in Proceedings of the 2015 International Image Sensor Workshop (IISW)
Vaals, The Netherlands June 8-12, 2015

Color Filter Array Patterns Designed to Mitigate Crosstalk Effects in Small Pixel Image Sensors

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Abstract – As pixel sizes approach the diffraction limit, optical and carrier crosstalk will increase substantially. Very high crosstalk leads to a reduction in SNR and color reproduction quality when conventional color filter arrays (CFAs) such as the Bayer patterns (RGB and CMY) are used. We present the design and analysis of new color filter array patterns for improving the color error and SNR deterioration caused by crosstalk in these sub-diffraction-limit (SDL) pixels.

1. INTRODUCTION

As state of the art CMOS image sensor pixels approach the submicron threshold, a number of challenges emerge which have to be addressed. One fundamental challenge is the reduction in light collection but this is largely mitigated by a variety of approaches including the use of microlenses and backside illumination (BSI). Another problem that remains persistent in small pixels is the increased occurrence of crosstalk. Crosstalk occurs in two different ways. Firstly, light incident above one pixel, may penetrate into a neighboring pixel and generate photocharge. This is known as optical crosstalk and tends to be very important in front side illuminated (FSI) pixels. As pixel sizes decrease to levels comparable to the visible light wavelength, increased diffraction will increase this form of crosstalk in both FSI and BSI pixels. In the second crosstalk mechanism, photocharge generated in one pixel diffuses into neighboring pixels where it is collected. This is known as electrical or diffusion crosstalk.

In color image sensor pixels, crosstalk diminishes the color signal of affected color channels and increases the overlap in the spectral responses of the different color channels. For instance, in the Bayer pattern, the crosstalk in the red pixel extends its spectral response into the green wavelength region and decreases the response in the red spectral region. The diminished color signal and increased spectral overlap reduce the color gamut that can be reproduced from the raw color signal without color correction.

Typically, color correction can be used to transform sensor output to produce colors within the standard sRGB color gamut. However, if the crosstalk substantially diminishes the color gamut of the device, more intensive color correction will be required. The color correction must perform an amplification operation to transform the reduced gamut. Some signal subtraction will also be required in the color correction process to compensate for the increased overlap in spectral responses. Increased crosstalk therefore increases the noise amplification of the color correction process and leads to reduced SNR performance. Color correction matrices for sensors with increased crosstalk will therefore sacrifice either color reproduction accuracy or SNR or both.

2. COLOR FILTER ARRAY PATTERNS

The design of CFA patterns is often discussed with regards to specifications such as spatial resolution, aliasing and immunity to color artifacts. However, for small pixels also known as sub-diffraction limit (SDL) pixels, where the pixel pitch may be less than the Airy disk diameter of the diffraction-limited point response of the optical system, restrictions on spatial sampling frequency become trivial thus opening up many CFA pattern possibilities. The Airy disk diameter for an optical system is dependent on its F-number F, and the wavelength of the illumination.

$$D = 2.44\lambda F \qquad (1)$$

In image sensor concepts such as the Quanta Image Sensor (QIS) [1], pixels/jots are expected to be only a fraction of a micron.

The Bayer pattern [2], which is inarguably the most widely used CFA pattern for image sensors in digital cameras, has its red and blue pixels surrounded vertically and horizontally by green pixels. Crosstalk signal into red and blue pixels is therefore predominantly from green pixels. This extends the red and blue pixel responses into the green region of the spectrum. Likewise green pixels receive crosstalk signal from 2 red and 2 blue pixels. This has the effect of reducing the actual signal for each of the red blue and green pixels whilst increasing the overlap in their spectral responses.

