

Image Intensifier

Image Intensifiers are light amplifiers that can detect and image objects at extremely low light levels. The largest application for Image Intensifiers is in night-vision devices, used to “see” at night under moonlight or starlight conditions.

However their use in many scientific and industrial applications has grown given their low noise, high sensitivity and unique high-speed gating capabilities. While night vision devices are typically viewed directly by eye, in most other applications image intensifiers are readout by digital cameras known as Intensified CCD's (ICCD.) With nanosecond (ns) gating capabilities, Image Intensifiers provide a unique ability to image very high speed phenomena. Applications are as diverse as fluorescence lifetime imaging, astronomy, combustion science, laser induced breakdown spectroscopy and plasma science.

Construction

An image intensifier (see Figure 1) is a vacuum tube having three key components; 1) a photocathode to detect light and convert it into photo-electrons, 2) a microchannel plate to amplify the electron signal, and 3) a phosphor screen to convert the amplified electron signal back into light.

Operation within a vacuum tube is required to enable the photo-electrons to be accelerated to high energies without being impeded by gas molecules. Vacuum also enables very low noise amplification, difficult to match with other technologies. Image Intensifiers are available in sizes from 18 mm to 150 mm diameter with spatial resolution of 10 – 20 μm , providing millions of resolution elements.

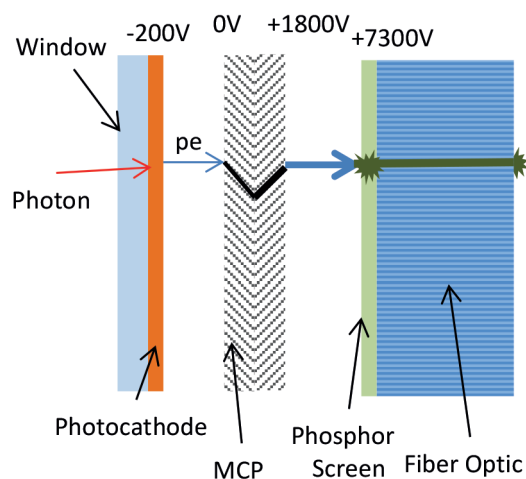


Figure 1: Cross-section of an Image Intensifier and sketch of its operation.

Photocathode

The input window of an image intensifier is selected to have good transmission for the light being imaged. Choices include borosilicate glass, fused silica, sapphire, Magnesium Fluoride (MgF₂) and fiber optic with their transmission curves given in Figure 2. The short wavelength response of the image intensifier is typically determined by the input window material. On the inside surface of the glass input window is a thin film semiconductor known as a photocathode.

The photocathode material is selected to provide high sensitivity to the light being imaged. When a photon, or quanta of light, is absorbed in the photocathode an electron is freed and can be emitted from the vacuum surface of the photocathode as a photo-electron (pe). The photocathode's Quantum Efficiency (QE) is defined as the ratio of photoelectrons emitted from the photocathode's surface (N_{pe}) to the number of photons incident on the photocathode ($N_{photons}$).

$$QE = \frac{N_{pe}}{N_{photons}}$$

The photocathode material also determines the spectral response and sensitivity of the image intensifier. Common types of photocathodes and their spectral responses are given in Figure 3.

In addition to detecting incident light, the photocathode is a source of thermally generated electrons that are indistinguishable from photoelectrons. These thermal electrons contribute to the dark noise of the image intensifier, signal that is measured when no light is incident on the image intensifier. Thermal noise increases with long-wavelength sensitivity since less energy is required to liberate an electron within the photocathode material, whether by an incident photon or by thermal excitation. Other sources of dark noise include radioactive material in the image intensifier components and internal light generation caused by Processes such as high voltage breakdown or electroluminescence of image intensifier components.

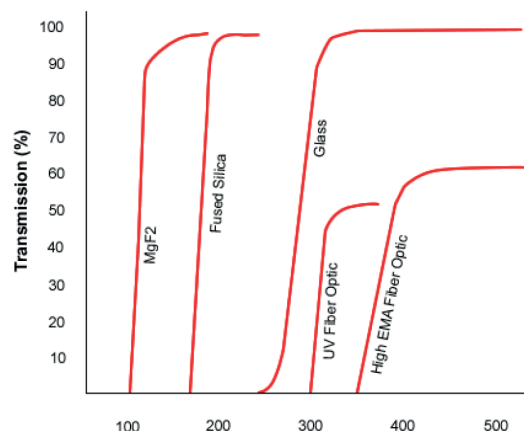


Figure 2: Transmission of various windows.

