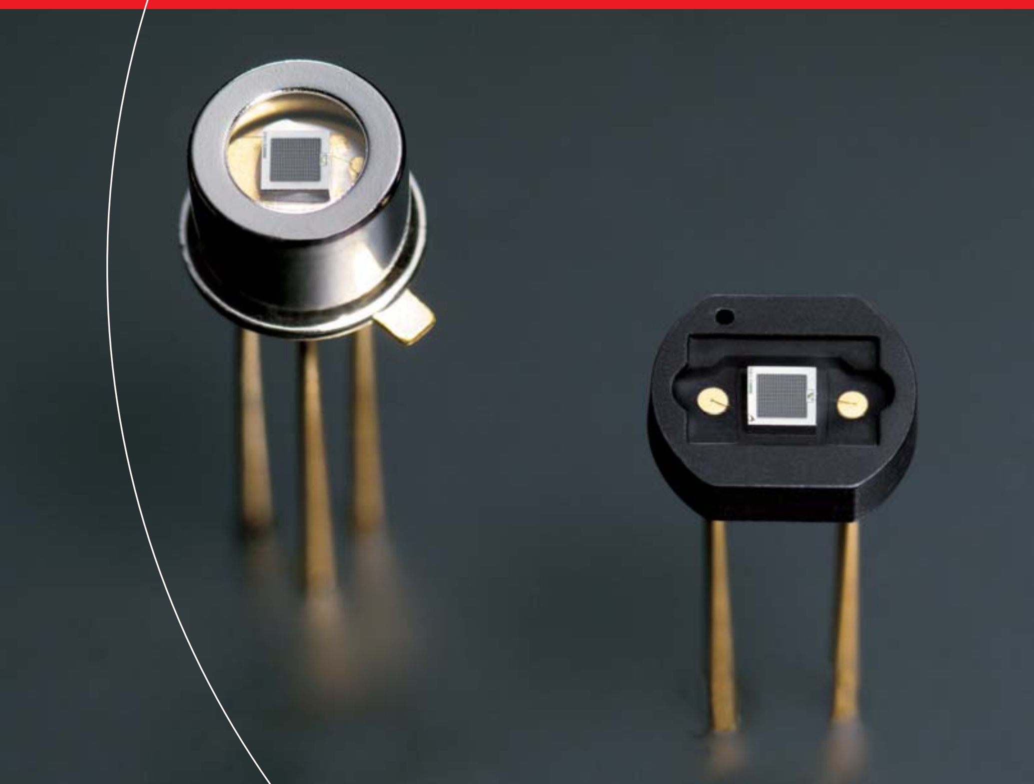
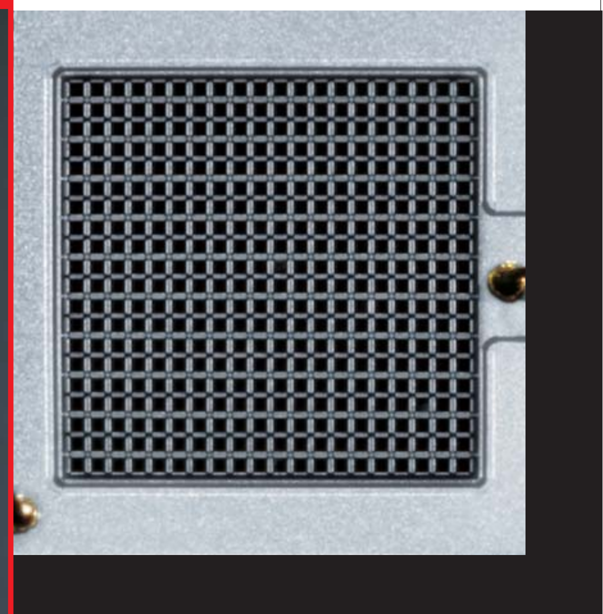
SOLID STATE DIVISION

Sep.2010

MPPC®

Multi-Pixel Photon Counter





Compact opto-semiconductors with excellent photon counting capability

HAMAMATSU

MPPC®

Multi-Pixel Photon Counter

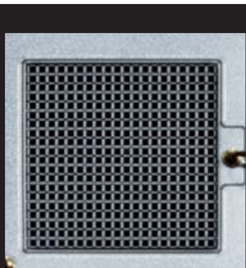
Compact opto semiconductors with excellent photon counting capabilit

New type of Si Photon-counting Device

The MPPC (Multi-Pixel Photon Counter) is a new type of photon-counting device made up of multiple APD (avalanche photodiode) pixels operated in Geiger mode. The MPPC is essentially an opto-semiconductor device with excellent photon-counting capability and which also possesses great advantages such as low voltage operation and insensitivity to magnetic fields.

Features

- Excellent photon-counting capability (Excellent detection efficiency versus number of incident photons)
- Room temperature operation
- Low bias (below 100 V) operation
- High gain: 10^5 to 10^6
- Insensitive to magnetic fields
- Excellent time resolution
- Small size
- Simple readout circuit operation
- Newly developed MPPC array (1×1ch / 2×2ch monolithic array, 4×4ch discrete array)
- MPPC module available (option)



What is the MPPC ?

The MPPC is a kind of so-called Si-PM (Silicon Photomultiplier) device. It is a photon-counting device consisting of multiple APD pixels operating in Geiger mode. Each APD pixel of the MPPC outputs a pulse signal when it detects one photon. The signal output from the MPPC is the total sum of the outputs from all APD pixels. The MPPC offers the high performance needed in photon counting and is used in diverse applications for detecting- extremely weak light at the photon-counting level.

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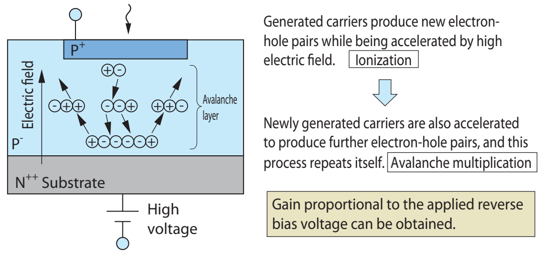
Photon counting by MPPC

The light we usually see consists of a stream of light particles (photons) that produce a certain brightness. When this brightness falls to a very low level, the incoming photons are now separate from each other. Photon counting is a technique to measure low light levels by counting the number of photons. Photomultiplier tubes and APDs (avalanche photodiodes) are the most popular photon-counting devices.

Operating principle example of APD



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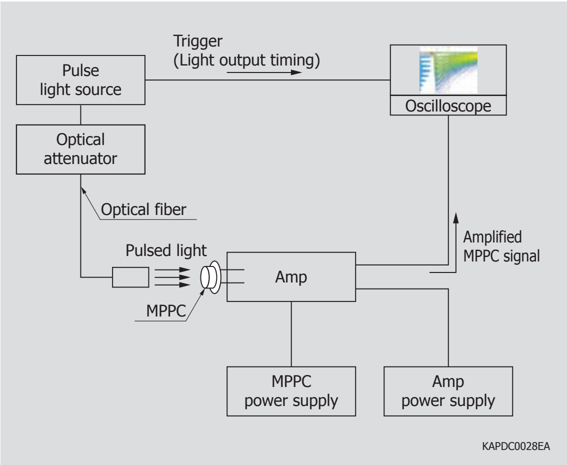
APDs are high-speed, high-sensitivity photodiodes that internally amplify photocurrent when a reverse voltage is applied.
When the reverse voltage applied to an APD is set higher than the breakdown voltage, the internal electric field becomes so high that a huge gain (10^5 to 10^6) can be obtained. Operating an APD under this condition is called "Geiger mode" operation. During Geiger mode, a very large pulse is generated when a carrier is injected into the avalanche layer by means of incident photon. Detecting this pulse makes it possible to detect single photons.
One pixel consists of a Geiger mode APD to which a quenching resistor is connected. An MPPC is made up of an array of these pixels. The sum of the output from each pixel forms the MPPC output, which allows the photons to be counted. HAMAMATSU MPPC has high sensitivity to short wavelength light emitted from commonly used scintillators. Its structure allows a high fill factor to ensure high photon detection efficiency.

Connection example
(MPPC output signal is displayed on an oscilloscope.)



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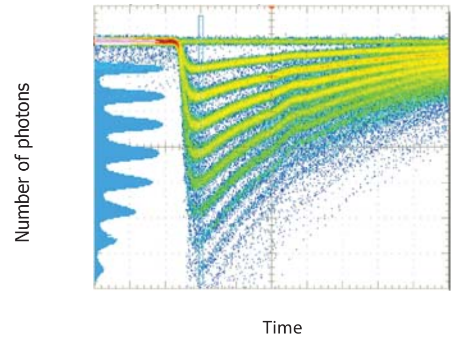
Excellent photon counting capability

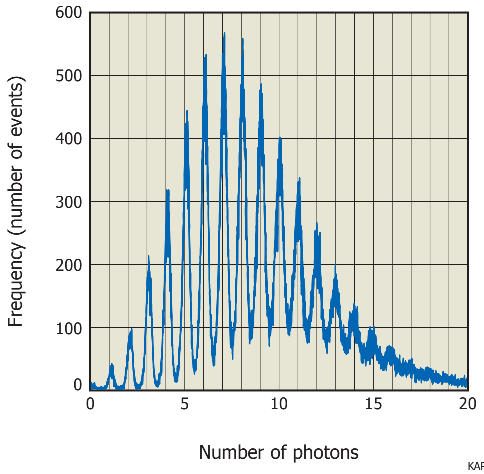
The MPPC delivers superb photon-counting performance. Connecting the MPPC to an amplifier will show sharp waveforms on an oscilloscope according to the number of detected photons.

