# CHAPTER 8
# PHOTOMULTIPLIER TUBE MODULES

*This chapter describes the structure, usage, and characteristics of photomultiplier tube (PMT) modules. These PMT modules consist of a photomultiplier tube, a voltage-divider circuit and a high-voltage power supply circuit carefully assembled into the same package.*

# 8.1 What Are Photomultiplier Tube Modules?

Photomultiplier tube (PMT) modules are basically comprised of a photomultiplier tube, a high-voltage power supply circuit, and a voltage-divider circuit to distribute a voltage to each dynode. In addition to this basic configuration, various functions such as a signal conversion circuit, photon counting circuit, interface to the PC and cooling device are integrated into a single package. PMT modules eliminate troublesome wiring for high voltages and allow easy handling since they operate from a low external voltage. Figure 8-1 shows the functions of PMT modules.

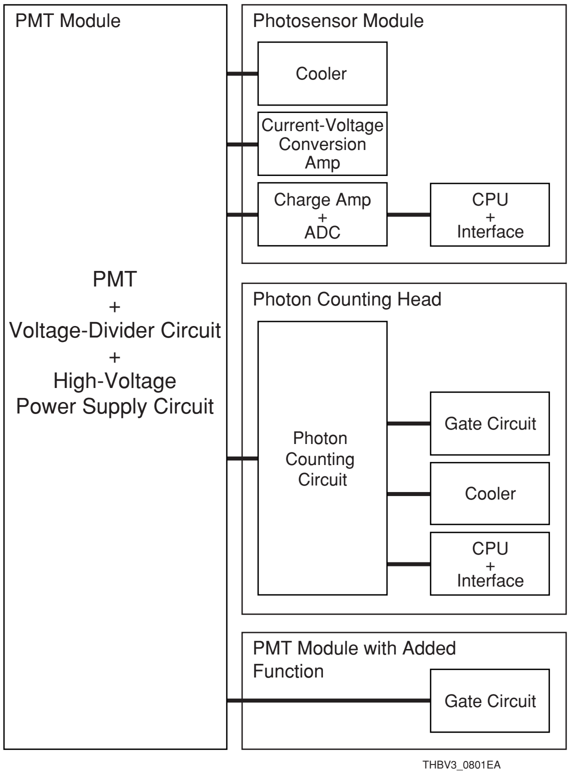


**Figure 8-1: PMT module functions**

# 8.2 Characteristics of Power Supply Circuits

## (1) Power supply circuits

There are two major types of power supply circuits used in PMT modules. One is a Cockcroft-Walton (CW) circuit and the other is a combination of a Cockcroft-Walton circuit and active divider circuit.

The Cockcroft-Walton circuit is a voltage multiplier circuit using only capacitors and diodes. As shown in Figure 8-2, capacitors are arranged along each side of the alternate connection points of the serially connected diodes. The reference voltage supplied to this circuit are doubled, tripled ... and the boosted voltage is applied to each dynode. This circuit features low power consumption and good linearity for both DC and pulsed currents and is designed to be compact.

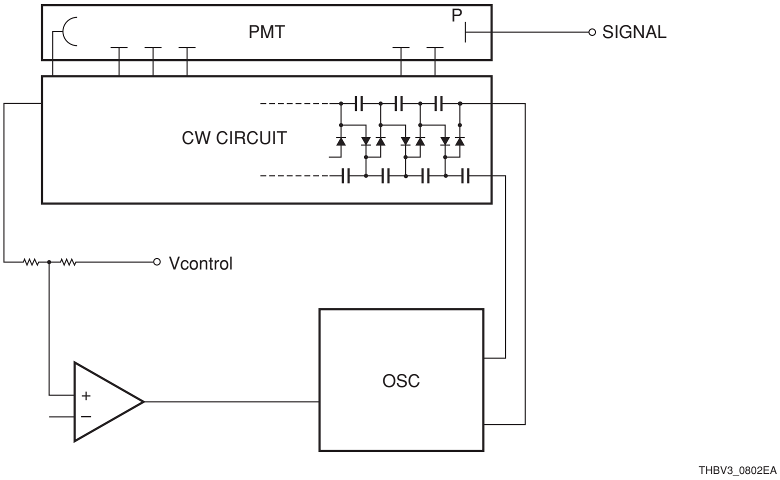


**Figure 8-2: Cockcroft-Walton power supply circuit**

Figure 8-3 shows a power supply circuit using a Cockcroft-Walton circuit combined with an active divider circuit. The Cockcroft-Walton circuit generates a voltage that is applied to the entire photomultiplier tube and the active divider circuit applies a voltage to each dynode. In this active divider circuit, several voltage-divider resistors near the last dynode stages are replaced with transistors. This eliminates the effect of the photomultiplier tube signal current on the interdynode voltage, achieving good linearity up to 60 % to 70 % of the divider circuit current. This circuit also features lower ripple and shorter settling time compared to power supply circuits using only a Cockcroft-Walton circuit.

