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# Versatile method for optical performances characterization of off-axis CMOS pixels with microlens radial shift

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## ABSTRACT

In this paper, we present a versatile characterization method we developed at STMicroelectronics for off-axis pixels (i.e. over the image plane) on CMOS image sensor. The solution does not require optics, making it suitable for early design phases as for optimizations and investigations. It is based on a specific design of color filters and microlens masks, which consists in several blocks. Inside each block, the filters and the microlens are shifted by a given amount, relatively to the pixel. Each block is related to a given chief ray and then defines a point in the chief ray angle space. Then, the performances of these angular points can be measured by rotating the sensor, using conventional uniform illumination setup with controlled f-number. Then it is possible to map these data on the image plane, knowing the chief ray angle versus focal plane coordinate function. Finally, we present some characterizations and optimizations based on the fact that the shift is arbitrary defined during circuit layout step, so it is possible to test the sensor with higher chief ray angles than those present in the product, or to optimize the shift of the microlens versus the chief ray angle for a given pixel architecture.

**Keywords:** CMOS image sensors, pixel, characterization

## 1. INTRODUCTION

Complementary Metal Oxide Semiconductor (CMOS) technology is nowadays largely used on image sensors thanks to the possibilities of high integration, on-chip digital functions, low power consumption [1]. Therefore CMOS sensors are now widely used on mobile phones, webcams or digital still cameras. In most of these applications, strong pressure is pushed on the sensor size either along the optical axis (to reduce the overall thickness) or on the footprint of the image module (i.e., the sensor, the objective lens, the lens barrel and holder mounted on the package). This trend leads to the reduction of both pixel size and back focal lens. Nevertheless, these shrinks must not compromise the image quality. Size reduction will decrease the sensitivity of the pixel, so the design and the process have to be tuned to maximize it as much as possible. This optimization involves design tuning and process development [2], but also electrical and optical simulations [3-6] and electro-optical characterization. Back focal length reduction impacts the angle of incidence of light at the edge of the image, thus the microlens placed on top of each pixel are shifted, accordingly to the angle, for maximizing the sensitivity. This shift is strongly linked to the objective lens.

In this paper, we present a characterization method we have developed for measuring the pixel performances of either on-axis pixels (pixels located at the centre of the image) or off-axis pixels. Because off-axis angle depends on pixel position inside the image plane and on objective lens parameters, off-axis performances are usually measured with the objective lens placed in front of the sensor. But, this technique of characterization has two main drawbacks: the objective lens has to be available and it can be difficult to separate lens effects and pixel effects. Our solution allows to characterize the pixel itself without needing lens and also to explore other illumination conditions than the one defined in the module camera, for instance higher angle of incidence.

In the section 2, we define the important illumination parameters for the characterization and describe the test bench and how it will be used. The section 3 presents the layout of the specific mask used. The characterization procedure and the followed indicators are detailed in section 4 before summarizing results obtain on a  $1.75\mu\text{m}$  pixel with optimized copper based process (section 5). We conclude in section 6 with the advantages of this new method and the perspective in terms of improvements.

## 2. PIXEL CHARACTERIZATION

### 2.1 Pixel illumination

The fine characterization of pixel performances is strongly linked to the illumination. Accordingly, the knowledge of the objective placed behind the sensor is essential. The straightforward method to fully characterize the sensor is to extensively measure the circuit performance when placed inside the module. Nevertheless, this requires the module to be fully defined and

available. Thus, the cycle time for full product optimization is quite long because the module design is a difficult trade-off exercise between many parameters like global size, optics performances (like field of view, sharpness, distortion, vignetting, aperture and vulnerability to stray light), industrialization capability and price. But all module performances are not required to optimize the pixel design and process. In addition, with this approach it is difficult to separate the contribution of the sensor itself from the module one (which includes several parameters like: objective lens design, infrared filter, stray light and mechanical design).

In order to better answer these points, we have looked for a characterization methodology which only requires few a priori knowledge of the module. As we will see below, only the objective aperture and maximum chief ray angle (CRA) inside the module have to be known. Chief ray is defined as the light ray passing by the center of the exit pupil of the objective lens and by the center of the microlens of pixel of interest. Then two kinds of pixels can be defined: on axis pixels with zero (or very small) CRA and off axis pixels with non-nil CRA. For the first kind, the illumination is defined only by the f-number (see Fig. 1-a). For off-axis pixel, the illumination definition also depends on the chief ray angle (see Fig. 1-b). This angle is then the main parameter in the definition of the microlens shift applied to center the light spot at silicon level on the photodiode.

