Comparison of SPAD, SiPM and APD performance for ToF LiDAR application

Andrii Nagai[1], Colin Barry[1], Stephen Bellis[1], Aidan Browne[1], Steven Buckley[1], Edel Cashman[1], Brian Couglan[1], Sean Foley[1], Mark Perry[1]

1. Depth Sensing, onsemi, Cork, T12CDF7, Ireland
Email: andrii.nagai@onsemi.com

***Abstract*—In this analysis, the SiPM, SPAD array and APD sensors are compared in term of performance for short and long range LiDAR application operating at +25 °C and 105 °C. The comparison was done using Signal to Noise analytical calculation which was verified with numerical toy Monte Carlo waveform simulation and experimental measurements performed with a LiDAR system demo. We found that system aperture should be optimized for a chosen photodetector (i.e. APD, SiPM or SPAD) and its dynamic range. Reducing the number of SiPM or SPAD array micro-cells per channel improves the sensor *SNR* and temperature stability but decreases the ambient light immunity.**

Keywords—LiDAR, SiPM, SPAD, APD, ToF, application

I. INTRODUCTION

Laser Imaging Detection and Ranging, LiDAR is a critical system for advanced driver assistance systems, ADAS, and autonomous driving, AD, vehicles, robotic mobility, and industrial automation. The signal to noise ratio, *SNR*, of the LiDAR system is a key parameter that limits the LiDAR detection probability, particularly at long distances. The LiDAR detection probability P_D may be approximated [1] as:

$$P_D \approx 0.5 \times erfc\left(\sqrt{-lnP_{fa}} - \sqrt{SNR + 0.5}\right) \qquad \text{Eq. 1}$$

where P_{fa} is the false trigger rate.

The *SNR* calculation method depends on sensor selection; this article presents the analytical calculation of *SNR* for SPAD, SiPM, and for Si APD sensors in a dToF LiDAR application.

We analyze *SNR* for two typical systems presenting short (up to 30 m) and long (250 m) range LiDARs. The effect of varying the system optical parameters is also explored since angular resolution and lens aperture (i.e., lens diameter) can impact the *SNR* performance in a different way depending on sensor choice. The analysis is performed for sensors operating at 25°C and 105°C.

II. LIDAR SYSTEMS DEFENITION

For *ADAS* vehicle, multiple LiDAR systems are required to resolve different tasks such as: emergency braking, pedestrian detection, collision avoidance, surround view, park assistance etc. Those tasks require different LiDARs with different specification such as: detection range, field of view *FoV*, angular resolution *AoV*, etc. Those systems might be divided into three main classes as: short, middle and long-range LiDARs. In this article we do a *SNR* calculation for short and long range LiDAR systems with system level specification presented in Table 1. We assumed that each of those systems might be equipped either with SPAD, SiPM or APD sensor. The detailed specification of sensors used for *SNR* calculation is presented in Table 2. We calculated *SNR* for SPAD array with different macro-pixel sizes of 2×2 and 7×7 micro-cells, while for SiPM device we assumed 2400 micro-cells.

Table 1 Typical LiDAR systems specifications used for SNR analysis

	Short	**Long**
FoV H×V	120° x 80°	120° x 25°
$AoV_x \times AoV_y$	0.3° x 0.3°	0.05° x 0.05°
P_{laser} per channel W	10	100
N_{shots}	20	1
d m	30	250
ε_{RX} %	90	
ε_{TX} %	90	
D_{lens} mm	1 to 50	
Λ nm	905	
Δλ nm	±15	
t_{laser} ns	5	
η %	10	
B_N MHz	1	
R_f kΩ	10	
$<V_{amp}>$ nV/√Hz	28	
ambient light flux kLux	100	

Table 2 Typical SPAD, SiPM and APD parameters used for SNR calculations

	SPAD		**SiPM**	**APD**
PDE @ 905 nm	30%			N/A
QE @ 905 nm	N/A			55%
N_{pixels}	2×2	7×7	2400	N/A
τ_{dead} ns	6		14	N/A
P_{XT} %	1		15	N/A
DCR KHz/mm²	25		150	N/A
F	1.01		1.19	4
R_0 A/W	N/A			0.4
M or G	1E5			100
I_D, pA	2			50

