Introduction to Image Intensifiers for Scientific Imaging

Introduction

An image intensifier is a vacuum tube device, generally 18-25 mm in diameter. The intensifier comprises a photocathode input, which is a coating of multi-alkali or semiconductor layers on the inside of the input window, and a phosphor screen, which is a fluorescing phosphor coating on the inside of the output window. Also included are either simple grid-shaped electrodes (i.e., early intensifier technology) to accelerate electrons through the tube or, in later intensifiers, a complex electron-multiplying microchannel plate (MCP) (**Figure 1**). MCP technology is discussed later in this note.

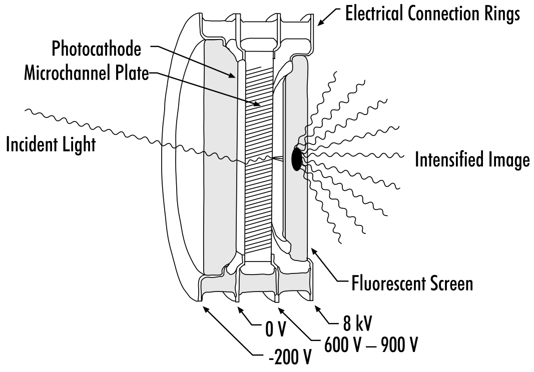

Figure 1. *Components of an image intensifier tube.*

A portion of the incident photons striking the photocathode causes the release of electrons via the photoelectric effect. These electrons are then accelerated (and multiplied in more recent intensifiers) to the phosphor screen, where they strike the coating and cause it to release light. This released light consists of many photons for every incident light photon striking the photocathode surface.

The development of image intensifiers has been primarily motivated by use in the military for night vision. Various types of imagers have been optimized for use in the near infrared (NIR), the main form of night illumination in battle environments. This military influence has led to the adoption of their official convention in the naming of the types of image intensifiers. The types are referred to as "generations" (Gen) and currently consist of (in order of technology development) Gen I, Gen II, Super-Gen II (or Gen II+), and Gen III. Distinctions among the intensifier generations are discussed later in this note.

The incorporation of image intensifiers into high-performance charge-coupled-device (CCD) cameras has produced intensified CCD (ICCD) systems for imaging and spectroscopy that possess high sensitivity in ultra-low-light conditions and allow temporal resolution of extremely short phenomena (less than 2 nsec). These ICCD systems are widely used for such state-of-the-art applications as laser-induced fluorescence (LIF), laser-induced breakdown spectroscopy (LIBS), combustion research, plasma studies, nondestructive testing (NDT), and single-molecule fluorescence imaging.

Components of an Image Intensifier

Photocathode

The photocathode is the first major component in an image intensifier. Photocathode coatings convert a portion of the incident light photons into electrons. Photons that are not captured by the photocathode are lost from the final signal produced by the intensifier. Therefore, quantum efficiency (QE), defined as the percentage of incident photons converted to electronic charge, is very important for intensifiers.

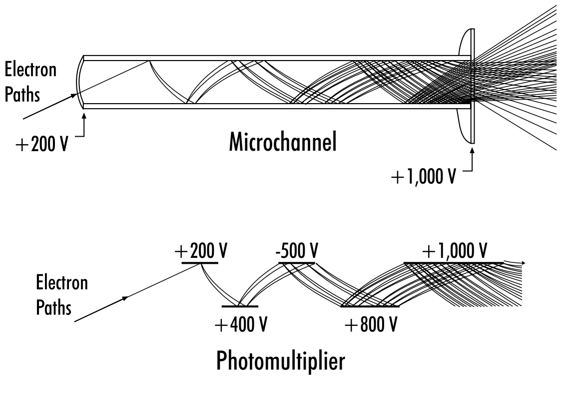

Figure 2. *Schematic drawing of a MCP channel (top), which acts analogously to a photomultiplier (bottom).*

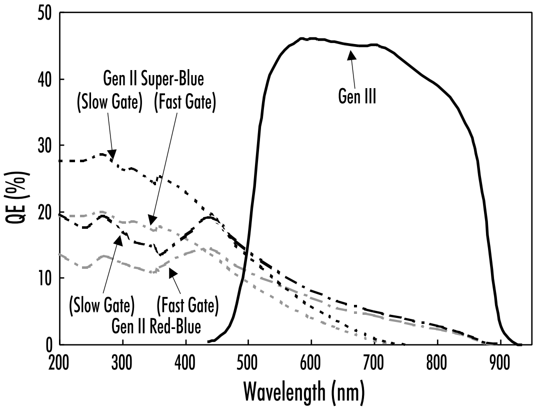

Figure 3. *Comparison of Roper Scientific Gen II red-blue (balanced-response) and super-blue photocathodes with Gen III GaAs photocathode.*

