SYSTEM TEST OF ELECTRON MULTIPLYING CCD CHARACTERIZATION

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ABSTRACT

This paper presents the results obtained for the development of a test system used for the characterization of a photo detector based on a charge-coupled device with electron multiplication, (EMCCD). In the process, the test system comprises a luminous source and test chamber is characterized too, to guarantee a good stability when the dates are acquired. The photo-detection system is part of the Brazilian Tunable Filter Image (BTFI) to be integrated in the SOAR telescope, for improving observations with adaptive optics. The purpose is thus to assess the performance of the detector system in laboratory before the whole system be ready for direct use in the BTFI instrument.

1. INTRODUCTION

Electron multiplying charge coupled devices (EMCCD) use the phenomenon of ionization impact on silicon to obtain an amplification of signals of interest as a way to increase the electrons from the photoelectric conversion increasing the detection performance. [1].

The performance main requirements include, but are not limited to the noise factor, dark current, and multiplication gain. The dark current is mostly due to thermal generation and timing process to generate the electrons multiplication [2]. For the purpose of assessing performance and the characteristics of detector system, it is necessary for the assembly of the EMCCD to be turned on (first step with a EMCCD prototype level) inside a cooled camera with a Peltier cell or liquid nitrogen and for the detector to be put into operation together with a electronic controller and a source with light constant and variable intensity.

A preliminary validation is a required step before finalizing the project of new scientific EMCCD, which it will use a larger area chip that will effectively be used in BTFI.

2. THE EMCCD

EMCCDs correspond to new technology devices in which the detection of photons is performed by bombardment of electrons to provide gain in the charge domain without affect the quantum efficiency and the resolution features of a conventional CCD [1, 3].

2.1. Principle operation

The image, store and read-out information register are of conventional design. In a conventional CCD is extended a section of multiplication register and is placed between the normal serial register and the charge to voltage conversion circuitry (Analog to Digital Converter) [1, 4].

During image readout, this gain register multiplies the amount of charge in each pixel before it reaches to the readout amplifier. Since charge multiplication occurs prior to readout of the device, the readout noise can be effectively eliminated by using a high-multiplication gain.

The inclusion of a multiplying serial register is appropriate for applications in which the image of interest is obtained from sources of low light intensity but which do not need to include external intensifiers of image, means that it can utilize the full quantum efficiency of the silicon sensor, which can be as high as 95% [4,5,6], because the multiplying gain is originated by the process mentioned of ionization impact on silicon (Figure 1).

Figure 2 illustrates the load transfer gates. Note that two of the gates $\phi 1$ and $\phi 3$ are clocked with normal amplitude drive pulses (10 or 15 Volts) and those pulses are applied to both sections of the readout register, the pulses applied to phase 2 of the multiplication register has a higher amplitude, 35 to 50 volts and is followed by a gate of low level DC voltage.

The potential difference between the dc gate and the high level of $\phi 2$ can be set sufficiently high so that signal electrons can undergo impact ionization [1], in which new electrons appears, increasing the charge package as it passes through a multiplication element.

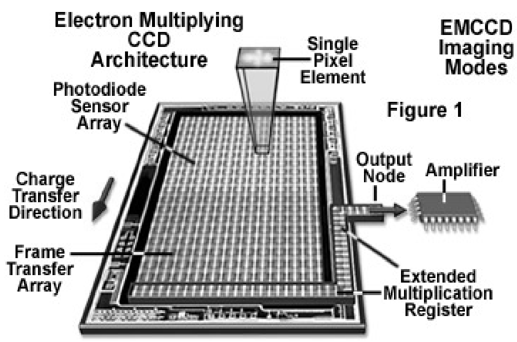

Figure 1 structure of EMCCD [4]

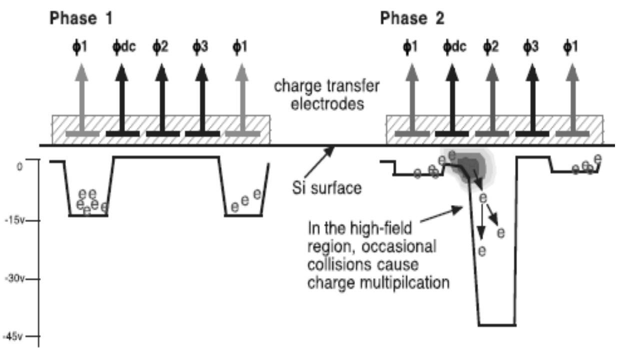

Figure 2 Energy diagram of an electron-multiplier CCD amplifier. [3]

