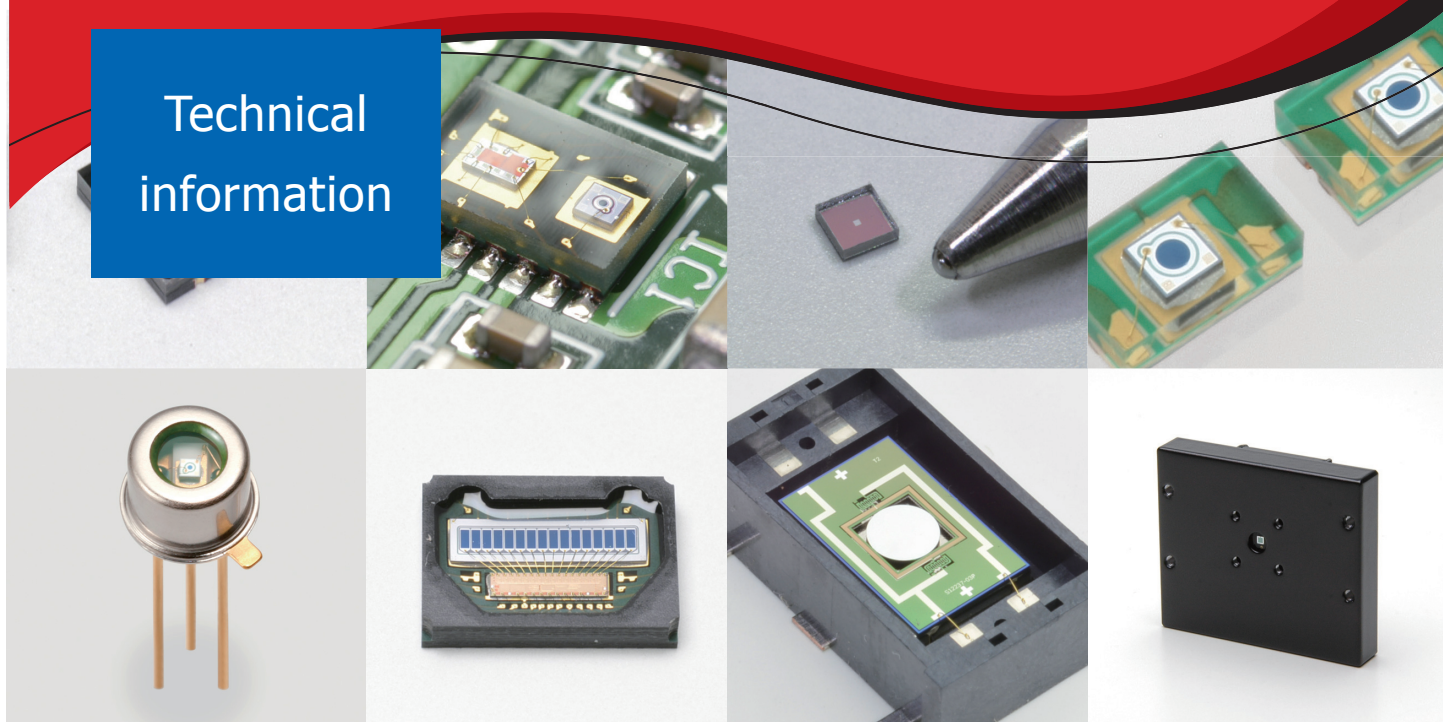


# Detector for distance measurement

Technical  
information



This document provides technical information for using Hamamatsu photosensors in distance measurement applications. Please refer to this document when considering or using Hamamatsu detectors such as MPPCs, APDs, and PIN photodiodes in optical distance measurement.

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## Distance measurement methods

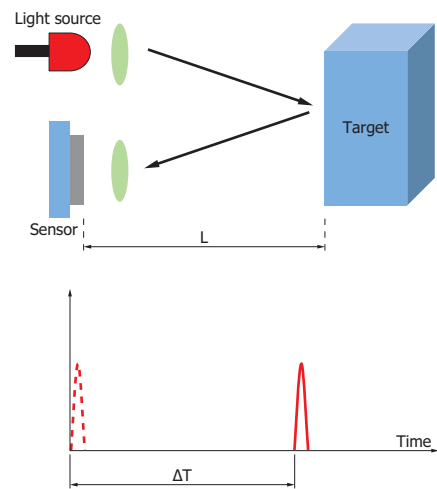
Common methods for distance measurement include direct TOF, indirect TOF, and triangulation.

### ➤ Comparing distance measurement methods

Parameter	Direct TOF	Indirect TOF	Triangulation
Measurement range	Long	Middle	Middle
Accuracy	Middle	High	High
Optical system size	Small	Small	Large
Readout circuit	Complex	Complex	Simple
Array	Suitable	Suitable	Unsuitable
Ambient light immunity	High	Middle	Low

### ■ Direct TOF

The direct TOF method calculates the distance to a target by measuring the time ( $\Delta T$ ) required for pulsed light emitted from the light source to reach the target and return to the sensor. This method offers the advantages that the distance measurement range is wide and the optical system can be made compact. A disadvantage is that the circuit design and configuration are more complex to read out pulsed light at high speeds.



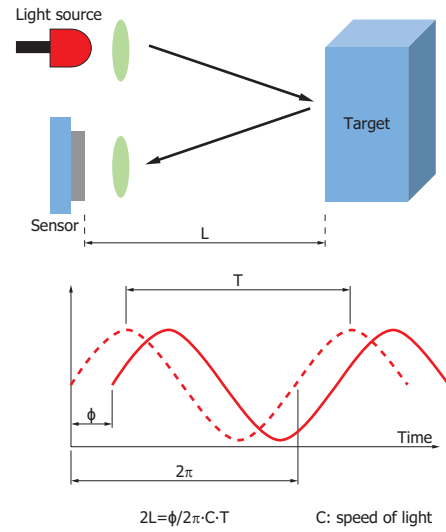
$$2L = C \cdot \Delta T$$

C: speed of light

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## ■ Indirect TOF

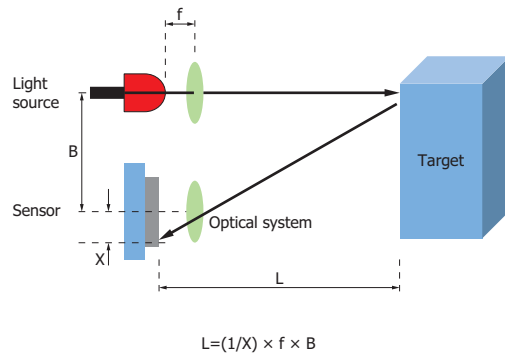
The indirect TOF method calculates the distance to a target by measuring the phase difference between the signal and the return light. Compared to direct TOF, this method provides better accuracy in short distance measurement. Also, since no time measurement circuit is needed, the circuit can be made compact and so is ideal for use with array sensors. However, this method is less suited for long distance measurement since it cannot perform one or more cycles of distance measurement.



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## ■ Triangulation

The triangulation method calculates the distance to a target by measuring the position (X) to which the light reflected from the target returns. This method offers the advantage that the accuracy in short distance measurement is high, but has the drawbacks that miniaturizing the circuit is difficult and the measurement is affected by ambient light.

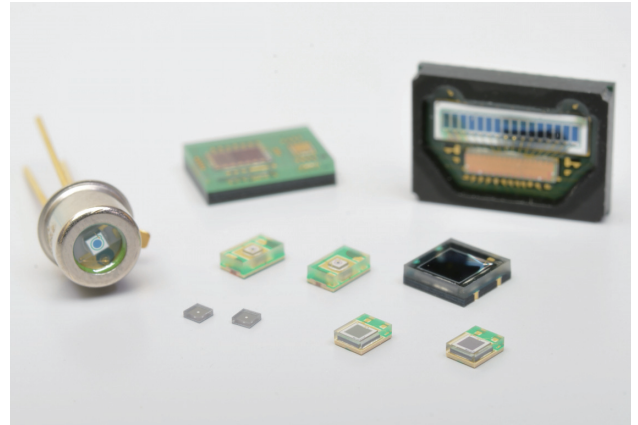


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## Detector demands for rangefinder and LIDAR application

Detectors used for distance measurement are required to have the following characteristics from the perspective of response and operating environment.

- High sensitivity
- Low noise
- High speed response
- Usable under strong ambient light condition
  - Especially in automotive application
- Wide dynamic range
  - From a distance black target (very weak reflected light) to nearby shiny target (too much reflected light)
- Usable under wide temperature range
- Mass productivity and low cost
- Array capability



## Detector comparison

Recommended Hamamatsu detectors are MPPC, APD, and PIN photodiode. Each detector has its own characteristics, so select the appropriate detector by considering the distance to be measured, measurement accuracy, and so on.

### ■ MPPC®

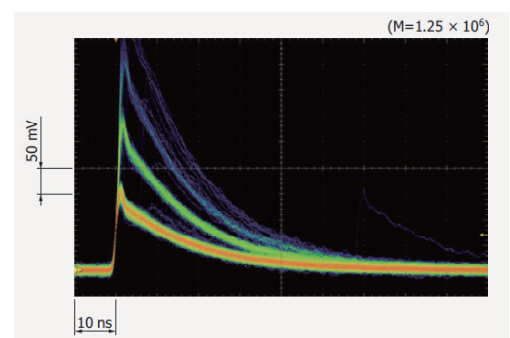
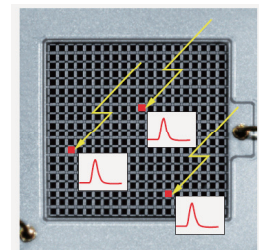
The MPPC is one of the devices called silicon photomultipliers (SiPM). It is a device using multiple APD pixels operating in Geiger mode. Although the MPPC is essentially an opto-semiconductor device, it has excellent photon-counting capability and can be used in various applications for detecting extremely weak light at the photon counting level.

It is the latest of the light-receiving element which will easily obtained multiplication factor of  $10^5$  to  $10^6$ .

As for the distance meter, treat of background light becomes more important. Most simply as for the distance meter, the minimum reception level is the background light intensity. Optical bandpass filter will be more important. The readout circuit, good S/N is obtained in the high-impedance type circuit. It is possible to reduce the readout circuit, you can achieve a low-cost range finder system in total. In addition, as an array type, that the received circuit is simple it is advantageous.

Suitable for:

- Long range
- Array / Large area
- Direct TOF
- Low cost



### ■ APD

It is widely used as a highly sensitive light-receiving element for range finder.

By electron multiplication, it will be able to increase the S/N until the shot noise limit.