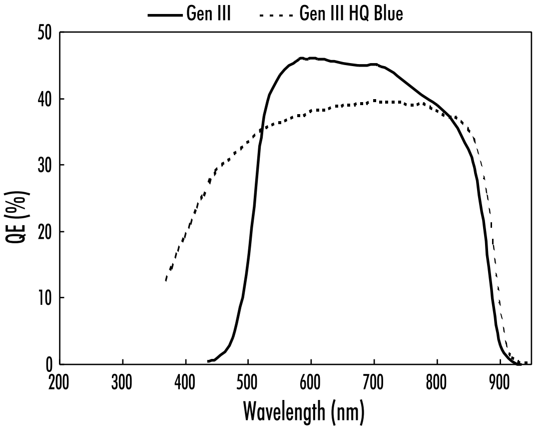

Figure 4. *Comparison of QE for Gen III and new Gen III HQ Blue photocathodes.*

Early intensifiers used multi-alkali coatings consisting of compounds with fair photoconversion performance in the visible (VIS) and ultraviolet (UV) regions, but relatively limited response at NIR wavelengths. These coatings were generally analogs of sodium, potassium, antimony, cesium, or silver. Gallium arsenide (GaAs) is a more recent semi-conductor, low-bandgap coating with high QE in the VIS and NIR regions. In contrast to military needs for intensifiers with higher NIR sensitivity, scientific ICCD usage usually focuses on the blue/green region of the spectrum. This has led to the development of photocathode coatings for ICCD use with QE improvements in the blue/green region. For example, Roper Scientific®, the leading manufacturer of high-performance ICCD camera systems, offers proprietary Gen II red-blue "balanced-response" and super-blue photocathodes (**Figure 3**). Gen III HQ Blue photocathodes have also found some utility in military aircraft applications (**Figure 4**).

GaAs as a photocathode coating is chemically fragile and sensitive to the ionized gases present in small amounts in image intensifiers. These ions are forced by the electronic field back to the photocathode, where they rapidly destroy the GaAs coating. To reduce this deterioration, a thin ion-barrier film of a metal oxide is applied to the MCP surface to block the migration of ions to the photocathode. The film is only partially transparent to incoming photoelectrons and also reduces the capture of the secondary electrons created on the input surface. The net optical effect of these two factors is that the ion-barrier films reduce QE by as much as 30%, but devices with the film are still considerably more sensitive than Gen II devices in the visible portion of the spectrum.

A component of the noise in an intensifier comes from thermally generated electrons from the photocathode and is known as equivalent background illumination (EBI). These electrons are indistinguishable from those generated by light photons and therefore contaminate the image signal. EBI can be reduced by cooling the image intensifier and is usually negligible in gated applications.

MCP

The MCP is the second and most sophisticated component of an image intensifier. It is a slightly conductive glass substrate (approximately 2 cm in diameter and 0.5 mm thick) with millions of parallel traversing channels containing a secondary electron emitter (e.g., cesium iodide, copper iodide) on their inner walls. Early MCPs generally had channels 10-12 μm in diameter, arranged in a hexagonal pattern with 12–15-μm, center-to-center spacing. More recent MCPs have been developed with 6-μm channels, leading to enhanced image spatial resolution (>64 line-pairs/mm).

Electrons generated by the photocathode are driven through the channels by a constant field from a voltage (600-900V) applied to the MCP. A portion of the electrons passing through strikes the walls, causing the formation of more electrons. Multiple collisions continue, with a single entering electron producing many thousands of electrons that finally exit the plate (**Figure 2**). To provide electrical contact for all the channels, the MCP input web surface is generally coated with nichrome, which also has a low secondary electron emission coefficient. Because of this latter characteristic, electrons missing the channels and striking the input surface (which comprises up to 55% of the MCP) create secondary electrons, some of which are then pulled into nearby channels by electrostatic forces. This allows for recovery of some of the

