Characterization of CMOS Image Sensor

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Utsav Jain
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Faculty of Electrical Engineering, Mathematics and Computer Science · Delft University of Technology

Delft University of Technology
Department of
Electrical Engineering

The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled
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by

Utsav Jain

in partial fulfilment of the requirements for the degree of
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Supervisor(s):

prof. dr. ir. Albert J.P. Theuwissen

M.S.EE Dirk Uwaerts

Reader(s):

prof. dr. ir. Albert J.P. Theuwissen

prof. ing. H.W.(Henk) van Zeijil

Dr. Bert Luyssaert

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Abstract

CMOS image sensors comprise of two processes: designing and measurement/testing. They are designed with certain characteristic performance and it is important to measure these characteristics accurately. CMOS image sensor converts light information into digital information which can be reproduced in the form of an image. Conventional 4T pixel with a pinned photodiode is a popular choice for designing image sensors; with certain modification in the pixel architecture better characteristic performance can be achieved with trade-offs.

Quantum efficiency, linearity, full-well capacity, conversion gain, noise, non-uniformity, dark current, modulation transfer function and image lag are the main characterises of a CMOS image sensor. The quantum efficiency defines the photon-electron conversion and collection efficiency of the image sensor which ideally should be 100 percent i.e. 1 electron-hole pair for every photon incident with linear photo response. Higher full-well capacity means more number of electrons that can be stored. Conversion gain tells the image sensors ability to convert the electrons generated into a voltage, higher the better. Noise sets the dynamic range of the image sensor by defining the lower limit of signal level, continuous advances have been made to reduce the noise and some image sensors can achieve noise level of $1e^-$. Modulation transfer function defines the spatial resolution and contrast relation of the image sensor, which is also the measure of crosstalk of the image sensor. Another characteristic which is more of an advantage over CCD image sensors is the image lag which is also known as memory effect; defines the image sensors ability to completely transfer the charge from photodiode to floating diffusion. These characteristic parameters define the CMOS image sensor and having a standard measurement procedure for computing this characteristic is necessary.

This report presents the standard measurement procedure to characterize CMOS image sensors. This project is an internal project for Caeleste CVBA, Mechelen, Belgium, hence the measurement procedures are more specific to Caeleste requirement and follows EMVA 1288 standards. Measurement procedure includes all the details to evaluate the characteristic parameter: measurement background, block diagram, procedure and data processing are some of the key elements of the procedures. At Caeleste different methods are performed to compute a characteristic parameter accurately and precisely. Also, the software library and hardware tools were updated for improving the measurement accuracy and speed.

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1. Chapter 1

Introduction

Standard and accurate measurement procedures are key to a successful image sensor design. The importance and the need of standard measurement procedure for CMOS image sensor cannot be stressed more. The measurement of any opto-electrical system is an art by itself and it should be precise and accurate. With the ever-growing technology, many technical advances and improvements have been reported in the CMOS image sensor literature, so it becomes challenging to accurately determine the performance parameters, hence it is important to have a standard procedure to characterize the image sensor.

The main motivation for my thesis was to get a deep understanding of the CMOS image sensor, right from the fabrication process and finally to test and characterize the imager. As I first learned about the CMOS image sensor, I was fascinated and curious to learn more and decided to do my master thesis in CMOS image sensor. During my academic curriculum, I did research about CMOS image sensor to get more insight about them and wrote a couple of reports about it. This thesis project combines my motivation and challenges involved for accurate measurements, so the objective of my thesis work is to standardize measurement procedure for characterization of CMOS image Sensors. This work presents the standard procedure for measurement of characteristic parameters of a CMOS image sensor.

As a part of internal project at Caeleste CVBA, Mechelen, Belgium, we performed various measurements and testing to improve and upgrade the measurement procedure for key characteristic parameters that includes quantum efficiency (QE) and responsivity, noise, non-uniformity, dark current, linearity, full well capacity, conversion gain, modulation transfer function (MTF) and image lag of the CMOS image sensor, also upgrading the software library and hardware tools for fast and accurate measurements.

The project started with characterizing the LED light source that is used for performing measurement on CMOS image sensors, as the light source is one of the most important device used during the measurements of an imager. The stability, spatial homogeneity and spectral response are the key parameters of the light source and knowledge about these parameters assisted in accurate measurements on CMOS image sensor.

This project also addresses the influence and limitations of the instruments, environmental condition and interfacing devices on measurement results. The fifth chapter of this report consists of standard measurement procedures for all the characteristic parameters.

Thesis Organization

This thesis report consists of 7 chapters. The first chapter gives an introduction about this project which illustrates the objective and motivation for this project. Then Chapter 2 gives necessary background information for this project which includes a basic overview of CMOS image sensor, the working principle of a pinned photodiode and working and timing operation of conventional 4T pixel architecture. Chapter 3 elaborates on the importance of an LED light source and its characterization and draws the conclusion about the present light source which will be helpful in building new improved light source at Caeleste. It is followed by Chapter 4 which explains all the characteristic parameters for which the measurements are performed and how they define the performance of the CMOS image sensor. Then Chapter 5 includes all the

measurement procedures that are performed at Caeleste and standardized for characterizing CMOS image sensors that Caeleste designs. Chapter 6 contains the conclusions of the thesis work. Finally, chapter 7 presents the appendix which includes information that supports my work.

2. Chapter 2

Overview of a CMOS Image Sensor

This chapter gives a brief introduction to the CMOS image sensor and a 4T CMOS active pixel sensor which is followed by a brief explanation about the pinned photodiode and its structure in Section 2.1. Then section 2.2 discusses the 4T APS architecture in detail and explains it's working. Section 2.2.1 introduces two electronic shutter modes for CMOS image sensors: Global shutter and Rolling shutter mode.

2.1. Background of CMOS image sensor

CMOS Image Sensors (CIS) are semiconductor device used for making a digital camera. They detect information in the form of light or any other electromagnetic radiation and create an image that represents the information. CMOS image sensors consist of integrated circuits that sense the information and convert it into an equivalent current or voltage which is later converted into digital data.

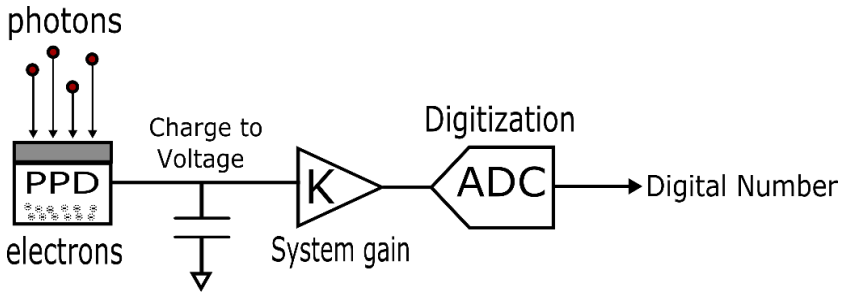


Figure 2.1-1- Physical model of a camera.

In 1967, Weckler proposed the operation of charge integration on a photon-sensing p-n junction which was treated as the fundamental principle of CMOS image sensor [1]. This charge integration technology is still being used in the CMOS image sensors. Shortly, in 1968, Weckler and Dyck proposed the first passive pixel image sensor [2]. In 1968, Peter Noble described the CMOS active pixel image sensor and this invention laid the foundation for modern CMOS image sensors [3]. Yet one had to wait until the 1990s solving the limitations of CMOS technology for active pixel image sensors to develop rapidly [4].

In modern days, CMOS image sensors have overtaken CCD's in most of the fields. A CMOS image sensor as an integrated technology offers a wide range of functionality, fast read out, low power consumption, low cost and some better characteristics parameters. Although CCDs had an excellent imaging performance, their fabrication processes are dedicated to making photo sensing elements instead of transistors and hence it is difficult to implement good performance transistors using CCD fabrication processes. Therefore, it is very challenging to integrate circuitry blocks on a CCD chip. However, if the similar imaging performance can be achieved using CMOS imagers, it is even possible to implement all the required functionality blocks together with the sensor, i.e. a camera-on-a-chip, which may significantly improve the sensor performance and lower the cost. In 1995, the first successful CMOS image sensor was demonstrated by JPL [5]. It included on-chip timing, control, correlated double sampling, and fixed pattern noise suppression circuitries.

Active pixel sensors are state-of-the-art implementation of CMOS image sensor, they are integrated circuit consisting of an array of pixels and signal processing unit. They are discussed in detail in the following section. This work addresses important characteristic parameter of a CMOS image sensor and test methodologies to compute and evaluate them. Ideally, a CMOS image sensor should have 100% quantum efficiency, high frame rate, low noise, linear response, no optical cross talk and no image lag [6].

2.2.Pinned Photodiode

The photodiode is a semiconductor device that converts light into a current. Photodiodes work on the principle of the photoelectric effect which states that when a photon with sufficient energy is incident on a photodiode it creates an electron-hole pair. So these free carriers can be swept with an electric field which results in current in the diode. A pinned photodiode is a variation in photodetector structure with large depletion region, that is currently used in almost all CCD's and CMOS image sensor due to its low noise, low dark current and high quantum efficiency [7].

The pinned photodiode (PPD) has p+/n/p regions with a shallow p+ implant in an n-type diffusion layer over a p-type epitaxial substrate layer referring to Figure 2.2-1. Pinning, refers to Fermi level pinning or pinning to a certain voltage level, or also forcing or preventing of Fermi level/voltage from moving in energy space [8] [9]. A PPD is designed to have the collection region which fully depletes out when resets. As the PPD depletes it gets disconnected from the readout circuit and will drain all charge out of the collection region (accomplishing complete charge transfer). The major effect is that the diode can have an exact "empty" state, and allows therefore to do "correlated double sampling" (CDS) in a simple way, cancelling the kTC noise of the conversion node. Also, the p+ pinning layer decreases the dark current by preventing the interface to be depleted and also by absorbing the carriers due to surface generation and preventing them from reaching the depletion region. When, you design the depletion of the PPD to deplete at a certain voltage you are pinning that PPD to that voltage.

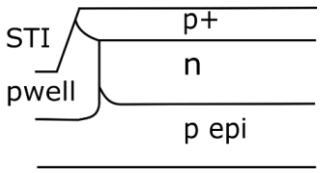


Figure 2.2-1- Cross section of the PPD structure [10].

2.3.The 4T Active Pixel Sensor Architecture

A modern CMOS image sensor uses a 4T active pixel sensor system architecture for photo sensing and readout. Earlier, CMOS image sensors used to have just a photodiode in the pixel for photo charge collection and then came the passive pixel sensor with a photodiode and a switch for row select in the pixel with a column amplifier. The main advantage of the PPS was a small pixel size but the slow column read out and large noise resulted in the design of an APS [11]. The APS consist of a photodiode, a switch and a pixel level amplifier which result in fast readout and low noise 4T pixel.

There are two common architectures for an active pixel sensor are the 3T and the 4T pixel, the difference seems to be of a single transistor but there is a significant difference in their performances. The difference will be discussed in the following section which describes the design and working principle of a 4T pixel. Figure 2.3-1 shows the schematic diagram of a 4T

pixel. It consists of a p+/n/p pinned photodiode, a transfer gate TG to transfer charges from the pinned photodiode to the floating diffusion node FD of capacitance C_{FD} to store charge from the photodiode. Also, a reset transistor to reset the FD node after every read out, a source follower which act as a buffer, an amplifier that isolate the sense node from the column bus capacitance and a row select switch. The difference between the 3T pixel and the 4T pixel is the transfer gate, which separates the pinned photodiode from the floating diffusion node or storage node. Hence, a 4T pixel enables signal buffering that allows performing the integrate while read operation: read out the signal of the previous frame while integrating the next frame, which will improve the read-out speed and SNR. Also, unlike a 3T pixel, the 4T pixel enables implementation of correlated double sampling CDS, which is a useful technique to eliminate reset noise and will be discussed during the 4T pixel operation. The other advantage of the transfer gate is that it prevents crosstalk between neighboring pixel which also mitigate blooming (overflow of charges to neighboring pixel when the pixel saturates) [12].

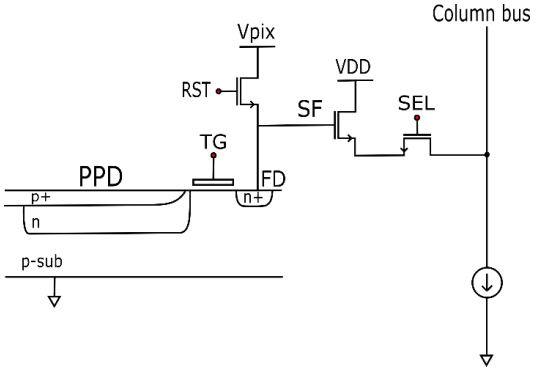


Figure 2.3-1- Schematic of a CMOS 4T APS with a PPD.

The operation and timing of 4T APS are shown in Figure 2.3-2. The Figure 2.3-2 shows that how the potential (voltage) of all the components of 4T pixel changes during the pixel operation and also the timing diagram of the different signals applied to obtain the CDS signal. The first step starts with an integration period during which the photodiode generates the free charge carriers according to incident photons and at the same time the FD node is reset so that new read out is not influenced by any charges from the previous read out, which also set the reset level. Now the transfer gate is turned ON and all the charges accumulated in the photodiode are transferred to the floating diffusion node and then the source follower buffers this charges and converts them into voltage signal which is then sampled via row select switch [13] [14] [15] [16].

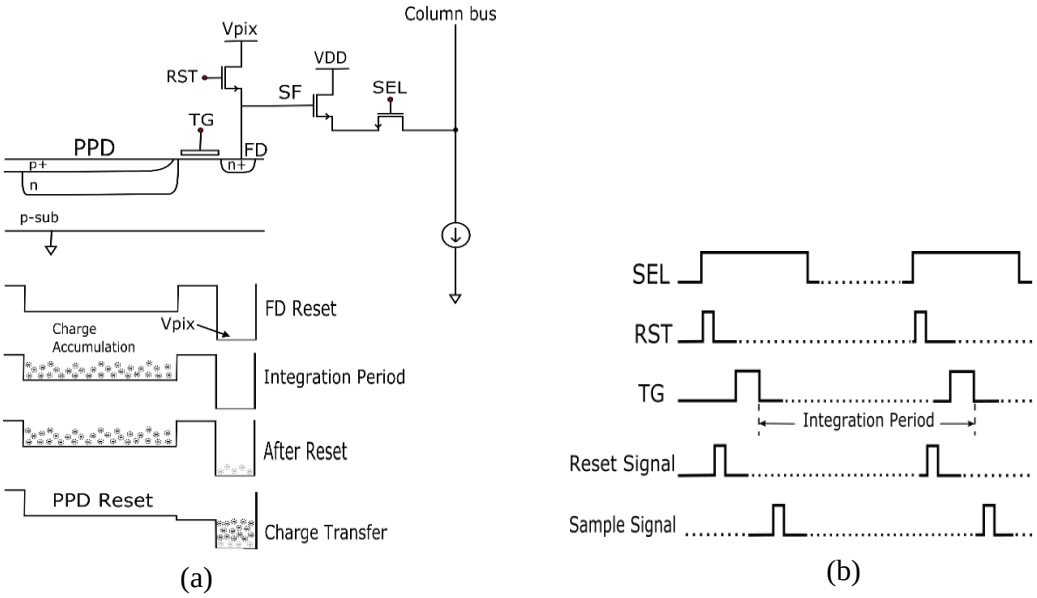


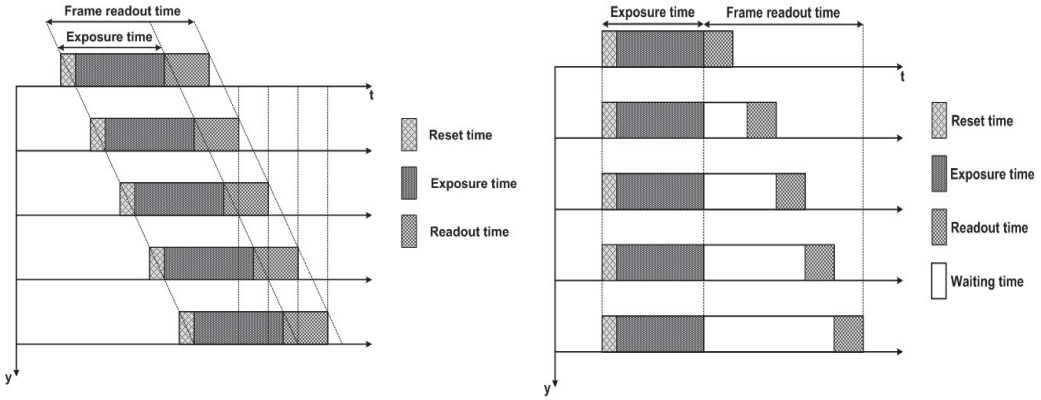
Figure 2.3-2- (a) Operation of a 4T APS with potential diagram, (b) Timing diagram of signals.

There are certain sampling techniques used during the read out of the signal to improve the performance of the image sensor. In a CDS technique the pixel is read out twice, once for the reset signal and once for the sample signal and the difference between the two values is the signal value. This technique has quite some advantages in the performance of a CMOS image sensor, not only it eliminates reset/kTC noise and the offset but also suppress 1/f noise (only for low frequency, that is correlated) [17]. The timing diagram in Figure 2.3-2-(b) shows the CDS readout technique in which the reset signal is read out and then after the transfer of the charges the sample signal is readout. The other sampling technique is correlated multiple sampling; in which both reset and signal levels of pixel outputs are sampled for multiple times and summed up, and the difference of the average of the two levels is taken as the signal value [18].

2.3.1.Electronic shutter modes

CMOS image sensor can operate in two types of electronic shutter modes namely global shutter mode and rolling shutter mode. In rolling shutter mode pixels are addressed row by row i.e. pixels of one row are exposed/reset simultaneously and then the next row and so on. This mode of operation causes motion artifact in images, like moving blades of a fan or a helicopter, this problem can be solved in global shutter mode. In global shutter mode, all the pixels of the imager are exposed/reset at the same time and the charge from each row is stored and later all the charges are read out row by row.

Figure 2.3-3 shows the timing diagram of the pixel operation for both the modes of operation. In Figure 2.3-3 (a) shows timing sequence of the rolling shutter mode, the pixels of different rows in a pixel array are exposed and readout one after the other resulting in total frame readout time equal to the time between starting of the exposure of the first row to end of the readout time of the last row. In contrary to rolling shutter mode the Figure 2.3-3 (b) shows the timing sequence of the global shutter mode, all the rows in a pixel array are exposed simultaneously and read out one after the other to construct an image [19].



(a) (b)

Figure 2.3-3- Working principle of (a) Rolling shutter mode and (b) Global shutter mode [19].

There can be many variations in the pixel architecture depending on the requirement and specification, with the current technology it is possible to design a digital pixel sensor which includes a pixel level ADC. There are various trade-offs between fill factor, read out speed and size of the pixel that leads to the choice of pixel architecture.

3. Chapter 3

LED Light Source

Light emitting diodes (LEDs) offer a number of advantages over conventional light sources, including reduced power consumption, better spectral purity, longer lifetime and lower cost. With the rapid development of the LED industry during the past decades, LEDs have become popular in an increasing amount of applications and are considered as key replacements for conventional light sources.

The LED-array light sources are used for image sensor characterization; it is essential to know their specifications. The LED light source key characteristics are spatial uniformity, temporal and thermal stability and spectral response and this information will help while characterizing CMOS image sensors. Caeleste uses its in-house customized LED light source which consist of a 8×8 square matrix of LED's; the project started with characterizing the LED light source and the measurement results helped in designing an improved LED light source. It is very important to have a stable and uniform light source as it directly affects the measurement results of CMOS image sensors. This report presents a measurement procedure that was performed to characterize the LED light source and results of the measurements.

3.1. Stability

Light sources should emit a constant optical power with constant intensity. There should be no variation in light intensity with time and temperature i.e. the light source should have temporal and thermal stability. LED's take some time to get thermally stable; so it is important to know how much time an LED light source takes to get stable. Additionally, an LED light source should not have any hysteresis effect.

1. Measured the photocurrent by means of a reference Hamamatsu photodiode which can be converted into light intensity for 20 min with a step of 10 seconds at a distance of 20cm between the LED light source and photodiode. The intensity of the LED source can be set by its supply current.
2. The measured photocurrent (A) can be converted into light intensity (W/cm^2) by using a conversion factor for a specified light source wavelength available from a standard datasheet.
3. Simultaneously measured the temperature of the light source using pt-1000.

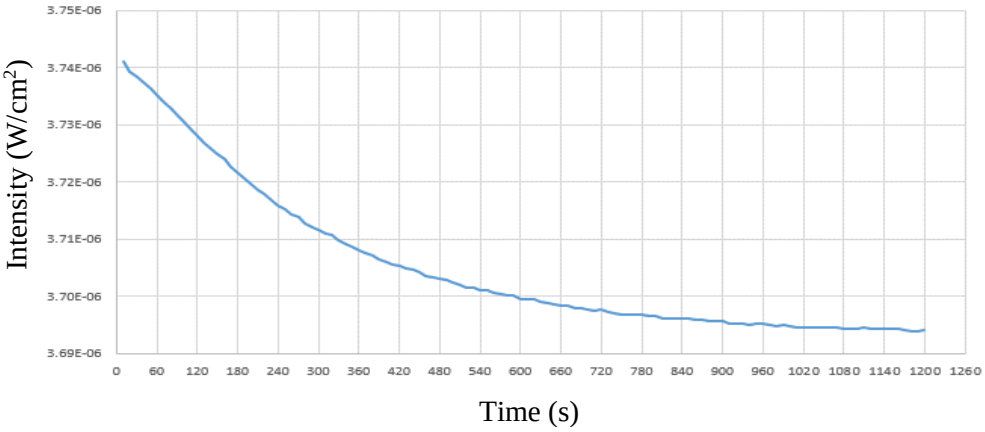


Figure 3.1-1- Intensity of an LED light source as a function of time.

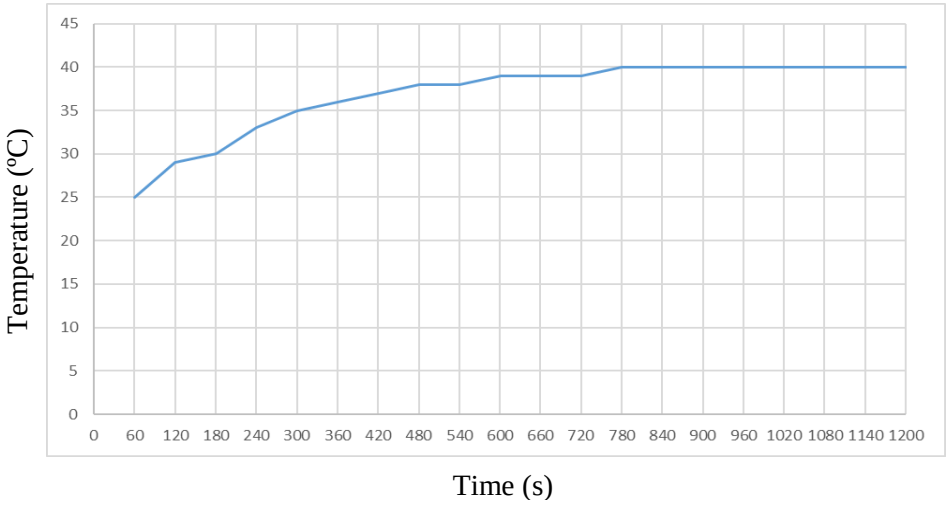


Figure 3.1-2- Temperature of the LED light source in function of time.

From the Figure 3.1-1 it can be concluded that the LED light source takes around 10 minutes to deliver constant intensity with intensity variation of 1nW/cm^2, which is in validation with temperature graph shown in Figure 3.1-2 which shows that the LED light source needs approximately 10 minutes to get thermally stable.

3.2.Spectral Response

The spectral response is defined by the spectral response of the LED's. Generally, LED's manufacturers provide this information. For the characteristic measurement of quantum efficiency, it is important to know the spectral response of the light source.

1. Replaced the lamp of the monochromator with the LED light source.
2. Measure the photocurrent by sweeping the wavelength of the monochromator with a step of 1nm.
3. This measurement was repeated for Red, Blue and Green light source.

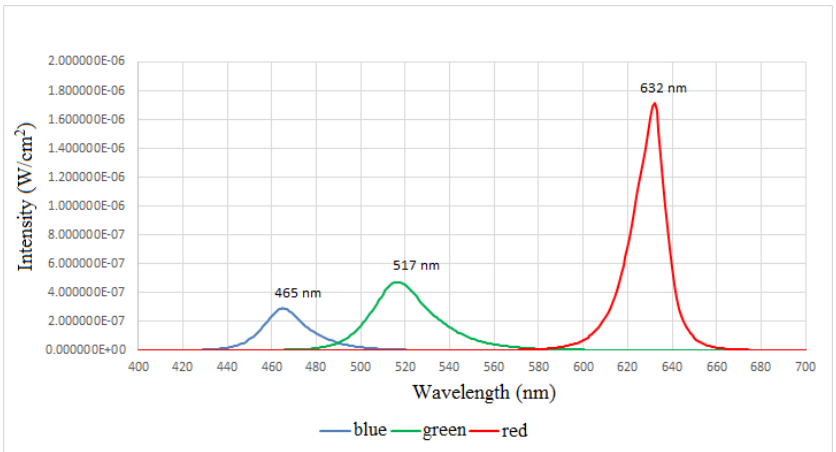


Figure 3.2-1- Spectral response of Blue, Green and Red LED light source.

Table 3.2-1- Spectral specification of LED light source.

LED Light Source	Peak Wavelength	Full Width Half Maximum
Red	632nm	16nm
Green	517nm	30nm
Blue	465nm	22nm

3.3.Spatial uniformity

The spatial uniformity is one of the most important characteristic of any light source. A LED light source should be spatially uniform i.e. equal level of intensity in space at equal distance from the source.

1. Measured spatial photocurrent by means of a reference Hamamatsu photodiode by scanning the LED light source using precision stepper motor, with a step size of 0.5mm.
2. A $2\times2cm^2$ 3D plot of spatial light intensity is generated for the light field.
3. The measurement was performed at different distances of 10cm, 20cm and 30cm between the light source and the photodiode.

