Invited Paper

Satellite laser ranging in the near-infrared regime

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Abstract

Satellite Laser Ranging Systems typically operate on the second harmonic wavelength of a pulsed Nd:YAG laser at a wavelength of 532 nm. The absence of sufficiently sensitive photo-detectors with a reasonably large active area made it beneficial to trade the conversion loss of frequency doubling against the higher quantum efficiency of the detectors. Solid state silicon detectors in the near infra-red regime at $\lambda = 1.064$ μm also suffered from high thermal noise and slow signal rise times, which increased the scatter of the measurements by more than a factor of 3 over the operation at $\lambda =$ 532 nm. With the availability of InGaAs/InP compound - Single Photon Avalanche Diodes the situation has changed considerably. Their quantum efficiency has reached 70% and the compound material of these diodes provides a response bandwidth, which is commensurate with high high speed detectors in the regime of 532 nm. We have investigated the properties of such a diode type Princeton Lightwave PGA-200-1064 for its suitability for SLR at the Nd:YAG fundamental wavelength with respect to the quantum efficiency and their timing properties. The results are presented in this paper. Furthermore, we provide remarks to on the performance of the diode compared to state of the art detectors, that operate at the Nd:YAG second harmonic wavelength. Finally, we give an estimate of the photoelectron statistics in satellite laser ranging for different operational parameters of the Wettzell Laser Ranging System.

Keywords: SLR, photoelectron statistics, SPAD, InGaAs/InP

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1. INTRODUCTION

Early laser based distance measurements to objects in space were carried out in 1964 employing pulsed ruby lasers [1] at a wavelength of 694.3 nm . The quantum efficiency of the applied photo-multipliers were of the order of 10%. The situation changed with the advent of Nd:YAG lasers during the seventies, which are lasing at 1064 nm. These kind of lasers are favorable compared to ruby lasers because of their higher efficiency, shorter pulses and higher repetition rates. To overcome the lack of suitable receivers in the near infrared, second harmonic generation was used, which shifted the operating wavelength to $\lambda = 532$ nm. For this wavelength a number of photo-multipliers and solid state detectors were available with quantum efficiencies well in excess to overcome the power loss from the frequency conversion process.

Later, high speed solid state Single Photon Avalanche Diodes (SPADs) on a silicon base became available and also became the most popular detectors in satellite laser ranging community. These detectors are also most sensitive in the visible spectrum of light and reach a peak detection efficiency of 60%. Since then several attempts were made to go back to the laser primary wavelength [2,3]. This was done for two reasons. Firstly we wanted to operate the SLR system on two different optical frequencies simultaneously in order to derive an improved atmospheric refraction correction. Secondly we wanted to exploit the higher atmospheric transparency at the near-infrared regime. When the detectors are not the limiting factor, the link budget is improved, when ranging is performed at the lasers primary wavelength. Doubling the wavelength leads to twice the number of photons emitted in a single laser pulse with the same energy level. Another factor of two can be expected, because the second harmonic generation process has a conversion loss of typically 50%. The atmospheric transmission reduces mainly for two reasons, namely the process of Rayleigh- and Mie-

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Scattering. For Rayleigh-scattering, which is usually dominant in clear sky conditions, the backscattering cross section is proportional to the inverse fourth power of the wavelength. For Mie-Scattering the back-scattering cross section generally is much higher compared to the case of Rayleigh-scattering. This process causes significant loss for particles which are of the same size or larger than the incident wavelength. For both cases the primary laser wavelength is favorable. However, until recently the link budget in satellite laser ranging at a wavelength of 1064 nm could not compete with that for 532 nm. Since single photon avalanche diodes with a compound material structure and sufficient large optical acceptance area have become available the situation has changed. We have tested their suitability for satellite laser ranging in 2013 at the Wettzell Laser Ranging System [4]. While the previous paper focused on the theoretical model for a detailed investigation of the timing-properties of single photon avalanche diodes (SPADs), we report here on the general characterization of these devices in terms of their detection efficiency and their timing characteristics. In addition, the previously published results, especially the possibility to derive the statistics of the number of photo-electrons seeding the avalanche breakdown is applied to the use case of satellite laser ranging, thus providing the means of a reduction of systematic range biases.

