

Both imaging and spectroscopic applications benefit from customized designs of intensified CCD detectors.

Spectral improvements extend uses of intensified CCDs

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Laser Focus World

The benefits of the scientific intensified CCD (ICCD) have made it an enabling component in research. Now, the technology has matured to the point where manufacturers are customizing the performance of intensifiers and providing complete integrated camera systems for specific applications.

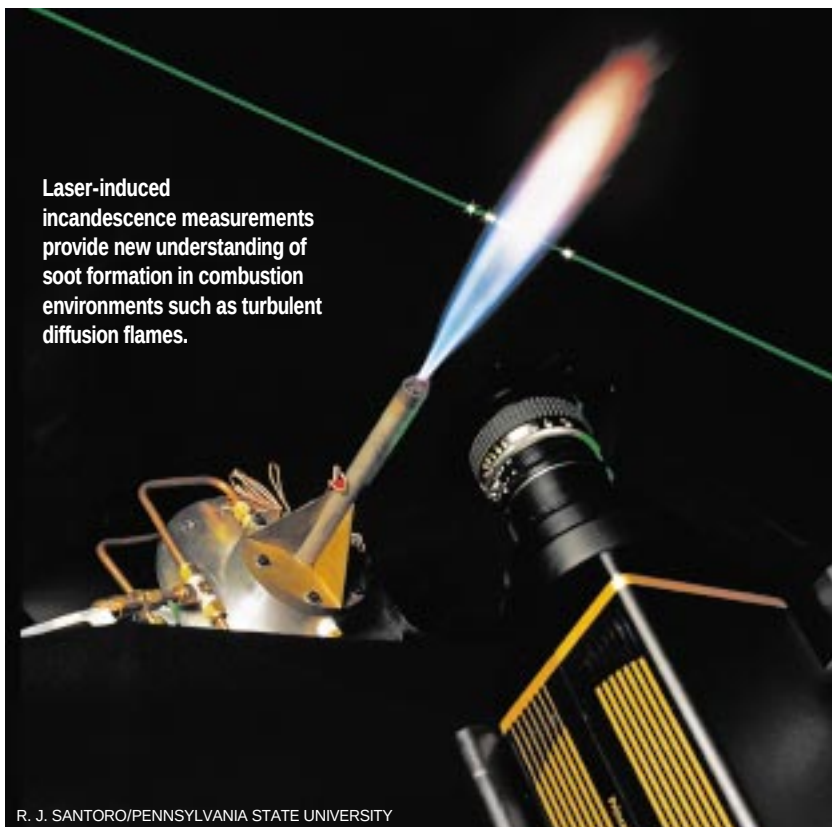
The scientific ICCD camera is a unique light-detection tool, integrating the two-dimensional imaging advantages of a low-noise CCD with a third dimension, time, provided by the high-speed gating of an image intensifier. Every ICCD camera head contains an image-intensifier tube optically coupled to a CCD array. The intensifier tube serves two purposes. First, it amplifies low light signals above the noise floor of the CCD array. Second, it can be rapidly gated on and off, allowing fast, time-resolved photodetection.

Applications for ICCDs can be grouped roughly into two areas: those that involve imaging and those that are strictly spectroscopic (detection of dispersed light from a spectrograph). For this reason, high-performance ICCD camera designs offer a choice between rectangular, spectroscopic CCDs (typically 1024×256 pixels) and square, imaging CCDs (typically 512×512 pixels). To understand the need for the latest ICCD performance improvements, it is useful to look at specific applications of both types.

Laser-induced breakdown spectroscopy

Laser-induced breakdown (LIB) spectroscopy is a fast-growing alternative to inductively coupled plasma (ICP) spectroscopy, which allows samples to be quantitatively analyzed for elemental composition. A short (<20 ns) laser pulse, usually from a 1064-nm Nd:YAG laser, is focused onto the surface of a sample. This creates a small plume of highly excited atoms, radicals, and ions. Light emitted from this plume is focused through a fast (low *f*-number) lens into a spectro-

Laser-induced incandescence measurements provide new understanding of soot formation in combustion environments such as turbulent diffusion flames.