In many cases, the minimum reception level is determined by the shot noise of background light. For this reason, in the range finder, often used is several tens of times of the multiplication factor to 10 times. It will be possible to capture the distance of distant target than in the case of PIN photodiode. In order to reduce the shot noise due to the background light, it is used in conjunction with optical bandpass filters. The readout circuit, as in the case of PIN photodiode, transimpedance amplifier will be used.

Suitable for:

- Long range
- Direct TOF/In-direct TOF array
- High ambient light with bandpass filter

### ■ PIN photodiode

As for range finder, it is the most simple light-receiving element. Its sensitivity is stable, it is uniform. Wide dynamic range. It can also be used under strong background light. The read circuit, and the transimpedance amplifier is widely used. The minimum receive level is determined by the noise of the readout circuit.

Suitable for:

- Short range
- Direct TOF / In-direct TOF
- Low cost
- Array / Large area
- High ambient light
- Low voltage operation

### ☒ Comparison chart

Parameter	MPPC <sup>®</sup>	APD	PIN photodiode
Range	Middle	Long	Short
Accuracy	High	High	High
Readout circuit	Simple	Complex	Complex
Operation voltage	to several tens of V	100 to 200 V	to 10 V
Gain	10 <sup>5</sup>	10 to 100	1
Temperature sensitivity	Middle	High	Low
Response time	Fast	Medium	Medium
Ambient light immunity	Medium	Medium	High
Array	Suitable	Suitable	Suitable
Gap	Narrow	Wide	Wide
Uniformity	Good	Depends on the size	Good
Main factor of noise	Sunlight power	Shot noise	TIA thermal noise

## Front-end IC

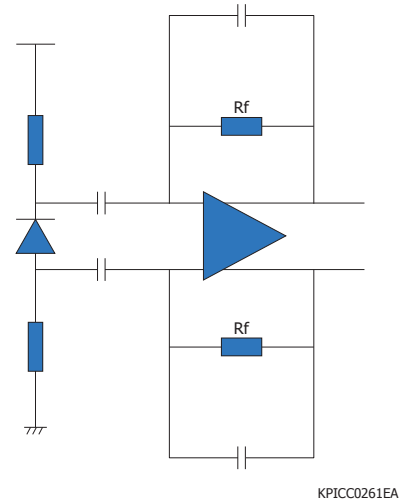
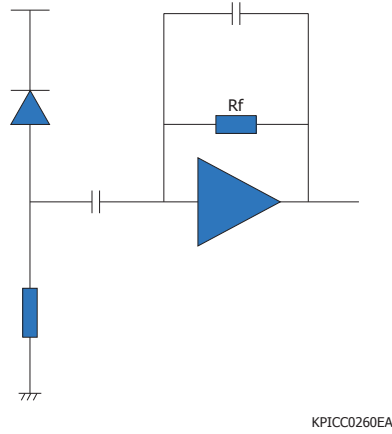
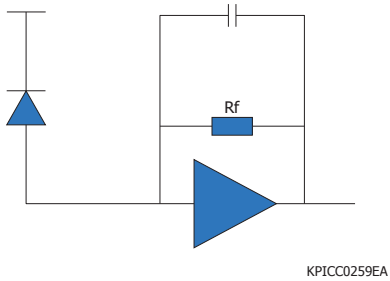
In distance measurement applications, the presence of a front-end IC for processing the signal from the detector is a must. The front-end IC receives current output from the detector and converts it into voltage. It is used not only for distance measurement but in various applications such as optical communication equipment, analytical instruments, and scientific measurement instruments.

Hamamatsu has developed three types of high-performance front-end IC: TIA (transimpedance amplifier) types, CSA (charge sensitive amplifier) types, and Resistance load types, all of which have the following characteristics. Hamamatsu also offers photosensor with front-end iC that integrate a front-end IC and a photosensor in one package.

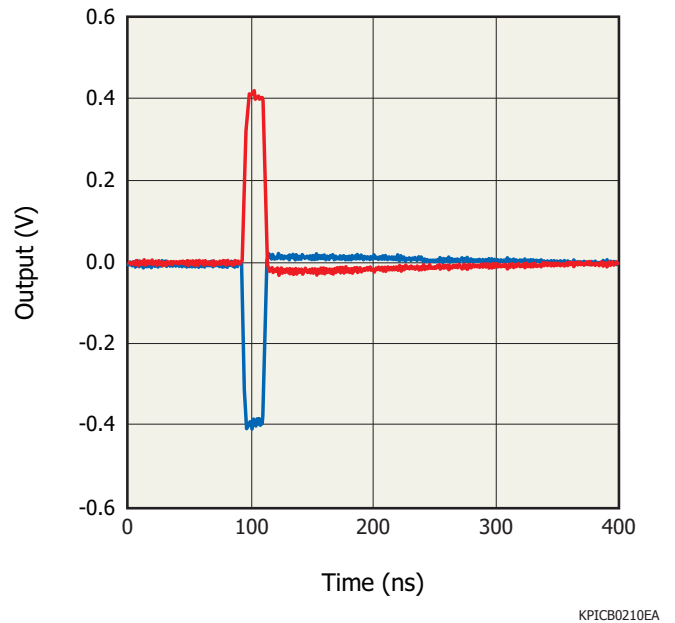
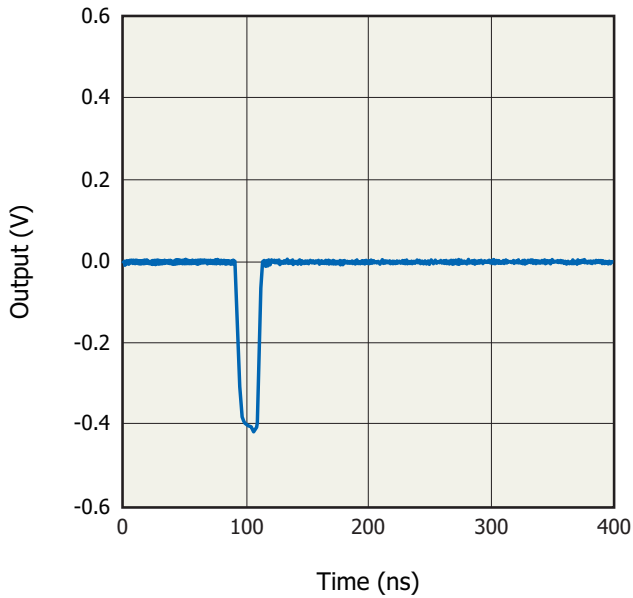
Parameter	TIA	CSA	Resistance load
Power consumption	High	High	Low
Array	Suitable	Suitable	Suitable
Speed	High	Medium	Low
Gain	Medium	High	Medium
Noise	Medium	Low	Medium
Readout circuit	Complex	Complex	Simple
Suitable photosensors	MPPC, APD, PIN photodiode	MPPC, APD, PIN photodiode	MPPC

## ■ TIA types

A TIA is a high-speed amplifier that converts photocurrent generated in a photodetector into voltage, and is frequently used in direct TOF for timing detection. The higher the feedback resistance ( $R_f$ ), the higher the gain and the better the S/N ratio, but the slower the response speed becomes.

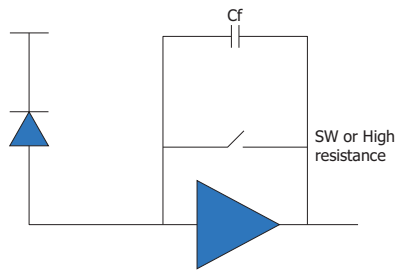


## ▷ Example of TIA output

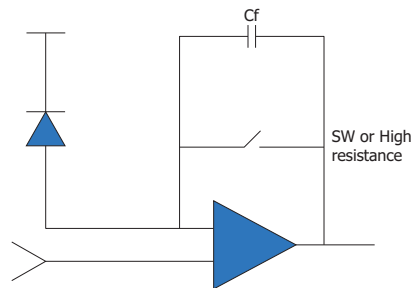


## ■ CSA types

Compared to a TIA, CSA have very high (more than 100 k $\Omega$ ) feedback resistance ( $R_f$ ), so the response speed is slow but the gain and S/N ratio are high. This makes charge sensitive amplifiers ideal for use with array detectors having small photosensitive areas where the incident signal light levels are low.



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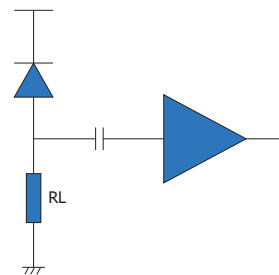
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## ■ Resistance load types

The Resistance load type is basically a resistor and has no amplifier for current-to-voltage conversion. This means that power consumption is very low and the circuit configuration is small and simple, making it ideal for use with array detectors. A disadvantage is that the response speed is slow when compared to TIA.



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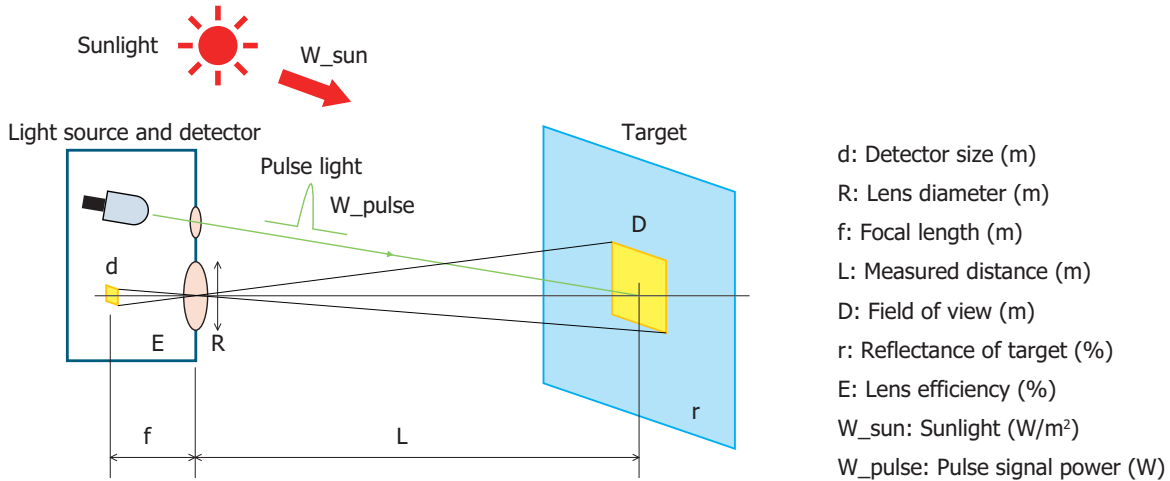


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**Measurement distance calculation method of detectors in direct TOF**

**Measurement distance calculation method**



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\* On P.9 to P.13, calculations are based on the following conditions, unless otherwise specified.

