A study on modulation transfer function and signal-to-noise ratio for Tetracell CMOS image sensors with sub-micrometer scale unit pixels

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ABSTRACT

As the unit pixel size of CMOS image sensors (CISs) decreases to sub-micrometer scale, it has become a controversial issue that an increase of resolution without enlargement of chip size leads to an improvement of image quality. In this study, we introduce a novel image simulation methodology to predict the image quality of CISs with sub-micrometer scale pixels. We predict modulation transfer function (MTF) and signal-to-noise (SNR) trends of the Tetracell CISs when the pixel size decreases from 0.8 to 0.4 μm. In results, MTF of the Tetracell CISs shows an improvement until the pitch of 0.45 μm. The reason of this trend is discussed together with the degeneration of color crosstalk and SNR.

I. INTRODUCTION

The industrial demands for high resolution camera make the pixel pitch scaled down to 0.64 μm [1]. As the unit pixel size of CMOS image sensors (CISs) shrinks to sub-micrometer scale, signal-to-noise ratio (SNR) degrades due to lower optical sensitivity. This issue can be compensated by new schemes such as Tetracell, Nonacell, and 2×2 on-chip lens [1,2]. However, another limitation of smaller pixel pitch, blur effect due to the optical diffraction is still arguable [3].

Until now, various methods of image simulation systems including the full camera chain with module lens, pixels, and image signal process (ISP) have been presented [4]. However, most of these works have only shown the image evaluation results by convolution of the point spread function (PSF) of module lens. In this study, we present a novel imaging simulation method considering the diffraction effects across pixels. We expect that this study would provide valuable intuition on current image quality issues related to pixel size reduction.

II. IMAGIN SIMULATION SYSTEM

Conventional image simulation method has its limited scope in estimating blur effect via simple PSF convolution. To accurately estimate the sharpness and sensitivity of the camera, full Fourier optical approach of both lens and the pixel structure is necessary. Image signal processing (ISP) to affect the final image quality should be considered as well.

The proposed simulation method has two steps: 1) spatial effects incorporating actual lenses and diffraction effects across pixel array structures with optical simulation, and 2) calculation of camera output including key camera parameters such as noise and the effects from ISP as shown in Fig.1. We defined the distribution of the number of electrons in each pixel as the pixel point spread function (PPSF), which is obtained from finite-difference time domain (FDTD) simulation on actual pixel array structures. The final images are achieved from convolution of the piecewise defined PPSFs and non-blurred image signals.

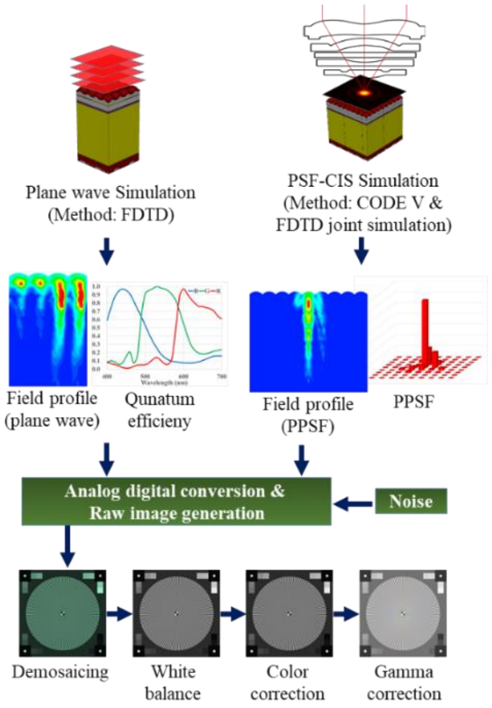


Figure 1. Simple pipeline of overall image simulation

The PPSF simulation methodology is evaluated by comparing a measured MTF curve and a conventional PSF-based MTF curve on the Tetracell with a pitch of 0.8µm. As shown in Fig. 2, proposed PPSF method shows more accurate MTF prediction compared with PSF-based convolution method. This model is embedded into a virtual CMOS image sensor (VCIS) solution, which was inherited from an image design assistant system (IDAS) to design next generation CIS pixels [5].