In our proposed color filter array patterns, we insert a secondary color pixel between every two primary color pixels in the regular Bayer pattern. The secondary color introduced is the color obtained by summing the two Bayer primary colors. A yellow pixel is placed between red and green pixels and a cyan pixel between blue and green pixels as shown in figure 1. A green pixel is situated in the middle in one CFA pattern. This is because the middle position has the same neighbors as the primary green in the expanded Bayer pattern. This is depicted as RGBCY. An alternative design aimed at increasing light sensitivity uses a white/panchromatic filter in place of the middle green. This pattern is depicted as RGBCWY.

In the new patterns, spectral overlap caused by crosstalk is minimized since most of the crosstalk is now in the same spectral region as the signal. Each primary color pixel is surrounded vertically and horizontally by secondary color pixels. The individual primary color pixels have negligible crosstalk contributions to each other. As a result of this spectral overlap reduction, the color

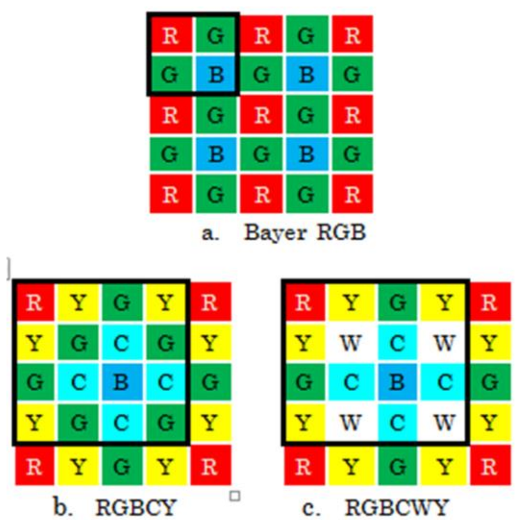

Fig.1. CFAs of the Bayer pattern and two proposed patterns with black square demarcating the kernel for each CFA

Most of this paper was previously published in J. Opt. Soc. Am. A, Vol. 32(1), pp. 28-34 January 2015 as disclosed to the Technical Program Committee. The authors believed it might be suitable as a poster at IISW since JOSA-A is not widely read by the image sensor community, and thus allow discussion and feedback for this proposed CFA approach.

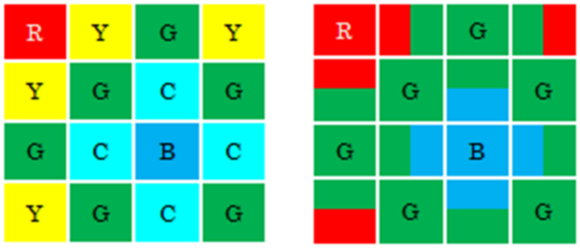

Fig.2. Transformation of the RGBCY kernel to sRGBCY showing yellow pixels composed of half red and half green filters and cyan pixels half-covered by blue and green filters.

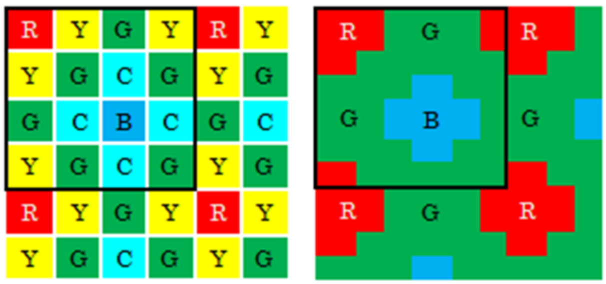

Fig.3. Full CFA pattern showing RGBCY pattern and its modified form sRGBCY which uses 2 half primary filters for each secondary color filter.

correction process causes less noise amplification and SNR reduction when the proposed patterns are used.

The new CFA patterns have 5 or 6 colors channels resulting in 6xN or 5xN outputs following interpolation. Color correction will therefore require 3x6 and 3x5 color correction matrices respectively. It is understood that these color correction matrices will increase computational costs. Also the added Color Filters will increase fabrication costs since two additional masks will have to be used. However, for the purpose of comparing these patterns to the Bayer RGB and CMY patterns, the 5 and 6 channel outputs combined to produce R, G, B channels that can then utilize 3x3 matrices.