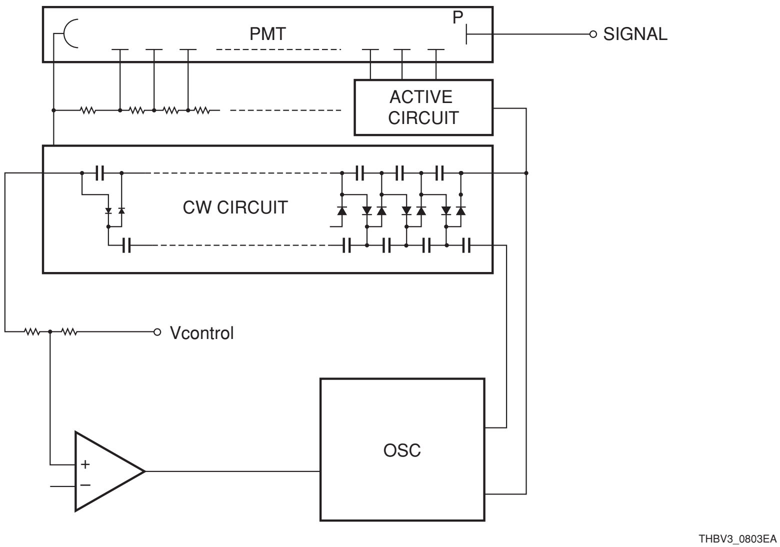


**Figure 8-3: Power supply circuit using Cockcroft-Walton circuit combined with active divider circuit**

## (2) Ripple noise

Since high-voltage power supplies in PMT modules use an oscillating circuit, the unwanted oscillation noise is usually coupled into the signal output by induction. This induction noise is called "ripple". This ripple can be observed on an oscilloscope by connecting the signal cable of a PMT module to the input of the oscilloscope while no light is incident on the PMT module. For example, under the conditions that the load resistance is 1 MΩ, load capacitance is 22 pF and the coaxial cable length is 45 cm, you will see a signal output along the baseline in a low voltage range. This signal output has an amplitude from a few hundred µV to about 3 mV and a frequency bandwidth of about 300 kHz. Figure 8-4 shows an example of this ripple noise.

Hamamatsu PMT modules are designed to minimize this ripple noise. However, it is not possible to completely eliminate this noise. Use the following methods to further reduce ripple noise.

1. Place a low-pass filter downstream from the PMT module signal output.
2. Raise the control voltage to increase the photomultiplier tube gain and lower the amplifier gain.

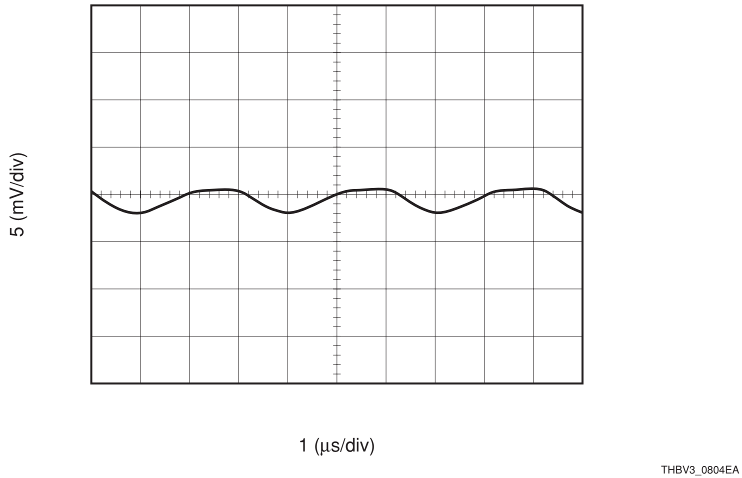


**Figure 8-4: Ripple noise**

## (3) Settling time

The high voltage applied to the photomultiplier tube changes as the input voltage for the PMT module control voltage is changed. However, this response has a slight delay versus changes in the control voltage. The time required for the high voltage to reach the target voltage is called the "settling time". This settling time is usually defined as the time required to reach the target high voltage when the control voltage is changed from +1.0 V to +0.5 V. Figure 8-5 shows a change in the high voltage applied to the cathode.

