MPPC®, MPPC modules

1. MPPC

The MPPC (multi-pixel photon counter) is one of the devices called Si-PM (silicon photomultiplier). It is a new type of photon-counting device using multiple APD (avalanche photodiode) pixels operating in Geiger mode. Although the MPPC is essentially an opto-semiconductor device, it has an excellent photon-counting capability and can be used in various applications for detecting extremely weak light at the photon counting level.
The MPPC operates on a low voltage and features a high multiplication ratio (gain), high photon detection efficiency, fast response, excellent time resolution, and wide spectral response range, so it delivers the high-performance level needed for photon counting. The MPPC is also immune to magnetic fields, highly resistant to mechanical shocks, and will not suffer from "burn-in" by incident light saturation, which are advantages unique to solid-state devices. The MPPC therefore has a potential for replacing conventional detectors used in photon counting up to now.
The MPPC is a high performance, easy-to-operate detector that is proving itself useful in a wide range of applications and fields including medical diagnosis, academic research, and measurements.

1-1. Operating principle

Photon counting

Light has a property in both a particle and a wave. When the light level becomes extremely low, light behaves as discrete particles (photons) allowing us to count the number of photons. Photon counting is a technique for measuring the number of individual photons.
The MPPC is suitable for photon counting since it offers an excellent time resolution and a multiplication function having a high gain and low noise. Compared to ordinary light measurement techniques that measure the output current as analog signals, photon counting delivers a higher S/N and higher stability even in measurements at very low light levels.

Geiger mode and quenching

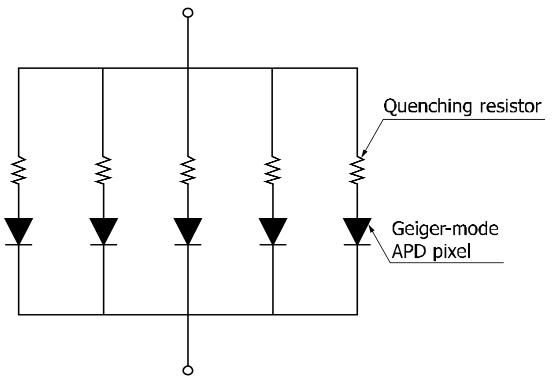
When the reverse voltage applied to an APD is set higher than the breakdown voltage, the electric field in the APD becomes high enough to cause a discharge (Geiger discharge) even by input of very weak light. The condition where an APD operates at this voltage level is called Geiger mode. The Geiger mode allows obtaining a large output by way of the discharge even when detecting a single photon. Once the Geiger discharge begins, it continues as long as the electric field in the APD is maintained.
To halt the Geiger discharge and detect the next photon, an external circuit outside the APD must lower the operating voltage. One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with the APD. This quickly stops avalanche multiplication in the APD because a drop in the operating voltage occurs when the output current caused by the Geiger discharge flows

in the quenching resistor. The output current caused by the Geiger discharge is a pulse waveform with a short rise time, while the output current when the Geiger discharge is halted by the quenching resistor is a pulse waveform with a relatively slow fall time.

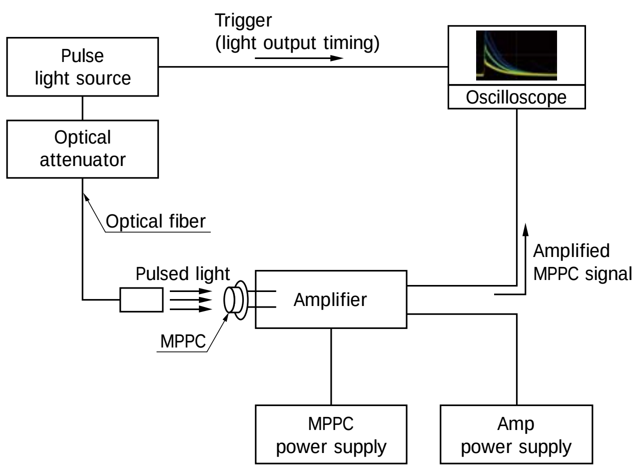
Structure

Figure 1-1 shows a structure of an MPPC. The basic element (pixel) of an MPPC is a combination of the Geiger mode APD and quenching resistor, and a large number of these pixels are electrically connected and arranged in two dimensions.

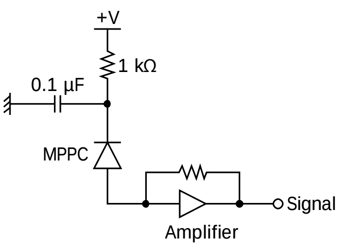
[Figure 1-1] Structure



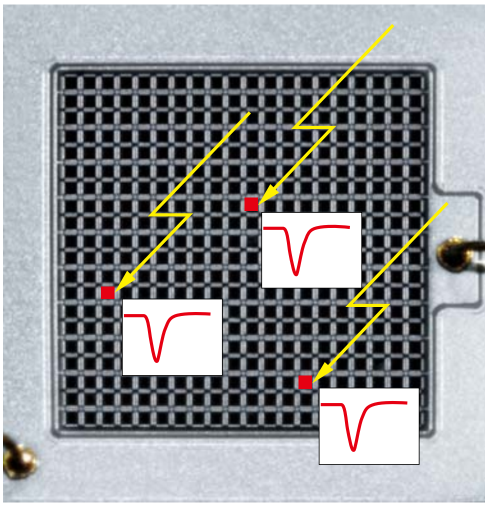
[Figure 1-2] Block diagram for MPPC evaluation (with an oscilloscope)



[Figure 1-3] Basic connection diagram for MPPC



[Figure 1-4] Image of MPPC's photon counting



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Basic operation

Each pixel in the MPPC outputs a pulse at the same amplitude when it detects a photon. The pulses generated by multiple pixels are output while superimposed onto each other. For example, if four photons are incident on different pixels and detected at the same time, then the MPPC outputs a signal whose amplitude equals the height of the 4 superimposed pulses.

Each pixel outputs only one pulse and this does not vary with the number of incident photons. So the number of output pulses is always one regardless of whether one photon or two or more photons enter a pixel at the same time. This means that MPPC output linearity gets worse as more photons are incident on the MPPC such as when two or more photons enter one pixel. This makes it essential to select an MPPC having enough pixels to match the number of incident photons.

The following two methods are used to estimate the number of photons detected by the MPPC.

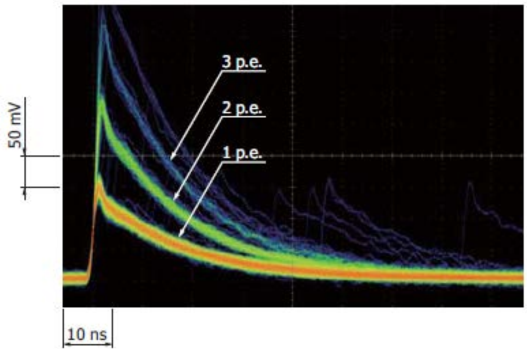
(1) Observing the pulse

(2) Integrating the output charge

(1) Observing the pulse

When light enters an MPPC at a particular timing, its output pulse height varies depending on the number of photons detected. Figure 1-5 shows output pulses from the MPPC obtained when it was illuminated with the pulsed light at photon counting levels and then amplified with a linear amplifier and observed on an oscilloscope. As can be seen from the figure, the pulses are separated from each other according to the number of detected photons such as one, two, three photons and so on. Measuring the height of each pulse allows estimating the number of detected photons.

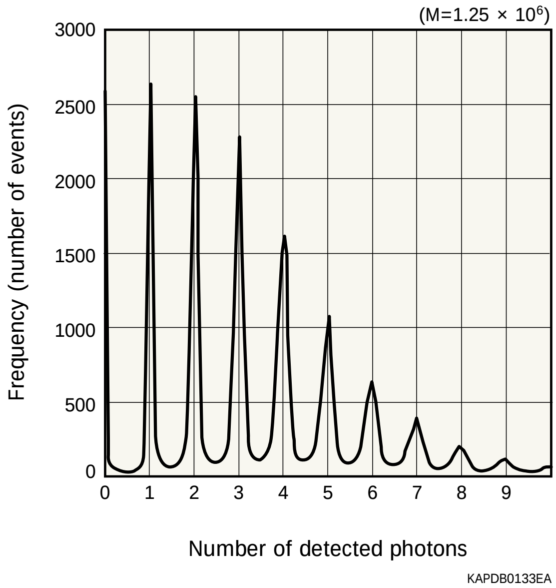
[Figure 1-5] Pulse waveforms when using a linear amplifier (120 times) [S10362-11-050U, M=7.5 × 10^5]



(2) Integrating the output charge

When the timing at which light enters an MPPC is different, the number of photons detected within a certain time period can be estimated by integrating the MPPC output using an integrating amplifier or similar device. Figure 1-6 shows a distribution plotted for the amount of charge accumulated in the integration time. Each peak from the left corresponds to the pedestal, one photon, two photons, three photons and so on. Since the MPPC gain is high enough to produce a large amount of charge, the distribution can show discrete peaks according to the number of detected photons.

[Figure 1-6] Pulse height spectrum when using charge amplifier (S10362-11-025U, M=2.75 × 10^5)



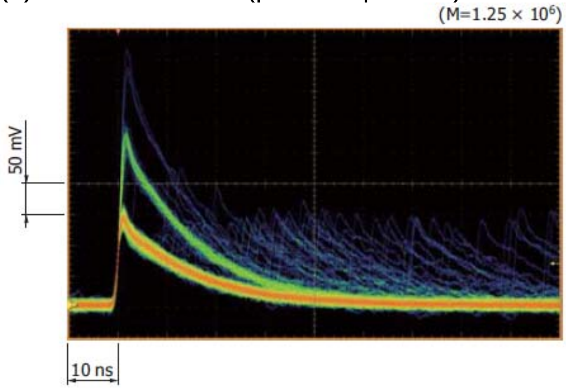
1-2. Features

Low afterpluse

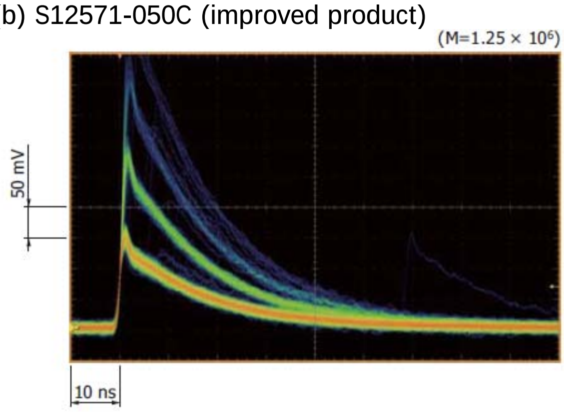
When an MPPC detects photon, the output may contain spurious signals appearing with a time delay from the light input to the MPPC. These signals are called afterpulses. Compared to our previously marketed products, new MPPCs have drastically reduced afterpulses due to use of improved materials and wafer process technologies. Reducing afterpulses brings various benefits such as a better S/N, a wider operating voltage range, and improved time resolution and photon detection efficiency in high voltage regions.