The results of the abovementioned procedure are shown in Figure 3.3-1. The color graph shows the 3D view of the normalized light intensity emitted from the LED light source with maximum light intensity at the center and minimum light intensity at the corners of the LED light source. Similarly, the black and white graph shows the 2D view of the intensity variation in gray. Also from the results, it seems that the LED light source gets more uniform as the distance from the light source to the photodiode is increased and for the 30cm distance, the variation is less than 1% for $2\times2cm^2$ area which is comparable to the size of the image sensors at Caeleste.

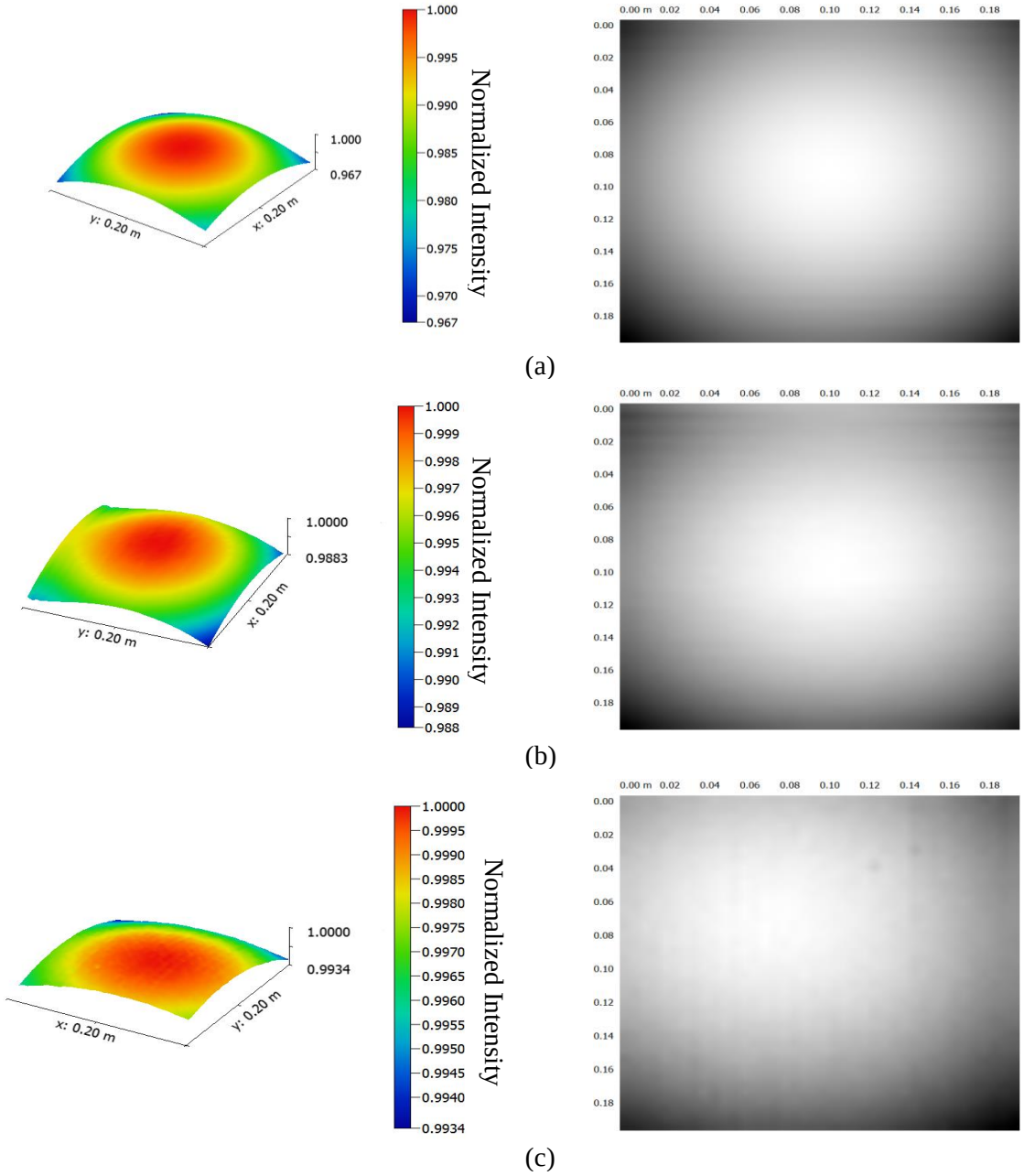


Figure 3.3-1-3D and 2D plot of Spatial intensity of the LED light source at (a) 10cm, (b) 20cm and (c) 30cm distance between monochromator output and photodiode.

3.4.Conclusions

These measurements were performed at an earlier stage and based on the results Caeleste designed an improved light source with optical feedback and proportional-integrative-derivative controller, yielding much better accuracy and stability.

4. Chapter 4

Characteristic Parameter of CMOS Image Sensor

This chapter introduces all the characteristic parameters of a CMOS image sensor and provides a brief introduction on crucial parameters that are used to evaluate the performance of a CMOS image sensor. The purpose of the thesis is standardizing measurement procedures for these characteristics parameters, so it is important to understand these parameters and also their relation with the pixel design. Although some of them are mainly limited by the readout circuitries, the vast majority of them are either determined by or already limited by the pixel design, i.e. the quantum efficiency, dynamic range, saturation level, signal-to noise ratio, dark current, image lag, non-uniformity and non-linearity of the photon response. This section gives detailed explanations of these important performance characteristics.

4.1. Quantum Efficiency and Spectral Response

4.1.1. Definition

Quantum efficiency (QE) is one of the most important characteristics of any electro-optical device including the CMOS image sensor. QE is the ratio of the average number of electrons generated (μ_e) in the pixel contributing to the output signal to the average number of impinging photons (μ_p) on the pixel during the exposure time. The Figure 4.1-1 shows electron-hole pair generation in a p-n junction due to incident photons with a certain wavelength and energy.

$$\mathrm{QE}(\lambda) = \frac{\mu_e}{\mu_p} \qquad (4.1\text{-}1)$$

When a photon is absorbed by the PPD, it generates free carriers (electrons-holes) and these free carriers contribute to the conductivity of the material and the phenomena is known as photoelectric effect. In general, PPDs have two modes of operation: Photovoltaic mode, where the electron-hole pair is converted to electron current by the built-in electric field and photo resistive mode where the free carrier(s) increase the overall conductivity of the material and QE quantifies the relation between photons absorbed and free carriers generated that contribute to output signal.

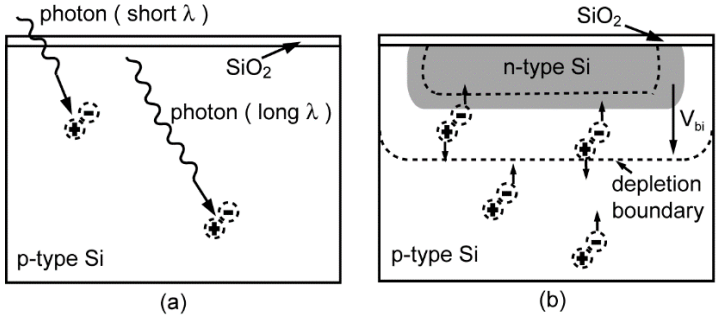


Figure 4.1-1-(a) Electron-hole generations by photons with different wavelength, (b) Photon-generated carriers by a p-n junction/photodiode.

In the field of CMOS image sensors, one typically considers the total quantum efficiency including fill factor i.e. QE that is referred to the total area occupied by an image sensor single pixel (not only the light sensitive area). QE is expressed in units of percent or simply a value from zero to one.

Ideally for an image sensor QE should be as high as 100 percent i.e. 1 electron-hole pair for every impinging photon, but in reality, the photoelectric phenomena in a PPD is not perfect there are some limitations associated with it. The first limitation is the loss of impinging photons which can be due to various optical phenomena like photons reflection at the sensor's surface or photons absorption by the layers above the depletion region and hence the impinging photons do not reach the photosensitive area of the pixel and thus QE of the system decreases. The second limitation is the inefficiency of the photodiode to collect all the electron-hole pairs generated by the impinging photons, this inefficiency is the result of free carrier's generation outside the depletion region of the PPD. As the absorption of impinging photons depends on the absorption coefficient of silicon which depends on its wavelength, so photons with longer wavelength will penetrate deep inside the PPD and the free carrier generated by these photons can be outside the depletion region and hence it will be difficult to collect those carriers' and this will result in lower QE.

Another important characteristic of an image sensor is called Spectral Response (SR) or Spectral Sensitivity and it determines how much photocurrent is generated by the image sensor per impinging photon of given energy and it is expressed in units of A/W. Both QE and the spectral response of a photodiode depend on the energy and the wavelength of the impinging photons hence the term spectral [20].

$$\mathrm{SR\ [A/W]} = \frac{\mathrm{QE \cdot \lambda \cdot q}}{\mathrm{hc}} \qquad (4.1\text{-}2)$$

Where,
λ: Wavelength of the impinging photon [nm]
q: electron charge = $1.602*10^{-19}$ [C]
h: Planck's constant = $6.626*10^{-34}$ [J·s]
c: speed of light= $2.99792*10^{10}$ [cm/s]

4.1.2.Measured value versus Theoretical value

Nearly every CMOS image sensor today is fabricated using silicon material, therefore the spectral properties of the image sensor are governed by silicon and the spectral response of the PPD is defined by the spectral response of silicon, hence QE and SR are fabrication process dependent. With the information of the absorption coefficient of silicon, thickness of the silicon and wavelength of the impinging photons, a designer can estimate the QE value of the image sensor at the designing stage. The QE should be measured including the fill factor (FF) and the designer knows how much light (photons) will reach the pixel depending on the pixel design, so while designing, the QE value can be estimated [21].

Also, there is a standard set of results available, based on various test and measurement performed for different pixels to evaluate QE and SR. So if the technology, fabrication material and thickness of the material are known, the QE of the image sensor can be estimated.

The other way to crosscheck the accuracy of the measurement results is to verify the results from the alternative method by computing QE from the CVF (Charge to voltage factor) data available for the image sensor. This method is described in the measurement procedure.

4.1.3.Fringing effect or Etaloning effect

In the measurement results; QE and SR can suffer from fringing effect as shown in Figure 4.1-2, this is due to the optical phenomena that occur within the different layers above the PPD.

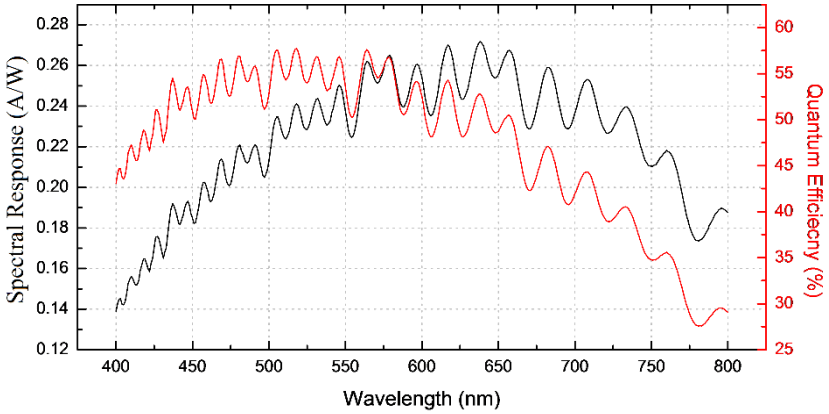


Figure 4.1-2- Fringing effect in QE and SR measurement result.

When a photon with a certain wavelength hits a PPD, it transverse through SiO_2 layers and part of the epitaxy layer before reaching the depletion region. Spectral fringing is a result of the interference patterns created by multiple reflections of the photons back and forth within these layers which are due to the difference in reflective and transmission ability of these layers and the layers behave as etalons; they don't allow 100% transfer of photons [22] [4.3]. The Figure 4.1-3 describes the principle of etalons for the light transmitting through two surfaces separated by air, similar phenomena occur when impinging photons transmit through different layers in the pixel [23].

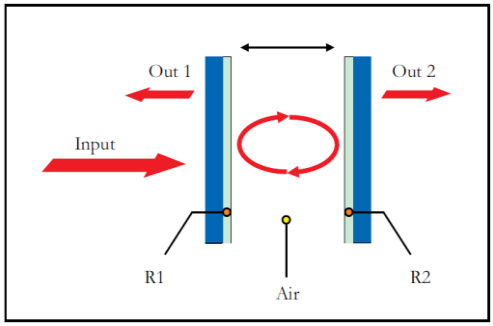


Figure 4.1-3- Principle of etalons [24].

4.2.Photo Response Curve

4.2.1.Definition

The photo response of an image sensor is the measure of the sensor's ability to convert optical incident power (number of impinging photons on the sensor for a given integration time) into an electrical signal (gain of the system multiplied by the number of electrons generated). It is a function of wavelength.

Photo response curve gives a good insight into many characteristic parameters of CMOS image sensor like CVF if the QE value is available, non-linearity, saturation voltage and full well capacity of the image sensor. Photo response is generally performed for a specific spectral wavelength (mostly at peak response wavelength).

4.2.2.Non-Linearity

Ideally, a CMOS image sensor should have a linear behaviour i.e. it should respond linearly to the incident light (photons) but due to nonlinear devices in the pixel and in the signal processing unit, the sensor deviates from a perfectly linear response. The major source of non-linearity in the image sensor comes from the source follower MOSFET in the 4T pixel design, as it is used as trans-impedance amplifier and its gain depends on the source resistance which induces the non-linearity [25]. Other transistors are just used as a switch and thus do not contribute much to the non-linearity of the image sensor. Other sources of non-linearity are [26]:

1. Image lag in the PPD.
2. The non-linearity of the photodiode or of the floating diffusion.
3. Non-linearity's in the further downstream analog processing and multiplexing.

The non-linearity can be classified into Integral non-linearity (INL) and differential non-linearity (DNL). INL is the measure of maximum deviation or error from the ideal response and DNL quantifies the deviation of two consecutive output values corresponding to ideal output values of the image sensor. In the case of an image sensor, only INL is calculated, as there are no DACs used in the imager for signal processing. So the photo response tells the response of the sensor for incident optical power and ideally it should be linear, and INL is evaluated from the actual response to the ideal response of the sensor [27].

$$\mathrm{INL}[\%] = \frac{\mathrm{E_{max}}}{\mathrm{FS}} \times 100 \qquad (4.2\text{-}1)$$

Where,
INL = Integral non-linearity,
E_{max} = maximum error from best-fit straight line [Volts/DN],
FS = full-scale value or maximum output of sensor [Volts/DN].

4.2.3.Full well capacity (FWC)

FWC defines/tells the charge generating/storing capacity of the pixel and the state when the pixel reaches its FWC is called as saturation. Image sensors absorb photons and generate free carriers (electrons-hole), depending on the way the PPD is designed. Usually, a PPD has a wide depletion region where all the free carriers are collected and the amount of charge that can be collected by PPD depletion region defines the FWC. The other way to define the FWC is the capacity of the floating diffusion to store charges and for a good pixel design both of this quantity should be equal. So according to the design, there is a limit to the number of free carriers that can be generated in a PPD and it should be equal to the amount of charge that can be stored on the floating diffusion.

The FWC can be computed by calculating the maximum amount of charge that can be stored in the floating diffusion capacitance during the charge integration process. The formula for FWC can be derived by considering a photodiode operating in charge integration mode as shown in Figure 4.2-1. V_{res} is the reset voltage of the photodiode, i_{ph} is the photocurrent, C_{PD} is the photodiode capacitance, and V_{PD} is the photodiode voltage [40].

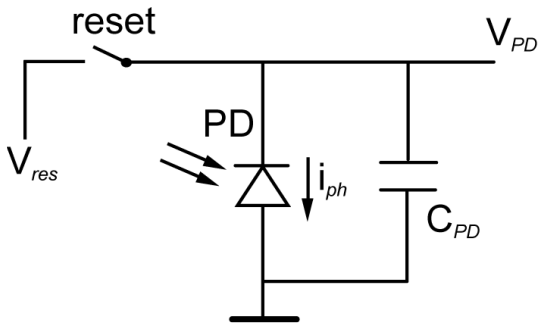


Figure 4.2-1- Simplified circuit of a photodiode operating in charge integration mode [40].

For the photodiode shown in Figure 2-3, its full-well capacity is given as:

$$\mathrm{FWC} = \frac{1}{q}\int_{V_{res}}^{V_{PD(min)}} C_{PD} \cdot V_{PD}\, dV \qquad (4.2\text{-}2)$$

Where, q is electron charge and $V_{PD(min)}$ is the minimum value of V_{PD}. The full well capacity is expressed in number of electrons.

The FWC can be determined by the photo response of the image sensor, but first it is important to define the full well capacity. For the measurements at Caeleste, FWC is defined w.r.t. the saturation level of the image sensor; so it is defined as the point of intersection of the best line fit and the line joining the 10% and 90% saturation level points on the image sensor photo response.

4.2.4.Saturation (V_{sat})

A pixel is said to be saturated when it reaches its FWC for incident optical power and the output of the sensor does not depend on illumination level anymore. It can be graphically computed from the photo transfer curve as the point after which the image sensor output becomes constant.

4.2.5.Charge to voltage factor (CVF)

Charge to voltage factor also known as conversion gain is the conversion factor that tells how much output voltage (V_{signal}) is corresponding to a particular number of electrons (μ_e) generated by the pixel. It is defined at the output of the image sensor. The conversion gain is one of the most important parameters of a CMOS imager pixel. The linearity and uniformity of the pixel response, light sensitivity, and the pixel noise are all influenced by its value and distribution.

$$\mathrm{CVF}\ [\mu V/e^{-}] = \frac{V_{signal}}{\mu_e} \qquad (4.2\text{-}3)$$

Where,
CVF: Charge to voltage factor/ Conversion gain,
V_{signal}: mean output signal from the sensor,
μ_e: number of photon-generated electron.

It can be calculated from the photo response curve; as the curve gives the relation between output voltage and incident optical power (i.e. the number of photons). The number of photons can be converted into number of electrons from the QE value of the pixel at that wavelength; which results in a relation between the output voltage and the electron (charge) i.e. the CVF. The CVF can be classified as internal and external conversion factor. Internal conversion factor

takes the path gain into the consideration which allows Caeleste to compare different pixel design, independent of the surrounding circuit and external CVF is the property of the chip, which is important for their customers.

An alternative method used for determining CVF is the mean-variance curve; it is based on the basic laws of physics. The method employs the fact that the photon shot noise (PSN) level is proportional to the square root of the signal level [28]. Hence CVF can be determined as the slope of the curve between Noise (Variance) and the mean signal.

4.3.Modulation Transfer Function

4.3.1.Definition

The MTF (modulation transfer function) is the image sensor's ability to transfer contrast at a particular spatial frequency. It is a direct measure of the sensor image quality and resolution. The ideal response of a pixel is an impulse of a certain width defined by the pixel pitch, but the pixel suffers from optical and electrical cross-talk i.e. pixel shares their information with the neighbour pixel which is shown in the Figure 4.3-1. Hence this result is more or less a Gaussian response rather than an impulse response. This optical and electrical cross-talk can be quantified by the MTF which is basically the FFT of the pixel response [29].

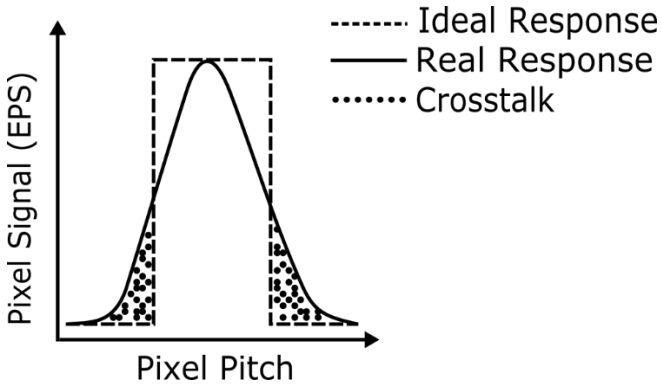


Figure 4.3-1- Optical cross talk in a single pixel.

To compute the frequency response, the pixel can be exposed to alternating black/white lines pattern with a line thickness equal to pixel pitch. The special situation where the black/white spatial line frequency corresponds exactly to 2 times pixel pitches is called the "Nyquist frequency" (f_N). The MTF at Nyquist frequency is often used as a crosstalk measure [30].

4.3.2.Sources of cross talk

1. Lateral diffusion of the photons when incident light (photons) bounces around inside the chip.
2. Optical crosstalk due to different optical phenomena like diffraction, refraction, scattering, interference and reflection of light (photons).
3. Electrical crosstalk results from photo-generated carriers having the possibility to move to neighboring charge accumulation sites (pixels).
4. Other physical limitation like the limit of the main (cameras) lens or angle of incidence of incident light also contribute to crosstalk.

4.3.3.Slanted Edge method

There are several methods to measure the MTF of the image sensor like the sine target method, knife edge method but this method suffers from drawbacks of long computation time and also needs a large number of images respectively. But the slanted edge method is fast and requires just 1 image to compute the MTF. The method is based on ISO 12233 standard; consists of imaging an edge onto the detector, slightly tilted with regard to the rows (or the columns). So a vertically oriented edge allows obtaining the horizontal Spatial Frequency Response (SFR) of the sensor. In that case, the response of each line gives a different edge spread function (ESF) due to different phases and the ESF data is used to compute the MTF [29].

4.3.4.Correct Image and Lens Setting

Images that are captured suffer from non-uniformities and offset. So to measure the MTF accurately, captured images need to be corrected first and to remove this artifact flat-field correction is applied.

$$C = \frac{(\text{Edge}-\text{Dark})\cdot m}{(\text{Light}-\text{Dark})} \tag{4.3-1}$$

Where,
C: Corrected image
Edge: Raw image of target edge.
Dark: Dark frame.
Light: Flat-field light image.
m: Average value of (Light-Dark)

It is also important that the slanted edge is located at the center of the image and the center of the lens; the image contrast and resolution are typically optimal at the center of the image, and due to the imperfect lens; deteriorate toward the edges of the field-of-view. Another important point to consider is that while capturing images using a lens, a defocus reduces the sharpness and contrast of the image and thus degrades the MTF. Hence, it is very important to have a well-focused image. Basically, any optical aberration degrades MTF of the system [31] [32].

4.4.Noise and Non-uniformity

4.4.1.Definition

Every integrated circuit suffers from noise and so do CMOS image sensor. Image sensors convert light information into an electrical signal and while processing the information, a CMOS image sensor suffers from two types of noise; temporal noise and spatial noise. Noise is any fluctuation in signal value and the noise waveform can be conventionally modelled as a random process. Mathematically, the noise power can be estimated by computing the variance of the signal. Hence, by computing the variance of the fluctuation in signal gives the mean signal and thus mean number of electrons [33]. The current state-of-the-art CMOS image sensors can achieve noise level as low as of $1e^-_{rms}$.

Before measuring the noise, it is important to know what type of noise comes from which part of the sensor. Below in Figure 4.4-1 a CMOS image sensor based on a standard 4T pixel architecture is shown and it describes what kind of noise originates from which specific part of the pixel. This Figure 4.4-1 only indicates the major source of the noise: reset noise, dark current, flicker noise (1/f noise), photo response non-uniformity (PRNU) and dark signal non-

uniformity (DSNU), there are other noise components as well which contribute to the total noise of the system.

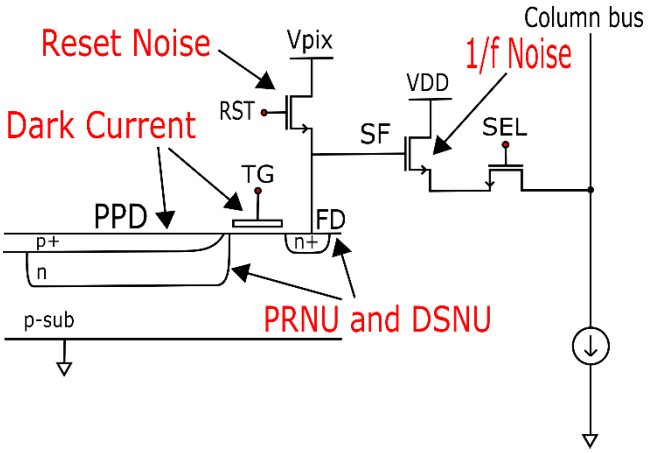


Figure 4.4-1- Major Noise sources in a 4T pixel PPD.

4.4.2.Temporal Noise

Temporal noise is the variation in pixel response for a constant illumination over a period of time. It can be evaluated by computing the standard deviation of the pixel response for every pixel through a number of frames taken over a period of time for a specific illumination. Temporal noise consists of the following noise components:

1. Johnson noise of all resistive components (Thermal noise).
2. 1/f noise of the MOS transistors (mainly from the source-follower in CMOS pixels).
3. kTC noise (if not cancelled by CDS).
4. Quantization noise of the ADC.
5. EMI and other interference.
6. Timing jitter.
7. Any other noise contribution from the extra electronics on-chip or off-chip.

To estimate the noise in the image sensor, it is important to model the noise mathematically. The most often used random variable in noise analysis is the Gaussian random variable. It is used to describe the magnitude distribution of a large variety of noise sources including; thermal noise, shot noise and 1/f noise. If the noise signal is a Gaussian random variable, then the white noise process is a white Gaussian noise (WGN). Two of the most important noise processes in integrated circuits, thermal and shot noise, are modelled as WGN processes [33].

4.4.2.1.Photon shot noise

The photon shot noise is due the statistical variation on generated/excited electron-hole pairs due to random arrival of impinging photons under illumination and it obeys a Poisson statistic. Therefore, the magnitude of the photon shot noise (η_{photon}) equals to the square root of the photon-generated electron (μ_e) [28]:

$$\eta_{photon} = \sqrt{\mu_e} \tag{4.4-1}$$

It is possible to compute the conversion gain/CVF from equation 4.2-3 and 4.4-1 -

$$CVF = \frac{V_{signal} \cdot A}{\eta^2_{photon}} \tag{4.4-2}$$

Where, A is the voltage gain of the signal processing unit.
Photon shot noise is the most fundamental noise of any photonic system as it comes from the basic laws of physics and not from the image sensor design. Its square root dependency on illumination level is utilized to characterize the image sensor. Hence, the conversion gain derived from this relation is very accurate.

