Modeling and investigation of auto focus disparity sensitivity for CMOS image sensors with sub-micrometer scale pixel size

Euiyoung Song
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
eyy.song@samsung.com

Jae Ho Kim
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
icosa.kim@samsung.com

Kwanghee Lee
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
kh1009.lee@samsung.com

Jongsu Yoon
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
jongsu.yoon@samsung.com

Sungchul Kim
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
sungchul.kim@samsung.com

Dongun Shin
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
dongun.shin@samsung.com

Seunghyun Hong
Sensor Solution Team
Samsung Electronics Co., Ltd
Hwaseong-si, Korea
stksxk.hong@samsung.com

Sung-Su Kim
Sensor Solution Team
Samsung Electronics Co., Ltd
Hwaseong-si, Korea
ssis.kim@samsung.com

Yonghee Park
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
central.park@samsung.com

Dae Sin Kim
Computational Science and Engineering Team
Samsung Electronics Co., Ltd
Yongin-si, Korea
daesin.kim@samsung.com

***Abstract*— Modeling of simulation of auto focus (AF) disparity sensitivity for dual pixel CIS is conducted including module lens, pixel diffraction effect, and image signal processing. Additionally, investigation of the disparity sensitivity with respect to sub-micrometer scale pixel size are performed under the trend of reducing pixel size for high resolution. This methodology can be used to predict the AF performance from an imaging system perspective when scaling the pixel size below the subwavelength.**

Keywords*— *AF, CIS, AF disparity Sensitivity, high resolution

I. Introduction

Dual pixel CIS is one of the ways to implement PDAF (Phase Detection Auto Focus). It has two sub-photodiodes in each pixel and the signals from the individual sub-photodiodes (PDs) are used for phase detection. There are two main indicators of the AF performance of dual pixels: AF-contrast [1] (AF-C) and AF disparity sensitivity [2]. First, as shown in Fig.1(a), AF-C is calculated as the sensitivity ratio of the two sub-PDs when oblique light is incident on the pixel. This method is useful for measuring the AF performance of the pixel itself. However, AF-C is not suitable for measuring the AF performance of the whole imaging system including the module lens, because AF performance is affected by the whole imaging system, not just the pixel itself, but also the module lens, ISP(Image Signal Processing), etc. On the other hand, as shown in Fig. 1(b), AF disparity sensitivity can be used to determine the AF performance of the whole imaging system including the module lens and ISP, because it calculates the ratio of defocus size to disparity. However, to the best of our knowledge, there is no established methodology for simulating AF disparity sensitivity with the integration of module lens, pixel, and ISP.

In this paper, we propose a novel imaging simulation methodology to calculate the AF disparity sensitivity in a sensor imaging system including the module lens, pixel, and ISP. To our best knowledge, this is the first exemplification that has been proposed to calculate the AF disparity sensitivity taking into account both the diffraction effect within the pixel and the module lens. In addition, we investigate the change trend of the AF disparity performance as the pixel size decreases from 1μm to 0.6μm. We expect that this study will provide useful information and insight on the AF performance when developing smaller sub-micron pixels to achieve higher resolution.

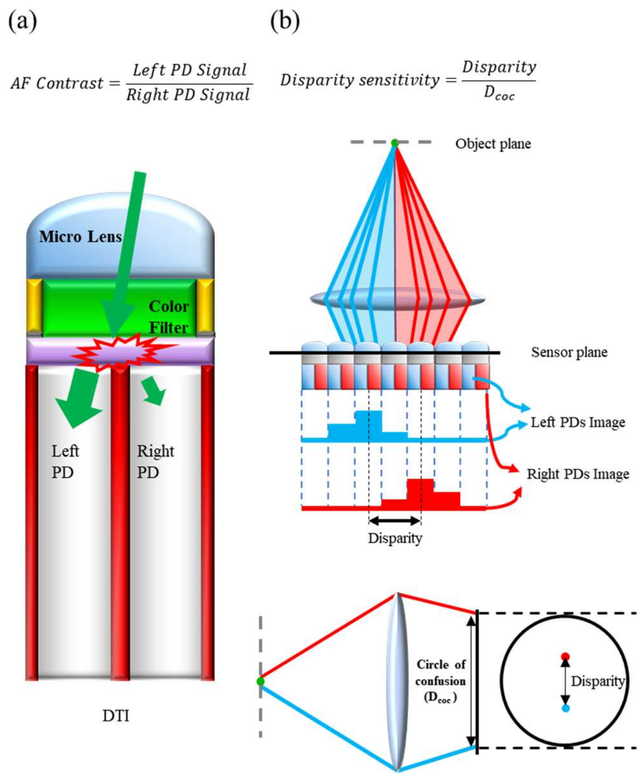

Fig. 1. Two methods to calculate AF performance. (a) AF-C and (b) AF disparity sensitivity