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graph and detected by an ICCD. The ability to gate the response of the ICCD is essential, as the early, bright incandescent emission consists of many excited overlapped bands with little resolvable structure. However, several milliseconds after the laser pulse, the plume has cooled substantially, and the weak emission consists of sharp, distinct atomic emission lines. These can be simply assigned and their relative intensity easily measured.

The availability of compact, diode-pumped solid-state lasers with low power consumption has created much interest in the development of portable LIB spectroscopy systems. These can be used to perform *in situ* analysis on mine/ore samples, environmental pollutants, and lead in paint. This has placed new demands on the ICCD, specifically, requiring a more rugged implementation.

In addition, although many useful atomic emissions are in the visible spectrum, taking full advantage of potential LIB

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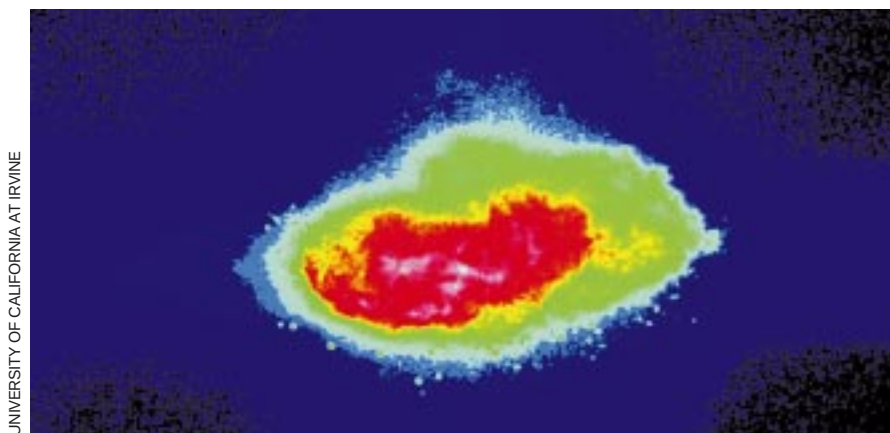


FIGURE 1. Image of fluorescence from laser-ignited deuterium was acquired with a 576×384 fiber-coupled intensified camera.

spectroscopy applications requires the ability to detect atomic emissions from the UV through near-IR. This has created a need for ICCDs with a wider choice of intensifier-tube photocathodes.

An imaging application of high technological importance using ICCDs is the analysis of combustion in flames, furnaces, and particularly automotive engines. Manufacturers of automotive engines in Asia use such systems in their R&D facilities. Specific details vary, but, in a typical setup, cylindrical optics reshape a laser beam into a broad, flat sheet of light, which is then passed through a window in a special test cylinder. Fluorescence or Raman scatter excited by this sheet of laser light is collected in an orthogonal direction by imaging optics and detected by an ICCD (see photo at beginning of article). The light of interest (for example, hydroxyl emission) is separated from the background using a narrow-bandwidth filter. This scheme allows a complete cross section of the combustion region to be sampled at once (see Fig. 1). Measurements can include relative concentrations of species and instantaneous temperature contours. Alternatively, the system can image fuel-injection sprays and flow patterns using simple light-scatter (Rayleigh) detection.

Imaging applications place similar demands on ICCD performance as LIB spectroscopy. Extended spectral range allows the same camera to detect blue and UV fluorescence from combustion intermediates such as hydroxyl and formaldehyde and to image fuel flow

using Rayleigh scatter from 1064-nm laser pulses. Fast gating enhances detail on dynamic events such as flame front progression, which in turn provides insight about engine knocking.

Both spectroscopy and imaging applications benefit from intensifier tubes with improved spatial resolution. In the case of spectroscopy, this translates into spectral (wavelength) resolution for sharp-line analysis and chemometric fitting. In imaging applications, particularly in biology, image detail improves (see Fig. 2).

Intensifier advances

During the past few years, developments in ICCD technology have improved spectral response and temporal resolution. To understand how this has been achieved, it is necessary to review ICCD design.