4.4.2.2.Dark current shot noise

The dark current shot noise is a result of thermally random generation of electrons-hole pairs in dark i.e. the dark current and it depends exponentially on temperature. As it also follows Poisson statistics dark current shot noise (η_{dc}) is given as:

$$\eta_{dc} = \sqrt{\mu_{dark}} \tag{4.4-3}$$

Where, μ_{dark} is the number of electrons generated in dark.

4.4.2.3.Read Noise

The read noise is the inherent noise of an image sensor due to temporal variation in the pixel value over period of time and it is associated with the signal processing electronics. It is the result of various noise sources like- kTC noise, ADC noise and temporal row noise. It is measured for a very short integration time (t_{int}) to avoid DSNU and is measured in dark to keep photon shot noise minimum. The read noise is measured on a temperature stable system. It is calculated by computing variance for each pixel over the series of frames taken in the dark for same integration time and then taking the average of all the pixel's variance to get the noise over an image.

4.4.2.4. Reset Noise

It is the thermal noise of the reset switch sampled over a capacitor and is also known as "kTC noise". It is the noise sampled on the floating diffusion capacitor C_{fd} due to charge redistribution and uncertainty of the charge on the capacitor when the reset switch is turned ON/OFF. A reset transistor and a capacitor can be modelled as a resistor in series with a switch and a capacitor as shown in Figure 4.4-2 [34]. But in a modern CMOS image sensor using a CDS technique, the reset noise is cancelled out. Mathematically, the reset noise is given as:

$$V_{res} = \sqrt{\frac{kT}{C_{fd}}} \tag{4.4-4}$$

Where,
V_{res}: Reset noise voltage.
k: Boltzmann constant.
T: Absolute temperature.
C_{fd}: Floating diffusion capacitance.

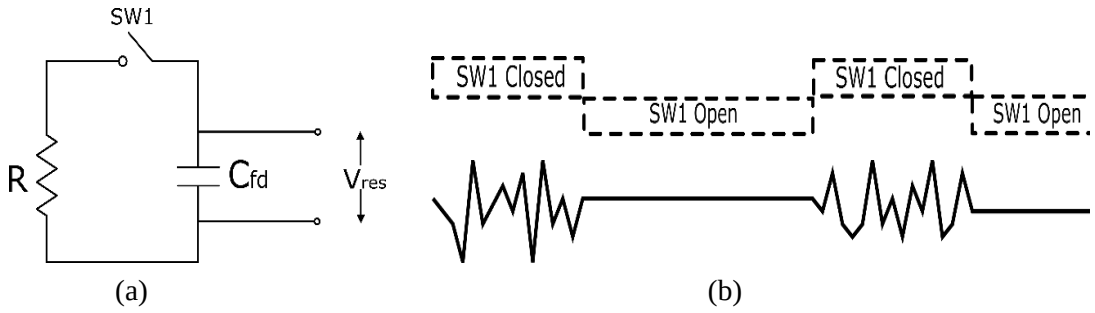


Figure 4.4-2- (a) nMOS transistor modelled as switch and a resistor in series with the floating diffusion capacitor, (b) KTC noise sampled when switch is opened and closed.

4.4.2.5.1/f Noise

1/f noise also known as flicker noise is the noise power density which is inversely proportional to the frequency. 1/f noise depends on the CMOS technology used and with the downscaling of transistors, it is becoming the dominant source of read noise. The main sources of 1/f noise in CMOS image sensor are the MOS transistors. It is a result of random fluctuations in charge carrier density due to the random capture and emission of carriers by traps in the gate oxide and also due to fluctuations in the mobility of the carriers. These two effects are correlated and are considered together during noise the modelling [35]. There are different models to quantify 1/f noise of which the K.K Hung model [36] is most commonly used.

4.4.3.Spatial noise

Spatial noise is the variation of pixel response within a frame i.e. pixel to pixel variations which are steady over time. These are statistical variations in “offset” and “gain” of the pixel over a frame and are fixed at a constant illumination therefore referred as fixed pattern and hence fixed pattern noise (FPN). Spatial noise can be evaluated by computing the coefficient of variation across a frame. The good thing about spatial noise is that it can be calibrated.

4.4.3.1. Dark fixed pattern noise

Dark fixed pattern noise is the FPN noise in dark and is often considered to be as an offset because the variations are fixed for a given pixel at a fixed integration time. FPN in the dark is the result of a mismatch of pixel-level transistors and mismatch of column-level transistors of the image sensor and also due to variations in dark currents of the different pixels of the image sensor. Generally, FPN due to the mismatch in transistors is cancelled during correlated double sampling (CDS) performed while reading out pixel signal. FPN in dark due to dark current signal is often referred as dark current non-uniformity (DCNU) which represents the variations in the dark current signal of pixels in a pixel array. Dark FPN is normally evaluated by so-called dark signal non-uniformity (DSNU), which represents the distribution of the dark voltage output of each individual pixel of the whole array. Since the extracted DSNU is normalized with respect to the dark current, it is independent of the exposure time.

4.4.3.2.Photo response non-uniformity

Photo response non uniformity (PRNU) also called as “gain” noise is the result of variations in photo-responsivity of a pixel in an array and it is proportional to the illumination. There are several components of PRNU, primarily it is due to imperfection in the photodiodes during the fabrication process. The imperfection in the fabrication process can result in a different value of diode junction capacitance, which results in variations in depletion width and hence

variations in pixel's photo response. Also, mask misalignment results in the different size of photodiodes which result in variation in active regions of the pixels in an array [25]. The other variations that can result in PRNU are photodiode capacitance variation, photodiode collection volume variations, variation in device gain, variation in conversion gain and floating diffusion capacitance variations.

It is important to understand that while measuring PRNU, FPN in the dark is also included. FPN in dark due to transistor mismatch is supposed to be cancelled during CDS and to eliminate FPN due to dark current, either FPN in dark needs to be subtracted or the PRNU measurement should be performed by keeping a minimum integration time to make the DCNU negligible.

4.5.Dark current

4.5.1.Definition

The dark current is the small leakage current that flows in a photosensitive device even when no photons are incident and in CMOS image sensor it is due to random generation of electrons and holes in PPD. The dark current is a result of many different semiconductor physical phenomena that occur in the PPD, these phenomena will be discussed further in this section. But the dark current is not just restricted to PPD, FD and TG also contribute to the total dark current of the pixel. The dark current itself does not create a problem for image sensor as it can be calibrated by performing "dark frame subtraction" from the signal frame but it is temporal variability of the dark current that introduces noise into the system. In high-speed cameras, the dark current is negligible because of the very short integration time and then read noise dominates.

4.5.2.Mechanism

Dark current is the pixel response under no illumination. Its generation depends on the fabrication technology and the design of the CMOS imager. Major factors influencing dark current are silicon defect density, the electric field of the photo-sensing element, and the operation temperature. There are several components of dark current which are the result of different physical mechanisms. The following section will discuss all the mechanism briefly.

4.5.2.1.Generation center

Generation center is a physical location which is responsible for the random generation of electrons and holes that result in dark current. These generation centers are the result of impurities, dislocation faults, vacancies, mechanical stress, lattice mismatch, interface states etc., which are the side effects (by-products) of the fabrication process. The physical size of a generation center is in the order of 1-2 inter-atomic distances.

4.5.2.2.Thermal generation

Thermal generation and recombination is a common phenomenon in any opto-electrical device. In the absence of photons (light), the thermal generation-recombination of carriers is a result of impurities and defects in the crystal. In silicon trap assisted generation-recombination (GR) is a dominant phenomenon compared to other generation-recombination mechanisms. Due to impurities and defects in the crystal, some electrons have an energy above Fermi level which results in an indirect transition of an electron in the conduction band and thus it will contribute to the dark current. The electrons in transition between bands pass through a state created in the middle of the band gap by an impurity in the lattice. The localized state can absorb differences in momentum between the carriers, and so this process is the dominant generation

and recombination process in silicon and in other indirect bandgap materials [37]. Also, the PPD is reverse-biased, therefore the minority carrier concentration is lower than the equilibrium concentration hence generation process is dominant over recombination process to re-establish the equilibrium. This complete process can be characterized by the Shockley–Read–Hall (SRH) process; hence the rate of electron-hole pair generation inside the depletion region is given as [38]:

$$G = \left[\frac{\sigma_p \sigma_n \upsilon_{th} N_t}{\sigma_n \exp\left(\frac{E_t - E_i}{kT}\right) + \sigma_p \exp\left(\frac{E_i - E_t}{kT}\right)}\right] \quad (4.5\text{-}1)$$

Where,
σ_n: electron capture cross section,
σ_p: hole capture cross section,
υ_{th}: thermal velocity of either electrons or holes (assuming they are equal),
N_t: density of the generation centers (silicon defects),
E_t: defect energy level,
E_i: intrinsic energy level,
k: Boltzmann's constant and
T: absolute temperature.
The dark current caused by thermal generation in the depletion region is:

$$J_{gen} = \int_0^W q\, G\, dx \approx qGW = \frac{q n_i W}{\tau_g} \quad (4.5\text{-}2)$$

Where,
W: Depletion width,
q: electronic charge,
n_i: intrinsic concentration, and
τ_g: generation life time.
As shown in Eq. (4.5-2), the dark thermal generation current is proportional to the intrinsic concentration n_i. The temperature dependence of n_i is given by [3.3]:

$$n_i = \sqrt{N_c N_V} \exp\left(-\frac{E_g}{2kT}\right) \quad (4.5\text{-}3)$$

Where, N_c and N_v are the carrier densities and E_g is the energy bandgap. By combining both Eq. (4.5-2) and Eq. (4.5-3), it can be concluded that the temperature dependency of thermal generation current is proportional to the exponential value of a half silicon bandgap.

4.5.2.3.Surface generation

The phenomenon behind surface generation is same as of thermal generation, the only difference is the location of the traps, defects or impurities. Surface generation is a result of imperfection at the Si-SiO_2 interface of the PPD, hence the lattice structure becomes non-uniform at the interface which results in traps at the surface. There are different measures taken to reduce surface generation, a p+ implant is one of the techniques i.e. PPD is not completely depleted: a thin p+ layer is left at the interface, so if there is any surface generation the carriers will be absorbed in the thin p+ layer itself [39].

4.5.2.4.Tunneling

It is a common phenomenon that occurs in heavily doped p-n junctions which result in a thin depletion layer. During the tunneling process the valance band carriers "penetrate" through the bandgap into the conduction band instead of overcoming the barrier, see Figure 4.5-1. This

phenomenon may occur in a PPD under the high-electric field, carriers can tunnel through the p-substrate to n depletion region and contribute to the dark current of the pixel. As more doping results in more impurities and thus more dark current. The most straightforward way to reduce the dark current caused by tunneling is to reduce the electric field [37].

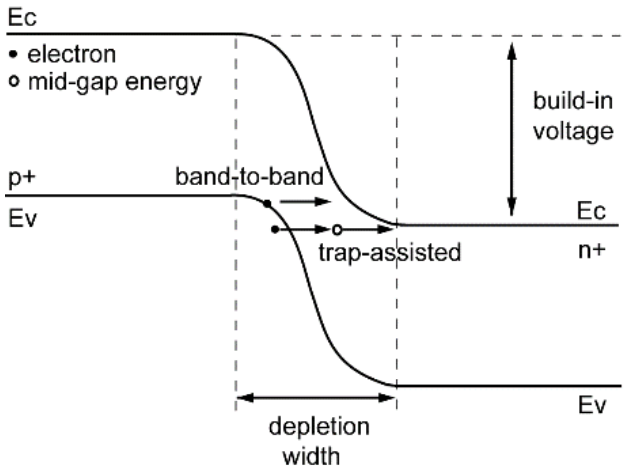


Figure 4.5-1- Energy band diagram of the tunnelling process of a heavily doped p-n junction [40].

Avalanche multiplication/impact ionization is a rare phenomenon and is most unlikely to occur in 4T pixel PPD as the bias applied to the pixel is not strong enough to initiate this phenomenon.

4.5.2.5.Diffusion current

The diffusion current is the current that is a result of the difference in concentration level in two regions in a p-n junction diode, so whenever one region is at higher potential than the other, then there is net movement of carriers from higher concentration to lower concentration and this movement of charge carrier's results in a current called diffusion current. Due to a heavy doping concentration in the n-layer, the dark current due to diffusion of holes is negligible. Hence the equation of the dark current due to the diffusion current of electrons can be given as [38]:

$$J_{diff} = \frac{qD_n n_{p0}}{L_n} = q\sqrt{\frac{D_n}{\tau_n}} \cdot \frac{n_i^2}{N_A} \qquad (4.5\text{-}4)$$

Where,
J_{diff}: Diffusion current due to electrons,
n_{p0}: electron concentration in boundary condition,
D_n: electron diffusion coefficient,
L_n: diffusion length,
τ_n: carrier lifetime,
n_i: intrinsic concentration.

From the temperature dependency of the intrinsic concentration n_i, the Eq. 4.5-4 shows the temperature dependency of the diffusion current on the exponential value of one silicon bandgap.

4.5.2.6.Dark current from fabrication process

The STI (Shallow Trench Isolation) is widely used in integrated circuits as a device isolation technique. STI is used to separate adjacent semiconductor device components in most MOS and bipolar technologies. STI overcomes the disadvantage of local oxidation of silicon (LOCOS) isolation technique with no “bird beak” encroachment. The key steps of the STI process involve etching a pattern of trenches in the silicon, depositing dielectric material (such as silicon dioxide) to fill the trenches and removing excess dielectric material using CMP (Chemical Mechanical Polishing) process. The key advantage of this technique is that it prevents electric current leakage between the adjacent devices which has a direct effect on the power dissipation in the integrated circuit.

Many CMOS image sensors use STI for preventing crosstalk between pixels due to diffusion of carriers: photo carriers generated in a substrate. The side effect of this technology is that the oxide layer of STI creates traps and these traps will result in undesired trapping and release of carriers that will result in dark current and 1/f noise. To solve this issue, a common approach is to extend the p+ pinning layer to cover the whole STI as shown in Figure 4.5-2. Thus, the STI interface traps can be filled. Also, it has been discovered that the total dark count depends very much on the distance between the side wall interface of the STI and the photodiode. To decrease the dark current, it is possible to increase the distance between the photodiode and the STI, but at the expense of lowering the pixel fill factor [40].

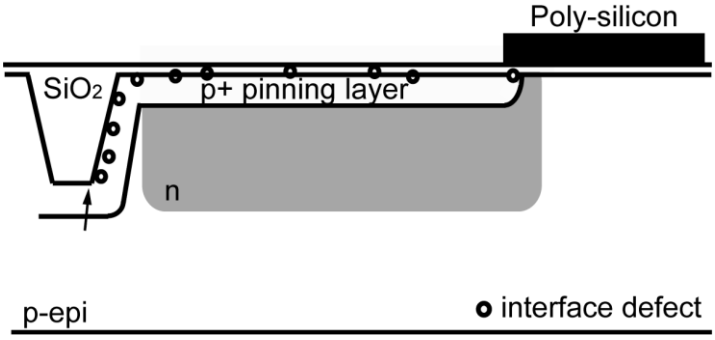


Figure 4.5-2- Cross section of a pinned 4T APS pixel with STI and interface defects [40].

4.6.Image Lag

4.6.1.Definition

Image lag is defined as a memory effect of the pixel due to the insufficient charge transfer to the floating diffusion from the PPD. Thus, the remaining charge end up in the next frame. In a 4T pixel, the complete transfer of signal charge from the PPD to the floating diffusion node is critical to the pixel performance in terms of noise and image lag. The potential profile under the transfer gate must be properly tailored to establish a proper barrier height between the photodiode and the floating diffusion node to achieve full charge transfer when the transfer gate is at a high voltage. The relative position and the geometry of the n-type diffusion layer of the PPD, combined with the shape and size of the transfer gate directly affect some key device characteristics such as noise, dark current, and image lag [41]. It is a trade-off between a large full well, low dark current and significant image lag for a 4T pixel designer.

4.6.2.Causes of Image Lag

1. Potential barrier between the PPD and the TG

The pinned photodiode can be modeled as a lumped RC network, hence there is a certain time constant (delay) for the charge to deplete through the diode or across the potential barrier. Now, if the pulse applied to transfer gate is smaller than the time constant (delay) then it will result in a residual charge in the photodiode and therefore the image lag in the sensor.
Or,
In a 4T pixel, this is due to the emptying time constant of charge that is limited by the potential barrier. Charge transfer from the pinned photodiode can mathematically correspond to the current through a MOSFET in sub-threshold or to the forward current through a diode. Hence it requires a certain time constant to overcome the barrier and this emptying time constant can then be directly translated into image lag.

2. Insufficient electric field
   If the applied electric field to transfer the charges is not enough then there will be residual charges in the pixel which will result in image lag.
3. Trapping effect in TG
   It is a common phenomenon in MOSFET, where charge carriers are being trapped at the transfer gate interface and these traps can capture free carriers and can release them anytime which results in Image lag.
4. Large signal level
   The large signal can also result in image lag as some electrons can fall back in the PPD if the applied potential to the TG is not enough w.r.t large amount of charge [26].

The image lag can be computed by grabbing a certain black frames followed by illuminated frames and vice versa by illuminating the sensor by a light pulse of the same duration as t_{int} and synchronized with begin/end of the t_{int}. The image lag is then estimated as an average signal level in the dark state expressed in percent of the signal level in the illuminated state.

$$\text{Lag}\,[\%] = \frac{\mu_{light} - \mu_{dark}}{\mu_{light}} \times 100 \qquad (4.6\text{-}1)$$

Where,
μ_{dark}: mean value of the first dark frame taken just after the light frame.
μ_{light}: mean value of the last light frame.

5. Chapter 5

Measurement Procedure Overview

It is important that the reasons for undertaking a measurement are clearly understood so that the measurement procedure can be properly planned. Good planning is vital in order to produce reliable data to time and to cost. The planning process should cover aspects such as the objectives of the measurement, background information, selection of the method, the required level of accuracy and confidence and finally reporting [42]. The following measurement procedures are planned for accurate, robust and fast measurements.

The following section includes measurement procedures for all the characteristic parameters of a CMOS image sensor. Measurements were performed on different samples and prototype sensors; different characteristics parameters are computed using different standard methods. The measurement procedures are friendlier with the Caeleste working environment, but can be used to characterize any CMOS image sensor in general with suitable hardware and software tools. The tests are performed with different sensor settings to get more accurate and precise results like for some measurements high gain mode is used and for some measurements low gain mode, some measurements are performed for the same integration time and constant light source intensity and some with changing integration time and changing light source intensity.

Measurement procedures include all the basic information about the characteristic parameter, image sensor specification and settings, measurement setup and environmental condition under which the measurement procedure is/should be performed. The procedures also suggest alternative methods to compute characteristic parameters and also to cross-check the measurement results. Measurement procedures include graphs and figures for some standard results that may or may not comply with actual results. The MTF measurement procedure is based on ISO 12233 test standard. Along with creating the measurement procedures, the software library and hardware equipment’s are also updated for fast and accurate measurements.

5.1.Quantum Efficiency and Spectral Response

5.1.1.Objective

Quantum efficiency (QE) is one of the most important characteristics of any electro-optical device including the CMOS image sensors. QE is the ratio of the average number of electrons generated (μ_e) in the pixel contributing to the output signal to the average number of impinging photons (μ_p) on the pixel during the exposure time. This document gives a brief introduction on quantum efficiency and spectral response, explains necessary measurement procedures and provides data analysis protocol.

5.1.2.Measurement Background

5.1.2.1.Method Description

In the field of image sensors, one typically considers the total quantum efficiency: QE that referred to the total area occupied by an image sensor single pixel (not only the light sensitive area). QE expressed in units of percent or simply a value from zero to one. Another important characteristic of a photodiode or image sensor is called spectral response and it determines how much photocurrent will be generated by the device under test (DUT) per impinging photon of a given energy. Therefore, it is expressed in units of A/W. Both, QE and spectral response of a photodiode depend on the wavelength of the impinging photons. By knowing QE one can derive the SR and vice versa. Depending on the project two situations can appear:

1. The image sensor design has a special QE test structure intended for QE and SR measurements only.
2. No specialized QE test structure is available within current image sensor project.

5.1.2.2.Specialized QE structure

A dedicated QE structure consists of a set of pixels (referred as QE or ‘real’ pixels) identical to those of the original sensor’s pixel array in terms of photodiode, transfer gate and metallization properties. The main advantage of the QE structure is that, it allows direct measurement of photocurrent instead of voltage. Additionally, the QE structure has a set of guard pixels that prevent charge leakage into the QE pixels from outside. The QE test structure is either a part of the image sensor die (hence, accessed via sensor’s dedicated bonding pads/pins) or designed as a separate die. Figure 5.1-1 shows a typical layout of a QE structure: three pads corresponding to substrate (SUB), QE pixels (diode) and the guard pixels and the pixel array consisting of real pixels surrounded by guard pixels. Figure 5.1-2 shows the electrical connection of the QE structure. Both, guard and real pixels are biased with an external power supply. An ampere meter is placed into the QE-pixel net for photocurrent measurements.

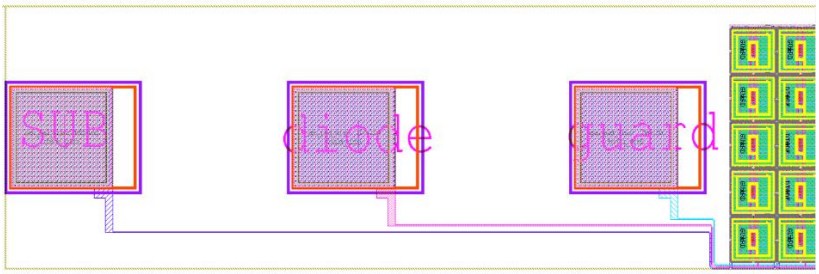


Figure 5.1-1-Layout of QE test structure (full pixel array is not shown).

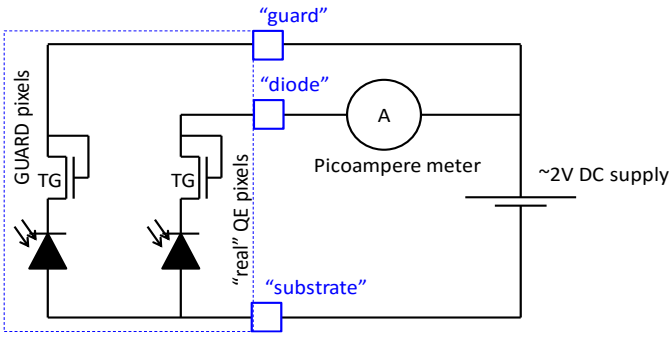


Figure 5.1-2-QE structure connection diagram.

5.1.3.Measurement Setup

5.1.3.1.List of Equipment

From the explanation in the previous section, it is clear that one needs a monochromatic light source, a calibrated light intensity radiometer and a high precision electrometer for photocurrent measurements. The setup should be mounted on a rigid optical bench or breadboard in a dark cabinet. Typical list of equipment employed for QE measurements:

1. DUT/QE structure.
2. Reference detector (Hamamatsu Si reference diode).
3. Power supply (CI-0033 TTi_QL355TP_Power_supply).
4. Electrometer (CI-0013 Keithley 6514 electrometer).
5. Monochromator (TMc300).

5.1.3.2.Block Diagram

The test setup for the QE measurements is shown in Figure 5.1-3. The setups assume the use of a monochromator for obtaining QE at various wavelengths, whose principle of operation is explained in detail in Figure 5.1-3. The light from a broadband light source enters the monochromator via its input slit and is then collimated onto a diffraction grating. The latter splits the continuous spectrum into separate wavelengths reflected at different angles. A focusing mirror collimates this light onto the output reflector, which together with the exit slit outputs the light of one particular wavelength. Light from the output of the monochromator is then projected onto the device under test. Both, the monochromator and the electrometer are computer-controlled. In case the measurement needs to be done only at one wavelength, a nearly monochromatic light source can be used such as LED whose emission spectrum is known. For this procedure, consider the use of a monochromator for obtaining QE and SR spectra in this document.

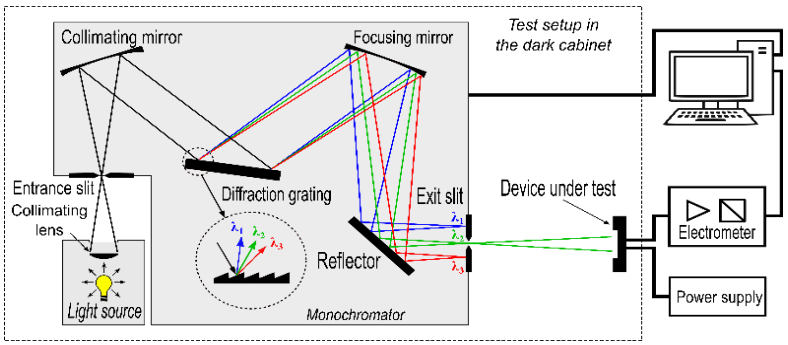


Figure 5.1-3- QE measurement setup schematic.

5.1.3.3.Software Tools

1. Iron Python-based Caeleste software environment.

5.1.4.Measurement Procedure

5.1.4.1.Algorithm

The principle behind the QE measurement is that first, measure the photocurrent of the reference-calibrated detector as a function of wavelength to determine the intensity (standard conversion table provided from photodiode manufacturer) of the light incident on the structure i.e. irradiance E (directly tells about the number of impinging photons on the DUT). Then measure the current of the DUT structure for the same illumination as a function of the wavelength to calculate the spectral response (which tells us about the number of electrons generated) and if the CVF is known then the output voltage of the DUT can be converted into a number of electrons at the output of DUT. Now calculate QE as the ratio of the number of electrons by the number of impinging photons.

5.1.4.2.Procedure

1. Use the Bentham Halogen light source with its dedicated stable current source and allow it to reach thermal equilibrium for at least 20 minutes after switching it ON. (Do not switch off the light source until you complete all the measurements.)
2. Select the appropriate slit width at the monochromator exit to get the desired bandwidth of light from Figure 5.1-4. (Refer Table for slit width vs bandwidth from monochromator user manual).