The electrons are transferred from phase 1 to phase 2 in a normal clocking sequence. Furthermore the charge multiplication by transfer only is reduced within a range of values between 1.010 and 1,016. The cumulative gain over the significant number of pixels in the multiplication register is substantial, and can be of hundreds or thousands of times. The multiplication gain is exponential, proportional to the high voltage applied to phase 2, and can only be increased or decreased depending on the variation of the clock voltage amplitude. [3].

2.2. EMCCD noise

The gain process in low-light systems introduces excess noise and a noise factor k can be defined by: [7]

$$k_{EMCCD} = \frac{n_{AFTER\ GAIN}}{M \cdot \langle n_{BEFORE\ GAIN} \rangle}$$

Where $\boldsymbol{M}$ is the total gain of multiplication register, the overall gain depends upon the number of multiplying cells $\boldsymbol{N}$ and the mean gain per cell $\boldsymbol{g}$: $\boldsymbol{M=g^N}$. If the gain does not add noise, there is no excess noise ($\boldsymbol{k_{EMCCD} = 1}$) [12]. The excess noise factor is

$$k^2{}_{EMCCD} \approx 2\frac{M-1}{M^{\frac{N+1}{N}}} + \frac{1}{M}$$

However, the stochastic multiplication process and any loss mechanisms introduce noise. The EMCCD excess noise factor tends to $2^{½}$ as the gain is increased [2]

2.2.1. Read noise

Readout noise is usually quoted for a CCD in terms of the number of electrons introduced per pixel into your final signal upon readout by the amplifier of the device.

The electronics themselves will introduce spurious electrons into the entire process, yielding unwanted random fluctuations in the output. The physical size of the on-chip amplifier, the integrated circuit construction, the temperature of the amplifier, and the sensitivity all contribute to the read noise for a CCD [8,9].

2.2.2. Dark Current

Dark current for an EMCCD is usually specified as the number of thermal electrons generated per second per pixel or as the current generated per area of the device (i.e., picoAmps cm^{-2}). At room temperature, the dark current of a typical EMCCD is near $2.5x10^4$ electrons /pixel/second. In readout mode the dark current electrons are converted in part of the signal, indistinguishable from astronomical photons or the original input signal. [3, 9]

2.2.3. Clock induced charge (CIC)

CIC is caused by impact ionization of the holes as they move in and out of the Si/SiO2 interface during clocking. The charge generated is dependent on the number of transfers through the CCD not the integration time. This is dependent on clock amplitude, transfer rate, clock timing and this noise source is a weak function of the device temperature [3,6].

Clock induced charge is a noise source that could be neglected on conventional CCDs [1]. CIC appear during the transfer of charges when the EMCCD is operated at high gain, in which induced charges will appear at the output amplifier as a normal event, thus creating a false event impossible to discriminate from a real event [10,11].

The following principles of operation are recommended to minimize the generation of CIC: The parallel transfer frequencies should be made as large as possible, up to the maximum specified by the device datasheet and Clock edge rise and fall times should not be made too fast [11].

Shot noise, thermal dark current and spurious charge are all amplified by the electron-multiplication process, but since multiplication gain occurs before the on-chip output amplifier, readout noise is not increased [10,11,12]. A key advantage of the EMCCD is that when the device is cooled, so that dark current is effectively eliminated, readout noise and other on-chip noise sources are small compared to the multiplied signal level.

3. TEST SYSTEM

The Brazilian Tunable Filter Image will carry out the CCD97 detector, a new model of e2v technologies; this device uses a novel output amplifier circuit capable of operating at an equivalent output noise of less than one electron at pixel rates of over 11 MHz. The size of the image area is 8.192mm x 8.192mm, which contains 512 x 512 pixels (the pixel size is 16µm x 16µm). [13].

