

# Fast MTF measurement of CMOS imagers at the chip level using ISO 12233 slanted-edge methodology

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## ABSTRACT

MTF measurement methods for imaging devices usually require the use of an optical system to project the image of the object onto the detector. So, MTF results quality strongly depends on the accuracy of the optical adjustments (alignments, focusing...). Dedicated edge patterns have been implemented at the chip level on a CMOS imager. One of them emulates the target used in the ISO 12233 slanted-edge technique and the others one are inspired by the knife-edge method. This allows to get the MTF data without optical focusing. In order to validate the results, comparisons have been made between MTF measurements using these patterns and results obtained through direct measurements with the transmissive slanted-edge target and sine target.

**Keywords :** CMOS Image Sensors, Modulation Transfer Function, Slanted-Edge method

## 1. INTRODUCTION

Image quality is one of the most important characteristics for all image sensing systems and the Modulation Transfer Function is a common metric used to quantify it. It is defined as the modulus of the Optical Transfer Function (OTF) which is the Fourier Transform of the impulse response of the system. It defines the ability of an optical system to resolve a contrast at a given resolution (or spatial frequency). Traditional methods for MTF measurements (sine target or bar target utilization, slit or knife-edge technique) were initially designed for devices forming continuous images. However, these techniques can give erroneous MTF results, due to the fact that the sampling of digital devices is not properly taken into consideration. Additionally, MTF results can depend on the chosen technique.

In the case of an image sensor, the MTF is a combination of different MTFs, each degrading the overall performance of the device. The main components are the geometric and the diffusion MTFs. The first one takes into account the influence of the pixel size (giving the spatial sampling frequency) but also the photosensitive area size and shape. The diffusion MTF describes the image degradation due to optical crosstalk between adjacent pixels.

In CMOS sensors, the fill-factor is less than 100 percent. In fact, the pixel contains several distinct areas : the photosensitive element (photodiode or photogate), the readout circuitry (MOS transistors) and some opaque mandatory patterns (metal line, contact, vias...) as illustrated in figure 1.

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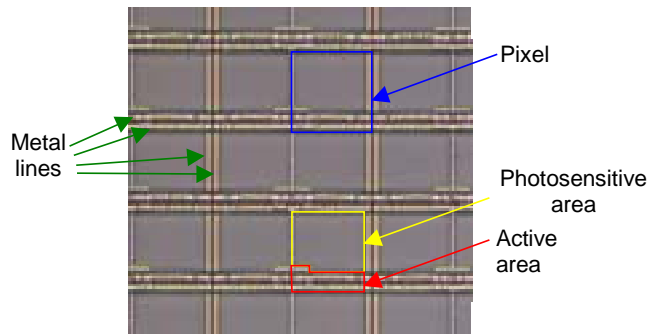


Figure 1 : Photograph of  $20\mu\text{m} \times 20\mu\text{m}$  pixels

Optical transmission is not homogenous on the entire pixel area and the readout circuitry area affects slightly the signal of the pixel. Moreover, photosensitive and readout elements can have various shapes in the pixel, which induces different MTF in the two main directions (horizontal and vertical).

Due to the influence of various parameters in the case of CMOS image sensors, modeling MTF is very difficult and measurements at different wavelengths are required in order to get a better knowledge of pixel organization import.

Traditional measurement methods are now well-established but still present some disadvantages, the main one being the long measurement time. The ISO 12233 methodology [1] has been established in order to provide a fast MTF measurement method based on only one image. In such a standardized way, the MTF data from various digital input devices may be easily and correctly compared. Although the ISO 12233 slanted edge methodology was originally designed mostly for digital still cameras MTF evaluation, it can successfully be applied at the image sensor level [2].

Projection MTF measurement methods, including slanted-edge method, require a specific setup and a rigorous focusing procedure, implying a long measurement time. In order to obtain MTF results without using optical focusing, dedicated edge patterns, emulating the target used in the ISO 12233 technique and knife-edge method, have been implemented at the chip level on CMOS photodiodes pixels arrays ( $13\ \mu\text{m}$  pixel pitch, 2P3M  $0.35\mu\text{m}$  technology). These on-chip patterns, if proved efficient in term of MTF measurements, would be potentially adapted in order to obtain instantaneous MTF data of any CMOS imagers.

