# Calculation of polarization sensitivity of image sensors

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**Abstract.** The work deals with the analysis of effect of image sensors structure on the distribution of polarization on its area. It is also about polarization sensitivity calculation with the method based on Jones matrix formalism.

## 1. Introduction

CCD and CMOS detectors have many applications. Such sensors are in particular used for measurements, but because of complexity of their structure many factors can decrease its accuracy. First of all, many researches of effect of signal-noise ratio on the accuracy are known [1-4]. Relative orientation of polarizers in polarization CCD camera also exerts a strong influence on received signal [5, 6]. As for polarization sensitivity, there are only researches of SeGA detectors known [7]. But polarization sensitivity of general familiar sensors of quartz is no less important.

CCD or CMOS sensors are usually made of isotropic materials, so they are considered not to be sensitive to polarization. However, when a detector is disposed at an angle to the axis of incident light beam, it becomes polarization sensitive. It can be critical in precise measurement performed in polarized light.

Therefore, the main purpose of this research is to find out, how does the polarization sensitivity of specific photosensors affect the result of polarimetric and ellipsometric measurements.

## 2. Theoretical aspects

When a photosensitive element is disposed at an angle to the axis of incident light beam, the transmittance of boundary between electrode end detector's crystal is defined by

$$T = \frac{n_2 \cos\varepsilon''}{n_1 \cos\varepsilon}\left(t_s^2 \cos^2\alpha_{in} + t_p^2 \sin^2\alpha_{in}\right) = T_s^2 \cos^2\alpha_{in} + T_p^2 \sin^2\alpha_{in} \quad (1)$$

Here, $\varepsilon$ is the incidence angle, $\varepsilon''$ is the refraction angle, $T_s$ and $T_p$ are transmission coefficients for light which is polarized parallel and perpendicular to incidence plane, $\alpha_{in}$ is an azimuth of incident polarization, $t_s$ are $t_p$ the transmission coefficients of orthogonal Jones vector's components, which are given by

$$t_s = \frac{2n_1 \cos\varepsilon}{n_1\cos\varepsilon + n_2\cos\varepsilon''}, t_p = \frac{2n_1\cos\varepsilon}{n_2\cos\varepsilon + n_1\cos\varepsilon''} \quad (2)$$

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Photocurrent is defined by

$$i(\lambda,\varepsilon,\alpha_{in}) = \Phi \frac{e\eta\beta\lambda}{hc}\left[T_p(\varepsilon)\sin^2\alpha_{in} + T_s(\varepsilon)\cos^2\alpha_{in}\right] \quad (3)$$

where $e$ is the electron charge, $\eta$ is sensors's quantum efficiency, $\beta$ is the coefficient of separation of charge carriers couples, $h$ is the Planck constant, $c$ is the speed of light in vacuum, λ is the wavelength.

So the sensitivity of sensors is characterized by two values: to light, polarized parallel ($s_p$) and perpendicular ($s_s$) to incidence plane. Normalized dependences of sensitivity on incidence angle are calculated with the following equations:

$$s_p(\varepsilon) = \frac{n_2 \cos\varepsilon''}{n_1 \cos\varepsilon} t_p^2, s_s(\varepsilon) = \frac{n_2 \cos\varepsilon''}{n_1 \cos\varepsilon} t_s^2 \quad (4)$$

The main parameter of polarization sensitive sensor is the effective polarization sensitivity, which is the difference between $p$- and $s$- components. The signal's amplitude is proportional to this value, thus it depends on refraction and absorbtion indices of photodetector crystal, on quantum efficiency of detector, on incidence angle and light wavelength. Consequently it is advisable to consider the changing of signal magnitude owing to variation of detector orientation. For this purpose it is necessary to calculate the distribution of polarization sensitivity as a function of the light incident angle at each pixel.

