Chromatic Aberration in Thick Fully Depleted CCDs

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Abstract. We explore the wavelength–dependent aberration effect appearing in high-aperture system with thick hi-rho CCD. It's through optical and geometric characteristics of the device. The effect is prominently manifested in fully depleted CCDs in the near infrared spectrum part. We obtained FWHM of point spread functions from mathematical model, allows correcting the signal in processing stage to increase the image spatial resolution.

Keywords: instrumentation: detectors

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1 Introduction

For increase a quantum effectiveness of CCD in wide spectral range are used a technologies like: backside illumination, deep depletion and hi-Rho thick substrate. A logical consequence of technology progress was creation the devices with full depletion of substrate, in which the width achieves several hundred microns. That in combination with appropriate antireflection coating can give a quantum yield of about 100% in the red and near infrared spectrum. Though the negative side of that can be reducing a spatial resolution of the image system. One of such example is the diffusion of charges. This effect is especially obvious for short-wave spectrum. Another effect, we are talking about, is obvious for red and near infrared and it is related with absorption length of photons. In this case, PSF is emerging caused by using of thick CCD in high-aperture systems. Focused light of point source has a range of incidence angles on CCD. Since the photon absorption is a probabilistic process, part of the light, that was incident at angle to the normal, is absorbed in some area. The certain size of this area determined by angular aperture, wavelength and CCD thickness. Bellow, we will calculate PSF of the occurring aberration and consider the possibility of improving the spatial resolution.

2 Theoretical View

For description of chromatic aberration in thick fully-depleted CCD we assume the next. A point light source is located at quite large distance, which indicates that the light falls parallel to the entire area of the lens and focused at one point on the matrix surface. For general case, the lens is not directly targeted at the object and the image is located at some distance from projection of optical axis on CCD surface. The image is built inside the isoplanatic zone, and the lens is ideal and apochromatic. Also, we ignore the light scattering in the crystal. And in first approximation, we do not consider the presence of anti-reflective coatings (see Fig. 1)

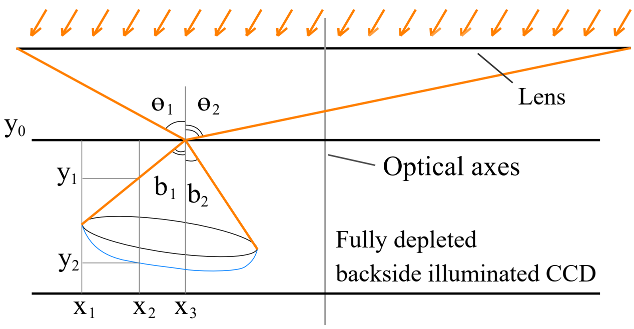

Fig. 1. Scatter pattern

According to the Beer–Lambert–Bouguer law, attenuation of a parallel monochromatic beam can be expressed by follow equation

$$I_p(l) = I_{in} \cdot e^{k_\lambda l} \tag{1}$$

where $I_p(l)$ is the light flux passed through the material sample of thickness l, I_{in} is the incident light flux and k_λ denotes the attenuation coefficient. k_λ is in inverse ratio to length in which flux decreases by 2.74 times here.

We can represent equation (1) as the ratio of absorbed light to incident, in two coordinates

$$I(x, y) = I_{ab}/I_{in} = 1 - e^{-k_\lambda \sqrt{x^2+y^2}} \tag{2}$$

One-dimensional PSF on the radius from the optical axis projection to the focus point for each of two distribution parts plotting right and left from the focus point can be determined like

$$I(x) = \int_{y_1}^{y_2} \frac{\delta I}{\delta y} dy \tag{3}$$

where

$$\frac{\delta I}{\delta y} = \frac{k_\lambda y \cdot exp(-k_\lambda \sqrt{x^2 + y^2})}{\sqrt{x^2 + y^2}} \tag{4}$$

The lower limits of integration y_1 is determined by the extreme angles β. The upper limit is the CCD thickness $y_2 = d$. Thus

$$I(x) = \int_{x \cdot cot(\beta)}^{d} \frac{\delta I}{\delta y} dy \tag{5}$$

$$I(x) = e^{-\frac{k_\lambda x}{sin(\beta)}} - e^{-k_\lambda \sqrt{x^2 + d^2}} \tag{6}$$