Section 2 describes ISO 12233 methodology and makes the comparison with others measurement methods. Section 3 presents the patterns implemented on the sensor and their advantages with regard to sine and slanted-edge target methods. MTF measurements have been made at different wavelength (500, 580, 650 and 800nm) with the previous methods and results are presented in section 4.

## 2. SLANTED-EDGE METHODOLOGY

In this section, we describe the measurement method employed in the ISO 12233 and the software which computes the MTF. We compare this method to the other ones, particularly to sine target method.

### 2.1 SLANTED-EDGE METHOD

The International Standard 12233 specifies methods for measuring resolution of electronic still-picture cameras and defines a test chart for performing these measurements. It allows the evaluation of visual resolution, limiting resolution, aliasing ratio, spatial frequency response, compression artifacts...

Slanted-edge method consists in imaging an edge onto the detector, slightly tilted with regard to the rows (or the columns) [3]. So, a vertically oriented edge allows to obtain 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. These ESF are undersampled but it is possible to increase mathematically the sampling rate by projecting data along the edge. The

figure 2 represents the target used to apply slanted-edge method. It is a transmissive prototype target made on Kodak 35mm film.

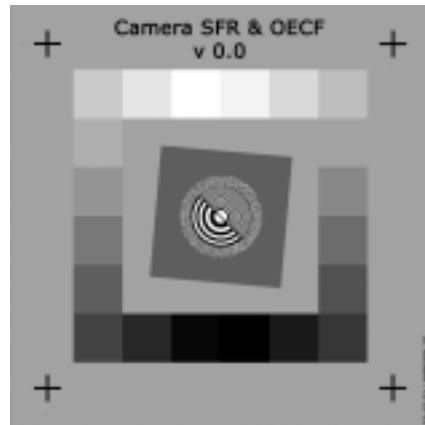


Figure 2 : Slanted-edge prototype target

From slanted-edge image given by the detector, the associated software (Matlab) computes the SFR. By selecting a rectangular region-of-interest (ROI), the region over which the calculations are done is defined, as shown in the figure 3.

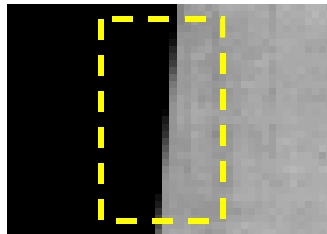


Figure 3 : Selected ROI

Edge is located for each line of the selected ROI so the slope can be calculated. Data of each line are projected along the edge direction and accumulated in 'bins' whose width is less than the pixel pitch.

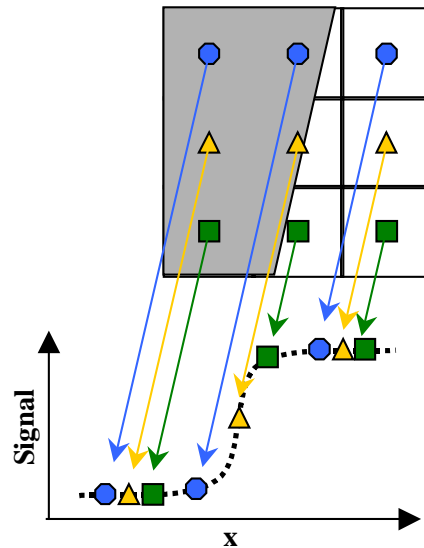


Figure 4 : Projection of data along the edge

The oversampling factor, determining the width of the bins, is equal to 4 by default but can be modified by the user. This process increases the sampling rate by forming a supersampled ESF and reduces the influence of signal aliasing of the measured SFR. The resulting ESF is then derived to get the LSF. The figures 5 and 6 show the ESF and LSF computed from a ROI of 15x25 pixels (10µm pitch, 0.25µm technology) with an oversampling factor of 4.