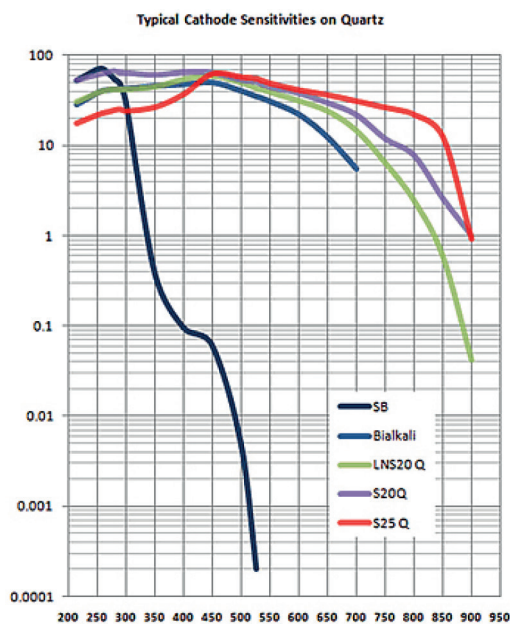


Figure 3: Photocathode Spectral Response.

Photek has developed proprietary techniques to minimize light generation internal to the image intensifier and can use low noise Micro Channel Plates (MCPs) so that dark counts are dominated by thermal noise.

Characteristic dark count rates are given in Table 1. Notice that the highest dark counts are found with the red sensitive S20 photocathode while the lowest dark counts are for the UV Solar Blind cathode. In general the optimum choice of photocathode is one which provides the highest sensitivity for the light being detected while minimizing the dark noise. If noise is critical to the application, the image intensifier can be cooled to significantly reduce thermal noise.

Table 1: Dark Noise

Photocathode	Dark Noise
S20	> 200 cps/cm ²
Low Noise S20	30 - 50 cps/cm ²
Bialkali	5 - 20 cps/cm ²
Solar Blind	< 5 cps/cm ²

Another important property of the photocathode is its resistivity, which can limit the rate at which electrons flow through the photocathode in response to either photo-current or gating of the image intensifier, as discussed below. In situations where fast gating is required either a fine metallic grid or a semi-transparent conductive film can be evaporated onto the input window, enabling fast switching of voltages between the photocathode and the MCP.

Photoelectrons emitted from the photocathode have a component of transverse velocity which causes them to spread laterally away from their point of interaction. This spreading can reduce the spatial resolution of the image intensifier. To minimize this spreading the gap between the Photocathode and the input of the MCP is made as thin as possible, roughly 200 μm , and a high voltage is applied, typically 200 V – 500 V. This ensures that photoelectron spreading does not significantly limit the tubes resolution. The high electric field also increases both the photocathode QE and the electron gain at the input of the MCP.

Micro-Channel Plate

A Micro-Channel Plate (MCP) is a glass capillary plate which has been processed to function as an electron amplifier (see Figure 4.)

The MCP is usually ≤ 1 mm thick with millions of pores between 3 μm and 25 μm in diameter. A typical 25 mm diameter MCP has 6 μm pores on 8 μm centers with a pore Length-to-Diameter (L:D) ratio of 60:1, giving a total thickness of 360 μm .

When a 200 – 500 eV photoelectron strikes the wall of an MCP pore it produces secondary electrons that re-enter the pore. The nominal 1000 V applied across the MCP results in an electric field inside the glass pore, accelerating the secondary electrons toward the anode.

These electrons eventually strike the wall of the pore causing more secondary electrons, with the full electron cascade resulting in a gain of up to 15,000 e-/pe in a single MCP. The bias angle of the MCP is typically between 5° and 15° and is chosen as a tradeoff between gain, resolution and ion feedback. With multiple MCPs stacked together gains of up to 10^7 e-/pe are possible. This is essential for photon counting mode described overleaf.