Pulse waveform when using an amplifier (120 times) (S10362-11-050U, M=7.5 × 10^5)



The fact that the individual peaks are clearly separate from each other in the pulse height spectrum below, proves there is little variation between the gains of APD pixels making up the MPPC.

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



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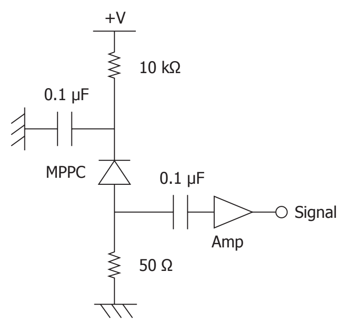
Basic connection diagram for MPPC



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1 Line-up

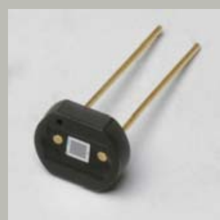
HAMAMATSU provides a variety of MPPC devices to make them even easier to use and more benefical in more applications.

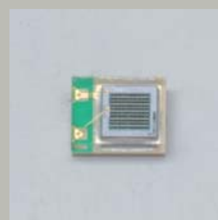
MPPC

Active area: 1 × 1 mm type

P.5

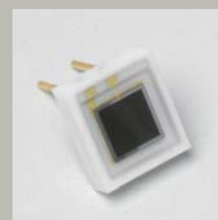

Metal type

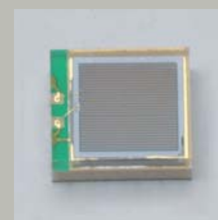

Ceramic type


SMD type

Active area: 3 × 3 mm type

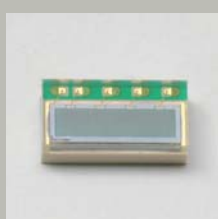
P.7

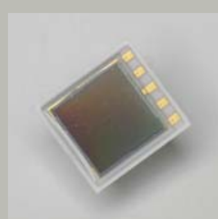

Ceramic type


SMD type

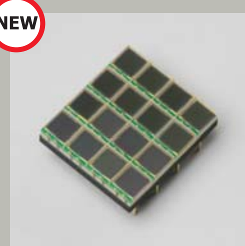
MPPC array

P.9


1 × 4 ch type


2 × 2 ch type

NEW


4 × 4 ch type

TE-cooled type

P.11

NEW


Metal type

MPPC module

P.15


Standard type

P.16

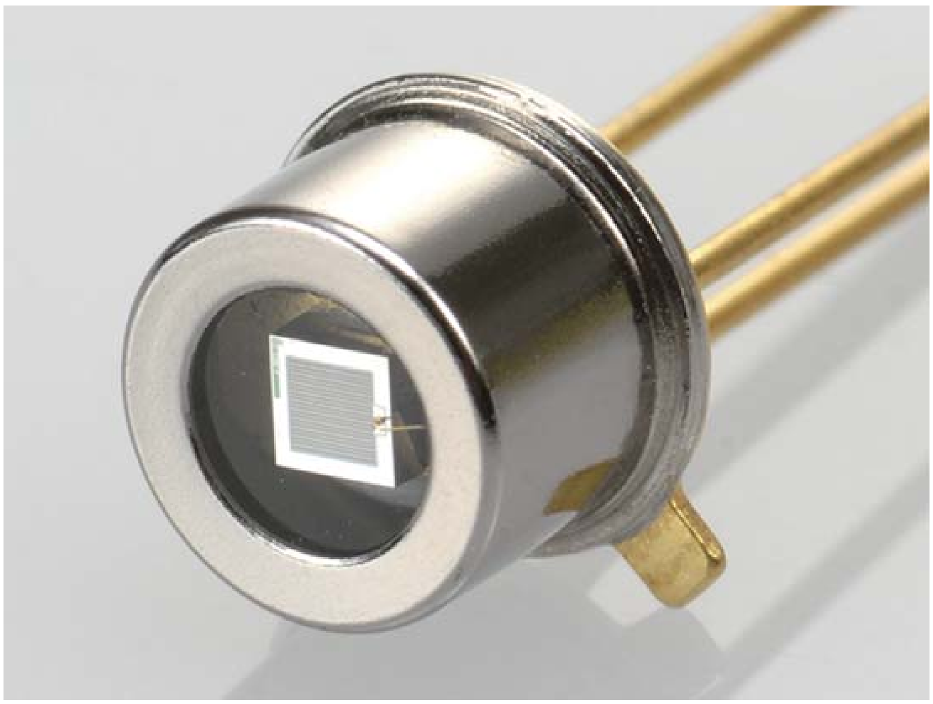

CE compliant type

NEW

P.17


TE-cooled type

MPPC



2-1. Active area: 1 × 1 mm type

2-2. Active area: 3 × 3 mm type

2-3. MPPC array (1 × 4 ch type, 2 × 2 ch type, 4 × 4 ch type)

2-4. TE-cooled type

1. Active area: 1 × 1 mm type

These MPPCs have an effective active area of 1×1 mm.They are available in three different packages (metal, ceramic, and SMD) each for different applications.The metal package is suited for installation into precision equipment, the ceramic package for coupling to a scintillator, and the SMD package for high-volume production.

S10362-11-025U/-050U/-100U　S10362-11-025C/-050C/-100C　S10362-11-025P/-050P/-100P

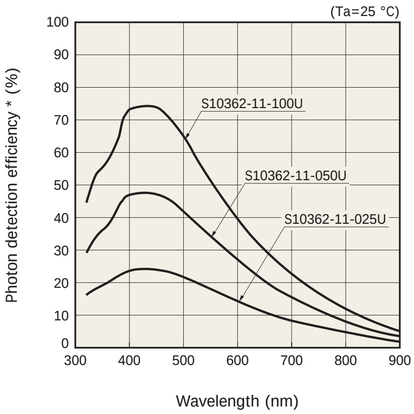
- Metal type:
  S10362-11-025U, S10362-11-050U, S10362-11-100U
- Ceramic type:
  S10362-11-025C, S10362-11-050C, S10362-11-100C
- SMD type:
  S10362-11-025P, S10362-11-050P, S10362-11-100P

Specifications (Typ. Ta=25 °C, unless otherwise noted)

Parameter	Symbol	S10362-11 series			Unit
		-025U, -025C, -025P	-050U, -050C, -050P	-100U, -100C, -100P	
Effective active area	-	1 × 1			mm
Number of pixels	-	1600	400	100	-
Pixel size	-	25 × 25	50 × 50	100 × 100	μm
Fill factor *1	-	30.8	61.5	78.5	%
Spectral response range	λ	320 to 900			nm
Peak sensitivity wavelength	λp	440			nm
Photon detection efficiency *2 (λ=λp)	PDE	25	50	65	%
Operating voltage range	-	70 ± 10 *3			V
Dark count *4	-	300	400	600	kcps
Dark count Max. *4	-	600	800	1000	kcps
Terminal capacitance	Ct	35			pF
Time resolution (FWHM) *5	-	200 to 300			ps
Temperature coefficient of reverse voltage	-	56			mV/°C
Gain	M	2.75×10^5	7.5×10^5	2.4×10^6	-

*1: Ratio of the active area of a pixel to the entire area of the pixel
*2: Photon detection efficiency includes effects of crosstalk and afterpulses.
*3: For the recommended operating voltage of each product, refer to the data attached to each product.
*4: 0.5 p.e. (threshold level)
*5: Single photon level
Note: Each value was measured at recommended operating voltage (refer to the data attached to each product).
The last letter of each type number indicates package materials (U: metal, C: ceramic, P: SMD).

Photon detection efficiency (PDE) vs. wavelength (typical example)



* Photon detection efficiency includes effects of crosstalk and afterpulses.

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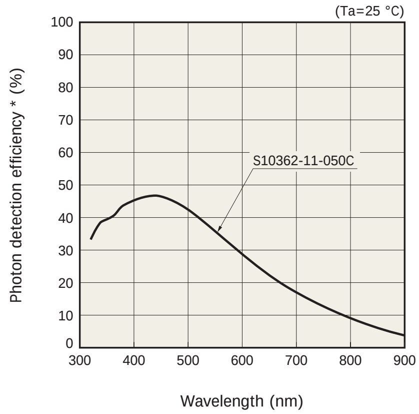
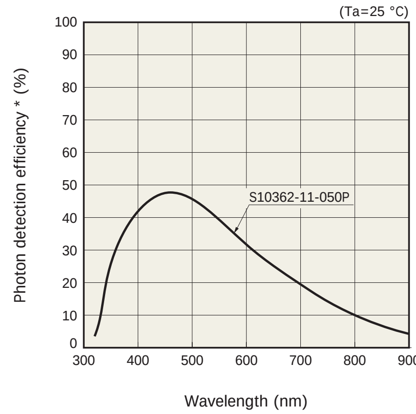


* Photon detection efficiency includes effects of crosstalk and afterpulses.

KAPDB0171EA



* Photon detection efficiency includes effects of crosstalk and afterpulses.