[Figure 1-7] Pulse waveforms

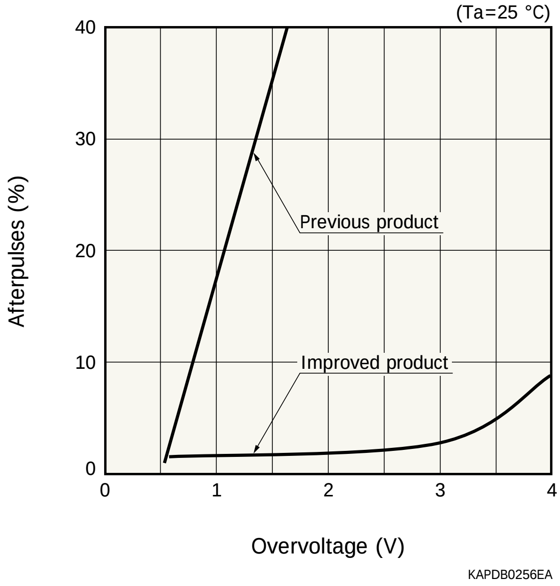
(a) S10362-11-050C (previous product)



(b) S12571-050C (improved product)



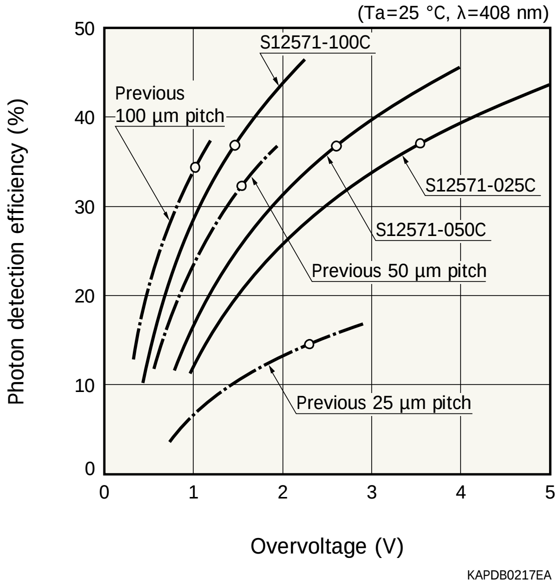
[Figure 1-8] Afterpulses vs. overvoltage (typical example)



High photon detection efficiency

The MPPC has a peak sensitivity at a wavelength around 400 to 500 nm. The MPPC sensitivity is referred to as photon detection efficiency (PDE) and is calculated by the product of the quantum efficiency, fill factor, and avalanche probability. Among these, the avalanche probability is dependent on the operating voltage. Our 25 μm pitch MPPC is designed for a high fill factor that vastly improves photon detection efficiency compared to our previous types. Using this same design, we also developed 10 μm and 15 μm pitch MPPC that delivers a high-speed response and wide dynamic range as well as high photon detection efficiency. The fill factor of 50 μm and 100 μm pitch MPPC is almost the same as that of previous types because increasing the fill factor also causes a significant rise in crosstalk.

[Figure1-9] Photon detection efficiency vs. overvoltage (typical example)



Photon detection efficiency does not include crosstalk and afterpulses.

[Table 1-1] Recommended overvoltage

Pixel pitch (μm)	Recommended overvoltage Vov	
	Previous type (V)	S12571 series (V)
25	2.3	3.5
50	1.5	2.6
100	1.0	1.4

$$Vov = Vop - V_{BR} \quad \cdots\cdot \ (1)$$

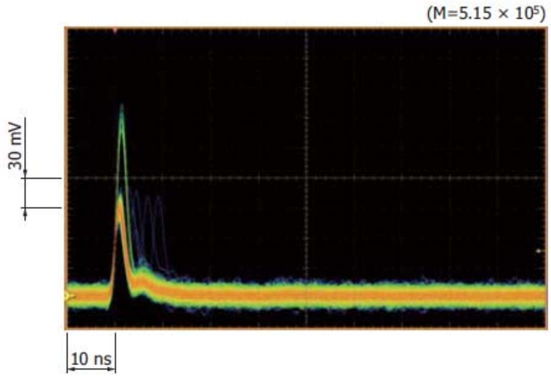
Vov: overvoltage
Vop: operating temperature
V_{BR}: breakdown voltage

Wide dynamic range

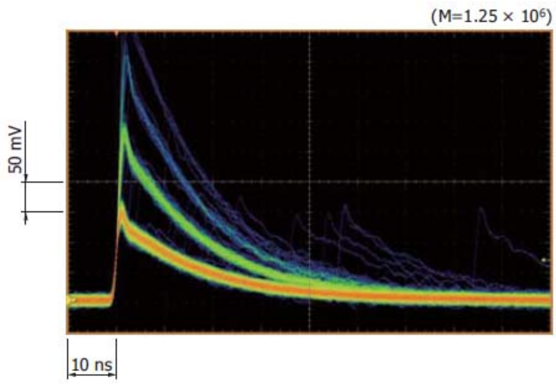
The MPPC dynamic range is determined by the number of pixels and the pixel recovery time. Hamamatsu has developed the MPPC with the smallest pixel pitch of 10 μm, which increases the number of pixels per unit area and shortens the response time. This drastically extends the MPPC dynamic range.

[Figure 1-10] Pulse waveforms

(a) High-speed, wide dynamic range type S12571-010C (pixel pitch: 10 μm)



(b) General measurement type S12571-050C (pixel pitch: 50 μm)

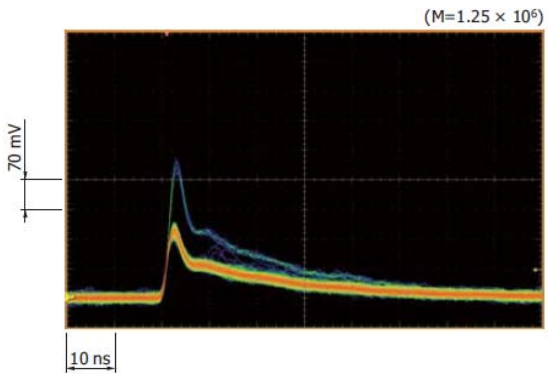


Low crosstalk

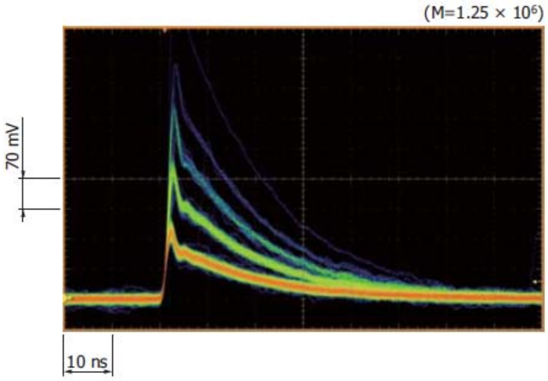
The pixel that detects photons may affect other pixels, making them produce spurious pulses. This phenomenon is called crosstalk. Hamamatsu has drastically reduced the crosstalk in precision measurement MPPC by creating barriers between pixels.

[Figure 1-11] Pulse waveforms

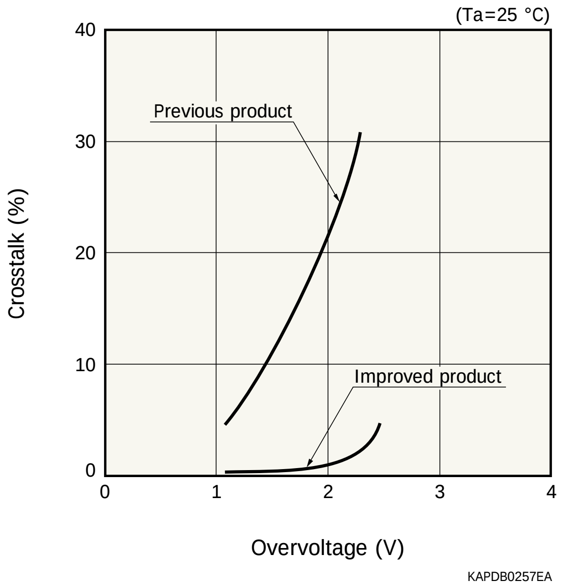
(a) Precision measurement type S12651-050C (pixel pitch: 50 μm)



(b) General measurement type S12571-050C (pixel pitch: 50 μm)



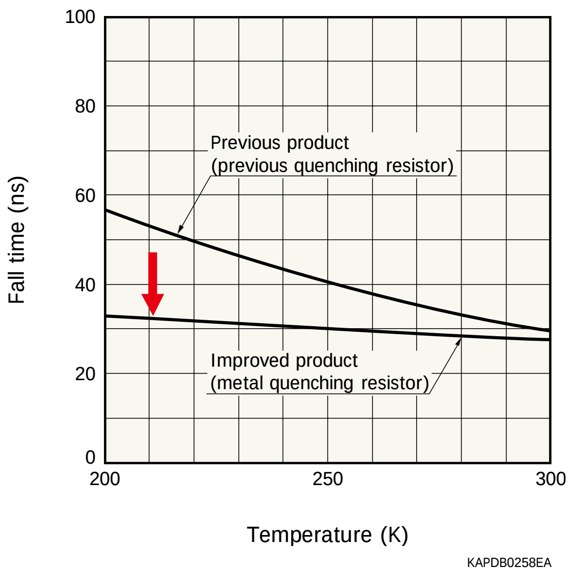
[Figure 1-12] Crosstalk vs. overvoltage (typical example)



Metal quenching resistor

Using a metal quenching resistor has reduced a the resistance temperature coefficient to one-fifth of the previous types. This suppresses variations in the fall time in the low temperature region and so improves the output waveforms at low temperatures. For information on the operating temperature range, refer to the individual catalogs.

[Figure 1-13] Fall time vs. temperature (photosensitive area: 1 mm sq, pixel pitch: 50 μm, typical example)



1-3. Characteristics

MPPC lineup and characteristics

To meet a diverse range of applications and needs, Hamamatsu provides a full lineup of MPPC types in different pixel sizes and photosensitive areas. The MPPC packages include metal, ceramic, PWB (printed wire boards), and CSP (chip size packages). As multichannel array detectors, Hamamatsu also provides MPPC arrays having uniform characteristics on each channel and narrow dead space between the channels.

MPPC types with a larger pixel size are suitable for applications where a high gain and high photon detection efficiency are required, while types with a smaller pixel size are suitable for applications requiring high-speed response and a wide dynamic range. Types with a larger photosensitive area are suitable for a wide-dynamic-range measurement or detection of light incident on a large area, while types with smaller photosensitive area are suitable for applications where a high speed and low dark count are needed.

The MPPC characteristics vary with the operating voltage. To deal with various applications, the MPPC operating voltage can be adjusted as desired over a wide setting range. To obtain an optimum MPPC performance, the operating voltage should be set higher in applications requiring a high gain, high photon detection efficiency, and superior time resolution, while it should be set lower in applications requiring low noise (low dark, low crosstalk, and low afterpulses).

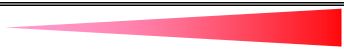
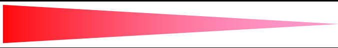
[Table 1-2] MPPC characteristics versus pixel size

Pixel size	Small ◄——► Large
Gain	(increases toward Large)
Photon detection efficiency	(increases toward Large)
Dynamic range	(increases toward Small)
Repetition rate	(increases toward Small)

[Table 1-3] MPPC characteristics versus photosensitive area

Photosensitive area	Small ⟷ Large
Dynamic range	
Light detection area	
Repetition rate	
Dark	

[Table 1-4] MPPC characteristics versus operating voltage

Operating voltage	Low ⟷ High
Gain	
Photon detection efficiency	
Time resolution	
Noise	

Gain

(1) Definition

The MPPC gain is defined as the charge (Q) of the pulse generated from one pixel when it detects one photon, divided by the charge per electron (q: 1.602×10^{-19} C).

$$M = \frac{Q}{q} \cdots\cdots (2)$$

M: gain

The charge Q depends on the reverse voltage (V_R) and breakdown voltage (V_{BR}) and is expressed by equation (3).

$$Q = C \times (V_R - V_{BR}) \cdots\cdots (3)$$

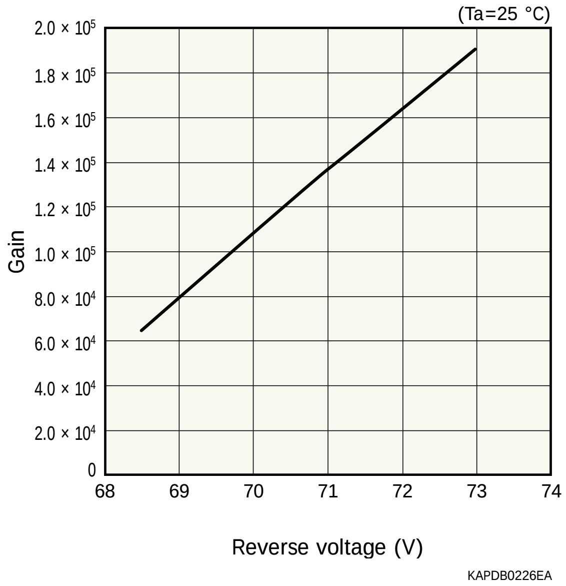
C: capacitance of one pixel

Equations (2) and (3) indicate that the larger the pixel capacitance or the higher the reverse voltage, the higher the gain will be. On the other hand, increasing the reverse voltage also increases the dark and afterpulses. So the reverse voltage must be carefully set to match the application.

(2) Linearity

As the reverse voltage is increased, the MPPC gain also increases almost linearly. Figure 1-14 shows a typical example.