2. SPAD Characterization

In Satellite Laser Ranging large optical telescopes are used to guide short laser pulses, with a width of only a few picoseconds, towards earth orbiting objects. There, the signal is reflected back towards the ground station where the signal is collected from the telescope and finally focused onto the small light sensitive area of single photon sensitive detector. During this process, the time of flight of the light pulse is measured. The outcome of a large number of repeated measurements is a probability distribution of the time-intervals determined. The centroid of this distribution can be related to the geometrical reference point of the system and provides the distance to the object. To minimize systematic effects causing variations of the shape of the distribution, time correlated single photon counting is applied. This means, that the signal level is kept at an echo rate of below 10%. In this idealized case, it is assumed that for each outgoing laser pulse a single photon triggers the detector, leading to a constant detection delay.

One critical point at the ground station is the fact, that the telescope aperture must be focused on the active area of the SPAD. In the case of the Wettzell Laser Ranging System, a 0.75 m aperture telescope in combination with a 80 µm active area InGaAs/InP-SPAD from Princeton Lightwave, type PGA-200-1064, has to be matched. For a wide field of view, the focal length of the final lens must be as short as possible. Nevertheless, the acceptance angle of a SPAD usually does not allow for large input angles. For our case an acceptance angle of 40 degree was measured. Together with an appropriate lens, this gives a theoretical field of view of 18 seconds of arc, which, with careful alignment, is adequate for satellite laser ranging.

Considering the high signal loss in satellite laser range measurements of up to 180 dB, the requirements for the detection efficiency of the detector are very demanding. The single photon quantum efficiency Q_E, which describes this property of a detector, can be defined as [5]:

$$Q_E = \frac{P_C - P_D}{1 - e^{-N_0}} \tag{1}$$

Here P_C is the overall count probability, including dark counts. P_D is the dark count probability and N_0 is number of incident photons on the active area of the device. From the equation, it can be seen, that the detection efficiency describes a trade-off between the dark count probability and the quantum efficiency of a detector. In Satellite Laser Ranging the signal typically is expected at a time-interval of about 100 ns after the gate-on time. Therefore, we measured the relative detection efficiency of the device under this condition and with the device mounted in a cryostat (Figure 1). It can be seen, that in general the efficiency is increased with lower chip temperatures. As the temperature increases, the number of trapped carriers in the conduction band of the diode goes up. Releasing these carriers causes dark counts and therefore decreases the detection efficiency. Increasing the bias voltage above the breakdown voltage of the device improves the detection efficiency up to the point, where tunneling effects, which increase the dark count probability enormously, occur. For the following experiments a bias voltage above the breakdown voltage of the diode, which is -78 Volt, of 18 Volt was chosen. For these measurements the diode was removed from the cryostat. Instead, we used a three stage Peltier cooler, which is mounted on the chip. This allows for a minimum operating temperature of 220 Kelvin. The application of the Peltier cooler simplifies the experimental setup and the conditions for the optical alignment tremendously. The diodes performance with respect to detection efficiency is still adequate. A good estimation of the detection efficiency of this diode for the ranging to the lunar reflectors in the NIR regime in comparison to a measurement with a state of the art silicon diode, a PESO Consulting K14 SPAD, at a wavelength of 532 nm can be found in [6]. For 1064 nm ranging they use the same kind of detector, that is used in this paper and gained an improvement of a factor of 2 to 10, depending on the reflector that was measured. This is in good agreement with our experience.

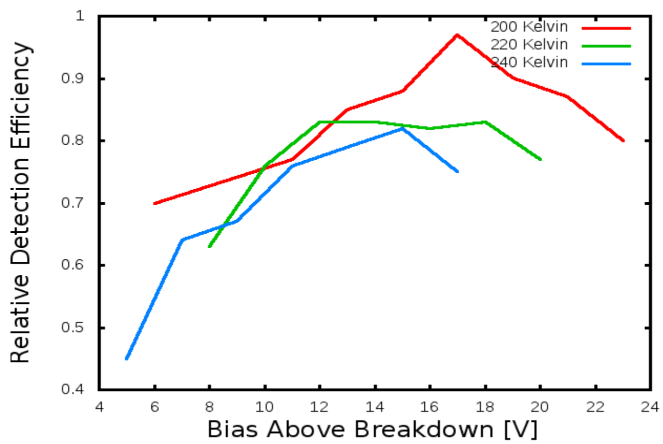

Figure 1. Relative Detection Efficiency of a Princeton Lightwave PGA-200-1064 single photon avalanche diode as a function of the chip temperature and the bias voltage above the breakdown voltage of the device.