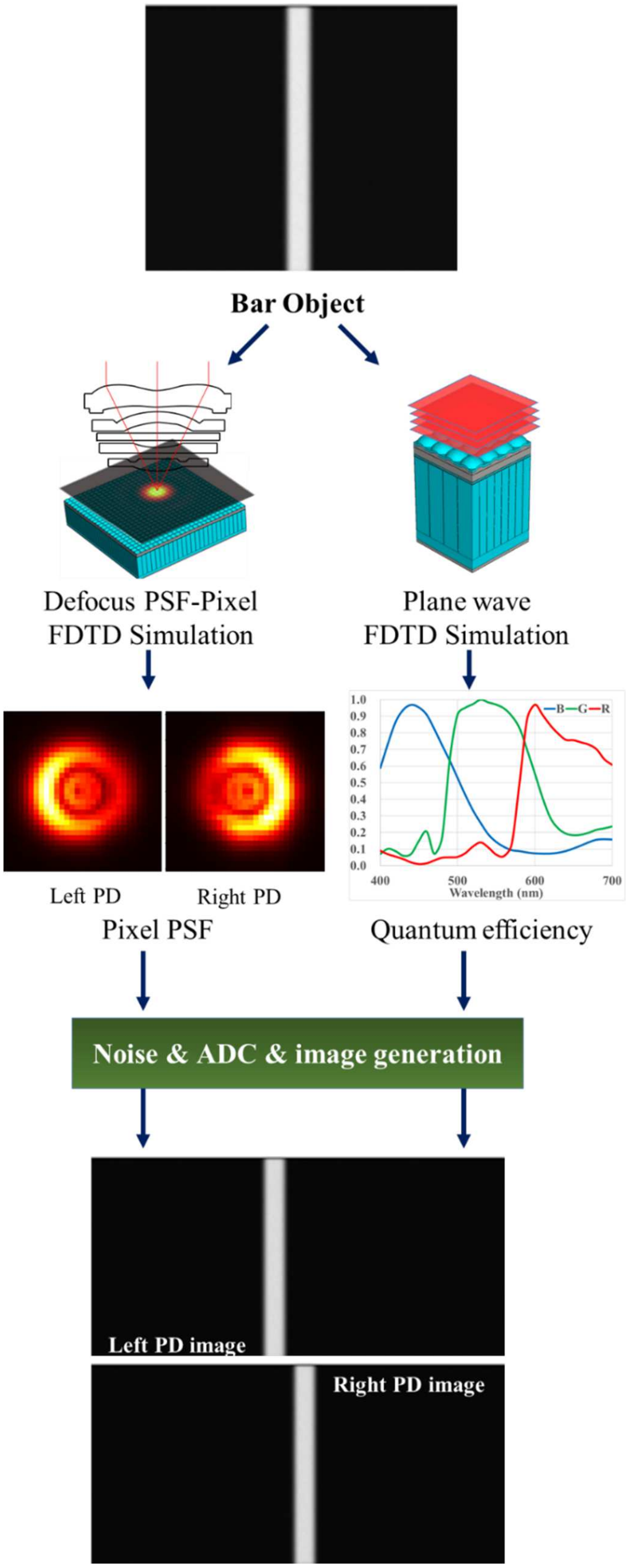

Fig. 2. Pipeline of image simulation for calculating disparity

II. AF DISPARITY SENSITIVITY SIMULATION SYSTEM

The proposed simulation method was modeled based on our previous study [3]. The core idea of this simulation methodology is to use the PSF(Point Spread Function) of the lens as a vector field in the form of input light in the FDTD(Finite-Difference Time Domain) and to obtain the signal of each pixel by incidence on a large-area pixel array, and to construct a PPSF(Pixel Point Spread Function) to generate an image. To generate this image, the QE of the pixel is obtained to construct a blur-free ideal image, and then the PPSF is convolved to obtain the final image.

However, there are two major modifications in this paper compared to the previous paper, which are shown in Fig. 2. First, the disparity simulation illuminates a defocused PSF, which is a few tens of micrometers away from the focal point, rather than a focused PSF to calculate the PPSF. This is because the PPSF of a perfectly focused PSF will have the same signal in the left and right sub-pixels.