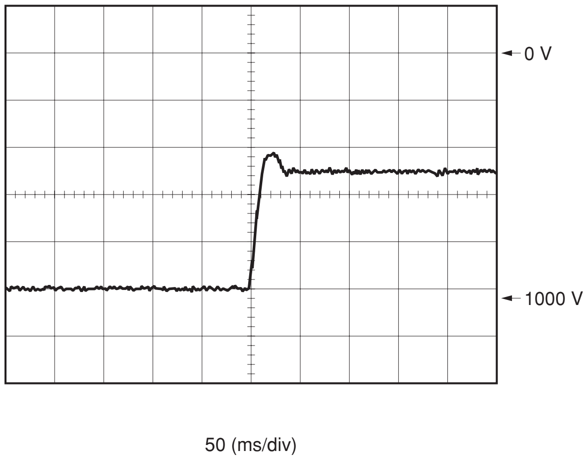


**Figure 8-5: Changes in cathode voltage when control voltage is changed from +1.0 V to +0.5 V**

# 8.3 Current Output Type and Voltage Output Type

## (1) Connection method

Since PMT modules have an internal high-voltage power supply and voltage divider circuit in their packages, there is no need to apply a high voltage from an external power supply. All that is needed is simple wiring and low voltage input as shown in the connection diagram. When using a typical PMT module, supply approximately 15 V to the low voltage input, ground the GND terminal, and connect the control voltage and reference voltage input according to the gain adjustment method.

When the low voltage input is within the range specified in our catalog, the high voltage applied to the photomultiplier tube from the power supply circuit in the PMT module is kept stable. This holds true even if the output of the low-voltage power supply fluctuates somewhat. However, if high noise pulses are generated from the low-voltage power supply, they may cause erroneous operation or a breakdown in the PMT module.

## (2) Gain adjustment

The photomultiplier tube gain can be adjusted by changing the control voltage. There are two methods for adjusting the control voltage.

When directly inputting the control voltage as shown in Figure 8-6, the control voltage input range must always be below the maximum rating. The output terminal of the reference voltage must be left unconnected. Be careful not to connect it to ground.

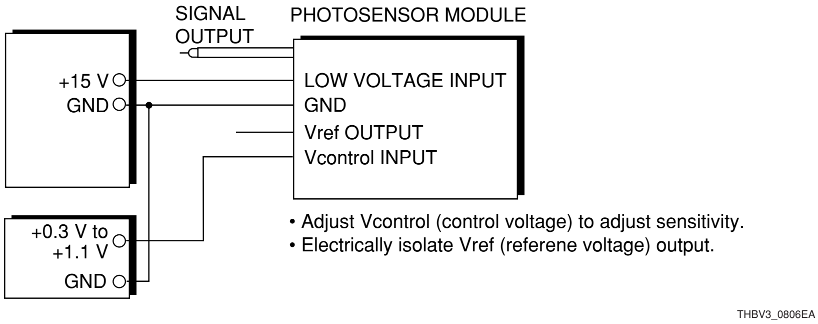


**Figure 8-6: Sensitivity adjustment by changing voltage**

Figure 8-7 shows a gain adjustment method using a trimmer potentiometer which is connected between the control voltage and reference voltage outputs. When adjusting the trimmer potentiometer, do so carefully and correctly while monitoring the control voltage with a voltmeter or tester.

