector input. The optical lengths of the two beam paths were adjusted to be equal within a fraction of a millimeter. This way the time of arrival of the photon onto the photon counting detector is determined by means of the fast photodiode. The fast photodiode is operated in a linear detection mode with a gain equal to unity.

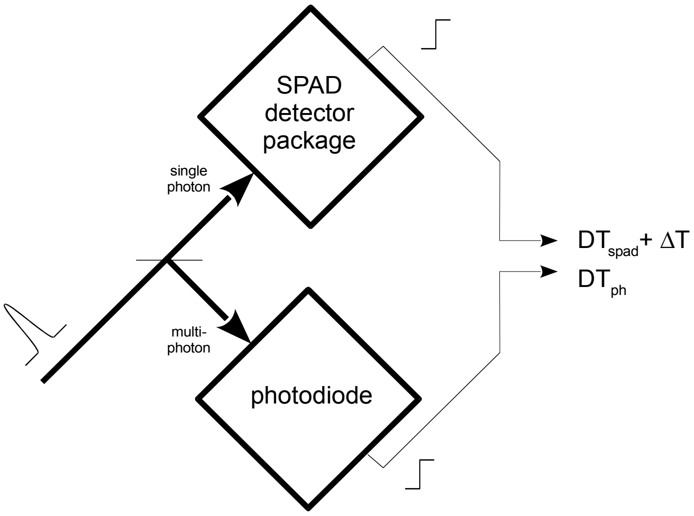

Figure 2: Scheme of the experiment.

The resulting optical to electrical detection delay of the photon counting detector can be computed as follows:

$$T_{spad} = (DT_{spad} - DT_{pd}) + T_{pd} - T_{las} + T_{cor} \tag{1}$$

where

T_{spad}	is optical to electrical delay of the photon counting detector
DT_{spad}	is the relative delay of the photon counting detector
DT_{pd}	is the relative delay of the fast photodiode
T_{pd}	is the optical to electrical delay of the fast photodiode
T_{las}	is the time correction related to the laser pulse width
T_{cor}	is the time correction related to the detection chain bandwidth/risetime

The values of DT_{spad} and DT_{pd} are measured directly in the experimental setup described below.

The optical to electrical delay of the fast photodiode T_{pd} is significantly smaller and may be determined with higher accuracy in comparison to that one of the photon counting detector. The optical propagation delay of the fast response semiconducting photodiode T_{pd} is composed of the following contributors: optical propagation delay, photon to carrier conversion, signal propagation within a semiconductor and an electrical propagation delay within a package.

The time correction related to the laser pulse width Tlas is expressing the fact that the fast photodiode and its output signal is sensed on its risetime, in fact at half maximum of a pulse leading edge. However, the response of the photon counting receiver in evaluated as an average and is related to the center of the pulse. Considering the laser pulse shape close to the Gaussian one, this correction has a value equal to [6]

$$T_{las} = 0.5\ \mathrm{FWHM} \qquad (2)$$

Where FWHM is a laser pulse full width at a half maximum. The time correction parameter T_{cor} expresses the fact of limited bandwidth of the recording channel consisting of the fast photodiode and the recording instrument itself. Its value has been determined experimentally as described below.

2.2 SPAD delay in particular

The electrical output signals of the fast photodiode and the photon counter were recorded on a Digitizing Oscilloscope Tektronix DPO7254. It provides up to 40 Gs/s and an analogue bandwidth of 2.5 GHz. The oscilloscope was triggered by the electrical trigger signal provided by the laser source. The digitizing oscilloscope was used for both signal processing and time interval measurements. For time interval measurements the custom designed data processing software package was developed. The overall system timing resolution of the measurements chain consisting of the laser source, fast photodiode and the oscilloscope with the data processing was 25 ps. The timing stability was better than 20 ps/hour, this value was limited mostly by the stability of the laser sources. Two different laser sources have been used, the Hamamatsu Picosecond Light Pulser C4725. It provided pulses 42 ps long at the wavelength of 778 nm and the second harmonic output of the diode pumped delivering 8 ps long pulses at the wavelength of 532 nm [7].

For detection delay measurement the series of signal readings of the fast photodiode DT_{pd} and the photon counting detector DT_{spad} were recorded consecutively. Equal signal cable and equal oscilloscope settings were used for these series. Just the oscilloscope vertical sensitivity was changed between 10 mV per division for photodiode and 100 mV per division for photon counter signal readings. An independent test was used to verify that changing the oscilloscope vertical sensitivity setting does not affect the recorded signal delay.

The oscilloscope custom software evaluates the delay of the recorded pulse versus pre-defined trigger level. Additionally it enables identifying the valid photon responses within the background optical noise pulses.

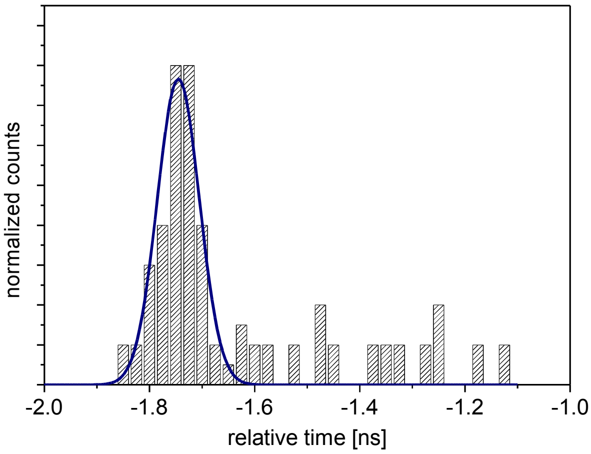

Figure 3: Example of DT_{spad} results.

3. Results

The optical to electrical delay T_{pd} of the fast photodiode PD package was estimated mostly on the basis of its mechanical design. Considering the photodiode package dimensions, internal electrical signal path length and the dielectric used, the signal propagation delay of 160 ps was determined with the picosecond accuracy. The optical to electrical delay of the detection process itself was estimated on the basis of the detection chip geometry and the charge carriers mobility. The resulting value of 40 ps corresponds well to the detection chip rise-time of 35 ps claimed by the manufacturer. The photons to carriers conversion time is of the order of one picosecond. The total optical to electrical delay T_{pd} of the fast photodiode package was calculated to be 211±5 ps.

For each measurement series the set of typically 100 readings of the fast photodiode signal DT_{pd}, were acquired, the typical precision was 24 ps rms. For the photon counting detector typically 2000 readings of DT_{spad} were collected. The example of measured detection delays DT_{spad} is plotted in figure 3. The data peak corresponds to the useful results, the mean value of 72 valid readings is −1.745 ns with the precision of 34 ps rms. The corresponding normal data distribution curve is added. Note the data distribution, which is the property of the photon counting detector.

In the measurements of DT_{pd} the trigger level for the fast photodiode signal was defined as one half of the pulse amplitude. For the DT_{spad} measurements the trigger level for the electrical output of the photon counting detector was defined at a fixed level of +250 mV. In both cases the leading edge of the pulse marked the time event.

Completing the series of pulses recordings the delays DT of the recorded pulses versus pre-defined trigger levels were determined, the mean values of T_{spad} and the standard deviations within each series were evaluated for both lasers.

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