The test system is composed of a constant light source with a variable intensity (figure 4), the principle of operation of it is based on a variable current source. For a good performance and functioning of the EMCCD it is necessary mount it inside a vacuum chamber. This chamber is placed on a dark box where several tests using the EMCCD were performed. The current source has a functionality to control the intensity of light emitted to the EMCCD detector. This light is generated by common LEDs located inside the dark box built to fit the EMCCD detector, and carry out various tests to characterize the detector. The cooling of the test chamber for the first test is made with a cell Peltier, which is not very cold in comparison with other cameras, which use liquid nitrogen.

3.1. Test chamber

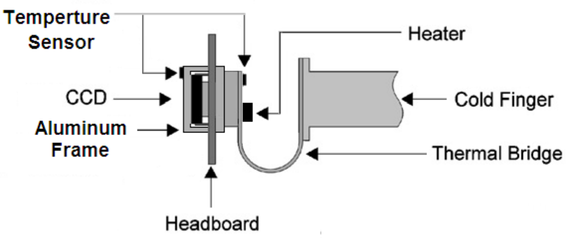

Figure 3 cold components assembly

The chamber has ports for the connection of vacuum equipment and electrical feed through on their bulkheads.

First, a Peltier cell was used for removing heat of the test chamber, but it was not efficient removing heat on the EMCCD, this cell was changed by a cold finger cooled with liquid nitrogen.

The high vacuum pressure was maintained at $1.33x10^{-8}$ bar by a combined mechanical / turbo molecular pump connected to the chamber ports. An aluminum frame was mounted inside of the headboard to get a good transfer of heat between the EMCCD and the cold finger. The thermal bridge is made of cooper and it has purpose to remove the heat to the cold finger.

Two temperature sensors were mounted inside the test chamber. The distance between the EMCCD and one temperature sensor was kept as small as possible to get a correct temperature on the device. Another temperature sensor was mounted at the end of the aluminum frame to evaluate the temperature on the cold finger. A heater was placed near the thermal bridge to control the temperature on the EMCCD detector. The temperature sensors and heater are connected to an external temperature controller unit.

3.2. Constant light source

The constant light source is composed of an operational amplifier of low noise and a high precision voltage regulator, which are configured together how a variable current source, which controls the current that circulate on each LED. The variable resistance (R1) allows the variation of the luminosity on the source, and R7 adjusts the maximum value of current on the LED. The switches allow the turning on of each LED.

The colors of the LEDs of light source are green, orange and red, which it is placed inside the dark-box to obtain an illumination to the EMCCD. First, the luminosity operation source, in which the luminous stability is observed and measured, has to be verified with a Multi-Function optical meter model 1835-C with ± $0.0001 nW/cm^2$ of accuracy and full scale accuracy of 0.05%. The light source with maximum luminosity provides values of $0.120 nW/cm^2$, the measurement was made during three hours verifying the luminous stability and heating of the LEDs.

When the detector is placed in the camera test in the dark box, with a LED off matrix is possible to measure the properties of dark current and read noise.

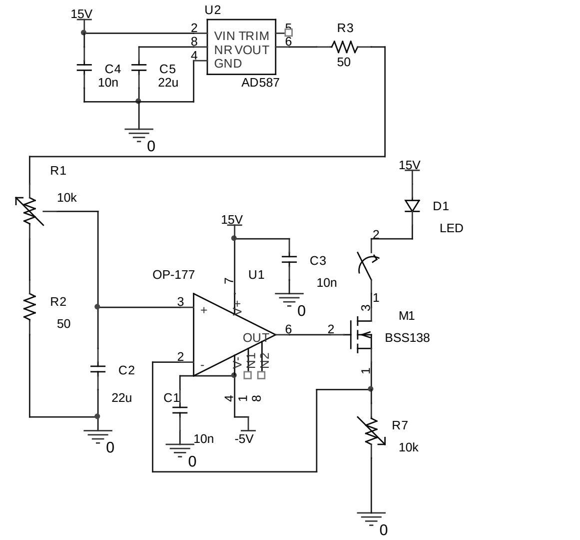

Figure 4 Circuit section of the current source to LED luminosity control.

Afterward the LEDs array is turned on, with a controlled intensity, and can measure the linearity and the gain properties to find the best performance data.

4. RESULTS

4.1. Measurement of luminous intensity

The characterization of the luminous source was made from variation of the luminous intensity at different current values for each LED. The intensity is plotted as a function of the current applied on each LED; the graph was made for each LED color (Figure 5).