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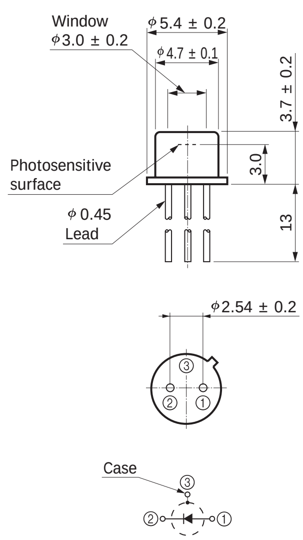
Dimensional outlines (unit: mm, tolerance: ±0.1 mm unless othierwise noted)

S10362-11-025U/-050U/-100U



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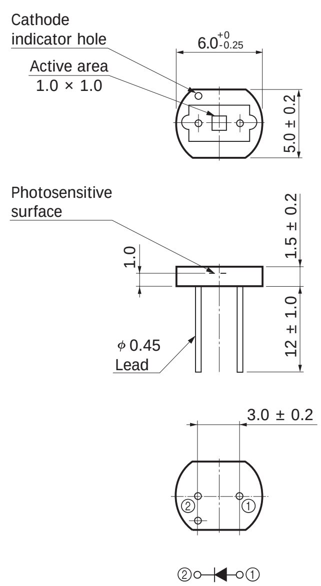
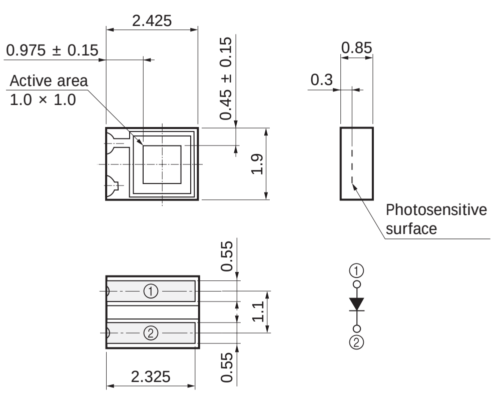
S10362-11-025C/-050C/-100C



KAPDA0122EA

S10362-11-025P/-050P/-100P



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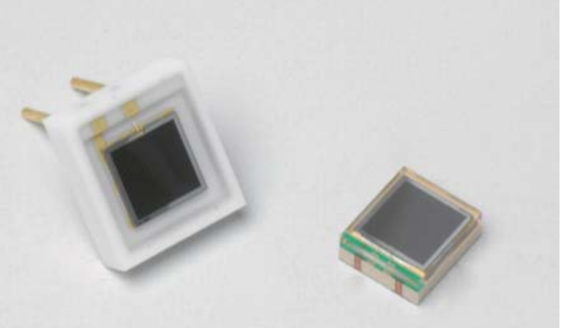
2. Active area: 3 × 3 mm type

These MPPCs have an effective active area of 3 × 3 mm and are available in two different packages (ceramic and SMD).

- Ceramic type:
  S10362-33-025C, S10362-33-050C, S10362-33-100C

- SMD type:
  S10931-025P, S10931-050P, S10931-100P



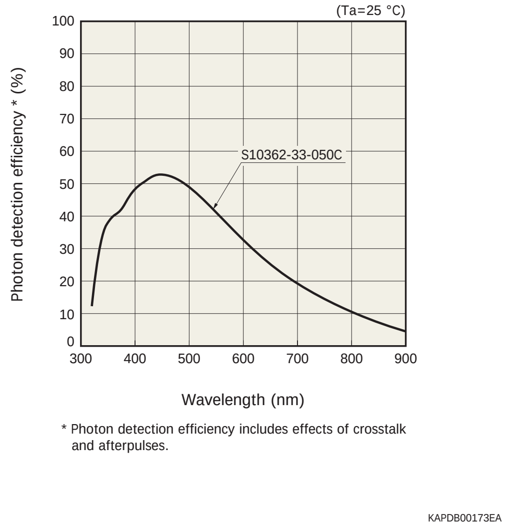
S10362-33 series S10931 series

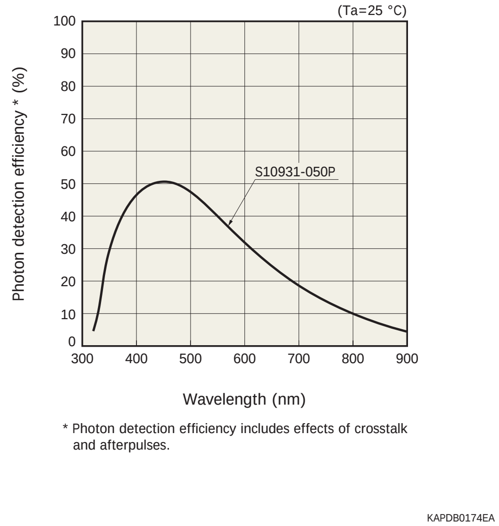
Specifications (Typ. Ta=25 °C, unless otherwise noted)

Parameter	Symbol	S10362-33 series			S10931 series			Unit
		-025C	-050C	-100C	-025P	-050P	-100P	
Effective active area	-	3 × 3			3 × 3			mm
Number of pixels	-	14400	3600	900	14400	3600	900	-
Pixel size	-	25 × 25	50 × 50	100 × 100	25 × 25	50 × 50	100 × 100	μm
Fill factor *1	-	30.8	61.5	78.5	30.8	61.5	78.5	%
Spectral response range	λ	320 to 900			320 to 900			nm
Peak sensitivity wavelength	λp	440			440			nm
Operating voltage range	-	70 ± 10 *2			70 ± 10 *2			V
Dark count *3	-	4	6	8	4	6	8	Mcps
Dark count Max. *3	-	8	10	12	8	10	12	Mcps
Terminal capacitance	Ct	320			320			pF
Time resolution (FWHM) *4	-	500 to 600			500 to 600			ps
Temperature coefficient of reverse voltage	-	56			56			mV/°C
Gain	M	2.75×10^5	7.5×10^5	2.4×10^6	2.75×10^5	7.5×10^5	2.4×10^6	-

*1: Ratio of the active area of a pixel to the entire area of the pixel
*2: For the recommended operating voltage of each product, refer to the data attached to each products.
*3: 0.5 p.e. (threshold level)
*4: Single photon level
Note: Each value was measured at recommended operating voltage (refer to the data attached to each product).
The last letter of each type number indicates package materials (C: ceramic, P: SMD).

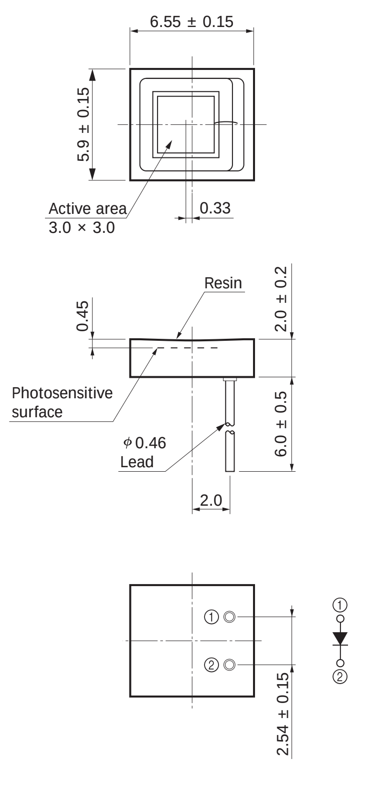
Photon detection efficiency (PDE) vs. wavelength (typical example)

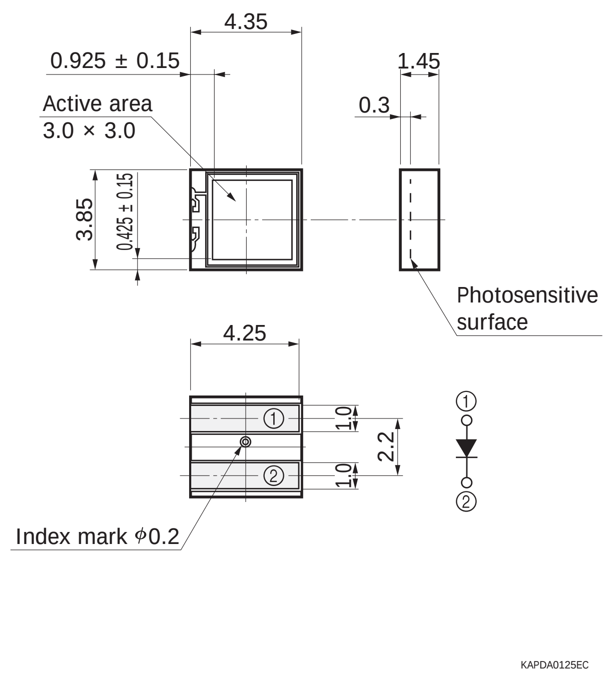




Dimensional outlines (unit: mm, tolerance: ±0.1 mm unless otherwise noted)

S10362-33-025C/-050C/-100C	S10931-025P/-050P/-100P





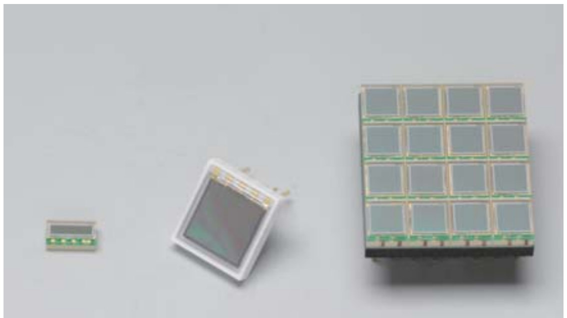
3. MPPC array

These MPPC arrays consist of multiple MPPC chips. Their large active areas allow efficient coupling to a scintillator, etc.

・1 × 4 ch array: S10984-025P, S10984-050P, S10984-100P
These are 1 × 4 ch MPPC arrays with active areas of 1 × 1 mm each. Their monolithic structure eliminates gaps between elements.