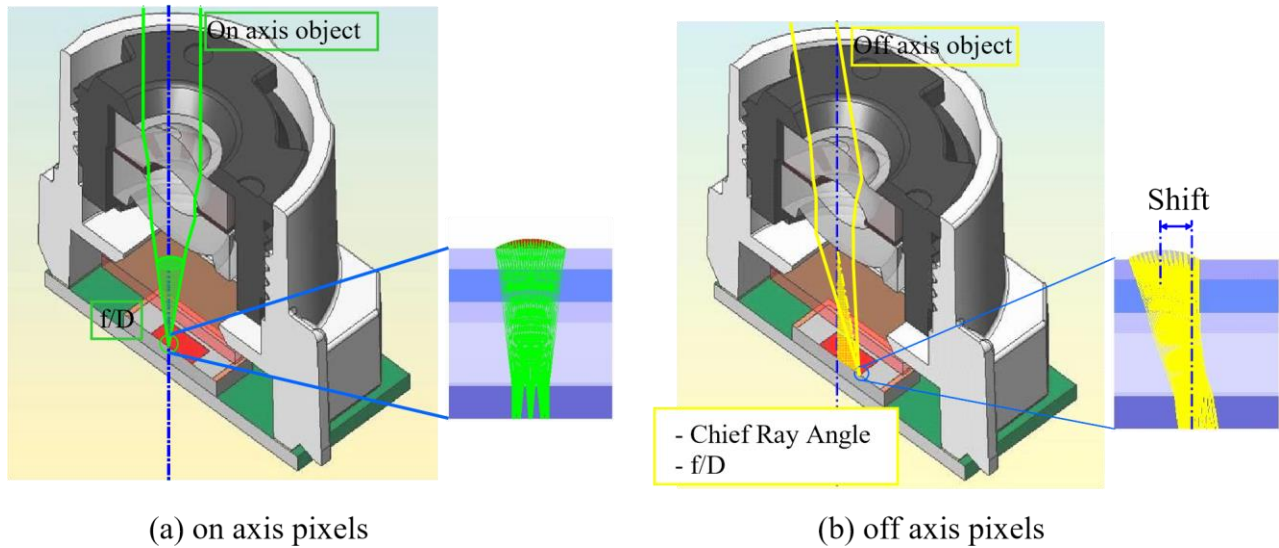


Fig. 1. Illumination of pixels inside module: (a) for an on-axis pixel, defined by the f-number, (b) for an off-axis pixel, defined by f-number and chief ray angle.

Our method is based on a specific layout for the microlens and the color filters (described in section 3) and the emulation of the CRA on test bench.

## 2.2 Characterization bench

For characterization we have developed test benches allowing us to tune illumination parameters: intensity, spectrum, fnumber and CRA. For that we use halogen light source with infrared filters which remove the unwanted part of the spectrum. Then the intensity is controlled with several neutral density filters ensuring fine level control (optical density from 0 to 5 by 0.1 steps) without changing significantly the spectrum. Narrow band filters can also be inserted to provide quasi-monochromatic light (typically 450nm, 530nm and 630nm). Then, a beam splitter redirects a small fraction of the light to a calibrated photodiode for real-time light level control. The final part of the light source controls the shape of the illumination: diffuse light with give f-number. This is done by an Opal diffuser and the control of the diffuser to sensor distance (see Fig. 2).

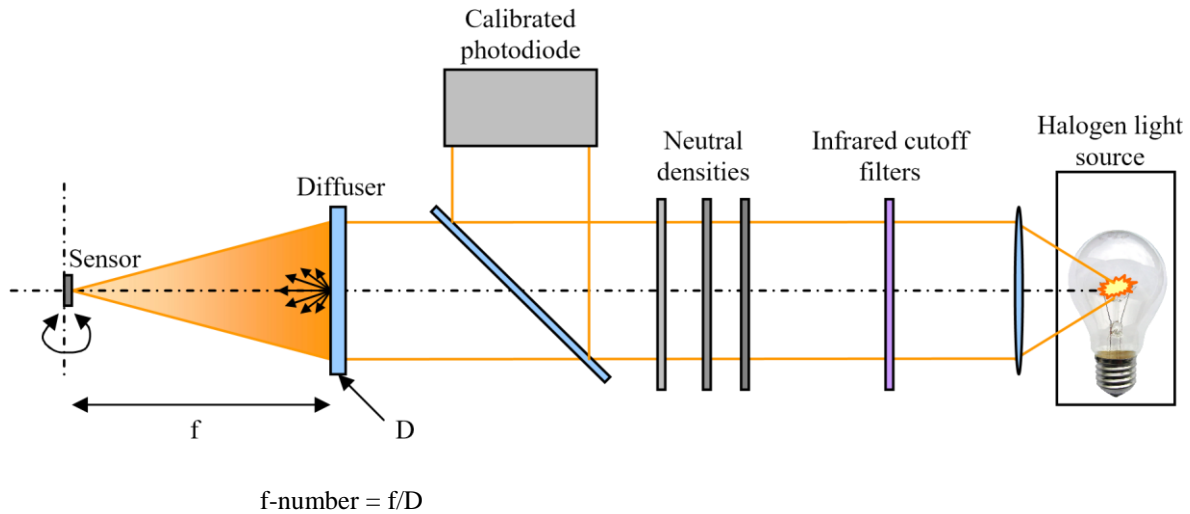


Fig. 2. Typical test bench configuration: sensor to test is uniformly illuminated (placed behind a diffuser).

If the diffuser diameter is large enough, the size of the sensor can be neglected then we can consider that all pixels inside the sensor see the same illumination shape, defined by the  $f$ -number. In the configuration presented in the Fig. 2, the sensor is illuminated under normal incidence.

Then any chief ray angle can be emulated by tilting the sensor. However, we must pay great attention to the rotation axis which must be located inside the sensor plane. This constraint is mandatory to keep constant both the  $f$ -number and the flux on the pixels of interest. This setup must be combined with a specific microlens and color filter layout, described in the following section.

