

Multiple-Target Laser Rangefinding Receiver Using a Silicon Photomultiplier Array

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Abstract—In this paper, a silicon photomultiplier (SiPM) array module is evaluated and implemented as the receiver of laser rangefinding experiments to simultaneously measure the range of multiple targets. The array consists of 4×4 SiPMs on a single chip. Each SiPM is followed by a transimpedance amplifier to have an adequate output signal voltage. The 4×4 array is capable of measuring the range of 16 targets. A SiPM is an avalanche photodiode that operates in Geiger mode, where a huge multiplication factor, as high as 1 000 000, is obtainable. Thus, it can achieve high sensitivity. Our performance evaluation results show that the sensitivity of the measured SiPMs actually approaches the quantum limit. The SiPM can detect one single photoelectron in the depletion region. Each SiPM has a large active area, i.e., 8 mm^2 , and can collect much more returned light compared with typical silicon avalanche photodiodes (Si-APDs). The rise time of output voltage waveforms from SiPMs varies from 6 to 300 ns, depending on incident light power. The rising edges of output waveforms are compared for time measurement. Using a digital oscilloscope, the time of flight can be measured with 1-ns accuracy. This corresponds to a range resolution of 15 cm.

Index Terms—Avalanche photodiode (APD), Geiger mode, laser rangefinder, optical receiver, silicon photomultiplier (SiPM) array.

I. INTRODUCTION

A LASER rangefinder measures the distance of a target using a laser beam. It operates on the time-of-flight (TOF) principle. The transmitter sends a laser pulse toward the target. The laser pulse reflected from or scattered by the target is detected by a receiver. The round-trip TOF of the laser pulse determines the target distance. Laser rangefinders have widely been used in surveying, reconnaissance, sports, and military [1]. Two most important performance indicators of a rangefinder are “range” and “range resolution.” The “range” is the maximum distance that can be measured. It is dictated by the system loss budget and the reflectance of the target. The loss budget is the difference between transmitter power and receiver sensitivity in decibel scale. The range resolution is usually determined by the rise time of the returned pulse after it is detected by the receiver. High-sensitivity receivers on the market use a silicon avalanche photodiode (Si-APD) as the light detector.

Commercially available rangefinding receivers can achieve 3-nW sensitivity at $1.06\text{-}\mu\text{m}$ and 28-ns pulsewidth values [2]. In this paper, we use a Si photomultiplier (SiPM) array as the light detector of the receiver. We further evaluate a new technique of improving the range resolution by comparing the returned pulse waveform with a reference waveform.

A SiPM is a Si-APD operating in Geiger mode [3]. In Geiger mode, the APD is reverse biased beyond its avalanche breakdown voltage. An external circuit would limit the resulting current. A SiPM array consists of many SiPMs built on a single silicon chip. The array used in this paper has 4×4 SiPMs, and each SiPM has an active area of $2.85 \text{ mm} \times 2.85 \text{ mm}$ [4]. All 16 SiPMs in the array are independent of each other. Each SiPM has its own amplifier and output. Thus, the array is capable of detecting and measuring the range of pulses returned from 16 different targets simultaneously. In principle, the same technology can be extended to InGaAs photomultipliers for a 1550-nm eye-safe wavelength window.

Other than multiple-target capability, the rangefinding receiver built with a SiPM array has several more advantages. The SiPM has a very high gain (multiplication factor), i.e., 100 000 to 1 000 000, versus 100 of typical Si-APDs. This huge gain greatly reduces the required amplification gain. The SiPM also has very high sensitivity. In this paper, a sensitivity value of 0.1 nW at 50-ns pulsewidth is measured. The Si-APD used in high-sensitivity receivers on the market has an active diameter of 0.8 mm, i.e., an area of 0.5 mm^2 . In comparison, each SiPM of a 4×4 array has an area of 8 mm^2 , 16 times of the Si-APD. This means that, for the same experimental setup, each SiPM can collect 16 times the light power collected by the Si-APD.

In what follows, we briefly review the SiPM structure with microcells. A laser transmitter built using an ordinary laser diode (LD) on the market for measurement purposes is described. Performance evaluation of a 4×4 SiPM array module is reported. Rangefinding experiments are then presented, including a waveform comparison technique to improve the range resolution. A short summary is then given.