・2 × 2 ch array: S10985-025C, S10985-050C, S10985-100C
These are 2 × 2 ch MPPC arrays with active areas of 3 × 3 mm each, and can be used as a 6 × 6 mm large-area MPPC. Their monolithic structure eliminates gaps between elements.

・4 × 4 ch array: S11064-025P, S11064-050P
These are 4 × 4 ch, large-area MPPC arrays made up of individual 3 × 3 mm active areas and mounted at high densities on SMD packages. These provide stable data since performance fluctuations between elements are minimal.



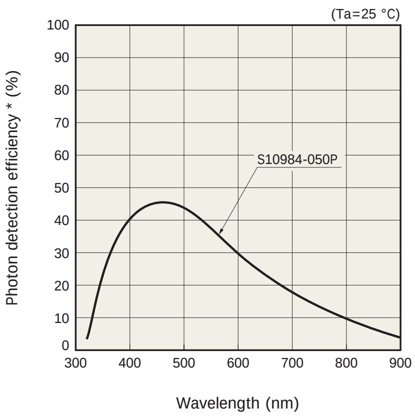
S10984-025P/-050P/-100P　S10985-025C/-050C/-100C　S11064-025P/-050P

Specifications (Typ. Ta=25 °C, unless otherwise noted)

Parameter	Symbol	S10984 series			S10985 series			S11064 series		Unit
		-025P	-050P	-100P	-025C	-050C	-100C	-025P	-050P	
Number of channels	-	4 (1 × 4)			4 (2 × 2)			16 (4 × 4)		ch
Effective active area/channel	-	1 × 1			3 × 3			3 × 3		mm
Number of pixels/channel	-	1600	400	100	14400	3600	900	14400	3600	-
Pixel size	-	25 × 25	50 × 50	100 × 100	25 × 25	50 × 50	100 × 100	25 × 25	50 × 50	μm
Fill factor *1	-	30.8	61.5	78.5	30.8	61.5	78.5	30.8	61.5	%
Spectral response range	λ	320 to 900			320 to 900			320 to 900		nm
Peak sensitivity wavelength	λp	440			440			440		nm
Operating voltage range	-	70 ± 10 *2			70 ± 10 *2			70 ± 10 *2		V
Dark count/channel *3	-	300	400	600	4000	6000	8000	4000	6000	kcps
Dark count Max. /channel*3	-	600	800	1000	8000	10000	12000	8000	10000	kcps
Terminal capacitance/channel	Ct	35			320			320		pF
Temperature coefficient of reverse voltage	-	56			56			56		mV/°C
Gain	M	2.75×10^5	7.5×10^5	2.4×10^6	2.75×10^5	7.5×10^5	2.4×10^6	2.75×10^5	7.5×10^5	-

*1: Ratio of the active area of a pixel to the entire area of the pixel
*2: For the recommended operating voltage of each product, refer to the data attached to each products.
*3: 0.5 p.e. (threshold level)
Note: Each value was measured at recommended operating voltage (refer to the data attached to each product).
The last letter of each type number indicates package materials (C: ceramic, P: SMD).

Photon detection efficiency (PDE) vs. wavelength (typical example)



* Photon detection efficiency includes effects of crosstalk and afterpulses.

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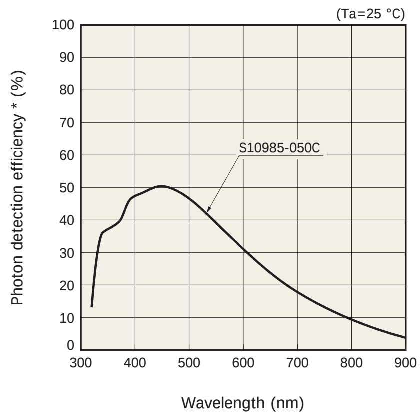
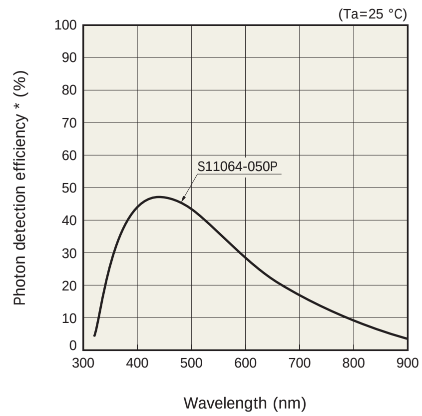


* Photon detection efficiency includes effects of crosstalk and afterpulses.

KAPDB0177EA



* Photon detection efficiency includes effects of crosstalk and afterpulses.

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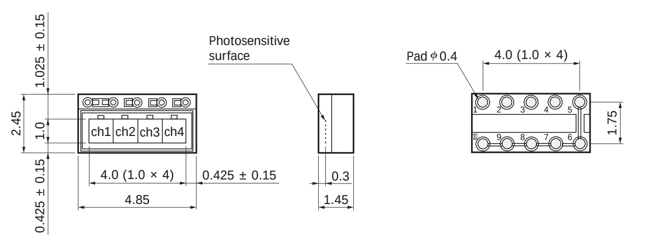
Dimensional outlines (unit: mm)

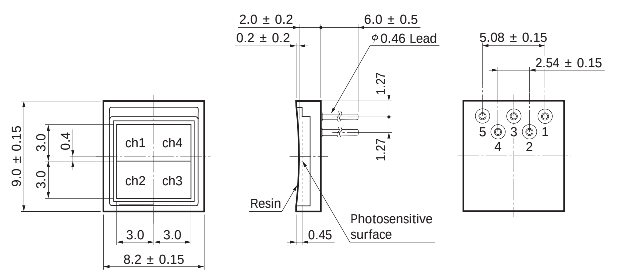
S10984-025P/-050P/-100P



Pad No.	Connection
1	anode ch4
2	anode ch3
3	anode ch2
4	anode ch1
5	Cathode (common)
6	Cathode (common)
7	Cathode (common)
8	Cathode (common)
9	Cathode (common)
10	Cathode (common)

KAPDA0126EA

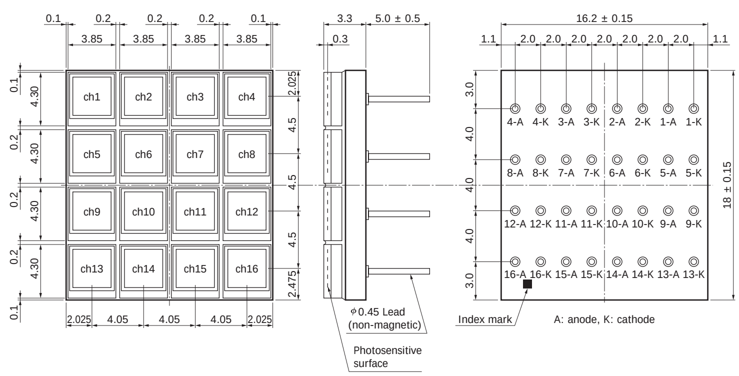
S10985-025C/-050C/-100C



Pin No.	Connection
1	anode ch1
2	anode ch2
3	Cathode (common)
4	anode ch3
5	anode ch4

KAPDA0127EA

S11064-025P/-050P



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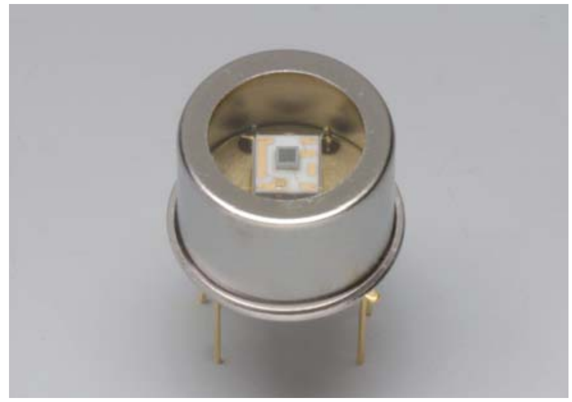
4. TE-cooled type

The S11028 series is a photon counting detector that integrates a 1 × 1 mm MPPC with a thermoelectrically cooler . It also contains a thermistor for temperature monitoring, allowing stable measurement over long periods of time. A temperature controller (C1103-04)* is also provided (sold separately).

* Please see our website: http://jp.hamamatsu.com/

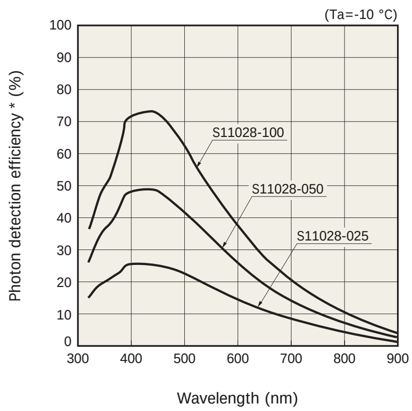


Specifications (Typ. Ta=25 °C, △T=-35 °C)

Parameter	Symbol	S11028 series			Unit
		-025	-050	-100	
Effective active area	-	1 × 1			mm
Number of pixels	-	1600	400	100	-
Pixel size	-	25 × 25	50 × 50	100 × 100	μm
Cooling	-	Two-stage TE-cooled			-
Fill factor *1	-	30.8	61.5	78.5	%
Spectral response range	λ	320 to 900			nm
Peak sensitivity wavelength	λp	440			nm
Photon detection efficiency *2 (λ=λp)	PDE	25	50	65	%
Operating voltage range	-	68.25 ± 10 *3			V
Recommended cooling temperature	-	-10			°C
Dark count *4	-	15	20	30	kcps
Dark count Max. *4	-	30	40	50	kcps
Terminal capacitance	Ct	35			pF
Time resolution (FWHM) *5	-	200 to 300			ps
Temperature coefficent of reverse voltage	-	50			mV/°C
Gain	M	2.75×10^5	7.5×10^5	2.4×10^6	-

*1: Ratio of the active area of a pixel to the entire area of the pixel
*2: Photon detection efficiency includes effects of crosstalk and afterpulses.
*3: For the recommended operating voltage of each product, refer to the data attached to each products.
*4: 0.5 p.e. (threshold level)
*5: Single photon level
Note: Each value was measured at recommended operating voltage (refer to the data attached to each product).

