Properties and capabilities of a low-light imaging sensor using a crossed-strip anode

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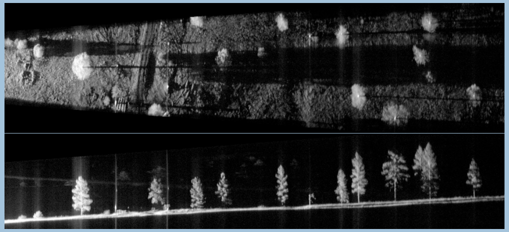
The RULLI XS low-light imaging system



The Remote Ultra-Low-Light Imaging (RULLI) program at Los Alamos National Laboratory is in the process of developing low-light camera system based on a crossed-strip (XS) sensor. The XS sensor is a photon counting imager that provides the time and position information for each photon that enters the camera, a distinct technique from traditional cameras that collect a large number of photons in each pixel to provide an average result. Low-light photon-counting imaging systems have numerous national security and science applications, including the following:

- *Low-light imaging from moving platforms and of dynamic scenes.* The high sensitivity of the XS sensor permits the persistent surveillance of an area using only ambient light. In contrast with traditional cameras, where there is a tradeoff between sensitivity (long integration times) and sharpness in a changing scene (short integration times), the photon-by-photon position and time information provide the ability to reconstruct a scene where the motion of the camera relative to the scene is not known *a priori*.

- *Three-dimensional imaging utilizing laser time-of-flight methods.* Knowing the time of the photon emission from the pulsed laser and the time of the photon arrival at the sensor permits the construction of a three-dimensional image. Three-dimensional imaging has been used for the mapping of a saltwater marsh where traditional LIDAR techniques, which depend on a large number of photons to define a surface, would be overwhelmed by the strong return from overlying vegetation. In principle, only a handful of photons are required to define a surface using XS.

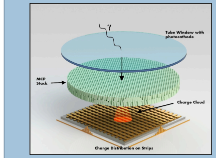
- *Astronomy.* A photon-counting imaging sensor provides the capability to measure dim or transient objects from relatively few photons.

- *Time-resolved fluorescence imaging.* The requirements for the measurement of light emission from a low concentration of molecules in solution are detectability—the identification of individual photons—and separability—the high time and position resolution needed to distinguish separate molecules as the sources of the photons.

These uses require a sensor capable of accepting a high photon flux while maintaining high temporal and spatial resolution. The XS sensor is being developed by LANL and UC Berkeley's Space Science Laboratory to increase capability beyond that of current low-light imaging systems. The current generation RULLI sensor is based on a crossed-delay-line anode that limits the photon rate to about 1 MHz and that suffers from temporary, localized loss of gain following a photon event due to a relatively high amplification (~10^7). The XS camera has the goal of reaching a 100 MHz photon rate with 20 µm FWHM position resolution and sub-nanosecond time resolution.

Preliminary design of the XS camera system.

The XS sensor

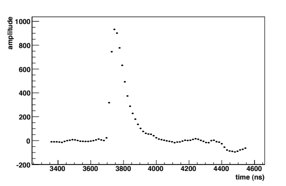


A diagram of the interior of the XS sensor. Figure courtesy of Ossie Siegmund, UC Berkeley.

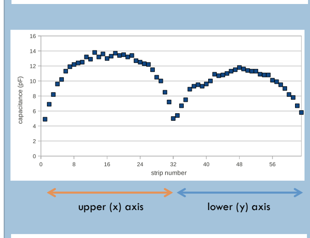
The exterior of the 1.8" XS sensor, looking down on the photocathode window.

The XS sensor, shown at left, consists of a photocathode, a multichannel plate (MCP) stack, and a crossed-strip anode, all packaged in an evacuated glass container. A photon enters the window and strikes the photocathode, which emits a single electron through the photoelectric effect. A voltage bias causes this electron to accelerate toward the MCP stack. The MCPs are two plates of small glass tubes tilted at a slight angle and combined to form a chevron. As the electron passes through the MCP pore, it strikes the wall repeatedly, each time producing a shower of electrons with a final gain of ~10^5. This lower amplification reduces the likelihood of a localized loss of gain in the MCP and increases the possible photon rate. The pulse of electrons emerges from the MCP pore and is directed toward the anode strips. Self-repulsion of the electrons leads to broadening of the charge cloud as it falls onto the anode strips. The upper strips have gaps that reveal the lower strips so that each strip has an equal area exposed. The goal is to have the charge cloud cover several strips in each direction to measure the distribution. The outputs of all strips are continuously digitized to create a time record of the charge pulses absorbed by each strip. By correlating pulse times from all of the strips, the charge distribution can be reconstructed and the centroid calculated.

