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Mitigation technique for use of CMOS image sensors in megajoule class laser radiative environment


Presented is a new mitigation technique to improve the radiation tolerance of CMOS image sensors to the radiation constraints associated to the fusion by inertial confinement experiments at megajoule class laser facilities. Using the global reset mode, results acquired at the OMEGA facility show the efficiency of this technique to reduce by more than 70% the number of white pixels induced by the mixed 14 MeV neutron and γ-ray pulse.

Introduction: Both French (Laser Megajoule (LMJ)) and US (National Ignition Facility (NIF)) megajoule class laser facilities are devoted to the study of nuclear fusion by inertial confinement (ICF). Today, the different technologies useful for the LMJ and NIF plasma diagnostics for high neutron yield experiments are identified and work is in progress to improve the tolerance of the different subsystems to the harsh environment associated with such experiments [1, 2]. However, some of the existing diagnostics for capturing and analysing the fusion plasma cannot stand the high neutron yields associated with the future experiments planned at these facilities. One of the main limitations comes from the most sensitive part of some diagnostics: the solid-state image sensor. Depending on the experimental conditions (laser power, target designs, etc.), the fusion reaction generates an intense mixed radiation pulse, constituted by high-energy X- and γ-rays as well as neutron particles that will affect the sensor performances [2]. These particles generate free parasitic carriers in the solid-state sensor that can dramatically degrade the image quality or even blind the sensor.

The most common solid-state image sensors used for plasma diagnostics are charge-coupled devices (CCD). The standard timing diagram of CCD-based plasma diagnostic instruments is presented in Fig. 1. After a laser shot, the radiation pulse to image is generated and interacts with a radiation to light converter (RLC) (e.g. a scintillator) to shift the signal to useful signal range. In this case, a long-decay RLC is required and the useful signal is acquired in the frame following the dump phase. A second mitigation technique has been proposed for CCD [3]: the fast dump and read technique. In this operating mode, an anti-blooming gate is used to quickly perform the dump phase to improve the signal-to-noise ratio, reducing the time required to remove the parasitic charges from ≏300 μs [3] to 2 μs [4].

Experimental details: A dedicated CIS has been designed and manufactured using a 0.18 μm CMOS process optimised for imaging application. The tested CIS is constituted by 128 × 128-10 μm-pitch pixels, each with three transistors and one photodiode. To perform the fast dump and read, a GR function was implemented in the sensor. When the GR signal is active, all the reset transistors of the array are turned on, leading to a synchronous reset of all the pixels. Thanks to this function, the fast dump and read operation is performed as illustrated in Fig. 1 (CIS global reset). First, the GR mode is activated several milliseconds before the laser shot to empty the array of dark charges. When the parasitic radiation pulse passes through the imager, the generated parasitic charges are instantaneously dumped and the GR mode is disabled after a very short delay (GR delay) to start the integration of the useful signal.

The experiment was conducted during the neutron derby of 10 April 2012 at the OMEGA facility of the Laboratory for Laser Energetic (LLE), University of Rochester, New York, USA. A dedicated radiation hard test bench has been developed to simulate a plasma diagnostic instrument, to acquire the images and to operate the sensor in GR mode. The useful signal is generated by a pulsed ultraviolet (UV) light emitting diode (LED) synchronised with the radiation pulse to excite a long-decay RLC (persistence around a few milliseconds). A test pattern was placed after the RLC to validate that the sensor acquires the useful signal properly. The average neutron yield induced by the laser shots considered in this study was of about 1013 neutrons per shot (∼3 × 106 n/cm² at the detector level).

Results: The images of the test pattern captured with the standard timing diagram (useful signal and parasitic signal acquired simultaneously) and with the GR fast dump technique are presented in Fig. 2. A dedicated CIS has been designed and manufactured using a 0.18 μm CMOS process optimised for imaging application. The tested CIS is constituted by 128 × 128-10 μm-pitch pixels, each with three transistors and one photodiode. To perform the fast dump and read, a GR function was implemented in the sensor. When the GR signal is active, all the reset transistors of the array are turned on, leading to a synchronous reset of all the pixels. Thanks to this function, the fast dump and read operation is performed as illustrated in Fig. 1 (CIS global reset). First, the GR mode is activated several milliseconds before the laser shot to empty the array of dark charges. When the parasitic radiation pulse passes through the imager, the generated parasitic charges are instantaneously dumped and the GR mode is disabled after a very short delay (GR delay) to start the integration of the useful signal.