Grating Groove Density (l/mm)		2400	1200	600	400	300	150	100	75	50
Reciprocal Dispersion (nm/mm)		1.35	2.70	5.40	8.11	10.81	21.62	32.42	43.23	64.85
Slit widths (mm)	Part no. for pair of slits	Bandwidth produced (nm)								
0.05	FS (0.05)	0.07	0.14	0.27	0.41	0.54	1.08	1.62	2.16	3.24
0.1	FS (0.10)	0.14	0.27	0.54	0.81	1.08	2.16	3.24	4.32	6.48
0.2	FS (0.20)	0.27	0.54	1.08	1.62	2.16	4.32	6.48	8.65	12.97
0.37	FS (0.37)	0.50	1.00	2.00	3.00	4.00	8.00	12.00	16.00	23.99
0.4	FS (0.40)	0.54	1.08	2.16	3.24	4.32	8.65	12.97	17.29	25.94
0.5	FS (0.50)	0.68	1.35	2.70	4.05	5.40	10.81	16.21	21.62	32.42
0.56	FS (0.56)	0.76	1.51	3.03	4.54	6.05	12.10	18.16	24.21	36.31
0.74	FS (0.74)	1.00	2.00	4.00	6.00	8.00	16.00	23.99	31.99	47.99
1	FS (1.00)	1.35	2.70	5.40	8.11	10.81	21.62	32.42	43.23	64.85
1.12	FS (1.12)	1.51	3.03	6.05	9.08	12.10	24.21	36.31	48.42	72.63
1.48	FS (1.48)	2.00	4.00	8.00	12.00	16.00	31.99	47.99	63.98	95.97
1.85	FS (1.85)	2.50	5.00	10.00	15.00	19.99	39.99	59.98	79.98	119.97
2	FS (2.00)	2.70	5.40	10.81	16.21	21.62	43.23	64.85	86.46	129.69
2.78	FS (2.78)	3.76	7.51	15.02	22.53	30.05	60.09	90.14	120.18	180.27
3.7	FS (3.70)	5.00	10.00	19.99	29.99	39.99	79.98	119.97	159.96	239.93
4	FS (4.00)	5.40	10.81	21.62	32.42	43.23	86.46	129.69	172.92	259.39
5.56	FS (5.56)	7.51	15.02	30.05	45.07	60.09	120.18	180.27	240.36	360.55
8	FS (8.00)	10.81	21.62	43.23	64.85	86.46	172.92	259.39	345.85	518.77
10	-	13.51	27.02	54.04	81.06	108.08	216.16	324.23	432.31	648.47

Figure 5.1-4 - Slit width and bandwidth configuration [43].

5.1.4.2.1.Measurement from known CVF

1. Place the reference detector under illumination and measure the current at the wavelength of interest. Use the reference detector calibration data (in A/W) to calculate

the irradiance the E in [W/cm^2] from the detector output current [A]. This will result in the mean number of impinging photons (μ_p).

2. Record exactly the location of the reference detector (within a few mm in X, Y and Z) and place the DUT to be measured at the same location.
3. Now illuminate the DUT at the same wavelength, capture the image for known integration time (t_{int}), subtract the ambient light or dark image and measure the mean output signal [Volts] of the DUT. One can evaluate the mean number of electrons generated (μ_e) by using mean output signal and CVF.

Note: It is advisable to take the same ROI as the size of the reference detector to get an accurate result.

5.1.4.2.2.Measurement from a dedicated QE structure

1. Place the reference detector in the light beam and measure the intensity from the monochromator at every wavelength of interest. Use the reference detector calibration data (in A/W) to calculate the light intensity in [W/cm^2] from the detector output current [A] and subtract ambient light from the measurement.
2. Record exactly the location of the reference detector (within a few mm in X, Y and Z) and place the QE structure to be measured at the same location.
3. Perform a wavelength scan with exactly the same parameters (bandwidth, wavelengths etc.) to measure the spectral response and subtract the ambient light from the measurement.

Note: Step size of the scan should be lower than the FWHM of the light.

5.1.4.3.Replacing the reference detector with DUT at same location

1. One method to replace the device and place it at the exact same location is to use a Convex Lens and place it between the reference detector and the monochromator.
2. Adjust the position of the lens so that one should get a small spot of light (convex lens converges light at the focal point) focused at the middle of detector reference detector and now place the DUT and align it so that you get the same small beam of light on at middle DUT.

5.1.4.4.Pay attention

1. The F-number of the light towards the QE structure and the reference detector should be identical.
2. Both QE structure and reference detector should be perfectly homogenously illuminated.
3. The signal level of the sensor output should be well above the dark current for the accurate result.

5.1.4.5.Further recommendations

1. If no specific F-number is required the measurement is best done using a plain monochromator output (at F/4 diverging) in a dark cabinet, without any additional optics.
2. A direct or diffuse illumination will give different results for the QE structure; clearly report the method of illumination. The Bentham reference diode can be used for both.
3. Make sure that your connection cables are not twisted or rounded as at times communication freezes.

5.1.5.Accuracy of the method

The accuracy depends on the non-idealities and assumptions. Following factors may affect accuracy of the result:

1. Unstable light source.
2. Misalignments during replacing reference photodetector with the QE structure. In the Figure 5.1-5 you can see the deviation in measurement results when the setup was assembled and dismantles 4 times. Maximum difference in QE is around 2.68%.

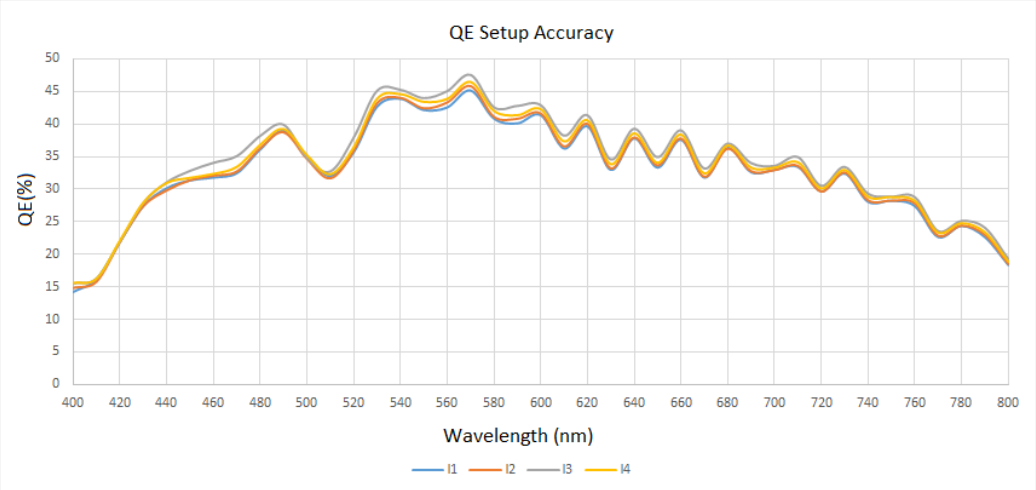


Figure 5.1-5 - QE setup accuracy diagram.

5.1.6.Alignments

Alignment is very important for this measurement. During measurement following points should be kept in mind:

1. The light source should be parallel to the DUT and the distance between them should be within light source uniformity and intensity range (Refer monochromator data sheet).
2. The QE structure and the reference detector should be placed exactly at the same position.

5.1.7.Data Processing

5.1.7.1.Calculating SR and QE

5.1.7.1.1.CVF method

The quantum efficiency (QE) is the ratio of the average number of electrons generated in the pixel (μ_e), to the average number of impinging photons on that pixel (μ_p) and is wavelength (λ) dependent:

$$QE(\lambda) = \frac{\mu_e}{\mu_p} \tag{5.1-1}$$

The mean number of photons μ_p incident over the pixel area A [cm^2] during the integration time t_{int} [s] can be computed from the known irradiance E [W/cm^2] with:

$$\mu_p = \frac{A \cdot t_{int} \cdot E}{hc/\lambda} \tag{5.1-2}$$

Where c and h are the speed of light and Planck's constant respectively.

In addition, the mean number of electrons is given by:-

$$\mu_e = V_{out}/CVF \quad (5.1\text{-}3)$$

The photo induced charge Q_{ph} is the number of electrons μ_e multiplied by the elementary charge q.

$$Q_{ph} = \mu_e . q \quad (5.1\text{-}4)$$

The spectral response (SR) expressed in units A/W is the ratio between the average photocurrent (I_{ph}) and the irradiance per pixel area (E*A):

$$SR = \frac{I_{ph}}{E \cdot A} = \frac{Q_{ph}/t_{int}}{E \cdot A} = \frac{q(V_{out}/CVF)}{t_{int} \cdot E \cdot A} \quad (5.1\text{-}5)$$

Where $I_{ph} = Q_{ph}/t_{int}$ is the pixel photocurrent expressed as a photoinduced charge collected during the integration time t_{int}.

Where,
λ: wavelength [nm]
q: electron charge = $1.602*10^{-19}$[C]
h: Planck's constant = $6.626*10^{-34}$ [Js]
c: speed of light= $2.99792*10^{10}$ [cm/s]

5.1.7.1.2.QE structure measurement method
The spectral response is ratio of the current generated and the power of incident light on the QE structure. Now determine SR by the following formula:

$$SR[A/W] = \frac{I_{ph}}{E \cdot A} \quad (5.1\text{-}6)$$

The quantum efficiency can be determined from the spectral response by replacing the power of the light at a particular wavelength with the photon flux for that wavelength. This give:

$$QE[\%] = \frac{SR \cdot hc}{\lambda \cdot q} \times 100 \quad (5.1\text{-}7)$$

Where,
I_{ph}: measured photocurrent through the "QE structure" [A]
A: Effective area of "QE structure" [cm^2]
P: Intensity of light, which is incident on the sensor [W/cm^2]

5.1.8.Graphs and Figures

Figure 5.1-6 shows a standard plot from one of the Caeleste's image sensors. Both QE and SR are plotted as a function of wavelength, where QE is expressed as a percentage (%), SR in (A/W) and the wavelength in (nm).

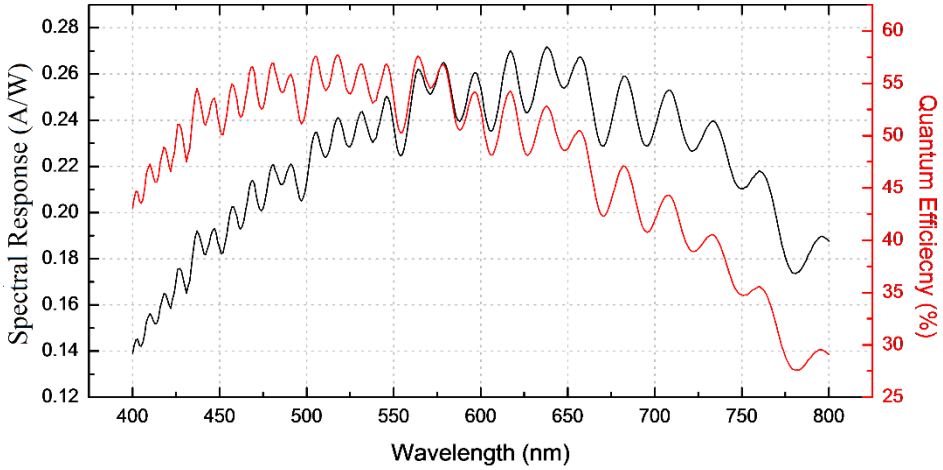


Figure 5.1-6 - Plot of QE and SR as a function of wavelength.

5.2.Photo Response

5.2.1.Objective

The photo response of an image sensor is the measure of the sensor ability to convert the optical incident power (number of photons hitting the sensor for a given integration time) into an electrical signal (gain of the system multiplied by the number of electrons generated). Photo response is a function of wavelength. The main result from this procedure is a photo response curve and the charge to voltage factor (CVF). Further from the curve, one can determine other parameters like saturation voltage, non-linearity and full well capacity.

5.2.2.Measurement Background

5.2.2.1.Method description

To determine the photo response two parameters are required, 1st the incident input optical power, which can be calculated using reference calibrated photodetector for a particular wavelength and 2nd the output electrical signal of the DUT, which is determined by measuring the output signal over a fixed integration time for different illumination levels of the sensor i.e. from saturation to dark. Hence at a given wavelength and for given input optical power one can evaluate the photo response.

5.2.3.Measurement Setup

5.2.3.1.Block Diagram

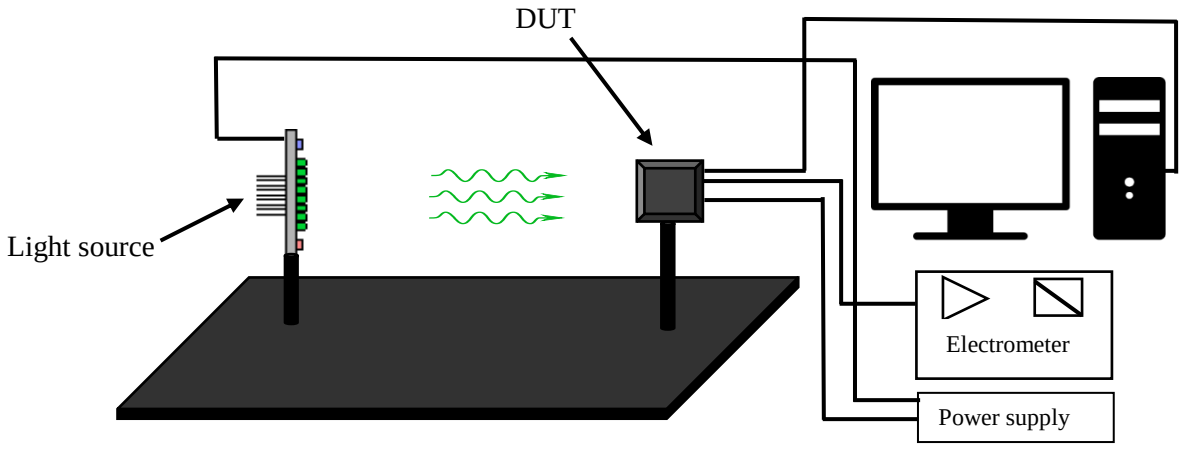


Figure 5.2-1- Setup diagram for PR and CVF measurement.

The block diagram in Figure 5.2-1 illustrates the setup for the measurement. The Camera Link and Frame Grabber are used to capture the images and the reference photodetector is used to measure the light intensity from the light source. The setup should be mounted on a rigid optical bench or breadboard in a dark cabinet. Typical list of equipment's employed for this measurement are:

5.2.3.2.List of Equipment

1. DUT.
2. Reference detector (CI-0046 Hamamatsu Si reference diode H1).
3. Mounting rails.
4. Camera link and frame grabber.
5. Power supply (CI-0033 TTi_QL355TP_Power_supply).

6. Electrometer (CI-0013 Keithley 6514 electrometer).
7. Caeleste's LED light source.
8. Connection cables.

5.2.3.3.Software Tools

1. Iron Python-based Caeleste's software environment.

5.2.4.Measurement Procedure

5.2.4.1.Algorithm

To calculate the optical input power of a light source, measure the current of the reference-calibrated detector to find the irradiance E (standard conversion table provided from photodiode manufacturer). Simultaneously measure the output electrical signal of the DUT i.e. the output of ADC for different illuminations levels (saturation to dark) to obtain the photo response curve. Measuring the DUT signal means: grab a sequence of at least 10 images and calculate the mean of all the images to obtain the final image.

5.2.4.2.Setup

1. Place the light source, DUT and reference detector at an appropriate position on the optical bench.
2. Switch on the light source at maximum power and allow 10 minutes to get it thermally stable.
3. Check that with the given placement, deep saturation of the DUT can be reached near the maximum light source power such that you can still take a couple of measurements after saturation to get the better result.
4. Record the position of the light source, DUT and the reference detector in X, Y and Z to within a few mm. Make sure the parts can be removed from the optical bench and positioned later in the same location.

5.2.4.3.Determine the correction factor for the reference detector

1. In case if you cannot replace the DUT and reference detector at the same location one can use 2nd reference detector to cancel the error caused due to misalignment.
2. Remove the DUT and place a 2nd reference detector at the DUT position.
3. Measure the light intensity at both detector locations and determine the scaling factor. Check that whether this factor is constant for different light intensities.
4. Remove the 2nd reference detector.

5.2.4.4.Procedure

1. Record the DUT identification and test conditions in the test report header template and place the DUT at its position.
2. Control the LED source current to obtain different steps (smaller the better) in illumination level from saturation to dark.
3. At each illumination step acquire a series of images (e.g. 10, 20) from the sensor and take the mean of the images [Volts] and simultaneously measure the irradiance E [W/cm^2] of illumination using reference detector, apply the displacement correction factor to the detector measurement value.
4. Also, capture an image in dark (μ_{dark}) for offset reference.
5. Plot the mean output signal (μ- μ_{dark}) [Volts or DN] versus the light intensity [W/cm^2] to obtain the photo response curve as shown in Figure 5.2-2.

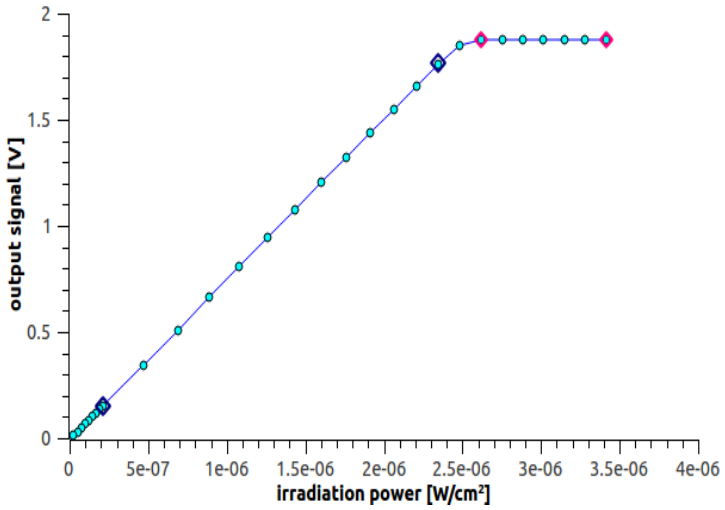


Figure 5.2-2- Photo response curve.

5.2.4.5.Further recommendations

1. Light source / illumination field non-flatness, non-uniformity: For large DUTs, it is advisable to use only a window of pixels to calculate the pixel average. This window must have about the same size as the reference detector and should be located at the X/Y position of the 2nd reference detector during the determination of the displacement correction factor.

5.2.5.Accuracy of the method

The measurement procedure accuracy depends on how accurately you measure the incident optical power and also the stability of the light source. Also, it is important to accurately process the images that are captured to remove any offset and non-uniformities, but this procedure is accurate to obtain the nonlinearity, V_{sat} and the full well capacity.

5.2.6.Data Processing

The characterization of the photo response curve gives us information about a number of useful parameters like full well capacity, CVF, linearity, saturation. One can evaluate all these parameters using the data collected by following the above-mentioned procedure.

5.2.6.1.Non Linearity

The non-linearity is the measure of the maximum deviation of the output signal from an ideal (best line fit) response of the sensor. The non-linearity is defined within a certain range of illumination intensity for e.g. 10% to 90% of the saturation level. In this case, the best fit line will be the straight line joining all output voltages between at 10% and 90% of the saturation value.

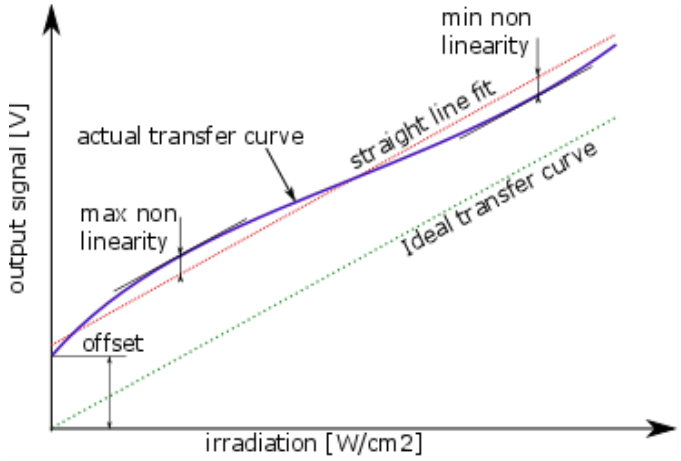


Figure 5.2-3- Non Linearity from Photo response curve.

$$\mathrm{INL}[\%] = \frac{E_{max}}{FS} \times 100 \qquad (5.2\text{-}1)$$

Where,
INL = Integral nonlinearity,
E_{max} = maximum error from best-fit straight line [Volts or DN],
FS = full-scale value or maximum output of sensor [Volts or DN].

Note that E_{max} is the maximum deviation in any direction. The full-scale value is the value of the highest measurement taken which is still within the linear performance range. Normally this is set to be as close to the actual full-scale capability of the A/D converter as it is practical during camera calibration.

5.2.6.2.Saturation (V_{sat})

It is the point in the photo response curve after which the output of the image sensor does not depend on illumination level anymore. The saturation point is shown in Figure 5.2-4.

5.2.6.3.Full well capacity

It is important how you define the full well capacity. Here full well capacity is referring to the saturation level of the sensor. Hence it is given as the point of the intersection of the line joining e 10% and 90% saturation level point and the best-fit line for V_{sat} on the photo response curve as shown in Figure 5.2-4 below.

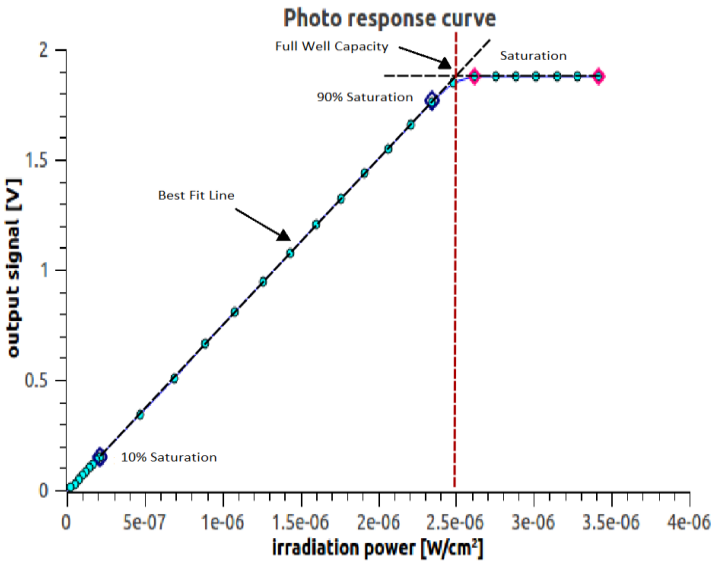


Figure 5.2-4- Photo response curve showing full well capacity.

5.2.6.4.Alternatively, from mean-variance method

The full well capacity is the point in the noise plot where the temporal noise curve as shown in Figure 5.2-5 reaches its maximum. This is because the image sensor is in saturation region hence the output signal does not depend on illumination level anymore and therefore the average noise of the image sensor goes down.

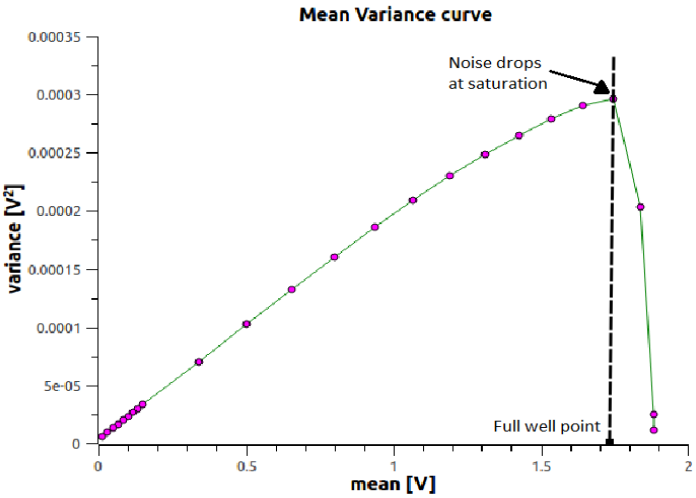


Figure 5.2-5- Full well from Mean-Variance curve.

Note: Full well capacity is not always determined by the floating diffusion, here the full well capacity is defined by considering that the saturation level of the ADC is greater than the saturation level of the sensor.

5.2.6.5.CVF

The charge to voltage conversion factor tells you the voltage equivalent of the number of electrons generated and vice versa. Depending on the data available there are two different methods to determine CVF:

5.2.6.5.1.First method- (photo response curve if quantum efficiency value is known)
Convert the irradiance into number of electrons generated by following calculations:

Firstly, the mean number of photons μ_p impinging on the pixel area A [cm^2] during the integration time t_{int} [s] can be computed from the known irradiance E [W/cm^2] as:

$$\mu_p = \frac{At_{int}E}{hc/\lambda} \tag{5.2-2}$$

Where, c and h are the speed of light and Planck's constant respectively and λ is the wavelength of incident light.
Now, the quantum efficiency (QE) is the ratio of the average number of electrons generated in the pixel (μ_e) to the average number of photons impinging on that pixel (μ_p) and therefore one can calculate number of electrons generated for known QE value:

$$\eta(\lambda) = \frac{\mu_e}{\mu_p} \tag{5.2-3}$$

Now you can plot V_{out} (mean output signal) versus μ_e (number of electrons) to get a CVF plot. And the 1st derivative (slope) of the curve will give the CVF [Volts/e^-].

Where,
λ: Wavelength [nm]
q: electron charge = $1.602*10^{-19}$[C]
h: Planck's constant = $6.626*10^{-34}$ [Js]
c: speed of light= $2.99792*10^{10}$ [cm/s]

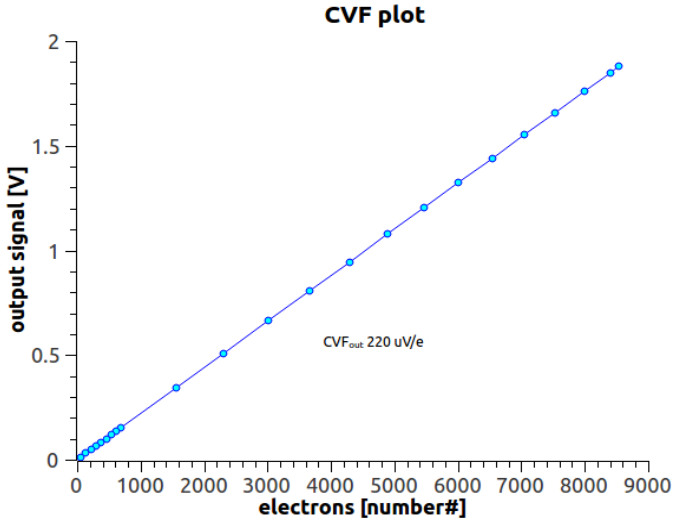


Figure 5.2-6- CVF from Photo response curve if the Quantum efficiency value is known.

