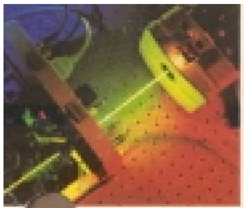

Photomultiplier Tubes See the Light — One Photon at a Time

by Earl Hargert and Craig Walling

Efficient detectors help analyze bones, food, stars and pollution.

Archaeologists, fishermen, food service professionals, astronomers and environmental agencies are among those who have recently found new ways to exploit the relationship between light and the composition of substances. Dating archaeological finds, locating schools of fish, measuring food contamination, mapping the stars and monitoring pollution levels are all applications that require extremely sensitive detection of very low levels of light.

As these applications grow, the need for easy-to-use detectors with extremely high sensitivity, low noise and stability is paramount. Although solid-state technologies such as avalanche photodiodes get a lot of attention, the photomultiplier (an electron tube) commonly known as the photomultiplier tube (PMT), still has a commanding lead in demanding applications such as photon counting.

In all of these applications, exceptional signal-to-noise ratios are required. Photocathode and electro-optic research and design has improved, and over the past 10 years photocathode quantum efficiency has increased, with some devices boasting up to 40 percent quantum efficiency. This has led to the detection of ever lower levels of photons, which has, in turn, enabled ever higher numbers of applications.

Figure 1. A photomultiplier tube's high sensitivity is an asset in analysis applications, such as checking for contamination by E. coli bacteria on food processing machinery.

Through the window

A typical end-window PMT (Figure 2) comprises a glass envelope, a photocathode, dynodes and an anode — all in a vacuum. A photon enters the glass window, and the photocathode converts it to an electron. The photon must be energetic enough to drive the electron out of the photocathode and into the vacuum of the PMT. In the vacuum, an electric field accelerates the electron between the electrodes to the first dynode.

Each dynode is coated with a secondary-emission surface, which releases many electrons each time one electron strikes it. These electrons accelerate to the next dynode, and the process continues through the nine to twelve dynode stages.

At the end of the process, the electron cloud contains more than 10^6 electrons. The anode collects all of these electrons and passes them to an external circuit.

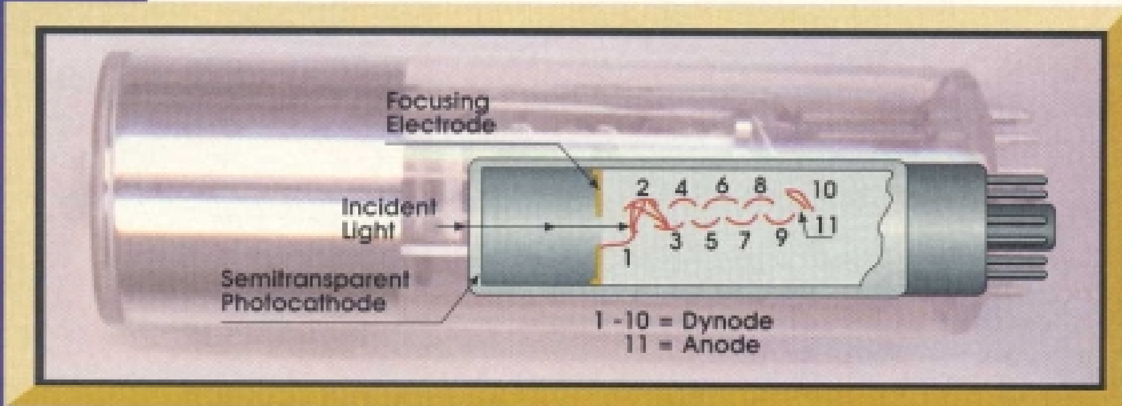

Figure 2. *The PMT's photocathode changes incoming photons to electrons, which bounce through a series of dynodes. Each dynode multiplies the number of electrons that strike it.*