III. *SNR* CALCULATION AND COMPARISON

The *SNR* for SiPM or SPAD devices can be calculated from the number of fired microcells (for more details, please follow Ref. [2]) as:

$$SNR = \sqrt{N_{shots}}\frac{N_{laser}}{\sqrt{N_{amb} + N_{elec.}^2}} \qquad \text{Eq. 2}$$

where N_{shots} is the number of dToF measurements per point, $N_{elec.}$ is the number of microcells occupied due to electronic noise:

$$N_{elec.}^2 = \left(\frac{\tau_{dead}}{e\times G}\right)^2 \times B_N \times \left(\frac{4k_BT}{R_f}+\frac{\langle V_{amp}\rangle^2}{R_f^2}\right) \tag{Eq. 3}$$

where B_N is noise bandwidth (frequency at which amplifier gain is equal to 0 dB), e is electron charge, G is SiPM or SPAD gain, T is temperature in K, <Vamp> is amplifier input voltage noise density and R_f is feedback resistance.

As described in Ref. [2] the SNR of an APD-based LiDAR system can be calculated as:

$$SNR_{APD} = \frac{\sqrt{N_{shots}\times R_0^2\times P_S^2}}{\sqrt{2eB_N\times F\times (R_0\cdot P_B+I_D)+\frac{B_N}{M^2}\left(\frac{4k_BT}{R_f}+\frac{\langle V_{amp}\rangle^2}{R_f^2}\right)}} \tag{Eq. 4}$$

where R_0 is APD responsivity without multiplication[1], F is APD excess noise factor, I_D is APD dark current, M is APD multiplication factor or Gain, P_S and P_B are return laser and background light power respectively.

The SNR variation with temperature was calculated by assuming that SiPM and SPAD *DCR* doubles every 8°C, while APD`s dark current I_D increases 1.1 times per 1°C. In this calculation the variation of SiPM and SPAD dead time with temperature was neglected.

The SNR as a function of P_S and P_B for SPAD, SiPM and APD based systems are presented in Figure 1. For comparison, the condition at which $SNR = 10$ is highlighted by red solid line for $T = 25$°C and dashed orange line for $T = 105$°C. We can observe that due to small active area and small *DCR* and fast recovery time the SPAD devices are one order of magnitude more sensitive to return laser light power with respect to SiPM and more than two orders of magnitude more sensitive with respect to APD. Also the SPAD devices show the smallest degradation of SNR with temperature due to small DCR. As a drawback, due to limited number of microcells the dynamic range of the channel is reduced therefore the background light power (falling on the channel) should be controlled. The APD device, due to limited photon sensitivity and great linearity shows the highest immunity to ambient light. As a drawback, due to smallest internal gain APDs are much more sensitive to read-out electronics noise as was presented in Ref. [2]. APD is most affected by temperature variation due to I_D. The expected value of P_S and P_B for short and long range LiDARs configurations (See Table 1) are presented by white and black lines for guidance. The SNR at 25°C and 105°C for those two systems as a function of D_{lens} is plotted in Figure 2 as a solid and dotted lines respectively. We can observe that independent of test system, the highest SNR for LiDAR system with SPAD devices could be achieved if optics with small aperture are used (i.e. D_{lens}), while for APD based system high aperture optics ($D_{lens} > 25$ mm) is preferable. The SiPM based system presents the intermediate solution between SPAD and APD. Also, we can observe that APD based system shows the highest SNR variation with T.