### 3. MICROLENS AND COLOR FILTER LAYOUT

The objective of the microlens and color filter mask is to reconstruct a camera module image using our test bench. This will be done by defining blocks corresponding to a given point in the module image and by placing these blocks in the right place to characterize them. So the first step is to choose how the module image will be sampled (section 3.1). Knowing the sampling direction and the number of samples, we can define the geometry of one block (section 3.2) and assembled all the blocks for characterization (section 3.3).

#### 3.1 Image plane sampling

We choose to sample the image plane along 8 directions (see Fig. 3):

- 2 horizontal directions: from center to left and right
- 2 vertical directions: from center to top and bottom
- 4 diagonal directions: from center to top left, top right, bottom left and bottom right corners

This is a trade off between the number of directions, and the final size of the layout which must fit inside the test chip.

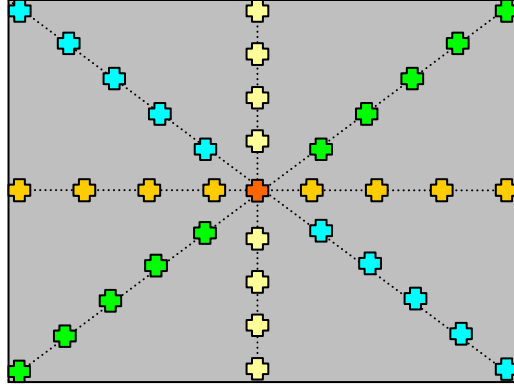


Fig. 3 Sampling of image plane in 8 direction including the central point (CRA = 0°)

### 3.2 Block layout

The base pattern of the mask is a block of pixels with color filters and microlens globally shifted (see Fig. 4). Inside the block, the color filters and the microlens layout is the standard one, for instance the Bayer pattern. The shift of these components is calculated accordingly to the standard routine, for instance for a dielectric stack height  $h$  with a mean refractive index  $n$ , for a given CRA  $\theta$ , the corresponding shift  $\delta$  is given by:

$$\delta = h \cdot \tan \left\{ \arcsin \left[ \frac{\sin(\theta)}{n} \right] \right\} \quad (1)$$

More complex calculation can be used like evaluation using ray tracing simulation [3] or advanced electromagnetic simulation [4-6].

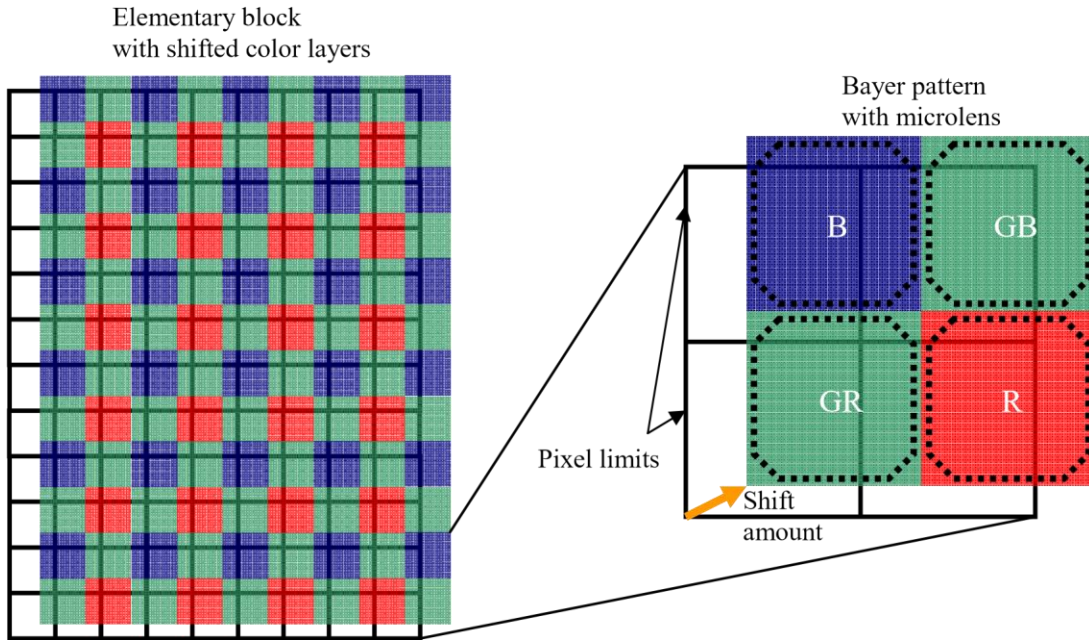


Fig. 4. Typical block design: the color filters and the microlens are shifted relatively to the pixel boundary. The first step is to choose the elementary block size by trade of between:

- The amount of pixel per color plane and so the reduction of spatial noise by averaging
- The whole size of the block-shifting design
- The number of CRA samples

The next step is to fix the aspect ratio of the block. It depends on the sampling directions in the image plane as seen on the following section.

### 3.3 Block placement

All blocks must be carefully arranged on the mask. The guideline is: for a given image plane position (*i.e.*, for a given chief ray angle), the block is positioned on the test chip, along the rotation axis used to emulate the chief ray angle. This axis (on test bench) is orthogonal to the direction of chief ray (on product) as seen on Fig. 5.