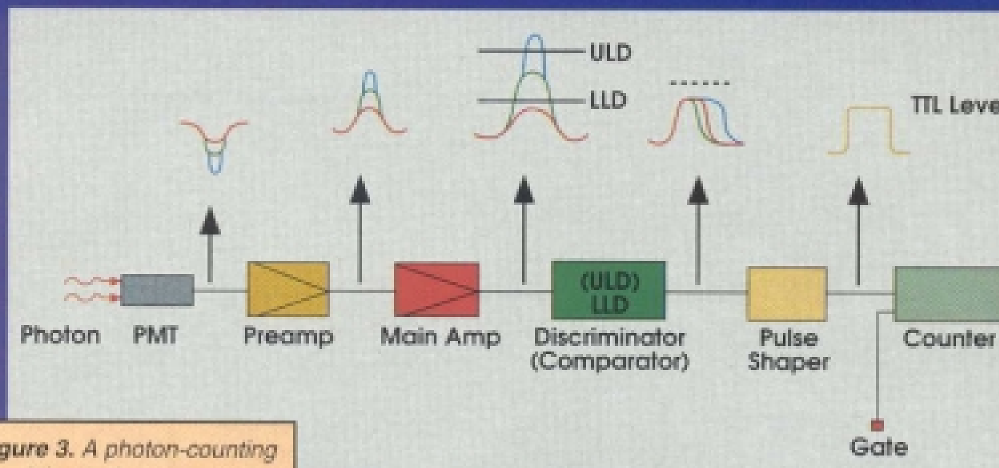

Figure 3. *A photon-counting circuit is much more complicated than an analog circuit, but it significantly improves a PMT's performance.*

In the simplest analog circuit, a resistor spans the anode and ground, and the current pulses flow through this resistor and create a voltage pulse across it. A measuring instrument such as a voltmeter or oscilloscope integrates these voltage pulses, producing a DC voltage corresponding to the light level.

Counting photons

A more complicated circuit, the photon-counting circuit (Figure 3), converts the individual current pulses to a voltage and amplifies them with a preamplifier and main amplifier stages.

A discriminator (comparator) then eliminates low-amplitude pulses to minimize noise. The discriminated pulse is passed to a pulse shaper that converts the pulse to a standard electronic logic level. An external frequency counter can then tally the signals.

The photon-counting circuit is more complicated, but its benefits outweigh the disadvantage of replacing the simple resistor design: It significantly improves signal-to-noise (S/N) ratio, stability and ease of use.

The photocathode and all dynodes emit spurious electrons, which collectively become the PMT's dark current. The photocathode's spurious electrons cascade through the entire dynode chain, indistinguishable from the light-generated signal. Spurious signals from the dynodes do not go through the entire multiplication process; therefore the amplitude of their pulses is smaller than those originating at the photocathode.

The shot noise of the dark current is the primary noise source in a PMT, and it arises from such sources as the quantum nature of the photon, uncertainty in photon arrival rates and electron emission probability.

Another significant noise source is statistical fluctuations on the dynode gain mechanism, also known as its "excess noise factor." The following equations illustrate PMT signal-to-noise ratios:

Analog:

$$S/N \propto \frac{I_{ph}}{\sqrt{2\,eF\left(I_{ph}+2I_d\right)}}$$

where

I_{ph} = signal current produced by incident light

I_d = dark current resulting from cathode and dynode spurious emissions

e = electron charge (coulombs)

F = excess noise factor

Photon counting:

$$S/N \propto \frac{N_s}{\sqrt{2\left(N_s+2N_d\right)}}$$

where

N_s = signal counts

N_d = photocathode spurious emission counts only

Photon counting produces two improvements in signal-to-noise ratio: The discriminator eliminates spurious emissions from the dynodes, thus lowering the dark noise; and the technique removes the excess noise factor, resulting in a signal-to-noise ratio improvement of about 1.4 to 1.6.

Easier to use

Photon counting also resists variations in supply voltage, resulting in better operational stability. In the analog mode, a 1 percent change in supply voltage increases the gain by 10 percent. The technique is inherently less susceptible to changes in gain and supply voltage.