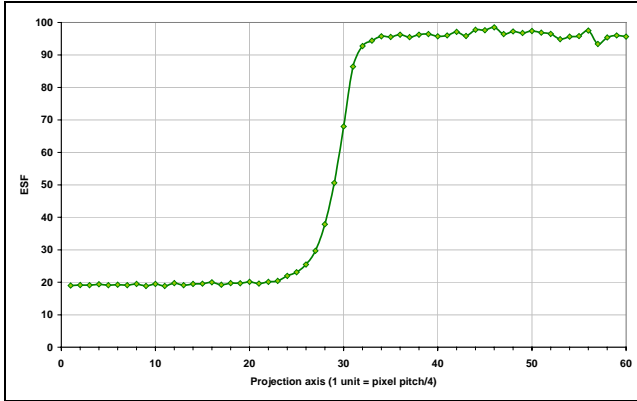


Figure 5 : Computed ESF by projecting data along the edge

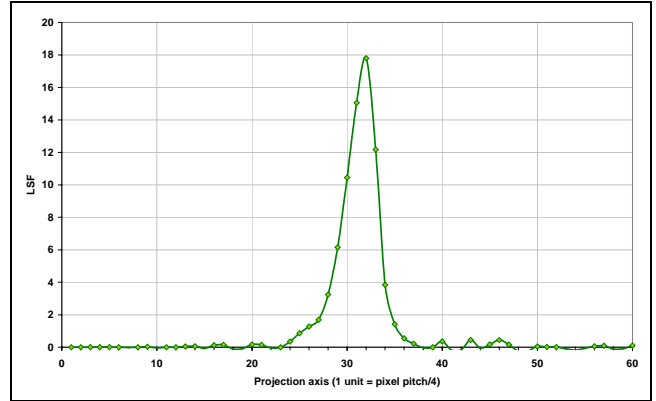


Figure 6 : LSF (derived from ESF)

To reduce the effects of the Gibbs phenomenon that results from truncation of an infinite series, a Hamming window is applied to the LSF. The system SFR can then be computed by a Fast Fourier Transform. The system MTF is deduced of the system SFR by the relation :

$$MTF_{\text{system}}(f, \lambda) = \frac{SFR_{\text{system}}(f, \lambda)}{FR_{\text{target}}(f) \times MTF_{\text{deriv}}(f)}$$

First, the frequency response of the target  $FR_{\text{target}}$  must be taken into account. It can be approximated by a polynomial so dividing frequency-by-frequency  $SFR_{\text{system}}$  by  $FR_{\text{target}}$  is easy. Furthermore, it is also necessary to correct errors due to the 3-point derivation process that has been applied by dividing by a corrective factor  $MTF_{\text{deriv}}$  (equivalent to an MTF).  $MTF_{\text{deriv}}$  is given by [4]:

$$MTF_{\text{deriv}}(f) = \frac{\sin(\pi\delta kf)}{(\pi\delta kf)} \quad \text{with} \quad \left\{ \begin{array}{l} \delta = \frac{\text{pixel pitch}}{\text{oversampling factor}} \\ k = 2 \text{ (for the 3-point derivative)} \end{array} \right.$$

It is represented on the figure 7 for an oversampling factor of 4. Spatial frequencies are normalized with regard to the sampling frequency which is defined as follow :

$$\text{Sampling frequency} = \frac{1}{\text{Pixel pitch}}$$

$$\text{Nyquist frequency} = \frac{1}{2 \times \text{Pixel pitch}}$$

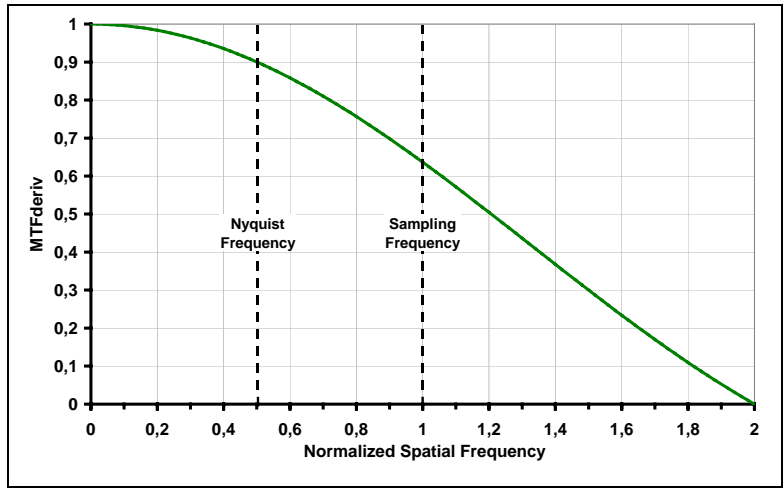


Figure 7 : Derivative error MTF (corrective factor)

As can be seen, this derivation can have an important effect on the measured SFR, that must be removed.

The system SFR depends on the value of the edge-tilting angle and allows to obtain the system MTF at this angle. It has been shown [2] that system MTFs obtained with small angles (up to 10°) are very close. In fact, smaller is the angle and better is the horizontal (or vertical) MTF approximation (the ISO 12233 standard recommends an angle of 5°).