5.2.6.5.2.Second method (Mean-Variance method or PTC curve method)
The mean-variance method employs the fact that the photon shot noise (PSN) level is proportional to the square root of the signal level, expressed in electrons. The Figure 5.2-7 shows the mean variance curve with the offset correction. Thus, by measuring the signal and its variance one can obtain the CVF. Take the following steps to evaluate CVF:

1. From the set of captured images, compute the signal variance (temporal noise) and the mean signal for each pixel over the series of images at a given illumination level

(however, watch out for non-linearity). The result is the average over all pixels of signal variance (σ^2) [Volts^2 or DN^2] and mean signal (μ) [Volts or DN] for that series and μ_{dark} serves as offset reference.

2. Plot (σ^2) and (μ - μ_{dark}) and in the range where (σ^2) has a square root behavior i.e. the linear region, the ratio between (σ^2) and mean (μ - μ_{dark}) is actually the CVF [Volts/e^-].

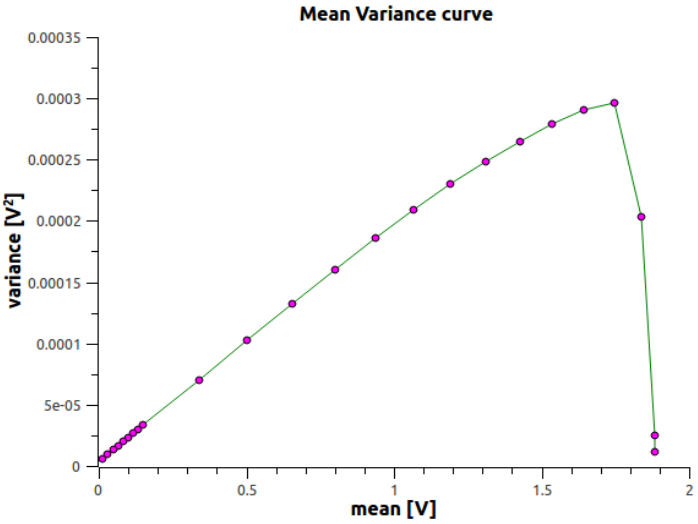


Figure 5.2-7- CVF from PTC curve using mean variance method.

5.2.7.Accuracy of the method

Among the two method described; the photo response curve method seems more accurate as mean-variance method is only accurate for the linear part of the image sensor's response. Also, the mean-variance method assumes that only photon shot noise contributes to the total noise which is not the case in reality. So the photo response curve is preferred for the CVF measurement.

5.3.Modulation Transfer Function

5.3.1.Objective

The Modulation Transfer Function (MTF) is a measure of the image sensor's ability to resolve a contrast at a particular spatial resolution. The MTF quantifies the overall imaging performance of a system in terms of the resolution and the contrast. The following measurement procedure is based on Slanted-Edge method and will result in the Edge Spread Function (ESF), Line Spread Function (LSF) and the MTF of the sensor.

5.3.2.Measurement Background

5.3.2.1.Slanted-Edge method

The slanted-edge method based on ISO 12233 standard consists on imaging an edge onto the detector as shown in Figure 5.3-1, slightly tilted with regard to the rows (or the columns). Hence, a vertically oriented edge allows obtaining the horizontal Spatial Frequency Response (SFR) of the detector. In that case, the response of each line gives a different ESF, due to different phases of the signal [29].

5.3.2.2.Method description

In order to calculate the MTF of the system, first determine the ESF, which is the summation of SFR of all the lines perpendicular to the slanted edge. The response of a single line will give an under-sample ESF, so by combining response of multiple lines with a slightly different position of the edge (hence the slanted edge) the sampling of the ESF becomes much better. Now calculate the LSF which is the derivative of the ESF. Then by performing a Fast Fourier Transform (FFT) of the LSF will result in the Optical Transfer Function (OTF). Finally, the MTF of the sensor is the normalized modulus of the OTF. The Figure 5.3-2 shows the numerical relationship between all these parameters.

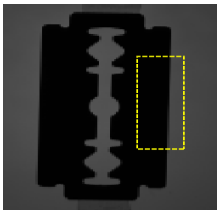


Figure 5.3-1-Slanted edge with ROI.

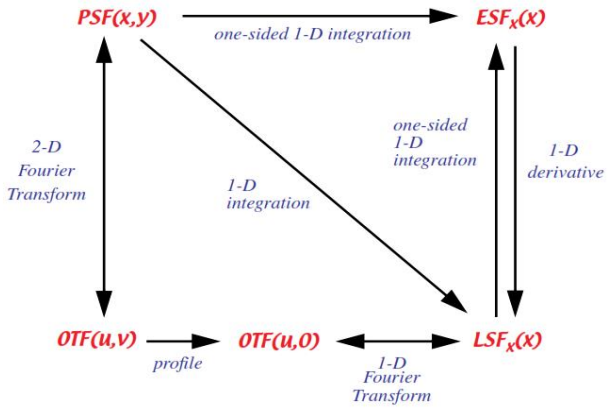


Figure 5.3-2- Relationship between PSF, ESF, LSF and OTF [44] .

5.3.3.Measurement Setup

5.3.3.1.Block Diagram

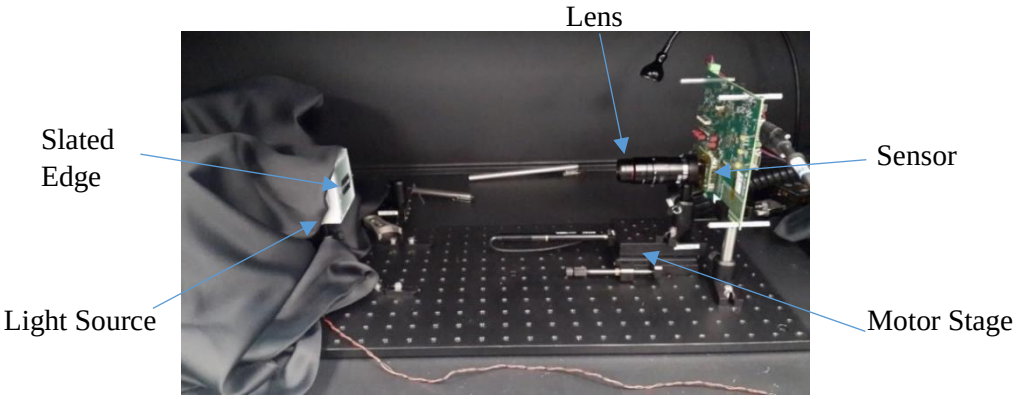


Figure 5.3-3- Setup for the MTF measurement inside the dark chamber.

Build the setup as shown in Figure 5.3-3, mount the calibrated lens on a motor stage such that the center of the lens is focused at the center of the slanted edge and use the motor stage to change the distance to get the best-focused image. Place the object (slanted edge) between the sensor and the light source. The setup should be mounted on a rigid optical bench or breadboard in a dark cabinet. Typical list of equipment's required for MTF measurement are:

1. DUT.
2. Power supply (CI-0033 TTi_QL355TP_Power_supply).
3. LED light source.
4. Slanted edge object (razor blade).
5. Flex TC (Thermal control unit).
6. Camera Lens (F = 2.8 and OBJ = 0.3m).
7. Camera link and frame grabber.
8. Thorlabs motor stage.

5.3.3.2.Software Tools

1. Iron Python-based Caeleste software environment.

5.3.4.Measurement Procedure

5.3.4.1.Algorithm

First, correct the images for non-uniformities using a flat-field correction. Then find the transition point (position of the edge) i.e. position of the pixels where the pixel value crosses 50% of the maximum intensity and then determine the response SFR for every transition. Now shift the response for every line of the slanted edge image over each other to get the oversampled transition curve i.e. the ESF as shown in Figure 5.3-4. Further, the LSF is calculated by taking the derivative of the ESF. And finally, MTF is calculated as modulus of Fast Fourier Transform of the LSF. If needed various mathematical operations can be performed like- linear polyfit on the transition position values for the small pixel size, interpolation on the oversampled ESF data and filtering for smoothing of the LSF curve.

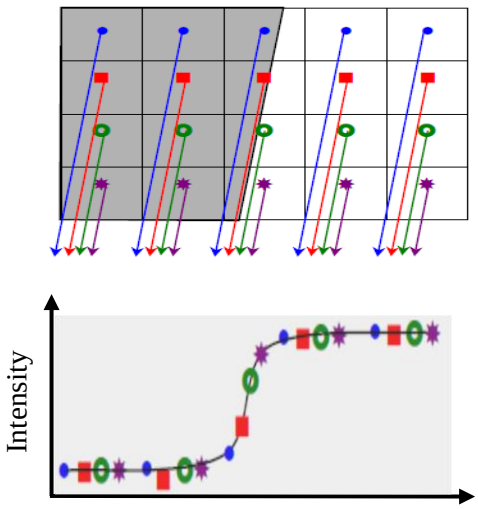


Figure 5.3-4- ESF curve obtained by projecting data from the slanted edge image [29].

5.3.4.2.Procedure

1. Build the setup as described in the measurement setup and place the edge (Target) at a distance (OBJ) of 30cm from the DUT to capture the images.
2. Make sure that the captured image does not saturate the pixels by setting an appropriate light source intensity (50% saturation).
3. Set the correct lens setting (F = 2.8 and OBJ = 0.3m).
4. Capture the three images under the same camera setting and environment condition for different distances to get the best-focused image:
    a. Take a dark image as your reference.
    b. Take a light image as your second reference.
    c. Take an image of the slanted edge (target).
5. Correct the images for the dark non-uniformity and for the non-uniformities under light of the pixel response using the flat-field correction.

5.3.4.3.Pay attention

1. Make sure that the captured images do not saturate.
2. The slanted edge should be within 1º-10º angle as the MTF value depends on the angle of edge.
3. Make sure that you have the correct lens setting.

5.3.5.Accuracy of method

The thing that can go wrong with this measurement is the misalignment in placing the target (slanted edge) and removing the edge while capturing reference images under light and in dark. Also, the stability of light source is important.

5.3.6.Data Processing

It is the main part of the procedure. To calculate the MTF of the sensor perform the following steps:

Note- Following calculations are for the vertical edge, for the horizontal edge interchange the columns with the rows.

5.3.6.1.Correcting image

For the three images (dark, edge, light) taken at every position, perform the flat-field correction as following:

1. Both the EDGE and LIGHT images are corrected for their offset and dark non-uniformities by subtracting the DARK reference image, which leads to normalizing the images with black = 0 and white = 1.
2. The obtained correction (LIGHT-DARK) will be used to create a gain map for each pixel, called as correction factor (gain factor).
3. The obtained correct image will be (EDGE – DARK) / (LIGHT-DARK).
4. Now linearly normalize the correct image.

5.3.6.2.Calculate the ESF

The ESF is the summation of SFR of all the transitions. To determine SFR first, compute the pixel position ($Threshold_{col}$) for which the pixel value is greater than 0.5 for every row as shown in Figure 5.3-5. And then determine the exact transition point ($Col_{intercept}$) for all the lines (rows) of the edge from the following formula -

$$\mathrm{Col}_{\mathrm{intercept}} = \mathrm{Threshold}_{\mathrm{col}} + \frac{(\mathrm{col}_0 - 0.5)}{(\mathrm{col}_1 - \mathrm{col}_0)} \qquad (5.3\text{-}1)$$

Where,
$Col_{intercept}$: transition point,
$Threshold_{col}$: column position where pixel value is > 0.5,
col_0: pixel value at $Threshold_{col}$ for that line (row),
col_1: pixel value at ($Threshold_{col}$ -1) for that line (row).

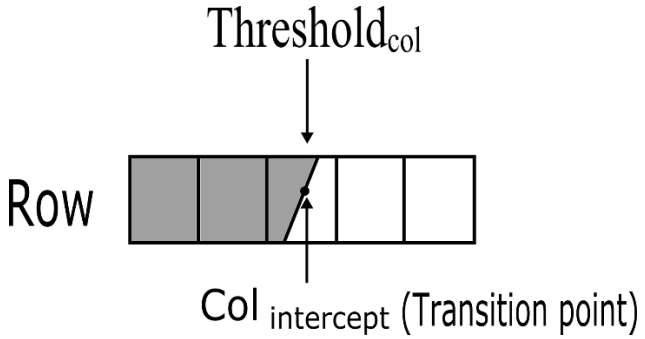


Figure 5.3-5- Single row from a pixel array indicating transition point which tells the location of the edge in the slanted edge image.

Note: It is better to take linear poly-fit value for $Col_{intercept}$ if the pixel size is small.

Now record the pixel value at $Col_{intercept}$ (transition point) and for the 10 (can be any number) pixels on either side of the $Threshold_{col}$ to generate the SFR for every row as shown in Figure 5.3-6. Then combine all the SFR and plot them with respect to pixel position to generate the ESF curve. The data for the ESF is highly oversampled and erratic, so one should perform a linear interpolation over the ESF data.

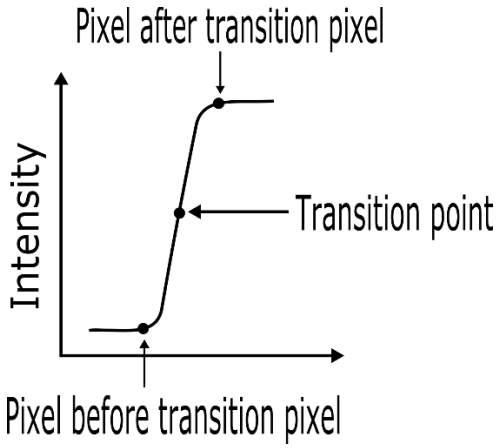


Figure 5.3-6- Spatial frequency response generated by recording transition pixel and neighbouring pixel values from single row.

5.3.6.3.Calculate the LSF

The LSF is the derivative of the ESF. So one could employ Three Point Derivative Method to determine the LSF-

$$\mathrm{LSF(x)} = \frac{\mathrm{d}}{\mathrm{dx}}\mathrm{ESF(x)} \tag{5.3-2}$$

$$\mathrm{LSF_i} = \frac{1}{2}\left(\frac{\mathrm{ESF_{i+1}}-\mathrm{ESF_i}}{\mathrm{col_{i+1}}-\mathrm{col_i}} - \frac{\mathrm{ESF_i}-\mathrm{ESF_{i-1}}}{\mathrm{col_i}-\mathrm{col_{i-1}}}\right) \tag{5.3-3}$$

Note: One can apply a smoothing filter (Savitzky–Golay filter) for the LSF data smoothing.

5.3.6.4.Calculate the MTF

The MTF is calculated by performing a FFT over the LSF and taking the normalized modulus of the result.

$$\mathrm{MTF} = |\mathrm{FFT(LSF)}| \tag{5.3-4}$$

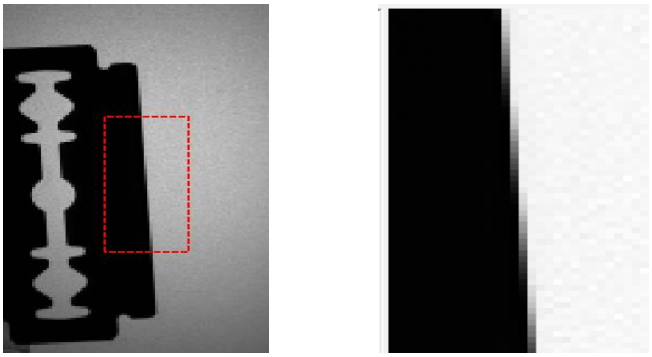
The Nyquist frequency is the fastest signal that can be reliably sampled, hence Nyquist frequency = 2×pixel pitch.

Also, the Nyquist frequency can be determined by calculating the perfect MTF from the perfect LSF. A perfect LSF is an ideal impulse of finite width and the Nyquist frequency is the frequency at first zero. The MTF calculated from Eqn. 5.3-4 consist of the MTF of the lens as well, so the final MTF of the sensor normalized from 0 to 1 is given as-

$$\mathrm{MTF_{sensor}} = \frac{\mathrm{MTF_{measured}}}{\mathrm{MTF_{lens}}} \tag{5.3-5}$$

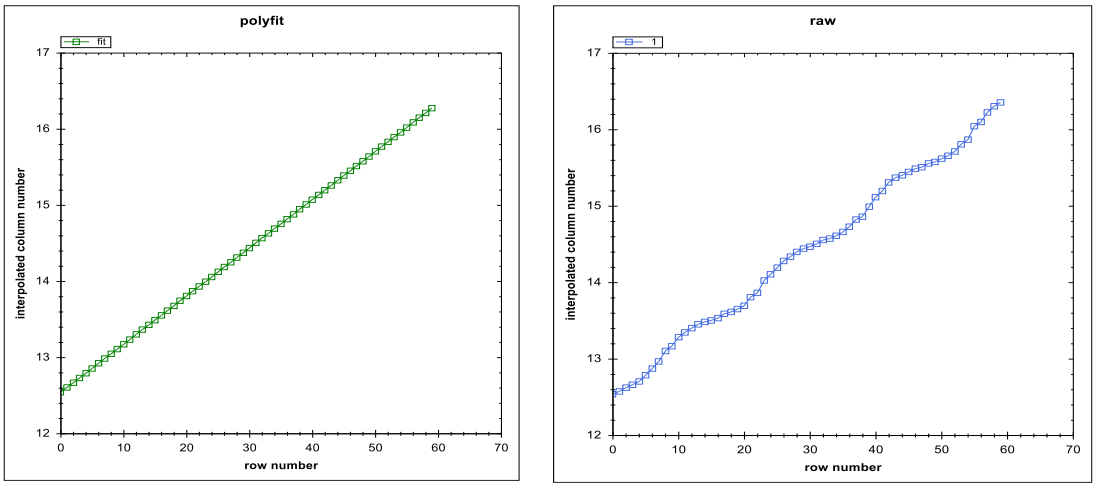
5.3.7.Graphs and Figures

The following figures and graph depict the process to compute the MTF. The Figure 5.3-7 shows the selected target edge and corresponding corrected image. Next step is to compute transition point and Figure 5.3-8 shows raw and polyfit transition point. The Figure 5.3-9 shows the graph of normalized ESF, which is the response of all the transition points. Then Figure 5.3-10 shows the corresponding LSF graph and perfect LSF graph. Finally, Figure 5.3-11 show the MTF of the corrected edge image along with the perfect MTF obtained from the perfect LSF.



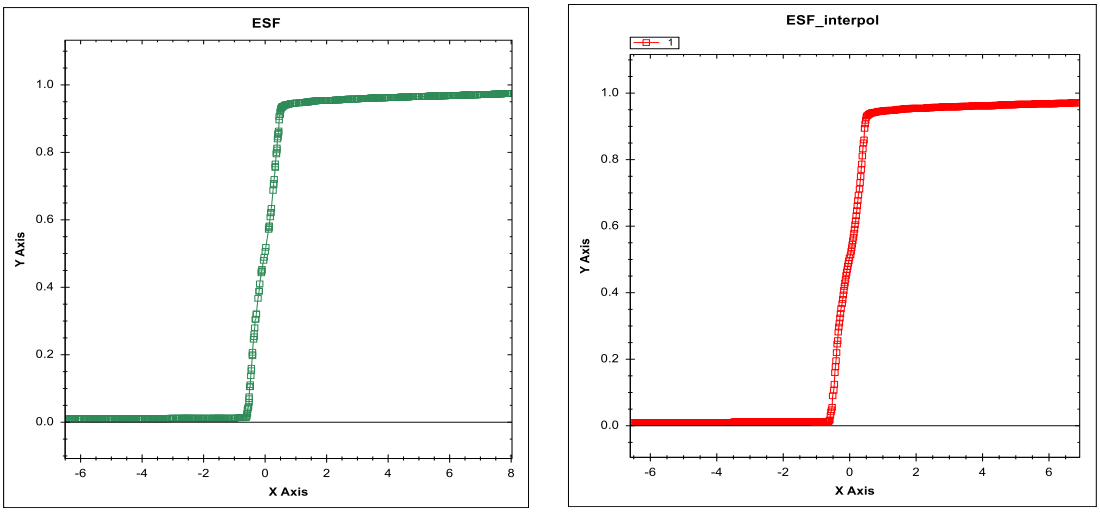
(a) (b)

Figure 5.3-7- (a) Target edge with a ROI and (b) Flat-field corrected image for computing the ESF.



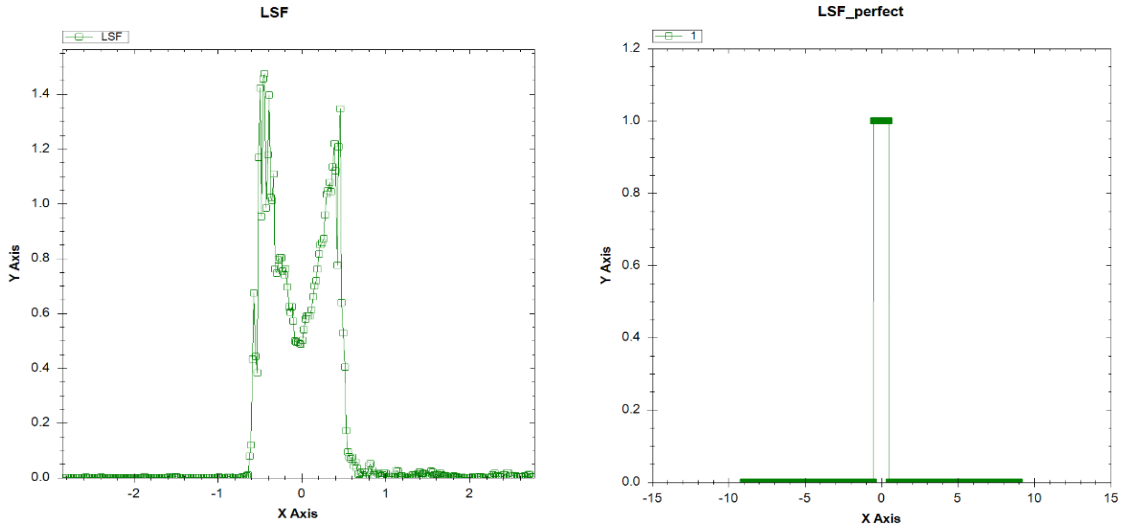
(a) (b)

Figure 5.3-8- Graph between interpolated column number and row number (a) Linear polyfit data of the column values and (b) Raw data of the column values.



(a) (b)

Figure 5.3-9- Edge spread function of the edge image, on y-axis normalized signal level and on the x-axis the pixel number, (a) Using the raw data and (b) Interpolated data for the pixel number.



(a) (b)

Figure 5.3-10- Line spread function of the corrected edge image, (a) LSF from the actual data and (b) LSF of a perfect edge.

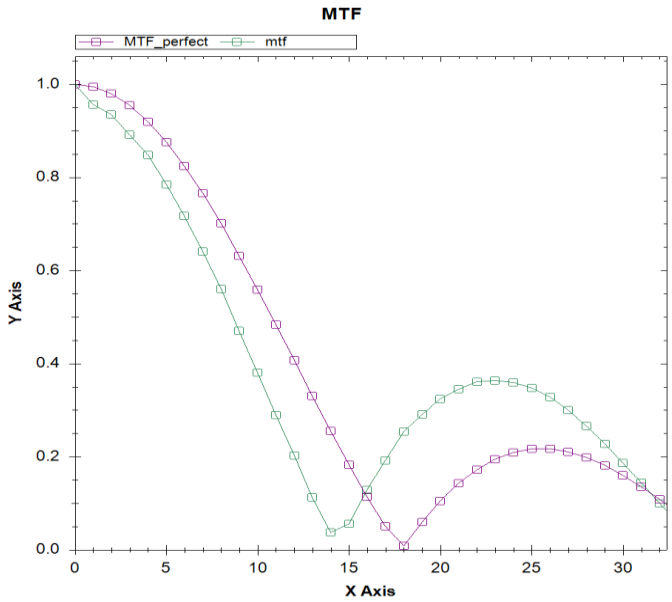


Figure 5.3-11- MTF of the corrected edge image along with the perfect MTF obtained from a perfect LSF.

5.3.8.Code Description
Class Modulation Transfer

Description
A class that measures and computes Modulation Transfer Function. This class computes the best focus position for the Lens and then capture images on and around the focus positon and then correct the images to compute the MTF of the sensor.

Function - position_array()
This function generates a list of all the position on which motor stage will move depending on the parameters passed.

position_array(mid_pos, range_pos, step_pos)

Parameters-
mid_pos <float> - start position in mm,
range_pos <float> - range of motor stage in mm,
step_pos <float> - step size of motor stage in mm.
Returns-
p_array <list> - List of all the positons of motor stage.

Function - focus_area()
This function captures an image and ask user select ROI of area to be focused. Coordinates of ROI are stored in vector which are later used to find focus.

Returns-
roi <vector> - coordinates of focus area.

Function - find_focus()
This function finds the best focus position for the Lens mounted on motor stage depending on the parameters passed, to capture image for computing MTF.

find_focus(self,range_, step)

Parameters-
range_ <float> - range of motor stage in mm,
step <float> - step size of motor stage in mm.
Returns-
focus_position <float> - best focus position.

Function - capture_image()
This function captures images according to specified experiment_type (dark, light and edge) at different positons and saves them in NAS directory corresponding to current project.

capture_image(self,range_, step)

Parameters-
range_ <float> - range of motor stage in mm,
step <float> - step size of motor stage in mm.

Function - correct_horizontal_image()
This function corrects the horizontal edge image by applying flat-field correction, take ROI of the images and normalize, rotate and flip if needed.

Returns-

img_edge <vector> - vector of all the images corrected.