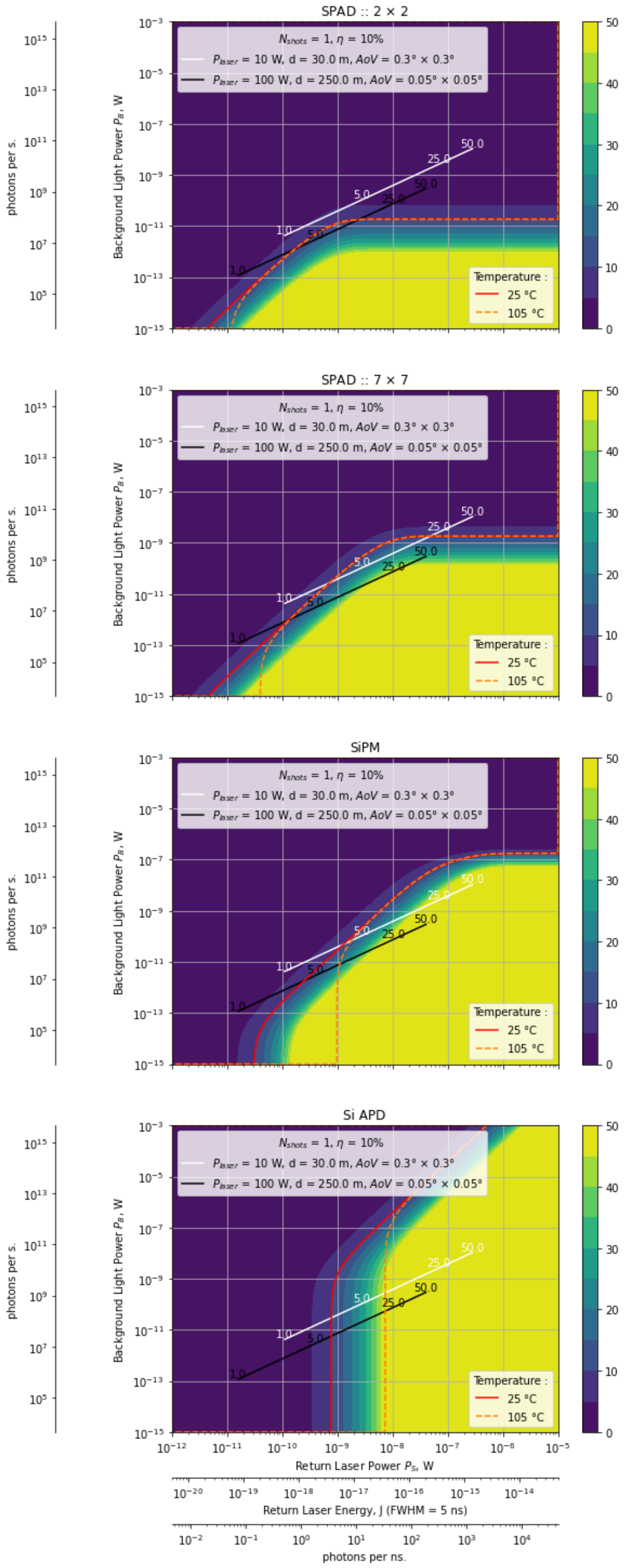

Figure 1 SNR at 25 ℃ as a function of return laser P_S and background P_B powers for SPADs (with 2x2 and 7x7 micro-pixels), SiPM and APD. The expected P_S and P_B as a function of D_{lens} for short and long LiDAR systems are presented by white and black lines. The SNR of 10 at 25 ℃ and 105 ℃ is presented by red solid and orange dashed lines. SNR is limited to 50 for better visibility.

---

[1] Typically, the responsivity after multiplication $R=R_0\times M$ is presented in APD datasheets