II. SiPM WITH MICROCELLS

A SiPM is a Si-APD that operates in Geiger mode [5]–[7]. The SiPM is very different from the conventional photomultiplier, which is a vacuum tube. The photomultiplier tube (PMT) is several inches long and operates at a high dc voltage, up to several kilovolts, to achieve a huge current gain, up to 1 000 000. In contrast, a SiPM device is rather thin and needs a relatively low dc voltage, less than 100 V, to function [8], [9]. Since it is a semiconductor device, many SiPMs can

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be built together with electronics on the same chip. Eventually, one can have a SiPM array module that provides digital output data in whatever data partitions the designer wants: serial, serial-parallel, or parallel. The module can even include signal processing electronics and computer interface.

In an operating Si-APD, a photon absorbed in the depletion region generates an electron and hole pair [10]. The charge carrier such as an electron drifts in the depletion region and multiplies in number by impact ionization. Typical Si-APDs operate at a multiplication factor of 50–200, where the multiplication action is usually described as an avalanche action. The output signal is proportional to the incident light power and the multiplication factor. Thus, Si-APDs are linear devices and used in high-sensitivity rangefinding and optical receivers.

On the other hand, the Geiger-mode APD is biased at 10%–15% above its breakdown voltage. The impact ionization process is similar, but the multiplication factor is much larger, approaching infinity. Thus, one photoelectron can trigger an avalanche breakdown. The reverse-biased voltage beyond the breakdown voltage enhances the impact ionization process and makes the electrons multiply faster. The resulting photocurrent thus exponentially grows in time [11], [12]. The multiplication factor can practically reach 1 000 000. This multiplication action results in a current gain of the same factor. A single photon getting into the depletion region can produce a significant output current, making photon counting possible. In applications, a series resistor is connected to the Geiger-mode APD to constrain the current that flows through the device. The voltage drop on this resistor reduces the bias voltage on the APD and thereby quenches the avalanche breakdown action. The APD is then recharged to its original bias voltage above the breakdown voltage after some recovery time, which is the RC time constant of the resistance and diode capacitance.

The sequential processes of avalanche breakdown, passive quenching, and recharge allow the Geiger-mode APD to count photons [13], [14]. As a result of the huge gain, the Geiger APD functions as a binary device that can determine only whether there is “a photon” or “no photons at all” in the depletion region. In other words, it cannot differentiate between “one-photon” and “multiple-photon” situations. This is the nature of Geiger operation mode. The practical question is how to make the Geiger APD into an analog device so that its output signal is proportional to the incident photon intensity. To achieve this, each SiPM device is designed and built to contain numerous Geiger microcells, where each microcell is an individual APD. All the microcells of one SiPM device are connected to a common resistive load. One photon incident on one microcell (APD) produces an output signal of one unit. Ten photons incident on ten different microcells, one photon per microcell, would produce an output signal of ten units. However, ten photons incident on the same microcell produce an output signal of only one unit. This microcell design can count photons incident on different microcells of the same SiPM device. It, however, cannot count photons incident on the same microcell. If the number of photons incident on one microcell at one time is equal to one or zero, then the output signal of a SiPM device is proportional to the number of Geiger microcells at

TABLE I
IMPORTANT PARAMETERS FOR THE SiPM ARRAY

Number of SiPM devices	4 X 4
Sensing area of each SiPM	$2.85 \times 2.85 \text{ mm}^2$
Number of microcells per SiPM	3640/pixel
Recovery time	100 ns
Microcell size	35 microns
Microcell fill factor	59 %
Max. current gain	1 million
Number of Geiger APDs	450/mm ²
Breakdown voltage	28 V
Typical bias voltage	29.5 V
Quantum efficiency (QE)	6% @ 660nm
Trans-impedance of amplifier	470 Ω

ON-state. The number of absorbed photons can be counted quite precisely. At present, this is the best design for photon counting.

Table I summarizes the important parameters of a SiPM array [4]. The size of each microcell is $35 \mu\text{m} \times 35 \mu\text{m}$, and the typical recovery time is 100 ns. The SiPM quantum efficiency (QE) measured by the manufacturer at 660-nm wavelength is 6%. The QE is the ratio of the number of photoelectrons generated to the number of incident photons. It takes 16 incoming photons to produce a photoelectron. There is still room for improvement by the manufacturer. Although there are SiPM devices with much larger photon detection efficiency (PDE) for the same wavelength [15], we did not have access to the high PDE SiPM devices indicated in [15]. If high PDE SiPM devices were available, the sensitivity of the rangefinding receiver would accordingly improve.