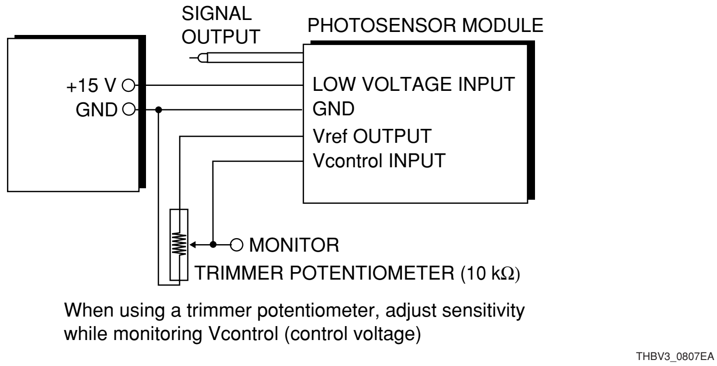


**Figure 8-7: Sensitivity adjustment using trimmer potentiometer**

## (3) Current output type module

In current output type PMT modules, the anode current of the photomultiplier tube is directly available as the output from the module. This current output from the photomultiplier tube must be converted to a voltage by an external signal processing circuit. An optimal current-to-voltage conversion method must be selected according to the application and measurement purpose.

## (4) Voltage output type module

In voltage output type PMT modules, an op-amp is connected near the photomultiplier tube anode to convert the current to a voltage. This is more resistant to external noise than when extracting the current output of a photomultiplier tube by using a signal cable. Using an internal amplifier is especially effective in measurement frequencies ranging from several tens of kilohertz to a few megahertz where external noise effects first become noticeable. However, amplifier power consumption tends to increase in frequency bands higher than 10 MHz. Using an external amplifier connected to a current output type PMT module might be better in this case.

Voltage output type PMT modules incorporate an op-amp for current-to-voltage conversion. The amp's feedback resistor and capacitor also function as a charge amplifier, making it possible to perform pulse measurement such as scintillation counting.

# 8.4 Photon Counting Head

Photon counting heads contain a low level discriminator and pulse shaper along with a photomultiplier tube and a high-voltage power supply. Figure 8-8 shows the block diagram of a typical photon counting head. The current pulses from the photomultiplier tube are amplified by the amplifier, and then only those pulses higher than a certain threshold are discriminated by the comparator and converted to voltage pulses by the pulse shaper for output. In photon counting heads, the high voltage to be applied to the photomultiplier tube is preadjusted based on the plateau voltage measured prior to shipment. Supplying a low voltage from an external power supply is all that is needed for photon counting.

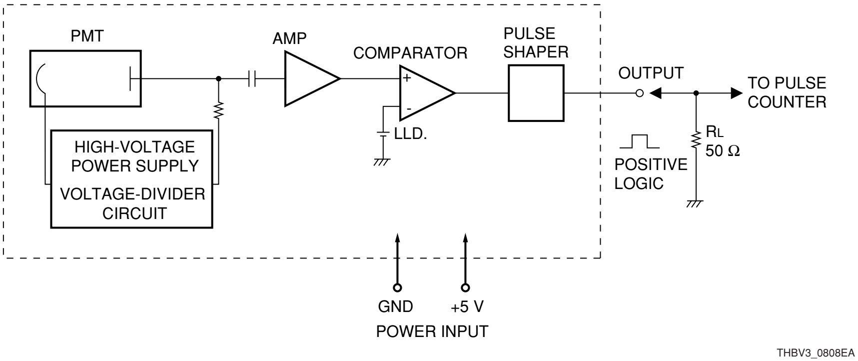


**Figure 8-8: Block diagram of photon counting head**

## (1) Output characteristics

Each type of photon counting head is slightly different so that the internal circuit constants match the time characteristics and pulse waveforms of the photomultiplier tube being used. Because of this, output characteristics such as the pulse voltage and pulse width differ depending on individual photon counting heads, though their output is a positive logic signal.

The output impedance of photon counting heads is designed to be approximately 50 ohms in order to handle high-speed signals. When connecting a photon counting head to a measurement device with a cable, a 50-ohm impedance cable is preferable and the input impedance of the measurement device should be set to 50 ohms. If the input impedance of the external circuit is not around 50 ohms and an impedance mismatch occurs, the pulses reflected from the input end of the external circuit return to the photon counting head and then reflect back from there. This might result in erroneous counts. When the input impedance of the external circuit is 50 ohms, the amplitude of the signal voltage will be one-half that at the input end. So it is necessary to select an external circuit that matches the minimum input voltage specifications.

## (2) Counting sensitivity

Counting sensitivity indicates a count value obtained from a photon counting head when an absolute amount of light (pW) at a certain wavelength enters the photon counting head. Counting sensitivity is directly related to quantum efficiency and collection efficiency.