W <sub>sun</sub> : 1000 W/m <sup>2</sup>	r: 50 %	B: 200 MHz	x: 0.2
d: 0.1 mm	E: 90 %	Rf: 5 kΩ	
R: 20 mm	BPF: 5.7 % (850±30 nm)	M: 100	
f: 30 mm	T: 27 °C	A: 0.5 A/W	

**Calculation method of natural light**

Photosensitive area d is magnified L/f times by the lens and projected on the target object. ( $D = d \times L/f$ ) Given sunlight W<sub>sun</sub>(W/m<sup>2</sup>), the light level at the projection area (W<sub>sun1</sub>) is  $W_{sun1} = W_{sun} \times D^2$ .

The light level that the detector receives through the light receiving lens is expressed as  $W_{sun2} = W_{sun1} \times \Omega \times r \times 1/\pi \times E \times BPF = W_{sun} \times (d \times R/2f)^2 \times r \times E \times BPF$ .

Ω: Light receiving lens solid angle [sr]  $\Omega \approx (R/2)^2 \times \pi/L^2$

r: Reflectance of the target object [%]

E: Lens efficiency [%]

BPF: Band-pass filter transmittance (transmittance of sunlight) [%]

R: Lens diameter [m]

L: Distance to the target object [m]

Based on the above equation, sun light can be reduced by decreasing the projection size D and increasing the band-pass filter attenuation. Sun light must be reduced as much as possible because it is related to noise.

## ■ Calculation method of signal light

The light level that is received by the detector after the signal light  $W_{\text{pulse}}$  reflects off of the target object is expressed as  $W_{\text{pulse1}} = W_{\text{pulse}} \times \Omega \times r \times 1/\pi \times E = W_{\text{pulse}} \times (R/2L)^2 \times r \times E$ .

$\Omega$ : Light receiving lens solid angle [sr]  $\Omega \approx (R/2)^2 \times \pi/L^2$

r: Reflectance of the target object [%]

E: Lens efficiency [%]

R: Lens diameter [m]

L: Distance to the target object [m]

The light level received by the detector  $W_{\text{pulse1}}$  is inversely proportional to the square of the distance L. To increase the incident light level, the signal light's pulse power  $W_{\text{pulse}}$  or the lens diameter R must be increased.

## ■ Noise

(1) TIA noise

When a PIN photodiode and APD is used in a distance measurement application, signals are often read using TIAs.

Equivalent input power noise of TIA thermal noise  $In1[W]$  is expressed by the following equation.

$$In1^2 = \frac{4 \times k \times T \times B}{R_f \times M^2 \times A^2}$$

k: Boltzmann's constant  $1.38 \times 10^{-23}$

T: Temperature [K]

B: Bandwidth [Hz]

$R_f$ : TIA feedback resistor [ $\Omega$ ]

M: APD gain (1 in the case of a PIN photodiode)

A: PD spectral sensitivity [A/W]

Increasing  $R_f$  is effective in reducing thermal noise, but there is a trade-off with the TIA bandwidth. Moreover, when compared to a PIN photodiode, the noise of an APDs is reduced by the amount of gain. As such, the dominant factor of noise for an APD is shot noise, and that for a PIN photodiode is thermal noise (depending on the natural light).

### (2) Shot noise

Shot noise due to sun light  $In_2[W]$  is expressed by the following equation.

$$In_2^2 = \frac{2 \times q \times IL \times B \times M^x}{A^2}$$

q: Charge per electron  $1.6 \times 10^{-19}[C]$

IL: Photocurrent [A] when  $M=1$  ( $IL=A \times W_{sum2}$ )

B: Bandwidth [Hz]

M: APD gain

x: Excess noise index

A: PD spectral sensitivity [A/W]

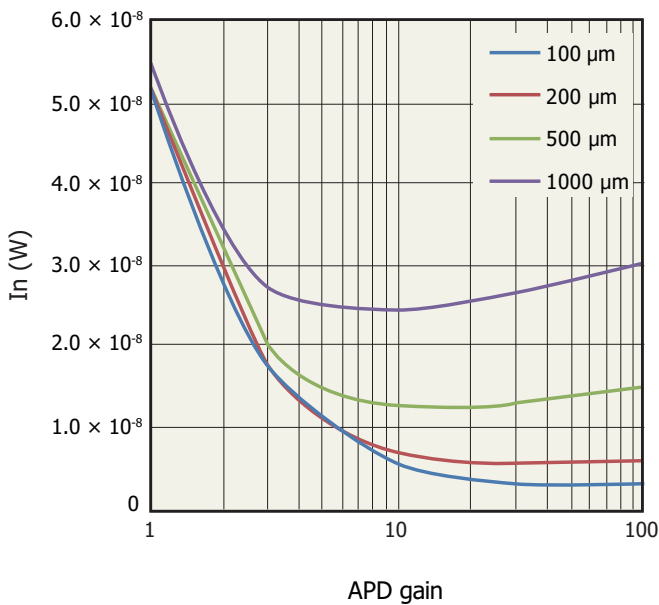
In the case of an APD, increasing the gain increases the signal, but this also increases shot noise according to the excess noise index. As such, high gain does not necessarily result in high S/N. There is an optimal gain.

Given the above, the total noise ( $In$ ) can be expressed as

$$In^2 = In_1^2 + In_2^2$$

$$= \frac{4 \times k \times T \times B}{R_f \times M^2 \times A^2} + \frac{2 \times q \times IL \times B \times M^x}{A^2}$$

### ☞ In vs APD gain (d=100 μm to 1000 μm)



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The smaller the detector size, the less the natural light, which results in less noise.

## ■ Calculation method of pulse signal power that causes S/N to be 1

The S/N of the APD and PIN photodiodes is determined from  $W_{pulse1}$  { : the detected signal level of the light emitted at pulse signal power ( $W_{pulse}$ ) reflected from the target} and  $I_n$  (: the combined noise of TIA shot noise with TIA thermal noise). As such, the  $W_{pulse}$  value that would cause the S/N of the APD and PIN photodiodes to be 1 can be determined by calculating the value that would produce a  $W_{pulse1}=I_n$  relationship.

On the other hand, the S/N of the MPPC is determined from  $W_{pulse1}$  and  $W_{sun2}$  { : the detected signal level of the sunlight ( $W_{sun}$ ) reflected from the target}. The  $W_{pulse}$  value that would cause the S/N of the MPPC to be 1 can be determined by calculating the value that would produce a  $W_{pulse1}=W_{sun2}$  relationship.

Following figures show the relationship between the measurement distance, natural light and pulse signal that causes S/N to be 1. At  $1000 \text{ W/m}^2$ , the S/N is better with the APD than the MPPC.

This is because with the APD shot noise is the dominant factor and therefore the noise is root times the natural light, but with the MPPC, the noise is directly affected by the intensity of the natural light, which means that the pulse signal must be stronger than the natural light. As such, the field of view and the bandwidth of the band-pass filter must be narrowed more than the APD to reduce the natural light.

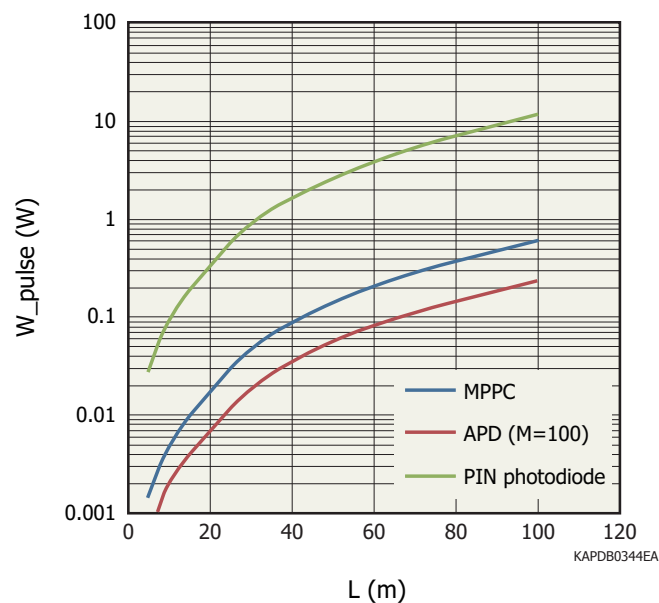
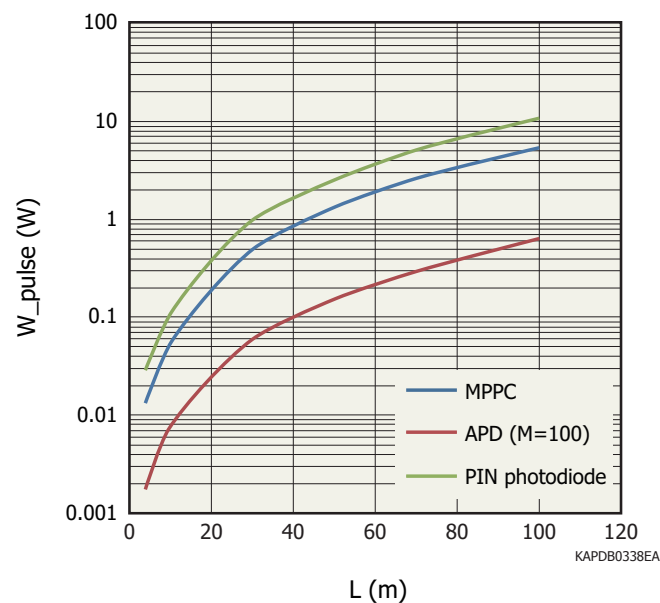
Figure B and Figure D show cases where the natural light received by the detector is reduced to about one-tenth of its original signal level (Figure A and Figure C) by changing the focal length ( $f$ ) from 30 mm to 100 mm and reducing the area of view. The S/N of the MPPC is improved about 10 times. Under the calculation conditions in this document, the S/N of the APD is better than that of the MPPC for  $W_{sun}=1000 \text{ W/m}^2$ , but there are cases where the MPPC would be better by further reducing the natural light.

At the same time, the MPPC is advantageous in that its operating voltage is lower than that of the APD, that a TIA is not necessary for the readout circuit, and that it is a resistive load. Therefore, the construction of the rangefinder can be made simpler than using an APD.