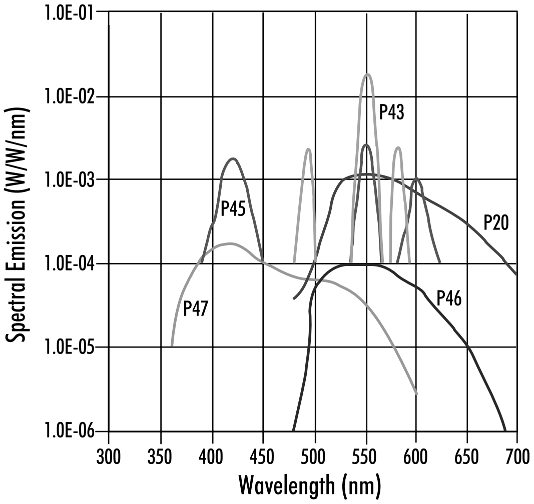

Figure 5. *Emission spectra of intensifier phosphor screen coatings. P20 = Y_2O_2S:Eu. P43 = Gd_2O_2S:Tb. P45 = Y_2O_2S:Tb. P46 = $Y_3Al_5O_{12}$:Ce. P47 = Y_2SiO_5:Ce.*

Phosphor	Decay Time Down to 1%
P20	60 msec
P43	3 msec
P46	2 μsec
P47	0.4 μsec

Table 1. *Fluorescence decay times of phosphors.*

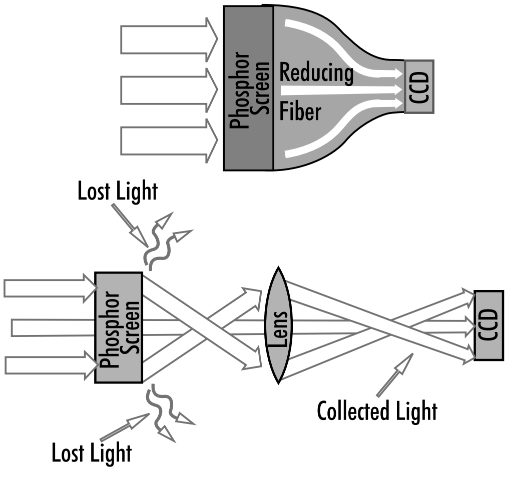

Figure 6. *Comparison of fiberoptic-coupled (top) and lens-coupled (bottom) CCD camera.*

electronic charge that would otherwise be lost by electrons missing channel openings. In essence, each MCP channel acts analogously to a standard photomultiplier device.

Phosphor Screen

The third major component of an image intensifier is the phosphor screen. Electrons exiting the MCP are accelerated by a constant voltage (5-8 kV) and strike the screen, where they are converted back into light photons for detection by the CCD. Phosphor screens usually emit green light and are made of rare earth oxides or halides (e.g., gadolinium, lanthanum, yttrium), with decay times of a few hundred nanoseconds to a few milliseconds. **Figure 5** shows some typical phosphor emission spectra at various wavelengths. **Table 1** shows fluorescence decay times of a variety of phosphors commonly used in ICCDs.

Coupling of Image Intensifiers to CCDs

The intensifier in an ICCD camera can be coupled to the CCD either with a lens or a fiberoptic bundle (**Figure 6**). Lens coupling offers the advantage of flexibility: (1) the intensifier can be removed and the camera used as a standard CCD imager, and (2) an intensifier can be added cost effectively to an existing CCD camera. Disadvantages of lens coupling include lower light throughput (5%-10%) and increased stray light in the camera system.

Coupling via fiberoptics offers better light throughput (>60%) between intensifier and CCD than lens-coupled configurations. Fiberoptic-coupled ICCD cameras are capable of sensitivities approaching single-photoelectron detection and have a much better signal-to-noise ratio (SNR) than lens-coupled devices. Disadvantages are that the fiberoptic coupling is permanent and the detector must be operated in a dry, non-vacuum, inert environment. Advanced ICCD cameras, such as those produced by Roper Scientific, incorporate such operating conditions in a sealed, maintenance-free package. For more information, see Roper Scientific technical note #9 (Comparison of Lens-Coupled and Fiberoptic-Coupled ICCD Cameras) and #6 (Fiberoptic Tapers in High-Resolution Scientific Imaging).

Image Intensifier Gating

Temporal resolution in an ICCD is made possible by switching the intensifier on and off (gating) very rapidly. If the photocathode is biased more positively than the MCP, electrons will not enter the MCP and the intensifier is gated off. If the photocathode is negatively biased, electrons will be accelerated into the MCP and the intensifier is gated on. Typical fast-gate intensifiers have minimum gate widths (FWHM = full width at half-maximum gate pulse) of approximately 2 nsec. For slow-gate devices, FWHM is about 50 nsec.