To evaluate the timing-properties of the diode, its output pulse of about -600 mV was directly connected to an Event-Timer based on Thales Event Timing Modules. The trigger-level of the device was set to -250 mV. An evaluation of the probability distribution of a time-interval measurement of a fixed distance at a low echo rate of 16% revealed a single photo-electron root mean square value of about 25 picoseconds (Fig. 2, purple curve). This is close to that of state of the art silicon photo detector [7, 8], which provide a root mean square value of about 15 picoseconds on the second harmonic of the Nd:YAG laser. However, these detectors also make use of more sophisticated electronic readout circuits, which improve the timing-performance. Furthermore, the distribution is close to that of a Gaussian probability distribution, except for a small tail region towards longer time-intervals, which is typical for SPAD diodes in general. The green curve in Fig. 2 shows the probability distribution of a time-interval measurement at higher echo rates, namely 62%. In this case a second peak at shorter time-intervals arises. This peak is caused from multiple absorbed photons speeding up the avalanche breakdown breakdown process and causing a systematic error for the range measurement. The respecetive model for this process can be found in [9]. This response of SPAD diodes with respect to the input intensity is critical for highly accurate satellite laser ranging. One way to compensate this effect can be found in [10]. In this paper, the rise time dependence of the output signal of the SPAD on the input signal strength of the diode is used to compensate the detection delay electronically. However, it is important to note that the presence of multiple photo-electron events is not only critical for the timing-behavior of the detector, it also introduces systematic range errors by inserting a negative delay (shortening effect) for the actually measured range to the satellite. This can be explained due to a shift of the centroid of the impulse response of the satellite caused by the geometry of the retroreflector array and a shift of the centroid of the impulse response of the usually close to Gaussian distributed laser source. Therefore, a complete control of the accuracy of SLR measurements can only be achieved, when the full signal response of the intensity – detector relationship can be recovered. The current approach of deriving this response is to use the optical response of satellites with negligibly small target signature to simulate the system noise [11]. However, this approach is based on empirical data and may not be applicable for variations of the atmospheric state, therefore it is certainly not complete.

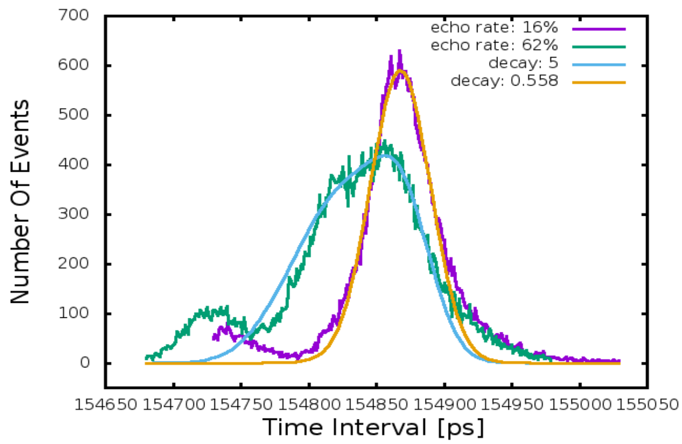

Figure 2. Probability distribution of a time-interval measurement with a Princeton Lightwave PGA-200-1064 single photon avalanche diode with a chip temperature of 220 Kelvin, a bias voltage above the breakdown voltage of the diode of 18 volt and a trigger level of -250 mV.

