A 1×16 SiPM Array for Automotive 3D Imaging LiDAR Systems

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Abstract

We present a vertical line sensor composed of a 1 × 16 array of analog silicon photomultipliers (SiPM) optimized for 3D time of flight (ToF) imaging LiDAR in advanced driver assistance systems (ADAS) and autonomous driving (AD) vehicles. The sensor has been designed for enhanced red-sensitivity performance with a PDE of greater than 8% and can operate in outdoor environments with high ambient light noise of 100 klux and targets that have a low reflectivity from 10%. The SiPM array enables long distance ranging greater than 100 m and allows for superior low reflective target distance ranging over APD and PIN diode based systems. The SiPM array is to be demonstrated in an electro-mechanical scanning imaging LiDAR system consisting of a transmitter based on an eye-safe 905 nm laser diode array the 1×16 SiPM array as receiver, collimating optics and an electro-mechanical rotating mirror for horizontal scanning of a 80° × 5° at 30 fps. Simulation results are presented here to validate the concept of long distance LiDAR based on SiPM receivers.

The Silicon Photomultiplier for Solid State, Long Distance LiDAR

LiDAR is a important part of the fusion of sensors that is required for advanced driver assistance systems (ADAS) and autonomous driving (AD) applications, to provide object identification at long distance. The SiPM is now being recognised as an improvement over the more conventional linear APD for this task.

SiPM sensors are based on summed arrays of single photon avalanche photodiodes (SPAD) which are characterized by a high internal gain of ~10^6 when biased above their breakdown voltage in Geiger-mode. A single photon causes a macro-current to be generated at the three output terminals: anode, cathode and fast output. SensL SiPM sensors feature:

High gain: This leads to single photon sensitivity which is desired for long distance automotive LiDAR where the intensity of the return laser pulse may be extremely weak. The high internal gain of SiPM sensors overcomes the low noise limitation of the amplification stage in linear avalanche photodiode (APD) and PIN diode sensors.

Sensitivity: SensL's R-Series process was developed to achieve 8.4% PDE at 905nm. This is required to provide the long range detection probability planned for this work.

Uniformity: The CMOS process used to create the SensL SiPM sensors is inherently uniform and leads to high reliability.

Low bias: The single photon sensitivity of the SiPM is achieved with a bias of ~30V.

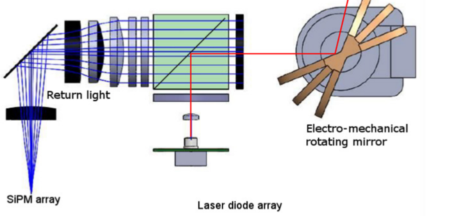
Dynamic Range: The number of SPAD cells in each SiPM pixel contribute to the dynamic range since the light can be spread over multiple SPAD sensors, reducing the average amount of photons incident on each SPAD by a factor equal to the number of cells.

Noise: DCR (dark count rate) is the primary source of noise in an SiPM and is mostly at the single photon level. The primary noise source in an outdoor LiDAR system is solar ambient noise.

SensL LiDAR Demonstrator Overview

SensL have built a long range LiDAR demonstrator system that is based upon the 1×16 SiPM array as receiver. The demonstrator is an electro-mechanical scanning imaging LiDAR system, that uses direct time of flight (ToF). It is comprised of:

- Eye-safe 905 nm laser diode array
- Electro-mechanical rotating mirror for horizontal scanning of a 80° × 5° at 30 fps
- Collection optics
- 1×16 SiPM array as receiver and associated readout and control electronics.



Schematic of the SensL demonstrator system that incorporates the 1x16 SiPM array.

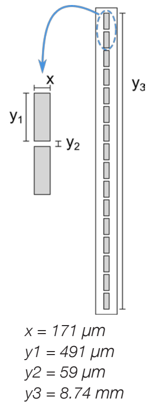
Parameter	Value
Array size	1 x 16
SiPM pixel length x	171 μm
SiPM pixel height y_1	491 μm
Pixel spacing y_2	59 μm
Total array length y_3	8.741 mm
SPAD cells per pixel N_{cells}	133
PDE @ 905nm	8.4%
SPAD cell dead time τ_{dead}	23 ns
SiPM pixel gain G	10^6
SiPM rise time τ_{rise}	100 ps
Laser divergence	0.1° x 5°
Laser peak power P_{laser}	400 W
Laser pulse width τ_{pulse}	1 ns
Laser pulse repetition rate PRR	500 kHz
Frames per second	30 fps
Optical aperture D_{lens}	22 mm
Scanning angle of view	80° x 5°
Static angle of view AoV_x x AoV_y	< 0.1° x 5°
Angular resolution	0.1° x 0.312°
Optical bandpass $\lambda \pm \Delta\lambda$	(905 ± 25) nm

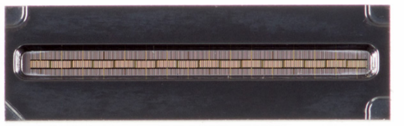
SensL LiDAR demonstrator key specifications. The values are used in the modelling of the system.

SiPM Sensor Array

The ArrayMR-0116A20 has been developed specifically for the SensL long-range LiDAR demonstrator, specifically taking into account the requirements of dynamic range in extreme ambient light conditions, and the use of simple, off-the-shelf optics:

- Monolithic linear array of 1x16 SiPM sensors, packaged in a QFN
- SiPM are created using SensL's R-Series process that has high responsivity at 905nm, of the order of 100kA/W (8.4% PDE)
- Each SiPM pixel is 171 μm × 491 μm in size, with a pixel spacing of 59μm to minimize optical crosstalk
- Each pixel is comprised of 133 SPAD cells of 20 μm × 20 μm active area
- Each SiPM pixel has a fast output that is used for determining precise ToF information.