An alternative implementation of the RGBCY pattern uses three primary color filters, like the Bayer pattern thereby eliminating the additional mask costs. In this alternate form, referred to as sRGBCY, each secondary color filter is replaced with two half primary filters whose colors sum up to give the secondary color. Thus the active region of each yellow pixel is half covered by a red filter and half-covered by a green filter as shown in figure 2. The red half of the yellow pixel is the half closest to the red pixel and the green half is closest to the neighboring green pixel. In a similar fashion, the cyan pixels are half-covered by blue filters and half-covered by green. The kernel of the new CFA is transformed as shown in figures 2.

It should be noted that using two half primary color filters in place of the secondary color filters will reduce their light transmission by half. The resulting pattern, sRGBCY now has the same sensitivity as the Bayer pattern. The CFA pattern obtained using this alternative implementation is shown in Figure 3.

3. IMAGE FORMATION MODEL SIMULATION

In our investigation of the new color filter array patterns, only computer simulations have been performed thus far. Test images were created for the different CFA patterns. The color filters used in this simulation were Gaussian curves centered at the wavelengths stated in table 1 above. It is assumed that the secondary color filters are a combination of the two primary color filter responses and primary filters are scaled to have a maximum transmittance of 0.33 at the center wavelength. We also assume an ideal imager such that, the only source of variability is the shot noise.

In our simulations, the pixel response was determined using the incident photon flux, $\Phi(\lambda)$ in $\mathrm{photons}/\mu\mathrm{m}^2\mathrm{s}$, the target spectral reflectance $M(\lambda)$ and the spectral transmittance $CT(\lambda)$ of the color filter above each pixel. The signal collected at each pixel is given by

$$S(\lambda) = k \cdot \Phi(\lambda) \cdot M(\lambda) \cdot CT(\lambda). \qquad (2)$$

The target used is the Macbeth chart. The proportionality constant k, accounts for pixel parameters such as pixel size, lens F# etc.

Five CFA patterns were simulated and compared. These include the Bayer RGB and CMY patterns and the new RGBCWY, RGBCY and sRGBCY patterns. For each CFA, a 240x360 test image of Macbeth chart was created using equation (2) to generate pixel responses. Shot noise is simulated by means of the poisson random function generator in MATLAB.

In our simulations pixel crosstalk is modeled through a crosstalk kernel similar to the approach in [3]. The crosstalk kernel for each pixel location is a 3x3 matrix that depicts the loss of signal from the central pixel into adjacent pixels.

$$X_R = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \qquad (3)$$

The middle element a_{22} represents the fraction of signal that remains in the pixels after crosstalk signal has been subtracted. The surrounding terms represent the fraction of signal the middle pixel loses to its neighbors. This crosstalk model is illustrated in figure 4. The figure shows the crosstalk for red green and blue pixels respectively. In the illustration in figure 4, it is assumed that only the central pixel is illuminated. Therefore, the off-center pixels ideally should have no signal if crosstalk is absent. Crosstalk values used in our simulations are linearly scaled versions of data obtained by means of TCAD simulation. These crosstalk values are listed in Table I.

In our analysis, we assume that crosstalk only occurs between horizontal and vertical neighbor pixels. Crosstalk to diagonally neighboring pixels is negligible. For ease of analysis, we also assume that the crosstalk is independent of the wavelength in the different spectral regions. Thus all wavelengths in the red region have the same crosstalk which is higher than crosstalk for wavelengths in the green and blue owing to the deeper penetration. This is less so in BSI pixels where the photodiode is located away from the light-incident surface.