It is possible that the extreme angles will be in the same quarter, in this case the upper limit is defined as $x \cdot cot\beta$, therefore

$$I(x) = \int_{x \cdot cot(\beta 1)}^{x \cdot cot(\beta 2)} \frac{\delta I}{\delta y} dy \tag{7}$$

$$I(x) = e^{-\frac{k_\lambda x}{sin(\beta 1)}} - e^{-\frac{k_\lambda x}{sin(\beta 2)}} \tag{8}$$

3 Application Factors

We can estimate the impact of the aberration by the equation (6) at 900 nm and 1000 nm wavelengths on the charts in fig.2(a)(b) for 450 μm thick matrix. FWHM is 2 μm and 17 μm respectively.In the case, of all light comes to surface from the same quarter by the equation (8) is a significant blurring of the PSF peak Also, here we have a shift of the peak in the opposite to the optical axis direction (see Fig.2(c)(d)(e)).

Considering the chromatic aberration in the overall modulation transfer function needs to using numerical integration results by equations (5),(7) taking into account the spectral and angular dependence of the surface transmittance (Fig.3)

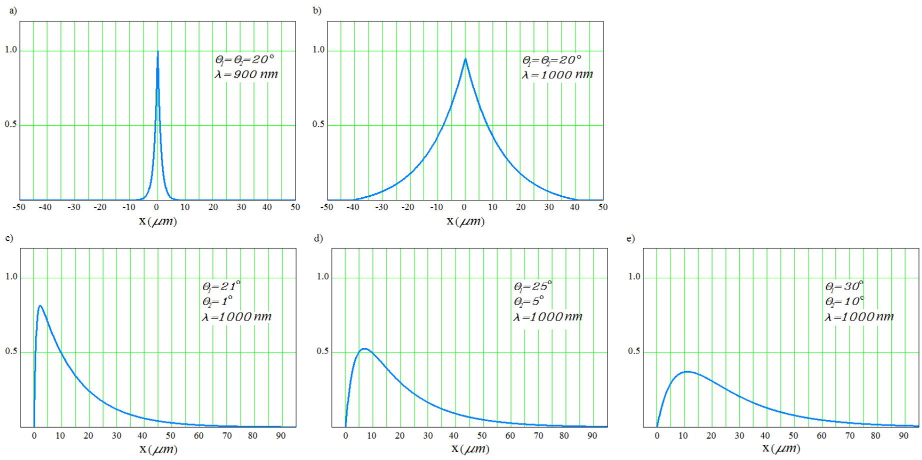

Fig. 2. PSF of the chromatic aberration for 900 nm (a) and 1000 nm wavelengths (b) of normal incidence light, and 1000 nm same quarter incident at different angles (c)(d)(e) for aperture equivalent to f/2.6 optical system

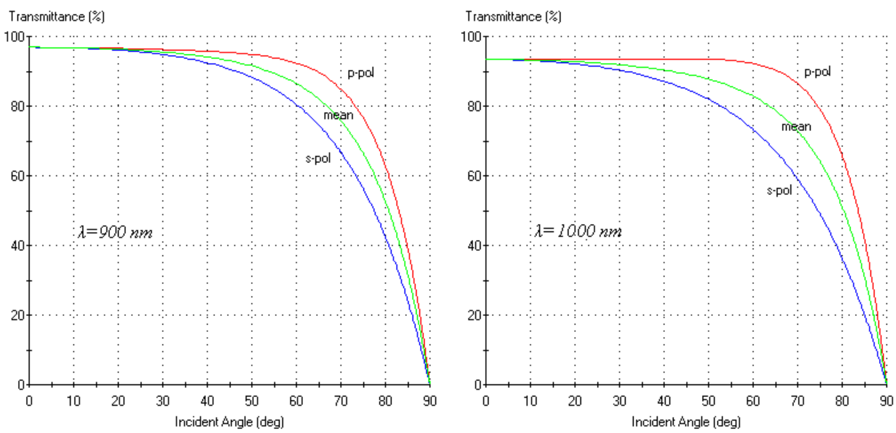

Fig. 3. Surface transmittance of monocrystalline silicon with HfO2 quarter-wave anti-reflective layer at different angles for 900 nm and 1000 nm wavelength