[Figure 1-14] Gain vs. reverse voltage (photosensitive area: 1 mm sq, pixel pitch: 10 μm, typical example)



(3) Temperature characteristics

As with the APD, the MPPC gain is also temperature dependent. As the temperature rises, the crystal lattice vibrations become stronger. This increases the probability that carriers may strike the crystal before the accelerated carrier energy has become large enough, making it difficult for ionization to occur. To make ionization easier to occur, the reverse voltage should be increased to enlarge the internal electric field. To keep the gain constant, the reverse voltage must be adjusted to match the ambient temperature or the element temperature must be kept constant.

Figure 1-15 shows the reverse voltage adjustment needed to keep the gain constant when the ambient temperature varies.

[Figure 1-15] Reverse voltage vs. ambient temperature
(photosensitive area: 1 mm sq, pixel pitch: 10 μm, typical example)

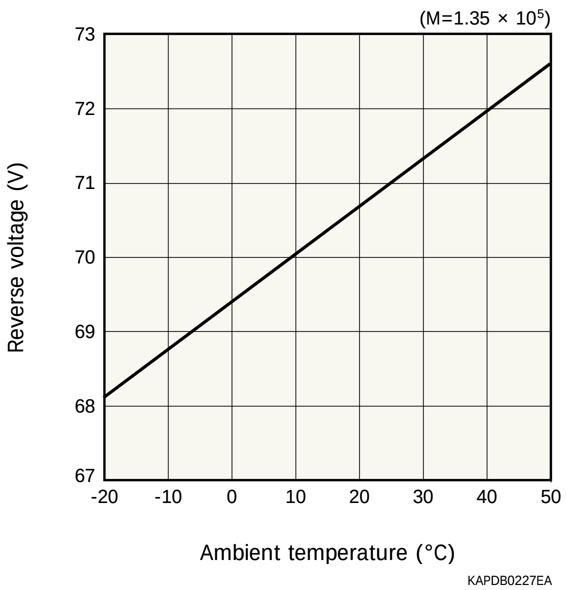
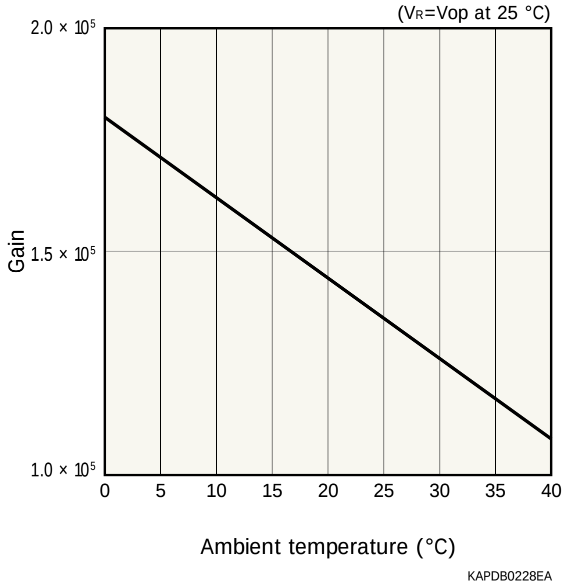


Figure 1-16 shows the relation between gain and ambient temperature when the reverse voltage is a fixed value.

[Figure 1-16] Gain vs. ambient temperature

(photosensitive area: 1 mm sq, pixel pitch: 10 µm, typical example)

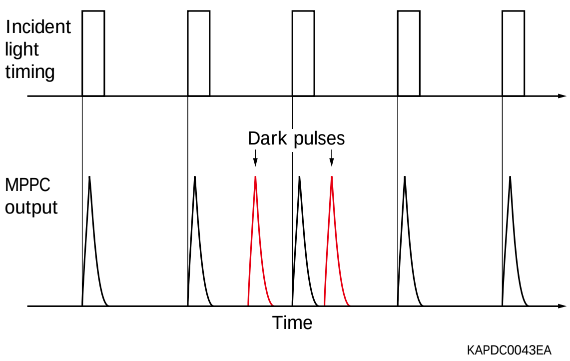


Dark count

(1) Definition

In the MPPC operation just the same as with APD, pulses are produced not only by photon-generated carriers but also by thermally-generated carriers. The pulses produced by the latter are called the dark pulses. The dark pulses are observed along with the signal pulses and so cause detection errors. Thermally-generated carriers are also multiplied to a constant signal level (1 p.e.). These dark pulses are not distinguishable by the shape from photon-generated pulses [Figure 1-17].

[Figure 1-17] Dark pulses



The number of dark pulses observed is referred to as the dark count, and the number of dark pulses per second is termed as the dark count rate [unit: cps (counts per second)]. The dark count rate of Hamamatsu MPPC is defined as the number of pulses that are generated in a dark state and exceed a threshold of 0.5 p.e. This is expressed as $N_{0.5\ p.e.}$.

(2) Temperature characteristics

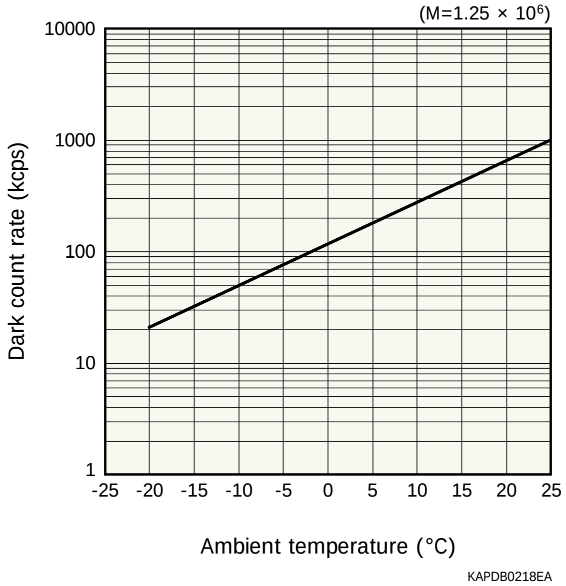
Since dark pulses are produced by thermally-generated carriers, the dark count rate varies with the ambient temperature. The dark count rate is given by equation (4) within the operating temperature range.

$$N_{0.5\,p.e.}(T) \approx AT^{\frac{3}{2}} \exp\left[\frac{Eg}{2kT}\right] \cdots\cdots (4)$$

A: arbitrary constant
Eg: band gap energy [eV]
T: absolute temperature [K]
k: boltzmann's constant [eV/K]

Figure 1-18 shows a relation between the dark count rate and the ambient temperature when the gain is set to a constant value.

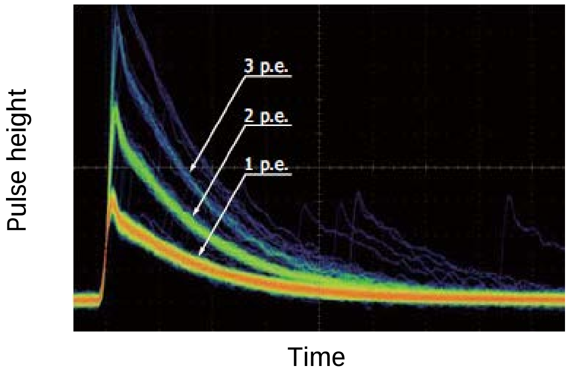
[Figure 1-18] Dark count rate vs. ambient temperature
(photosensitive area: 3 mm sq, pixel pitch: 50 μm, typical example)



Crosstalk

When light enters one MPPC pixel, there may be cases where a pulse of 2 p.e. or higher is observed. This is because secondary photons are generated in the avalanche multiplication process of the MPPC pixel and those photons are detected by other pixels. This phenomenon is called the optical crosstalk.

[Figure 1-19] Crosstalk example

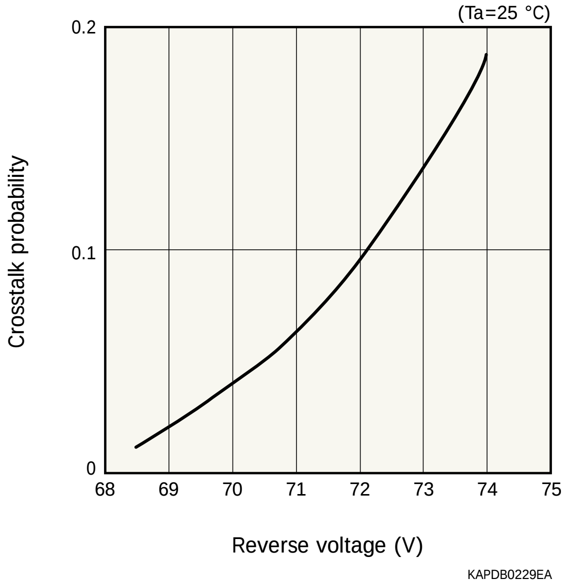


We define the crosstalk probability as equation (5).

$$P_{crosstalk} = \frac{N_{1.5\,p.e.}}{N_{0.5\,p.e.}} \cdots\cdots (5)$$

The crosstalk probability has almost no dependence on the temperature within the rated operating temperature range. The probability that the crosstalk will occur increases as the reverse voltage is increased [Figure 1-20].

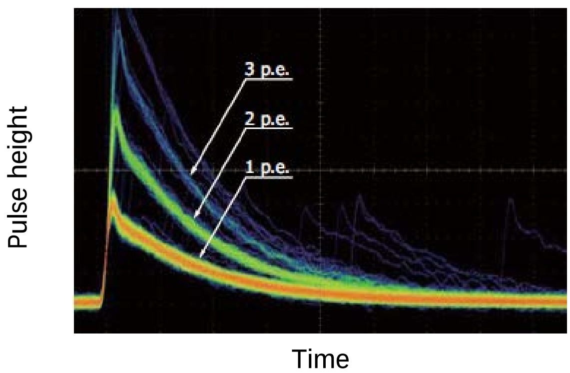
[Figure 1-20] Crosstalk probability vs. reverse voltage
(photosensitive area: 1 mm sq, pixel pitch: 50 μm, typical example)



Afterpulses

During the avalanche multiplication process in MPPC pixels, the generated carriers may be trapped by lattice defects. When these carriers are released, they are multiplied by the avalanche process along with photon-generated carriers and are then observed as afterpulses. The afterpulses are not distinguishable by shape from photon-generated pulses.

[Figure 1-21] Afterpulse observed



Dark current

Output current produced even when operated in a dark state is called the dark current. The MPPC dark current (I_D) is expressed by equation (6).

$$I_D = Is + Ij + Ib \quad \cdots\cdot \quad (6)$$

Is: surface leak current
Ij: recombination current
Ib: bulk current

When the MPPC is operated in Geiger mode, the bulk current is expressed by equation (7), assuming that the number of pixels generated per unit time during avalanche multiplication is Nfired.

$$Ib = q\ M\ Nfired \quad \cdots\cdots \quad (7)$$

q: electron charge
M: gain

Since the MPPC gain is usually 10^5 to 10^6, the bulk current Ib is dominant in equation (6) and equation (7) can then be approximated to equation (8).

$$I_D \approx Ib = q\ M\ Nfired \quad \cdots\cdots \quad (8)$$

In a dark state, the number of pixels where avalanche multiplication occurred equals the dark count rate, so the dark current I_D can be approximated to equation (9) using $N_{0.5\ p.e.}$ and Pcrosstalk. If the gain and crosstalk probability at a particular reverse voltage are known, then the dark current can be roughly estimated from the dark count rate and vice versa.

$$I_D \approx q\ M\ N_{0.5\ p.e.} \frac{1}{1 - Pcrosstalk} \quad \cdots\cdots \quad (9)$$

Photosensitivity and photon detection efficiency

The photosensitivity and the photon detection efficiency are used to express the MPPC light detection sensitivity. The photosensitivity is expressed as the ratio of the MPPC output current (analog value) to the amount of continuous light incident on the MPPC. The photon detection efficiency is a ratio of the number of detected photons to the number of incident photons during photon counting where the pulsed light enters the MPPC. Both photosensitivity and photon detection efficiency relate to parameters such as fill factor, quantum efficiency, and avalanche probability.

The fill factor is the ratio of the light detectable area to the entire pixel area of an MPPC. Unlike photodiodes and APD, the MPPC photosensitive area contains sections such as the inter-pixel wiring that cannot detect light, so some photons incident on the photosensitive area are not detected. Generally, the smaller the pixel size, the lower the fill factor.

The quantum efficiency is defined as probability that carriers will be generated by light incident on a pixel. As in other types of opto-semiconductors, the MPPC quantum efficiency is dependent on the incident light wavelength.

The avalanche probability is the probability that the carriers generated in a pixel may cause avalanche multiplication. The higher reverse voltage applied to the MPPC will obtain the higher avalanche probability.