Bilinear interpolation was used to create full test images for each CFA pattern. Since the new filter array patterns have a kernel size of 4x4 pixels, they require an interpolation kernel size of at least 5x5 pixels. We use the same interpolation kernel size for the Bayer RGB and CMY test images so that a fair SNR comparison can be made. White balance weights were also determined to equalize the mean

Table I. Sensor Simulation Parameter Values

Parameter	Value
Illuminants	D65, CIE A
Pixel parameter constant, k	$0.27\ \mu\mathrm{m}^2\mathrm{s}$
Red Filter Center/halfwidth	600 / 50 nm
Green Filter Center/halfwidth	555 / 66 nm
Blue Filter Center/halfwidth	450 / 33 nm
Red Pixel Crosstalk	45%
Green Pixel Crosstalk	30%
Blue Pixel Crosstalk	20%

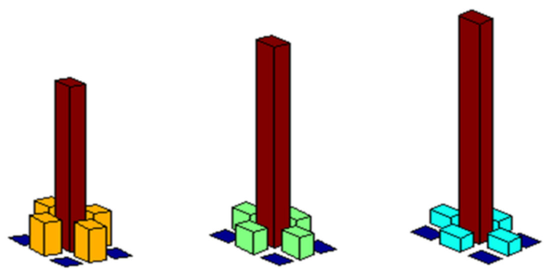

Fig.4. Crosstalk illustration– Only Central pixel illuminated but the surrounding pixels receive some signal due to crosstalk from the illuminated pixel. a. b. and c. depict Red, Green and Blue Central pixels respectively

values of R, G and B channels of the white patch in the test image.

Following the white balance operation, color correction matrices were determined for the test images. The color correction process entails finding a transformation matrix which maps the measured sensor outputs to reference values for the Macbeth chart patches. In our simulations, the method presented in [3] is used. Correction matrices are determined which both minimize the color error and the noise variance in the transformed image. The objective function minimized to determine the CCM is a weighted sum of the color difference and the noise variance and is given by

$$J = \varepsilon_C + \omega \cdot \varepsilon_N \qquad (4),$$

Where ε_C the color is difference and ε_N is the noise variance. The weight ω allows us to trade off color accuracy for reduced noise. At $\omega = 0$, only the color difference is minimized and so the CCM for producing optimum color is obtained.

4. PERFORMANCE COMPARISON

To evaluate and compare the performance of the different CFA patterns in the presence of crosstalk, we consider two metrics. The deterioration in color reproduction accuracy caused by crosstalk is quantified by means of the CIELAB color difference metric ΔE_{ab}. The SNR deterioration as a result of crosstalk addition is also quantified using the color SNR as defined in ISO 12232. It is understood that color error and SNR performances are greatly dependent on the CFA as well as the source of illumination. Therefore two illumination sources have been used in these simulations. Results are reported for D65 and CIE A illuminants.

A. Color Reproduction Accuracy

The ΔE_{ab} gives a perceptually uniform measure of the difference between two colors in CIELAB color space and is given by

$$\Delta E_{ab} = \left[\left(L_{Ref} - L_{test}\right)^2 + \left(a_{Ref} - a_{test}\right)^2 + \left(b_{Ref} - b_{test}\right)^2\right]^{\frac{1}{2}} \qquad (5)$$

For each test image, the color difference value is calculated for each patch of the Macbeth chart and the mean color error over all patches can be determined using equation (6)

$$\Delta E = \frac{1}{N}\sum_{i=1}^{N} \Delta E_i \,, \qquad (6)$$

where N=24, is the number of patches of the Macbeth color checker. The color error for each CFA was determined by performing 100 runs using the 240x360 test images – the poisson random function generator in MATLAB was used to introduce shot noise so that images varied from run to run. The average color difference of the 100 runs is computed for each CFA pattern.

From the simulations, the Bayer pattern has the best color reproduction for both D65 and CIE A illuminants when there is no crosstalk between pixels. However, when crosstalk is added, the Bayer RGB and CMY patterns record the worst color performance for both illuminants. On the other hand, the new CFA patterns have the best color reproduction when crosstalk is substantial. Crosstalk addition doesn't cause any significant decrease in the color performance of the new CFA patterns whereas the color difference for the Bayer RGB and CMY patterns increases by more than 50%.