## ☒ Relationship between distance and pulse optical power that causes S/N to be 1 ( $W_{sun}=1000 \text{ W/m}^2$ )

(Figure A)  $f=30 \text{ mm}$

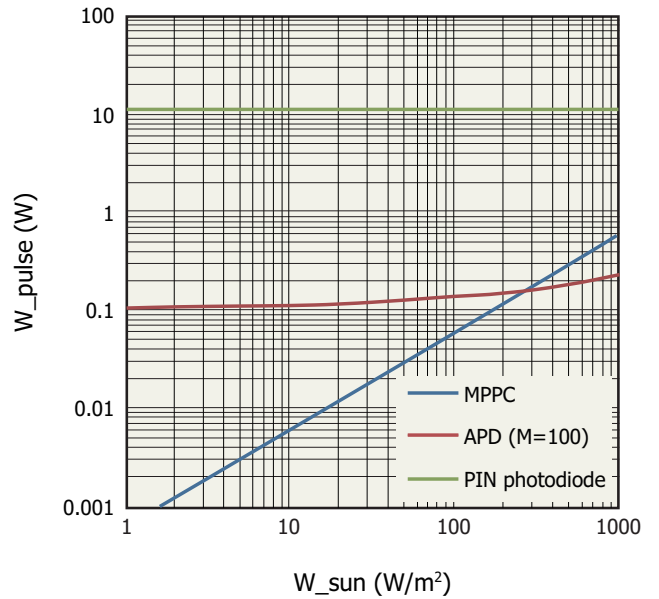
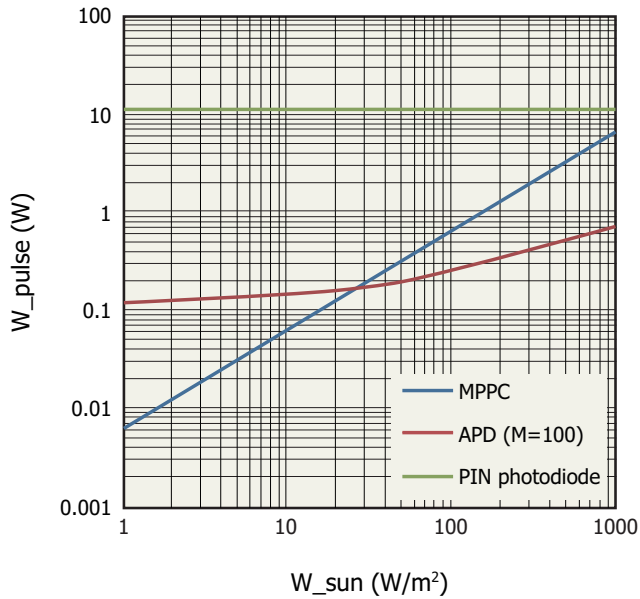
(Figure B)  $f=100 \text{ mm}$



**> Relationship between sun light and pulse optical power that causes S/N to be 1 (L=100 m)**

(Figure C) f=30 mm

(Figure D) f=100 mm



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**APD/MPPC temperature compensation**

(1) For stabilizing the gain

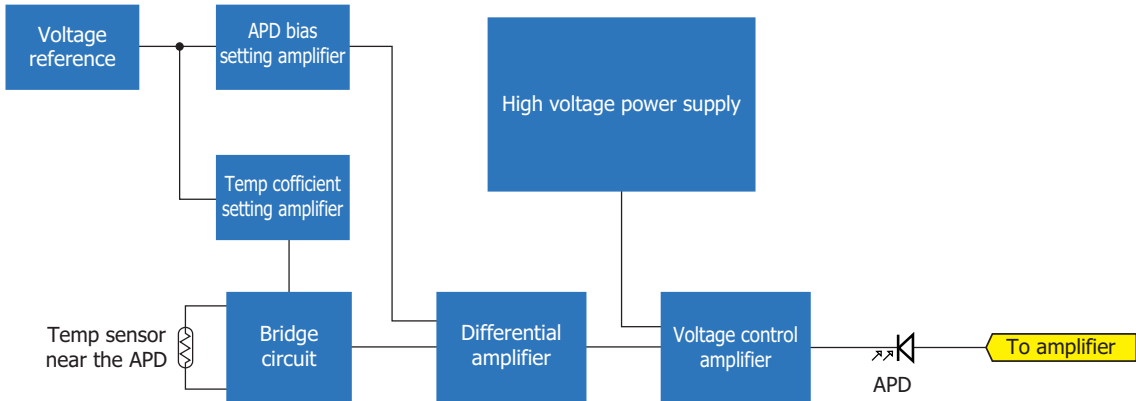
The MPPC gain and the APD gain have temperature-dependent characteristics. As the temperature rises, the crystal lattice vibrates more heavily, increasing the possibility that the accelerated carriers may collide with the lattice before reaching a sufficiently large energy level and making it difficult for ionization to take place. Therefore, the gain at a certain reverse voltage becomes small as the temperature rises. Because the MPPC/APD gain varies depending on the temperature, to use it over a wide temperature range, you need to use temperature compensation by which the reverse voltage is controlled according to the temperature variation or use temperature control by which the MPPC/APD temperature is kept constant. In temperature compensation, a temperature sensor is installed near the MPPC/APD to control the reverse voltage according to the MPPC/APD's temperature coefficient. In temperature control, a TE cooler element or an equivalent device is used to maintain a constant MPPC/APD temperature.

Temperature compensation is a method by which high voltage is varied according to the change in the ambient temperature based on the temperature information received from temperature sensors. It can be constructed using a fairly easy circuit configuration, but to achieve high stability, the ambient temperature must be varied and the temperature coefficient of the device must be measured. On the other hand, the temperature control method using a thermoelectric cooling element does not require the temperature coefficient of the device to be measured by varying the ambient temperature, but this method (1) has operating limitations when used in a wide temperature environment due to the constraints of  $\Delta T$  of the thermoelectric cooling element, (2) requires sufficient heat dissipation mechanism, and (3) has cost issues.

(2) Temperature compensation circuit

There are several temperature compensation methods depending on the temperature sensor in use. Here, we introduce a temperature compensation circuit employed by the APD module. The circuit block diagram is shown below.

**Temperature compensation circuit**



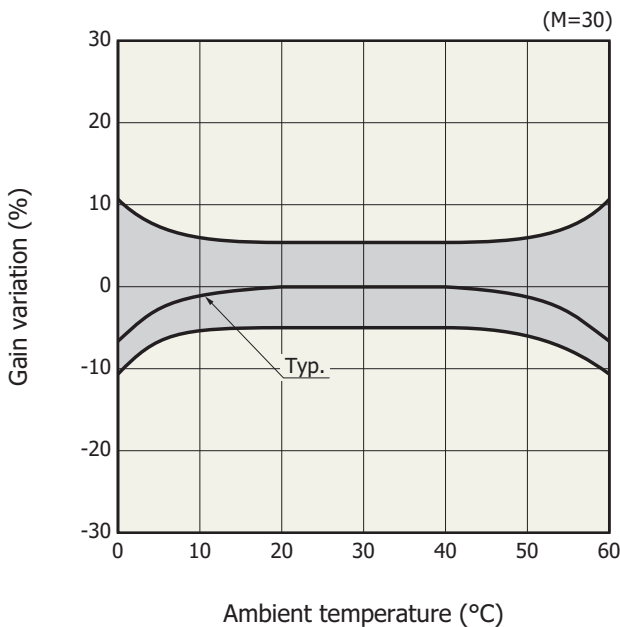
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For the temperature sensor, a resistance thermometer whose resistance changes linearly with the ambient temperature is used in the bridge circuit. The circuit reflects the differential voltage from the bridge circuit when the temperature changes in the bias voltage. With the APD module, the ambient temperature is varied, and the temperature compensation setting circuit is adjusted according to the temperature coefficient of the APD in use. In addition, since each APD requires a different bias voltage to achieve the same gain, both the gain and temperature coefficient are adjusted according to each APD using an APD bias setting circuit in order to keep the APD gain almost constant even when the ambient temperature changes.

(3) Temperature stability when a temperature-compensation circuit is used

The following graph is an example of temperature stability after using a temperature-compensation circuit to adjust the APD module.

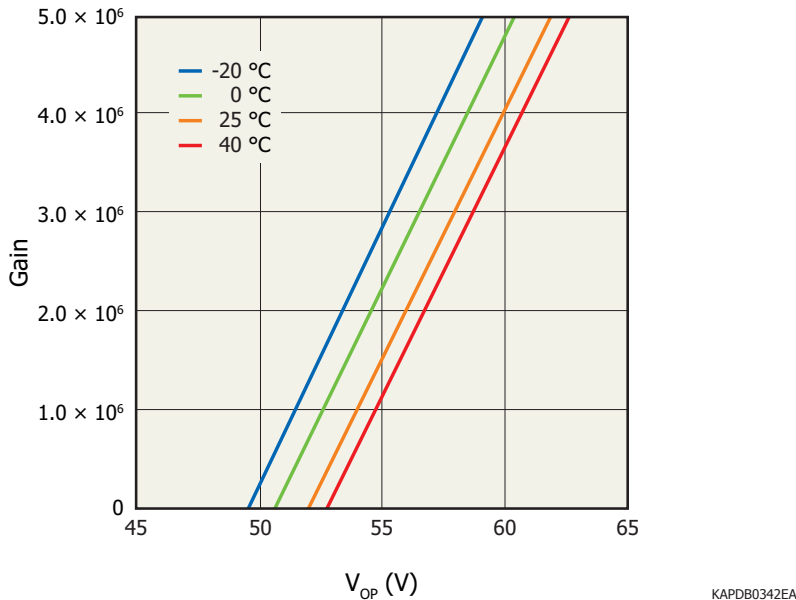
**Gain temperature characteristics**



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Like the APD, the MPPC also has a temperature coefficient. Therefore, temperature compensation or temperature control is also required in order to use the MPPC over a wide temperature range.

### Gain vs. operating voltage



The MPPC gain is defined by the product of the overvoltage and the capacitance of one pixel, but because the MPPC's terminal capacitance is small, we can see that the influence of the temperature on the gain is not the magnitude of the temperature coefficient value itself.