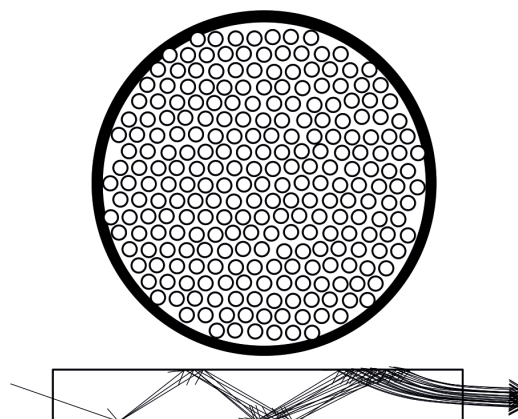


Figure 4: MCP cross-section and amplification process

PHOTON COUNTING MODE

The MCPs are processed to have reduced resistivity along the pore walls. For a typical MCP the total resistance may be in the range of 30 – 300 MΩ. For a single MCP operated at 1000 V the result is a current flow of 3 – 30 μA, known as the MCP's strip current. This strip current replenishes charge extracted from the MCP in the gain process with a time constant on order of 1 ms. This also provides a limitation on the total charge that can be extracted from an MCP: roughly 10% of the strip current.

Assuming a gain of 1000 at 700 V (see figure 5), an image intensifier with a 100 MΩ MCP can operate with an output current of 7×10^{-7} A, equivalent to 2×10^{10} photons/s incident on the image intensifier at a QE of 20%. This calculation assumes a uniform distribution of photons over the face of the image intensifier. For high gain image intensifiers using multiple MCPs, the current limitation is more severe. With a gain of 10^7 at 2100 V with three 100 MΩ MCPs the maximum light levels are reduced to 10^6 photons/s.

There are many applications such as high speed photography requiring high frame rates. In these circumstances MCPs with lower resistance can be specified. However, if the resistance is lowered too much, the increased power dissipation ultimately heats the MCP to unacceptable temperatures during pro-longed use.

To provide electrical connection to the MCP electrodes are deposited on the top and bottom surfaces. At the output surface of the MCP, electrode material is often deposited into the pore by up to several diameters. This process, called end-spoiling, helps to focus the electrons leaving the MCP, reducing their transverse velocity and thereby improving resolution.

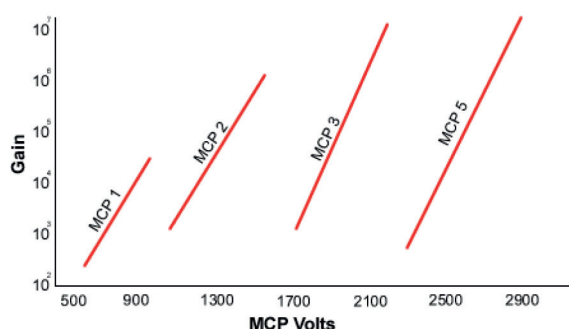


Figure 5: Typical Image Intensifier Gain Curves.

Phosphor Screen

The electron cloud leaving the MCP is accelerated through a large voltage, typically +5 kV, to the output phosphor screen, where its energy is converted back into light, completing the light amplification process.

Many different phosphors can be used depending on the application requirements. Selection of the phosphor is based on its efficiency, emission wavelength and decay time. Phosphors with higher efficiency, measured as photons/electron at 5 kV, provide more light gain and could result in lower MCP gain requirements. If speed is of primary importance a phosphor with fast decay and minimal afterglow is best.

FS phosphor is a good choice for high speed video applications to 100 kHz; the fastest regular phosphor is GOS with over 1 MHz capability. Occasionally Zinc Oxide with a decay time of around 1 ns has been used, but this phosphor is so inefficient that double MCP construction is usually required. Since high frame rate cameras have reduced sensitivity in proportion to frame rate, the phosphor screen voltage is often increased to +10 kV to compensate for this reduced camera sensitivity. A list of phosphor characteristics is given in Table 2.

Table 2: Phosphor Characteristics

Type	Color	Peak Emission (nm)	Efficiency (Photons/e ⁻ @ 5 kV)	Decay Time (μs to 10%/1%)
P11	Blue	446	120	3000/50,000
P20	Green	540	320	250/1000
P24	Green	500	120	22,000/>10000
P43	Green	548	240	1200/2400
P46	Green	530	55	0.3/0.9
P47	Blue	410	64	0.1/0.4

The phosphor screen is deposited on a glass window or fiber optic. Due to the high voltages employed a relatively thick piece of glass is used. The three main types of output windows used include borosilicate glass, a fiber optic plate or an integrated fiber optic taper. A standard glass window is only used when the image intensifier is going to be viewed through a lens system. In this case the phosphor surface is imaged through the glass window. A fiber optic window is required if the image intensifier is being directly coupled to a CCD or other imaging detector. The fiber optic window transfers the phosphor image to the output surface of the window where it can be coupled directly to a CCD or a lens system can image it. Directly coupling a CCD to a fiber optic window provides better light coupling efficiency than using a lens system. If the image intensifier is too large to directly couple to a CCD, an integral fiber optic taper can be used as the output window providing demagnification to match the CCD. While additional light is lost in this configuration, it is still more efficient than a typical lens coupled demagnification.