B. Luminance Signal-to-Noise Ratio

The luminance signal to noise ratio (YSNR) discussed in [5] is the most widely used metric for comparing different color images because it provides a single overall SNR measure that combines the SNRs of the different color channels using their luminance coefficients. However, this YSNR metric ignores the correlation between color channels as a result of different color processing steps. As a result, this metric tends to underestimate the contributions of the blue channel to the visible noise and overemphasize the green channel contribution [6].

For the purpose of this investigation, the visual noise calculation is performed using the noise metric specified in ISO 12232 [7]. The SNR is calculated as the ratio of the luminance to the visual noise. The luminance evaluated using linearized RGB values is given by

$$Y = 0.2125R + 0.7154G + 0.0721B. \qquad (7)$$

The visual noise is calculated from the noise in the luminance channel and two chrominance channels (R − Y) and (B − Y), and is given by

$$\sigma = \left[\sigma^2(Y) + C_1\sigma^2(R-Y) + C_2\sigma^2(B-Y)\right]^{\frac{1}{2}}, \qquad (8)$$

where $C_1 = 0.279$ and $C_2 = 0.088$.

The SNR for each CFA's test image was determined both with and without crosstalk. The color correction matrices used earlier in

Table II – Color Error for simulations with and without crosstalk

CFA Pattern	Mean ΔE_{ab} – D65		Mean ΔE_{ab} – CIE A	
	No Crosstalk	With Crosstalk	No Crosstalk	With Crosstalk
Bayer RGB	3.6	5.1	3.1	4.7
CMY	4.3	5.1	4.3	6.8
RGBCWY	4.0	4.1	4.1	4.0
RGBCY	3.9	4.0	3.7	3.7
sRGBCY	4.1	4.1	4.0	3.9

Table III – SNR results for different CFA patterns

CFA Pattern	SNR (dB) – D65		SNR (dB) – CIE A	
	No crosstalk	With Crosstalk	No Crosstalk	With Crosstalk
RGB	28.1	24.2	28.4	24.9
CMY	25.5	24.3	27.1	25.4
RGBCWY	26.4	26.1	27.5	27.3
RGBCY	27.0	26.8	27.7	27.8
sRGBCY	26.2	26.3	27.1	27.2

section 4.A. for optimal color reproduction were used here so that a fair comparison of the SNRs for the different CFAs can be done. It should be mentioned that the SNRs calculated here are only meant to highlight SNR decrease due to crosstalk assuming optimal color reproduction is desired.

To compare the different CFA patterns, the SNR of the fourth grey patch on the Macbeth chart which has a reflectance value closest to 18% is used Again, 100 runs are performed and the luminance (Y) and chrominance (R – Y and B – Y) values are stored for each run. The standard deviations of luminance and chrominance channels at each pixel location are calculated and used in equation (8) to determine the visual noise.

Table IV shows the SNR calculated from simulations using the same color correction matrices which were determined for optimum color accuracy. It can be noticed that, the Bayer RGB pattern has the highest SNR in the absence of crosstalk regardless of the illuminant used. However, upon addition of crosstalk, the SNR of the Bayer RGB decreases by nearly 4 dB (for D65) whereas the new patterns show no significant decrease in SNR. This trend holds true for both D65 and CIE A illuminants. Therefore, when the color correction matrices are optimized for the best color reproduction, the new CFA patterns we propose have both better color reproduction and SNR performance than the conventional CFAs under conditions of high crosstalk.

C. Trade-off between YSNR and Color Reproduction

Color correction matrices optimized for minimizing color error tend to produce less than optimal SNR performance. Generally SNR performance can be improved at the expense of the color accuracy. In this section, we investigate the SNR – Color Accuracy trade-off behavior for the different CFAs.