Parameter	Temperature dependence
V <sub>BR</sub>	54 mV / °C
Gain	2.74E+4 / °C (1.8% / °C)
PDE	0.17% / °C (V <sub>over</sub> = 5 V)

$$\text{Gain} = M, \text{Vov} = \text{VOP} - \text{VBR}$$

$$M = 1/q \times C_p \times \text{Vov} = 1/q \times C_p \times (\text{VOP} - \text{VBR})$$

$$dM/dT = -1/q \times C_p \times d\text{VBR}/dT$$

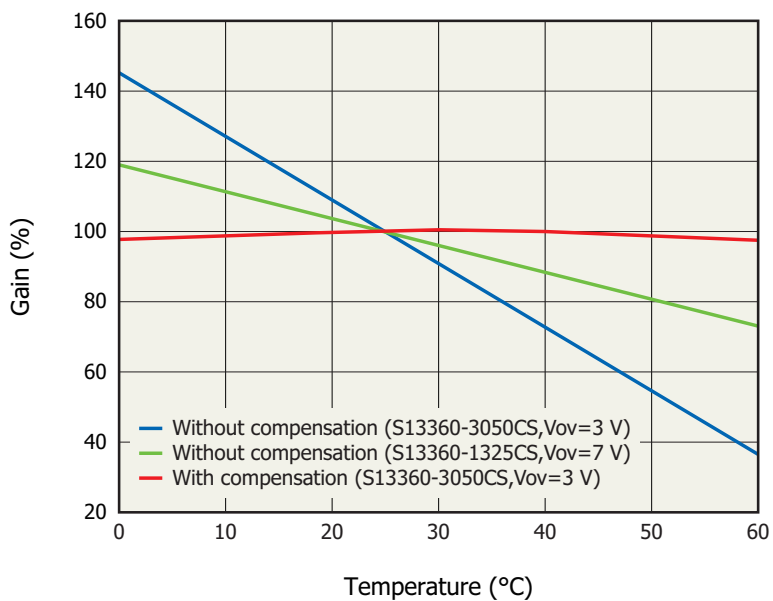
$$dM/dT \times 1/M = -d\text{VBR}/dT / (\text{VOP} - \text{VBR}) \text{ [%]}$$

Gain variation is decided by C<sub>p</sub> and V<sub>BR</sub>. One of the MPPC feature, **MPPC is low C<sub>p</sub>**.  
If anywhere, MPPC **require power supply with temperature compensation**.

But, if a highly accurate gain-temperature stability is required, temperature compensation must be performed. As such, Hamamatsu provides the C11204 series high voltage power supply module for MPPC that incorporates a high accuracy temperature-compensation circuit.

The gain variation was measured when temperature compensation was applied to the MPPC using the C11204-01 and when it was not.

### > Gain vs. temperature (using the C11204-01)



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If temperature compensation is applied with the C11204-01, gain variation can be reduced significantly over a wide temperature range. On the other hand, reducing the pixel size and using the MPPC at a high operating voltage can also reduce temperature-dependent gain variation even without a temperature-compensation circuit or temperature compensation adjustment.

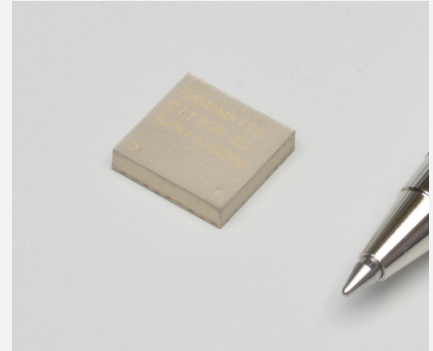


**Power supply for MPPC**

**■ Bias power supply with built-in high precision temperature compensation**

**C11204-02**

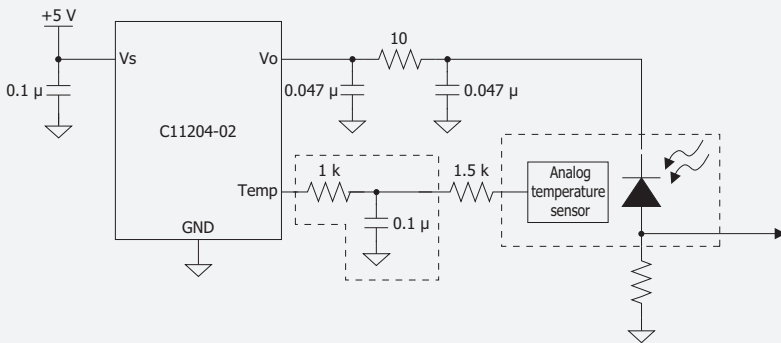
The C11204-02 is a high voltage power supply that is optimized for MPPCs (multi-pixel photon counters). It can output up to 90 V. It contains a temperature compensation function that constantly optimizes the MPPC operation even in environments with varying temperatures. It also has built-in output voltage monitor and output current monitor. All functions can be controlled from a PC via its serial interface (UART). The C11204-02 is compact and surface mount type of the C11204-01.



Parameter	Symbol	Condition	Min.	Typ.	Max.	Unit
Current consumption	I <sub>cc</sub>	V <sub>o</sub> =72 V, no load	-	20	40	mA
Output voltage	V <sub>o</sub>	No load	-	40 to 90	-	V
Output current	I <sub>o</sub>		0	-	2	mA
Ripple noise*	V <sub>n</sub>	V <sub>o</sub> =72 V, no load	-	0.1	0.2	mVp-p
Setting precision	-	V <sub>o</sub> =72 V, no load	-	±10	-	mV
Setting resolution	-		-	1.8	-	mV
Temperature stability	-	25 ± 10 °C V <sub>o</sub> =72 V, no load	-	±10	-	ppm/°C
Interface	-	RXD, output voltage control	Serial communication (UART)			-
Low level input voltage	V <sub>il</sub>	RXD, output voltage control	0	-	0.4V <sub>s</sub>	V
High level input voltage	V <sub>ih</sub>	TXD, status monitor	0.65V <sub>s</sub>	-	V <sub>s</sub>	V
Low level output voltage	V <sub>ol</sub>	TXD, status monitor	-	-	2.0	V
High level output voltage	V <sub>oh</sub>		V <sub>s</sub> - 2.0	-	V <sub>s</sub>	V

\* Using the recommended circuit

**> Circuit example**



Note:

For the bypass capacitor to connect to V<sub>o</sub>, use a high-withstand-voltage, low-ESR capacitor. Provide a noise filter near the Temp pin.

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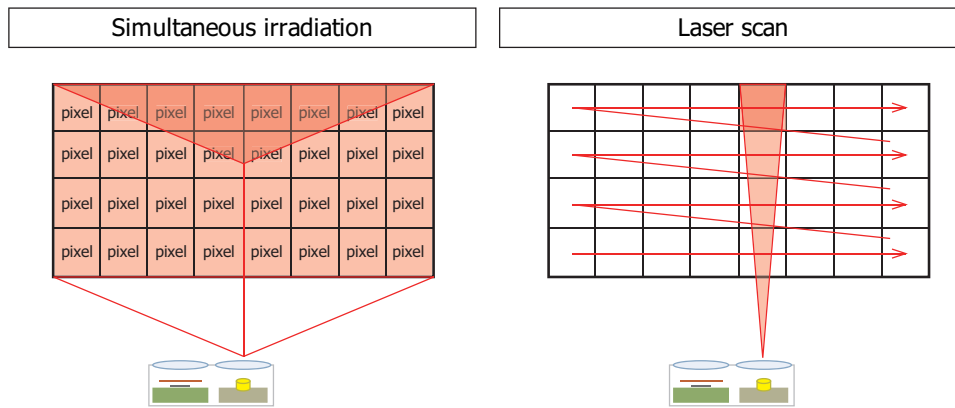
## Using detector arrays

There are two light pulse emission methods when the detector is an array: simultaneous irradiation and laser scan.

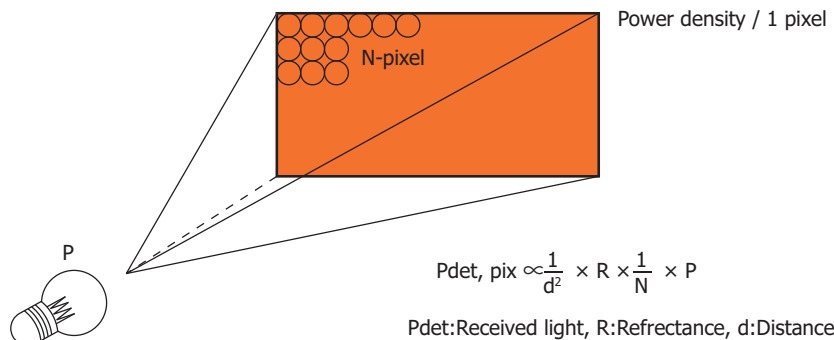
In the simultaneous irradiation method, light is collectively irradiated on the target object, so distances can be obtained at the same time, but because the light source must be widened, the power density is reduced, and this makes it unsuitable for long distance measurement. In addition, because the signals must be processed simultaneously, a processing circuit is required for every pixel, which increases the circuit scale.

In the laser scan method, light whose field of view is reduced to a single pixel or several pixels (1 row of pixels for example) is scanned. As the light source size is smaller when compared to collective irradiation, the power density is higher, which makes it suitable for long distance measurement. But, because the light source is scanned, distance measurement cannot be performed at the same timing. In addition, because the light source is scanned, a motor and MEMS mirror become necessary.

### > Using detector arrays



Good	This method can measure all the pixels in the simultaneous timing.	Improvement of power density. For long distance range
Bad	Power density decreases. (Long distance, wide angle and low reflectance target measurement is difficult.)	Measurement in different timing (trade-off between resolution and fps)
[Example] The choice of light source	LED (or LD)	LD + Scanning device (Motor, MEMS mirror)

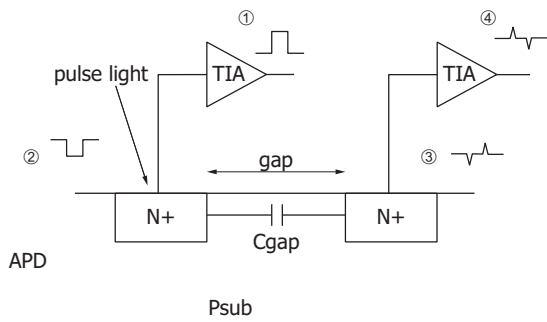


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## ■ Crosstalk

Crosstalk in an array detector is an unwanted signal output from channels other than the channel where the signal light has entered. In distance measurement applications, if such crosstalk exceeds the comparator threshold value, false detection of an object might occur even if no such object exists. Crosstalk is generated by the signal that is transferred across adjacent channels through the parasitic capacitance between each channel of the detector. This means that crosstalk can be reduced by widening the gap between each channel, but this also lowers the open area ratio and requires making the chip size larger. In addition to widening the gap to reduce crosstalk, Hamamatsu can reduce crosstalk by engineering the photodiode structure and circuit.