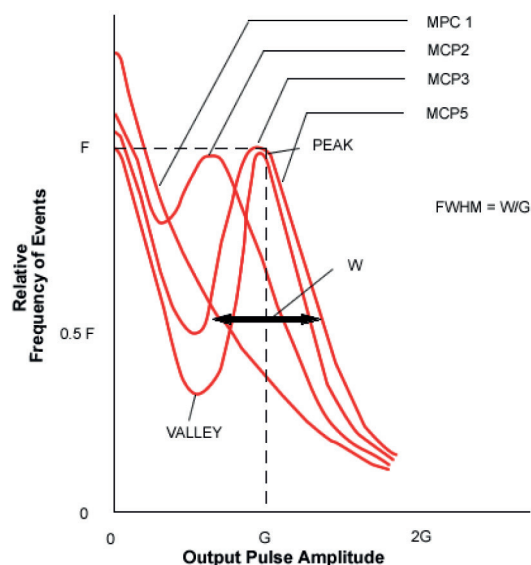


Figure 6: Pulse Height Distributions illustration Photon Counting Operation.

Photon Counting

A useful property of MCPs, when operated at very high gain, is a phenomenon known as gain saturation. When the electron cloud within a single pore becomes large enough its continued amplification is limited by space charge effects, essentially creating an equilibrium number of electrons in the pore once saturation is reached. For a single MCP, gain saturation due to a single photoelectron occurs at a gain on the order of 10^5 . This is difficult to achieve with a single MCP, however by stacking MCPs together saturation in the rear MCP becomes possible. Since the pores of the two MCPs are not directly aligned, the charge cloud exiting the first MCP will be split between multiple pores in the second MCP. Each of these pores receives 100s of electrons so that charge saturation occurs near the output of each pore. If, say, 10^5 pores are involved and saturation is 2×10^5 for each pore, the total signal obtained will be 2×10^6 , a signal equal to ten saturated pores. The result is that the distribution of gains for a single photoelectron becomes tighter and a clear peak appears in a pulse height distribution of the output pulse, as illustrated in Figure 6. As additional MCPs are added the distribution becomes more pronounced, and true photon counting operation is achieved.

Another benefit of this high gain operation is that the centroid of the charge cloud produced by a single photoelectron can often be localized to within a pore diameter assuming the readout sensor has sufficient resolution. Image intensifiers are unique in their ability to provide photon counting over large areas with high spatial resolution.

Gating

An Image Intensifier can be gated on and off by changing the voltage applied between the photocathode and MCP. Normally the input electrode on the front MCP is held at ground potential while the photocathode is at -200V, providing an accelerating voltage for photoelectrons emitted from the photocathode. If the photocathode bias is changed to be positive relative to the MCP input, say +50V, electrons are unable to flow to the MCP and the image intensifier is "gated off." A Gating Module is used to provide a high speed pulse that directly drives the photocathode voltage. With a metal mesh deposited onto the input window, under the photocathode, the minimum gate width is typically 1 - 3 ns. With specialized power supplies gate widths as low as 100 ps can be obtained.

Gating of an image intensifier can be used in several ways. To capture high speed phenomena with excellent clarity a gate pulse can be used as a shutter, freezing the motion to within a short period of time, down to a few ns. Special multi-frame CCDs can be used to capture a short sequence of images at MHz rates, as long as the decay time of the phosphor is faster than the frame rate.

Another use for gating is to quickly turn on or off the image intensifier to prevent unwanted signal from being detected. In Laser Induced Breakdown Spectroscopy, the light scatter caused by the laser pulses near the detector can overwhelm any detector, making it difficult to detect the weak return signal. An image intensifier can be gated off while the initial laser signal is being detected and then gated on to detect the weak signal which comes shortly after the laser is fired. The same situation exists in many LIDAR applications. The ability to gate on and off the image intensifier synchronized with a laser or other bright light source is unique and one of their most useful features.

In fluorescence lifetime imaging an image intensifier is used to optically gate the fluorescence signal being imaged through a microscope. To measure the decay time of the fluorescence a delay generator is used to "walk" an image intensifier gate through the decay of the fluorescence signal. Multiple excitations can be integrated into a single CCD frame with the signal obtained from the same time offset from the excitation. By taking images over a sequence of delays the full fluorescence decay at each pixel in the image can be determined.