The instrument used for the measurement was calibrated for each wavelength corresponding to the color of each LED, such as, red 660nm, orange 585nm, and green 565nm. The optical sensor was placed in the same position where the EMCCD will be placed.

The measurement allows associating the luminous intensity emitted to the EMCCD detector with a current value. Figure 5 shows the different luminosities for each LED, the red LED has a higher luminosity with a low

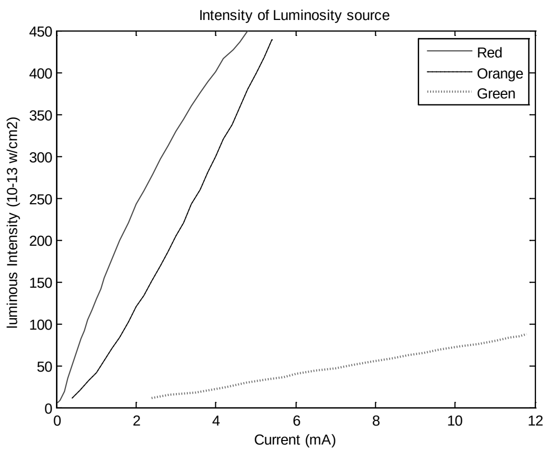

Figure 5 luminous intensity of light source as a function of the current LED.

current applied and green LED has a weaker luminosity with a higher current; the graphics are linear because the temperature on the LEDs was kept constant.

4.2. Assembly of test chamber

Figure 6 shows both assemblies of the test chambers, first, which has a heat removing system with Peltier cell and second chamber has a cold finger cooled with liquid nitrogen for removing heat of the EMCCD.

The chamber assembly with Peltier cell did not achieve a good temperature on the EMCCD detector, because the device did not have a perfect thermal coupling. The EMCCD only reached 10ºC of temperature, for which the outcome are high noise images. This was the reason to change the heat removing system for a cold finger. The EMCCD reached lower temperatures (around -100ºC) what minimize the noises generated from thermal effects, such as, read noise and dark current.

4.3. Shooting of images

After to characterize the luminous source is possible to shoot images witch the EMCCD, as bias, dark and flat images. Bias image is a type of image that has an exposure time approximate to zero seconds, with this image is possible to determine the read noise of the CCD detector. Dark image is taken without light with some exposure time; dark image is a method by which the thermal noise (dark current) in an EMCCD can be measured, for analysis of dark image needs to subtract the read noise that is added in the read process. In Flat image, the CCD is exposed to a light constant source with different values of exposure times, in which the gain and linearity can be measured.

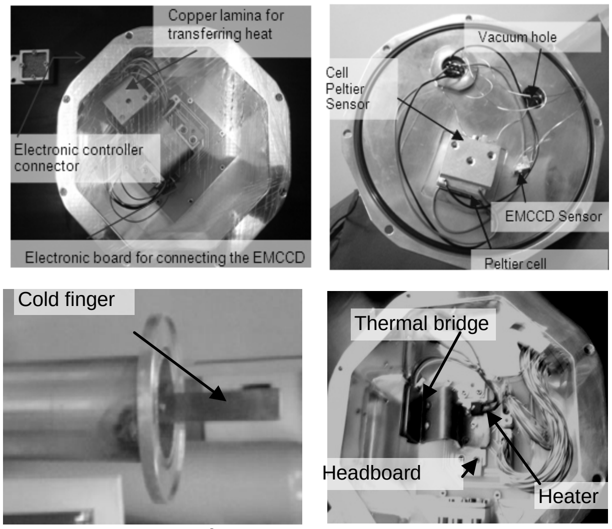

Figure 6 assembly of test chamber, up Peltier cell – down Cold finger

5. CONCLUSION

The luminous intensity stability emitted to the detector has been verified. The verification was made in a similar environment to the assembly of the EMCCD, ensuring a good reliability in measurements to characterize the device.

The variation of luminous intensity on the source is linear as a function of current applied to LED. The luminous source does not have temperature variation allowing a light emission stable for long times.

The change on the heat removing system with a cold finger and the characterization of luminous source is possible to accomplish the shooting image with a lower noise and good stability. Images acquisition was possible with the test system for different values of exposure time and luminous intensity levels.

6. REFERENCES

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