Optical Equalization Analysis for Position-Sensitive-Detector of the Type Quad-cell

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ABSTRACT

This paper presents an analysis methodology and experimental results to discover how to equalize a Position-Sensitive Detector (*PSD*) of the type quad-cell (*QC*), using four photodiodes with Active-Pixel Sensor (*APS*) circuit, in CMOS AMS 0.35µm technology. One of the boundary conditions to use a *QC* in applications is to determine how equal the responses of its photododiodes are. To develop this process a new parameter was determined the *equalization percentage*. The methodology presents an adjustable level of precision in order to meet demand of a wider range of users. A more uniform response for high intensities of light was observed in the analysis over the results.

Keywords

Quad-cell, photodetectors, PSD, Active Pixel Sensor, CMOS analog integrated circuits, light sensors.

1. INTRODUCTION

The need to find ways to determine the position of structures in space has increased with the development of new technologies, for example in tracking systems used in virtual reality applications [1] and industrial positioning systems [2].

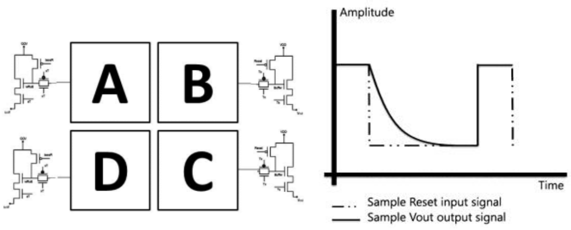
In these situations it is interesting to use position-sensitive detector (*PSD*). A *PSD* is a component capable of detecting a light beam (spot) on its surface and output measurable data that can be treated and adjusted to inform the spot's position [3]. A *QC* is a type of *PSD* comprised for four pixels, organized symmetrically. The pixel is the smallest optical element necessary to detect light, and is comprised of a photodetector and an amplifying circuit.

The construction process of a component with dimensions and materials as the ones of a detector based on photodiode sometimes implies on imperfections that can change the expected results. That being so, it is indispensable to know how reliable the results to endorse the overall work are. This verification plays a vital role on the basis of projects that employ a *QC* as a position detector, which is motivated by the need to measure minimal mechanical oscillations and deviations [4,5]. The objective of this article is to discuss and explain a technique to analyze the variations in the response of each photodiode from a *QC* and how to proceed in order to use it as a reliable detector in our main project.

2. QUAD-CELL OPERATION

A *QC* along with its pixels is represented on Figure 1a. There are several construction possibilities for the pixel, which is the smallest entity capable of detecting light. The type used here is the Four-Transistor Active Pixel Sensor (*4T APS*), composed by a photodetector and a control-amplifying circuit (Figure 2). That type of pixel in particular was chosen for its simple but versatile design which offers broad possibilities of control through its transistors and because it is already used in the laboratory, allowing it to be handled with relative ease, given the support granted. The pixel control is done using three transistors inputs: a *Reset* gate; a selection gate (T_s) and a transfer gate (T_x), sending signals on a sample and hold fashion [6]. The Buffer transistor is used for providing an output proportional to the voltage on the photodiode. Basically, the photodiode, while exposed to light or due to reverse dark current, continuously discharges an internal capacitance. That capacitance is only charged when the *Reset* input is on. The four transistors topology implements a T_x responsible for bridging the photodiode to the rest of the circuit. Its effect is to enable multiple non-destructive read-outs. To enable the pixel's output multiplexing, there is a T_s that bridges the pixel buffer with the data bus. However, in this work T_x and T_s are always active (for they are not needed in this application). Considering all that, what is observed at the output is a discharge of the photodiode proportional to the intensity of the light beam that is incident over its surface. That discharge acts on the Buffer gate and yields, if T_s is enabled, a V_{out} voltage value at the data line. V_{out} is the output that will be measured.

The V_{out} must be proportional to the capacitor discharge. When a square wave signal is applied to the *Reset* gate, what occurs once the signal is low is exactly that discharge. When *Reset gate* signal is high, the internal capacitance is recharged and the process restarts. What was described here can be visualized in Figure 1b.



a) b)

Figure 1. 1a Quad-cell representation with its electronic circuits. 1b Sample decay curve of a photodiode.