For this investigation, color correction matrices optimized for decreased noise amplification are calculated. As explained earlier, increasing the noise variance weight in equation (4) decreases the noise amplification of the CCMs. We therefore calculate CCMs for increasingly higher noise variance weights, and use these in simulations to obtain the SNR and color error.

Figures 5 shows the SNR - color error trade-off curves for the different CFAs tested. As expected, the SNR increases as we relax the color error increases (and color accuracy decreases). The Bayer RGB has higher SNR at all color error levels when there's no crosstalk. The new CFA patterns however have higher SNR than the Bayer pattern when crosstalk is considered. The CMY pattern shows the worst performance across the range of color error levels surveyed. The SNR advantage of the new patterns over the Bayer pattern is much higher at low color error levels. For instance, at $\Delta E_{ab} = 5$, the RGBCY pattern has an SNR value about 4 dB higher than the Bayer pattern. However, at $\Delta E_{ab} = 12$, this gap reduces to about 2 dB.

5. CONCLUSION

We have presented a comparative study of the effect of crosstalk on the color reproduction accuracy and SNR of images produced using various CFA patterns. In this work, new color filter array patterns are proposed for mitigating the effects of crosstalk. The CIELAB ΔE_{ab} metric was used to quantify the color error. The SNR metric was also used to compare different color filter array patterns. Evaluation of the filter array patterns was done for two different illuminants D65 and CIE A illuminants.

The analysis shows that the proposed CFA patterns have better color and SNR performance in high crosstalk conditions. Ideal Gaussian curves were used to model the spectral transmittance of the color filters used in this work. It is expected that the center

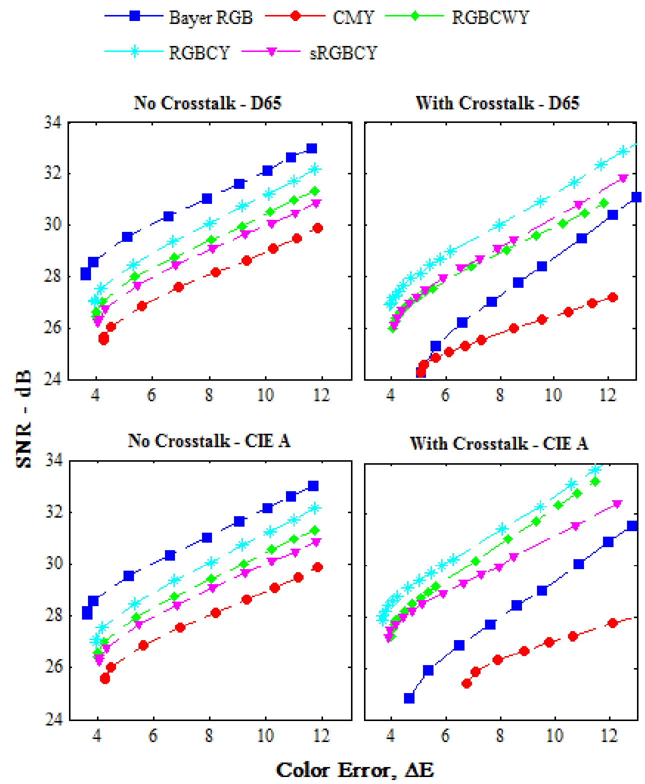

Fig.5. Color Error - SNR trade-off curves for simulations using D65 illuminant (Left) and CIE illuminant A (Right) in high crosstalk conditions

wavelength of these filters can be optimized to attain better performance. In conditions of low crosstalk, there isn't a significant advantage in the performance of the new color filter array patterns. The SNR - Color error trade-off relationship also shows that when the CCMs are optimized for the same color accuracy, the Bayer RGB and CMY have inferior SNR performance compared to the new patterns. The Bayer RGB only attains SNR levels comparable to the new patterns at high color error levels.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Rambus Inc. for this work.

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