## (3) Count linearity

When individual photons enter at constant intervals within the time resolution of a photon counting head, it is theoretically possible to measure the photons up to the reciprocal of pulse-pair resolution. Photon counting is usually used in low-light-level measurements of chemiluminescence and bioluminescence, so the light input is a random event. In this case, when the light level is increased and exceeds a certain level, the count value becomes saturated and is no longer proportional to the light level. Count linearity is a measure for indicating the loss in the counted value compared to the theoretical value. This is defined as the count value at 10 % loss. The pulse-pair resolution of the internal circuit determines the count linearity characteristics of the photon counting head. At a higher count rate, however, time characteristics of the photomultiplier tube also become an important factor.

Figure 8-9 shows typical count linearity characteristics of a photon counting head with a pulse pair resolution of 18 ns. The count value at 10 % loss is $6\times10^6$ $s^{-1}$.

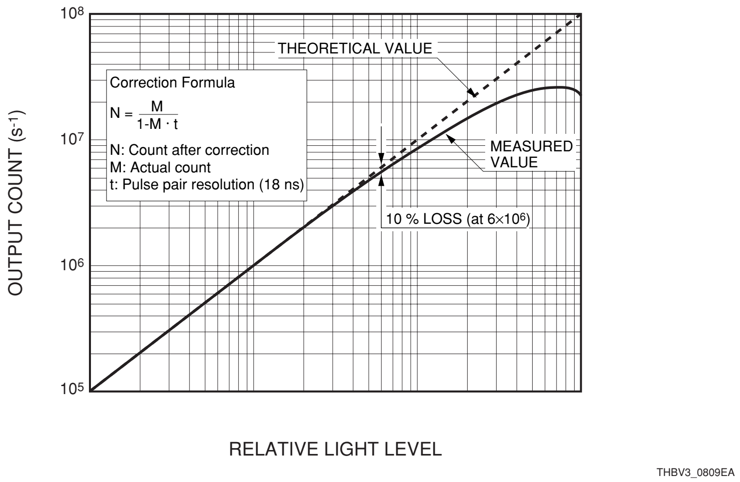


**Figure 8-9: Count linearity characteristics**

## (4) Improving the count linearity

When the count measured during photon counting exceeds $10^6$ $s^{-1}$, the pulses begin to overlap causing counting errors. To increase the count linearity:

1. Increase the pulse-pair resolution of the circuit.
2. Use a prescaler to divide the frequency.
3. Approximate the output by using a correction formula.

Figure 8-10 shows the improvement in count linearity when the output is approximated by a correction formula.

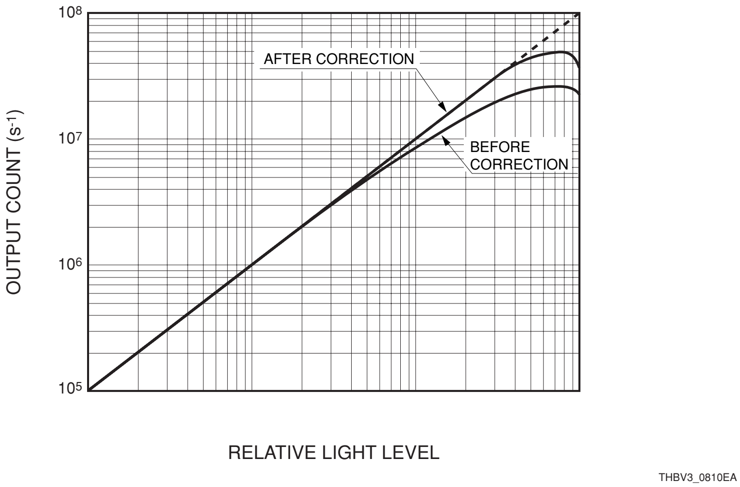


**Figure 8-10: Count linearity before and after correction**

## (5) Temperature characteristics

Since the photon counting method uses a technique that measures pulses higher than a certain threshold value, it is less affected by gain variations in the photomultiplier tube caused by output instability of the power supply and changes in ambient temperature. Changes in the count value versus temperature variations are plotted in Figure 8-11. The rate of these changes is about one-half the anode output temperature coefficient of photomultiplier tubes.