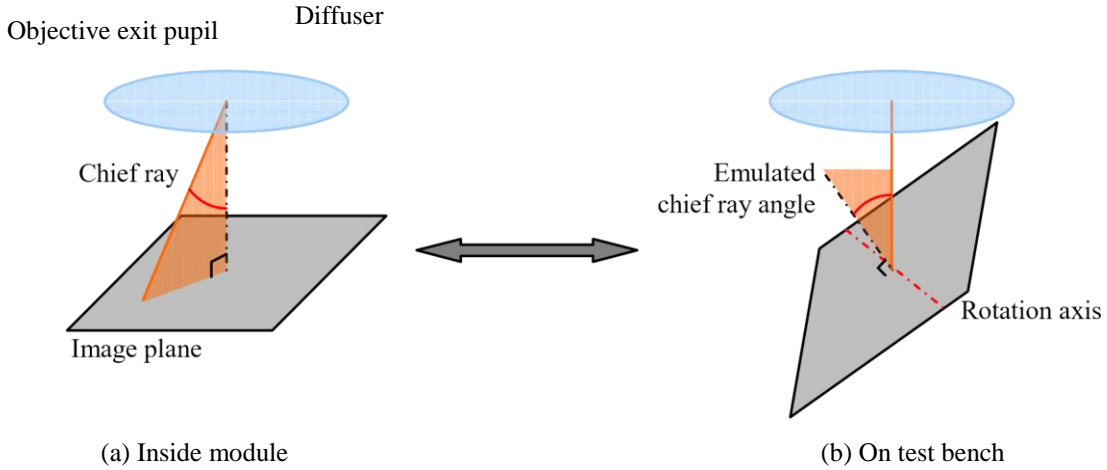


Fig. 5. Emulation of chief ray angle on test bench by tilting the sensor

If we choose to sample the image plane in 4 directions (see Fig. 6-a): horizontal, vertical and the two diagonals. Thus, the rotation axis on test chip will be vertical, horizontal and orthogonal to the diagonal. For a sensor with an aspect ratio (ratio between width and height) of 4:3, the rotation axis for diagonals lay along a line with a slope of 3:4 (see Fig. 6-b).

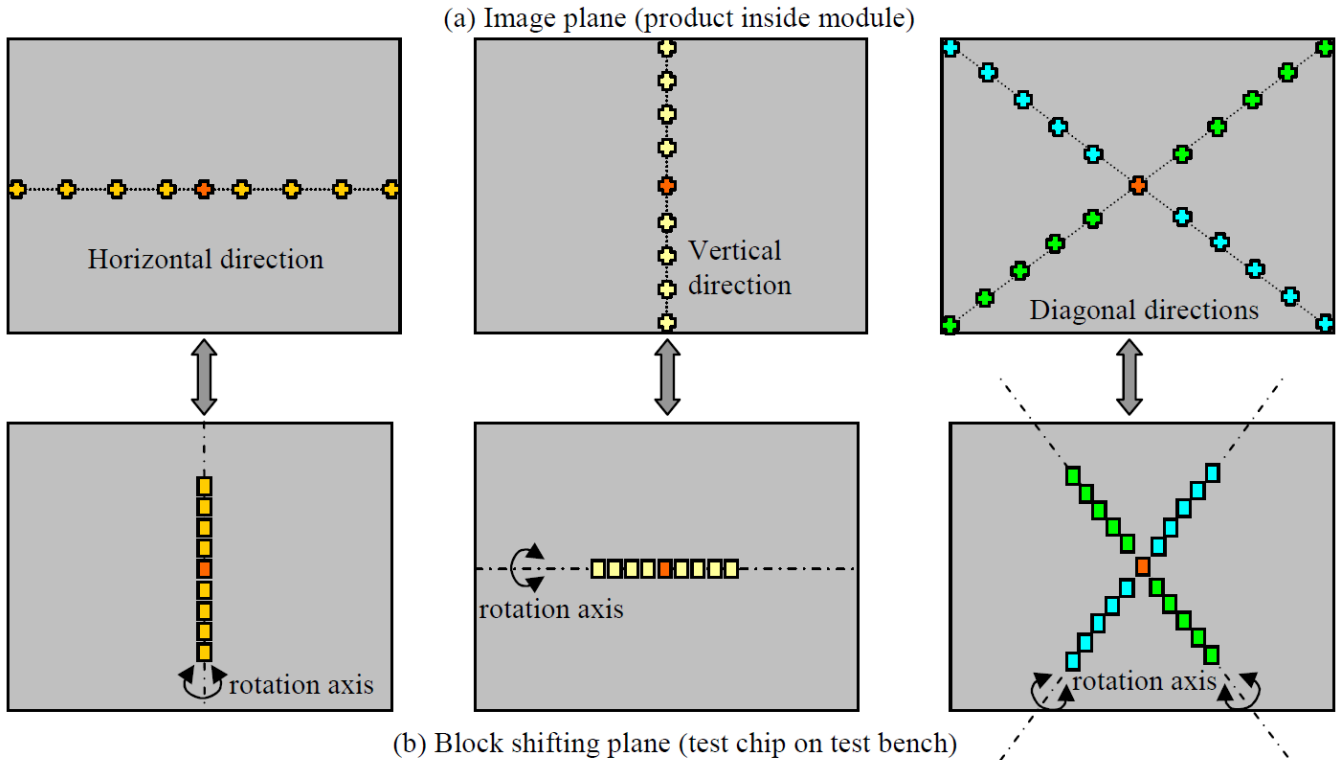


Fig. 6. (a) Image plane sampling and (b) corresponding block shifting positioning

## 4. CHARACTERIZATION

### 4.1 Data acquisition

Once the mask designed and the test chip processed, we can do extensive characterization of the pixel under oblique incidence. As a reference, the block without any shift gives the on-axis pixel performances. Then, for each shift implemented on the mask, the test board holding the sensor is tilted in front of the diffuser (see Fig. 7).