**2.2 COMPARISON OF THE METHODS**

MTF measurement using the knife-edge method, as with a slit or a point source, needs one image for each object position (number depending on the desired sampling). It's the same for the sine target method which need at least one image (depending on the number of pixel) for each spatial frequency. As focusing is required after each displacement of the target, the measurement time is depending on the desired number of point in the resulting MTF curve. MTF measurements using the slanted-edge target need only one focusing process per wavelength since one image is sufficient to compute the entire SFR. The figure 8 represents the system SFRs obtained at 500nm for different distances between the detector and the lens.

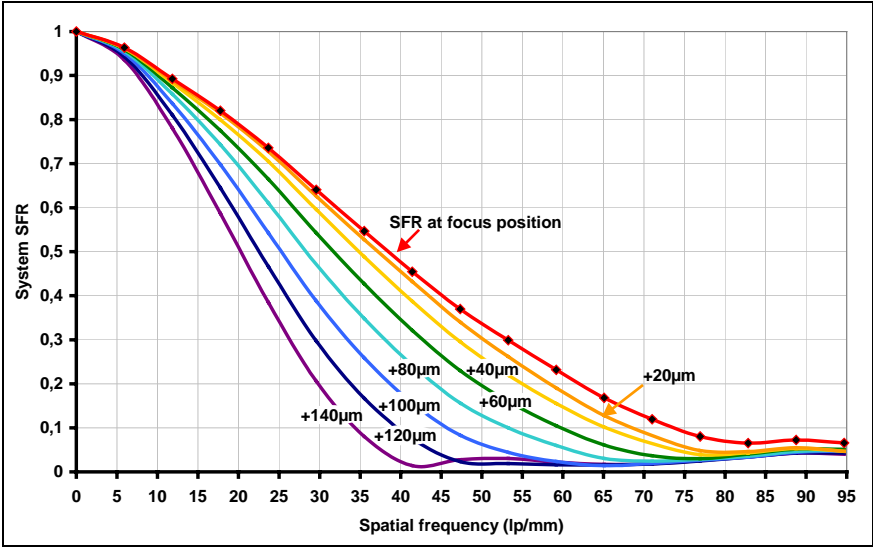


Figure 8 : System SFR dependency on focusing

So, the main advantage of the slanted-edge compared to others method is that it only requires a single image and so no displacement, thus giving a fast result. Measurement time is reduced, reducing the temperature stability requirement.

Constraints on vertical and horizontal alignments are reduced as tilted angle has only to be small enough to provide a good approximation of the horizontal (and vertical) MTF.

As a key point, this method doesn't require a large number of pixels. This number must be sufficient to compute a good ESF so smaller is the angle, bigger must be the ROI. The sine target method implies that at least one period of the sinus must be imaged onto the detector to compute the contrast. This can require a large number of pixels, especially for low spatial frequencies. So, slanted-edge method needs generally less pixels than sine target method. This property is really favorable when MTF measurements have to be made on test structures that are usually small structure arrays.

### **3. MTF DATA FROM ON-CHIP METAL PATTERNS**

#### **3.1 PROJECTION METHODS DISADVANTAGES**

All the techniques presented previously do require the mounting of a specific optical setup to measure the detector MTF. Although using the slanted-edge method reduces alignment constraints, some optical adjustments are always required. In fact, the detector must be strictly aligned with the lens, the object and the source and the planes must be parallels.

With regard to the focusing, for very low spatial frequencies, the contrast is nearly independent of the distance but it can be seen (figure 8) that a slight focusing error may produce an important error in the resulting contrast (or SFR).

The system MTF, once calculated, must be divided by the lens MTF in order to obtain the detector MTF. This one can be deduced of a Zemax simulation, performed at the wavelength and the working distance used during the measurements. It is obvious that the real lens MTF is not exactly as given by Zemax so this is an additional error source.

So, MTF results are strongly dependent on the good alignments and focusing and detector MTF values may be erroneous by lens MTF.

#### **3.2 METAL PATTERNS DESCRIPTION**

In an attempt to simplify MTF measurements, we have implemented test patterns at the chip level. These ones emulate the slanted-edge and knife-edge method, whose patterns can be easily reproduced. The on-chip patterns would allow getting quickly MTF data without the use of an optical setup, avoiding for a long measurement time and numerous measurement errors.