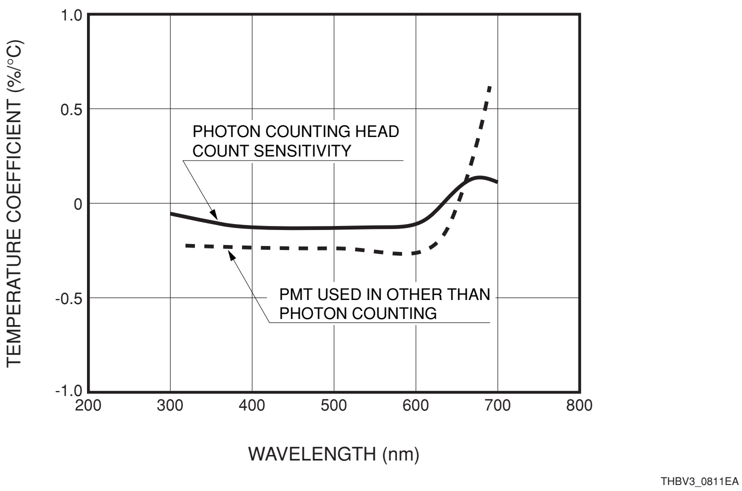


**Figure 8-11: Temperature coefficient comparison**

## (6) Photon counting ASIC (Application Specific Integrated Circuit)

A photon counting circuit is fabricated using many components such as ICs and resistors. The capacitance and inductance of those components and wiring impose limits on the frequency band and power consumption of the circuit. The circuit board of course requires a space for mounting component. The photon counting ASIC is an integrated circuit consisting of 16 amplifiers, 16 discriminators and 16 pulse shaping circuits, which are the basic elements for photon counting circuits. This ASIC simultaneously performs parallel processing of input signals from a maximum of 16 photomultiplier tubes or from a 16-channel multianode photomultiplier tube, and outputs a LVDC voltage pulse according to each input. The block diagram of a photon counting ASIC is shown below in Figure 8-12. Integrating the circuit gives the ASIC a counting efficiency of $1.0\times10^8$ $s^{-1}$ or more per channel, low power consumption and a compact size. This ASIC is also designed to allow LLD and ULD adjustments by 8-bit DAC from external control, so that the gain difference between photomultiplier tubes and the gain fluctuation between the anodes of a multianode photomultiplier tube can be corrected. Furthermore, accurate measurement can be performed not only by single photon counting but also in multi photon events, by matching the photomultiplier tube gain with the input charge range of the ASIC. In this case, one voltage pulse of positive logic is output in response only to a pulse signal that enters within the LLD to ULD input range or a pulse signal higher than the LLD threshold level. This allows measurement for taking timings. However, the output does not contain pulse height information.