To overcome the high resistance of the photocathode material, a nickel (Ni) underlayer is deposited on the photocathode to lower this resistance and enable fast gating. However, the Ni layer can reduce effective QE by as much as 40%. Slow-gate intensifiers have neither a Ni layer nor its effects on QE.

The on/off gating ratio of the intensifier is a direct measure of the quality of gating, with a high ratio being necessary to eliminate background and accurately reproduce the transient image. This parameter is defined as the ratio of light output when the intensifier is on to the output when the intensifier is off. In the VIS region of the spectrum, gating ratios of 10^7:1 are possible with standard intensifiers. In the UV region, ratios of only 10^4:1 were traditionally the best that could be attained due to energetic UV photons striking the MCP input surface and releasing secondary electrons. However, ratios as high as 10^7:1 in UV wavelengths can now be achieved with advanced gating technologies such as Roper Scientific's MCP Bracket Pulsing™. Other innovative gating techniques include Roper Scientific's "MCP Gating", where gating is carried out across the MCP instead of the photocathode. With MCP Gating, it is possible to achieve gate widths of 10 nsec or less without sacrificing the QE of a slow-gate tube. For more information, see Roper Scientific technical note #1 (ICCD Gating).

Gen I Intensifiers

Developed in the early 1960s, Gen I intensifiers employed electrostatic focusing and electron acceleration to achieve signal gains up to 150. Gen I intensifiers could detect images under ambient light intensity as low as .01 lux (roughly equivalent to the light intensity under a full moon at night). Problems included image distortion, short-lived components, and the large size of the devices. Gen I intensifiers are now obsolete.

Gen II and Super-Gen II Intensifiers

These are the most commonly used image intensifiers in ICCD cameras. Introduced in the late 1960s and early 1970s, these intensifiers incorporated MCPs. Substantially improved gain (up to 20,000) is accomplished by accelerating electrons, as well as by multiplying electrons in the MCP channels. Gen II intensifiers are only two-thirds as efficient as Gen I devices due to the loss of electrons striking the MCP input surface (discussed above) and to the lack of multiplying effects of those electrons passing through channels without striking interior walls. The Gen II devices have high resolution, are small, and produce no image distortion. Gen II intensifiers can detect images under ambient light intensity as low as .001 lux (roughly equivalent to the light intensity under a quarter moon at night).

Super-Gen II image intensifiers are Gen II devices that employ novel photocathodes with extended spectral range or high QE in a particular wavelength range. For the military, this generally involves response curves shifted in the red direction, which may reduce blue/green performance. For scientific ICCD applications, on the other hand, improved blue/green performance is usually the goal, with reduced NIR QE sometimes being an additional advantage.

Gen III Intensifiers

Gen III image intensifiers are Gen II technology with GaAs added as the photocathode coating. GaAs is extremely photosensitive in the NIR region above 800 nm, but is relatively poor in the blue/green region. Gen III intensifiers utilize high-resolution MCP plates (6-µm-diameter channels) and ion-barrier films. Some versions of Gen III are blue enhanced, with sensitivity in the blue/green region moderately improved for use in military fighter aircraft to visualize cockpit instrument displays, which are generally blue or green (**Figure 4**).

Gen III intensifiers are 2-3 orders of magnitude more sensitive to ambient light than Gen II intensifiers. Gen III devices can detect images under ambient light intensity as low as .00001 lux (roughly equivalent to the light intensity under a heavily overcast sky at night with the moon and all but a few stars completely obscured). Recently, Gen III devices have been further improved with the introduction of higher-resolution tubes (>72 lp/mm).

Conclusions

The development of image intensifiers has been driven primarily by the needs of large military markets, with these needs frequently not the same as those in scientific arenas. The result has been that improvement of intensifier technology for scientific ICCD use has been slower and relegated to smaller laboratories and intensifier manufacturers. Ingenuity in these groups has led to the fabrication of novel photocathode materials and configurations to meet many scientific image-intensifier requirements. The advent of the new, high-performance Gen III HQ Blue intensifier promises to be a major step forward for scientific ICCD camera applications.

Roper Scientific offers the state-of-the-art Princeton Instruments PI·MAX™ and I-PentaMAX™ lines of scientific ICCD cameras that feature a wide selection of Gen II and Gen III photocathodes. These systems offer lens or fiberoptic coupling, as well as a full array of advanced features and options. High-throughput, lens-coupled intensifiers are also available for retrofitting to non-ICCD cameras.

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