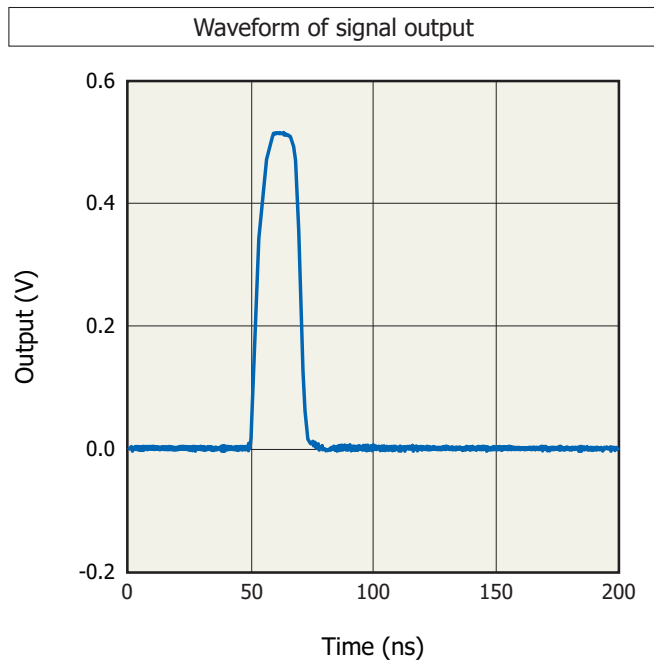
## ☒ Crosstalk



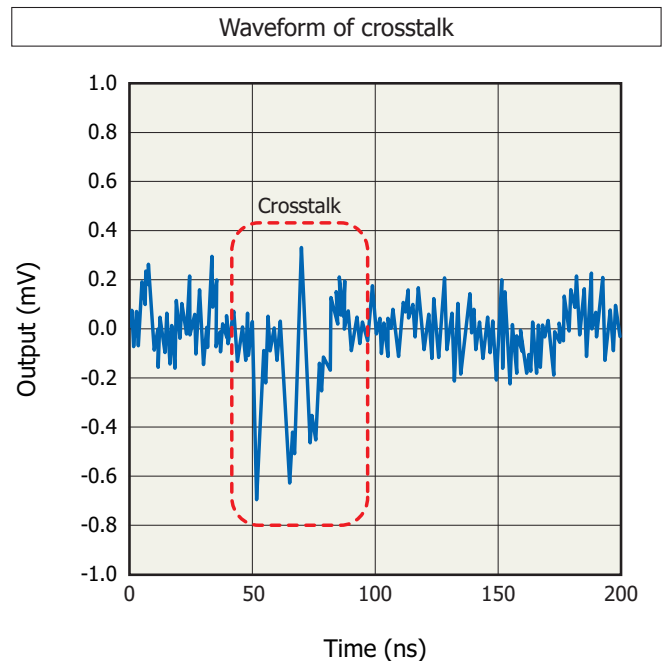
- ① Output of the light incident channel
- ② Gate voltage of the light incident channel
- ③ Differential of signal ②
- ④ Crosstalk

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## ☒ Waveform of signal output and crosstalk (S13645-01CR, M=50, low gain, light pulse width=20 ns, pulse power 10 $\mu$ W)



KPIC0211EA



KPIC0212EA

## Removal of background light (band-pass filter)

Photocurrent generated in a photodetector by background light affects the shot noise. In the case of an APD, the shot noise is determined by equation below.

$$I_n^2 = 2qILBM^{2+x}$$

$I_n^2$  : Equivalent input current noise

$q$  : Elementally charge

$I_L$  : Photo current ( $M=1$ )

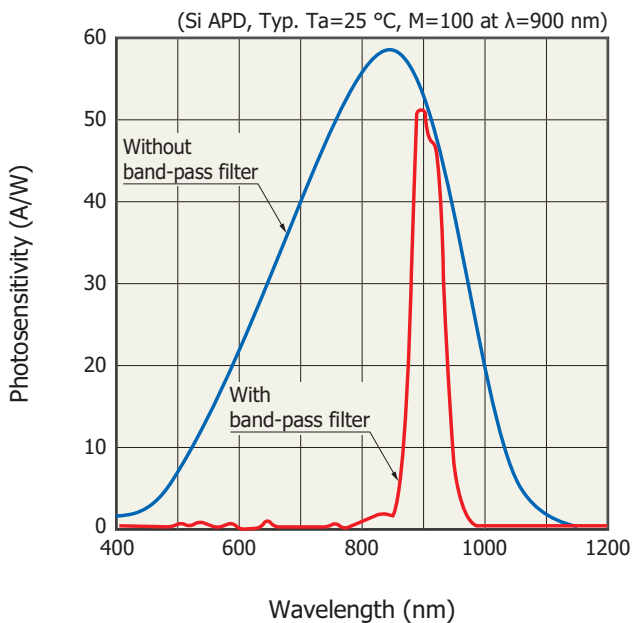
$B$  : Band width

$M$  : APD gain

$x$  : Excess noise figure

As seen from equation above, the shot noise increases as the photocurrent  $I_L$  rises due to an increase in the background light. The increased shot noise will degrade the measurement distance range and accuracy. To minimize effects from background light, using a band-pass filter proves effective in cutting off background light on wavelengths other than the signal light. The narrower the band-pass filter width, the more the background light can be removed, but the band-pass filter width should be selected by considering the margin for wavelength fluctuations and temperature characteristics of the signal light.

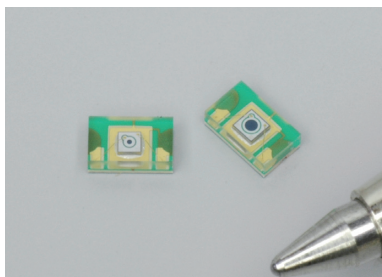
### > Band-pass filter implementation example



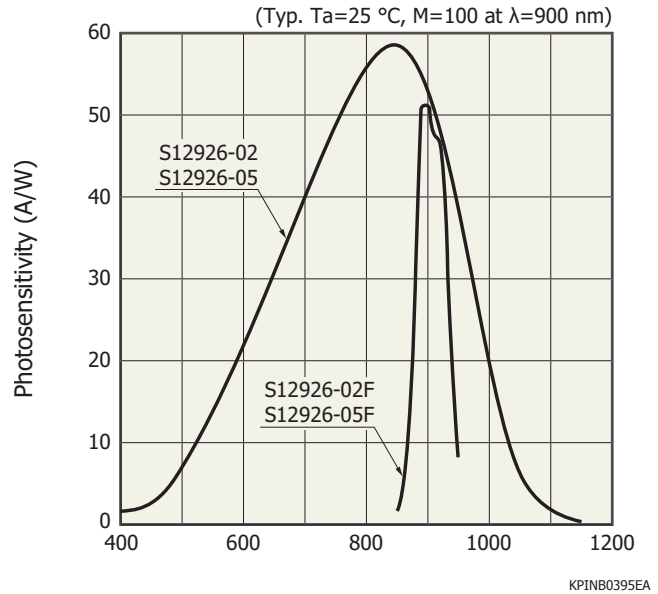
**IR-enhanced detector**

■ **Si APD for 900 nm band**

These Si APD (S12926 series) are designed to provide a peak sensitivity wavelength in the 900 nm band where optical rangefinders are increasingly used. The S12926 series is available in a small surface-mount package and operates at low bias voltage, making it ideal for handheld distance meters. IR-enhanced type of MPPC is also under development.

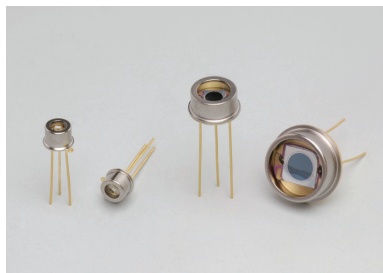


▷ **Spectral response**

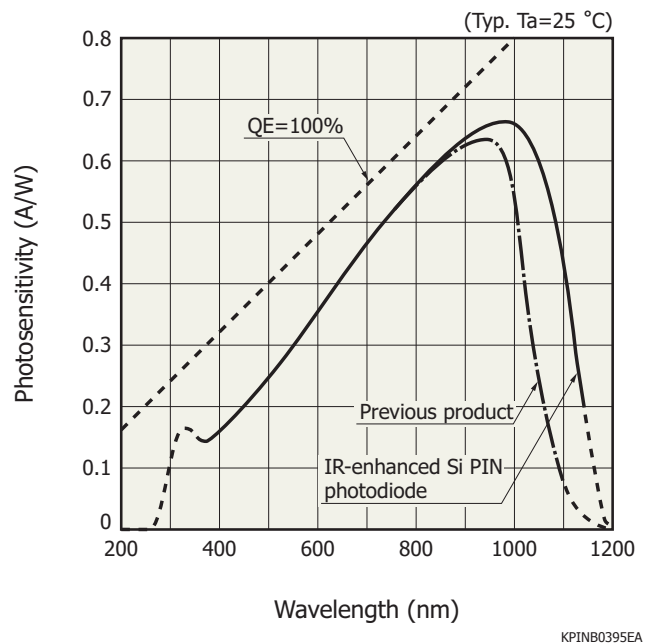


■ **IR-enhanced Si PIN photodiode**

The IR-enhanced Si PIN photodiode features drastically improved sensitivity in the near infrared region for wavelengths from 900 nm to 1100 nm. With the IR-enhanced Si PIN photodiode, special micromachining is applied to the backside to achieve high sensitivity in the near infrared region. For example, if this technology is applied to a Si photodiode whose quantum efficiency is 25% at a wavelength of 1.06 μm, a quantum efficiency of 72% (about three times higher) can be achieved. This technology allows photodiodes with high-speed and high sensitivity in the near infrared region to be produced, which was difficult in the past.

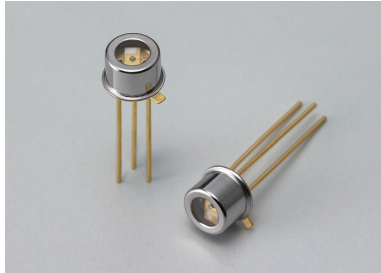


▷ **Spectral response**



## ■ InGaAs APD

The InGaAs APD features a higher peak wavelength than the Si APD. In distance measurement applications, this is advantageous in terms of (1) eye safety and (2) natural light reduction. The disadvantage is that it is expensive.