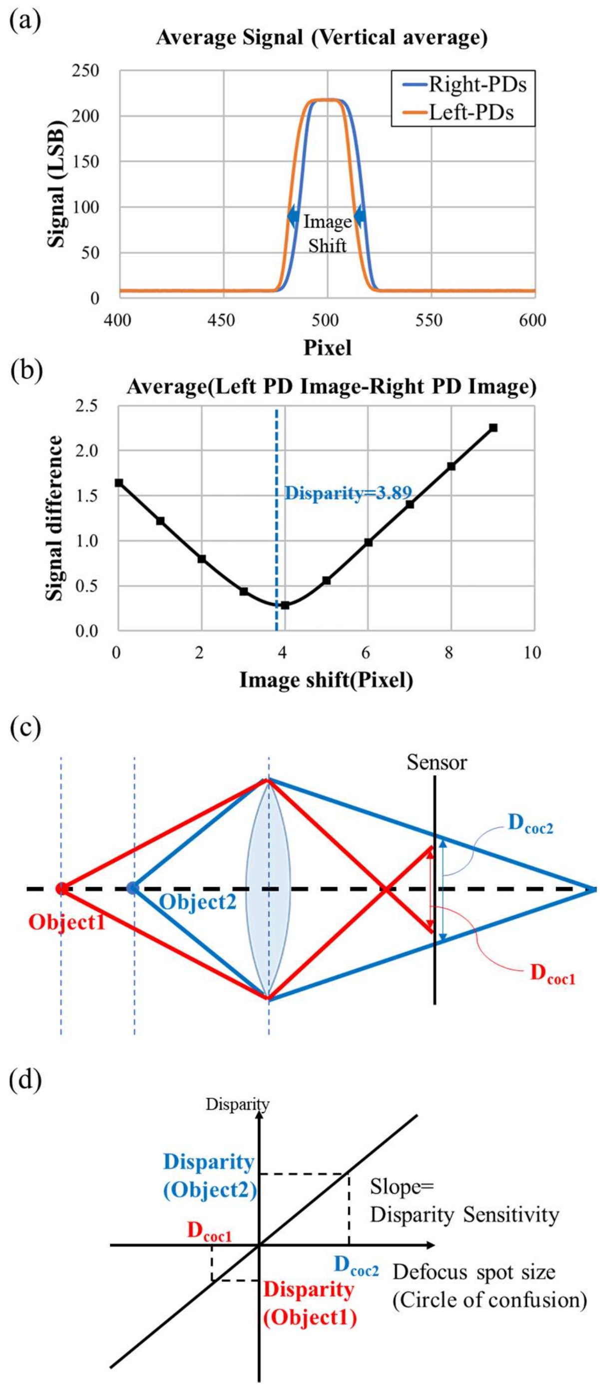

Fig. 3. The process of calculating the AF disparity sensitivity. (a) Vertical average of bar image (b) Average the difference between the left PD image and right PD image. (c), (d) Calculate the slope of the graph of defocus spot size vs Disparity

Second, the PPSF result is divided into sub-pixels of dual pixels, and the PPSF of the left sub-pixel and the PPSF of the right sub-pixel are calculated. These two PPSFs are applied to the bar image to obtain the output images of the left and right photodiodes, respectively. As can be seen from the PPSF image in Fig. 2, the centers of the PPSFs of the left and right photodiodes are shifted to the left and right, respectively. This shift determines the left-right disparity of the bar image.

The disparity value between the left photodiode image and the right photodiode image can be calculated as described in Fig. 3. Fig. 3(a) shows the result of plotting the average signal values of the bar images of the left and right photodiodes in the vertical direction. When the average signal graph of the right sub-photodiodes is shifted to the left and the difference from the average signal graph of the left photodiode is plotted, the result in Fig. 3(b) is obtained. However, since the shift value when moving the graph is only an integer, the difference value of the left and right signals can be fitted to a two-dimensional function, and the minimum value of this function can be defined as the disparity.

Finally, by dividing the disparity by the size of the defocused area (D_{coc}), the AF disparity sensitivity defined as the disparity per unit D_{coc} can be obtained, as shown in Fig. 3(c) and (d). As shown in Fig. 3(d), theoretically, if the disparity is obtained at a certain defocus distance, it is possible to obtain the disparity sensitivity, which is the slope, since the disparity is 0 at the focus point (x = 0 point). However, due to non-ideal effects in the actual simulation, the AF disparity is obtained by dividing the sensor into two cases: when the sensor is farther from the module lens than the focal point (red line) and when the sensor is closer to the module lens than the focal point (blue line), and the AF disparity sensitivity is obtained from these two points. If a more accurate value is desired, the AF disparity can be obtained at multiple defocus points, fitted to a one-dimensional function, and then the slope can be obtained.

If the defocus length is too short, the disparity may not be sufficiently secured, which can make the AF disparity sensitivity value inaccurate. Therefore, the defocus length was set to 80um to conduct the simulation. In this case, a large-area pixel array simulation of approximately 40um x 40um is required to obtain the PPSF using FDTD.