Probably the most significant advantage of photon counting is ease of use. There is virtually no dependence on performance variations in the amplifier or readout circuits. These characteristics ensure much more reliable operation. In the analog mode, the instrument must be calibrated regularly to adjust for changes in gain, drift in the amplifier circuit and the readout electronics (voltmeter, analog-to-digital converter).

The biggest hurdle to wide acceptance of photon counting has been the complexity of the circuits. However, recent improvements in the size and sensitivity of the PMT and a virtual revolution in size reduction, cost and integrated-circuit power consumption have enabled the manufacture of very small, low-power, complete photon-counting units.

Industry is finding these devices useful in a number of diverse applications. In one example, a portable PMT can be carried throughout a food processing plant to assess contamination that could lead to food poisoning. The US Department of Agriculture has compiled a final rule on pathogen reduction because of food poisoning's risks to society and increasing media coverage of major incidents. Traditional methods of verifying cleanliness at food processing plants, such as culturing cells and counting bacteria, can take two to five days. If the tests show contamination, public safety is at stake. As a result, some real-time testing of food contamination now relies on ATP bioluminescence, a technique for which a portable PMT-based device is an ideal detector.

In this technique, food processors test the cleanliness of their equipment (a chopping block, for example) by wiping the "clean" equipment with a swab. The swab is soaked with luciferase and another chemical that breaks into cell walls. This allows the escape of adenosine triphosphate (ATP), which cells use to store energy. Food residue, bacteria and other microorganisms all contain ATP. In the presence of luciferin/luciferase, ATP produces an oxidized form of luciferin and some very weak

Figure 4. ATP bioluminescence employs a PMT-based luminometer to quickly verify that food processing equipment is clean.

light emissions. The amount of biological material present is proportional to the number of photons emitted. A PMT-based luminometer can count those photons and determine whether the equipment is clean.

Size matters

In an application like this, where the instrument is carried from point to point for testing, instrument size is a major factor. PMT producers have met this challenge by offering smaller package sizes. Some examples include devices in a TO-8 package or a more traditional side-on style that is only ½ in. in diameter.

Another advancement that has helped this application is the supporting electronics. Handheld instruments are powered by batteries, so power consumption is important. A typical PMT requires a voltage of 1 kV. The driving circuit is a high-voltage power supply with a resistive voltage-divider chain to apportion the voltage into each dynode stage.

Resistive power loss can be reduced to less than one-third with a Cockroft-Walton voltage multiplier, a network of capacitors and rectifiers that rectify and multiply an AC input voltage. Instead of using resistors to perform the voltage division, a multistage voltage multiplier with one stage for each dynode is used.

The market demands not only that the instrument designer make a better, smaller and faster device, but also that the device reach the market more quickly. These shorter design cycles push the engineer to seek a higher degree of integration at the component level. In this way, each user need not master techniques like photon counting to enjoy their benefits.

The miniaturization, availability and increased functionality of integrated circuits have produced modular PMT assemblies that include all of the components needed for photon counting. One of the latest advancements has been the integration of a microcontroller that allows the user to communicate and control the device with software from a personal computer.

Benefits of photon counting outweigh circuit complexity.

A microcontroller can also increase the system's accuracy by correcting for a phenomenon called dead time. When an event begins, no other event can begin until the first event has completely passed through the PMT's circuits. The time between the start and end of the event is called dead time. At higher light levels, more photons hit the PMT every second, so there is high probability that an event will occur during the dead time, when the circuits cannot process it. This can result in two light photons being detected simultaneously and counted as one.

Medical applications

A modular PMT assembly's onboard intelligence can analyze incoming data and correct it based on the dead time of the detector. This can increase the dynamic range of photon counting by more than an order of magnitude. This level of performance is required in medical instruments, when components of blood react with luciferin/luciferase in a bioluminescence test to check the health of a patient.

Photon counting is not the simplest method of exploring the composition of substances, but its advantages easily outweigh its complexity. As PMT and digital circuit technology advance to produce higher levels of integration, photon counting becomes an extremely cost-effective, accurate measurement technique. This, in turn, will encourage diverse industries to employ PMT technology to solve their problems. □

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