### (1) Eye safety

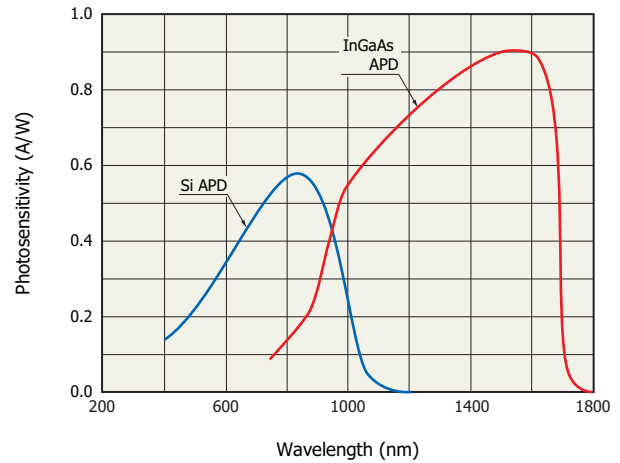
Because eyeball transmittance is high for visible light, the light in this spectral range passes through the eyeball and condenses on the retina and may cause damage. Therefore, safety standards have been established for the laser light intensity. One such standard is the laser light maximum permissible exposure (MPE).

When the MPEs for 905 nm and 1450 nm (wavelengths often used in lasers) are compared, the MPE for 1450 nm is about five orders of magnitude greater. When the pulse power is increased by five orders of magnitude, this is equivalent to about 300 times in terms of distance. In other words, the same distance can be measured even when the amplifier gain is five orders of magnitude smaller.

### (2) Natural light reduction

The right graph shows the power spectrum of sunlight. Near the 1400 nm region, there is hardly any effect of sunlight, and therefore the effect of shot noise can be drastically reduced.

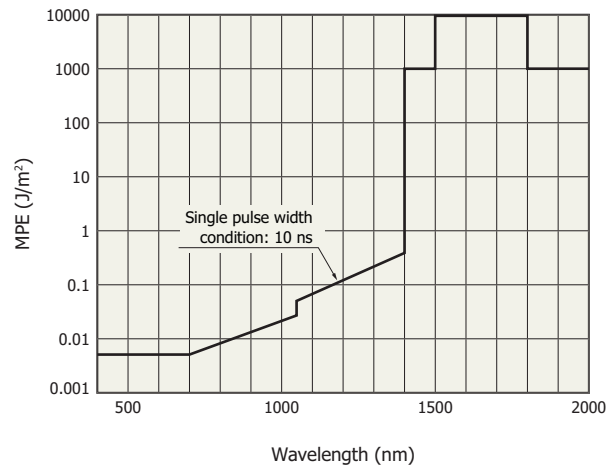
## > Spectral response (Si APD: S12426 series, InGaAs APD: G8931 series)



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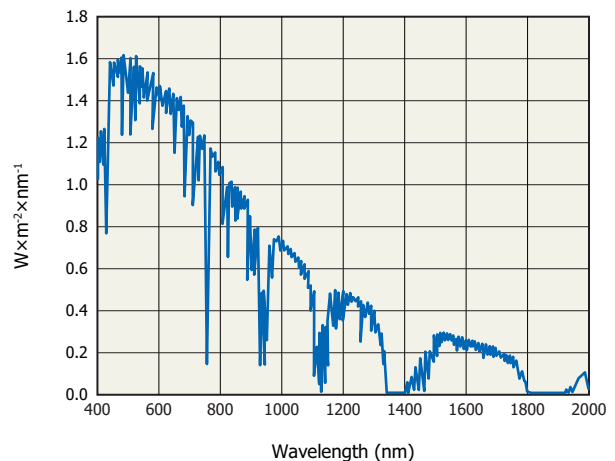
## > Maximum permissible exposure (MPE)

Reference: based on IEC 60825-1



KPICB0208EA

## > Power spectrum of sunlight



KPICB0213EA

**Rangefinders that use MEMS mirrors**

**Overview of MEMS mirror**

Our MEMS mirrors are miniature electromagnetic mirrors that incorporate our unique MEMS technology. Whereas electromagnetic mirrors are usually configured with a permanent magnet surrounding the mirror chip, our MEMS mirrors use a small, powerful magnet positioned under the mirror, a design that achieves an ultra-compact size. Within a magnetic field generated by the magnet, electrical current flowing in the coil surrounding the mirror produces a Lorentz force based on Fleming’s left-hand rule, and this force drives the mirror. Hamamatsu electromagnetic MEMS micro mirrors offer a wide optical deflection angle and high mirror reflectivity as well as low power consumption. An evaluation circuit with USB interface is also available.

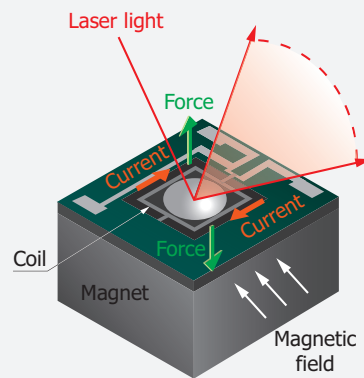
Features

- Low voltage drive (5 V or less)
- Low power consumption
- Wide optical deflection angle of mirror
- Compact size

Structure

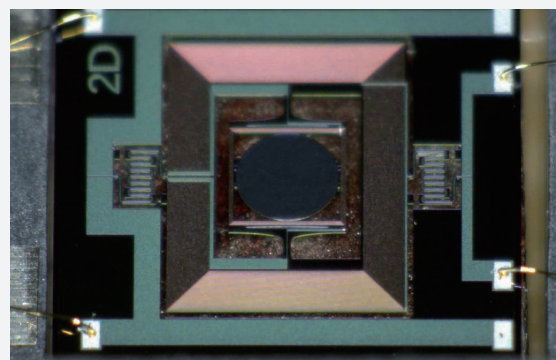
An electromagnetic MEMS micro mirror consists of a mirror chip consisting of a mirror, coil, and torsion bars, and a permanent magnet (see > Structure diagram). The mirror, coil, and torsion bars of the mirror chip are formed as thin films in a portion of a Si substrate using monolithic MEMS processing technology. The magnet is placed under the mirror chip instead of around the chip as with a typical electromagnetic mirror, and this results in a more compact size. The magnet is designed to provide an optimal magnetic field to the coil around the mirror formed on the mirror chip. There are two types of electromagnetic MEMS micro mirrors: a single-axis 1D type and a dual-axis 2D type.

> **Structure diagram**



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> **MEMS mirror chip**



## Operating principle

The basic operating principle for controlling the angle of the mirror is based on current, magnetic field, and Fleming's left-hand rule, which represents the relationship between the direction of the force, current and magnetic field. This rule states that when a coil is placed perpendicular to a magnetic field, and current flows in the coil, force is exerted on the coil. That force is called the Lorentz force, and its magnitude is proportional to the magnitude of the current that flows and the strength of the magnetic field.

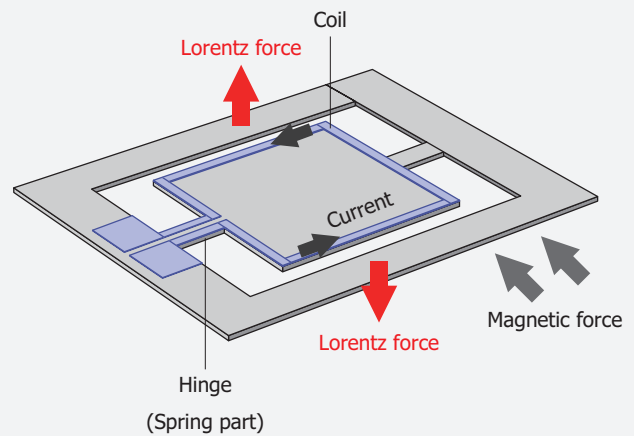
The mirror is supported by support plates called torsion bars, which serve as the axes of rotation when the mirror rotates and also as torsion springs for suppressing mirror rotation.

When current is passed through the coil-shaped electrical wiring formed around the mirror, rotational torque (the Lorentz force) that tilts the mirror is produced, and at the same time, a reaction force caused by the elastic force of the torsion bar springs is exerted, and the rotation of the mirror stops when these two forces balance each other. In other words, the angle of the mirror can be controlled by changing the magnitude of the applied current.

On the other hand, MEMS mirrors are machines, albeit very small ones, and they have their own natural resonance vibration, which is determined by their mass, structure and spring constant. Using this resonance vibration, it is possible to obtain a large mirror deflection angle very quickly and using only a small current. Since, in the case of resonance vibration, mirror movements are represented as sine waves and complex movements are not possible, resonance vibration is used for applications where constant reciprocating motion suffices.

Note that, as described later, the operation mode that uses resonance vibration is called resonant mode, and the operation mode that does not use resonance vibration is called non-resonant mode. Further, in view of the fact that the non-resonant mode is used for linear operation, it is called also linear mode. In this case, the resonant mode is called non-linear mode.

### Operating principle of MEMS mirrors



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## Differences in driving methods

Various driving methods based on a number of different principles are used for MEMS mirrors, each having advantages and disadvantages. The following table shows a performance comparison of the various MEMS mirror driving methods. This table shows that the electromagnetic method offers excellent balance, allowing use of a low voltage in both resonant mode and linear mode (non-resonant mode). Therefore, it can be applied to many applications as well as to battery-powered portable devices.



▷ Comparison by MEMS mirror driving method

	Electrostatic method	Piezoelectric method	Electromagnetic method
Rotational torque	Low	High	Medium
Control voltage	50 V to 150 V	20 V to 50 V	to 5 V
Control current	≈0 mA	up to 20 mA	up to 20 mA
Power consumption	<<1 mW	High	<100 mW
Optical deflection angle (resonant mode)	±10°	±25°	±25°
Optical deflection angle (linear mode)	±5°	Difficult control	±15°

Operating mode

As mentioned in "Operation principle" there are two types of operation mode for MEMS mirrors: linear mode (non-resonant mode) and non-linear mode (resonant mode). In principle, a MEMS mirror can be operated in either one of these modes, but normally, the design of MEMS mirrors is optimized for operation in one of these modes, and operating a MEMS mirror in the non-recommended mode involves a higher risk of breakdown. Therefore, it is recommended to use each MEMS mirror in its recommended operation mode.

■ Linear mode (non-resonant mode)

Linear mode is used to accurately control the mirror angle by means of the drive current. In this operation mode, the angle of the mirror changes also in accordance with changes in the drive current. However, the operation must be done at a frequency lower than the specific resonant frequency of the mirror so that the mirror does not resonate. Normally, operation using a frequency on the order of 1/5 to 1/10 of the resonance frequency, or even lower, is recommended.

In linear mode, the relationship between the drive current and optical deflection angle of the mirror exhibits excellent linearity, and the angle reproducibility relative to the drive current is excellent.

■ Non-linear mode (resonant mode)

Non-linear mode is the mode in which the mirror is driven at the resonant frequency of the mirror. This mode is used to drive a non-linear mode dedicated MEMS mirror, or to drive an axis specified for non-linear mode. As the input signal of the mirror, apply either a sine-wave or square-wave current signal at the same frequency as the resonance frequency of the mirror.