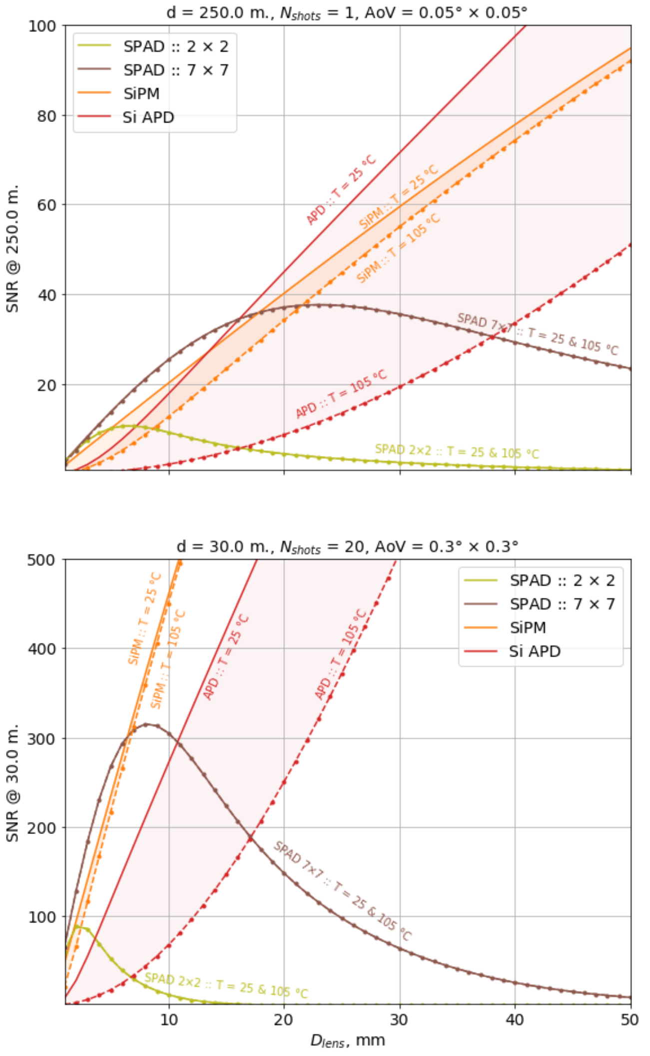

Figure 2 SNR as a function of D_{lens} for SPADs (with 2x2 and 7x7 micro-pixels), SiPM and APD at 25 ℃ and 105 ℃.

IV. MODEL VALIDATION

Proposed analytical calculation was validated with toy Monte Carlo Waveform Simulation [2] and experimental data acquired with onsemi Gen1 LiDAR demo [3]. The measurements were performed in lab for two targets with reflectivity η of 12% and 100% at distance of 1 m. The comparison between proposed analytical *SNR* calculation (Eq. 2), Monte Carlo simulation and measurements at different SiPM overvoltages ΔV (i.e. difference between bias voltage and breakdown voltage) is presented in Figure 3. We can observe a good agreement between measurements and calculations, beside a relatively big error bars related to peak laser power measurement.

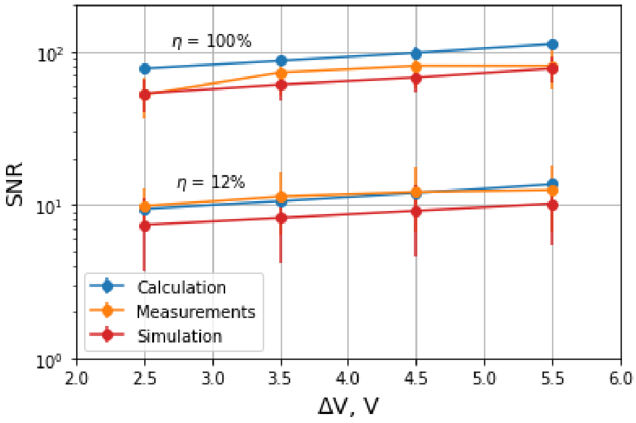

Figure 3 Comparison of measured, calculated and simulated SNR at different SiPM overvoltages and for two target reflectivity of 12% and 100%

V. CONCLUSIONS

To realize all the advantages the SiPM or SPAD could provide the optical system should be designed to suppress unwanted interference from ambient background light (i.e. small D_{lens} and *FoV*). In practice this leads to optical system miniaturization and high angular resolution. Comparing SPAD and SiPMs we observe that a smaller number of micro-cells leads to lower *DCR* and, as a result, improved *SNR* in low photon regime. SPAD array has better temperature stability. The drawback of SPAD array is limited dynamic range which limits device operation under high background light power. Therefore, the final performance of LiDAR system might gain significantly due to smart selection of the number of micro-cell per channel. For example, the small number of micro-cells might be beneficial for LiDAR systems operating under small background light power and wide temperature variation, while a high number of micro-cells is desired for a LiDAR system designed to operate under high background light power.

REFERENCES

[1] Bassem R Mahafza, "Radar Systems Analysis and Design using MATLAB," COLSA Corp, 2000. Chapter 4 Radar Detection Eq. (4.26)

[2] onsemi, AND90257 - Analytical Evaluation of Signal to Noise Ratios for SiPM and APD in dToF LiDAR Applications.

[3] onsemi, AND9781/D Gen1 Ranging Demonstrator Description