Princeton Instruments

Comparison of Lens-Coupled and Fiberoptic-Coupled ICCD Cameras

Introduction

Many intensified CCD (ICCD) camera users are interested in the relative merits and demerits of lens-coupled and fiberoptic-coupled ICCDs (see **Figure 1**). This technical note compares a variety of features of these high-performance cameras, concentrating primarily on camera sensitivity and signal-to-noiseratio (SNR) performance.

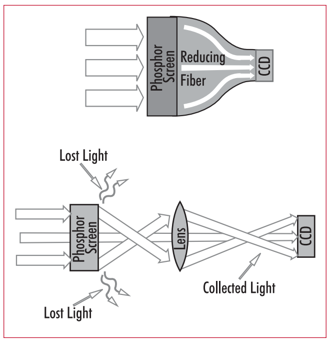

Figure 1. Comparison of fiberoptic-coupled (top) and lens-coupled (bottom) CCD camera.

Sensitivity and SNR

Sensitivity and SNR performance are often confused in discussions of ICCD cameras, especially in advertising literature. This is unfortunate and sometimes misleading to potential users. The reason for the confusion is that over most of their dynamic range, the SNRs of both lens-coupled and fiberoptic-coupled ICCDs are determined primarily by photon statistics. This fact makes it tempting for vendors with only lens-coupled ICCDs to claim that there is no difference between lens-coupled and fiberoptic-coupled ICCDs, or even that it is somehow beneficial (in SNR terms) to use a lens system with low throughput. However, sensitivity is not the same as SNR at very low light levels (i.e., under 100 photons per pixel).

At very low light levels, sensitivity is more closely related to gain. Basically, it is the ability to determine whether or not a photon has been emitted from the photocathode within a pixel in a frame. To consider sensitivity, we must therefore consider the probability of detection and the probability of false detection (a false alarm). A false alarm occurs whenever the CCD readout noise exceeds the false-alarm decision threshold. Random emission from the photocathode (i.e., equivalent background illumination or EBI) is another false-alarm source from the user's perspective. However, EBI is not considered a false alarm in the optical sense because an EBI primary electron is still an electron that should be detected. EBI can be reduced by cooling the intensifier and is normally negligible in gated applications. CCD cameras generally have between 250,000 and 1,000,000 pixels. Thus, to have a tolerably low probability of false alarm in an entire frame, the probability of a false alarm per pixel must be extremely small. Assuming the readout noise to be Gaussian, the false-alarm decision threshold must be many times the standard deviation of the readout noise. On the other hand, the pulse height distribution of the image intensifier is approximately exponential (see **Figure 2**), which means that some of the photoelectrons give rise to a relatively small light pulse.

Figure 3 shows the probability of detection for two values of probability (0.1 and 0.01) of false alarm per frame for a 512 x 512-pixel CCD camera in a system with the effective CCD readout noise (including support electronics and A/D noise) set to 1 A/D unit. While the setting of an acceptable false-alarm rate and probability of detection depends heavily on the experimental conditions, performance that is much worse than 90% detection probability and 10% probability of false

ICCD Coupling

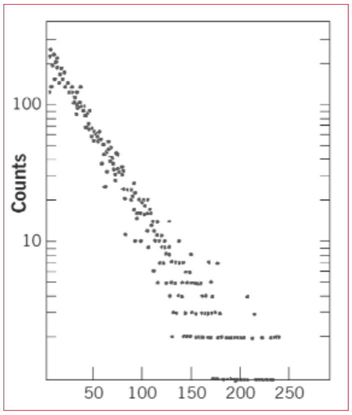

Figure 2. Pulse amplitude distribution from a straight-channel MCP. Counts are shown as a function of channel number.

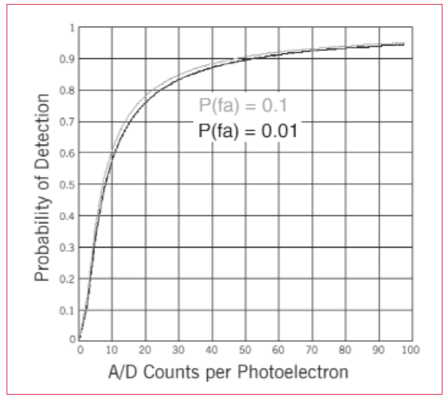

Figure 3. Probability of detection.

alarm per frame is hard to justify as true detection. **Figure 3** clearly demonstrates that to attain this level of performance, an average gain of about 50 A/D units per photoelectron is required. Even with current intensifier technology, this level of gain is impossible to obtain with a reasonable image-intensifier life span in a lens-coupled system using a singlestage intensifier. Furthermore, minimum-decay-time phosphors composed of rare-earth materials are often necessary to obtain excellent linearity. Unfortunately, these phosphors are four to ten times less efficient than standard coatings and produce even smaller signals in the CCD. While the superior coupling efficiency of the fiberoptic-coupled ICCD can still maintain good sensitivity, the lens-coupled ICCD is further strained under such circumstances.