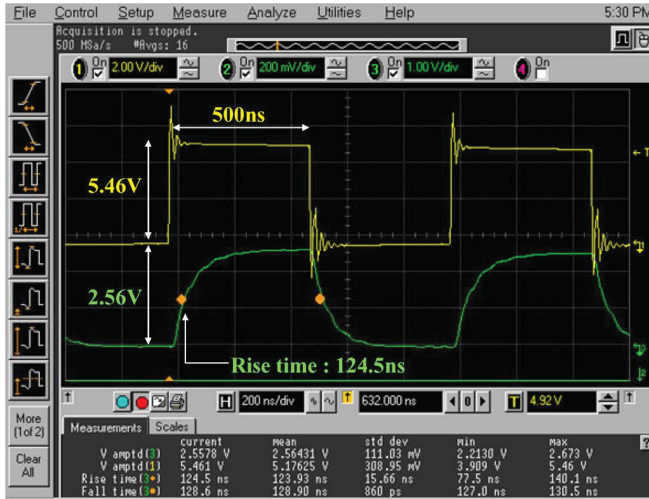
An important parameter to know is the saturation light intensity. It is the incident light intensity at which the output signal saturates. For uniform light illumination, saturation occurs when each microcell receives enough photons to produce one photoelectron. The corresponding intensity is calculated as

$$\frac{1.9 \text{ eV}}{6\%} \times \frac{1}{0.59 \times (35 \mu\text{m})^2 \times (100 \text{ ns})} = 70 \text{ nW/mm}^2 \quad (1)$$

where 1.9 eV is the energy of photons with 660-nm wavelength, and 0.59 is the fill factor of a microcell, respectively. For a SiPM device with 8-mm² active area, incident light power at saturation is 561 nW.

III. LASER TRANSMITTER CHARACTERISTICS

To test the performance of the rangefinding receiver using an SiPM array, a laser transmitter is needed. High-power pulsed LDs were not used due to safety concern. Instead, an ordinary LD of 660-nm wavelength and 35-mW optical power was used to build a simple transmitter. The LD was collimated using a compound lens with 4.5-mm focal length to form a parallel output beam. The dc resistance and operation current for the LD are 40 Ω and 65 mA, respectively. The ac resistance is 11 Ω . Thus, a 40- Ω resistor was connected in series with the LD so that the LD circuit matched the 50- Ω characteristic impedance of the coaxial cable connected to the pulse generator. In Fig. 1(a), the upper trace was the voltage waveform that drives the LD. It was displayed on channel 1 of a digital oscilloscope. The input impedance was set at 1 M Ω . It took 5.4 V to obtain



(a)



(b)

Fig. 1. (a) Voltage waveform that drives the LD (upper trace) and PD output voltage waveform (lower trace) with 1-M Ω oscilloscope input impedance. (b) PD output voltage waveform (lower trace) with 50- Ω oscilloscope input impedance.

65 mA of LD operating current. The pulsewidth was chosen at 500 ns. The laser beam was detected and measured using a reference photodiode (PD). For initial testing, the separation between the LD and the PD is 20 in. A 510- Ω load resistor was connected from the PD anode to the circuit ground. The cathode of the PD was connected to a 20-V dc voltage to reverse bias it. The voltage signal that incurs on the load resistor was displayed on channel 2 of the oscilloscope, shown as the lower trace in Fig. 1(a). It is seen that the voltage drop on the PD load due to photocurrent is 2.6 V. The input impedance of channel 2 was set at 1 M Ω so that it does not affect the load resistance. The responsivity R_λ and QE of the PD, at 660-nm wavelength, are 0.4 A/W and 76%, respectively. Hence, the corresponding optical power incident on the PD is

$$\frac{V_{PD}}{R_\lambda * R_{load}} = \frac{2.6 \text{ V}}{0.4 \text{ A/W} * 510 \Omega} = 12.5 \text{ mW}. \quad (2)$$

Next, the input impedance of oscilloscope channel 2 was changed from 1 M Ω to 50 Ω to get fast response. The result is

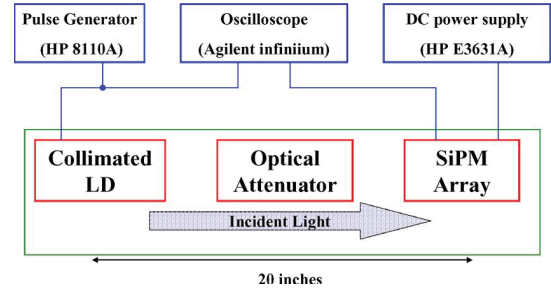


Fig. 2. Setup for light detection using the SiPM array.