Function - correct_vertical_image()
This function corrects the vertical edge by applying flat-field correction, take ROI of the images and normalize, rotate and flip if needed.

Returns-
img_edge <vector> - vector of all the images corrected.

Function - create_ESF()
Function creates ESF vector and generate ESF plot for all the images in img_edge, also generate plot for column intercept i.e. the transition position.

Returns-
ESF <vector> - 3D vector for intensity and interpolated column values for all the images.

Function- create_ESF()
Function creates LSF vector and generate LSF plot for all the images in img_edge. Also perform filtering for curve smoothing.

Returns-
LSF <vector> - 3D vector for intensity and pixel number for all the images,
LSF_filtered <vector> - 3D vector of filtered LSF values.

Function - create_MTF()
Function creates computes MTF of all the images in img_edge and generate MTF, MTF perfect plot.

Returns-
value <list> - List of MTF values of all the images at Nyquist frequency from LSF,
value_filt <list> - List of MTF values of all the images at Nyquist frequency from filtered LSF,
mtf <list> - List of values FFT of LSF.

5.3.9.Example

```
#creating instance for class
mtf = ModulationTransfer():
#Computes ROI coordinates for finding best focus image and return ROI
mtf.focus_area();
#find position for best focused image starting at start_pos for range of 10mm and with step size of 0.1mm and return focus_position
mtf.find_focus(5,0.1);
#capture image starting at focus_position for range of 10mm and with step size of 0.1mm
mtf.capture_image(10,0.1);
#correct horizontal images and return images in vector image_edge
mtf.correct_horizontal_image();
#correct vertical images and return images in vector image_edge
mtf.correct_vertical_image();
#compute ESF from corrected images in image_edge and return ESF vector
mtf.create_ESF();
#compute LSF from ESF vector and return LSF and LSF_filtered vector
mtf.create_LSF();
#compute MTF from LSF vector and return MTF value at Nyquist frequency
mtf.create_MTF();
```

5.4.Read Noise

5.4.1.Objective

This procedure is to perform a noise analysis of the sensor. The read noise is the temporal variation in the pixel value over period of time. It is the result of various noise sources like-kTC noise, ADC noise, temporal row noise and other noise sources.

5.4.2.Measurement Background

5.4.2.1.Method description

The read noise or the temporal noise in the pixel is the inherent noise of a sensor and is equal to the variance of the pixel value over a series of frame taken in dark. It is measured for short integration time (t_{int}) to avoid DCNU and the DUT is not illuminated to keep photon shot noise zero.

5.4.3.Measurement setup

5.4.3.1.Block Diagram

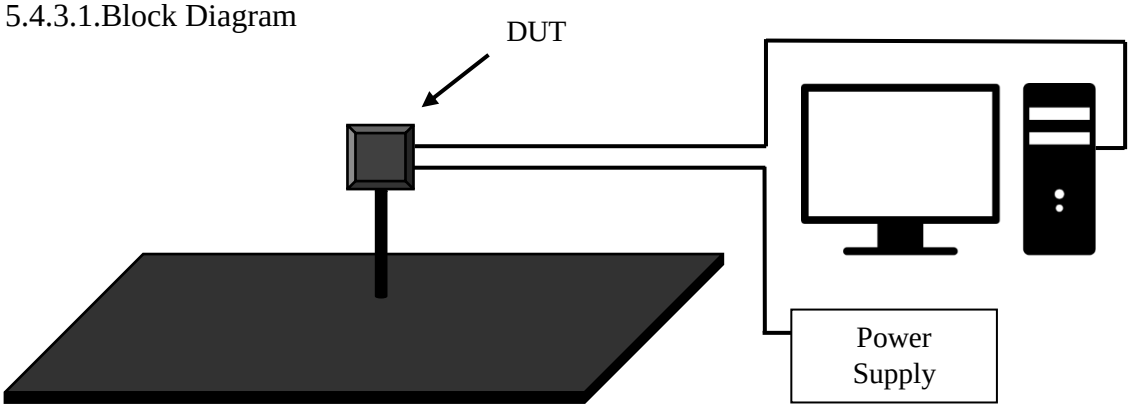


Figure 5.4-1-Setup for Noise measurement.

The block diagram shown in Figure 5.4-1 illustrates the setup for the measurement. The Camera Link and Frame Grabber are used to capture the images in the dark. The setup should be mounted on a rigid optical bench or breadboard in a dark cabinet. A typical list of equipment's employed for this measurement are:

1. DUT.
2. Camera link and frame grabber.
3. Power supply (CI-0033 TTi_QL355TP_Power_supply).

5.4.3.2.Software Tools

1. Iron Python-based Caeleste software environment.

5.4.4.Measurement Procedure

5.4.4.1.Algorithm

The idea behind the measurement is to calculate the read noise by computing the variance for each pixel over the series of images taken in dark for the same integration time t_{int}[s] and taking the average of all the pixel's value to get the noise over a frame.

5.4.4.2.Procedure

1. Built the setup as shown in Figure 5.5-1, place the DUT and connect the peripheral equipment and turn ON the supply.
2. First, capture some dummy images (e.g. 20, 30) for the system to get stable and then capture a certain number of images (e.g. 10, 20) for calculating the read noise.

5.4.4.3.Pay attention

1. Capture as many images (e.g. 10-20) for an accurate result and by taking their average one can remove all the offset and the fixed pattern noise.

5.4.5.Data Processing

The read noise is the random variation in the measurement values over a period of time, hence the noise is calculated in dark by evaluating the temporal signal variance over a series of frames for an individual pixels and then by taking the average of all noise values over all the pixel's value, tells the noise over an image.

$$\text{Variance } (\sigma^2) = \frac{\sum_{j=1}^{K} \frac{\sum_{i=1}^{N} (P_{ij} - M_j)^2}{N}}{K} \quad (5.4\text{-}1)$$

$$\text{Noise}_{rms} \text{ [Volts or DN]} = \sqrt{\sigma} \quad (5.4\text{-}2)$$

Where,
P_{ij} = j^{th} pixel value from i^{th} frame,
M_j = mean value of all the j^{th} Pixels of N frames,
N = Total number of frames acquired at specific illumination,
K = Total number of pixels.

Note: One can divide the read noise expressed in Volts by the CVF to get the noise expressed in electrons and also the abovementioned calculations can be performed on a row or a column level to get the row noise and the column noise of the image sensor.

5.4.6.Accuracy of the method

This method is very accurate for determining the read noise. The two things that are important for accurate result are:

1. The measurement should be performed at stable temperature condition, to minimize any variation in the dark current of the pixel.
2. Also, the integration time to capture the images should be as short as possible so that the influence of DSNU is minimized.

5.4.7.Graphs and Figures

The Figure 5.4-2 and Figure 5.4-3 show the percentage noise level w.r.t. the full-scale value of the image sensor for measurement performed for rows and columns respectively.

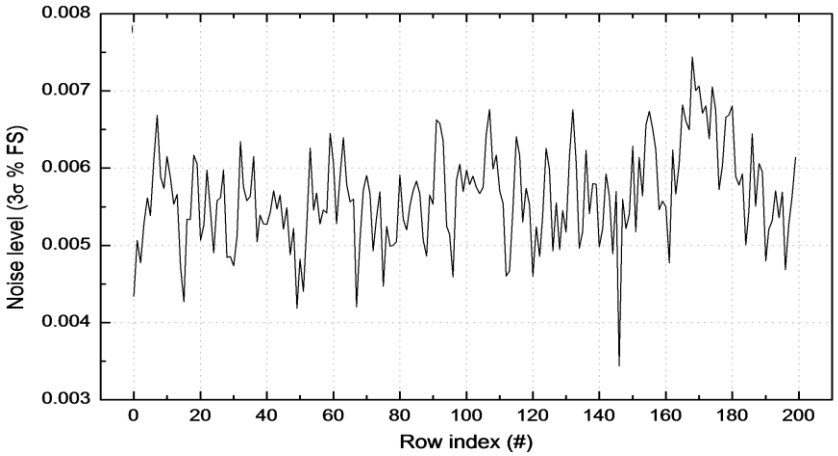


Figure 5.4-2- a) Noise of the image sensor per row.

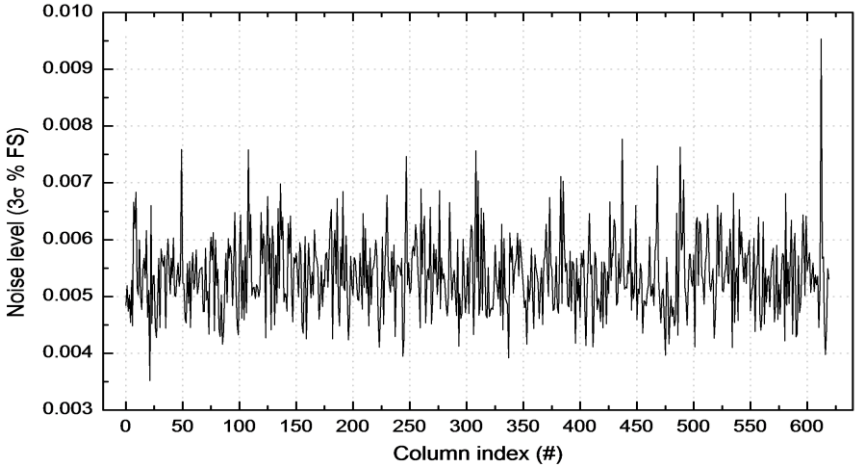


Figure 5.4-3- a) Noise of the image sensor per column.

5.5.Dark signal and Dark current non-uniformity

5.5.1.Objective

This procedure is to evaluate the dark signal i.e. the dark current that flows through the sensor even when no photons are incident and the Dark Current Non-Uniformity (DCNU) which is the spatial non-uniformity associated with the dark signal.

5.5.2.Measurement Background

5.5.2.1.Method description

The dark signal is the result of the dark current of the photodiode and is dependent on the temperature and the integration time. The DCNU are statistical variation on the generation/recombination level in each pixel i.e. the dark current. Hence by measuring the sensor output with respect to the time under zero illumination, the dark current and the DCNU can be evaluated.

5.5.3.Measurement setup

5.5.3.1.Block Diagram

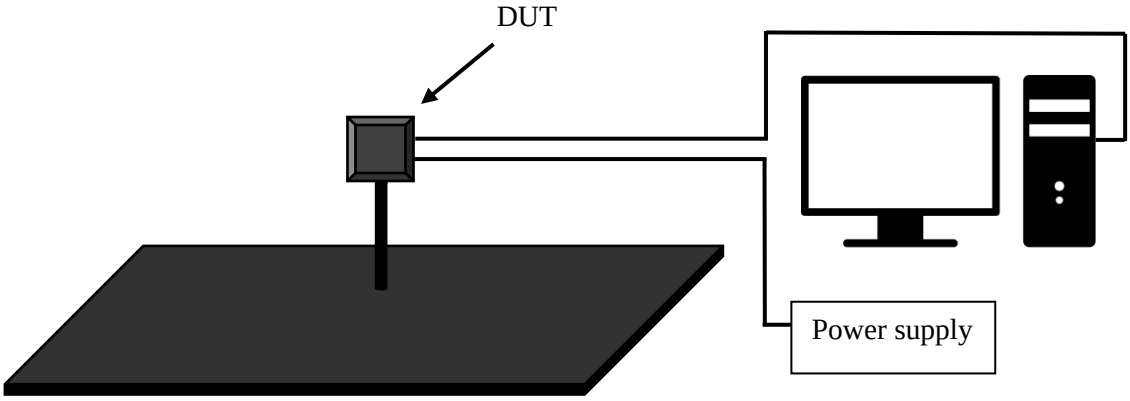


Figure 5.5-1- Setup for DS and DCNU measurement.

The block diagram in Figure 5.5-1 illustrates the setup for the measurement. The Camera Link and Frame Grabber are used to capture the images in the dark. The setup should be mounted on a rigid optical bench or breadboard in a dark cabinet. Typical list of equipment's employed for this measurement are:

1. DUT.
2. Camera link and frame grabber.
3. Power supply (CI-0033 TTi_QL355TP_Power_supply).

5.5.3.2.Software Tools

1. Iron Python-based Caeleste software environment.

5.5.4.Measurement Procedure

5.5.4.1.Algorithm

The idea is to capture two images one with short integration time t_{int1}[s] and one with long integration t_{int2}[s] and take their difference to compute the dark response and then computing the standard deviation $(\sigma)_{rms}$ of the dark response to determine the DCNU.

5.5.4.2.Procedure

1. Built the setup as shown in Figure 5.5-1, place the DUT, connect the peripheral equipment's and turn ON the supply.
2. Capture Image 1 with very short integration time t_{int1}.
3. Capture Image 2 with a long integration time t_{int2}, at least long enough to see a significant dark current.
4. Capture a dummy Image 3 for even a longer integration time then t_{int2} just to check that Image 1 and Image 2 are in the linear region.

5.5.5.Data Processing

The dark signal (DS) or dark count rate [e^-/sec] is the mean response of (Image 1- Image 2)/ (t_{int1} - t_{int2}). The DCNU [V_{rms}] is the standard deviation of this response / (t_{int1} - t_{int2}).

5.5.6.Accuracy of the method

The dark signal and DCNU depends on the temperature of the sensor, so the measurement should be performed on a temperature controlled system.

5.5.7.Graphs and Figures

The Figure 5.5-2 below shows the temperature dependency of the dark current. As expected the dark current increases more rapidly for higher temperatures.

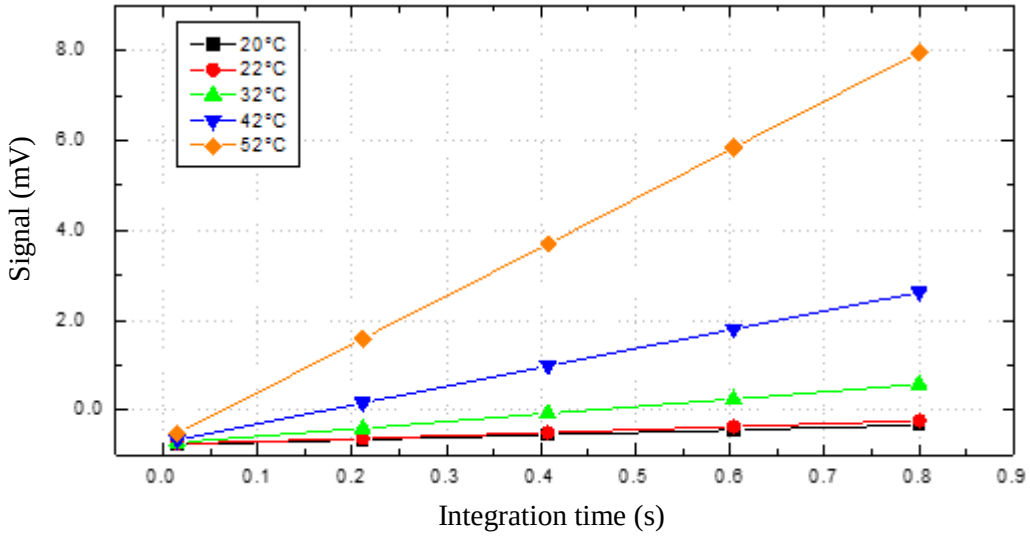


Figure 5.5-2-Signal level of the image sensor as a function of integration time at different temperatures.

The Figure 5.5-3 shows the comparison of dark current between the image sensor samples with different depletion voltage (V_{dep}) at 22°C. From the graph the dark current for the sample of V_{dep} = 1.4V is 0.073% FS/s and of V_{dep} = 1V is 0.034% FS/s, where FS is the full scale value.

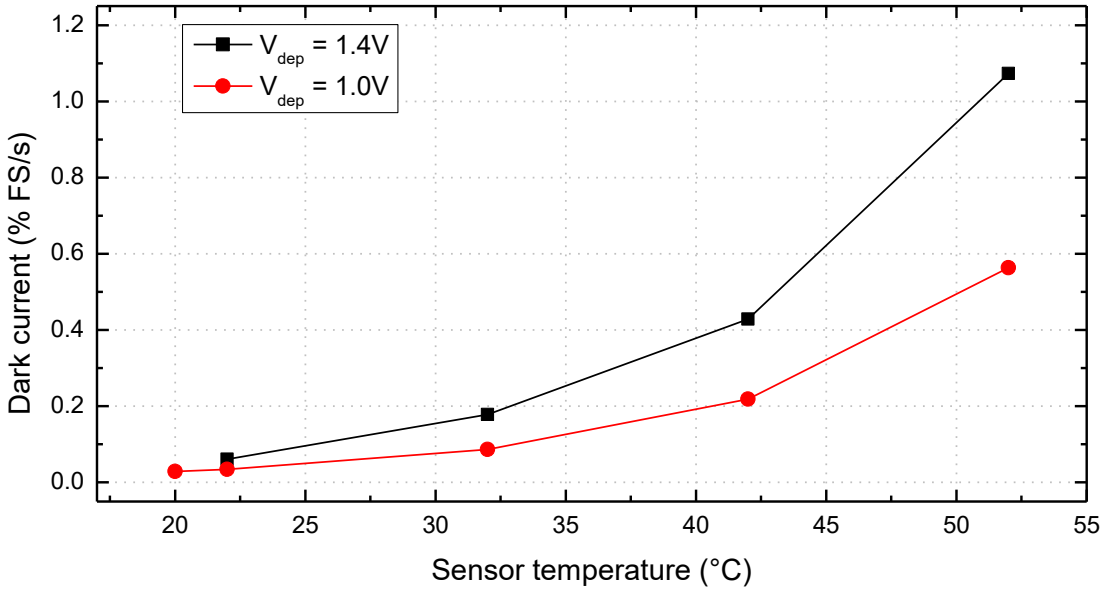


Figure 5.5-3- Dark current comparisons between samples with different depletion voltage (V_{dep}).

5.6.FPN and PRNU

5.6.1.Objective

This procedure is to perform a non-uniformity analysis of the image sensor. The statistical static variation of the “offset” (measure without light) or Fixed Pattern Noise (FPN) and “gain” (measure with light) or Photo Response Non Uniformity (PRNU).

5.6.2.Measurement Background

5.6.2.1.Method description

The fixed pattern noise is the type of spatial non-uniformities within an image, these non-uniformities are the result of the pixel to pixel variations. The two basic non-uniformity are “offset” FPN, which is also part of DSNU (Dark Signal Non Uniformity) which does not depend on the temperature and the integration time and the “gain” PRNU (Photo Response Non Uniformity) is the non-uniformity under illumination. Hence, by observing the pixel variation over a frame, FPN and PRNU can be evaluated in dark and under illumination respectively.

5.6.3.Measurement setup

5.6.3.1.Block Diagram

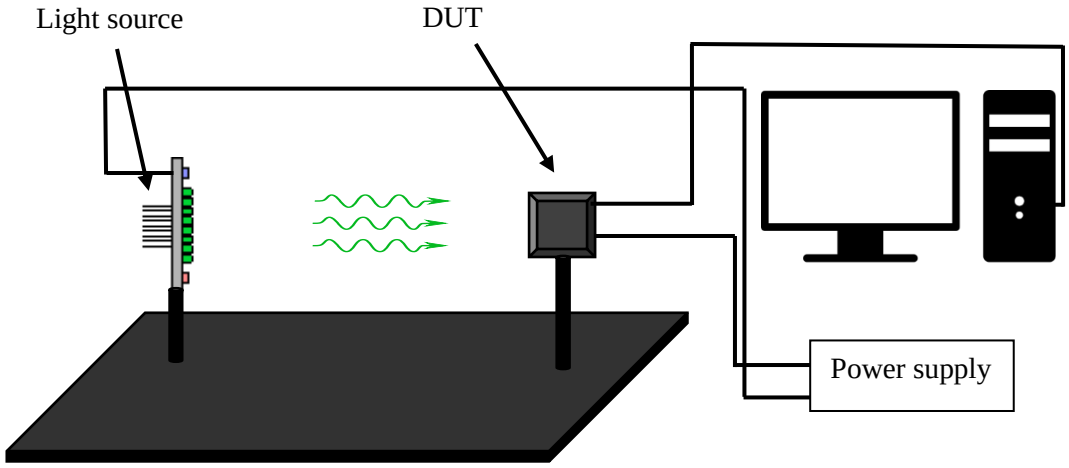


Figure 5.6-1- Setup for FPN and PRNU measurement.

The block diagram in Figure 5.6-1 illustrates the setup for the measurement can be recognized. The Camera Link and Frame Grabber are used to capture the images. The setup should be mounted on a rigid optical bench or breadboard in a dark cabinet. Typical list of equipment’s employed for this measurements are:

1. DUT.
2. Camera link and frame grabber.
3. Power supply (CI-0033 TTi_QL355TP_Power_supply).
4. Caeleste’s LED light source.

5.6.3.2.Software Tools

1. Iron Python-based Caeleste software environment.

5.6.4.Measurement procedure

5.6.4.1.Algorithm

To calculate the FPN and the PRNU, one needs to capture a certain number of images for three illumination settings dark, light and saturation. FPN is the variation in pixel dark signal over a frame and is determined by calculating STDEV of the mean image obtained from a set of frames taken in the dark with minimal integration time. PRNU as the name suggest is the non-uniformity in spatial variation of pixel value for specific illumination level, it can be determined by calculating the coefficient of variation (It is the ratio of the standard deviation to the mean value of the signal) of the image. Then take the mean of a number of images in order to remove the temporal noise. Images are taken for a short t_{int} to keep DCNU negligible.

5.6.4.2.Procedure

1. Place the light source and DUT at an appropriate position on the optical bench such that with the given placement deep saturation of the DUT can be reached at the maximum light source power.
2. Capture the number of images (e.g. 10, 20) in the dark.
3. Now power ON the light source and allow 10 minutes to get it thermally stable.
4. Now capture the number of images (e.g. 10, 20) for light (50% of saturation level) and for the saturation.
5. Calculate the mean of all the images captured for dark, light and saturation respectively to obtain the resultant images for all the three conditions.

Note- Capture images with a short t_{int} to keep DCNU negligible.

5.6.5.Data processing

The FPN is the static variation of the offset in the dark signal from pixel to pixel.

$$\text{FPN [Vrms]} = \text{STDEV (DARK)} \tag{5.6-1}$$

$$\text{FPN [\%]} = \frac{\text{FPN [V}_{\text{rms}}\text{]}}{\text{Saturation} - \text{DARK}} \times 100 \tag{5.6-2}$$

The PRNU as the name suggest is the non-uniformity or spatial variation of the pixel value for specific illumination (nominally at 50% of saturation level). It can be evaluated by calculating the coefficient of variation of an image.

$$\text{PRNU} = \frac{\text{STDEV (LIGHT} - \text{DARK)}}{\text{Mean (LIGHT} - \text{DARK)}} \tag{5.6-3}$$

Where,
DARK: resultant image by taking mean of all the images taken in dark.
LIGHT: resultant image by taking mean of all the images taken in light.
Saturation: resultant image by taking mean of all the images taken in saturation.
STDEV: Standard deviation.

5.7.Image Lag

5.7.1.Objective

The image lag is the memory effect in the image sensor due to the residual charge in the pinned photodiode. The measurement result is expressed in [%] of the residual charge in the next frame due to previous frame.

5.7.2.Measurement Background

5.7.2.1.Method Description

The purpose of this test is to estimate the lag of the image sensor. The pinned photodiode can be modeled as a lumped RC network, hence there is a certain time constant (delay) for the charge to deplete through the diode across a possible potential barrier. And if the width of the pulse applied to transfer gate is smaller than the time constant (delay) then it will result in residual charge at the photodiode, therefore, the lag in the sensor.

5.7.3.Measurement Setup

5.7.3.1.Block Diagram

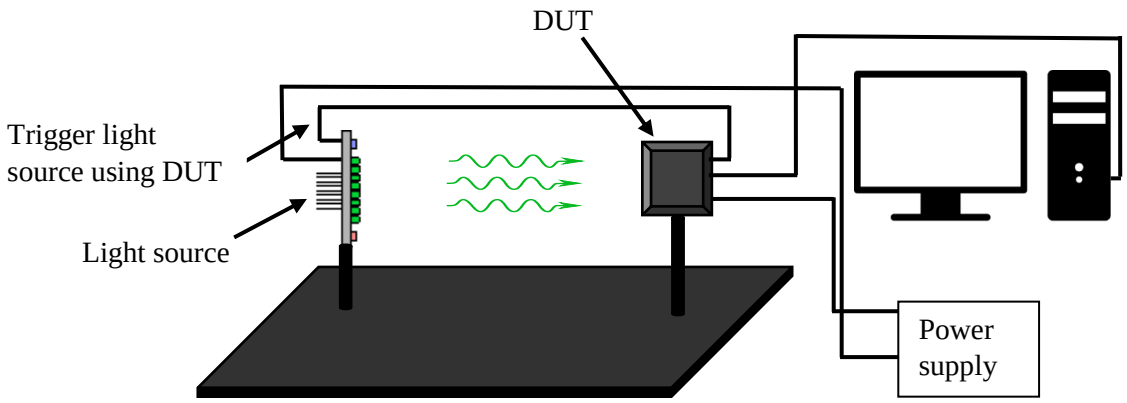


Figure 5.7-1- Setup for Image lag measurement.

The block diagram in Figure 5.7-1 illustrates the setup for the measurement. The Camera Link and Frame Grabber are used to capture the images and the light source is connected directly to the DUT for precise triggering. The setup should be mounted on a rigid optical bench or breadboard in a dark cabinet. Typical list of equipment's employed for this measurements are:

1. DUT.
2. Mounting rails.
3. Power supply (CI-0033 TTi_QL355TP_Power_supply).
4. Caeleste LED light source.
5. Connection cables.
6. Cameral link and frame grabber.

5.7.3.2.Software Tools

1. Iron Python-based Caeleste software environment.

5.7.4.Measurement Procedure

5.7.4.1.Algorithm

The idea behind the measurement is to grab a certain amount of (e.g. 10) black frames followed by illuminated frames and vice versa by illuminating the sensor by a light pulse of the same duration as t_{int} and synchronized with beginning/end of the t_{int}. The frame-to-frame crosstalk (image lag) is then estimated as an average signal level in the dark state expressed in percent of the signal level in the illuminated state.