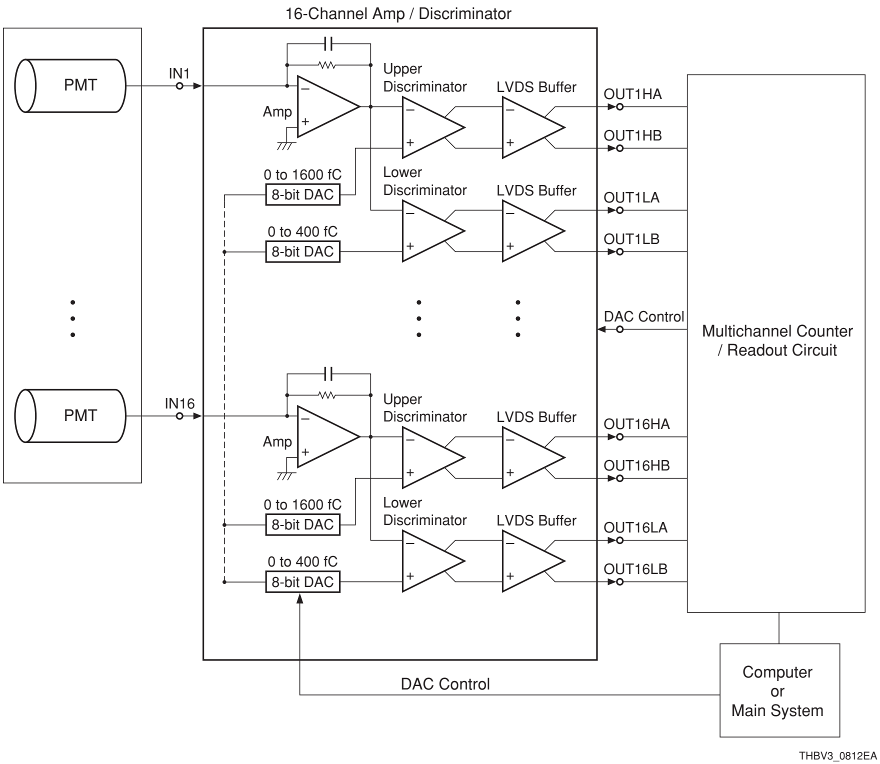


**Figure 8-12: Block diagram of photon counting ASIC**

# 8.5 Gate Function

When excitation light such as from a laser or xenon flash lamp enters a photomultiplier tube, the signal processing circuit may become saturated causing adverse effects on the measurement. There is a method to block such excessive light by using a mechanical shutter but this method has problems such a limited mechanical shutter speed and service life. On the other hand, electronic gating, which is controlled by changing the electrical potential on a dynode in the photomultiplier tube, offers much higher speeds and higher extinction ratio. The H7680 is a gated PMT module using a linear focused type photomultiplier tube that features fast time response. The H7680 delivers a high extinction ratio and high-speed gating since it controls the bias voltage applied to multiple dynodes.

There are two modes of gating: a normally-off mode that turns on the gate of the photomultiplier tube when a gate signal is input and a normally-on mode that turns off the gate when a gate signal is input. Select the desired mode according to the application.

## (1) Gate noise

Performing high-speed gate operation requires high-speed gate pulses. When a gate pulse is input, induction noise is induced in the anode signal through the electrostatic capacitance present between the electrodes of the photomultiplier tube as shown in Figure 8-13. This is referred to as "gate noise". This gate noise can be reduced by reducing the gate pulse voltage or by using a noise-canceling technique. However, completely eliminating this noise is difficult. So increasing the photomultiplier tube gain or using a photomultiplier tube with a higher gain is required so that the signal output becomes larger than the gate noise.

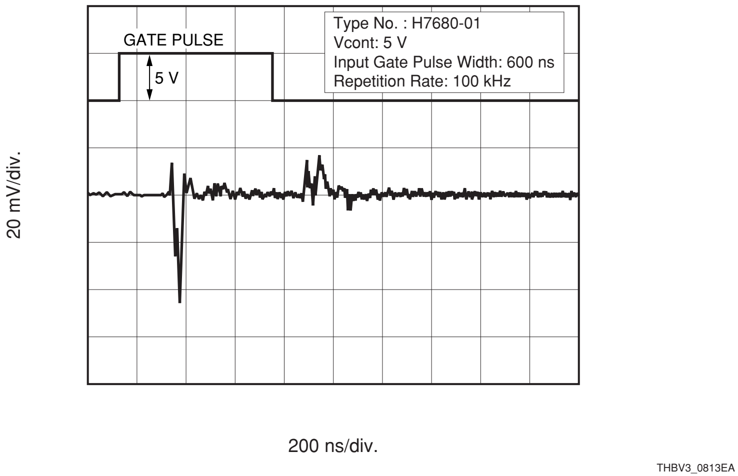


**Figure 8-13: Gate noise**

## (2) Extinction ratio

Gating allows suppressing the anode current of the photomultiplier tube even if the anode current exceeds the maximum rating or a strong light causing the external circuit to be saturated is input to the photomultiplier tube. The extinction ratio is the ratio of the output when the gate is "on" to the output when the gate is "off" while a constant light level is incident on the photomultiplier tube. For example, if the output at "gate-off" is 1 nA in normally-off mode, and the output at "gate-on" is 10 µA, then the extinction ratio is expressed in 1 nA : 10 µA = 1 : $10^4$.

Even if the current is being controlled by gate operation, a small amount of current equal to the percentage of the extinction ratio flows as the anode current. The anode current must be kept below the maximum rating of the photomultiplier tube even during gate operation. If high energy light such as a laser beam enters the photomultiplier tube, the photocathode structure itself might be damaged even if gate operation is performed. So some measures must be taken to prevent strong light from entering the photomultiplier tube.

# 8.6 Built-in CPU and IF Type

This type of PMT module has an internal CPU and interface for connection to an external unit. In this module, the output current of the photomultiplier tube is converted to a voltage signal by a current-to-voltage conversion amplifier. The voltage signal is then converted to digital data, or in photon counting, the output pulses are counted within a certain time. Digital data can be easily transferred to an external processing unit, while the PMT module is controlled by commands from the external unit. Since the signal processing circuit, control CPU and interface for data transfer are housed in a single package, there is no need to design a digital circuit or take noise abatement measures usually required when handling high voltage and high-speed signals.