The standard flow for data acquisition is:

1. Grab several “light” images (typically 10),
2. Grab several “dark” images in darkness (typically 10)
3. Average light and dark images, to reduce the effects of temporal noise
4. Subtract average dark image to average light image
5. Extract regions of interest (blocks designed in section 3.2) from resulting image
6. Extract color planes for each cropped region of interest: in case of Bayer color filters pattern, we differentiate four color planes: red pixel, green-red pixel (with green filter on top and on the same row than red pixel), greenblue pixel (with green filter on top and on the same row than blue pixel) and blue pixel.
7. Average the pixels of each color plane, to reduce effects of spatial noise

This flow gives four data for each angle of incidence. Based on these raw data, we compute several performance indicators.

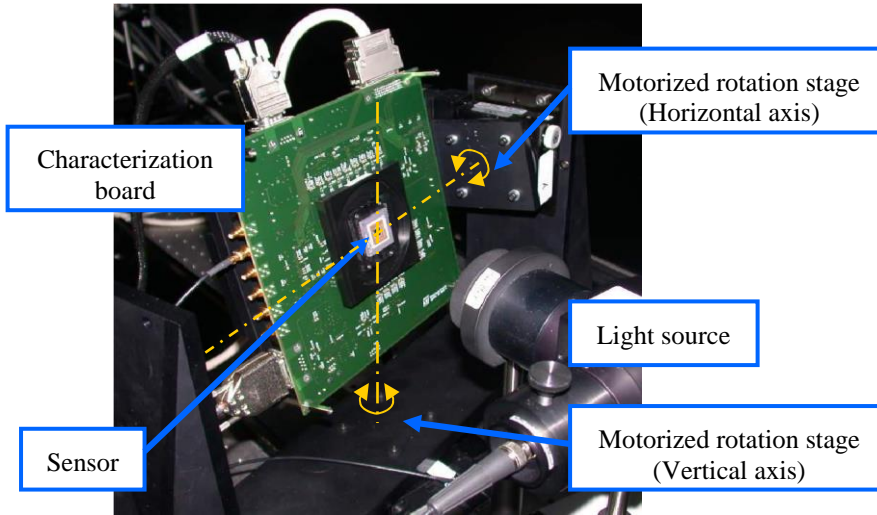


Fig. 7. Setup used for the characterization: tilted characterization board holding the sensor in front of the light source.

#### Relative illumination:

The relative illumination (RI) measurement evaluates the vignetting of the pixel. For a given chief ray angle, RI is defined by the ratio of the pixel sensitivity for this CRA over the sensitivity of the central pixel (normal incidence). This is a key parameter for the vignetting correction of the image.

The sensitivity  $S(\theta)$ , obtained by dividing the output signal of the sensor by the measured illuminance, is biased. On the test bench, the illuminance is measured on the optical axis while the sensor is tilted. So, we correct it by the geometrical factor due to the tilt, the relative illumination for a given chief ray angle  $\theta$  is calculated as follows:

$$RI(\theta) = \frac{S(\theta)}{S(0^\circ) \cdot \cos(\theta)} \quad (2)$$

#### Color tilt

From the four relative illuminations obtained, denoted  $RI_R(\theta)$ ,  $RI_{GR}(\theta)$ ,  $RI_{GB}(\theta)$ ,  $RI_B(\theta)$ , we define several color tilt indicators. They quantify the color uniformity after white balance. The white balance is done at  $CRA=0^\circ$  using the mean green  $G(\theta) =$



$[RI_{GR}(\theta) + RI_{GB}(\theta)]/2$ . Four white balance factors are computed for red, green-red, green-blue and blue planes, denoted respectively:  $WB_R$ ,  $WB_{GR}$ ,  $WB_{GB}$  and  $WB_B$ . Then we construct white balance corrected relative illuminations defined by:

$$\begin{aligned} R(\theta) &= WB_R \cdot RI_R(\theta) \\ GR(\theta) &= WB_{GR} \cdot RI_{GR}(\theta) \\ GB(\theta) &= WB_{GB} \cdot RI_{GB}(\theta) \\ B(\theta) &= WB_B \cdot RI_B(\theta) \end{aligned} \quad (3)$$

Then the color tilts are defined as follow:

- Red color tilt:  $\frac{R(\theta)-G(\theta)}{G(\theta)}$
- Green-red color tilt:  $\frac{GR(\theta)-G(\theta)}{G(\theta)}$
- Green-blue color tilt:  $\frac{GB(\theta)-G(\theta)}{G(\theta)}$
- Blue color tilt:  $\frac{B(\theta)-G(\theta)}{G(\theta)}$

From green-red and green-blue color tilts, we defined a fifth indicator: the green mismatch:  $\frac{GR(\theta)-GB(\theta)}{G(\theta)}$ . These parameters are essential for the color uniformity performance.