3. SPAD Model

A key to derive a complete model may be to exploit the distribution of the photo-electron statistics for repeated measurements during the satellite laser ranging process. A way to do that was described in our previous paper [4]. When the SPAD is installed in our gating circuit, the peak output voltage of the device is related to the number of seeding photo-electrons. Together with our model of this behavior, the underlying photo-electron statistics can be derived.

$$f(x) = d \cdot \sum_{n=1}^{20} \exp(n \cdot f) \cdot \exp\left(\frac{\left(x + c + e \cdot \log(n)\right)^2}{-2 \cdot b^2} \right) \qquad (2)$$

The model is a sum over 20 Gaussian distributed functions, with the mean of each of them shifted logarithmically with the number of seeding photo-electrons. For satellite laser ranging it was found, that the signal is approximately Boltzmann distributed at low signal levels and for a turbulent atmosphere [12,13]. Therefore, each function is scaled exponentially. The parameters b,c,e of the model are intrinsic diode parameters and have to be determined once for a specific operating point of the device. On the other hand, the parameters d and f may be adjusted in order to derive the decay rate of the photo-electron statistic during a measurement. In our model f is the negative inverse decay rate of a Boltzmann distributed signal. For an example, Figure 3 shows a sum over 5 functions and the corresponding envelope, which represents our model.

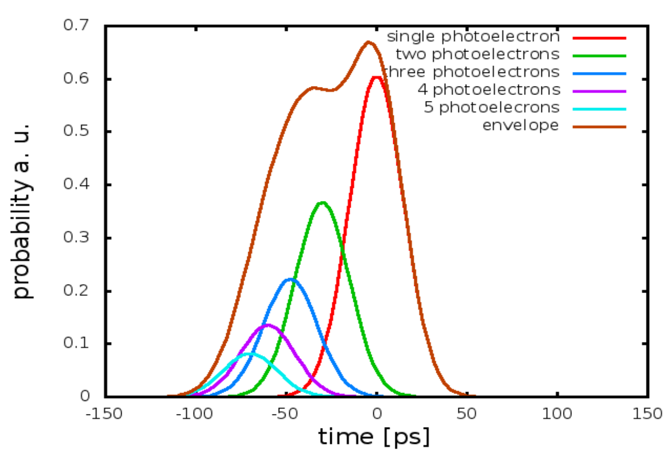

Figure 3. Model of the peak-output voltage and timing-behavior of a SPAD implemented in our gating-circuit for Boltzmann distributed photo-electron statistics.

A real data adjustment of the model for satellite range measurements can be seen in Figure 4. The range signals were gathered during a satellite laser ranging measurement targeting the GALILEO202 satellite at an echo rate of 5%. For the measurement the peak output voltage of the diode was recorded together with a time-stamp to be able to assign the peak output voltage data to the satellite echo in a post processing procedure. In other words, the dark count events are rejected in this distribution. It can be seen, that the model provides good agreement, except for a region at low peak output voltages. This region can be identified with the tail of outliers that were already shown in the distribution of the time-interval measurement. Actually, our model can be adjusted to the probability distribution of a time-interval measurement as well (Fig. 2). In Figure 2 it can be seen that the model also gives good agreement to the experimental data of a time-interval measurement. Again except for the outliers region. However, a mismatch towards shorter time-intervals is also visible for the distribution at a high echo rate. This mismatch is most probably caused by some light leakage of our laser source, which can be seen at the left side of the distribution. The light leakage prevents higher seeding photo-electrons to trigger the avalanche breakdown. Another reason may be, that the measurement was performed in the laboratory with no atmosphere involved. Instead, a diffusing optic was used to emulate a Boltzmann distributed signal.

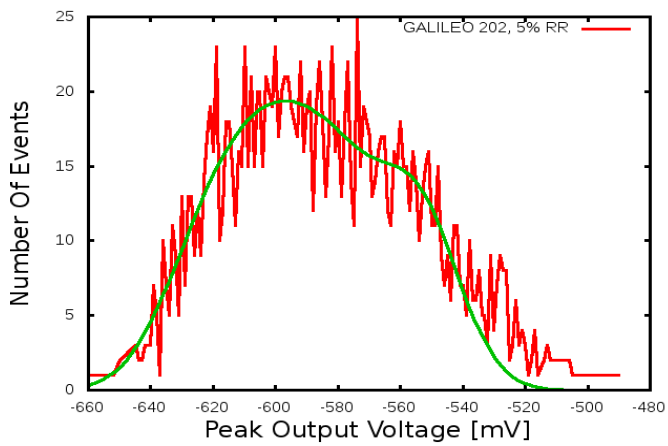

Figure 4. Model of the peak-output voltage of a SPAD adjusted to the data gained during ranging a GALILEO202 satellite with a Princeton Lightwave PGA-200-1064 SPAD at an echo rate of 5%.