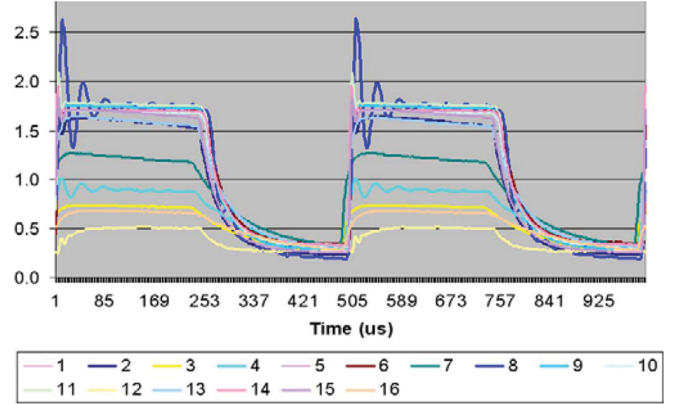


Fig. 3. Output voltage waveforms of 16 different SiPMs of the 4 $\times$ 4 array at 30-dB light attenuation.

displayed as the lower trace of Fig. 1(b). The load resistance seen by the PD is 50 Ω //510 Ω = 46 Ω . The voltage drop produced by the photocurrent is 221 mV. The measured rise and fall times are 12 and 13 ns, respectively. They are limited by the PD junction capacitance and parasitic wires. The rise and fall times of the laser pulses were measured to be less than 5 ns by a high-speed optical receiver.

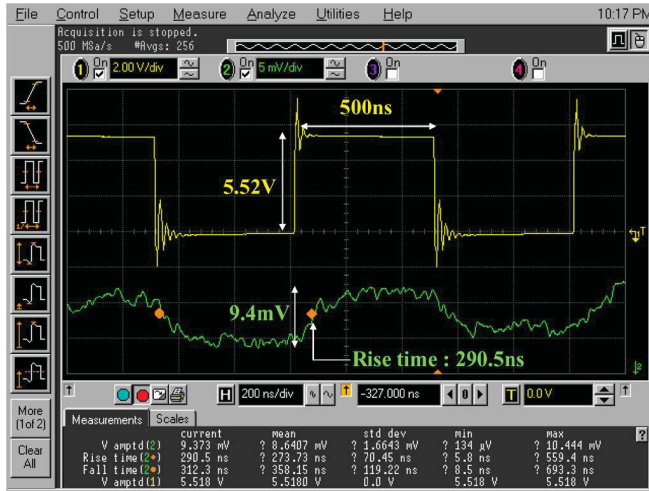
IV. PERFORMANCE MEASUREMENTS OF THE SiPM ARRAY

Fig. 2 displays the experimental setup for light detection using the SiPM array. Fig. 3 shows individual responses of the 16 SiPM devices in the array, each shone with a laser beam that was attenuated by 30 dB. The incident laser pulse power was 12.5 μ W, which is higher than the saturation incident power of 0.56 μ W. Ideally, all 16 SiPM devices should have the same responses. For this specific SiPM array sample provided by the manufacturer, ten SiPMs have nearly the same responses, but six SiPMs have much smaller responses.