#### 4.2 Data analysis

All the indicators (relative illuminations and color tilts) are extracted from the images. Then, they can be mapped either in an angular space, or in a focal plane-like space. The first one has the advantage to be independent to the module lens design and gives the pure sensor performances. The second one requires the knowledge of the function chief ray angle versus the position in the focal plane. It can only be used when the module is defined.

##### Angular space

This is the direct mapping of the indicators versus the chief ray angle in X and Y directions  $(\theta_x, \theta_y)$ : each sample point is placed along the right direction. Then interpolation gives a reconstructed image in angular space (see Fig. 8).



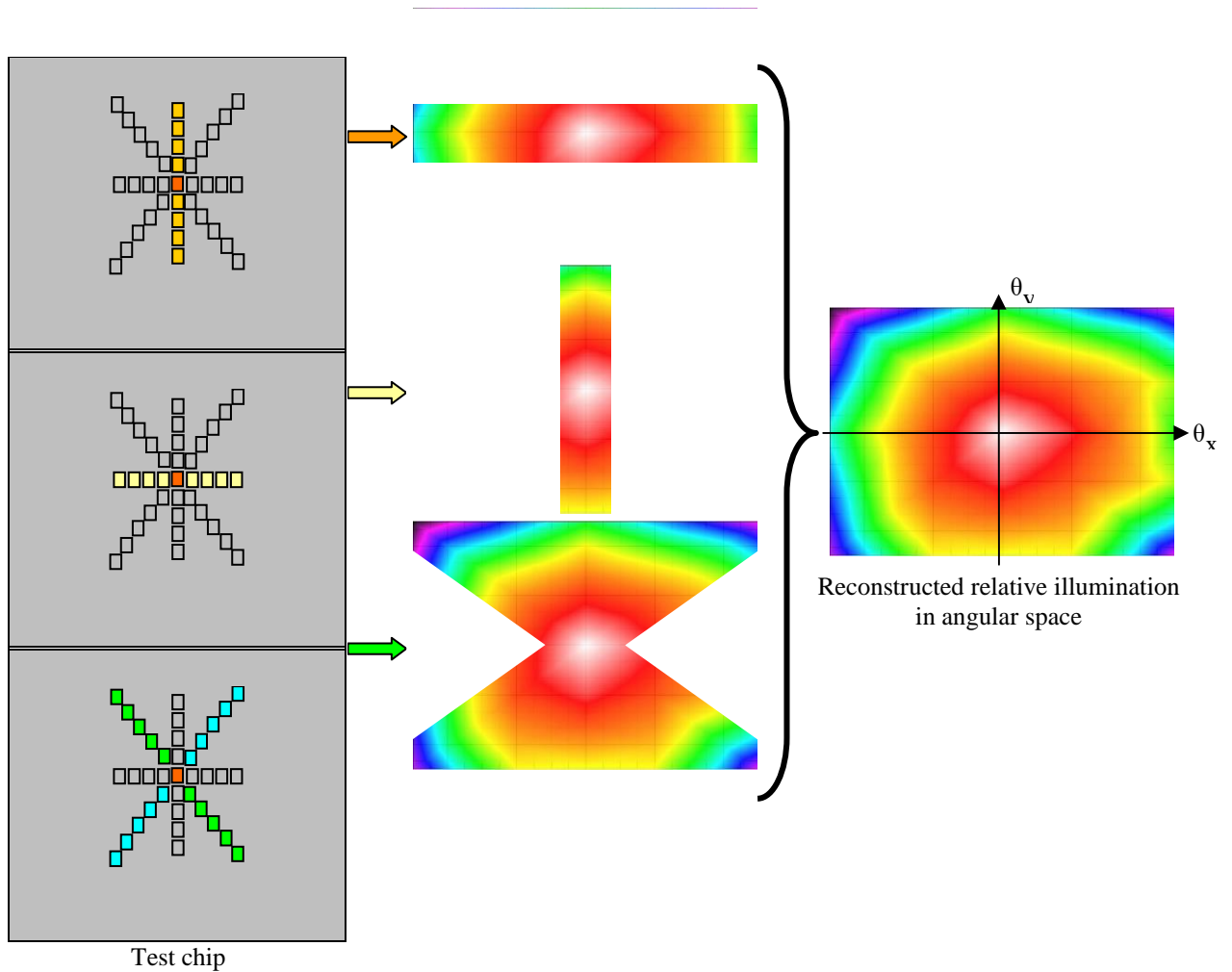


Fig. 8. Indicator reconstruction process: each measurement point is placed in  $(\theta_x, \theta_y)$  space and interpolation is used to produce a map.

With this representation, data are independent of module, so it is easy to test higher CRA or to optimize the angle for a given shift. By inverting this optimal function, we optimize the shift for any angle.

### Focal plane

To evaluate final performance of product, it is interesting to remap the relative illumination indicators on the focal plane. It requires the knowledge of the function CRA versus position inside the image. By inverting and applying it on the angular space representation, we obtain an image-like representation (see Fig. 9).