5.7.4.2.Procedure

1. Built the setup as shown in Figure 5.7-1, place the light source and DUT and connect the peripheral equipment and turn ON the supply.
2. Adjust the illumination level (via current, distance, extra attenuators) so that the signal level is (default, and if not, report this) at about 50% of saturation level when the light is ON.
3. Generate the sequence using either a waveform generator or SeqC and grab 10 frames in dark, followed by 10 illuminated frames and vice versa.
4. For accurate triggering of the light pulse, one should use a trigger pulse from the test board itself.

5.7.4.3.Accuracy of the method

There is hardly anything that can go wrong with this simple procedure, but still there can be some sources of error: -

1. Generated sequence is not perfectly aligned with begin/end of the t_{int}.
2. Light source instability can cause delay in switching ON/OFF of light pulse.

5.7.5.Data Processing

Image lag is calculated by computing the decaying response from illumination to dark or vice versa.

$$\text{Lag}\,[\%] = \frac{\mu_{\text{light}} - \mu_{\text{dark}}}{\mu_{\text{light}}} \times 100 \qquad (5.7\text{-}1)$$

Where,
μ_{dark}: mean value of the first dark frame taken just after the light frame.
μ_{light}: mean value of the last light frame.

5.7.6.Graphs and Figures

The Figure 5.7-2 shows the sample timing sequence for the signals to capture frames for image lag measurement. And the Figure 5.7-3 shows the result for the image lag measured for the image sensor by taking 50 frames with 5 consecutive light and dark frames.

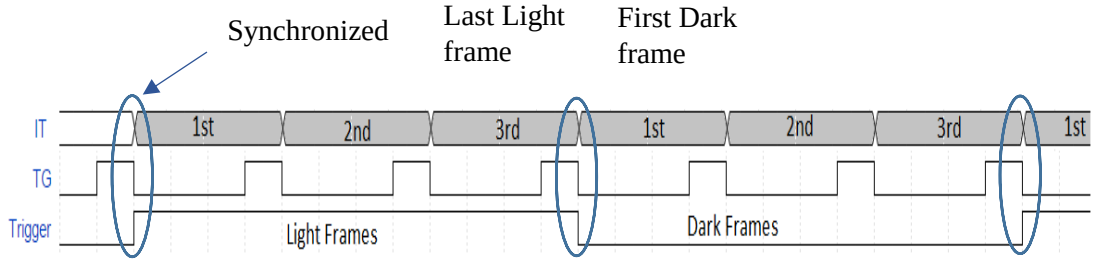


Figure 5.7-2- Timing diagram for Image Lag measurement.

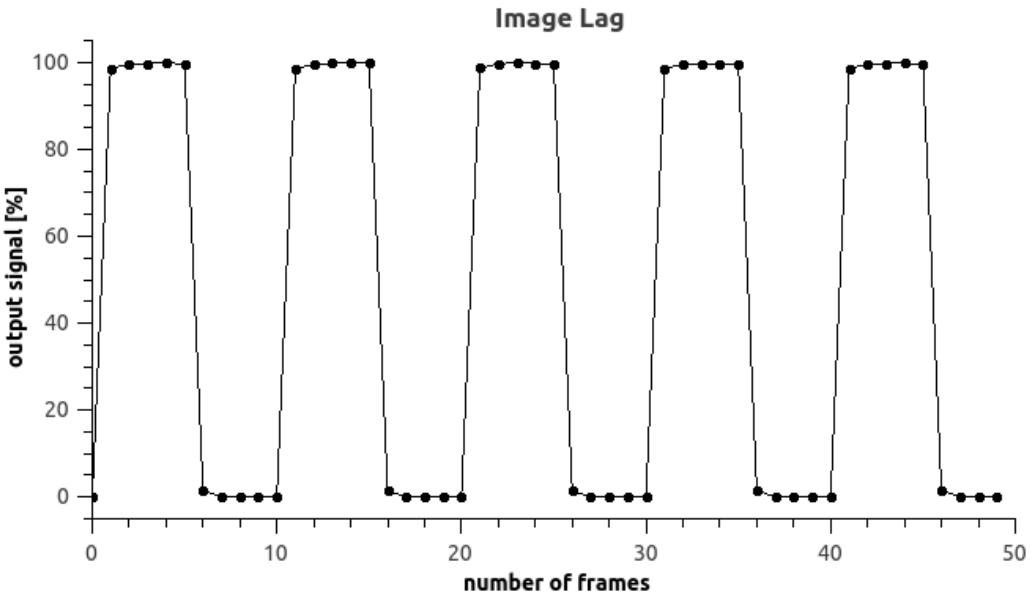


Figure 5.7-3- Image lag for 50 frames with 5 consecutive light and dark frames.

6. Chapter 6

6.1. Summary and Conclusions

This work presents the complete set of standard procedures for characterizing CMOS image sensors. The main objective of this work is to improve the measurement procedures, so after rigorous measurements and testing on different image sensor samples, standard procedures are created. Also, the software library to communicate with the test board and the image sensor are updated and the new hardware tools were incorporated for accurate and precise measurements. Here are some conclusions drawn on the basis of the measurements performed for characteristic parameters of the CMOS image sensors.

6.1.1. Conclusions

1. First and foremost, it is important to have a stable and accurate light source, all the characteristic measurement include a light source except for the dark signal measurement. Therefore, it is important that light source emits light with constant intensity and uniformity at desired wavelength over the DUT.
2. The characterization of Caeleste's LED light source shows that the light source takes a very long time to get it stable and also the uniformity is not good enough at short distance. Hence, Caeleste designed a new LED light source with optical feedback, Proportional Integral Derivative (PID) controller and some modifications in physical design to incorporate a cooling fan to improve the stability and uniformity. The initial result of the improved light source showed significant improvements in the stability of the light source.
3. Quantum efficiency is an important characteristic and for measuring the quantum efficiency Caeleste uses a dedicated test structure called QE structure. These QE structures are identical to those in the original sensor's pixel array in terms of photodiode, transfer gate and metallization properties. So this helps in performing accurate measurements as it eliminates large test boards and the influence of any extra circuit. For example, QE test structures consist of a guard pixel which prevents any charge leakage in the pixel from outside. The other method to compute the QE is from the conversion gain or charge to voltage factor value as described in section 5.1.7.1.1. This method is less accurate as compared to QE test structure method, as it depends on the accuracy of conversion gain value itself.
4. The other problem with the QE measurement is its setup accuracy. As it is important to place the QE test structure exactly at the same location as the reference photodiode so as to receive the same intensity of light for both the devices. But from the measurement results shown in Figure 5.1-5, the current setup results in inaccuracy of 2.68% in the quantum efficiency value, which is quite a lot. To solve this problem new hardware tools were ordered for precise alignment of devices under test to reduce the inaccuracy within 0.1%.
5. Next characteristic measurement is the photo response measurement of the image sensor which provides information on the linearity, full well capacity and the conversion gain value. The accuracy of this method entirely depends on the light source stability and how accurately the light intensity is measured using a reference photodiode because measurements are performed by changing the light intensity in a controlled way and computing the image sensor's response.
6. From the two methods to compute the conversion gain or CVF mentioned in section 5.2.6.5.1 and section 5.2.6.5.2, the photo response curve method is more accurate, as

the mean-variance method is only accurate in linear part of the image sensor response. So the photo response curve is preferred for the conversion gain or CVF measurement at Caeleste. The mean-variance method gives more accurate results for a linear image sensor.

7. The important thing to consider while computing the conversion gain from the mean-variance method is that the higher the number of frames taken to calculate the variance of the output signal the better is the accuracy of the result. As the accuracy of conversion gain depends on the number of samples taken.
8. Next characteristic measurement is the modulation transfer function, which is also the measure of the crosstalk. There are different methods to compute the MTF of which the slanted edge method is more accurate and a fast method.
9. This thesis work draws some conclusion about data processing involved during the MTF measurements as it involves lots of mathematical computation. The first and foremost is to get the oversampled data for the edge spread function. The measurements clearly show that more sampling points, increases the accuracy of generated ESF.
10. The other interesting thing about data processing while computing the edge location in the image: for a large pixel size it better to take raw sampled data and for a small pixel size it is better to apply linear polyfit on sampled data. This is because for small pixel size there are chances that sampled signal is a result of noise but not the actual data. This phenomenon can be seen in Figure 5.3-8.
11. Similarly, for the edge spread function data, there is a need for interpolation. The oversampled data obtained for the edge spread function is very erratic and inconsistent, so before computing the line spread function, the oversampled data needs to be interpolated first.
12. A generalized conclusion can be drawn for the noise measurements; it is important to know which type of noise is being measured. While measuring read noise, which is the inherent noise of the image sensor under no illumination, it should be characterize in complete darkness and should be measured on a temperature stable system. Similarly, while measuring the PRNU, the integration time for grabbing a frame should be as small as possible to eliminate any influence of DCNU.
13. The other important thing while measuring the signal level is that for accurate measurements the signal level should be significantly large with respect to the noise level.
14. Image lag is not much significant in CMOS image sensors, but with continuous increase in high speed and large full charge capacity requirements image lag can be a problem in the future.

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7. Chapter 7

Appendix

7.1. Python Code for Filtering

```
__author__ = 'utsav'
from TSSF import *
''' Filtering module '''

def savgol_filter(nl, nr, m, data):
    """savgol_filter(no. of points in left, no. of points in right, order, data)
        nl <int> = 'no. of point in left'
        nr <int> = 'no. of point in right'
        m <int> = '2 or 4' #order
            The order of the polynomial used to fit the samples.
            `m` must be less than `nl + nr + 1'.
        data <vector> = data you want to filter
        returns filter data in form of a vector

        np = window_length
            The length of the filter window (i.e. the number of coefficients).
            `window_length` must be an odd positive integer.
        ld(derivative) = 0 for smoothing optional
            The order of the derivative to compute.  This must be a
            nonnegative integer.  The default is 0, which means to filter
            the data without differentiating.
        check if all the given inputs are valid
        ld = 0 , np = nr + nl + 1 , m < nr + nl
        first modify the vector data by adding zero in start and end just to match size then
        generates filter data by performing convolution between data and filter coefficients
    """
    filter_data = Vector()
    #creating filter coefficients
    coeff = coefficients(nl , nr, m);
    i = 0
    j = 0
    filter_data = Vector(data.TotalSize)
    average = 0
    convolution = []
    modify_data = Vector(data.TotalSize + (coeff.TotalSize-1))
    while (i < data.TotalSize):
            #add zero in starting
        for j in range(0,(coeff.TotalSize-1)/2):
            modify_data[j] = 0
            #actual data
        for j in range((coeff.TotalSize-1)/2,(modify_data.TotalSize-          (coeff.TotalSize-
1)/2)):
            modify_data[j] = data[i]
            i = i + 1
            #add zero at the end
```

```
        for j in range((modify_data.TotalSize-(coeff.TotalSize-
            1)/2),modify_data.TotalSize):
            modify_data[j] = 0

    #performing convolution
    for i in range((modify_data.TotalSize - (coeff.TotalSize-1))):
        average = 0
        for j in range(coeff.TotalSize):
            average = average  + coeff[j]*modify_data[i+j]
        convolution.append(average)
    for i in range(len(convolution)):
        filter_data[i] = convolution[i]
    return filter_data

def coefficients(nl , nr, m):
    """ coefficients (no. of point in left, no. of point in right, order)
        nl = 'no. of point in left'
        nr = 'no. of point in right'
        m = '2 or 4' #order: int
            The order of the polynomial used to fit the samples.
            `m` must be less than `window_length`.
        returns coefficients in form of a vector
        np = window_length : int
            The length of the filter window (i.e. the number of
             coefficients).
            `window_length` must be an odd positive integer.
        ld(derivative) = 0 for smoothing optional
            The order of the derivative to compute.  This must be a
            nonnegative integer. The default is 0, which means to filter the data without
             differentiating.
        check if all the given inputs are valid
        ld = 0 , np = nr + nl + 1 , m < nr + nl
    """
    np = nr + nl + 1
    a = Vector(m+1 , m+1)
    d = 1
    #The order of the derivative to compute
    ld = 0
    indx = Vector(m+1)
    b = Vector(m+1)
    n = m+1
    #filter coefficients
    coeff = Vector(np)
    #this loop performs least square method
    for ipj in range(m*2+1):
        if (ipj != 0):
            sum = 0
        else:
            sum = 1
        for k in range(1, nr+1, 1):
            sum = sum + pow(k,ipj)
        for k in range(1, nl+1, 1):
```

```
            sum = sum + pow(-k, ipj)
        mm = min(ipj , (2*m -ipj))
        for imj in range(-mm, mm+1, 2):
            a[(ipj+imj)/2, (ipj-imj)/2] = sum
    #linear equation solution, LU decomposition
    ludcmp(a, m+1, indx, d);
    for j in range(m):
        b[j] = 0.0
        b[ld] = 1.0
    #linear equation solution, back substitution
    lubksb(a, m+1, indx, b);
    for kk in range(np):
        coeff[kk] = 0.0
    #generates filter coefficients
    for k in range(-nl, nr+1, 1):
        sum = b[0]
        fac = 1.0
        for mm in range(m):
            fac *= k
            sum = sum + (b[mm+1]*fac)
        coeff[k+nr] = sum
    return coeff

def ludcmp(a, n, indx, d):
    """linear equation solution, LU decomposition"""
    vv = Vector(1, n)
    Tiny = 1.0e-20
    for i in range(n):
        big = 0.0
        for j in range(n):
            temp = abs(a[i, j])
            if (temp > big):
                big = temp
        if (big == 0.0):
            print 'error'
        vv[i] = 1.0/big
    for j in range(n):
        for i in range(j):
            sum = a[i, j]
            for k in range(i-1):
                sum = sum - a[i, k]*a[k, j]
            a[i, j] = sum
        big = 0.0
        for i in range(j, n, 1):
            sum = a[i, j]
            for k in range(j):
                sum = sum - a[i, k]*a[k, j]
            a[i,j] = sum
            dum = vv[i]*abs(sum)
            if (dum >= big):
                big = dum
                imax = i
```

```
        if (j!= imax):
            for k in range(n):
                dum = a[imax, k]
                a[imax, k] = a[j, k]
                a[j, k] = dum
            d = -(d)
            vv[imax] = vv[j]
        indx[j] = imax
        if (a[j, j] == 0.0):
            a[j, j] = Tiny
        if (j != n):
            dum = 1.0/a[j, j]
            for i in range(j+1, n, 1):
                a[i,j ] *= dum
    return a

def lubksb(a, n, indx, b):
    """linear equation solution, backsubstitution"""
    ii=0
    for i in range(1, n+1, 1):
        ip = indx[i-1]
        sum = b[int(ip)]
        b[int(ip)] = b[i-1]
        if (ii != 0):
            for j in range(ii-1, i-1, 1):
                sum = sum - a[i-1, j]*b[j]
        else:
            if (sum != 0):
                ii = i
        b[i-1] = sum
    for i in range(n-1, -1, -1):
        sum = b[i]
        for j in range(i+1, n, 1):
            sum -= a[i,j ]*b[j]
        b[i] = sum/a[i, i]
    return b
```