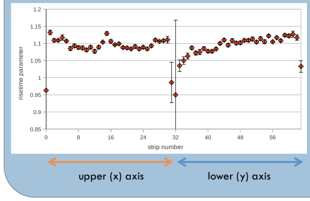
The XS data



Digitization
An example pulse from a development system using a 62.5M samples per second digitizer is shown at left. In the final system, each of the 64 anode channels will be digitized at a rate of 125M samples per second. While the determination of the amplitude of an individual pulse is straightforward, a substantial amount of pulse pile-up is expected under normal operating conditions. For a rate of 100 MHz in photons and assuming on average 4 strips are hit along each axis, a pulse can be expected on average every 80 ns. Algorithms have been developed that can separate pulses separated by as little as about 1.5 samples.



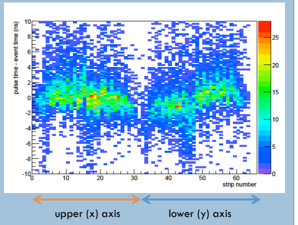
Capacitance
To investigate the effect of the varying strip length on the signal, the capacitance of the XS anode strips were measured, which is shown on the left. Note that the capacitance increases as expected with increasing strip length towards the center of the anode. The upper axis is strips 0-31, and the lower axis is strips 32-63.



Pulse shape
The figure to the left shows the most likely risetime parameter k for each strip in the sensor for an $A(t) = A\, t^k e^{-t/\tau}$ pulse model. The pulse shape was expected to trend with the capacitance but instead shows finer structure. The edge strips (1, 31, 32, and 63) deviate substantially from the otherwise mostly smooth trend, and these strips are likely to be affected by the edge effects of the electric field. The cause of the other features in the pulse shape trend is unknown—perhaps related to manufacturing—but can be accounted for in processing.

The position reconstruction

Time Correlation
The pulses are grouped into events by time correlation. At right is the difference, for each event, between the individual strips' pulse times and a weighted average of those pulse times. A systematic offset can be seen in the channel time differences, which can be calibrated out in the analysis. As with the pulse shape, the edge strips produce little useful data. Ultimately, the event time will be taken from the MCP pulse, which has a faster signal and will be sampled at a higher rate than the anode signals.



Position centroiding
Due to the statistical nature of the MCP amplification, there is variation in the size and shape of the charge cloud. Although an empirical model of the charge cloud distribution has been published, a simple Gaussian distribution has been found to work best. Because a pulse is the sum of the electrons in the charge cloud that fall onto the area covered by the strip, the integral of the Gaussian distribution is fit to the pulse profile. The average pulse amplitude on the x axis is about 1.6 times greater than that on the y axis despite the same total strip area being exposed, and some valid events on one axis do not have sufficient data on the other axis to perform an accurate reconstruction. The XS sensor bias voltage will need to be optimized to maximize the number of valid events.

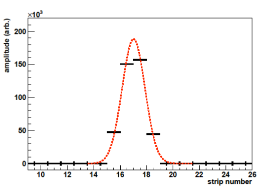
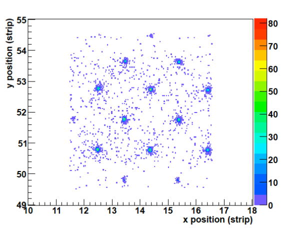
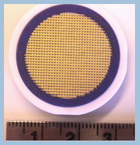


Image
Data has been collected using a prototype of the imbedded system's electronics that enables only six channels on each axis. The reconstructed image of a pinhole array from this small area can be seen at left. In this incomplete work, the pinholes are approximately 50 µm FWHM in size.



The future



A bare 1.8" XS anode.

- Continue refinement of analysis methods to reach the spatial resolution goal
- Complete development and construction of camera system
- Employ the MCP signal for high-resolution timing
- Fully implement analysis algorithm on imbedded FPGAs
- Optimize sensor voltage bias
- Measure target illuminated by a pulsed laser to determine time resolution
- Benchmark spatial and temporal resolution performance against increasing photon rate
- Demonstrate a fieldable detector by the end of FY 2012

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