Photon detection efficiency (PDE) vs. wavelength (typical example)



* Photon detection efficiency includes effects of crosstalk and afterpulses.

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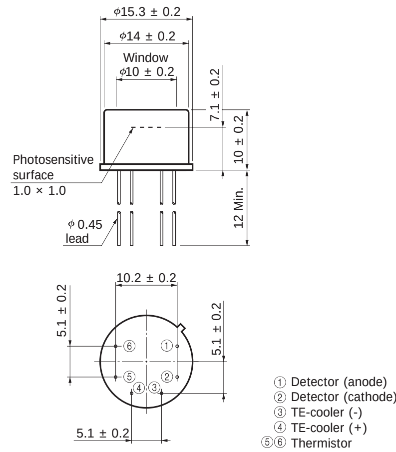
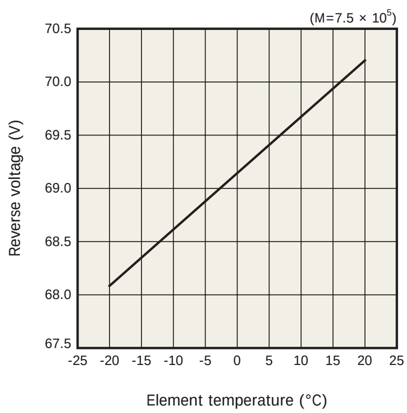
Dimensional outline (unit: mm)



KAPDA0129EA

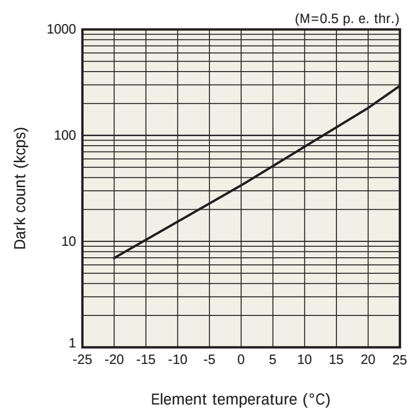
Characteristics of element

Dark current vs. element temperature (S11028-050, typical example)



KAPDB0165EA

Reverse voltage vs. element temperature (S11028-050, typical example)



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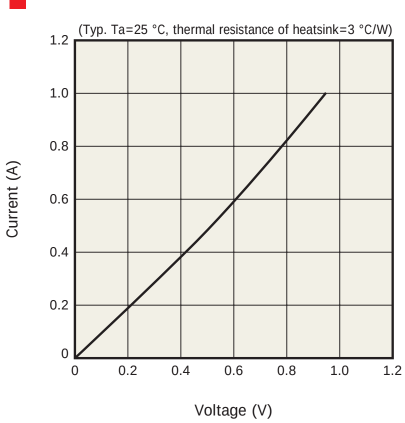
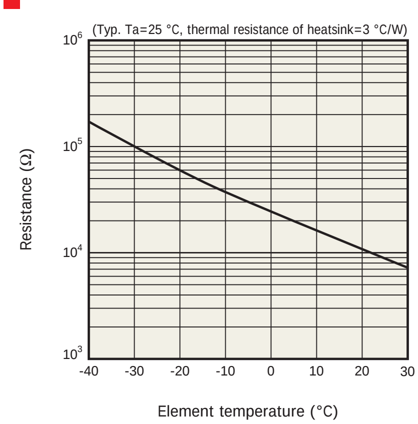
Characteristics of TE-cooler

Current vs. voltage



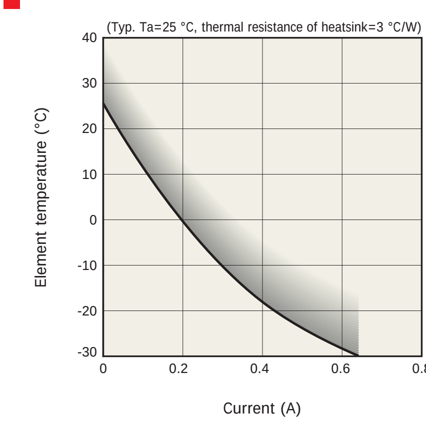
KAPDB0166EA

Thermistor characteristic



KAPDB0167EA

Cooling characteristics*



* This is plotted when MPPC is not operated. When MPPC is in operation, the plot will vary because the amount of heat generation in MPPC changes depending on the applied reverse voltage and incident light intensity.

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MPPC module

3-1. Standard type

3-2. CE compliant type

3-3. TE-cooled type

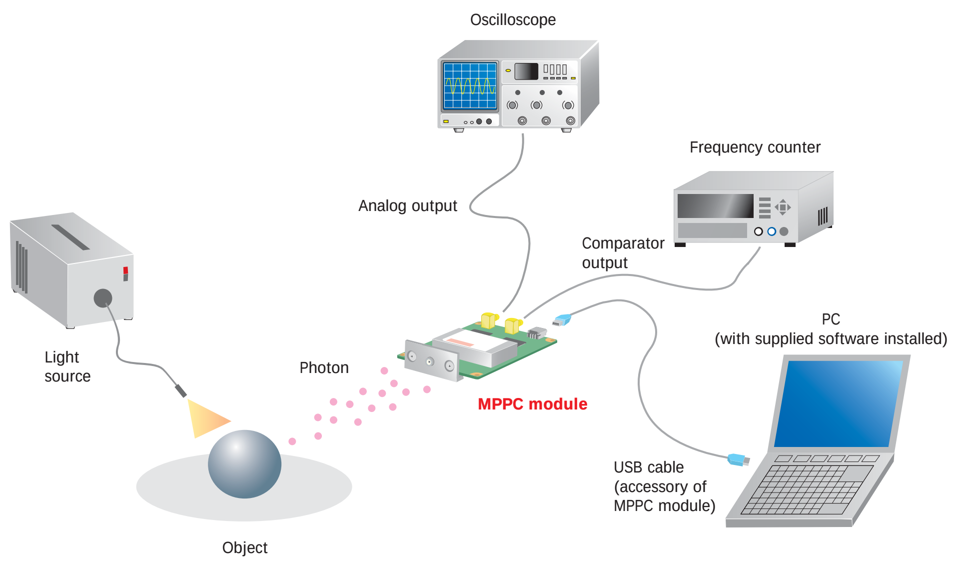
3-4. Characteristics and use

Making it easy to count photons

The MPPC module is a photon counting module capable of low-light-level detection. This module consists of an MPPC device, current to voltage converter circuit, high-speed comparator circuit, high-voltage power supply circuit, temperature-compensation circuit, counter circuit, and microcontroller. The module also has a USB port for connecting to a PC. The threshold level (detection level for one photon) can be changed from a PC. The MPPC module is designed to extract maximum MPPC performance and so yields excellent photon counting characteristics. Potential applications include, fluorescence measurement, DNA analysis, environmental chemical analysis and high energy physics experiments, as well as many other areas.

Connection example

To use the MPPC module, it must be connected to a PC through a USB 1.1 interface. The MPPC is powered by the USB bus power from the PC. Various MPPC module operations are performed on the PC, and the measurement data can be monitored on the PC. Connecting the analog output to an oscilloscope allows monitoring the output waveforms. Connecting the comparator output to a frequency counter allows obtaining the count value.



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1. Standard type

Standard type MPPC modules incorporate MPPC with an effective active area of 1×1 mm. Two types are provided: one uses a metal package MPPC and the other a ceramic package MPPC. Both types have a USB port for connecting to a PC to make photon counting easy.

- Metal type:
  C10507-11-025U, C10507-11-050U, C10507-11-100U

- Ceramic type:
  C10507-11-025C, C10507-11-050C, C10507-11-100C

C10507-11-025U/ -050U/-100U　　C10507-11-025C/ -050C/-100C

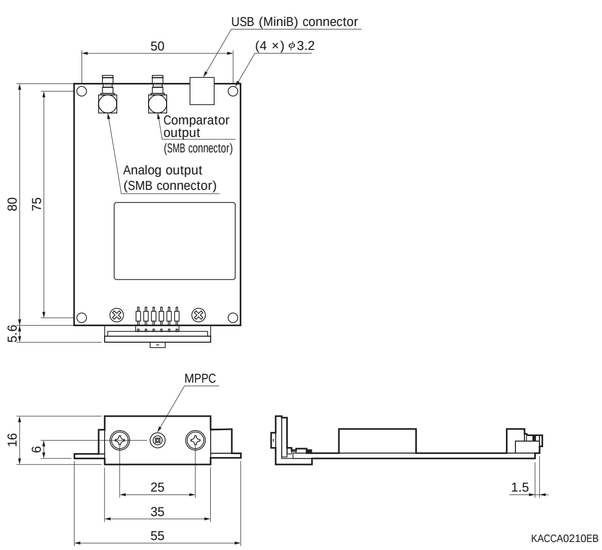
Specifications (Typ. Ta=25 °C, unless otherwise noted)