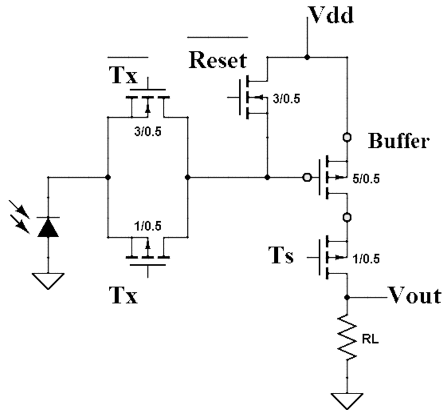


Figure 2. Basic diagram of the 4T APS

3. ANALYZING THE RESPONSE FROM THE *QC*

First, it was necessary to search for statistical tools which could provide sufficient parameters to judge if each pixel, inside an arbitrary range, was responding equally to the others, condition which defines the equalization. With the assistance of concepts like average $\langle X \rangle$, standard deviation σ (1) and coefficient of variation (*Cv*) (2) of each pixel sample, we developed an algorithm to obtain the *Equalization Percentage* (*EP*). The *Equalization Percentage* quantifies the equalization difference between the responses of the four photodiodes of the *QC.*

$$\sigma = \sqrt{\frac{\sum_0^n (X_n - \langle X \rangle)^2}{n}} \quad (1)$$

$$Vc = \frac{\sigma}{\langle X \rangle} \quad (2)$$

For each pixel, 1320 values were collected over time with 10 periods. For each period were obtained 132 points used to calculate an average period. Simultaneously, for each point, was calculated the standard deviation and the coefficient of variation. Thus, we obtain an average period with σ and *CV* for the 132 points of the response curve for each pixel. The average is calculated to minimize the multiple sources of noise influence.

An example period for the four photodiodes is shown on Figure 3, for a low intensity of light on Figure 3a and for high intensity on Figure 3b.

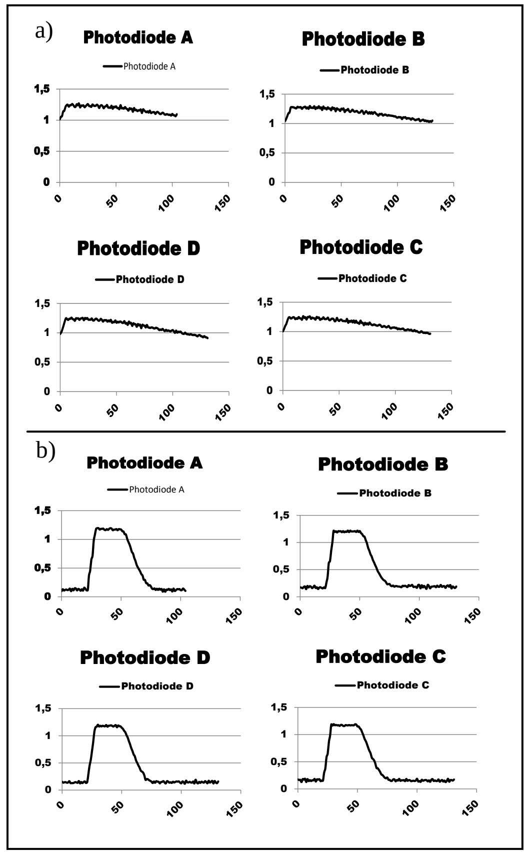
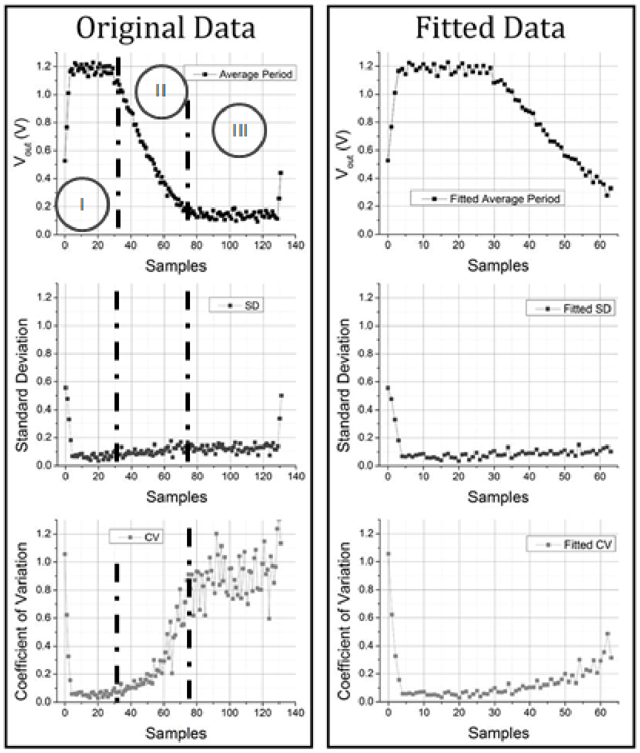


Figure 3. 3a Graph of data for low intensity of light. 3b Graph of data for high intensity of light.