The metal patterns are implemented on photodiodes pixels array (128x128 pixels, 13  $\mu\text{m}$  pixel pitch, 2P3M 0.35 $\mu\text{m}$  technology). They are made with the upper metal layer so they are located at some microns above the silicon surface. The figures 9 and 10 show a photograph of the array and an image obtained from the sensor.

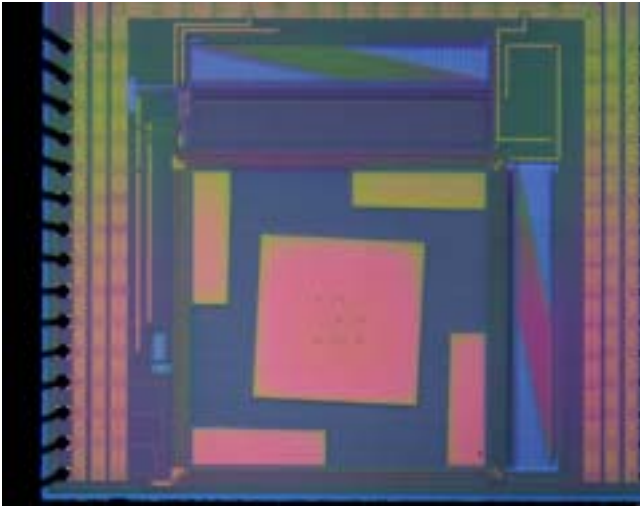


Figure 9 : Photograph of the chip

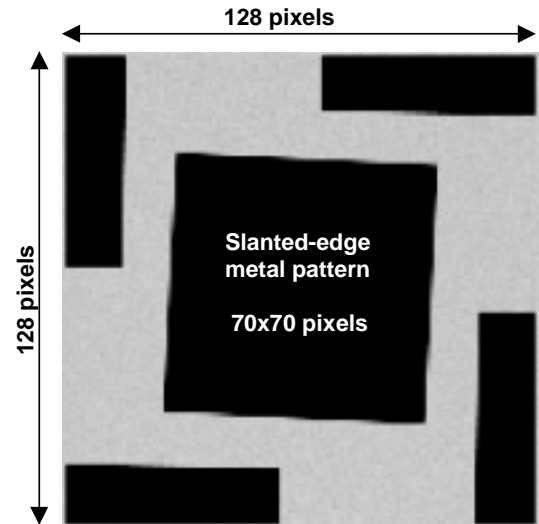


Figure 10 : Image given by the array

An inclination angle of about  $3^\circ$  has been chosen for the slanted-edge pattern in order to get the better approximation of the detector horizontal and vertical MTF. Due to the low value of the angle, the metal pattern must be large enough to get a sufficient number of cycles, required to compute a correct ESF. Using 70x70 masked pixels allows us to obtain nearly four cycles. The figure 11 shows the ESF obtained using an oversampling factor of four.

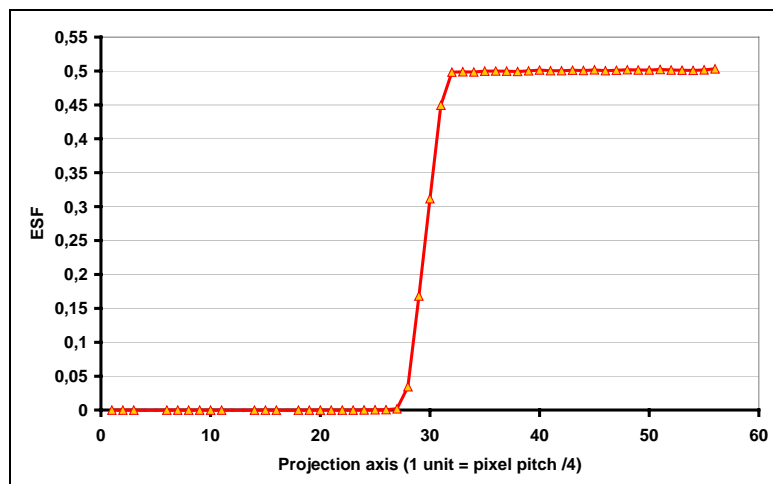


Figure 11: ESF computed from slanted-edge pattern (horizontal direction)

On the four others metal patterns (located in the corners), the edge is strictly aligned with the rows (or the columns) of the detector and is shifted by one micron every three pixels. That emulates the knife-edge method with a one-micron sampling. The figures 12 and 13 show how the ESF is constructed in this case using the left-top pattern.