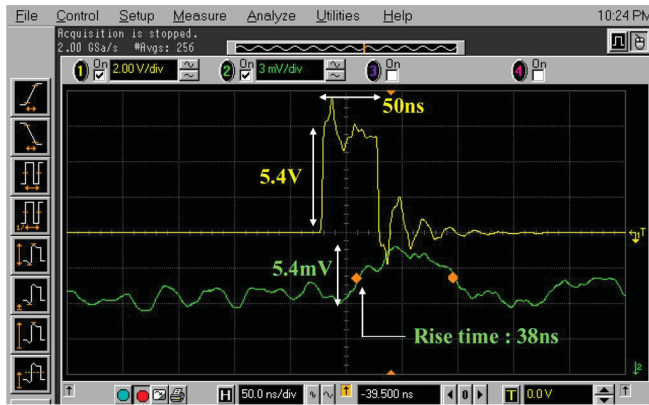
To test the performance of the SiPMs, the laser pulses with 500-ns width were attenuated by 30, 60, 75, and 81 dB, respectively, using neutral density filters and sent to the SiPMs. The breakdown and bias voltages are 28 and 29.5 V, respectively. Thus, the overvoltage was 1.5 V, and it was fixed in the experiment. What was changed is the optical power incident on the SiPM device. Results of SiPM 6 in the array are presented. Table II lists the responsivity, incident laser pulse power, number of photons per pulse, and rise time of the output voltage waveform. Results of the reference PD are also included for comparison. It is seen that, in general, the SiPM responsivity

TABLE II
INCIDENT LIGHT POWER AND RISE TIME OF SiPM 6 (A PD WITH A 510-Ω
LOAD IS ALSO LISTED AS A REFERENCE)

Attenuation	R_λ [A/W]	Light power	Photons/ 500ns pulse	Rise time
30dB	250	12.5μW	2.1×10^7	6ns
60dB	40,000	12.5nW	2.1×10^4	81ns
75dB	217,000	0.4nW	656	175ns
81dB	200,000	0.1nW	165	291ns
PD	0.4	12.5mW	2.1×10^{10}	12ns



(a)



(b)

Fig. 4. Voltage waveform that drives the LD (upper trace) and output voltage waveform from SiPM 6 (lower trace) with 81-dB attenuation, (a) Pulsewidth of 500 ns. (b) Pulsewidth of 50 ns.

drastically enlarges with lower light power. Fig. 4(a) exhibits the output voltage waveform resulting from the incident laser pulses with 81-dB attenuation. For reference, the voltage waveform driving the LD is shown as the upper trace. At 81-dB attenuation, the power of incident laser pulses is 0.1 nW. The output voltage pulses are clearly recognizable. The measured output voltage is 9.4 mV. The current after avalanche multiplication is $9.4 \text{ mV} / 470 \Omega = 20 \mu\text{A}$, where 470Ω is the transimpedance of the transimpedance amplifier that follows the SiPM device. The deduced responsivity is 200 000 A/W. The number of photons per 500 ns pulse is 165. Generally, the responsivity of a SiPM depends on overvoltage, PDE, and cell size. With a fixed overvoltage, the responsivity is constant in the linear region. From Table III, the responsivity values for very low

TABLE III
PERFORMANCE OF SiPM 6 AT A LOW LIGHT LEVEL
WITH DIFFERENT PULSEWIDTH VALUES

Pulse width	Attenuation	75dB	81dB
500ns	Output voltage	41mV	9mV
	# photons/pulse	656	165
	Rise time	175ns	291ns
300ns	Output voltage	39mV	10mV
	# photons/pulse	394	99
	Rise time	181ns	220ns
100ns	Output voltage	32mV	7mV
	# photons/pulse	131	33
	Rise time	74ns	71ns
50ns	Output voltage	14mV	5.4mV
	# photons/pulse	66	16
	Rise time	29ns	38ns

light power of 0.1 and 0.4 nW are 200 000 and 217 000 A/W, respectively. Thus, we attain that the responsivity of the SiPMs in the linear regime at 660 nm is about 200 000 A/W. The responsivity begins to become nonlinear as incident power increases. At very high light power, the responsivity has reached to several hundreds of amperes per watt and entered into the highly nonlinear regime.

In rangefinding applications, we used the rising edge of the pulse to determine the TOF. From Table II, it is also seen that the rise time significantly increases as the light pulse power decreases below $10 \mu\text{W}$. At light pulse power of 0.1 nW, the rise time increases to 300 ns. By comparing the returned output waveform with a reference waveform, the TOF can still be measured with a resolution of 1 ns. This technique will be presented in the next section.

To determine the ultimate ability to detect a single light pulse, the pulsewidth was reduced from 500 to 50 ns. Fig. 4 presents the results when the light pulse power is 0.1 nW. Table III also summarizes relevant measured data at two low light levels, i.e., 0.4 and 0.1 nW, respectively. As the pulsewidth becomes narrower, usually the rise time becomes shorter, and the output voltage gets smaller. With a 0.1-nW pulse at 50-ns pulsewidth, the rise time is reduced by a factor of 7.7 compared with the case of 500-ns pulsewidth. The output voltage is reduced by a factor of 1.7.