Lens-Coupled ICCD Advantages and Disadvantages

One of the most notable conveniences of lens-coupled ICCDs is the ability to use the camera as both an ICCD and a CCD by removing the intensifier. The lenscoupled system has the significant advantage that when the intensifier and lens are removed, the underlying CCD camera is a full-performance CCD device. The lens-coupled ICCD also represents a cost-effective way to add gating capability to an existing CCD camera if ultimate sensitivity is not required.

Potential ICCD camera users should be wary of statements by manufacturers that a single photoelectron will produce 100,000 photons from the phosphor. This value, which is often used to justify the use of inefficient lens coupling, is too high by almost one order of magnitude even for the most efficient (but not linear) P-20 phosphors. The value is exaggerated even for "fast" phosphors.

In addition, the lower light throughput of lens coupling (relative to fiberoptic coupling), typically at 5%-10%, is claimed by some manufacturers to be an advantage at medium light levels on the grounds that it results in fewer A/D units per photoelectron. This is said to make the camera able to withstand more photons per pixel before saturating. Since the SNR is presumably photon noise-limited at medium light levels, it is claimed that higher SNRs can therefore be achieved. While there is some truth to this argument, especially in cases where intensifier gating is used, Princeton Instruments cameras provide better alternatives.

By operating at higher light throughput (low f-number lens-coupled or fiberoptic-coupled), the opportunity exists to extend the life span of the intensifier by reducing the gain of the multichannel plate (MCP) with lower operating voltage. Operation at lower gain provides better linearity and far greater intensifier life span. By reducing the intensifier gain, the required output charge per photoelectron from the MCP is reduced, which in turn prevents any gain reduction due to local discharge of the MCP. It has been incorrectly argued that operating at higher gain increases the MCP standing current and therefore the linearity. The fallacy here is that the gain and the output charge requirement increase exponentially with the MCP voltage, but the standing current only increases linearly.

Lens coupling increases the stray light of the camera system, reducing the intrinsic dynamic range. This is especially important in systems that must detect small features in the presence of large backgrounds, such as emission from high-temperature plasmas or laser-induced fluorescence (LIF) in combustion analysis. Operation of lens-coupled ICCDs at very high gain results in a significantly reduced intensifier life span.

ICCD Coupling

Fiber Coupled ICCDs

Figure 4. Intensifier coupled to a CCD via fiberoptic offers highest possible sensitivity in low light level applications.

The integrated fiberoptic-coupled ICCD is the highest-performance ICCD available. Fiberoptic coupling provides highest coupling efficiency, as high as 60%, between intensifier and CCD. As discussed above, single-photoelectron detection is possible with this ICCD. When sufficient light is available, the MCP voltage (and gain) can be reduced to allow higher dynamic range and greatly extended intensifier life span. Furthermore, the effective noise associated with the electron multiplication process in the MCP is increased at higher voltages. The integrated fiberoptic-coupled ICCD does not operate at these high voltages even when set to 50-100 counts per photoelectron, so this ICCD provides better output SNR for a given signal than a lens-coupled ICCD.

Princeton Instruments is the leader in the manufacture of high-performance CCDs and ICCDs. The integrated fiberoptic-coupled ICCD is very difficult to design and produce as it requires optimum performance from various parameters that are naturally in conflict. These parameters include clean driving signals to the CCD, low-level signals from the CCD, efficient cooling and thermostating, high voltage wiring, intensifier cooling mechanics, and thermal insulation requirements. In fiberoptic-coupled ICCD cameras, the CCD and intensifier cannot be under vacuum. Therefore, these detectors must have a dry inert environment to prevent condensation. In the case of Princeton Instruments cameras (PI-MAX and and PI-MAX2), the head is sealed with dry nitrogen for maintenance-free operation. Finally, whenever the CCD is cooled, water or air is used to dissipate the heat generated by the thermoelectric cooler.

Conclusion

It is important to critically understand the differences between lens-coupled and fiberoptic-coupled ICCD detectors. Though lens coupling offers the flexibility to retrofit the intensifier to an existing CCD camera, the superior performance of integrated fiberoptic coupling outweighs that advantage. One of several distinct advantages of fiberoptic-coupled ICCDs is their ability to deliver the highest sensitivity at low light levels while still offering a long life span for expensive intensifier tubes.

Princeton Instruments provides the world's finest fiberoptic-coupled ICCD cameras with a wide selection of photocathodes (Gen II, Gen III, Gen III *filmless* and exclusive UNIGEN™ II). By utilizing intensifier tubes with the best QE in the wavelength of interest, the highest practicable sensitivity is ensured. Integrated high-voltage pulser design and the industry's most advanced programmable timing generator (PTG™) provide seamless operation and superior gating performance down to 500 ps. The full line of Princeton Instruments fiberoptic-coupled ICCD cameras is being widely used throughout the world in imaging and spectroscopy applications such as LIF, combustion research, laser-induced breakdown spectroscopy (LIBS), plasma studies, nondestructive testing (NDT), and singlemolecule fluorescence experiments.

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