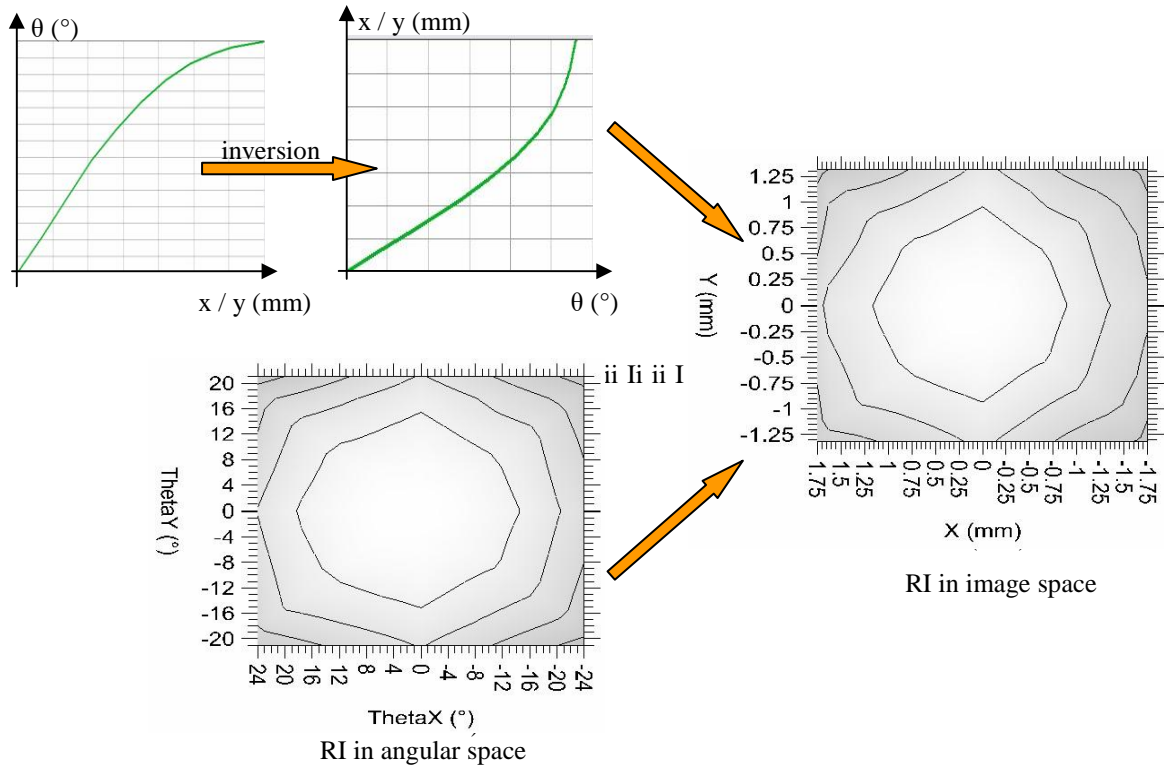


Fig. 9. Processing flow to transform data in angular space to image space

This representation is useful for the final product evaluation because data are correctly mapped and module effects (like main lens vignetting) can be added.

## 5. RESULTS ON 1.75 $\mu$ M PIXEL

On this section we present data obtained with a 1.75 $\mu$ m pixel in an optimized copper based process [2]. The example of a 3 mega-pixels sensor is used. On such product the maximum chief ray angle in the camera module is 24°. The CRA variation with the distance of the pixel to the center of the image is shown in Fig. 10.

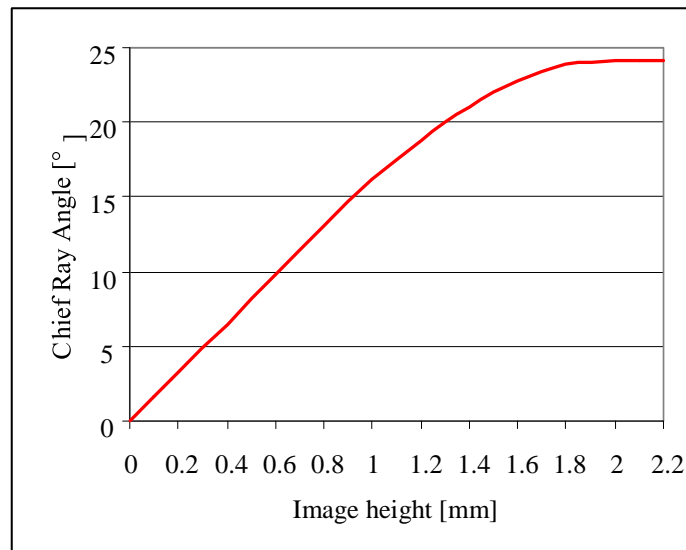


Fig. 10. Chief ray angle versus position of the pixel inside the image plane for 3 mega-pixels sensor

The green-red relative illumination is presented on angular space (see Fig. 11-a) and remapped on image space (see Fig. 11-b). The corners are only 15% less sensitive than the center of the sensor, thanks to optimized microlens and color filter placement.