A 0.1-nW light pulse of 50-ns pulsewidth can clearly be detected, as shown in Fig. 4(b). The corresponding pulse energy is $5 \times 10^{-18} \text{ J} = 31 \text{ eV}$. There are only 16 photons per pulse. Since the QE of the SiPM at 660 nm is 6%, 16 photons would produce one photoelectron. This result clearly indicates that the sensitivity of the SiPM has approached the quantum limit. One thing that remains to be improved by the manufacturer is the QE. Typical Si- or InGaAs-APDs have QE higher than 60%.

V. RANGEFINDING EXPERIMENTS

A. Initial Experiment

The 660-nm laser transmitter described in Section II was first used to verify the experimental setup. The waist of the collimated laser beam is 1.6 mm. The calculated far field distance is 97 cm. The rangefinding receiver, which is the SiPM array,

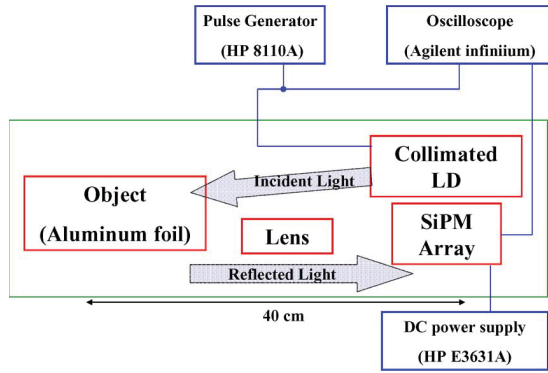


Fig. 5. Laser transmitter and SiPM array module.



Fig. 6. Voltage waveform that drives the LD (upper trace) and output voltage waveform from the SiPM that picks up the light pulse reflected from the target.

was positioned adjacent to the transmitter. A collection lens was placed in front of the receiver. It has an aperture of 29 mm and a focal length f of 99 mm. An object, namely, aluminum foil, was put at a distance 40 cm away from the transmitter and the receiver. The object was shone with the laser beam. The laser beam reflected from the object was detected by the SiPM array receiver. Fig. 5 illustrates the experimental setup. Fig. 6 displays the output voltage waveform from SiPM 6. With 100 ns of laser pulsewidth, the output voltage is 1.5 V, and the rise time is 5 ns. This rise time is surprisingly fast for a SiPM with an area of $2.85 \text{ mm} \times 2.85 \text{ mm}$. The output pulse is wider than the laser pulse because the SiPM device is driven into saturation. It takes some time for the electrons and holes in the depletion region to recombine. A widened output pulse will not be a problem in rangefinding applications because the rising edge of the pulse will be used to measure the TOF. The TOF result is longer than what is expected from 40-cm distance. The measured delay time is 20 ns, and the calculated delay time is 3 ns. According to the manufacturer, the postamplifier has a delay time of about 10 ns. The coaxial cable has a delay time of 6 ns/m.

B. Single-Target Rangefinding Experiment in the Laboratory

In this experiment, a metal plate at a distance of 13 m, which is the diagonal length of our laboratory, was used as the target.

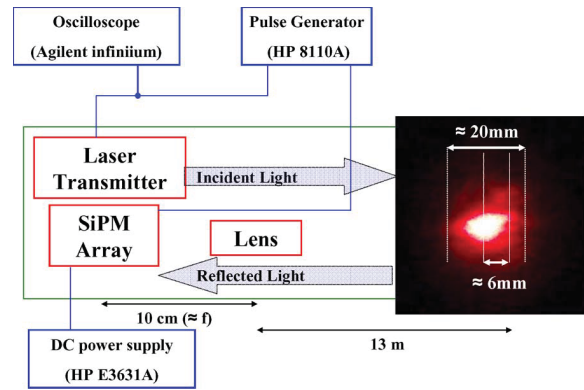


Fig. 7. Single-target rangefinding setup and illuminated target.



Fig. 8. Voltage waveform driving the LD (upper trace) and output voltage waveforms from SiPM devices in the array (all other traces) for the single-target rangefinding experiment. The light reflected from the target was projected on SiPM 6, which produced the highest output pulse voltage.