(1) Photosensitivity

Photosensitivity (S; unit: A/W) is a ratio of the MPPC output current to the light level incident on the MPPC, as expressed by equation (10).

$$S = \frac{I_{MPPC}}{\text{Incident light level [W]}} \cdots\cdots (10)$$

I_{MPPC}: photocurrent [A]

The photosensitivity is proportional to the gain, so the higher the reverse voltage applied to the MPPC, the higher the photosensitivity. Note that the photosensitivity includes a crosstalk and afterpulses.

(2) Photon detection efficiency

The photon detection efficiency (PDE) is an indication of what percent of the incident photons is detected, and is given by equation (11).

$$PDE = \frac{\text{Number of detected photons}}{\text{Number of incident photons}} \cdots\cdots (11)$$

The PDE can be expressed by the product of a fill factor, quantum efficiency, and avalanche probability.

$$PDE = Fg \times QE \times Pa \cdots\cdots (12)$$

Fg: fill factor
QE: quantum efficiency
Pa: avalanche probability

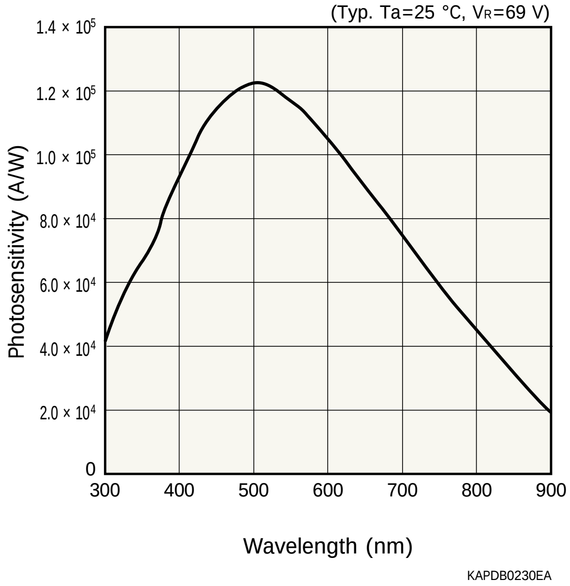
Equation (13) can also be established by using photosensitivity.

$$PDEcurrent = \frac{1240}{\lambda} \times \frac{S}{M} \cdots\cdots (13)$$

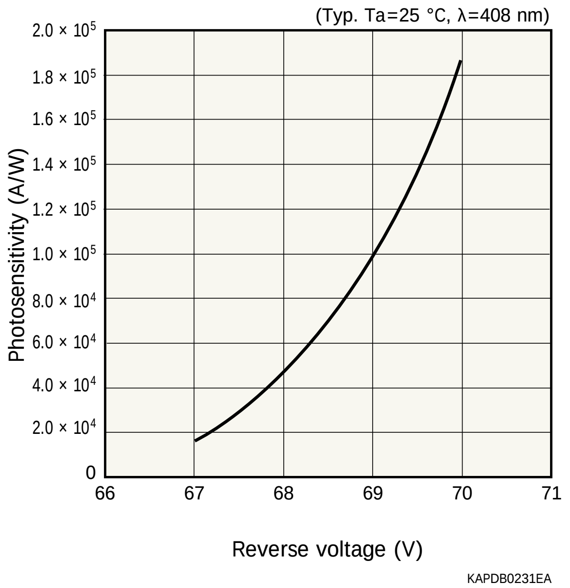
λ: incident light wavelength [nm]

As stated above, the photosensitivity includes crosstalk and afterpulses and so, the PDEcurrent becomes higher than the PDE.

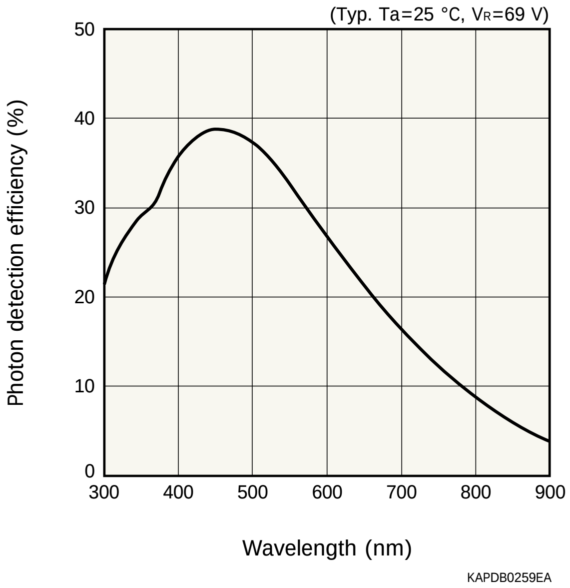
[Figure 1-22] Spectral response (pixel pitch: 25 μm, V_R=69 V)



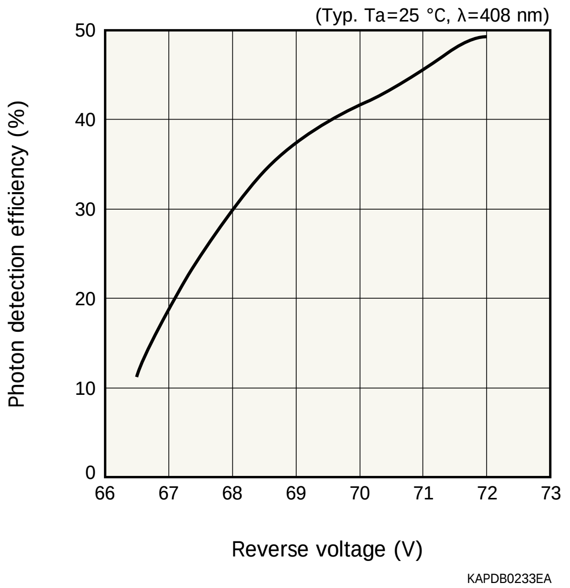
[Figure 1-23] Photosensitivity vs. reverse voltage (pixel pitch: 25 μm, λ=408 nm)



[Figure 1-24] Photon detection efficiency vs. wavelength (pixel pitch: 25 μm, V_R=69 V)



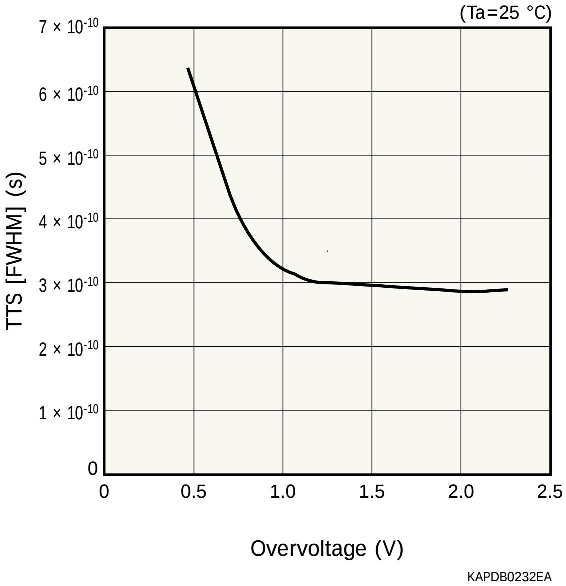
[Figure 1-25] Photon detection efficiency vs. reverse voltage (pixel pitch: 25 μm, λ=408 nm)



Time resolution

The time required for each pixel of the MPPC to output a signal after the incidence of light varies depending on the wiring length, etc. This variation is called TTS (transit time spread). Increasing the reverse voltage applied to the MPPC reduces and improves the TTS.

[Figure 1-26] TTS vs. overvoltage (photosensitive area: 1 mm sq, pixel pitch: 50 μm)

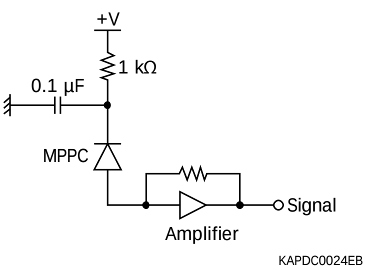


1-4. How to use

The MPPC characteristics greatly vary depending on the operating voltage and ambient temperature. In general, raising the operating voltage increases the electric field inside the MPPC and so improves the gain, photon detection efficiency, and time resolution. On the other hand, this also increases unwanted components such as dark count, afterpulses, and crosstalk which lower the S/N. The operating voltage must be carefully set in order to obtain the desired characteristics.

The MPPC can be used by various methods according to the application. Here we introduce a typical method for observing light pulses. Using a wide-band amplifier and oscilloscope makes this measurement easy. Figure 1-27 shows one example of a connection to a wide-band amplifier. The 1 kΩ resistor and 0.1 μF capacitor on the power supply portion serve as a low-pass filter that eliminates high-frequency noise of the power supply. The 1 kΩ resistor also plays a role in protecting the MPPC from excessive current. The MPPC itself is a low-light-level detector, however, in cases where a large amount of light enters the MPPC, for example, when it is coupled to a scintillator to detect radiation, a large current flows into the MPPC. This may cause a significant voltage drop across the protective resistor, so the protective resistor value must be carefully selected according to the application. The amplifier should be connected as close to the MPPC as possible.

[Figure 1-27] Connection example



In measurements utilizing the MPPC output pulse having a sharp rising edge, an appropriate wide-band amplifier and oscilloscope must be selected. Since the MPPC output pulses usually rise within a few nanoseconds, it is strongly recommended to use an amplifier and oscilloscope capable of sampling at about 1 GHz. Using a narrow-band amplifier and oscilloscope might dull or blunt the output pulse making it impossible to obtain accurate values.

1-5. Measurement examples

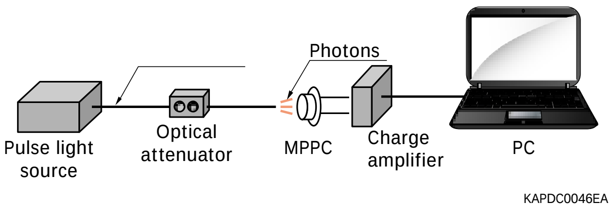
Examples of measuring MPPC characteristics are described below.

Gain

(1) Measurement using a charge amplifier

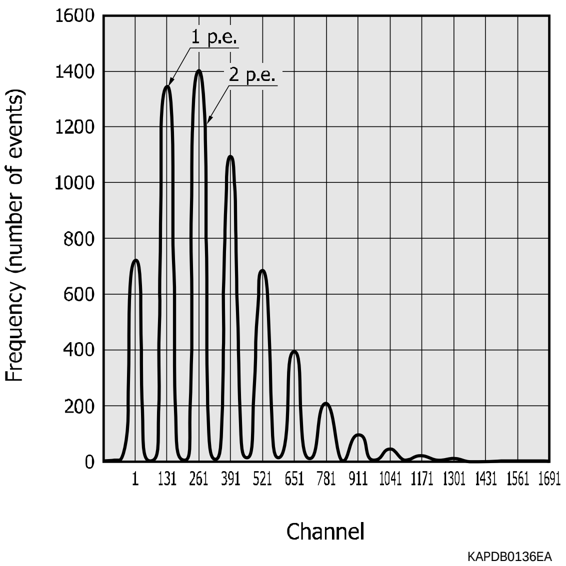
The gain can be estimated from the output charge of the MPPC that detected photons. Figure 1-28 shows a connection setup example for the gain measurement using a charge amplifier.

[Figure 1-28] Gain measurement connection example (using charge amplifier)



When the MPPC is illuminated with pulsed light whose light level is sufficiently reduced by an attenuator and the number of the output charges is plotted, a frequency distribution like that shown in Figure 1-29 is obtained.

[Figure 1-29] Frequency distribution example of output charge



In Figure 1-29, each peak on the curve from the left indicates the pedestal, 1 p.e., 2 p.e. and so forth. The pedestal is a basis of the output. This example shows that the MPPC has mainly detected one photon and two photons. The interval between adjacent peaks corresponds to the amount of the charge produced by detecting one photon. The gain (M) is given by equation (14).