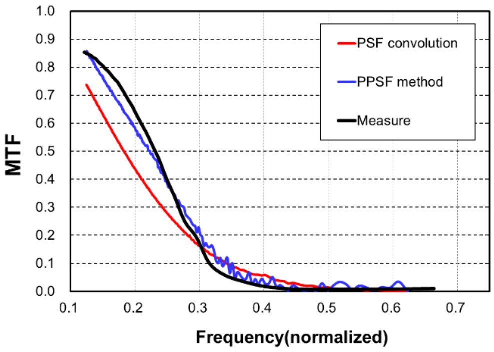


Figure 2. Comparison of PSF-based MTF, PPSF-based MTF, and experiment MTF curves.

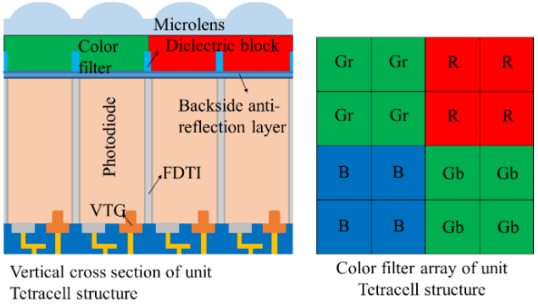


Figure 3. The schematic configuration of the pixel structure and Tetracell.

With the noble imaging simulation method, we estimated modulation transfer function (MTF) and SNR of Tetracell CISs as pixel size shrinks from 0.8 µm to 0.4 µm. Figure 3 shows the unit pixel structure of Tetracell, which is assumed to be fabricated with front-side deep trench isolation (FDTI) process. The FDTI process has the advantage of maintaining photodiode full-well capacity and improving SNR by completely blocking the electrical crosstalk.

The lens module has the optical format of 1/1.33-inch, f-number of 1.75, and a focal length of 5.43 mm. We obtained the PSF vector field of the module lens with a beam synthesis propagation function through a commercial ray optic simulation tool, Code-V.

The microlens module is formed with a top planarization layer (TPL), dielectric block, and backside anti-reflection layer (BARL). The optical structures are designed to have identical focal point. To investigate pixel scaling effect on MTF, we fixed total chip size and scaled down the pixel pitch as shown in Table 1.

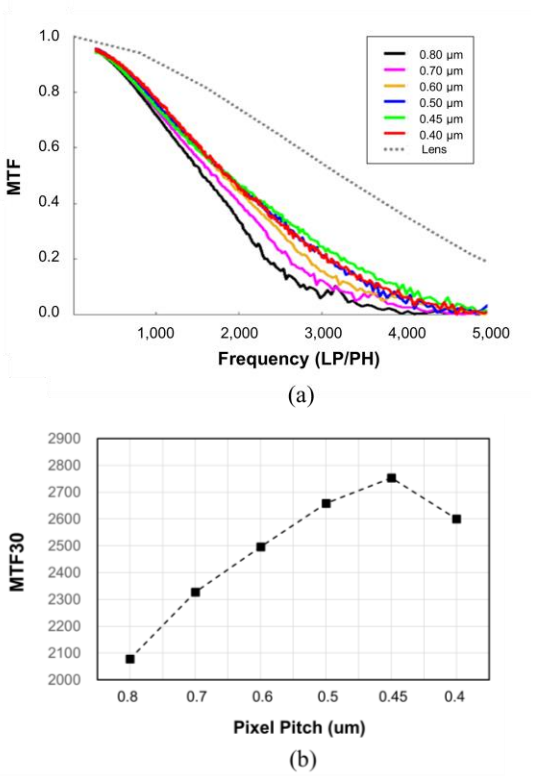
Pixel pitch	Resolution	Chip size
0.8 µm	108Mp	9.6 × 7.2 (mm)
0.7 µm	141Mp	
0.6 µm	192Mp	
0.5 µm	276Mp	
0.45 µm	341Mp	
0.4 µm	432Mp	

Table 1. Total Chip size and resolution with respect to pixel pitch

This work is focused on MTF and SNR of Tetracell CISs in remosaiced full mode and the center pixels. For more precise image quality prediction, we plan to study on image quality at chip edges in the near future.