## 3. Method of calculation

The suggested method of calculation is based on well-known Jones matrix formalism [8]. Each pixel of sensor array is concepted as a complex of boundaries between isotropic media. When passing through each one, the light is refracted, so the wave ort changes its orientation, namely it rotates at an angle $\alpha_i$. To get to new coordinate system, the boundary Jones matrix should be multiplied at the rotation matrix. Since a pixel is concepted as it is shown on the Fig. 1, its Jones matrix is given by

$$\mathbf{M}_{MPD} = \mathbf{M}_R(\alpha_5)\mathbf{M}_4\mathbf{M}_R(\alpha_4)\mathbf{M}_3\mathbf{M}_R(\alpha_3)\mathbf{M}_2\mathbf{M}_R(\alpha_2)\mathbf{M}_1\mathbf{M}_R(\alpha_1) \quad (5)$$

This equation contains matrices between following boundaries:

- $\mathbf{M}_1$ – air-microlens;
- $\mathbf{M}_2$ – microlens-color filter (red, green or blue);
- $\mathbf{M}_3$ – color filter-electrode (Si:H);
- $\mathbf{M}_4$ – electrode-dielectric ($SiO_2$);
- $\mathbf{M}_5$ – dielectric-photosensor (Si (p/n)).

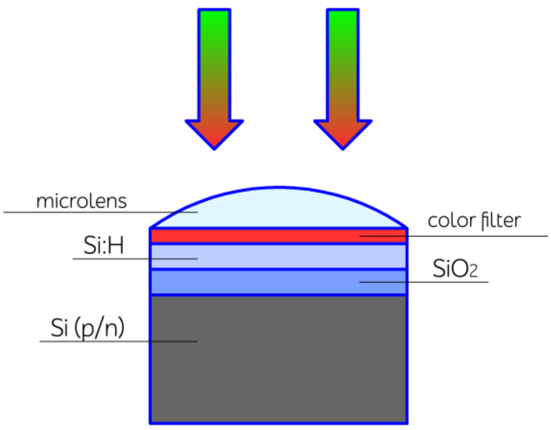


**Figure 1.** Pixel structure

Variation of this angle changes the transmittance of detectors structure, which accordingly causes the rotation of polarization plane. The value of this rotation is given by

$$\Delta\alpha_{out} = \arctan\frac{\tan(\alpha_1 - \alpha_{in})[1-(t_p/t_s)]}{1+(t_p/t_s)\tan^2(\alpha_1 - \alpha_{in})} \tag{6}$$

So, to perform the calculation, it's necessary to know the orientation of coordinate system, in which the light is described, and refraction indices of each aforesaid material. Indices of color filter were calculated from sensitivity specters of researched sensor OV5620 (Fig. 2) and sensitivity spectrum of the same sensor without color filters (Fig. 3) [9, 10].

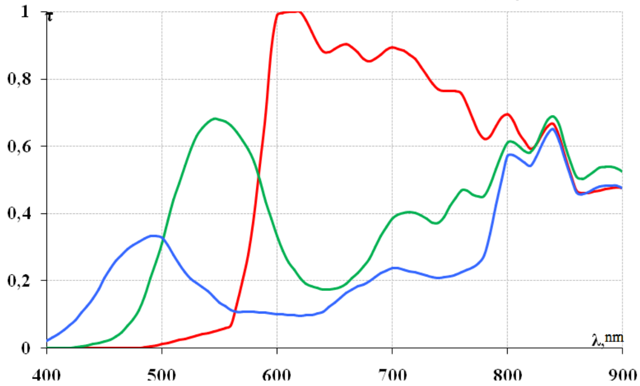


**Figure 2.** Sensitivity spectrum of OV5620 sensor with color filters

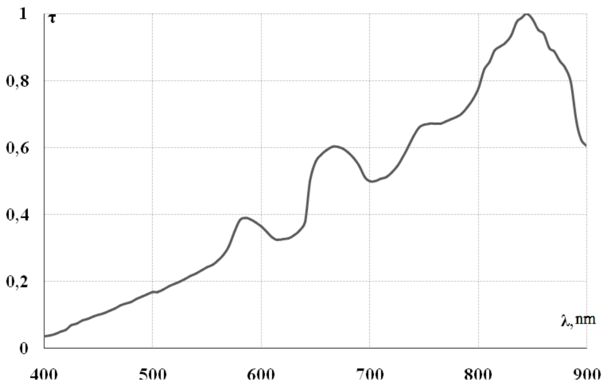


**Figure 3.** Sensitivity spectrum of OV5620 sensor without color filters

As a result, transmission spectres of filter look like it is shown at the Fig. 4.