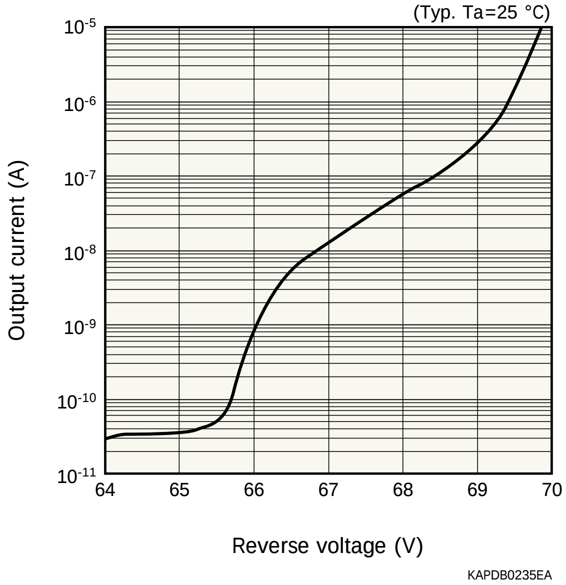
$$M = \frac{\text{Charge difference between adjacent peaks}}{q} \quad \cdots\cdots (14)$$

q: charge per electron

(2) dI/dV measurement

Figure 1-30 shows the output current vs. reverse voltage characteristics of the MPPC. If the voltage of Vpeak maximizes the value to the function [equation (15)] obtained by differentiating the output current by the reverse voltage, the breakdown voltage V_{BR} will be a sum of Vpeak and the offset voltage of each product.

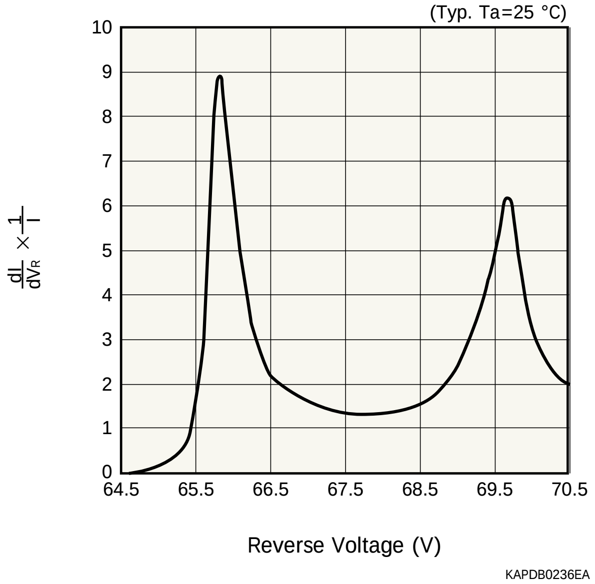
[Figure 1-30] Output current vs. reverse voltage (photosensitive area: 1 mm sq, pixel pitch: 50 μm)



$$\frac{d}{dV_R}\log(I) = \frac{dI}{dV_R} \times \frac{1}{I} \quad \cdots\cdots (15)$$

I: output voltage [V]
V_R: reverse voltage [V]

[Figure 1-31] Reverse voltage characteristics of $\frac{dI}{dV_R} \times \frac{1}{I}$



The gain is given by equation (16).

$$M = \frac{C \times (V_R - V_{BR})}{q} \quad \cdots\cdot (16)$$

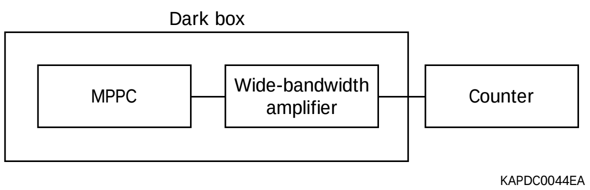
C: pixel capacitance [F]
q: electron charge [C]
V_{BR}: breakdown voltage [V]

Since the pixel capacitance is constant, the gain can be obtained from the breakdown voltage and reverse voltage that are obtained by dI/dV measurement. However, if the operating voltage applied to the MPPC is significantly higher than the recommended operating voltage, noise components such as afterpulses and crosstalk will increase and make accurate measurement impossible.

Dark

In dark count measurement, the MPPC is installed and operated in a dark box and the output pulse is input to a pulse counter. The number of events where the output pulse exceeds the predetermined threshold (0.5 p.e., etc.) is counted to determine the dark count rate. In this case, a wide-band amplifier must be used because the MPPC output pulse width is very short, down to a few dozen nanoseconds.

[Figure 1-32] Block diagram of dark measurement



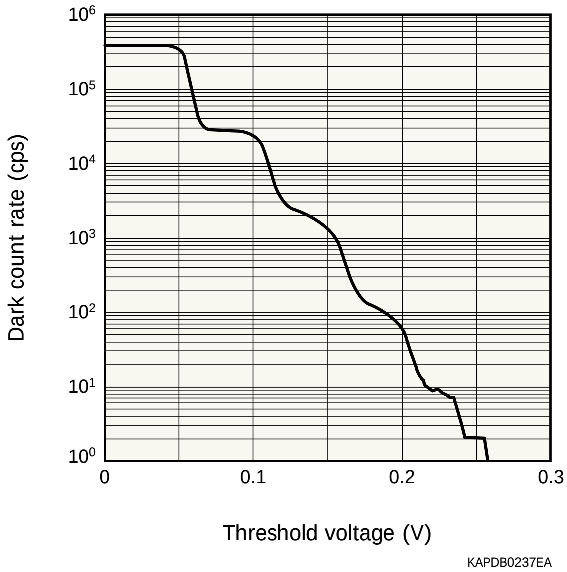
Crosstalk

When the threshold is set, for example, to 0.5 p.e. and 1.5 p.e., to measure the count rate of dark pulses exceeding the threshold, the dark count rates $N_{0.5\ p.e.}$ and $N_{1.5\ p.e.}$ at each threshold can be measured. Using these dark count rates, the crosstalk probability Pcrosstalk is calculated by equation (17).

$$\text{Pcrosstalk} = \frac{N_{1.5\ p.e.}}{N_{0.5\ p.e.}} \cdots\cdots (17)$$

If the threshold is swept, the dark count rate will be plotted as shown in Figure1-33. The threshold voltages at which the dark count rate abruptly decreases correspond to the levels of one photon, two photons, and so on from left. The dark count rates $N_{0.5\ p.e.}$, $N_{1.5\ p.e.}$, $N_{2.5\ p.e.}$ and so on can be obtained from this graph.

[Figure 1-33] Dark count rate vs. threshold voltage



Afterpulse

The dark pulses are generated randomly and the time interval of the dark pulse generation follows an exponential distribution. The dark pulse generation time interval Δtdark (unit: seconds) is expressed by equation (18).

$$\Delta\text{tdark} \propto \exp\left(\frac{\Delta t}{\tau\text{dark}}\right) \cdots\cdots (18)$$

Δtdark: elapsed time after dark pulse generation [s]
τ dark: time constant of dark pulse [s]

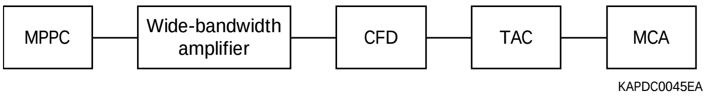
The time interval during afterpulse generation is expressed by several exponential distributions. The afterpulse generation time interval Δt_{AP} (unit: seconds) is given by equation (19).

$$\Delta t_{AP} \propto \sum_{k} A_k \times \exp\left(\frac{\Delta t}{\tau k}\right) \cdots\cdots (19)$$

k: number of time constants for Δt_{AP}
τk: time constant of dark pulse [s]
Ak: constant

Here, τ_{dark} differs greatly from τk ($\tau_{dark} >> \tau k$), so it is necessary to create a histogram of the elapsed time Δt after generation of a pulse and then perform a fitting of dark pulse components in the time region that does not include afterpulses. Then, subtracting the fitted components from the entire histogram gives the afterpulse components.
During measurement, a TAC and MCA are used to create the above mentioned histogram. The photons enter the MPPC and the detected signals are amplified by the amplifier and sent to the CFD. When the CFD receives a signal with an amplitude exceeding the threshold for photon detection, it sends the signal to the TAC. When the next signal is output from the MPPC, that signal is also sent to the TAC. The TAC then outputs a pulse whose amplitude is proportional to the time interval between the first MPPC signal and the next MPPC signal. The pulses received from the TAC and sorts them into different channels according to pulse height. The data stored in the MCA displays a histogram of Δt.

[Figure 1-34] Connection example of afterpulse measurement



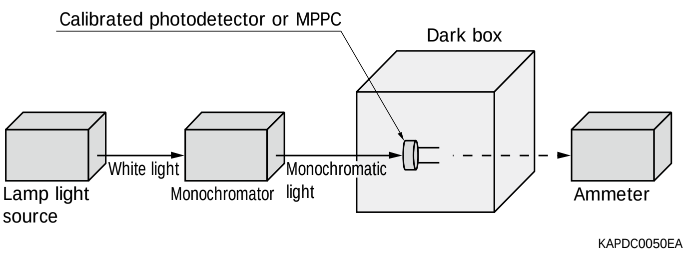
Photosensitivity

To measure the photosensitivity of an MPPC, the incident light from a monochromatic light source is first detected by a calibrated photodetector in a dark box and the light level (unit: W) incident on the photodetector is found from the output. Then, the MPPC is set in the dark box in place of the photodetector to make the same measurement and the MPPC photocurrent (unit: A) is measured. Based on these measurement results, the photosensitivity (S) of the MPPC is calculated as in equation (20).

$$S = \frac{I_{MPPC}}{\text{Incident light level}} \cdots\cdots (20)$$

I_{MPPC}: photocurrent [A]

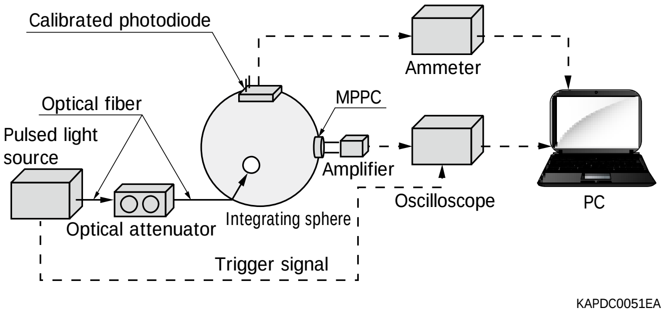
[Figure 1-35] Connection example of photosensitivity measurement



Photon detection efficiency

To measure the photon detection efficiency of an MPPC, a pulsed light source is used as shown in Figure 1-36. The monochromatic pulsed light emitted from the pulsed light source is passed through an optical attenuator to reduce the light level and is guided into an integrating sphere where the light is scattered and distributed equally in all directions. And then it enters a calibrated photodiode and the MPPC. The output current from the calibrated photodiode is measured with an ammeter and, based on that value, the number of photons incident on the MPPC is found.

[Figur 1-36] Connection example of photon detection efficiency measurement



The MPPC output signal is fed to an oscilloscope in synchronization with the trigger signal from the pulsed light source to measure the MPPC output waveform in response to the pulsed light. The MPPC output charge is then obtained from the response waveform. This output charge is obtained for many events to create a frequency distribution of the output charge like that shown in Figure 1-29. In an ideal case, when the pulsed light is so weak that only a few photons are emitted per pulse, this frequency distribution follows a Poisson distribution with a mean value of the number of photons detected by the MPPC. However, part of the events contains dark pulses and the events at 1 p.e. or higher are affected by crosstalk and afterpulses, distorting the actually measured distribution from the Poisson distribution. On the other hand, since the events at 0 p.e. are not affected by crosstlak and afterpulses, the effects of dark pulses can be corrected by counting the number of the events at 0 p.e. and so the mean value of the Poisson distribution can be found.
The Poisson distribution is defiened by equation (21).

$$P(n,x) = \frac{n^x e^{-n}}{x!} \cdots\cdots (21)$$

n: average number of photons detected by MPPC
x: number of photons detected by MPPC

If x=0 in equation (21), then the Poisson distribution is expressed by equation (22).

$$P(n,0) = e^{-n} \cdots\cdot (22)$$

The left side of equation (22) is expressed by equation (23) when the correction of dark pulses is included.

$$P(n,0) = \frac{\left(\frac{N_{ped}}{N_{tot}}\right)}{\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)} \cdots\cdots (23)$$

N_{ped}: number of events at 0 p.e. during pulsed light measurement
N_{tot}: number of all events during pulsed light measurement
N_{ped}^{dark}: number of events at 0 p.e. in dark state
N_{tot}^{dark}: number of all events in dark state