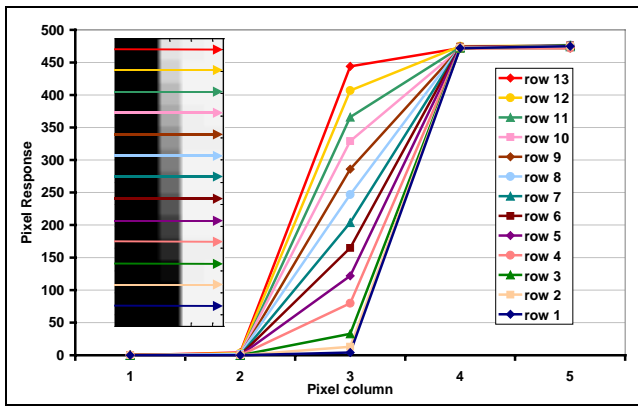


Figure 12 : Sections with regard to the rows

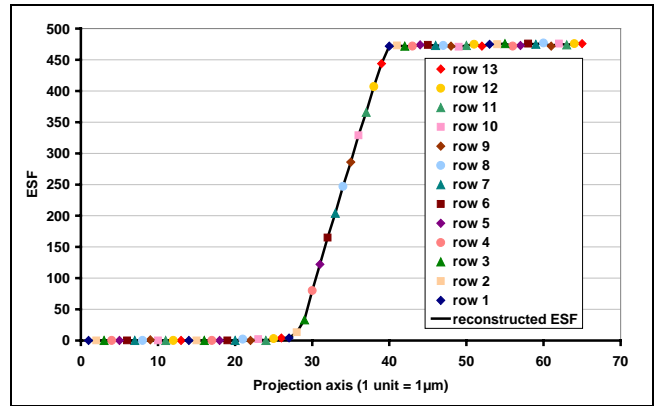


Figure 13 : ESF reconstruction

We can compare the both ESF obtained from slanted-edge and knife-edge patterns. Result is presented on the figure 14.

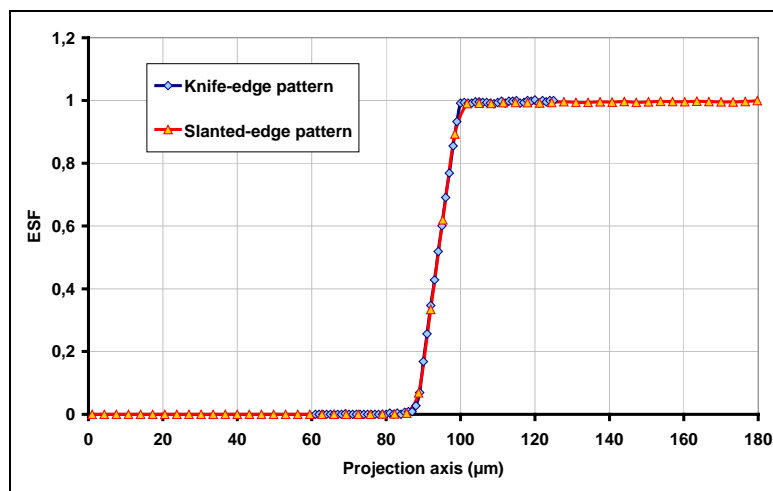


Figure 14: Comparison of the ESF computed from slanted-edge and knife-edge patterns

As can be seen, the both ESF are very close so it will be the same for the deduced MTF. Thus prove that slanted-edge and knife-edge methods, correctly used, are equivalent.

In that way, MTF measurements can be made without the use of a target so a specific optical setup is not necessary. So, there are no alignment constraints according to an optical axis and there are no longer any errors on the MTF data due to the estimation of the lens MTF. Additionally, the edge may be considered as sharp (mathematically equivalent to a Heaviside Step Function) so the frequency response of the pattern is equal to unity for all spatial frequencies.

The main advantage of using the metal pattern is the reduction of the measurement time since MTF data can be obtained in the same time as others detector characteristics (quantum efficiency for example).