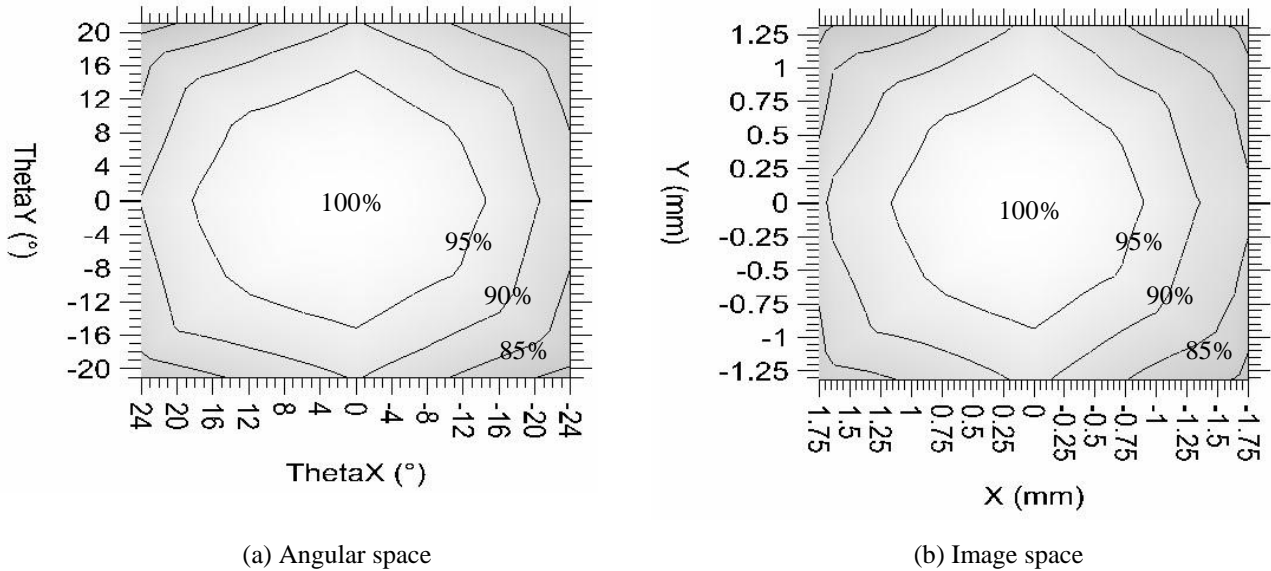


Fig. 11. Green-red mismatch of 3 mega-pixels sensor using 1.75 $\mu$ m pixel in (a) angular space, (b) image space.

The green-red and the green-blue color tilt in angular space is shown in Fig. 12. Little mismatch between the two green channels is visible (less than  $\pm 2\%$ ) and is due to the shared transistor architecture of the pixel. Here again, careful pixel design and microlens shift allows to keep the mismatch as low as possible.

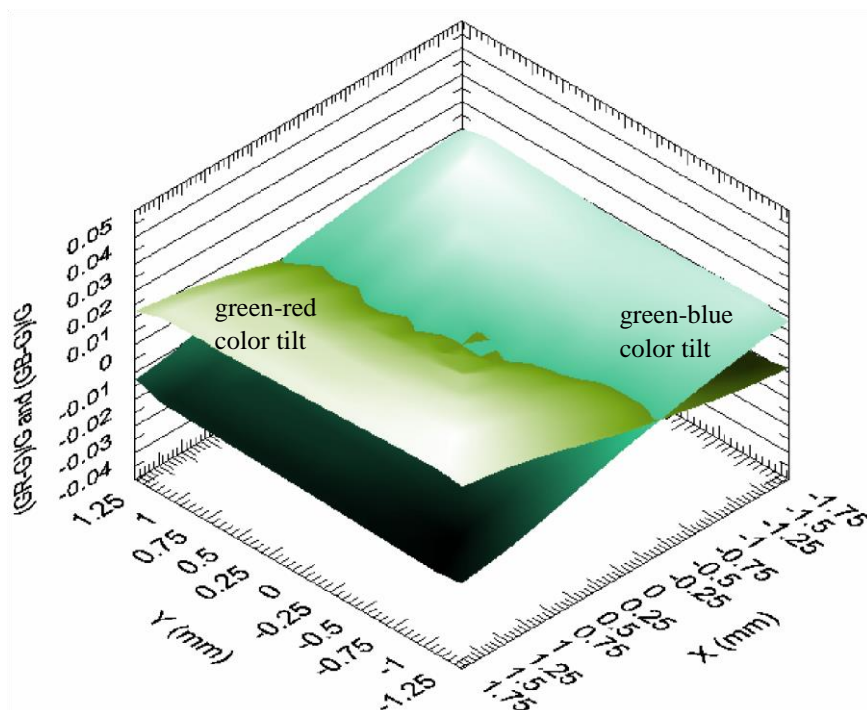


Fig. 12. Green-red and green blue color tilt of 3 mega-pixels sensor using 1.75 $\mu$ m pixel in image space

## 6. CONCLUSION

The method described in this paper allows the characterization of the off-axis pixel performances without needing an objective lens. It presents several advantages:

- The sensor is measured alone, so the performances measured are not affected by the objective lens (for instance vignetting).
- The sensor can be characterized before the camera module is available. Moreover, this characterization can be used to optimize the microlens radial shifting versus CRA. The cycle time for product development is then reduced.
- Chief ray angle as high as wanted can be measured (if the mask has been designed for it). This helps to set fact-based limits to maximum CRA on product and helps the lens designer in the definition and specification process. • Impact of process dispersion can be assessed, for instance overlay precision of microlens and color filter
- The performances of the sensor and the lens can easily be combined so the final product is evaluated.

The counterpart of this very versatile method is the design of a specific mask-set. However, it gives valuable data all along the sensor design, process development and module definition.

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