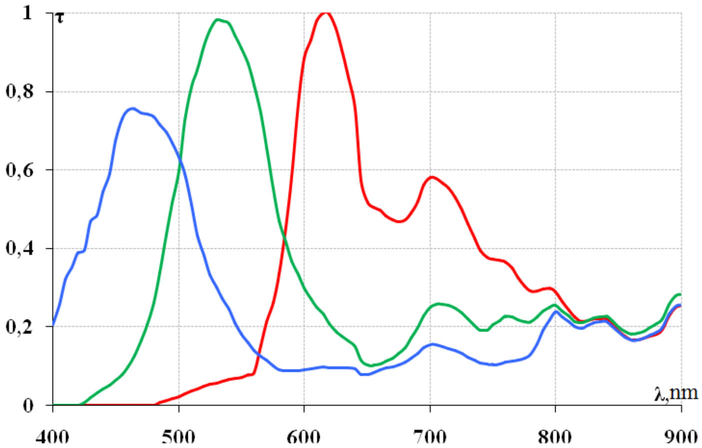


**Figure 4.** Transmission of color filters

The transmissions coefficients for λ = 532 nm, are: $\tau_R$ = 0,057165; $\tau_G$ = 0,9813; $\tau_B$ = 0,30062. Refraction indices were calculated using Fresnel equations: $n_R$ = 33,987; $n_G$ = 1,038; $n_B$ = 5,653.

## 4. Results of calculations

The software for calculation was developed in LabVIEW environment. The results of calculations for λ = 532 nm as a functions $\Delta\alpha_{out}(\alpha_{in})$ and $\Delta\alpha_{out}(\varepsilon)$ will be shown at Fig. 5 and 6.

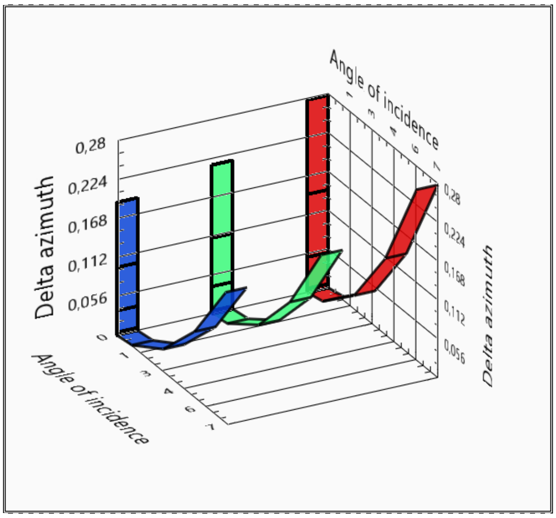


**Figure 5.** Changing of polarization azimuth depending on the incidence angle ($\alpha_{in}$ = 45º)

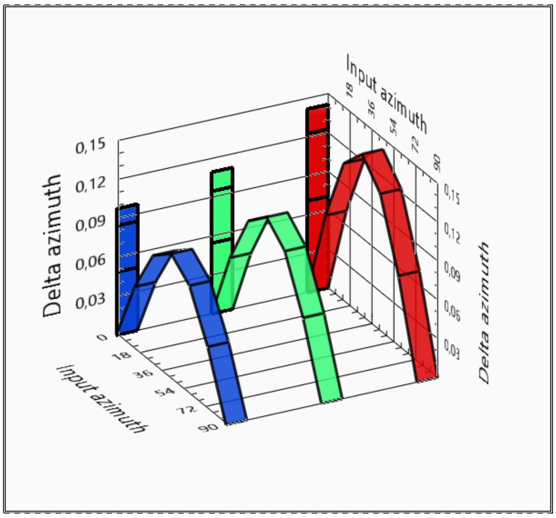


**Figure 6.** Changing of polarization azimuth depending on the input azimuth (ε = 5º)

Since the sensitive array is illuminated with parallel light beam, the distribution of output characteristics is uniform and depends only on transmittance of color filters. So, the value of $\Delta\alpha_{out}$ is the same for each red, green or blue pixel.