4. Experimental results

To get an estimate of the photo-electron statistics during satellite laser ranging, the decay rate was derived from the peak output voltage distribution for several different measurements. Each measurement was carried out with different system settings. For example, the parameters laser divergence and telescope aperture were changed. Also, during these measurements, the echo rate was kept at a level below 10% by means of adjusting the pump delay of our laser amplifier. All these measurements were performed at elevation angles above 70 degree. In addition, one measurement was performed at an elevation angle of 40 degree with an echo rate of below 10% and another one at an echo rate of 50% and an elevation angle above 70 degree. In both cases the laser was set to best collimated state and the telescope aperture was set to be completely open. All of these measurements were carried out during one night. Therefore, the atmospheric state can be assumed as constant. The results of the adjustment are shown in Table 1.

Table 1. Decay rates and the corresponding shift of the centroid of a time-interval measurement, derived from an adjustment of our SPAD model to the data gained during satellite laser ranging measurements with different system settings.

Elevation		**40**	**>70**
Decay Rate (Centroid Shift)		0.323 (-33 ps)	0.311 (-34)
Divergence	**15 arcsec**	**7 arcsec**	**Limited by Atm.**
Decay Rate (Centroid Shift)	0.389 (-29 ps)	0.337 (-33 ps)	0.311 (-34)
Aperture	**38%**	**50%**	**100%**
Decay Rate (Centroid Shift)	0.241 (-39 ps)	0.261 (-37 ps)	0.311 (-34)
Echo Rate		**50%**	**<10%**
Decay Rate (Centroid Shift)		0.239 (-37 ps)	0.311 (-34)

It can be seen, that decreasing the aperture to 38% (~30 cm) leads to a photo-electron statistic which is close to that of ranging with an echo rate of 50%. This means, that the fluctuation in the intensity of the received signal is high in this case. This behavior can be explained with the size of speckles. When decreasing the aperture of a telescope the number of speckles entering the telescope is reduced. For a small aperture this leads to twinkling of a star, rather than an interference pattern at the focus of a telescope [14]. It can also be seen, that increasing the divergence leads to higher decay rates. In this case, the distribution tends to be more into the direction of single seeding photo-electrons. Again, this can be explained considering the speckle pattern. The higher the divergence is, the smoother is the signal at the satellite side. This leads to lower variations in the signal strength. Considering the measurement at a low elevation angle, almost no variation was found compared to the case at a high elevation angle. Ideally this measurement must be repeated at different days to also have different atmospheric conditions involved.

Also shown in table 1 is the theoretical shift of the centroid of a distribution of a time-interval measurement based on the derived decay rate. For that evaluation, the parameter e of our model was chosen conservatively to 35 ps. This parameter defines the amount of the shift of the centroid of the distribution for a specific decay rate and is an intrinsic detector parameter. Usually, this parameter is of the order of 50 up to 100 ps. For all the measurements a peak to peak variation of the centroid of 10 ps was found. Converted to a variation in the distance measurement this is about 2 mm. However, more considerable is the systematic error in all of the measurements of about 34 ps or 6 mm. Especially, when keeping in mind that the parameter e was chosen conservatively and the fact that the shift of the centroid was derived from the detector model only. Effects from the satellite geometry and the laser pulse shape are not contained in this investigation. This will further increase the error budget.

5. Conclusion

The goal for the future is to use the measurement of the decay rate to determine the photo-electron statistics during a satellite laser ranging sequence and to correct for systematic errors in a post- processing step. By means of this parameter the single photo-electron probability distribution of the detector, the distribution derived from the satellites geometry and that of the laser pulse width can be converted to a mixed signal strength probability distribution. These mixed signal distributions may then be convoluted to finally derive the optical satellite response. A first step towards this can be found in [12]. Overall, the investigated InGaAs/InP single photon avalanche diode provides very reasonable performance for its application in satellite laser ranging, especially due to its high detection efficiency in combination with its good timing-properties which is close to that of state of the art silicon devices. Also its compound structure with separate absorption and multiplication layer provides a good contrast between the single and multi-photo-electron seeding events of the peak output voltage distribution. Such a high contrast could not be observed for silicon devices so far.

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