Fig. 7 exhibits the SiPM array receiver with the collection lens and the illuminated target. The lens was positioned so that the light reflected from the target was focused onto a specific SiPM of the array. Fig. 8 displays the LD driving voltage and the output voltage waveforms from SiPMs 5, 6, and 10, top down, respectively. The laser pulsewidth is 100 ns. It is seen that the reflected light was mostly projected onto SiPM 6. For multiple-target detection, it is essential to match every target region (space element) to a specific SiPM of the array. From Fig. 8, the TOF is 94 ns. The calculated one-way distance is 14 m. This agrees well with the actual distance of 13 m.

C. 785-nm Transmitter and Infrared Filter Setup

The wavelength of the LD used so far is 660 nm. This is within the fluorescent light spectrum. The 61-m-long hallway of a building was chosen to conduct the multiple-target experiment. The hallway fluorescent light must be blocked from entering the SiPM array receiver. To achieve this, a longer wavelength LD was used to build a new transmitter. Its wavelength is 785 nm, and its power is 100 mW. An infrared filter was placed over the SiPM array to block the ambient light, but to pass the laser light. The rise and fall times of the LD light pulses were measured to be 5 ns.

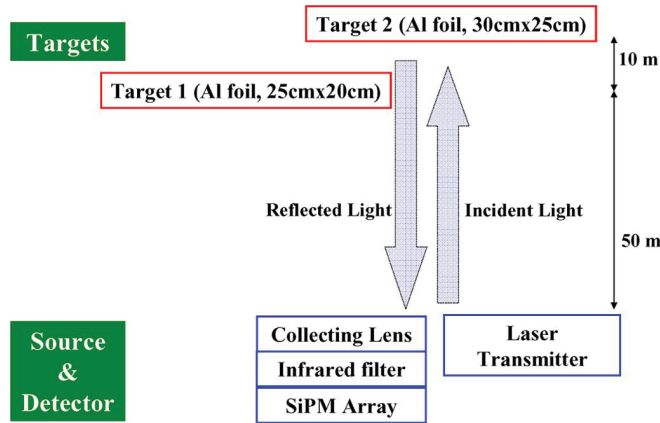


Fig. 9. Two-target rangefinding experimental setup in the hallway.

D. System Loss Budget

The 785-nm transmitter was driven to emit laser pulses with peak power of 100 mW, i.e., 20 dBm. The SiPMs can achieve sensitivity of 0.1 nW, i.e., -70 dBm. The system loss budget is 90 dB. Pulsed LDs with peak power as high as 200 W, i.e., 53 dBm, are readily available on the market. The loss budget can be increased to 123 dB using these high-power pulsed LDs.

E. Two-Target Rangefinding Experiment

Fig. 9 displays the two-target rangefinding setup in the 61-m-long hallway of 2-m width. Aluminum foils of 30 cm $\times$ 25 cm and 25 cm $\times$ 20 cm were used as two targets. The targets were placed at distances of 50 and 60 m, respectively, from the transmitter/receiver location, as shown in Fig. 9. A laser transmitter with 785-nm wavelength, an infrared filter, and a collection lens were employed in the experimental setup.

The laser light was shone on both targets. The light reflected from each target is focused to a specific SiPM of the array. Fig. 10(a) displays the SiPM output signals and the reference LD signal. The output signal corresponding to target 1 was displayed in channel 1 of the oscilloscope. The signal corresponding to target 2 was sent to channel 2. The returned lights from two targets were clearly focused to and detected by two different SiPMs of the array. This demonstrates two-target rangefinding capability. The round-trip TOF for target 1 (channel 1) is measured to be 342 ns. The TOF for target 2 (channel 2) is 413 ns. The resulting ranges are 51 and 61 m, respectively. The actual distances are 50 and 60 m, respectively.

For a pulsewidth of 100 ns, the waveform of returned optical pulses can clearly be observed when the pulse peak power is 0.1 nW, which is the sensitivity of the SiPM that was measured. The LD power needed to obtain 0.1 nW or more of returned optical pulses would depend on the target and the range. For the experimental setup in the hallway with a range of 60 m, the total system loss is 80 dB. Thus, only 10 mW of LD power is needed.