The *p*- and *s*- components of polarization sensitivity are calculated by equations (4). The dependences $s_p(\varepsilon)$ and $s_s(\varepsilon)$ with ε = 0-7º are shown at the Fig. 7.

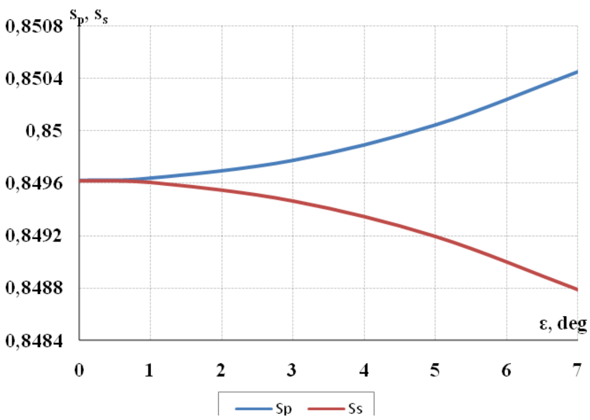


**Figure 7.** Components of polarization sensitivity

## 5. Experimental research

Experimental setup for validating the calculation was built by classical Stokes polarimeter scheme [11, 12]. It is shown at the Fig. 8.

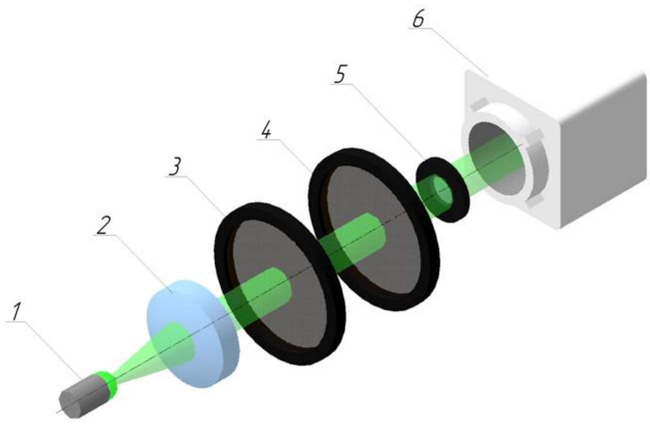


**Figure 8.** Experimental setup: 1 – LED (λ = 532 nm), 2 – collimating lens, 3 – polarizer, 4 – analyser, 5 – waveplate λ/4, 6 – camera with researched sensor

The comparison of theoretical and experimental results is shown at Fig. 9. Theoretical data are shown by solid lines, experimental data – by dashed lines.

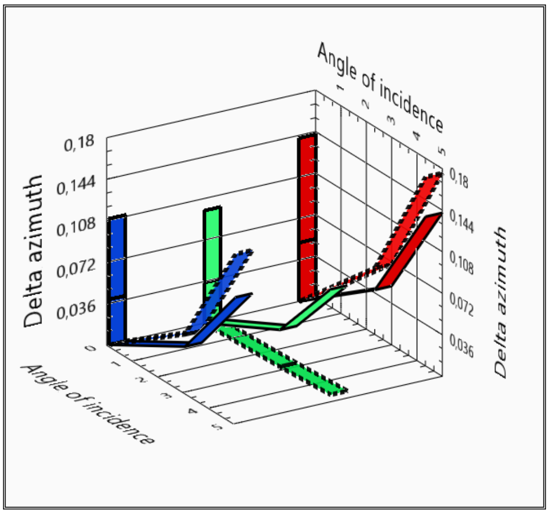


**Figure 9.** Changing of azimuth gotten by theoretical and experimental methods

This char shows, that the theoretical results for red end green pixel are correct within the error, and the experimental and theoretical results for green pixel are quite different. It is associated with experiment conditions and meathematical model validity. So, it is necessary to improve a mathematical model. Then we will get better results.

## 6. Conclusions

So, the program for calculation how the structure of detectors affects the polarizaton distribution on its sensitive area was developed basing on the Jones matrix formalism. The obtained results can be used for metrology attestation of specific CCD or CMOS detectors from the viewpoint of polarization sensitivity and also for considering the effect of photodetector on measurements results. It would improve measurements accuracy by its performing in polarized light.

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