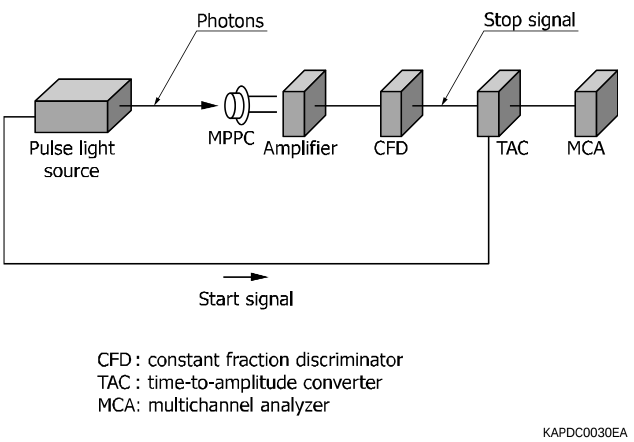
The average number of photons detected by MPPC, n, is given by equation (24). Photon detection efficiency can then be found by dividing n by the number of incident photons.

$$n = -\ln\left(\frac{\frac{N_{ped}}{N_{tot}}}{\frac{N_{ped}^{dark}}{N_{tot}^{dark}}}\right) = -\ln\left(\frac{N_{ped}}{N_{tot}}\right) + \ln\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right) \cdots\cdots (24)$$

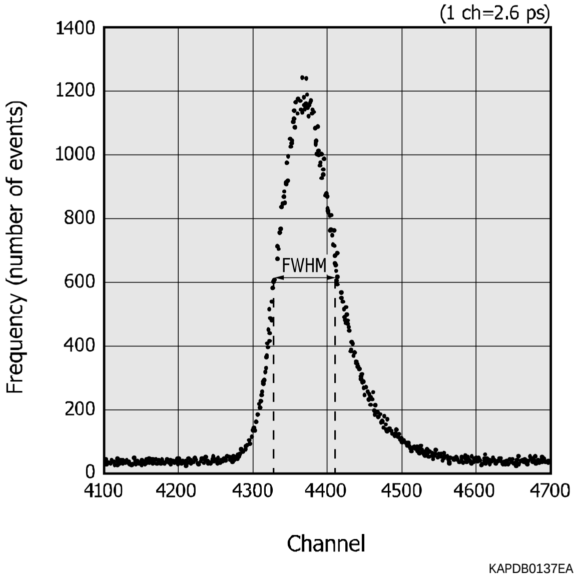
Time resolution

Figure 1-37 is an example of connection for time resolution measurement using the TTS method. The pulse light source emits photons and simultaneously sends a start signal to the TAC. The TAC starts measuring the time upon receiving the start signal. Meanwhile, the photons enter the MPPC and the detected signals are amplified by the amplifier and sent to the CFD. When the CFD receives a signal with an amplitude exceeding the threshold for photon detection, it sends the signal to the TAC. The TAC receives the signal from the CFD as a stop signal for time measurement. At this point, the TAC also provides a pulse output proportional to the time from when photons entered the MPPC until the signal is output. The MCA sorts the pulses received from the TAC and sorts them into different channels according to pulse height. The data stored in the MCA is a histogram of MPPC responses, and the time resolution is expressed as the full width at half maximum (FWHM) of this histogram.

[Figure 1-37] Connection example of time resolution measurement



[Figure 1-38] TTS (typical example)



Dynamic range

(1) Dynamic range for simultaneously incident photons

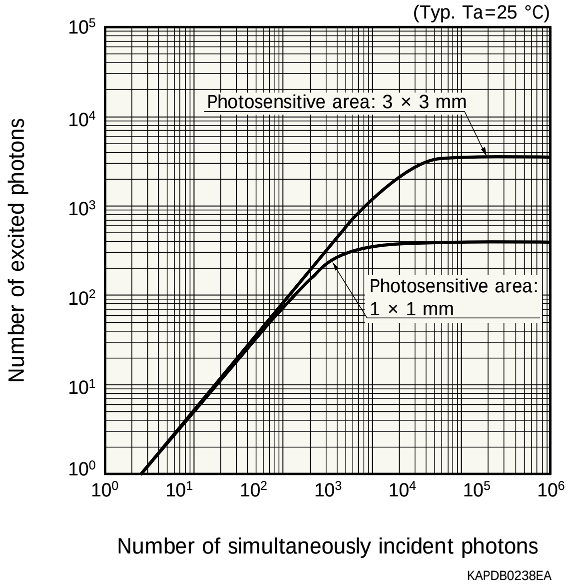
The dynamic range for simultaneously incident photons is determined by the number of pixels and photon detection efficiency of the MPPC. As the number of incident photons increases, two or more photons begin to enter one pixel. Even when two or more photons enter one pixel, each pixel can only detect whether or not the photons entered the MPPC. This means that the output linearity degrades as the number of incident photons increases.

$$\mathrm{Nfired} = \mathrm{Ntotal} \times \left\{ 1 - \exp\left(\frac{-\mathrm{Nphoton} \times \mathrm{PDE}}{\mathrm{Ntotal}} \right) \right\} \cdots\cdots (25)$$

Nfired: number of excited pixels
Ntotal: total number of pixels
Nphoton: number of incident photons
PDE: photon detection efficiency

Widening the dynamic range requires using an MPPC having a sufficiently large number of pixels compared to the number of simultaneously incident photons (namely, an MPPC with a large photosensitive area or a narrow pixel pitch).

[Figure 1-39] Dynamic range for simultaneously incident photons (pixel pitch: 50 μm)



(2) Dynamic range in photon counting

The number of MPPC excited pixels is given by equation (26).

$$\text{Nfired} = \text{Nphoton} \times \text{PDE} \quad \cdots\cdots (26)$$

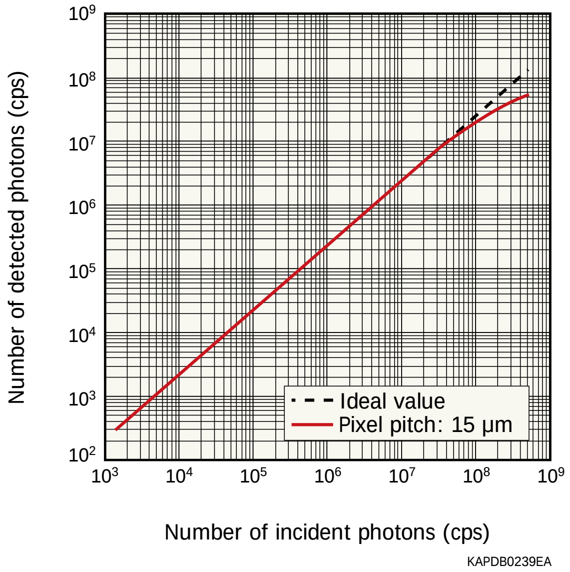
As the number of incident photons becomes larger, two or more output pulses overlap each other causing counting errors and degrading the output linearity. This linearity is determined by a parameter called the pulse-pair resolution. The pulse-pair resolution is determined by the MPPC recovery time (refer to “Recovery time” in “1-5. Measurement examples”) and the readout circuit characteristics. Eqaution (27) expresses the number of MPPC excited pixels that takes into account the pulse-pair resolution.

$$\text{Nfired} = \frac{\text{Nphoton} \times \text{PDE}}{1 + \text{Nphoton} \times \text{PDE} \times \text{Tresolution}} \quad \cdots\cdots (27)$$

Tresolution: pulse-pair resolution

To widen the dynamic range, an MPPC with a short pulse width should be selected.

[Figure 1-40] Dynamic range in photon counting (pixel pitch: 15 μm)



(3) Dynamic range in current measurement

The MPPC photocurrent (I_{MPPC}) is expressed by equation (28).

$$I_{MPPC} = Nphoton \times PDEcurrent \times M \times q \cdots\cdots (28)$$

M: gain
q: electron charge

The number of incident photons is expressed by equation (29) using the incident light level (unit: W).

$$Nphoton = \frac{W \times \lambda}{h \times c} \cdots\cdots (29)$$

λ: wavelength [m]
h: plank's constant
c: speed of light

As the incident light level increases, two or more photons tend to enter one pixel, also the next photon tends to enter the same pixel within its recovery time (refer to “Recovery time” in “1-5. Measurement examples”). These actions degrades the linearity. Equation (30) expresses the MPPC output current I_{MPPC} while taking these actions taken into account.

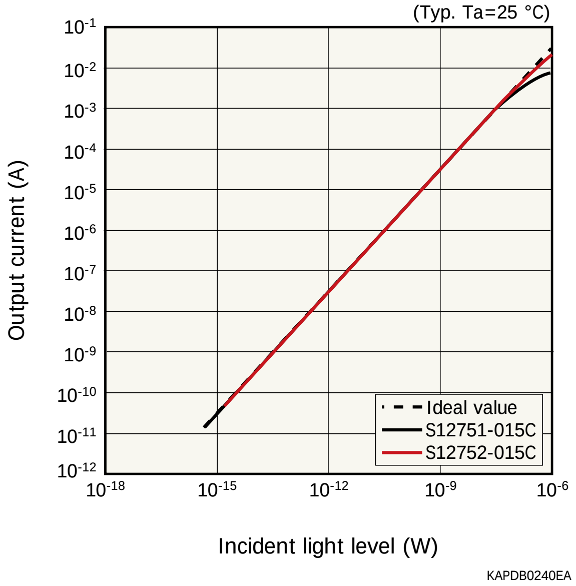
$$I_{MPPC} = \frac{Nphoton \times PDEcurrent}{1 + \frac{Nphoton \times PDEcurrent \times T_R}{Ntotal}} \times M \times q \cdots\cdots (30)$$

T_R: recovery time [s]

To widen the dynamic range, it is essential to select an MPPC having a large photosensitive area, a larger number of pixels, or a short recovery time (narrow pixel pitch).

When a large amount of light enters an MPPC, the output linearity may deteriorate because the MPPC itself heats up and the gain lowers. A large output current then flows which might lower the reverse voltage applied to the MPPC depending on the value of the protective resistor used. So a protective resistor having the right value must be selected to prevent this problem.

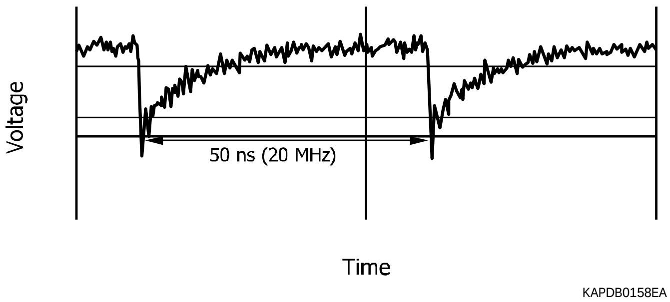
[Figure 1-41] Output current vs. incident light level (pixel pitch: 15 µm)



Recovery time

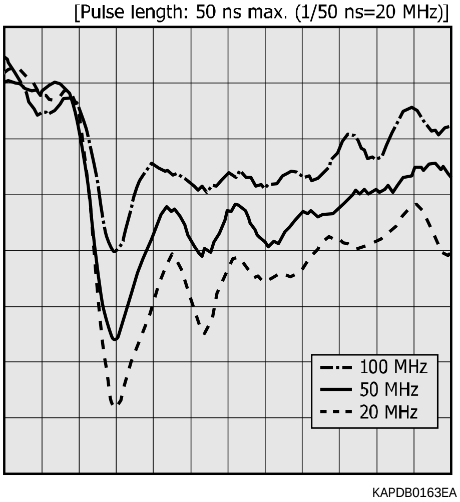
The time (recovery time) required for pixels to restore 100% of the gain depends on the photosensitive area and pixel size. In the case of the MPPC having a photosensitive area of 1 mm sq, the recovery time will be approximately 20 ns for 25 µm pixel pitch, 50 ns for 50 µm pixel pitch, and 100 to 200 ns for 100 µm pixel pitch. Figure 1-42 shows an output measured when light enters a pixel of the MPPC with a photosensitive area of 1 mm sq, and a pixel pitch of 50 µm, at a period equal to the pulse recovery time. It can be seen that the pulse is restored to a height equal to 100% of output.

[Figure 1-42] Pulse level recovery (photosensitive area: 1 mm sq, pixel pitch: 50 µm)



If the next input pulse enters before the output pulse is completely restored, then a small pulse is output, which does not reach the gain set by the operating voltage. In Figure 1-42, the rising region of the pulse indicates the process for charging the pixel. When the next photon is detected before the pixel is fully charged, the output pulse will have an amplitude that varies according to the charged level.
Figure 1-43 shows output pulse shapes obtained when light at different frequencies was input to a pixel.