Parameter	Symbol	Condition	C10507-11 series						Unit
			-025U	-025C	-050U	-050C	-100U	-100C	
Internal MPPC	-		S10362-11 series						-
			-025U	-025C	-050U	-050C	-100U	-100C	
Effective active area	-		1 × 1						mm
Number of pixels	-		1600		400		100		-
Pixel size	-		25 × 25		50 × 50		100 × 100		μm
Peak sensitivity wavelength	λp		440						nm
Analog output voltage	-		100						mV/p.e.
Dark count *1	-		500		600		900		kcps
Photon detection efficiency *2	PDE	λ=λp	20		35		45		%
Temperature stability of analog output	-	25±10 °C	± 5 Max.						%
Comparator threshold level	-		0.5, 1.5, 2.5, 3.5, Disable (adjustable 5 states)						-
Interface	-		USB 1.1						-
Board dimension	-		80 × 55						mm

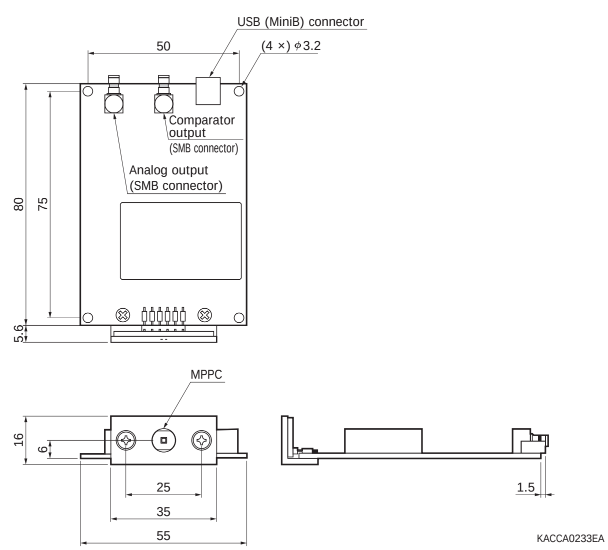
*1: 0.5 p.e. (threshold level)
*2: Photon detection efficency includes effects of crosstalk and afterpulses. 0.5 p.e. (threshold level)
Note: The last letter of each type number indicates package materials (U: metal, C: ceramic).

Dimensional outlines (unit: mm)

C10507-11-025U/-050U/-100U



C10507-11-025C/-050C/-100C



2. CE compliant type

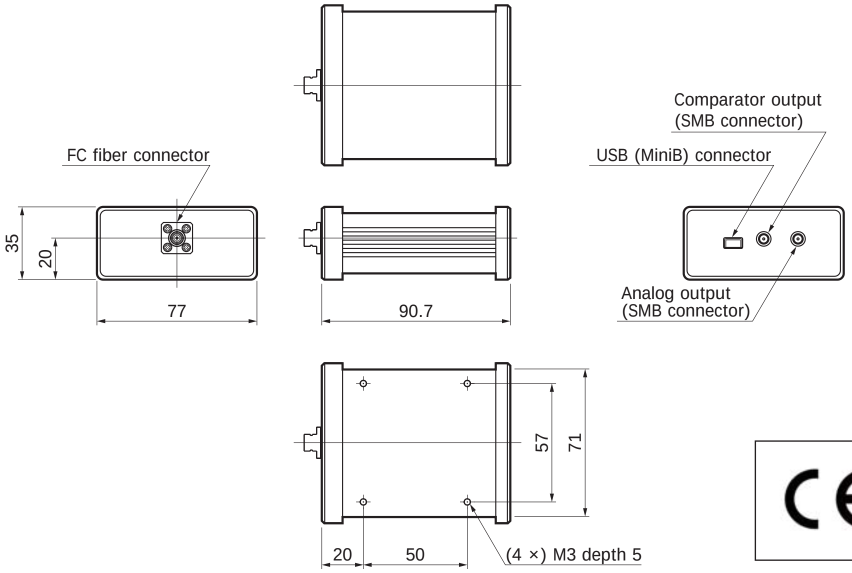
This MPPC module conforms to the European EMC directive (applicable standard: EN61326-1 Class B). It has a 1 × 1 mm active area MPPC (metal package type) and allows a light input fiber coupling (equipped with FC type optical fiber connector as standard).

Specifications (Typ. Ta=25 °C, unless otherwise noted)

Parameter	Symbol	Condition	C10751-01	C10751-02	C10751-03	Unit
Internal MPPC	-		S10362-11 series			-
			-025U	-050U	-100U	
Effective active area	-		1 × 1			mm
Number of pixels	-		1600	400	100	-
Pixel size	-		25 × 25	50 × 50	100 × 100	µm
Peak sensitivity wavelength	λp		440			nm
Analog output voltage	-		100			mV/p.e.
Dark count *1	-		500	600	900	kcps
Photon detection efficiency *2	PDE	λ=λp	20	35	45	%
Temperature stability of analog output	-	25±10 °C	± 5 Max.			%
Comparator threshold level	-		0.5, 1.5, 2.5, 3.5, Disable (adjustable 5 states)			-
Interface	-		USB 1.1			-
Dimension	-		90.7 × 77 × 35			mm

*1: 0.5 p.e. (threshold level)
*2: Photon detection efficency includes effects of crosstalk and afterpulses. 0.5 p.e. (threshold level)

Dimensional outline (unit: mm)



The C10751 series confirms to European EMC directives: EN61326-1 Class B.

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3. TE-cooled type

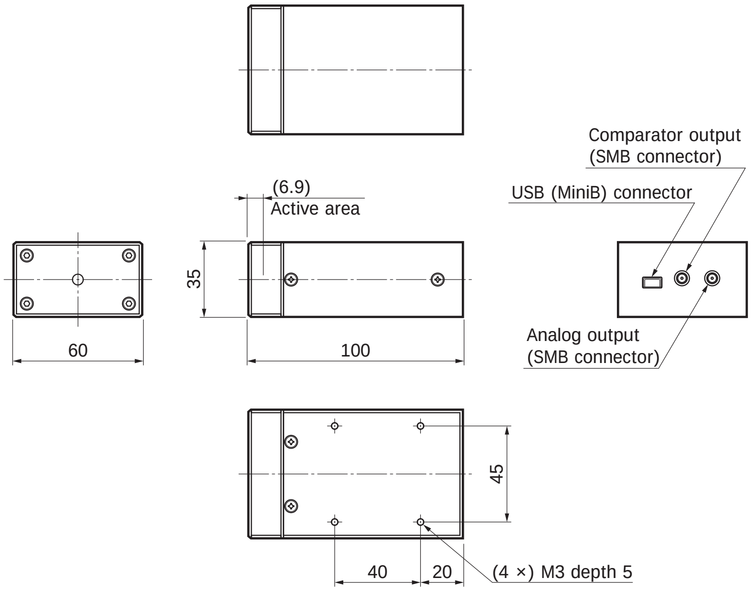
This MPPC module contains a thermoelectric cooler. Cooling the MPPC can reduce dark current noise components by one order of magnitude or more. Though the MPPC is an opto-semiconductor capable of photon counting at room temperature, it can measure at even lower count levels by reducing the dark count. This MPPC module conforms to the European EMC directive (applicable standard: EN61326-1 Class B).

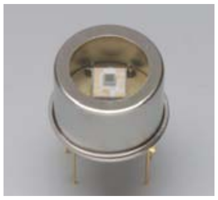
Specifications (Typ. Ta=25 °C, unless otherwise noted)

Parameter	Symbol	Condition	C11208-01	C11208-02	C11208-03	Unit
Internal MPPC	-		S11028-025	S11028-050	S11028-100	-
Effective active area	-		1 × 1			mm
Number of pixels	-		1600	400	100	-
Pixel size	-		25 × 25	50 × 50	100 × 100	μm
Peak sensitivity wavelength	λp		440			nm
Analog output voltage	-		100			mV/p.e.
Dark count *1	-		15	30	40	kcps
Photon detection efficiency *2	PDE	λ=λp	20	40	50	%
Temperature stability of analog output	-	0 to +35°C	± 4 Max.			%
Comparator threshold level	-		0.5, 1.5, 2.5, 3.5, 4.5, 5.5, 6.5, 7.5, Disable (adjustable 9 states)			-
Interface	-		USB 1.1			-
Dimension	-		100 × 60 × 35			mm

*1: 0.5 p.e. (threshold level)
*2: Photon detection efficency includes effects of crosstalk and afterpulses. 0.5 p.e. (threshold level)

Dimensional outline (unit: mm)





Built-in MPPC S11028 series

The C11208 series confirms to European EMC directives: EN61326-1 Class B.