III. RESULT & DISCUSSION

Figure 4 shows the MTF simulation results with a Siemens star chart. The result shows that MTF30 improves until the pixel pitch of 0.45 µm. To explore the reason of MTF degradation beyond 0.4 µm, we have analyzed QE spectrum, crosstalk, and SNR in Fig. 5. The results show that a crosstalk component steeply increases and Yc-SNR decreases from 0.7 µm, where Y-SNR means conventional luminance SNR and Yc-SNR means SNR considering color crosstalk effects [6].



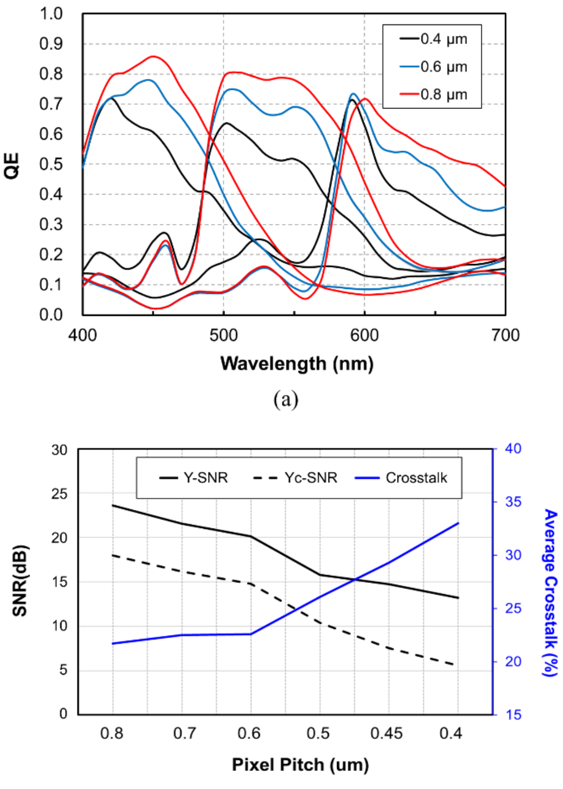
(a)

(b)

Figure. 4 (a) Frequency (LP/PH) dependent MTF curves, (b) MTF30 curves with respect to pixel pitch.

It means that the color noise degrades the resolution improvement effect obtaining from the pixel size reduction. These results imply that the color noise reduction technology and new microlens with high refractive index are crucial to scale pixels down to 0.4 µm pitch.

In addition, these results show that Tetracell CISs with sub-micrometer scale unit pixels with even smaller than 0.5 µm have a sufficient resolution improvement effect, as long as the crosstalk ratio remains below than 30%.



(a)

(b)

Figure. 5 (a) Calculated quantum efficiency(normalized) trend with respect to pixel pitch. (b) Y-SNR, and Yc-SNR with average crosstalk. SNR is calculated on 22nd-patch of Macbeth chart with 20 lux illuminance of D65 light.

IV. CONCLUTION

In this study, we have investigated the actual MTF and SNR trends of the Tetracell CIS when the pixel size decreases from 0.8 to 0.4 µm. For this purpose, we implemented a novel full camera chain image simulation model inside VCIS, taking into account with optical diffraction effects across pixel array structures. The simulation results showed that the MTF30 increases until 0.45 um pitch but decreases beyond 0.4 um. We showed that the MTF degradation is strongly correlated with Y-c SNR reduction. It means new crosstalk reduction technology is necessary to scale down pixel pitch more.

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