[Figure 1-43] Output pulses obtained when light at different frequencies was input
(photosensitive area: 1 mm sq, pixel pitch: 50 µm, typical example)



1-6. Selecting the digital mode or analog mode

The readout mode (digital mode or analog mode) should be selected according to the light level incident on the MPPC.

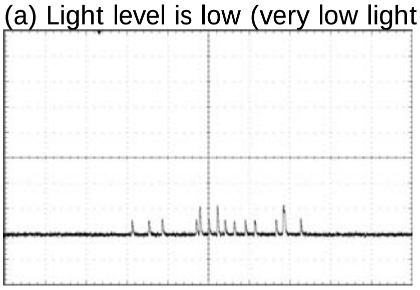
Figures 1-44 (a) (b) and (c) show the MPPC output waveforms measured at different incident light levels and observed on an oscilloscope. The incident light level was increased in the order of (a) (b) and (c), starting from (a) at very low light levels. The output signal of (a) as seen here consists of discrete pulses. In this state, selecting the digital mode allows measuring at a higher S/N, where the signals are binarized and the number of pulses is digitally counted. Since the digital mode can subtract the dark count from the signal, the detection limit is determined by dark count fluctuations.

As the light level increases, the output waveform consists of pulses overlapping each other [Figures 1-44 (b) and (c)]. In this state, the number of pulses cannot be counted and the analog mode should be selected to measure the analog output and find the average value. The detection limit in the analog mode is determined by the dark current shot noise and the cutoff frequency of the readout circuit.

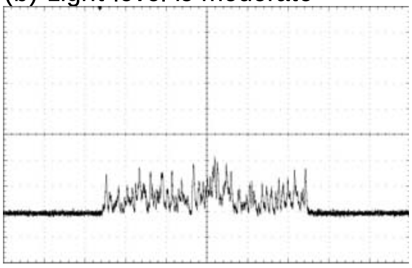
Figure 1-45 shows the incident light levels suitable for the digital mode and analog mode (MPPC photosensitive area: 3 × 3 mm, pixel pitch: 50 µm)

[Figure 1-44] Output waveforms

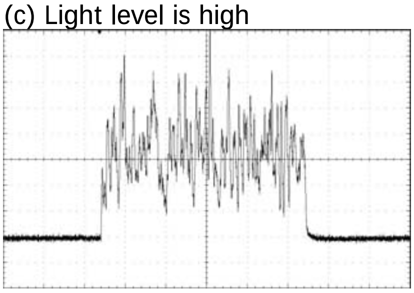
(a) Light level is low (very low light level)



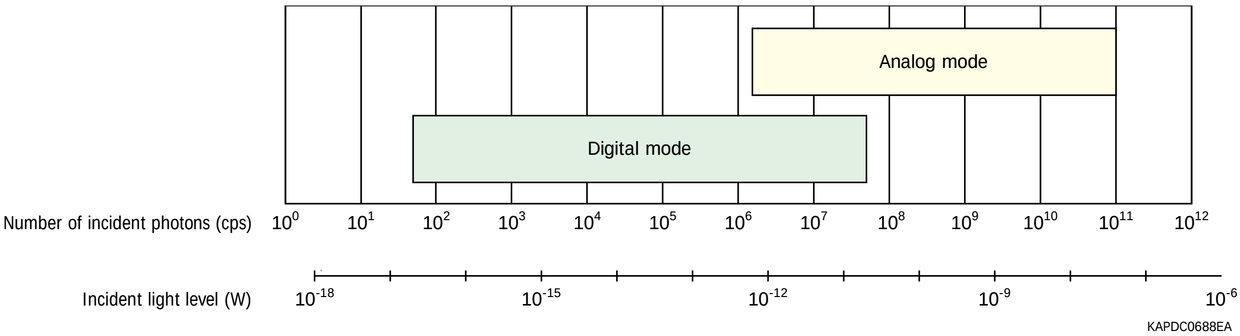
(b) Light level is moderate



(c) Light level is high



[Figure 1-45] Incident light level suitable for digital mode and analog mode
(photosensitive area: 3 mm sq, pixel pitch: 50 μm)



2. MPPC modules

Hamamatsu MPPC modules are optical measurement modules capable of measuring light over a wide range of light levels (10 orders of magnitude) from the photon-counting region up to the nW (nanowatt) region. MPPC modules contain a signal amplifier circuit, a high-voltage power supply circuit, and other components needed for MPPC operation.

MPPC modules operate just by connecting them to a power supply (±5 V).

Hamamatsu offers a wide lineup of MPPC modules including cooled modules that give a low dark count and non-cooled modules with a temperature compensation function for stable measurement. Hamamatsu also provides starter kits developed for making initial MPPC evaluations and a temperature-compensated high-voltage power supply module designed to operate an MPPC.

2-1. Features

Wide lineup to meet various applications and incident light levels (number of photons)

Our lineup includes analog output types for applications handling relatively large quantities of light where analog signals are required, digital output types for photon counting, and a starter kits for initial MPPC evaluation.

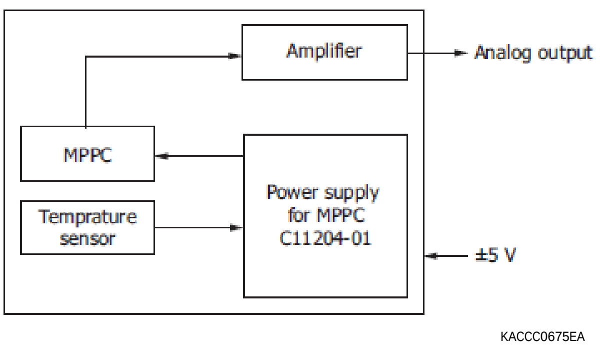
Contains a high-precision temperature compensation circuit or temperature control circuit

The MPPC is used in Geiger mode where the gain is very high. The gain varies with the ambient temperature even if the reverse voltage does not change. To keep the MPPC gain constant, the MPPC modules use temperature compensation that adjusts the MPPC reverse voltage as the ambient temperature changes or temperature control that regulates the MPPC element temperature using a thermoelectric cooler.

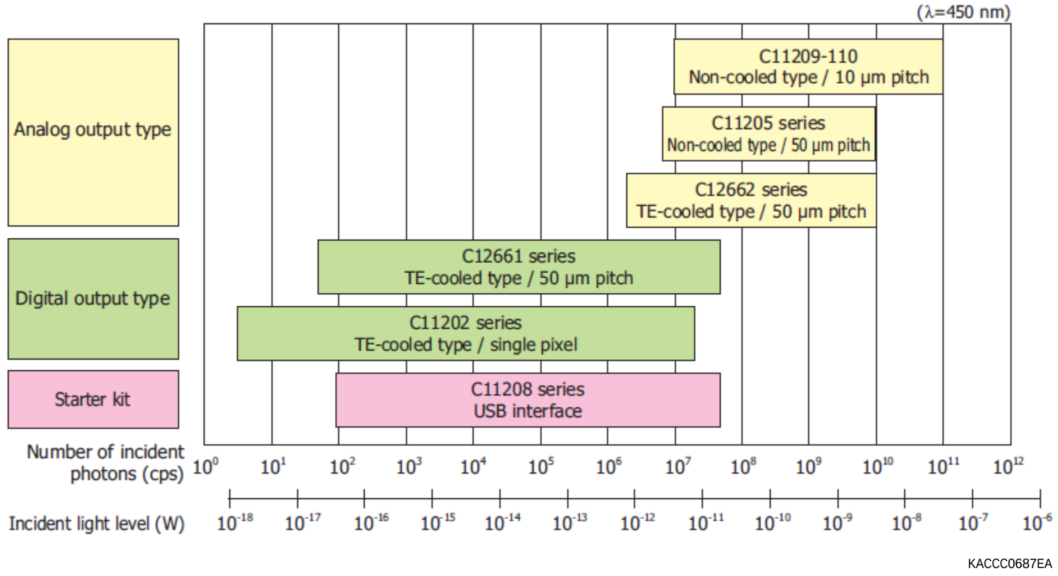
In temperature compensation, a high-precision temperature sensor is installed near the MPPC element to accurately sense the MPPC temperature. The reverse voltage applied to the MPPC is then adjusted according to changes in the ambient temperature so that the gain is kept constant accurately. In temperature control, the MPPC chip and a temperature sensor are mounted on a thermoelectric cooler in the MPPC. Based on information from the temperature sensor, the MPPC chip temperature is precisely controlled and maintained at a constant level so that the MPPC gain is kept constant even if the ambient temperature fluctuates.

- Includes a signal readout circuit optimized for MPPC
- Includes a low-noise high-voltage power supply
- Compact and lightweight

[Figure 2-1] Block diagram (C11205 series)



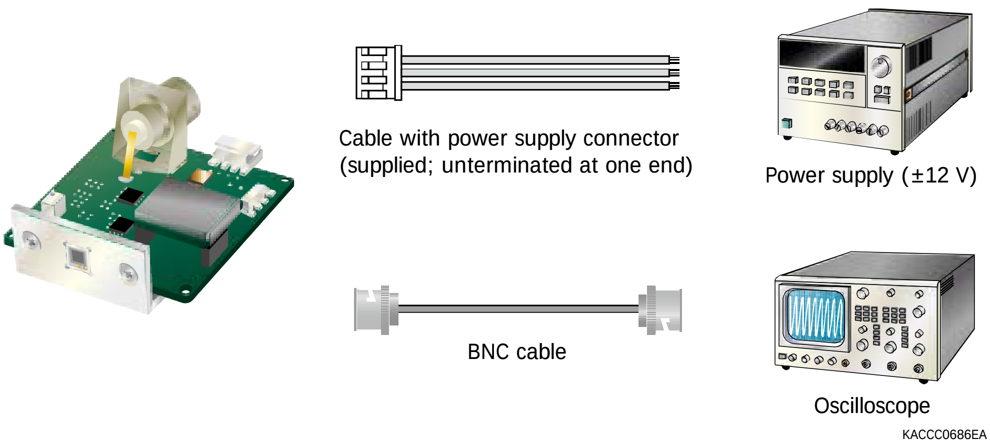
[Figure 2-2] Measurable light level range and lineup



2-2. How to use

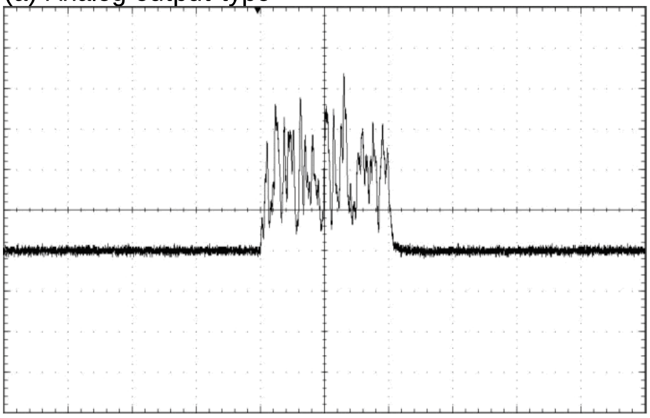
To use the MPPC module, connect it to an external power supply by using the power cable that came supplied with the MPPC module. The signal is output from the coaxial connector on the MPPC module. If using an analog output type MPPC module, the output waveforms can be monitored by connecting to an oscilloscope. If using a digital output type, the number of output pulses can be counted by connecting to a frequency counter, etc.