Top view of the Sensl ArrayMR-0116A20 1x16 SiPM array for LiDAR applications

Modelled Performance of the System

The system described above was modelled using Matlab, taking into account the system noise floor, the return signal level and the ambient light level (solar noise). These factors are used to determine the detection probability of a returned signal as a function of the target distance and reflectivity. This exercise was also repeated using the 'single-shot' and 'multi-shot' ToF techniques.

Noise and Signal Calculation

The noise floor at the pixel level (N_{pixels} = 16) is determined by the amount of ambient light incident on the sensor, and given by:

$$P_{amb} = \mathfrak{P}_{amb} \cdot A_{FoV} \cdot \frac{1}{2\pi d^2} \cdot \eta \cdot A_{aperture} \cdot \frac{1}{N_{pixels}}$$

where $\mathfrak{P}_{amb}$ is the solar power density contributing to the noise level, A_{FoV} is the area in the field of view at distance d. η is the reflectivity parameter and $A_{aperture}$ is the area of the receiving lens.

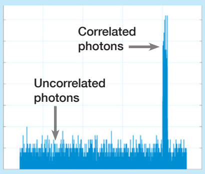
The intensity of the return laser pulse (P_{return}) can be similarly calculated:

$$P_{return}(d) = P_{laser} \cdot \frac{1}{2\pi d^2} \cdot \eta \cdot A_{aperture} \cdot \frac{1}{N_{pixels}}$$

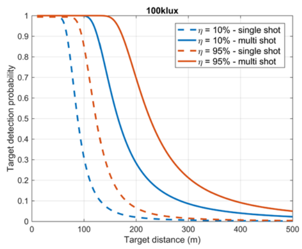
where P_{laser} is the peak laser power. This assumes that all the incident laser power onto the target is diffused back onto the aperture.

Single and Multi-Shot Techniques

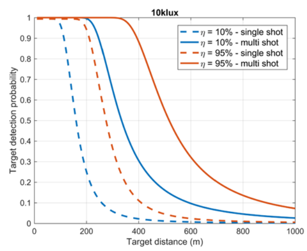
Single-shot ToF LiDAR calculates the distance to target for each pulse of the laser. However, at long distance, the returned signal reaches the level of the background noise, and so a multi-shot technique can be used to improve the performance and increase the probability of detection. A distribution plot of successive ToF values is created and correlated photons will form a visible peak, as in the example plot below. Acquiring multiple pulses per measurements allows increased target detection probability.



With a high laser pulse repetition rate, more than a single measurement can be obtained within the time allowed by the required frame rate.



The probability of detecting the return laser as a function of distance and target reflectivity, with 100klux ambient light.



The probability of detecting the return laser as a function of distance and target reflectivity, with 10klux ambient light.

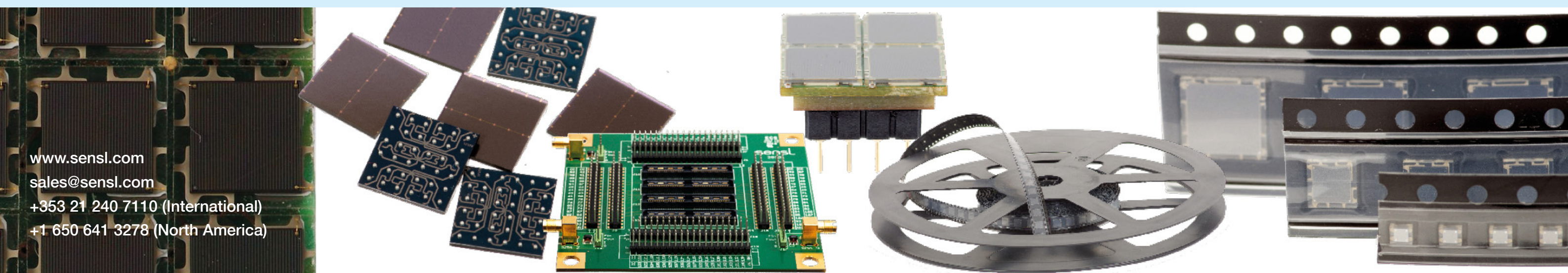
Conclusions

The work presented here describes the modelling of long-distance, SiPM based LiDAR demonstrator system currently under test at SensL. It was found that:

- The modelled results predict full operation in critical conditions such as 100klux of sunlight incident on the target in the field of view of the sensor and a range of reflectivity from 5% to 95%.
- A probability of detection above 95% is predicted up to 100 m for 5% reflective objects.
- A full image of 800×16 covering 80°×5° with a resolution of 0.1° × 0.312° with a 30 fps is achieved.

This performance is achieved due to some key system features:

- High responsivity (of the order of 100kA/W) of the SiPM at 905nm allows operation with an eye-safe laser transmitter at long distance even in full sunlight and light low reflective objects.
- The high responsivity is due to the PDE (8.4%) of the SensL R-Series SiPM process
- Each SiPM pixel provides sufficient dynamic range to avoid saturation.
- Ambient rejection is improved by the usage of bandpass filters around the chosen central wavelength without impacting the signal level.
- The narrow angle of view of the sensor gives the system a high spatial resolution in both horizontal and vertical directions.



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