7.2.Python Code for MTF measurement

```
"Author- Utsav"
# slanted edge
import os
import sys
import System
import inspect;
import TSSF;
from Toolbox.Utilities import DirectorySwap
from Toolbox.Utilities import filtering
from time import sleep;
from time import time;
from TSSF import UIUtil
import datetime
from TSSF.UIUtil import Plot, PlotRefresh, Ask  # import ironplot as ip
from TSSF import Vector
from TSSF import ImageLab
import glob
import clr, System
import shutil
import random;
from Toolbox import Equipment;
import Toolbox;
from Caeleste.Instruments.Thorlabs import TDC001;

clr.AddReference("System.Windows.Forms");
clr.AddReference("Caeleste.Instruments.Thorlabs");

def position_array(mid_pos, range_pos, step_pos):
    p_array = [mid_pos - range_pos];
    while p_array[-1] <= (mid_pos + range_pos):
        p_array.append(p_array[-1] + step_pos);
    return p_array

class ModulationTransfer():
    """
    Routines needed to perform a modulation transfer measurements
    """
    def __init__(self, intensity=1e-6, tolerance=0.25):
        #Procedure data
        self.img_edge = "";
        self.col_st = 0;
        self.col_end = 0;
        self.row_st = 0;
        self.row_end = 0;
        self._diff = "" ;
        self.focus_position = 0;
        self.start_pos = 2.5;                    #initial position of motor stage
        self.roi = Vector(4);
        self.numpoints = 1000 ;
```

```
    # here we find the product data...
    soft_dir = os.path.join(os.environ['PROJECTDIR'], 'python')
    sys.path.append(soft_dir)
    try:
        from ChipProperties import product;
        self.chip = product();
        self.chip.load_testboard();
        self.project_dir = self.chip.sensorname;
        print "Sensor class initialized. Chip mode is %s" % self.chip.mode;
    except:
        self.chip = '';
        self.project_dir = 'unknown';
        print "Could not load the chip properties. Exiting"
        return;
    self.test_dir = "Modulation Transfer Function";
    self.NAS_dir = os.path.join("\\\\192.168.2.40", "Public", "BulkData");
    self.output_dir = os.path.join(self.NAS_dir, self.project_dir, self.test_dir);
    #Folder for current experiment
    self.image_dir = "";

    # stage initialization
    try:
        self.stagex = TDC001.Connect('83847325');
        print "ThorLabs stage is initialized successfully";
    except:
        print "ThorLabs stage is not initialized!";

    # saving desired light intensity and tolerance settings
    self.lint = intensity;
    self.tol = tolerance;

    # Initializing the equipment
    try:
        self.glsc = Equipment.GLSC();
        print "GLSC initialized successfully. Calling its calibration functions";
        self.glsc.InitInstrument();
        self.glsc.Calibrate();
    except:
        print "Could not initialize the GLSC";
    # ready
    print "MTF method ready";

def focus_area(self):
    """
    place the lens at appropriate position using motor stage so that image is more
    or less focused and position is defined by self.start_pos during class initialization
    """
    self.stagex.MoveAbsolute(self.start_pos);
    self.glsc.set_intensity(False, self.lint, self.tol);
    self.chip.capture_image();
    handle = "Focus Select"
    ImageLab.Plot(self.chip.image[:,:,1], handle);
```

```
    select = Ask("Please select ROI and type ok")
    if select == 'ok':
        area = ImageLab.GetSession(handle)["ROI1"].Area;
        self.roi[0] = area.Left;
        self.roi[1] = self.roi[0] + area.Width;
        self.roi[2] = area.Top;
        self.roi[3] = self.roi[2] + area.Height;
    else:
        print 'Please select ROI'
    return self.roi

def find_focus(self, range_, step):
    """
    Use the thorlabs stages to define the best focal distance.
    Place image with slanted edge to define the focal distance
    select a roi. With median calculate the max stddev
    Input:
        range_  <float> - scanning range in mm
        step    <float> - scanning step in mm
    Return: self.focus_position:
    """
    # grab image
    # get median image
    # select ROI
    # start focus
    # raw check finds max stddev
    self._diff = 0;
    self.focus_position = 0;
    # create position array
    position = position_array(self.start_pos, range_, step);
    # raw measurement
    for pos in position:
        self.stagex.MoveAbsolute(pos);
        print "stage position %4.3f [mm]" % pos;
        self.glsc.set_intensity(False, self.lint, self.tol);
        self.chip.capture_image();
        dummy1 = self.chip.image[:,:,0];
        dummy2 = self.chip.image[:,:,1];
        cds = dummy2 - dummy1;
        difference =
         (cds[int(self.roi[0]):int(self.roi[1]),int(self.roi[2]):int(self.roi[3])].MedianFilter(5) -
         cds[int(self.roi[0]):int(self.roi[1]),int(self.roi[2]):int(self.roi[3])]).stddev();
        if difference > self._diff:
            self.focus_position = pos
            self._diff = difference
    # fine tuning
    position = position_array(self.focus_position, 0.1, 0.05);
    for pos in position:
        self.stagex.MoveAbsolute(pos);
        print "stage position %4.3f [mm]" % pos;
        self.glsc.set_intensity(False, self.lint, self.tol);
        self.chip.capture_image();
```

```
        dummy1 = self.chip.image[:, :, 0];
        dummy2 = self.chip.image[:, :, 1];
        cds = dummy2 - dummy1;
        difference =
         (cds[int(self.roi[0]):int(self.roi[1]),int(self.roi[2]):int(self.roi[3])].MedianFilter(5) -
         cds[int(self.roi[0]):int(self.roi[1]),int(self.roi[2]):int(self.roi[3])]).stddev();
        if difference > self._diff:
            self.focus_position = pos;
            self._diff = difference;
    self.stagex.MoveAbsolute(self.focus_position);
    return self.focus_position;
    # save position data

def capture_images(self, range_, step):
    """
        Scans the distance with a thor The MTF method class.
        You have to make sure this will not go beyond
        Input:
            self.focus_position <float> - current position in mm
            range_ <float> - scanning range in mm
            step    <float> - scanning step in mm
    """
    # initializing the test board
    if self.chip.test_board==None:
        self.chip.load_testboard();
        self.chip.capture_image();
    else:
        self.chip.capture_image();
    if self.chip.test_board==None:
        print "AcquireImages(): Could not initialize the test system!";
        return;

    # Configuring folders for saving the data
    devpartnum = Ask("Enter the device part number please");
    image_type = Ask("Enter the image type (edge, dark or light)");
    experiment_type = Ask("Enter the edge direction (horizontal or vertical)");

    # setting the light off if the image type is 'dark'
    if image_type=='dark':
        self.glsc.light_off();
    devtemp = Ask("Enter the device temperature");

    # folder for current experiment
    self.image_dir = os.path.join(self.output_dir, "PartNum_%s" % devpartnum,
                                                    experiment_type, image_type);
    DirectorySwap(path_to_directory=os.path.join(self.output_dir, "PartNum_%s" %
                            devpartnum, experiment_type), directoryName=image_type);
    os.mkdir(os. path.join(self.image_dir, 'CDSed'));
    pos = [];
    pos = position_array(self.focus_position, range_, step);
    numsteps = len(pos);
    print "scan range from %.2f to %.2f mm with step of %.2f" % (pos[0], pos[-1], step);
```

```
        # allocating the memory;
        reset = Vector(self.chip.width, self.chip.height, self.chip.test_board.no_frames);
        signal = Vector(self.chip.width, self.chip.height, self.chip.test_board.no_frames);
        imgcdsed = Vector(self.chip.width, self.chip.height, self.chip.test_board.no_frames);

        # Running the loop to move motor stage and capture image
        for i in range(numsteps):
            print "Setting new stage position at %.2fmm" % pos[i];
            self.stagex.MoveAbsolute(pos[i]);
            if not(image_type=='dark'):
                # setting the intensity
                self.glsc.set_intensity(False, self.lint, self.tol);
            self.chip.capture_image(); # acquiring the images
            print "Capturing images...";
            # averaging to get rid of temporal noise
            for k in range(self.chip.test_board.no_frames):
                reset[:, :, k] = self.chip.image[:, :, k*2];
                signal[:, :, k] = self.chip.image[:, :, k*2+1];
                imgcdsed[:, :, k] = signal-reset;

            # saving the data
            tmp = reset.mean(2);
            file_name = 'PartNum_%s_%s_%s_reset_%.2fmm.png' % (devpartnum,
experiment_type, image_type, pos[i]);
            tmp.Save(os.path.join(self.image_dir, file_name));
            tmp = signal.mean(2);
            file_name = 'PartNum_%s_%s_%s_signal_%.2fmm.png' % (devpartnum,
experiment_type, image_type, pos[i]);
            tmp.Save(os.path.join(self.image_dir, file_name));
            tmp = imgcdsed.mean(2);
            file_name = 'PartNum_%s_%s_%s_%.2fmm.png' % (devpartnum, experiment_type,
image_type, pos[i]);
            tmp.Save(os.path.join(self.image_dir, 'CDSed', file_name));
        print "Scanning is finished, light source set off";
        self.glsc.light_off();
        print "Setting initial stage position (at %.1fmm)" % self.focus_position;
        self.stagex.MoveAbsolute(self.focus_position);

        # Preparing the log file
        ts = time();
        date_today = datetime.datetime.fromtimestamp(ts).strftime('%Y/%m/%d %H:%M ')
        header = "%s project %s measurement report\n" % (self.chip.sensorname, 'Modulation
Transfer Function');
        header += "Date %s\n" % date_today
        header += "Integration time setting %fs\n" % (float(self.chip.integration_time/1e7));
        header += "Sensor part reference (entered by user): %s\n" % devpartnum;
        header += "Sensor temperature (entered by user) is %sC degrees\n" % devtemp;
        header += "Sensor operating mode: %s\n" % self.chip.mode;
        header += "Sensor gain (capacitor) setting: %i\n" %
                    self.chip.seqc_parameters['gain_value'];
```

```
    #vcmsrc = Ask("Type common-mode voltage source please");
    vcmsrc = 'provided by testboard ADC';
    header += "Common mode voltage source: %s\n" % vcmsrc;
    header += "Number of frames per illumination point %i\n" %
              self.chip.test_board.no_frames;
    header += "Light source intensity setting = %eW/cm2, tolerance = %.2f%%\n" %
              (self.lint, self.tol);

    # adding the data to header
    header += "Distance range from %.2fmm to %.2fmm with step of %.2fmm\n" %
              (pos[0], pos[-1], step);
    header += "Number of steps in this experiment is %i\n" % numsteps;
    header += "Image type (edge, dark, light) is %s\n" % image_type;
    header += "Edge direction (if specified) %s\n" % experiment_type;

    ts = time();
    st = datetime.datetime.fromtimestamp(ts).strftime('%Y%m%d_%H%M_');
    # make sure a timestamp is included in filename
    filename = "MTF_PartNum=%s__%s.txt" % (devpartnum, st);
    f = open(os.path.join(self.image_dir, filename), 'w')
    f.writelines(header);
    f.close();

def correct_horizontal_image(self):
    """
    take ROI of the images and normalize, rotate and flip if needed
    """
    devpartnum = Ask("Enter the device part number please");
    image_type = 'edge';
    experiment_type = 'horizontal';
    # folder for current experiment
    self.image_dir = os.path.join(self.output_dir, "PartNum_%s" % devpartnum,
    experiment_type);
    path1 = os.path.join(self.image_dir, image_type, 'CDSed');
    os.chdir(path1);
    # set ROI
    # load edge image
    # load all the images for different position
    images = glob.glob1(os.getcwd(), "PartNum_%s_horizontal_edge*" % devpartnum);
    dummy_image = Vector.Load(self.images[0]);
    handle = "ROI Select"
    ImageLab.Plot(dummy_image, handle);
    cont = Ask("Please select ROI of at least 21 rows and type ok");
    if cont == 'ok':
       #keep in mind to change ROI number
       area = ImageLab.GetSession(handle)["ROI1"].Area ;
       self.col_st = area.Left;
       self.col_end = self.col_st + area.Width;
       self.row_st = area.Top;
       self.row_end = self.row_st + area.Height;
       dummy = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
       #transition = "check if transition from black to white yes or no?"
```

```
        if dummy[0,0] > dummy[0,(self.row_end - self.row_st)-1] :
            transition = 'no';
        else:
            transition = 'yes';
        # clear previous data
        self.img_edge = " " ;
        for image in images:
            suf_x = image.split('_');
            res = Vector.Load(os.path.join(self.image_dir, 'edge',
          "PartNum_%s_%s_edge_reset_%s" % (devpartnum, experiment_type, suf_x[4])));
            sig = Vector.Load(os.path.join(self.image_dir, 'edge',
          "PartNum_%s_%s_edge_signal_%s" % (devpartnum, experiment_type, suf_x[4])));
            dummy_image = sig – res;
            edge = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
            res = Vector.Load(os.path.join(self.image_dir, 'dark',
          "PartNum_%s_%s_dark_reset_%s" % (devpartnum, experiment_type, suf_x[4])));
            sig = Vector.Load(os.path.join(self.image_dir, 'dark',
          "PartNum_%s_%s_dark_signal_%s" % (devpartnum, experiment_type, suf_x[4])));
            dummy_image = sig – res;
            dark = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
            res = Vector.Load(os.path.join(self.image_dir, 'light',
          "PartNum_%s_%s_light_reset_%s" % (devpartnum, experiment_type, suf_x[4])));
            sig = Vector.Load(os.path.join(self.image_dir, 'light',
          "PartNum_%s_%s_light_signal_%s" % (devpartnum, experiment_type, suf_x[4])));
            dummy_image = sig – res;
            light = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
            edge_correct = (edge - dark)/(light-dark);
            edge_image = (edge_correct - edge_correct.min())/(edge_correct.max()-
                          edge_correct.min());
            if transition == 'no':
                if self.img_edge:
                    edge_image = edge_image.Rotate90CW();
                    self.img_edge = Vector(self.img_edge.Append(edge_image));
                else:
                    edge_image = edge_image.Rotate90CW();
                    self.img_edge = edge_image;
            if transition == 'yes':
                if self.img_edge:
                    edge_image = edge_image.Rotate90CW();
                    edge_image = edge_image.FlipV();
                    self.img_edge = Vector(self.img_edge.Append(edge_image));
                else:
                    edge_image = edge_image.Rotate90CW();
                    edge_image = edge_image.FlipV();
                    self.img_edge = edge_image;
    else:
        print 'ROI not selected'
    return self.img_edge

def correct_vertical_image(self):
    """
    take ROI of the images and normalize, rotate and flip if needed
```

```
"""
devpartnum = Ask("Enter the device part number please");
image_type = 'edge';
experiment_type = 'vertical'
 # folder for current experiment
self.image_dir = os.path.join(self.output_dir, "PartNum_%s" % devpartnum,
experiment_type);
path1 = os.path.join(self.image_dir, image_type ,'CDSed');
os.chdir(path1);
# set ROI
# load edge image
# load all the images for different position
self.images = glob.glob1(os.getcwd(), "PartNum_%s_vertical_edge*" % devpartnum)  ;
dummy_image = Vector.Load(self.images[0]);
handle = "ROI Select"
ImageLab.Plot(dummy_image, handle);
cont = Ask("Please select ROI of atleast 21 column and type ok");
if cont == 'ok':
    #keep in mind to change ROI number
    area = ImageLab.GetSession(handle)["ROI2"].Area;
    self.col_st = area.Left;
    self.col_end = self.col_st + area.Width;
    self.row_st = area.Top;
    self.row_end = self.row_st + area.Height;
    dummy = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
    #transition = "Is transition from black to white yes or no?"
    if dummy[0,0] < dummy[(self.col_end - self.col_st)-1,0] :
        transition = 'yes';
    else:
        transition = 'no';
    # clear previous data
    self.img_edge = " ";
    for image in self.images:
        suf_x = image.split('_');
        res = Vector.Load(os.path.join(self.image_dir, 'edge',
     "PartNum_%s_%s_edge_reset_%s" % (devpartnum, experiment_type, suf_x[4])));
        sig = Vector.Load(os.path.join(self.image_dir, 'edge',
     "PartNum_%s_%s_edge_signal_%s" % (devpartnum, experiment_type, suf_x[4])));
        dummy_image = sig – res;
        edge = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
        res = Vector.Load(os.path.join(self.image_dir, 'dark',
     "PartNum_%s_%s_dark_reset_%s" % (devpartnum, experiment_type, suf_x[4])));
        sig = Vector.Load(os.path.join(self.image_dir, 'dark',
     "PartNum_%s_%s_dark_signal_%s" % (devpartnum, experiment_type, suf_x[4])));
        dummy_image = sig – res;
        dark = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
        res = Vector.Load(os.path.join(self.image_dir, 'light',
     "PartNum_%s_%s_light_reset_%s" % (devpartnum, experiment_type, suf_x[4])));
        sig = Vector.Load(os.path.join(self.image_dir, 'light',
     "PartNum_%s_%s_light_signal_%s" % (devpartnum, experiment_type, suf_x[4])));
        dummy_image = sig – res;
        light = dummy_image[self.col_st:self.col_end, self.row_st:self.row_end];
```

```
            edge_image = (edge - dark)/(light-dark);
            edge_image = (edge_image - edge_image.min())/(edge_image.max()-
                          edge_image.min());
            if transition == 'yes':
               if self.img_edge:
                  self.img_edge = Vector(self.img_edge.Append(edge_image));
               else:
                  self.img_edge = edge_image;
            if transition == 'no':
               if self.img_edge:
                  edge_image = edge_image.FlipV();
                  self.img_edge = Vector(self.img_edge.Append(edge_image));
               else:
                  edge_image = edge_image.FlipV();
                  self.img_edge = edge_image;
      else:
         print 'ROI not selected'
      return self.img_edge;

   def create_ESF(self):
      """
      Calculate the ESF of the image
      return ESF vector:
      """
      # choose what kind of intercepted column values you want
      data = Ask("polyfit(for small pixel) or raw(for large pixel)");
      if data == 'polyfit':
         self.numpoints = 1000;
         self.ESF = Vector(2, self.numpoints, len(self.images));
         for n in range(len(self.images)):
            image = self.img_edge[:, :, n];
            #determining transition and threshold value
            self.col_interp = Vector(image.Height);
            self.polyval = Vector(image.Height);
            y_list = Vector(image.Height);
            x_list = Vector(image.Height);
            for row in range(0, image.Height):
               col = 0
               while image[col, row] < 0.5:                    #check for transition
                  col = col + 1
               threshold_col = col
               col_0=image[threshold_col, row];
               col_1=image[threshold_col-1, row];
               #transition position
               self.col_interp[row]=((threshold_col) +((col_0-0.5)/(col_1-col_0)));
               x_list[row] = row;
               y_list[row] = self.col_interp[row];
            #Polyfit transition position according to row number
            #perform 1st order polyfit
            poly = y_list.PolyFit(x_list, order = 1);
            for i in range(0,x_list.TotalSize):
               self.polyval[i] = poly[1]*x_list[i] + poly[0];
```

```
UIUtil.Plot(x_list,self.polyval,str(n),'polyfit');
plothandle = UIUtil.Plot('polyfit');
plothandle.XAxis.Title.Text = 'row number';
plothandle.YAxis.Title.Text = 'interpolated column number';
#2nd way by taking polyval
#21 pixels for each row
col_integer = Vector(21*image.Height);
col_exact = [];
col_sort = Vector(21*image.Height);
intensity_sort = Vector(21*image.Height);
row = 0;
j = 0;
k = 0;
for row in range(image.Height):
   for j in range(-10,11,1):
      col_integer[k] = self.polyval.Floor()[row] + j;
      exact = col_integer[k] - self.polyval[row];
      col_exact.append(exact);
      k = k + 1;
col_exact.sort();
j = 0;
k = 0;
row = 0;
intensity = [];
for row in range(image.Height):
   for j in range(0, 21):
      intensity.append(image[int(col_integer[k]), row]);
      k = k + 1;
   row = row + 1;
intensity.sort();
for i in range(21*image.Height):
   col_sort[i] = col_exact[i];
   intensity_sort[i] = intensity[i];
UIUtil.Plot(col_sort,intensity_sort, str(n), 'ESF');
#perform interpolation
i = 0;
j = 0;
k = 0;
col_start = math.ceil(col_sort.min()) + 1;
col_end = math.floor(col_sort.max());
step = ((col_end-col_start)/(float(self.numpoints-1)));
self.col_interpol = Vector.FromRange(col_start, step, self.numpoints);
intensity_interpol = Vector(self.col_interpol.TotalSize);
polyval2 = [];
for i in range(self.col_interpol.TotalSize):
   k = 0;
   polyval2 = [];
   dummy_x = Vector(2);
   dummy_y = Vector(2);
   for k in range(col_sort.TotalSize-1):
      if ((self.col_interpol[i] >= col_sort[k]) and (self.col_interpol[i] <=
         col_sort[k+1])):
```

```
                for j in range(2):
                    dummy_y[j] = intensity_sort[k+j];
                    dummy_x[j] = col_sort[k+j];
                    poly2 = dummy_y.PolyFit(dummy_x, order = 1);
                polyval2.append(poly2[1]*self.col_interpol[i] + poly2[0]);
                intensity_interpol[i] = polyval2[0];
        for i in range(self.col_interpol.TotalSize):
            self.ESF[0, i, n] = self.col_interpol[i];
            self.ESF[1, i, n] = intensity_interpol[i];
        UIUtil.Plot(self.col_interpol,intensity_interpol, str(n), 'ESF_interpol');
else:
    self.numpoints = 1000;
    self.ESF = Vector(2,self.numpoints,len(self.images));
    for n in range(len(self.images)):
        image = self.img_edge[:, :, n];
        #determining transition and threshold value
        self.col_interp = Vector(image.Height);
        self.polyval = Vector(image.Height);
        y_list = Vector(image.Height);
        x_list = Vector(image.Height);
        for row in range(0, image.Height):
            col = 0;
            #check for transition
            while image[col, row] < 0.5:
                col = col + 1;
            threshold_col = col;
            col_0=image[threshold_col,row];
            col_1=image[threshold_col-1,row];
            #transition position
            self.col_interp[row]=((threshold_col)+((col_0-0.5)/(col_1-col_0))) ;
            x_list[row] = row;
            y_list[row] = self.col_interp[row];
        #Polyfit transition position according to row number
        #perform 1st order polyfit
        poly = y_list.PolyFit(x_list, order = 1) ;
        for i in range(0, x_list.TotalSize):
            self.polyval[i] = poly[1]*x_list[i] + poly[0];
        UIUtil.Plot(x_list,self.col_interp,str(n),'raw');
        plothandle = UIUtil.Plot('raw');
        plothandle.XAxis.Title.Text = 'row number';
        plothandle.YAxis.Title.Text = 'interpolated column number';

        #2nd way by taking polyval
        col_integer = Vector(21*image.Height); #21 pixels for each row
        col_exact = [];
        col_sort = Vector(21*image.Height);
        intensity_sort = Vector(21*image.Height);
        row = 0;
        j = 0;
        k = 0;
        for row in range(image.Height):
            for j in range(-10, 11, 1):
```

```
            col_integer[k] = self.col_interp.Floor()[row] + j;
            exact = col_integer[k] - self.col_interp[row];
            col_exact.append(exact);
            k = k + 1;
    col_exact.sort();
    j = 0;
    k = 0;
    row = 0;
    intensity = [];
    for row in range(image.Height):
        for j in range(0,21):
            intensity.append(image[int(col_integer[k]),row]);
            k = k + 1;
        row = row + 1;
    intensity.sort();
    for i in range(21*image.Height):
        col_sort[i] = col_exact[i];
        intensity_sort[i] = intensity[i];
    UIUtil.Plot(col_sort,intensity_sort, str(n), 'ESF');

    #perform interpolation
    i = 0;
    j = 0;
    k = 0;
    col_start = math.ceil(col_sort.min()) + 1;
    col_end = math.floor(col_sort.max());
    step = ((col_end-col_start)/(float(self.numpoints-1)));
    self.col_interpol = Vector.FromRange(col_start, step, self.numpoints);
    intensity_interpol = Vector(self.col_interpol.TotalSize);
    polyval2 = [];
    for i in range(self.col_interpol.TotalSize):
        k = 0;
        polyval2 = [];
        dummy_x = Vector(2);
        dummy_y = Vector(2);
        for k in range(col_sort.TotalSize-1):
            if ((self.col_interpol[i] >= col_sort[k]) and (self.col_interpol[i] <=
                col_sort[k+1])):
                for j in range(2):
                    dummy_y[j] = intensity_sort[k+j];
                    dummy_x[j] = col_sort[k+j];
                poly2 = dummy_y.PolyFit(dummy_x, order = 1);
                polyval2.append(poly2[1]*self.col_interpol[i] + poly2[0]);
                intensity_interpol[i] = polyval2[0];
    for i in range(self.col_interpol.TotalSize):
        self.ESF[0, i, n] = self.col_interpol[i];
        self.ESF[1, i, n] = intensity_interpol[i];
    UIUtil.Plot(self.col_interpol,intensity_interpol, str(n), 'ESF_interpol');
plothandle = UIUtil.Plot('ESF');
plothandle.XAxis.Title.Text = 'pixel number';
plothandle.YAxis.Title.Text = 'intensity';
plothandle = UIUtil.Plot('ESF_interpol');
```

```
        plothandle.XAxis.Title.Text = 'pixel number';
        plothandle.YAxis.Title.Text = 'ESF_interpolated';
    return self.ESF;

def create_LSF(self):
    """
    Calculate the LSF of the image from the ESF
    return LSF vector:
    """
    self.LSF_filtered = Vector(2, self.numpoints, len(self.images));
    self.LSF = Vector(2, self.numpoints, len(self.images));
    for n in range(len(self.images)):
        for i in range(1,self.col_interpol.TotalSize-1):
            self.LSF[1, i, n] = 0.5*(((self.ESF[1, i+1, n] - self.ESF[1,i,n])/(self.ESF[0,i+1,n] -
            self.ESF[0, i, n])) + ((self.ESF[1,i,n] - self.ESF[1,i-1,n])/(self.ESF[0,i,n] -
             self.ESF[0, i-1, n])));
        UIUtil.Plot(self.col_interpol,self.LSF[1, :, n], str(n), 'LSF');
        self.LSF_filtered[1, :, n] = filtering.savgol_filter(25, 25, 2, self.LSF[1, :, n]);
         #perform filtering on LSF data using filter coefficient from savgol_filter
        UIUtil.Plot(self.col_interpol,self.LSF_filtered[1, :, n], str(n), 'LSF_filt');
    return self.LSF;
    return self.LSF_filtered;

def create_MTF(self):
    """
    Calculate the MTF of the image from the LSF
    """
    LSF_perfect = Vector(self.col_interpol.TotalSize);
    for i in range(self.col_interpol.TotalSize):
        if ((self.col_interpol[i] > -0.5) and (self.col_interpol[i] < 0.5)):
            LSF_perfect[i] = 1;
    UIUtil.Plot(self.col_interpol, LSF_perfect, '1', 'LSF_perfect');
    mtf_perfect = LSF_perfect.DFT().norm(0);
    mtf_perfect = mtf_perfect/mtf_perfect.max();
    UIUtil.Plot(mtf_perfect, 'MTF_perfect', 'MTF');
    UIUtil.Plot(mtf_perfect, 'MTF_perfect', 'MTF_filt');
    self.value = [];
    self.value_filt = [];
    for n in range(len(self.images)):
        mtf = self.LSF[1, :, n].DFT().norm(0);
        mtf = mtf/mtf.max();
        self.value.append(mtf[9]);          #9 is Nyquist frequency obtained from perfect MTF
        UIUtil.Plot(mtf, str(n), 'MTF');
    for n in range(len(self.images)):
        mtf_filt = self.LSF_filtered[1, :, n].DFT().norm(0);
        mtf_filt = mtf_filt/mtf_filt.max();
        self.value_filt.append(mtf_filt[9]) #9 is Nyquist frequency obtained from perfect MTF
        UIUtil.Plot(mtf_filt, str(n), 'MTF_filt');
    return self.value;
    return mtf;
```

7.3.Camera Link and Frame Grabber

The camera link is a standard serial communication protocol designed for computer vision applications based on National Semiconductors interface channel link (C-link). It is used for transferring high-speed data.

A frame grabber is an electronic device that captures (i.e., "grabs") individual, digital still frames from an analog video signal or a digital video stream. It is usually employed as a component of a computer vision system, in which video frames are captured in digital form and then displayed, stored or transmitted. At Caeleste, the frame grabber is a PCI Express (Peripheral Component Interconnect Express) card with camera link interface, but other interfaces also exist.

7.4.Three Point Derivative Method

The derivative of a function is defined as-

$$f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h} \tag{7.4-1}$$

While h is small enough, we can use a centred difference formula to approximate the derivative:

$$f'(x_i) \approx \frac{f(x_i+h) - f(x_i-h)}{2h} \tag{7.4-2}$$

In practice, Origin (software) treats discrete data by the transform centred difference formula, and calculates the derivatives at point P_i by taking the average of the slopes between the point and its two closest neighbours.

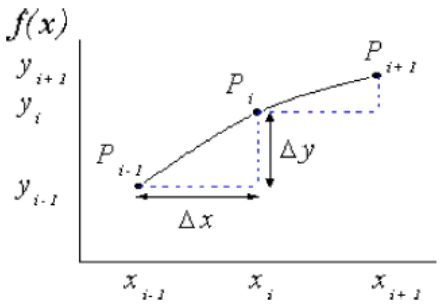

Figure 7.4-1- Three-point derivative method.

The derivative function applied to discrete data points can therefore be written as-

$$f'(x_i) = \frac{1}{2}\left(\frac{y_{i+1} - y_i}{x_{i+1} - x_i} - \frac{y_i - y_{i-1}}{x_i - x_{i-1}}\right) \tag{7.4-3}$$

7.5.SeqC

It is an in-house software tool at Caeleste. The SeqC (sequence compiler) is a software tool that compiles a formal textual description of a set of digital waveform sequences in a binary executable. This executable can be used to run on test system hardware or used to generate waveform plots or simulation files.

The main idea behind the tool is to provide a very simple unified way to generate a formal description of a waveform sequence. The Figure 7.5-1 shows the relation between different systems and how SeqC compiler generates binary code from textual description.

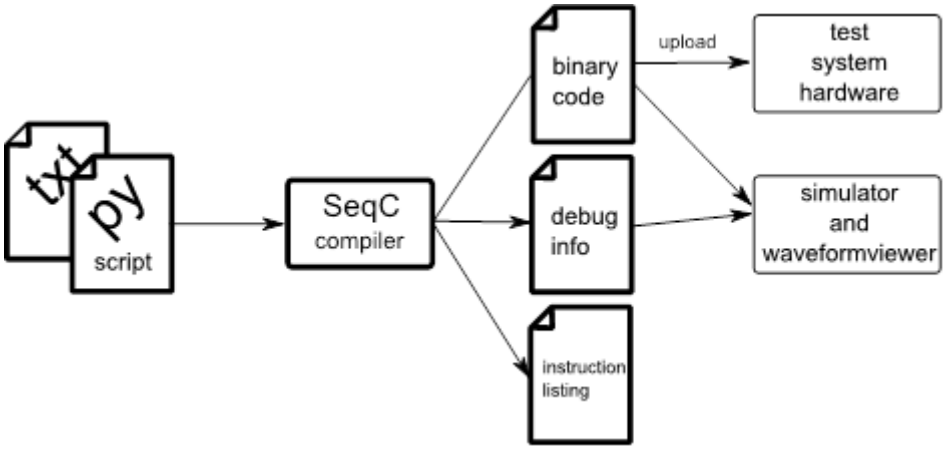

Figure 7.5-1-SeqC compiler generates binary code from textual description of sequences.

7.5.1. SeqC builder

Seqc builder is a graphical frontend for the SeqC compiler, simulator and waveform viewer. The Figure 7.5-2 below shows a snapshot of the SeqC builder.

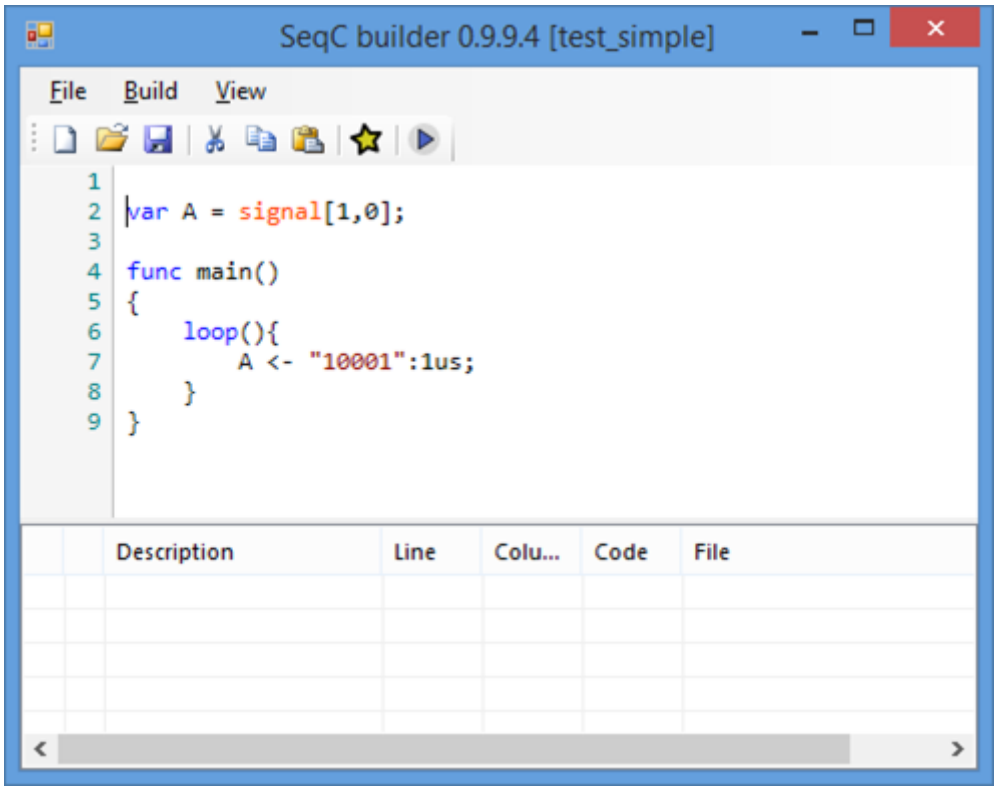

Figure 7.5-2- Frontend of a SeqC builder.

The SeqC builder tool has a built-in waveform viewer which is shown in the Figure 7.5-3:

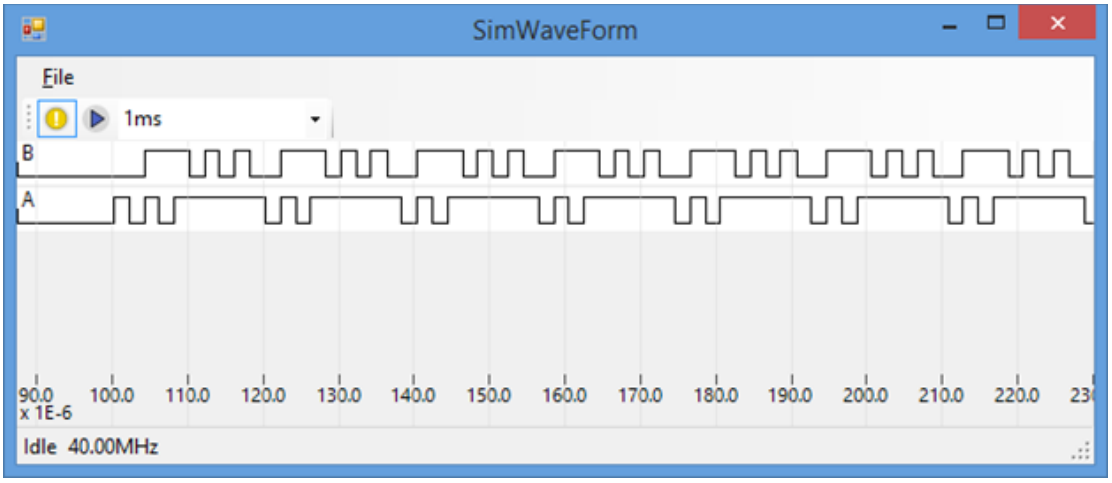

Figure 7.5-3- Waveform viewer of SeqC.

7.6.List of Acronym

ADC	Analog-to-Digital Conversion
APS	Active Pixel Sensor
BSI	Back Side Illuminated
CCD	Charge-Coupled Device
CDS	Correlated Double Sampling
CG	Conversion Gain
CVF	Charge to Voltage Factor
CMOS	Complementary Metal-Oxide-Semiconductor
DCNU	Dark Current Non-Uniformity
DR	Dynamic Range
DSNU	Dark Signal Non-Uniformity
FD	Floating Diffusion
FPN	Fixed Pattern Noise
FSI	Front Side Illuminated
FWC	Full Well Capacity
HDR	High Dynamic Range
MTF	Modulation Transfer Function
NL	Non-Linearity
PID	Proportional Integral Derivative

PPD	Pinned Photodiode
PPS	Passive Pixel Sensor
PRNU	Photo Response Non-Uniformity
PSD	Power Spectral Density
PWL	Piecewise Linear
QE	Quantum Efficiency
SNR	Signal to Noise Ratio
SPI	Serial Peripheral Interface
STI	Shallow Trench Isolation
S/H	Sample and Hold