Some precautions must be taken using this technique in order to avoid errors on MTF results. The metal-covered pixels have a low response and the detector may present a response non-linearity at low signal level. So it may be necessary to increase the integration time and to adjust the source luminance so that the response of entire array may be in the linearity range. More, metal-covered pixels may have a conversion gain (CVF) different of the one of non-covered pixels (pixel capacitance is modified by the metal layer). So the detector has to be entirely characterized in term of CVF before any MTF measurement. If changes in CVF are significant, the numerical response of each pixel must be corrected of its own CVF ; then SFR calculations will be done from the number of collected electrons. In our case, differences between measured CVF values are negligible due to the use of a metal layer sufficiently high.



## 4. MTF MEASUREMENTS RESULTS

### 4.1 MEASUREMENT SETUP USED WITH PROJECTION METHODS

The measurement setup is the same for the both techniques, sine and slanted-edge target. It consists in a uniform source associated with an integrating sphere to provide a uniform and monochromatical illumination. A MTF calibrated double-Gauss lens projects the image of the target onto the detector. Translation stages (manual and motorized), rotation stages and tilt tables allow optical alignments and focusing.

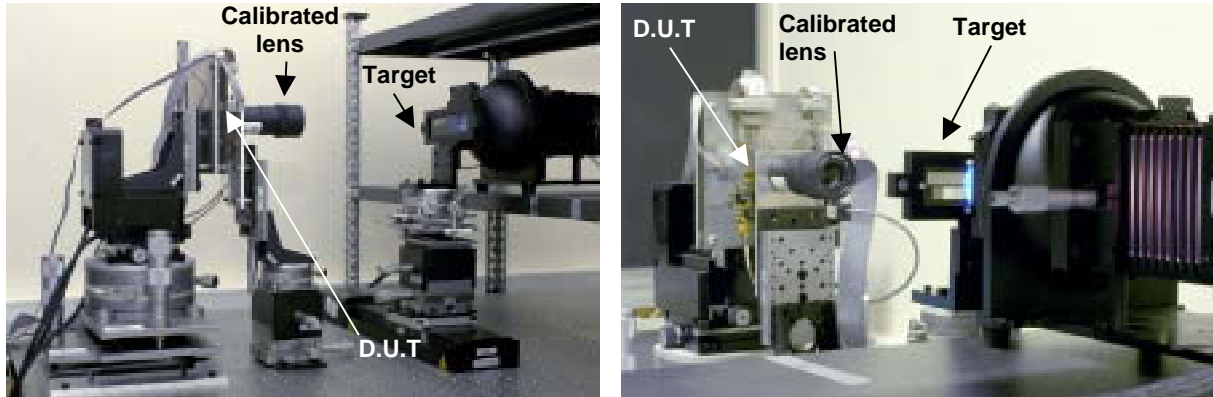


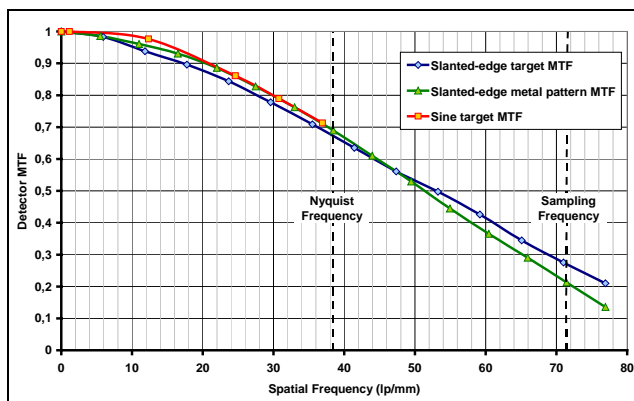
Figure 15 : Experimental setup for MTF measurements

All MTF measurements have been made according to the rows direction, at 500, 580 and 650 nm. The pixel pitch being of 13 $\mu$ m, the sampling frequency is equal to 76.9lp/mm and the Nyquist frequency is about 38.4lp/mm.