## (1) Photon counting type

This PMT module has an internal photon counting circuit followed by a 20-bit counter that counts voltage pulses. The 20-bit counter allows a maximum count of 1,048,575 within the gate time that was set. If the gate time is set long while the light level is relatively high, then the counter limits the measurement count to 1,048,575 or less. In this case, shorten the gate time and acquire the data several times. After measurements, software averaging of data acquired several times allows you to obtain the same result as obtained using a long gate time. Figure 8-14 shows the circuit block diagram of a photon counting type module.

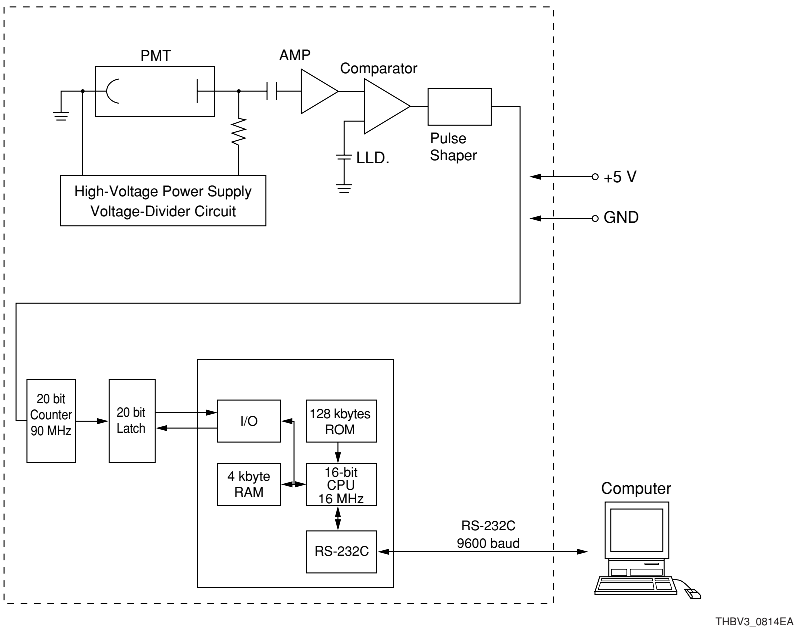


**Figure 8-14: Block diagram of photon counting type module**

### (2) Charge amplifier and AD converter type

Figure 8-15 shows the block diagram of a PMT module with an internal charge amplifier and AD converter. The anode of the photomultiplier tube is connected to the charge amplifier that accumulates charges obtained from the anode during a sampling time. The accumulated charge quantity is then converted to digital data by the AD converter.

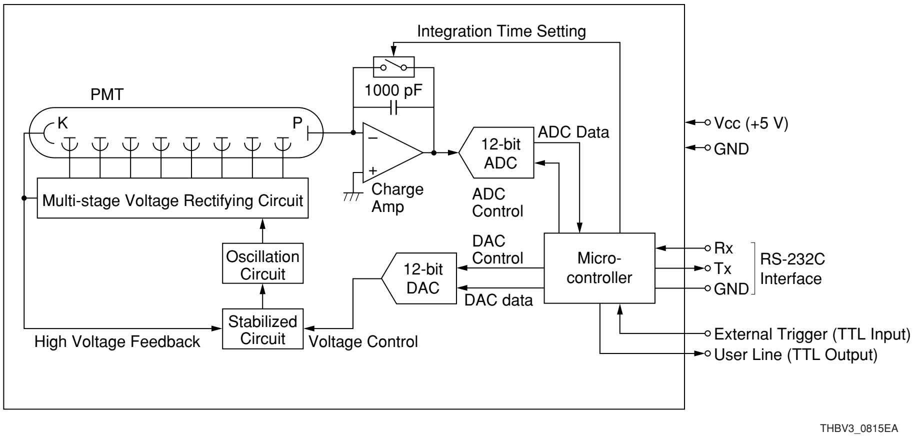


**Figure 8-15: Block diagram of charge amplifier and AD converter type module**

# References in Chapter 8

1) Hamamatsu Photonics Product Catalog: "Photomultiplier Tube Modules" (March, 2005)