On Figure 4a the average curve, its σ and *CV* are presented. The mean curve is composed by three parts, indicated on the figure. The region I is not used in the analysis because the internal capacitance of the photodiode is loaded. The region II is the one of interest, as it contains the decay curve, with the information about the variation of the intensity of light. On the region III it was registered a high value for the *CV* and for *σ*, which indicates high noise interference. This interference region is not useful for the study, thus it was removed. The criterion used for the elimination of region III on the algorithm was the *CV* that rises substantially only in this region. Therefore, a new curve with less interference was obtained, which contained the region of interest for this study Figure 4b. This selected section of the signal carries the information about light's intensity, which is obtained from the curve's inclination.



a) b)

Figure 4. Chart representing the steps of the methodology. 4a. Samples studied in its original form. 4b. Samples studied after reducing the noise

After this procedure it was possible to compare the curves obtained for each pixel of the *QC*. To compare them it was mandatory for them to have an equal amount of sample points. The one with the smaller quantity determined the number of points that would be used. Then, each point, referring to a certain instant, from the four curves, would be studied together.

To be classified as a selected point, which can be represented on a Boolean form as “true”, a given point from the pixel A response signal (Figure 1a) should be in the range of σ of the pixels B, C and D, in that same instant. Similarly, this procedure has to be applied over for each of the other pixels. Then, if in this specific instant, the points of all pixels are accepted, the point is classified as “true”. This procedure was repeated for different instants until the entire curve was analyzed. If any point did not fit in σ range, it would be labeled as reproved, or “false”.

To allow more flexibility to the algorithm, the Selection Factor (*SF*) was created. It consists of a divider factor for σ that is used to modify its range. This way, a higher *SF* gives a narrower range of σ, enabling fewer points to be marked as “true”. The opposite is also true; a lower *SF* gives a broader range and more points accepted. The chosen value for the *SF* depends on the aim of the work, and so, the user is in charge of choosing an acceptable value for the parameter.

The Quad-cell Equalization Percentual (*EP*) can be calculated, after deciding on a value for the *SF*, relating the number of points classified as “true” and the total amount of points analyzed on the curve, through a simple division. The final number, multiplied by 100 will be in percentage, indicating how much acceptance there was between the curves under a certain stimulus. Doing that, it is possible to determine if this number is sufficient to classify the intensity as one where the *QC* worked in an equalized way.

4. EXPERIMENTAL SETUP

The setup needed for the experiment in this study is represented on Figure 5. A printed circuit board (*PCB*) (1) was projected and built to access all the gates and get usable data from the chip that contains the *QC*. To measure and treat the data outputted by the *QC*, an Arduino DUE board (2) is used as a Data Acquisition device and controlling interface. It has a PWM generator that is online configured to 20 % of duty-cycle and 500 Hz (*Reset* gate frequency). The board collects two thousands values from each *QC* pixel in about 31.1 ms, packs all the values acquired and sent to a computer through a USB cable. The packaged data is then treated using LabVIEW software, where the processed and stored information can be converted into graphics, with 132 values of voltage per period displayed on the screen, and processed by our algorithm.

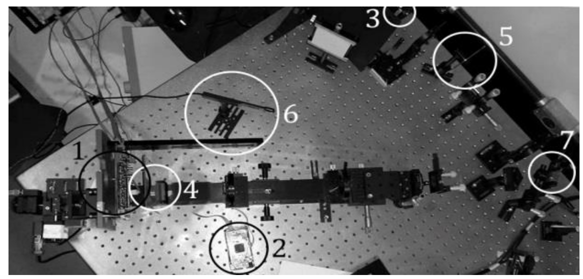


Figure 5. Optical table with the instruments and devices used for the experiment: 1-Chip’s *PCB*; 2-Arduino microcontroller board; 3-Laser source; 4-Etched glass; 5-Intensity filter; 6-Light power meter; 7-Beam splitter.