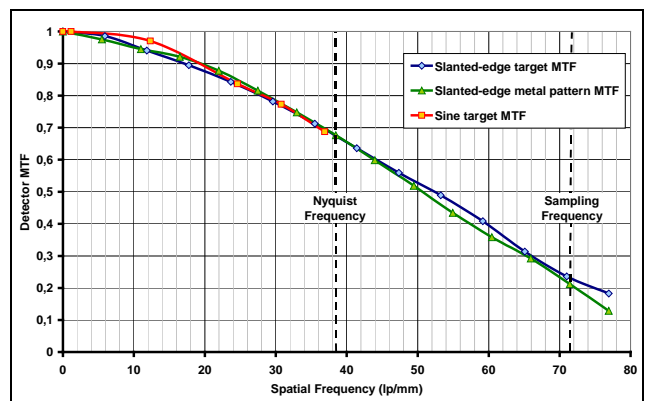
### 4.2 COMPARISON WITH METAL PATTERN MTF MEASUREMENTS

Due to the use of the on-chip metal pattern, there is no need of a particular setup. The integrating sphere is always used to provide the uniform and quasi-monochromatical illumination. Detector MTF is calculating using the same software as with slanted-edge target.

The following figures present the MTF results obtained with the three methods in the row direction at 500nm, 580nm, 650nm and 800nm.



a. 500nm



b. 580nm

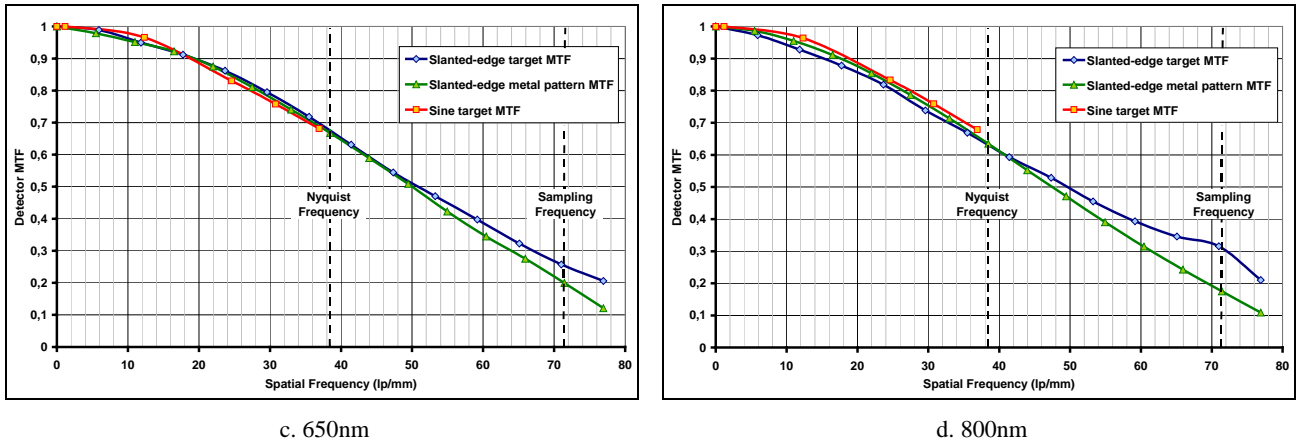


Figure 16 : Comparison of detector MTF obtained from target methods and metal pattern

MTF values obtained at Nyquist frequency are very closed to theoretical value computed from geometrical MTF expression. This one takes into account the photosensitive area size that is slightly less than the pixel pitch in the row direction.

Theoretical	500nm	580nm	650nm	800nm
70.3 %	69.0 %	67.6 %	66.8 %	63.5 %

The technology used is specifically designed for CMOS imagers, which can explain the high MTF values obtained and the low influence of the wavelength.

It can be considered that sine target method gives the horizontal MTF of the detector. The tilt angle of the edge in the case of the target was about 5° and about 3° in the on-chip metal pattern. MTF values, measured by sine target or slanted-edge target technique and by metal pattern technique, are very close for each wavelength.

When one image was sufficient to compute MTF with slanted-edge metal pattern, it took twenty images with slanted-edge target (due to focusing) and more than eighty with the sine target (twenty images per spatial frequencies). So, measurement and processing time were really reduced using the slanted-edge metal pattern.

These results lead to validate the use of the slanted-edge metal pattern in order to get easily and quickly detector MTF data.

## 5. CONCLUSION

ISO slanted-edge technique presents numerous advantages with regard to traditional MTF measurements methods. The reduction of alignment constraints and the need of only one image to compute the entire MTF curve reduce significantly the measurement time.

In order to make MTF measurements without the use of a specific setup, we have implemented test patterns at the chip level, using the upper metal layer. This removes errors factors due to optical alignments and adjustments (focusing) ; measurement time is also considerably reduced. A good agreement has been found between MTF results obtained using these patterns and target methods (sine and slanted-edge), validating the use of such metal patterns.

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