[Figure 2-3] Connection example (analog output type)

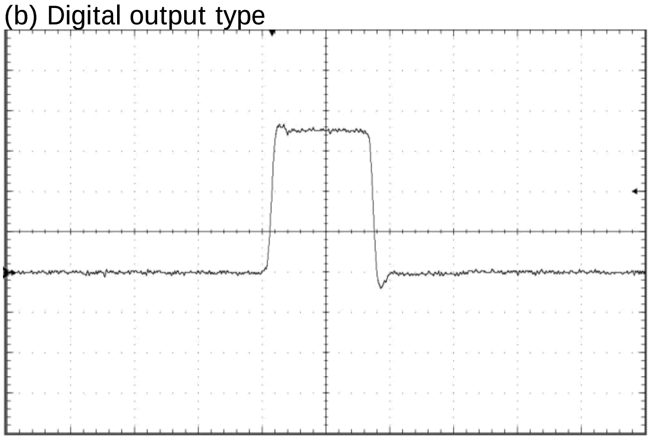


[Figure 2-4] Output waveforms

(a) Analog output type



(b) Digital output type



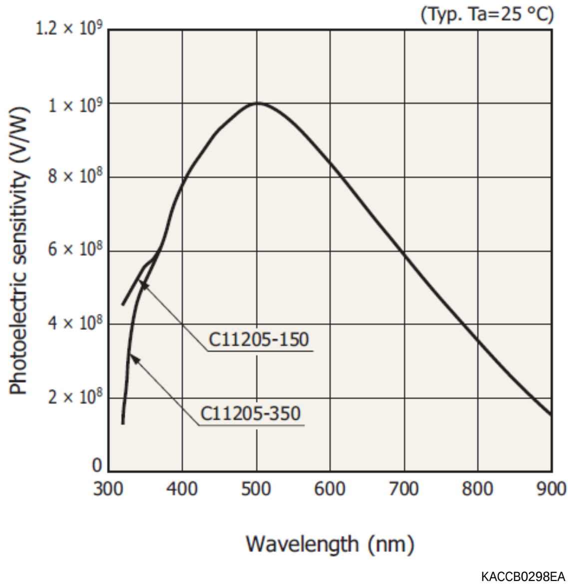
2-3. Characteristics

Sensitivity

(1) Photoelectric sensitivity (analog output type)

On analog output types, photoelectric sensitivity is defined as the output voltage from the MPPC module divided by the incident light level (unit: W) at a given wavelength, and is expressed in volts per watt (V/W).

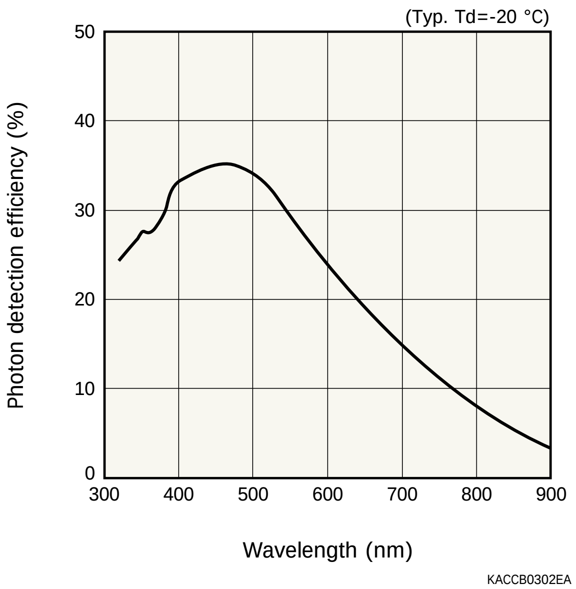
[Figure 2-5] Photoelectric sensitivity vs. wavelength (C11205 series)



(2) Photon detection efficiency (digital output type)

On digital output types, photon detection efficiency is defined as the number of photons detected by the MPPC module divided by the number of incident photons and is expressed as a percent.

[Figure 2-6] Photon detection efficiency vs. wavelength (C12661 series)



Dynamic range

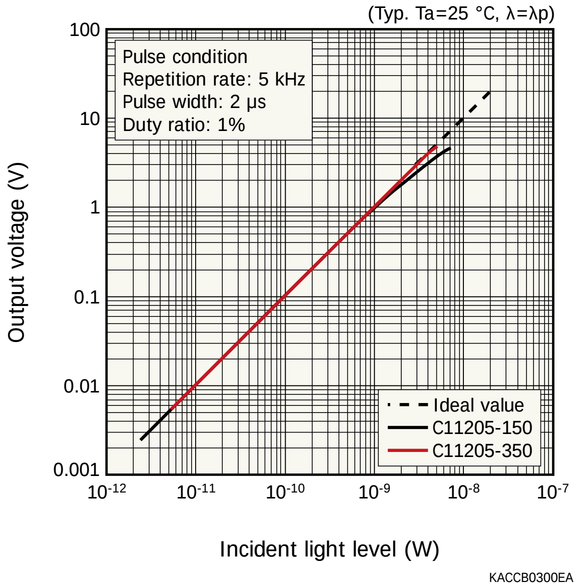
(1) Analog output type

Figure 2-7 shows typical dynamic ranges for analog output types (non-cooled type). Comparing the C11205-150 (photosensitive area: 1 mm sq) with the C11205-350 (photosensitive area: 3 mm sq) proves that the C11205-350 exhibits better linearity since it contains a larger number of pixels [Figure 2-7 (a)].

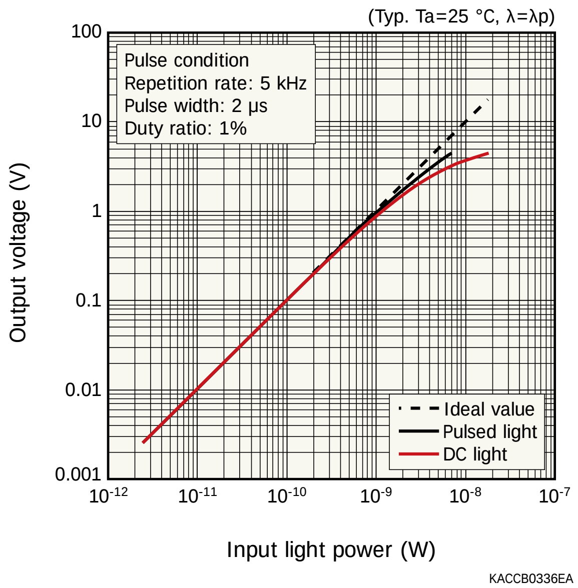
When the incident light level is high, the heat generated in the chip becomes too large to ignore. In this case, decreasing the duty ratio of the incident light is recommended [Figure 2-7 (b)]. If using a thermoelectrically cooled type, the element temperature will be maintained at a constant level, so the heat generated in the chip can be ignored in most cases.

[Figure 2-7] Output voltage vs. incident light level

(a) C11205-150 (photosensitive area: 1 mm sq), C11205-350 (photosensitive area: 3 mm sq)
[when pulsed light is input]



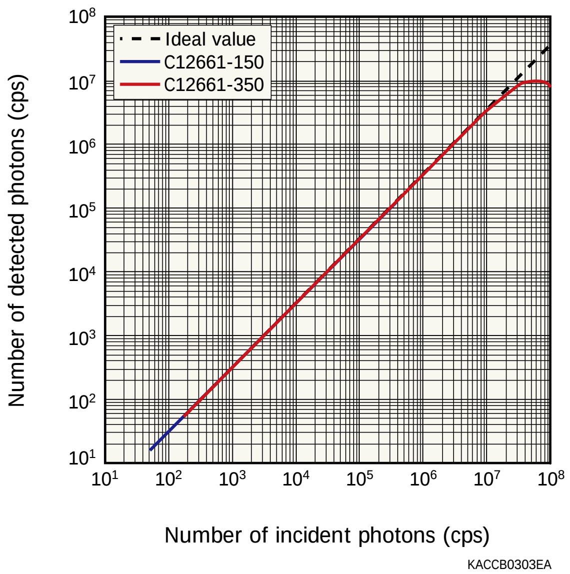
(b) C11205-150 (when pulsed light or DC light are input)



(2) Digital output type

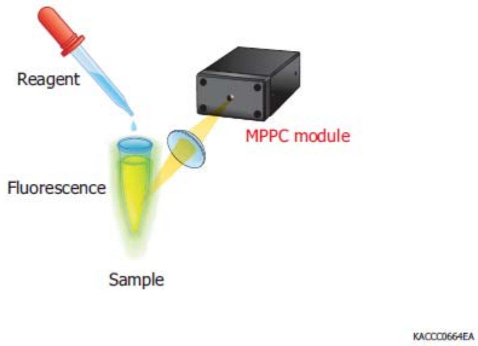
Figure 2-8 shows typical dynamic ranges for digital output types. Since the lower detection limit is determined by the dark count, the C12661-150 (photosensitive area: 1 mm sq) is better at the lower limit than the C12661-350 (photosensitive area: 3 mm sq). The upper detection limit is determined by the output pulse width, and the output pulse width is determined by the pixel pitch. So the upper detection limits on the C12661-150 and C12661-350 are nearly the same because they have the same pixel pitch. When the number of incident photons becomes larger, the output begins to deviate from the ideal linearity due to overlapping of pulses, so that eventually no pulses will appear in the output.

[Figure 2-8] Number of detected photons vs. number of incident photons (C12661 series)



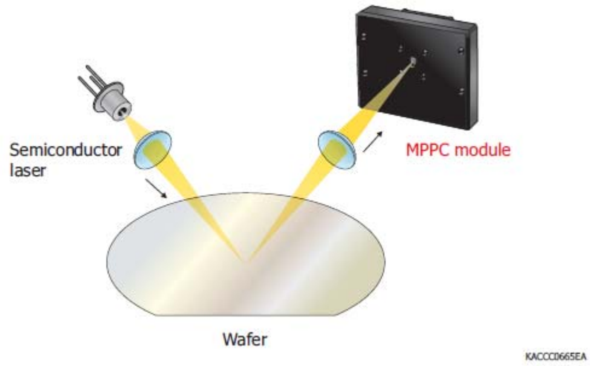
2-4. Application examples

[Figure 2-9] Fluorescence measurement



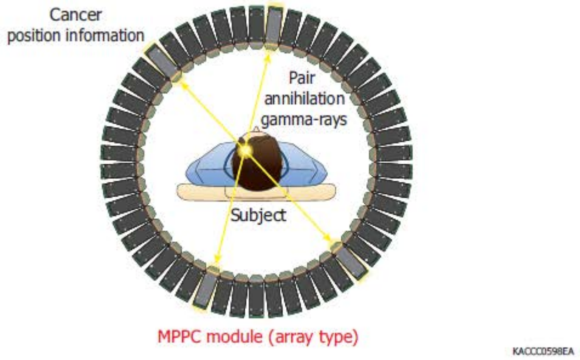
Major characteristics	High photon detection efficiency, low afterpulse
Suitable MPPC modules	C12661 series, C12662 series

[Figure 2-10] Disc surface inspection



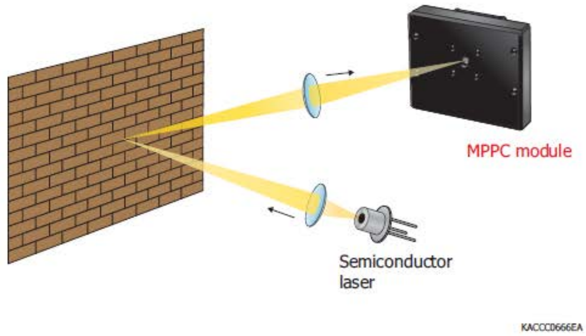
Major characteristics	High-speed response, wide dynamic range
Suitable MPPC modules	C11209 series

[Figure 2-11] Scintillation measurement



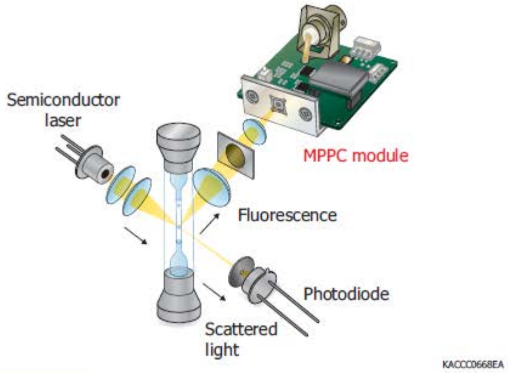
Major characteristics	Wide dynamic range
Suitable MPPC modules	C11205 series

[Figure 2-12] Distance measurement



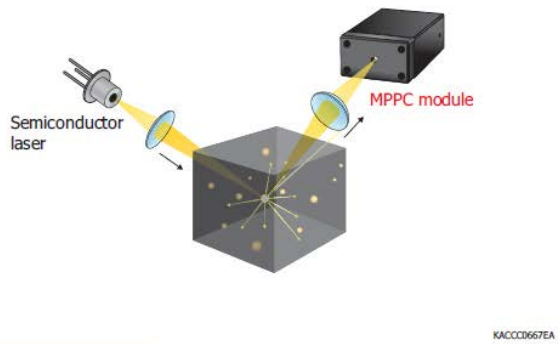
Major characteristics	High-speed response, wide dynamic range
Suitable MPPC modules	C11209 series

[Figure 2-13] Flow cytometry



Major characteristics	High photon detection efficiency
Suitable MPPC modules	C11205 series, C12662 series

[Figure 2-14] Particle measurement



Major characteristics	High photon detection efficiency, low afterpulse
Suitable MPPC modules	C11202 series

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