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Fig. 1 Timing diagrams illustrating standard CCD readout operation, dump and read technique and proposed CIS global reset technique

In this Letter, we propose a technique to transpose the CCD fast dump and read method to CMOS image sensors (CIS) by using a global reset (GR) mode. We present the first experimental validation of this principle. The main benefits of the GR mode are: 1. to benefit from all the advantages of CIS over CCD, such as a much higher tolerance to radiation or the possibility to use radiation hardening by design techniques, and 2. to possibly further reduce the time required to dump the parasitic charges.

A more detailed analysis can be performed if the test pattern is removed by subtracting an image of it captured in the absence of a radiation pulse, as done in Fig. 3. It confirms that the GR mode damps most of the radiation induced parasitic charges. Nevertheless, there are still some disturbed pixels in the image taken with the GR mode.

Fig. 2 RLC and test pattern image captured during laser shot
a) Image acquired with standard timing diagram (no GR)
b) Image acquired with GR fast dump phase

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Fig. 3 Dark image achieved by subtracting test pattern image from images presented in Fig. 2
a) Image acquired with standard timing diagram (no GR)
b) Image acquired with GR fast dump phase

To investigate the origin of these remaining charges, several GR phase durations have been used to see the impact of this parameter on the effectiveness of the dumping technique. This duration has been tuned by changing the GR delay between the radiation pulse and the end of the GR phase (see Fig. 1). Fig. 4 presents the number of disturbed pixels against this delay. To deal with the shot-to-shot discrepancy of the neutron yield, the number of disturbed pixels is normalised to a 1013
neutron yield shot. Thus, Fig. 4 represents the numbers of disturbed pixels expected for an equivalent $10^{13}$ neutron yield with the different GR conditions.

![Graph showing normalized number of parasitic white pixels for $10^{13}$ neutron fluence against GR delay. Value achieved with classical timing diagram (i.e. without GR) is represented by dashed line](image)

**Fig. 4** Normalised number of parasitic white pixels for $10^{13}$ neutron fluence against GR delay. Value achieved with classical timing diagram (i.e. without GR) is represented by dashed line

The number of disturbed pixels without GR mode is represented as a dashed line in Fig. 4 (~155 pixels). When a 0.9 $\mu$s delay is used, more than two thirds of the parasitic white pixels are removed, confirming the effectiveness of the proposed technique. The number of remaining white pixels after GR decreases slowly with the delay between the end of the GR phase and the radiation pulse. Two causes could explain this behaviour: 1. an electronic time constant, due to the sensor, or 2. a physical time constant, due to the radiative environment.

In the first case, it would mean that the GR phase during which the parasitic charges are evacuated is too short to dump all the pulse-induced charges. Such a phenomenon could lead to electronic delays in the microsecond range, but cannot explain why several milliseconds are necessary to dump all the charges (resetting the sensor when it is entirely saturated by a light pulse takes less than a few microseconds).

The second hypothesis would imply that the OMEGA mixed pulse is not strictly instantaneous (i.e. much shorter than 1 $\mu$s) and that some delayed high energy particles impinge on the sensor after the GR dump phase. High-energy neutrons are known to interact with the materials surrounding the target, constituting the experimental hall and the instruments through a scattering process. Some of the resulting scattered neutrons can possibly pass through the sensor several microseconds or even milliseconds after the radiation pulse. The evolution with time of this radiative environment is not yet precisely known at the location of the tested CIS, but work is in progress to confirm this second hypothesis that we suggest to be responsible for the observed CIS behaviour.

The absence of a sharp increase in the number of white pixels for the shorter delays used here strongly suggests that the electronic dump time constant is well below 1 $\mu$s. Thus, the minimum delay may probably be further reduced without any impact on the performance of the dump phase (if hypothesis 2 is correct).

**Conclusion:** The CCD fast dump-and-read mitigation technique for a megajoule class laser radiative environment has been transposed to CMOS image sensors by integrating a global reset function in the imager. This technique was tested and validated in a real inertial confinement fusion facility. About 70% of the parasitic charges are removed after a 1 $\mu$s global reset phase (100% after 10 ms). The remaining 30% of white pixels are most likely due to diffused neutrons that interact with the sensor after the end of the global reset phase. Several actions are planned to confirm this last hypothesis: 1. The CIS will be exposed to an intense X-ray pulse to verify that delays below 1 $\mu$s are sufficient to dump all the parasitic charges and that no electronic time constant limits the GR technique. 2. Physical Monte-Carlo simulation of the time-dependence of the harsh environments at the device location in the OMEGA target bay is led to confirm the presence of energetic particles several milliseconds after the shot. 3. Another experiment in an ICF facility will be conducted to measure this delayed radiation background.

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