The light beam with wavelength 632.8 nm is obtained by He-Ne laser (3). The etched glass (4), used to homogenize the light that reaches the *QC*, spreading it over the four photodiodes. The laser beam is treated to minimize diffraction effects before it reaches an etched glass. This procedure is done to reduce noise and ensure that any variation observed comes from the detectors. With the polarizing filter (5) it is possible to obtain different intensities of light.

A power meter (6), with an active area of 73.9 mm² was used to measure the laser’s power. Once we know the power over the device the light’s intensity can be calculated. The power meter was placed as close to the *PCB* as possible without touching it. To obtain the light’s intensity on the *QC* we divided the power value registered by the active area of the device. On our setup there is also a beam splitter (7), which allows more than one project to be developed using the same light source.

During the experiment, the room temperature was of 25.0 ºC. Then, the minimum and maximum values of intensity of light that reached the *QC* (limited by intensity filter and laser) were between 148.8 mW/m² and 945.9 mW/m². Given this range, seventeen equally spaced values of intensity were tested in our experiment.

Starting from the lowest value of intensity, the procedure was done for all the selected intensities. The highest value could be obtained by adjusting the polarized filter to pass the minimum of light through it.

After organizing the filter, the intensity is registered through the placement of the power meter, and the microcontroller collects the output from the V_{out} node. To treat the data we applied the method described on the previous sections processing it by using two *SF* values chosen for the experiment 0.5 and 1.0.

5. RESULTS

Using the presented methodology we were able to produce useful data to lead to the equalization of a *QC* in order to enable it to function as a position detector.

On Figure 6, a linear tendency curve was traced for better visualization. An important pattern was observed in both of them: the *QC*'s response was more equalized for higher light intensities, but the existence of an undesirable oscillation on it is visible. As expected, the results when the *SF* 0.5 was chosen were less selective than the ones when the *SF* 1.0 was chosen.

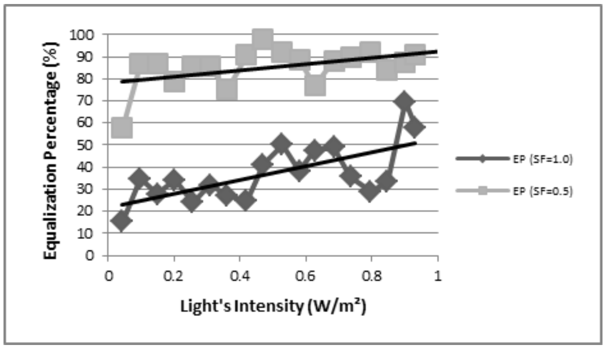


Figure 6. Results for different values of Standard Deviation.

The results indicate that, if we use a high *SF*, for lower intensities the percentages of equalization obtained are lower, meaning that they will most certainly be discarded from every application. But, as we can see on Figure 6, for lower SF values, even lower intensities show percentages as high as ones from higher intensities. That means that even with the pattern registered, some intensities can diverge, indicating that the *QC* can have a reasonably equalized response under them. Therefore, for lower intensities, a more accurate study can be made only if the *SF* is lower, enabling us to see these divergences.

After further analysis, in the search for the source of the oscillation, the algorithm was observed to give a variable percentage for the same intensity of light due to the selection process of the total number of points, which varies according to the noise, which is more prominent at high intensities of light. However, this can be minimized by making few modifications in the method, a procedure that is already in progress. Given that, better results are shortly expected.

It is important to notice that, to build this methodology, approximations were required. For example, there is no guarantee that the light spot is actually reaching the *QC* on a homogeneous form, but we assume that the etched glass is sufficient to lead to a homogeneous spot. Another approximation taken was with the instants where the points from the curve were compared, because the microcontroller used in the experiment does not collect the points in a fixed time. In other words, the points compared were not from the same instant for all of the pixels. That is why, in the analysis, it is important to work with the standard deviation, as it provides us a way to work with the uncertainty of the data.

6. CONCLUSION

On a *QC*, the proportion of light intensity in each quadrant is quantified and used to determine the spot position. Being that so, it is ideal for all four photodiodes in the *QC* to have a similar response for the same intensity; else the position acquired cannot be trusted. Therefore, before using a *QC* as a position detector, equalization is a very important step.

The process developed provides the *Equalization Percentage*, what allows quantify the relative difference between the photodiodes on the same *QC* to make experimental decisions.

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