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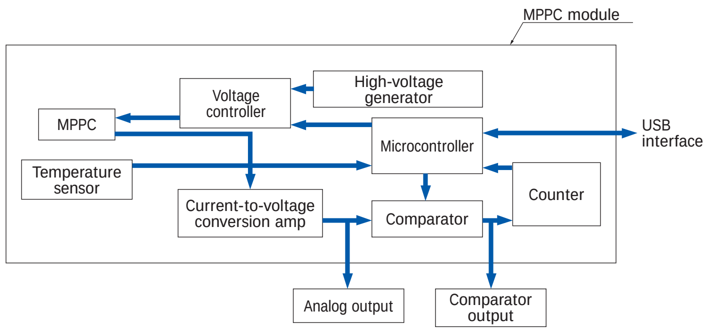
4. Characteristics and use

Block diagram



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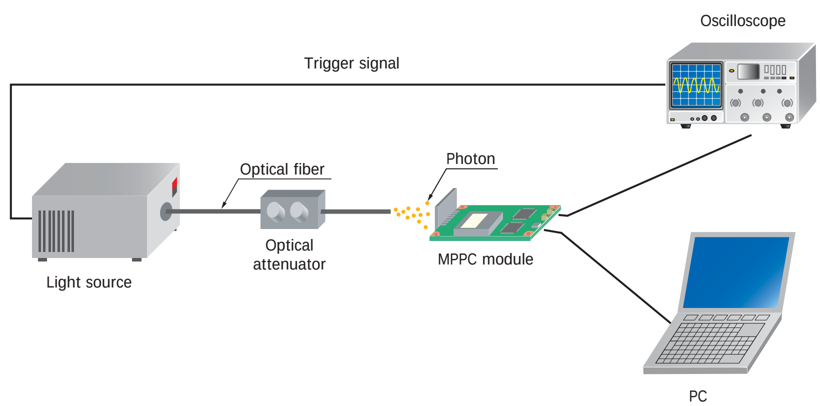
Measurement setup



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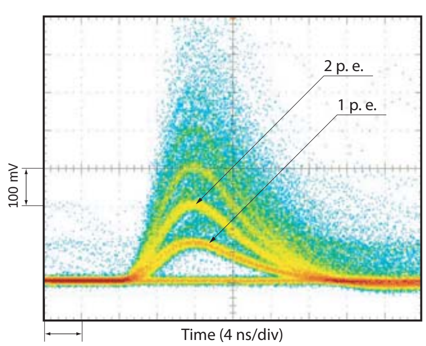
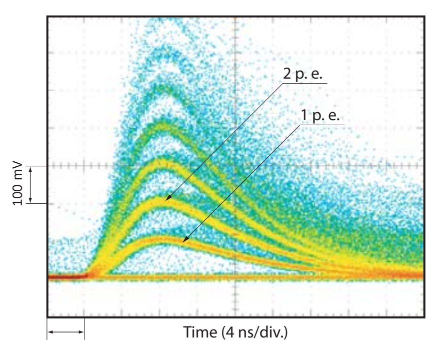
Measurement example

Analog output (C10507-11-025U)

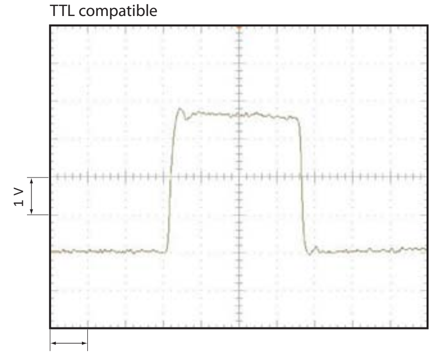


Analog output (C10507-11-050U)



Comparator output

TTL compatible



Sample software (supplied)

The sample software is designed to easily perform basic MPPC module operations. Using the sample software makes it easy to perform measurements. Basic functions of the sample software are acquiring data, displaying measurement data graphs, and saving data.

■ System requirements for sample software

The sample software operation is verified by the following systems. Operation with other systems is not guaranteed.

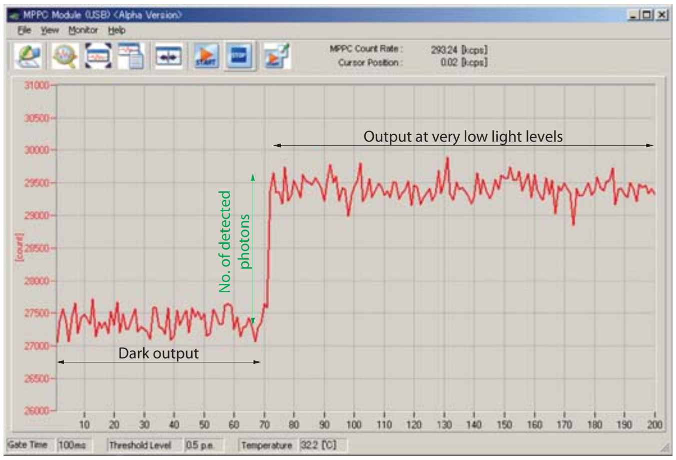
Microsoft Windows 2000 Professional SP4 *
Microsoft Windows XP Professional SP2

We recommend using a PC with a high-performance CPU and a large capacity memory. A high-performance CPU and large memory are especially important when operating two or more MPPC modules simultaneously.

* Microsoft Windows is either registered trademarks or trademarks of Microsoft Corporation in the United States and/or other countries

Example of measuring very low level light

This graph shows an output change when very low level light is input in dark conditions.



Vertical axis: number of input counts per gate time setting
Horizontal axis: time [1 second per scale division (10)]

Options (sold separately)

Fiber adapter (for C10507-11-025U/-050U/-100U) A10524 series

The A10524 series fiber adapters are designed to couple the MPPC module to an optical fiber. Two types are available for FC and SMA connectors. Using this adapter allows efficiently coupling the MPPC module to a GI-50/125 multi-mode fiber. This adapter screws on for easy attachment.

Suitable MPPC module :

C10507-11-025U, C10507-11-050U, C10507-11-100U

A10524-01 (FC type)

A10524-02 (SMA type)

Coaxial converter adapter A10613 series

The A10613 series is a coaxial adapter that converts the SMB coaxial connector for signal-output on the MPPC module to a BNC or SMA coaxial connector. This adapter allows connecting a BNC or SMA cable to the MPPC module.

A10613-01 (SMB-BNC)

A10613-02 (SMB-SMA)

Description of terms

[Afterpulse]

Afterpulses are spurious pulses following the true signal, which occur when the generated carriers are trapped by crystal defects and then released at a certain time delay. Afterpulses cause detection errors. The lower the temperature, the higher the probability that carriers may be trapped by crystal detects, so afterpulses will increase.

[Crosstalk]

In an avalanche multiplication process, photons might be generated which are different from photons initially incident on an APD pixel. If those generated photons are detected by other APD pixels, then the MPPC output shows a value higher than the number of photons that were actually input and detected by the MPPC. This phenomenon is thought to be one of the causes of crosstalk in the MPPC.

[Dark count]

Output pulses are produced not only by photon-generated carriers but also by thermally-generated dark current carriers. The dark current pulses are measured as dark count which then causes detection errors. Although increasing the reverse voltage improves photon detection efficiency, it also increases the dark count. The dark count can be reduced by lowering the temperature.

[Excitation]

This is a phenomenon in which electron-hole pairs are generated in a photodiode by the energy of input photon when the photon energy is greater than the band gap.

[Fill factor]

The ratio of the active area size of a pixel to the total pixel size including circuits.

[Gain (Multiplication)]

The ratio of the number of multiplied electrons to one electron excited by one photon incident on the APD.

[Geiger discharge]

When an APD is operated at a reverse voltage higher than the breakdown voltage, a high electric field is produced, so that a discharge occurs even from a weak light input. This phenomenon is "Geiger discharge".

[Geiger mode]

Operation mode in which an APD is operated at a reverse voltage higher than the breakdown voltage. Geiger mode operation makes it possible to detect single photons.

[Multi-channel Analyzer: MCA]

This is a pulse height analyzer for analyzing and sorting the input analog pulses into different channels according to pulse height.

[p.e.]

This is an abbreviation for "photon equivalent".

Example: 1 p.e. pulse = pulse with amplitude equivalent to one detected photon (including noise component)

[Time-to-Amplitude Converter: TAC]

Instrument for generating an output pulse height representing the time difference between two input signals.

[Time resolution]

The output pulse timing from an APD pixel may vary with the position of the APD pixel where a photon entered or with the photon input timing. Even if photons simultaneously enter different pixels at the same time, the output pulse from each pixel will not necessarily be the same time so that a fluctuation or time jitter occurs. When two photons enter APD pixels at a certain time difference which is shorter than this jitter, then that time difference is impossible to detect. Time resolution is the minimum time difference that can be detected by APD pixels and is defined as the FWHM of the distribution of the time jitter.

[Photon detection efficiency: PDE]

This is a measure of what percent of the incident photons were detected. Photon detection efficiency (PDE) is expressed by the following equation.

Pa becomes larger as the reverse voltage is increased.

$$PDE = QE \times fg \times Pa$$

QE: Quantum efficiency
fg : Geometric factor
Pa : Avalanche probability

[Quantum efficiency: QE]

Quantum efficiency is a value showing the number of electrons or holes created as photocurrent divided by the number of incident photons, and is usually expressed as a percent. Quantum efficiency QE and photo sensitivity S (in A/W units) have the following relationship at a given wavelength λ (in nm units).

$$QE = \frac{S \times 1240}{\lambda} \times 100\ [\%]$$

[Quenching]

This is the process of decreasing the voltage from V_R to V_{BR} to stop the Geiger discharge.

Addendum

Geiger-mode APD Arrays detect low light

Author: Earl Hergert and Maridel Lares, Hamamatsu Photonics Corp.

Geiger-mode APD Arrays detect low light

Solid-state photodetectors have evolved in their ability to detect low levels of light. Building upon silicon photodiodes, novel solid-state detectors have been developed to detect increasingly lower levels of light. The latest addition and most sensitive solid-state detector to date is the Geiger-mode avalanche-photodiode (APD) array, which is capable of detecting a single photon.

Silicon photodiodes convert light into an electrical signal. This conversion occurs when photons having more energy than the bandgap of the detector material are absorbed, exciting an electron from the valence band of the semiconductor to the conduction band, where it is read out as signal. Avalanche photodiodes use the same process, but they generate internal gain using an avalanche multiplication process. An avalanche region is produced within the APD, creating an area of very high electric-field strength. When a photogenerated (or thermally generated) electron in the conduction band moves into the avalanche region, the electric-field strength is sufficient to accelerate it to the point at which it can cause “impact ionization” and liberate another electron. Both of these electrons can be accelerated as well, creating an avalanche multiplication. This process results in detector gain. Typical gains for an APD are in the range of ten to a few hundred.