An image intensifier is a cylindrical vacuum device typically 18 or 25 mm in diameter. A film of alkali or semiconductor layers at the input end acts as a photocathode. Incoming photons whose energy exceeds the work function of the photocathode material may cause the release of free electrons by the photoelectric effect. A modest gate-voltage (typically 200 V) field accelerates the emitted electrons to a microchannel plate (MCP). Rapid voltage gating usually enables pulsed operation of the intensifier.

The MCP is a disk of special glass with many closely packed holes or channels passing through it. The glass is slightly conductive, so that an applied

voltage (typically 800–1000 V) results in a constant field along the length of the microchannels. The field causes the photoelectrons to accelerate through the holes, producing a cascade of secondary electrons as they glance off the channel walls. After leaving the MCP, the electrons are further accelerated into a phosphor screen by a large voltage (kilovolts), producing an amplified image of the original input light pattern. Since the advent of high-uniformity phosphors, the limit on spatial resolution has been determined mainly by the diameter and pitch of microchannels.

The nomenclature of technology advances in image-intensifier design,

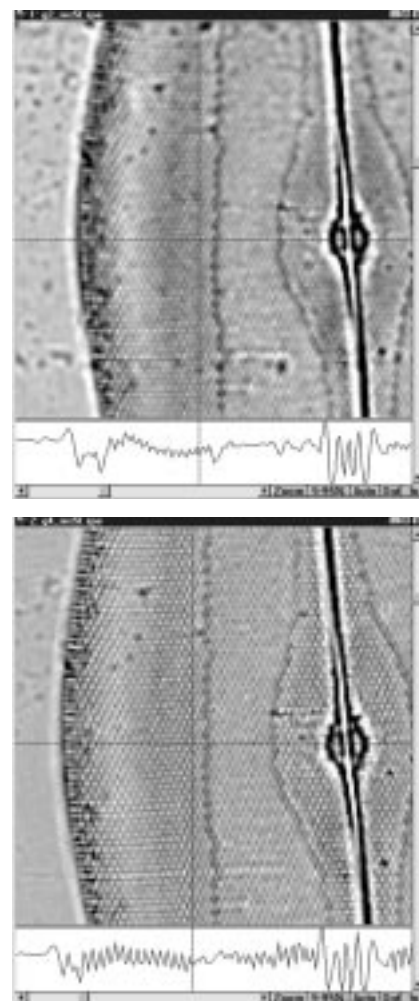


FIGURE 2. Biological applications in particular benefit from enhanced spatial resolution, as in diatom images (160×160 pixels) captured with Gen-II ICCD camera (top) and Gen-IV camera (bottom). The image cross-section plots quantitatively highlight the resolution differences.

for example, Gen-I, Gen-II, Gen-III, reflects its primary use as a night-vision device for military applications. The most common scientific ICCD cameras are based on Gen-II and so-called Super-Gen-II tubes. The difference between the two types is found in the spectral response of the photocathode material. The term “Super” refers to the use of novel photocathodes with either extended spectral range or high quantum efficiency (QE) in a particular spectral range. For example, Roper Scientific (Trenton, NJ) offers ICCDs with a proprietary “balanced-response” photocathode, which delivers similar QE at both red and blue wavelengths (see Fig. 3).

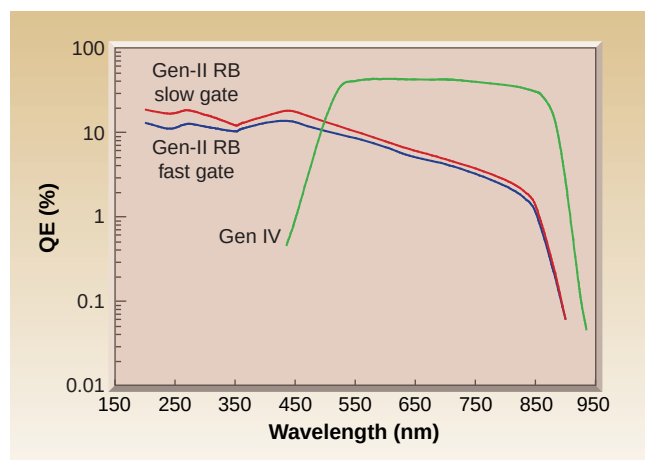


FIGURE 3. Proprietary Roper Scientific photocathodes deliver an extended UV response, whereas the latest GaAs photocathodes provide enhanced response at long wavelengths.