III. Simulation Result and Discussion

Fig. 4 (a) compares the AF disparity sensitivity simulated by the proposed method with that measured according to the CIS chip position (x=0 at the center of the chip). The simulation results follow the trend of the measurement results with a slight offset. In general, such offsets can be attributed to nonideal lens characteristics, such as lens tilt and vignetting, and process errors, including pixel micro-lens miss-alignment and module lens-sensor miss-alignment.

Fig. 4 (b) shows the AF disparity sensitivity and AF-C and pixel size. The results indicate that it is difficult to satisfy both smaller pixel size and better AF performance because the sub-pixel crosstalk due to diffraction in the pixel increases significantly as the pixel size decreases to the sub-wavelength. Physically, as the pixel size approaches the wavelength, the size of the PSF cannot be sufficiently reduced due to the diffraction limit, making it difficult for the sub-pixels of the dual pixel to distinguish a single PSF signal to the left and right. As the pixel size decreases, the diffraction limit causes the light passing through the micro-lens to leak to the right sub-pixel rather than the target left sub-pixel. To overcome this limitation, it is necessary to use a special optical router technology such as a meta-prism [4] to attract light of high angular components to the target sub-pixel

IV. Conclusion

We presented a novel method to calculate the AF disparity sensitivity including the module lens, pixel diffraction, and ISP. The comparison between the simulated AF disparity sensitivity and the measured value shows a good agreement except for a small offset. In addition, we showed that it is difficult to maintain the AF performance due to the diffraction limit when reducing the pixel size to sub-micrometer without special improvement techniques. Although the methodology for calculating the AF disparity sensitivity is complicated and requires large computing resources because a large-area PPSF simulation is performed, compared with the AF-C calculation method, the AF disparity sensitivity simulation modeling is meaningful in terms of simulating the operation of an actual camera and the stability of the index. We expect that this study will provide a good intuition for the AF performance when reducing the pixel size to sub-micrometer to achieve a higher resolution.

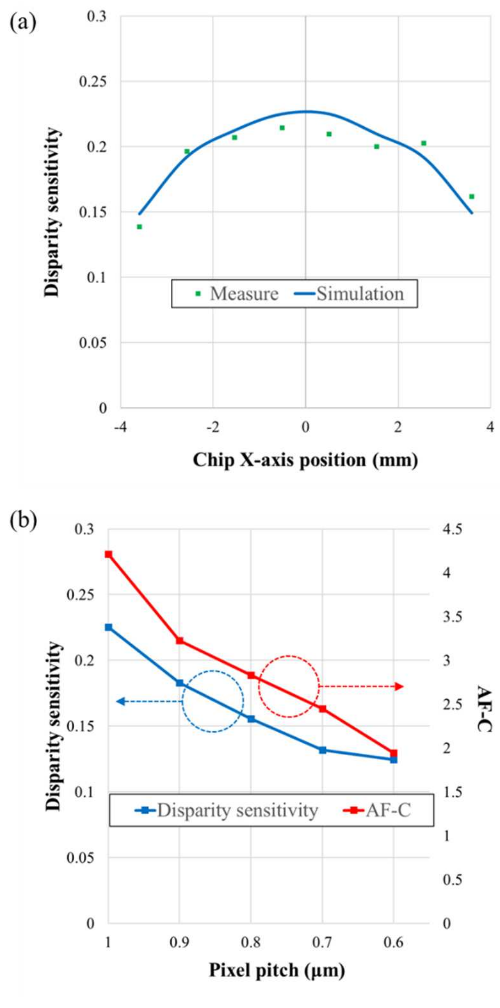

Fig. 4. Two methods to calculate AF performance. (a) AF-C and (b) AF disparity sensitivity

REFERENCES

[1] E. S. Shim et al., All-directional dual pixel auto focus technology in CMOS Image Sensor, 2021 Symposium on VLSI Circuits, pp. 1-2, 2021.

[2] A. Punnappurath et al., Modeling defocus-disparity in dual-pixel sensors, Proc. IEEE Int. Conf. Comput. Photography, pp. 1-12, 2020.

[3] J. H. Kim et al., A study on modulation transfer function and signal-to-noise ratio for Tetracell CMOS image sensors with sub-micrometer scale unit pixels, International Image Sensor Workshop (IISW), pp. 13-16, 2021.

[4] S. Yun et al., Highly efficient color separation and focusing in the sub-micron CMOS Image sensor, IEEE International Electron Devices Meeting (JEDM), pp. 30.1.1-30.1.4, 2021.