Geiger-mode operation can increase the modest gain of an APD to a more significant level. In a single-photon-counting APD (in Geiger mode), the electric field described above increases with increasing applied voltage, thereby increasing the APD gain. This works only up to a point. At some operating voltage, the semiconductor junction breaks down and the APD will become a conductor. In fact, the APD is stable above this breakdown voltage until an electron enters the avalanche region, resulting in the avalanche region breaking down and the APD becoming a conductor—this is known as a Geiger discharge. The current flow produced by the breakdown is large; therefore, the signal gain is large (more than 10^5) because a single electron resulted in a large flow of current.

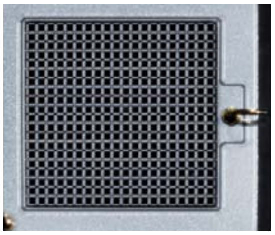


FIGURE 1. A multipixel photon counter is a photon-counting device consisting of multiple APD pixels operating in Giger mode. Each pixel outputs a pulse signal when it detects photons, and the output of the device is the total sum of the outputs from all the pixels

A device that triggers once, however, is not a very useful detector, so a means to stop the breakdown or to reset the APD is required. Typically the reset is accomplished by placing a resistor in series with the detector. When the junction breaks down, large current flows through the resistor, resulting in a voltage drop across the resistor and in the APD. If the voltage drop is sufficient, the APD voltage will drop below the breakdown voltage and be reset. The discharge-and-reset cycle is known as the Geiger mode of operation.

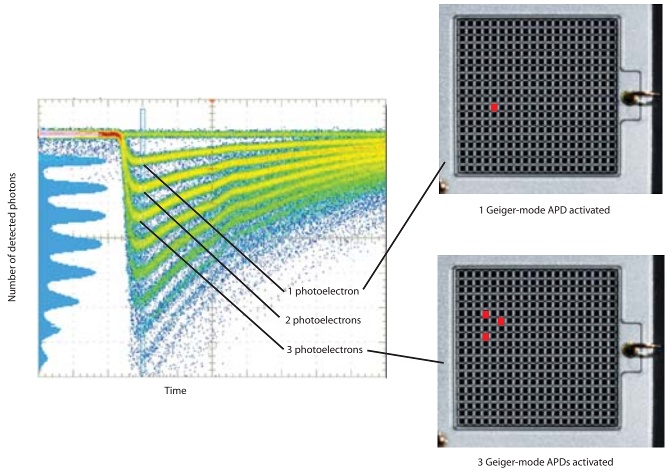


FIGURE 2. In two MPPC arrays of 20 × 20 Geiger-mode APDs, shown with an output waveform, the red pixels represent the discharge of the pixel when an incident photon is detected. In the top array a single photon detected resulting in one photoelectron output. In the lower array three simultaneously detected photons resulting in a pulse with an amplitude three times higher.

Geiger-mode APD arrays

A single APD operating in Geiger mode has a limitation: it is essentially on or off. It cannot distinguish between a single photon and multiphotons that arrive simultaneously. One only knows that the APD was triggered; it is not possible to tell if a single photon or multiple photons triggered the Geiger discharge. Single Geiger-mode APDs are suitable for photon counting at very weak light levels only.

Photon counting is a signal-processing technique that converts the output signal generated by a single photon into a digital pulse that is counted. No additional analog-to-digital converters are needed because the photon-counting circuit does the conversion. Photon counting follows Poisson statistics, so the signal-to-noise ratio is simply the square root of the number of signal counts. If one needs to improve the signal-to-noise ratio, the count is extended for a longer period of time (a count four times longer improves the signal-to-noise ratio by a factor of two).

An array of Geiger-mode APDs connected in parallel can overcome the limitation of a single device. These recently developed arrays can distinguish multiple-photon from single-photon events. One example of these devices, generically known as silicon photomultipliers, is the multipixel photon counter (MPPC) from Hamamatsu Photonics (see Fig. 1).

The sum of the output from each APD pixel forms the MPPC output. This allows the counting of single photons or the detection of pulses of multiple photons (see Fig. 2). When photon flux is low and photons arrive at a time interval that is longer than the recovery time of a pixel, the MPPC will output pulses that equate to a single photoelectron. The pulses can be converted to digital pulses and counted as described above. When the photon flux is high or the photons arrive in short pulses (pulse width less than the recovery time), the pixel outputs will add up, as shown in Fig. 2, as the 2-photoelectron and 3-photoelectron pulses. In this case, the MPPC is behaving in a pseudo-analog manner because it can measure the incident number of photons per pulse—not possible with single photon counting APDs.

One of the biggest advantages of the MPPC is that it's a solid state device. It is compact, rugged, easy to use (70 V operation), and low cost—making low-level-light detection possible in mass-produced instruments for applications such as point-of-care. Furthermore the MPPC is capable of high photon detection efficiency (PDE), in excess of a typical photomultiplier tube (PMT; see Fig. 3).[1]

Additional advantages of the MPPC are high gain and low multiplication noise (noise added by the multiplication process). The high gain makes detection of a single photon possible—a single detected photon produces a measurable signal. While single photon counting APDs could also detect single photons, they require cooling down to -30° C or -40° C. Furthermore, the active area of these devices is very small (typically less than a few hundred microns). The MPPC has an active area of 1 x 1 mm or 3 x 3 mm and can count photons at room temperature.

While the MPPC has many advantages, it is not perfect. One disadvantage is its sensitivity to temperature changes. Geiger-mode operation reduces the temperature sensitivity, but temperature stabilization or compensation is still required for any application using MPPCs.

The dark counts produced by the MPPC are much higher than for a similar PMT due to the lower work function of silicon. However, dark counts are not the same as dark noise. Since photon counting follows Poisson statistics, the standard deviation in the number of counts is simply the square root of the number of counts. This means that an MPPC with 400,000 dark counts has a dark noise of 632 counts. In principle, one could get a meaningful signal-to-noise ratio from about 1000 detected photons.

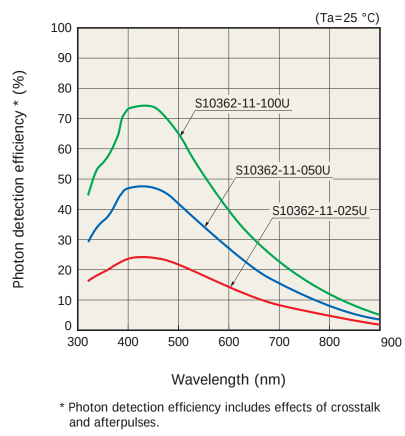


FIGURE 3. The photon detection efficiency (PDE) is a product of the APD' s quantum efficency, fill factor, and Geiger avalanche probability. The PDE data shown for three multipixel photon counters with differing numbers of pixels include the effects of crosstalk and afterpulsing.

Photon counting and the MPPC in particular can be used in variety of applications. In a flow cytometer, for example, the major components are a fluidics system, a laser, optics, photodetectors, and electronics. As cells pass single-file through the laser beam, they scatter light and possibly fluoresce. The forward-scattered light indicates the size of the cell, while the side-scatter light indicates its structural complexity. The fluorescence of any fluorophores bound to the cell indicates the presence of a specific cellular structure or biomolecule.

In flow cytometry, light from scattering and fluorescence are typically collected by photodetectors, usually PMTs. However, multipixel photon counters can be used as an alternative. They offer high photon detection efficiency, high gain, and detection limits near those of a PMT. The high dark count of an MPPC is not an issue because flow cytometry uses threshold levels—effectively cutting off the contribution from dark counts and only allowing higher signals to be detected. The dynamic range of the MPPC could be an issue though.

Another MPPC application is high-energy or particle physics, which studies subatomic particles like neutrinos. As neutrinos travel through space, they oscillate between three types or "flavors": νe (electron neutrino), νμ (muon neutrino), and ντ (tau neutrino). While the conversion of νμ to ντ has been studied, much is still unknown about the conversion of νμ to νe. The Tokai-to-Kamioka ("T2K") experiment is intended to shed light on the nature of this phenomenon with the MPPC playing a vital role. Next year, the Japan Proton Accelerator Research Complex (Tokai, Japan) will send an intense neutrino beam to the Super Kamiokande (Kamioka, Japan) 295 km away. By measuring and comparing the amounts of νμ and νe at the start and end of the beam's journey, physicists hope to observe the disappearance of νμ and the appearance of νe as the neutrinos oscillate.[1-2] The initial and final measurements will be performed by near detectors (ND280) and the Super Kamiokande, respectively.

To detect neutrinos, the ND280 detectors will use thousands of scintillators coupled to photodetectors by wavelength-shifting fibers. The MPPC from Hamamatsu Photonics was chosen as the photodetector for the ND280 because it fulfills most of the requirements. The MPPC is compact and can withstand the 0.2 T magnetic field. It also has gain greater than 5×10^5, and its PDE is higher than the quantum efficiency for a typical PMT. Although the combined crosstalk and afterpulses in an MPPC is higher than the ideal 10%, the measured values in 300 devices (13% to 22%) are still low enough to allow the MPPC to be used.[3] About 55,000 pieces of MPPC will be delivered for the ND280 particle detectors.

The MPPC represents a revolution in solid-state detection. It is now possible to count photons in very compact and low-power applications at room temperature.

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