F. Range Resolution Improvement by the Waveform Comparison Technique

In this rangefinding project, the rising edge of the receiver output waveform is used to measure the time. Thus, the rise

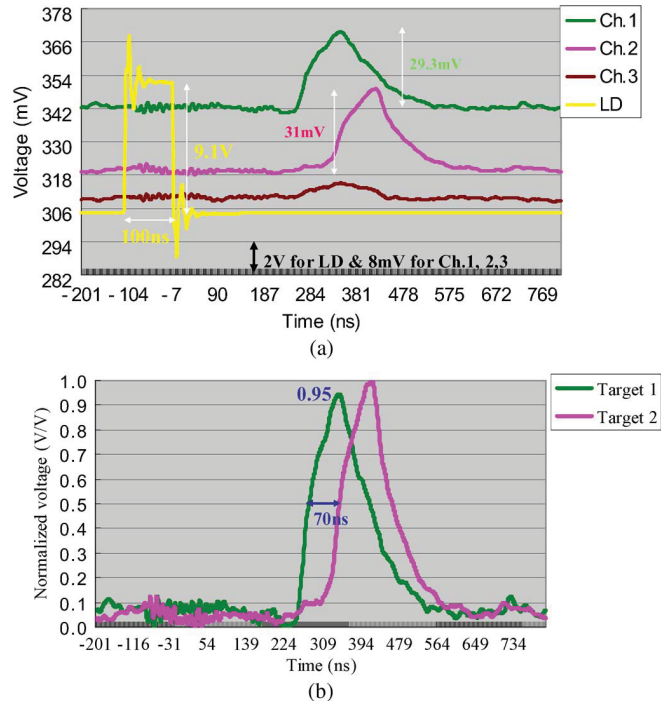


Fig. 10. (a) Voltage waveform that drives the LD (left leading trace) and voltage waveforms from two SiPM pixels of the array that pick up light pulses returned from two targets. (b) Comparison of normalized SiPM output waveforms resulting from two targets on the same reference level for time measurement at 50% of the rising profile of the waveforms.

time of output pulses determines how precise the time can be measured. This has been the commonly accepted method. In this approach, information on the rising profile of the output waveform is not utilized.

In principle, the rising profiles of receiver output waveforms due to laser pulses reflected from different flat targets should be all similar, i.e., of same shape but different magnitude. Inside the rangefinder, a very small portion of the transmitter light beam can be folded back to the receiver. The corresponding output waveform is adapted as a reference for time measurement. This reference waveform can actually be stored digitally. The output waveform due to a target is then compared with the reference waveform at 50% point of the rising profile. Using this waveform comparison method, the accuracy of time measurement is dictated by how precisely the electronic equipment records the waveforms. Consequently, time measurement accuracy is not anymore limited by the rise time.

A demonstration of this method now follows. For the two-target experiment presented previously, output waveforms caused by light pulses returned from two targets are exhibited in Fig. 10(a). These two waveforms are normalized and displayed at the same base level, as shown in Fig. 10(b). The difference in time between these waveforms measured at 50% of the rising profile is 70 ns. Using digital data of the waveforms, this time difference is measured with accuracy of 1 ns. From this time difference, the separation between target 1 and target 2 is calculated to be 10.5 m. The actual separation measured by a measuring tape is 10.4 m. The range accuracy depends on the time resolution of the waveforms that can clearly be displayed. The digital oscilloscope has 1-ns accuracy in time

measurement. This corresponds to a range resolution and accuracy of 15 cm.

VI. SUMMARY

In summary, a SiPM array with 4×4 elements on a Si chip has been implemented as a rangefinding receiver to measure the range of multiple targets. Each SiPM device in the array has its own transimpedance amplifier and output. Range measurement of two targets was demonstrated in the hallway of a building, and a range resolution of 15 cm was achieved. The SiPM is a Si-APD operating in Geiger mode. At a low light level, it achieved a carrier multiplication factor of 200 000. This is equivalent to an amplifying gain of 106 dB. Each SiPM has a large active area, i.e., 8 mm^2 , and can collect 16 times more light compared with Si-APDs used in high-sensitivity rangefinders on the market. The SiPM sensitivity was measured to be 0.1 nW, and it approaches the quantum limit. The SiPM has QE of 6%. There is still room for improvement by the manufacturer. With one 4×4 array module, the ranges of 16 targets can simultaneously be measured. Potential multiple-target rangefinding applications include reconnaissance, surveying, air traffic control, automotive, and military.

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