In non-linear mode, even if the mirror is driven with a square wave, the deflection angle of the mirror operates as a sine wave. Further, phase lag occurs for the deflection angle in relation to the drive current. Therefore, even when the drive current is monitored, the deflection angle is not proportional to the drive current, and thus in order to grasp the deflection angle position, a different approach must be taken by employing either one of the following two methods: monitor the operation status of the MEMS mirror, or perform an estimation using the high reproducibility of electromagnetic MEMS mirrors.

One way to monitor the operating status of MEMS mirrors is to monitor the back electromotive force.

When a rangefinder that uses a MEMS mirror is considered, the appropriate optical system is determined according to the characteristics of the photosensor and light emitter. This section explains coaxial optical systems and non-coaxial optical systems.

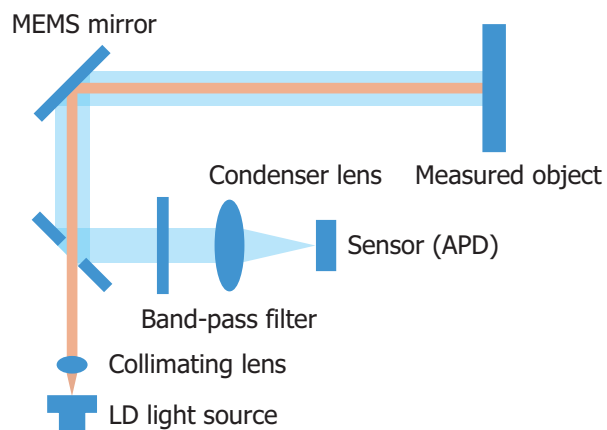
## ■ Coaxial optical system

In a coaxial optical system, the light emitting optical system and the light receiving optical system are on the same optical axis. Because a wide field of view is obtained by scanning through the MEMS mirror the emitted/received light combined on the same optical axis, a single type of device can be selected for the photosensor. In addition, as the condenser lens does not need to have a wide field of view, the system can be miniaturized.

The reflected light from the target always passes through the MEMS mirror. As such, the size of the MEMS mirror becomes the aperture, and this limits the light level and field of view. This achieves a highly robust system against background light but, at the same time, limits the measurable distance.

Further, in a coaxial optical system, the highest performance can be attained as a result of the light emitting system and light receiving system existing on the same optical axis, but the system is easily affected by any stray light that occurs on the optical axis. This means that a highly accurate optical alignment is required.

### ▷ Coaxial optical system



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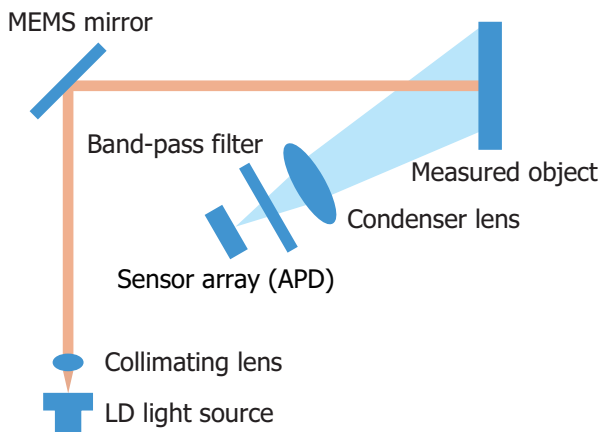
### ■ Non-coaxial optical system

In a non-coaxial optical system, a MEMS mirror is used only to scan the LD or other light source. The light receiving optical system uses a separate light condensing optical system to receive light. Because the effect of background light is extremely large when the reflected light from the entire target region is condensed to a single photosensor, it is a common practice to use a photosensor array for the light receiving system. To accurately condense the reflected light from the target to each pixel of the photosensor array, a light condensing system that uses multiple lenses is required. And this causes the system to become large. On the other hand, the light emitting system and light receiving system only need to be aligned just enough so that the entire emitted light can be received, so the accuracy required in assembly is not as stringent as the coaxial system.

In a non-coaxial optical system, the tilt angle of the MEMS mirror must be managed, and therefore position monitoring is a must.

The measurable distance depends on the effective aperture of the light receiving system. Because there is a trade-off between the effective aperture and the field of view, the lens field of view generally becomes narrower when longer distances are measured. To obtain both large effective aperture and wide field of view, the size of the lens system must be increased. However, though obtaining a wide field of view is possible by increasing the size of the lens system, this also increases the incident light level of background light. As a result, measures need to be taken to narrow the field of view per pixel of the photosensor.

### ☒ Non-coaxial optical system



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As described above, the coaxial optical system and non-coaxial optical system each have its own characteristics, and an appropriate optical system must be selected according to the required measurement range or measurement distance or the types of devices to be used for the light receiving system.

Parameter	Coaxial optical system	Non-coaxial optical system
Measurable distance	Short	Long
Photosensor	Single or Array	Array
Tolerance to background light	Good	Bad
System size	Small	Big
Difficulty in assembly	Hard	Middle

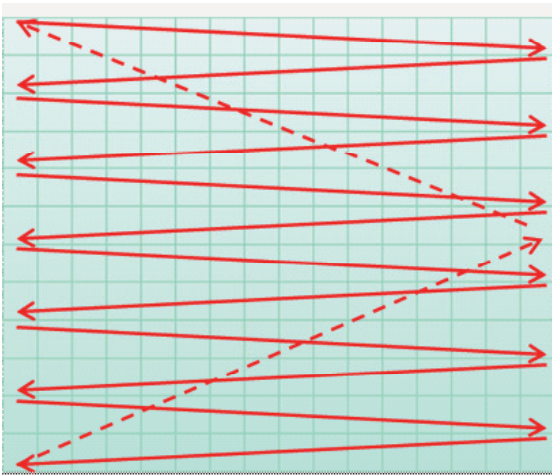
## MEMS mirror types and scan methods

There are several methods to scan a MEMS mirror two-dimensionally, and there is a suitable MEMS mirror type for each scan method.

There are three scan methods: raster, Lissajous, and vector. The vector scan is a method in which scanning is performed by moving directly between a point and another point in two-dimensional space, but this technical information will not go into the details of this method because it is not suitable for distance measurement applications.

### ■ Raster scan

The raster scan is a method in which scanning is performed two-dimensionally. A slight movement in the vertical direction is made while scanning once in the horizontal direction. In this case, the vertical scan rate is the same as the frame rate of the image. This requires that the horizontal scan speed be adequately fast relative to the vertical scan speed. As such, when implementing raster scanning using a MEMS mirror, a non-linear type, which provides wide deflection angle at high frequencies, is suitable for the horizontal axis, and a linear type, which enables synchronization with the horizontal axis, is suitable for the vertical axis.



The resolution in raster scanning is determined by the resonance frequency of the MEMS mirror and the required frame rate.

If a non-linear MEMS mirror is used for the horizontal axis, the time it takes to scan a single line,  $P_h$ , is one-half the resonance frequency. The horizontal resolution is the number of LD pulses that can be turned on during this scan period.

$$P_h = \frac{1}{2f_{H0}}$$

$f_{H0}$ : Resonant frequency of horizontal axis

As the time it takes to scan a single line is determined by the resonance frequency of the horizontal axis, the scan time for a sheet of image is determined by the required resolution. In addition, after completing the scanning of a sheet of image, there is a need to return to the scan start position. Therefore, the frame period is determined by the total of the image scan period and recovery period.

$$P_f = P_h \cdot R_v + P_r$$

$P_f$ : Period for single frame scan

$P_h$ : Period for single horizontal scan

$R_v$ : Vertical resolution

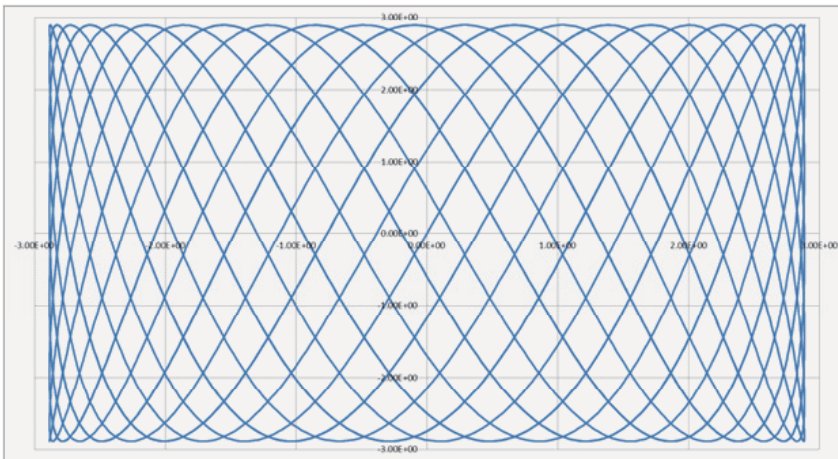
$P_r$ : Period for recovery scan

Normally, the recovery period is dead time that is not used for distance measurement, so recovering in a minimal time is desirable. But the linear mirror for the vertical axis also has a resonance frequency, and this limits the recovery period. If the recovery period is made short, the linear mirror will resonate causing unwanted vibration for scanning and will interfere with the accurate reproduction of the measurement position. As such, the recovery period must be adequately longer relative to the resonance frequency of the linear mirror.

As described above, to achieve high resolution and high frame rate requires a high resonance frequency, but because the resonance frequency and optical deflection angle are at a trade-off, appropriate specifications must be selected depending on the required resolution, frame rate, and scan range.

### ■ Lissajous scan

The Lissajous scan is a method in which scanning is performed asynchronously using a different constant frequency for the horizontal and vertical axes. Image is not complete after a single frame of scanning, but because the phase is off slightly due to different frequencies, a single sheet of image can be formed by superimposing multiple frames.



In a Lissajous scan, high-speed scanning is required for both the horizontal and vertical axes. Therefore, non-linear type mirrors are suitable for both axes. As non-linear mirrors provide high speed and wide deflection angle using resonant operation, system miniaturization can be expected.

However, because wide deflection angle is achieved through resonance, the deflection angle would drastically decrease if the mirrors were not operated at the resonance frequencies. The resonance frequency is unique to each object and varies due to changes in the ambient temperature.

Therefore, in Lissajous scanning where both axes are operated at resonance frequencies, the operating frequencies change depending on the ambient temperature, preventing the same positions from being scanned. This requires that the deflection angle of the MEMS mirror must be grasped at all times by the system.

# HAMAMATSU

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