Despite improved performance in the visible and UV, Super-Gen-II tubes only have limited response at near-IR wavelengths. More recently, ICCD cameras incorporating Gen-III and Gen-IV tubes also have become available. Gen-III tubes use a gallium arsenide (GaAs) photocathode. The low-bandgap material exhibits a high QE well into the near-IR spectral region. The latest Gen-IV tubes combine a GaAs photocathode with a high-resolution MCP plate. The 6- μm diameter of the Gen-IV microchannels enable an overall resolution of more than 64 line-pairs/mm.

Advances in ICCD implementation

The use of ICCD cameras for UV applications indirectly led to the gating problem of poor on-off response ratio. To enable gating speeds in the nanosecond domain, ICCD cameras switch the lowest voltage in the intensifier, that is, the accelerating voltage between the photocathode and the MCP. This results in an on-off response ratio of typically 10^7 in the visible and near-IR. A sizeable fraction of incoming photons pass completely through the photocathode. In the UV, however, photons have sufficient energy to create photoelectrons on impact with the MCP front surface. This has the effect of rais-

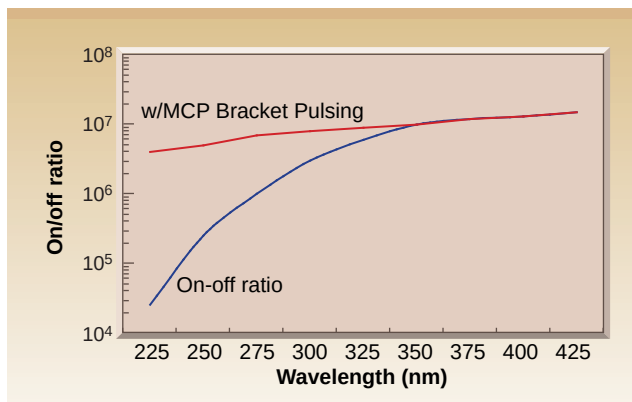


FIGURE 4. Roper Scientific's MCP Bracket Pulsing™ technique extends 10^7 on-off ratio into ultraviolet wavelength range.

ing the background or “off” response, resulting in an on-off ratio as low as 10^4 , which can limit the quality of transient data acquired from a long-lived or ambient background.

Engineers at Roper Scientific developed an innovative solution to this problem, called MCP Bracket Pulsing. Because of the MCP capacitance, potential risetime is somewhat slower than that of the gate potential, so the MCP potential is timed to bracket the gate voltage pulse. With this technology, UV on-off ratios have been raised to the 10^7 level (see Fig. 4).

Even with MCP Bracket Pulsing, the shortest gate times are limited by the speed of switching the gate potential. Intensifier manufacturers have addressed this issue by lowering the impedance of the photocathode using a conductive nickel undercoat on one of the photocathode surfaces. However, this approach involves a trade-off because nickel absorbs light, which lowers the effective QE. The best compromise gives a gate time of 1.5–2 ns. (In Gen-III and Gen-IV intensifiers, however, the speed is limited to 3 ns because of indirect factors associated with the use of GaAs as the photocathode material.)

Previous ICCD camera products required the user to integrate high-speed timing logic to gate the ICCD camera at the proper time. Engineers at Roper Scientific have recently eliminated this inconvenience by integrating the timing-control circuitry into the camera controller. The Programmable Timing Generator™ (PTG) minimizes the overall insertion delay—the time between triggering the camera and opening the gate. Minimizing insertion delay is paramount for experiments where a pretrigger is unavailable, and the trigger event must come from the laser light itself. While the pulse timing circuit is reacting to the trigger, the laser pulse continues to propagate at the speed of light (approximately a foot per nanosecond). This often mandates using optical delay lines to ensure the proper timing of the laser-generated event and the gating of the ICCD. The PTG also facilitates ICCD setup and use by providing timing control through a single software interface and eliminating the need for an external timing generator. □