Crosstalk metrics and the characterization of 1.1μm-pixel CIS

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ABSTRACT

Pixel crosstalk is one key image sensor performance index [1]-[2]. Yet, unlike other sensor parameters, there has been a lack of universal and simple metrics to facilitate the benchmarking across pixel generations, process technologies, and manufacturers. Conventionally, crosstalk is manifested by comparing the measured RGB spectra of a colored sensor with the monochrome spectrum multiplied by CFA transmittance, or specified by the color response ratios, (G/R, B/R), (R/G, B/G), (R/B, G/B) in pre-selected R, G, B bands, respectively (Fig. 1). However, multiple numbers are cumbersome for comparison and difficult to link to real color performance. In this paper, we propose 3 useful one-number crosstalk metrics and use them to characterize the 1.1um pixels of our 3MP test chips.

CCM-BASED CROSSTALK METRICS

One commonly accepted empirical measure on image sensor performance is the signal-to-noise ratio of luminance Y, described by formula (1) below, and the minimal scene illuminance required to reach YSNR=10 for a uniform 18%-reflecting gray target using a f#2.8 lens and 1/15 sec integration time, denoted as YSNR10 [3],

$$YSNR = \frac{a_R\mu_R + a_G\mu_G + a_B\mu_B}{\sqrt{a_R^2\sigma_R^2 + a_G^2\sigma_G^2 + a_B^2\sigma_B^2}}, \quad a_R = 0.299,\ a_G = 0.587,\ a_B = 0.114, \tag{1}$$

where the μ's and σ's represent the mean and the standard deviation of the color-corrected RGB data. Typically a 3-by-3 color-correction matrix (CCM) is used to transform the raw data R'G'B' into the corrected RGB after the white balancing. Neglecting the black-level offset adjustments and the over-flow clamping, we have [4]:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} c_{RR} & c_{RG} & c_{RB} \\ c_{GR} & c_{GG} & c_{GB} \\ c_{BR} & c_{BG} & c_{BB} \end{pmatrix} \begin{pmatrix} w_R & 0 & 0 \\ 0 & w_G & 0 \\ 0 & 0 & w_B \end{pmatrix} \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix}. \tag{2}$$

For simplicity, color correction and white balance may be merged into one combined CCM:

$$\begin{pmatrix} b_{RR} & b_{RG} & b_{RB} \\ b_{GR} & b_{GG} & b_{GB} \\ b_{BR} & b_{BG} & b_{BB} \end{pmatrix} = \begin{pmatrix} c_{RR} & c_{RG} & c_{RB} \\ c_{GR} & c_{GG} & c_{GB} \\ c_{BR} & c_{BG} & c_{BB} \end{pmatrix} \begin{pmatrix} w_R & 0 & 0 \\ 0 & w_G & 0 \\ 0 & 0 & w_B \end{pmatrix}. \tag{3}$$

We may assume there is no overall gain factor,

$$a_R\mu_R + a_G\mu_G + a_B\mu_B \approx a_R\mu_{R'} + a_G\mu_{G'} + a_B\mu_{B'}, \tag{4}$$

and, for gray patches, the individual R'G'B' noises are approximately equal and statistically independent:

$$\sigma_{R'} \approx \sigma_{G'} \approx \sigma_{B'};\ \mathrm{cov}(R',G') \approx \mathrm{cov}(G',B') \approx \mathrm{cov}(B',R') \approx 0. \tag{5}$$

As a result, the color correction process degrades the YSNR value by a weighted factor: (6)

$$\sqrt{\frac{a_R^2\left(b_{RR}^2 + b_{RG}^2 + b_{RB}^2\right) + a_G^2\left(b_{GR}^2 + b_{GG}^2 + b_{GB}^2\right) + a_B^2\left(b_{BR}^2 + b_{BG}^2 + b_{BB}^2\right)}{a_R^2 + a_G^2 + a_B^2}}$$

Above dimensionless constant shall be referred to as the CCM noise factor, since it consists of CCM elements exclusively and its effect is primarily increasing the noise denominator of YSNR. For an ideal sensor where colors are accurate without correction, the CCM would be a unity matrix and the CCM noise factor is exactly one. Our measured data of 1.1um pixels range from 1.4 to 2.7.

On one hand, the CCM noise factor expresses the price paid for color correction, leading to a potential trade-off between YSNR and color fidelity. On the other hand, it is a good candidate itself as pixel crosstalk metric. Higher crosstalk results in higher color mixing and larger CCM noise factor, vice versa.

In order to characterize crosstalk consistently, a robust and automated CCM extraction procedure is needed. In this study, we chose to minimize the RMS CIEDE2000 color difference [5] of 24 colors on the Macbeth ColorChecker. Fig. 2 shows a typical 1.1um-pixel color performance before and after color correction under a D65 illuminant in a light box. Fig. 3 shows an average error of 2.5ΔE over all DUTs can be achieved using a linear regression in XYZ space followed by a global nonlinear optimization in CIELAB space [6].

Fig. 4 illustrates the impact of the CCM noise factor in YSNR measurement by comparing the 1.1um and 1.4um pixels before and after the CCM. A bilinear interpolation is used for demosaicing the Bayer-patterned raw image. The average YSNR ratio of 1.4um vs. 1.1um pixel after CCM is about 1.60, while the ratio before CCM is about 1.30. Thus, an approximate extra 23% (1.6/1.3=1.23) YSNR degradation is attributed to increased crosstalk in 1.1um pixel, which is exactly reflected in the ratio of corresponding CCM noise factors. For this example, the measured YSNR10's are (57.3lux, 119.3lux) for 1.1um pixel before and after CCM, (42.8lux, 66.8lux) for 1.4um pixel before and after CCM, respectively.

COLOR ERROR BEFORE CORRECTION

One shortcoming of above approach is that in real applications, CCM is not necessarily optimized in order to trade off YSNR. Color appearance may also be adjusted according to other subjective criteria. Moreover, methods other than 3X3 matrix may be used for color calibration,

such as higher-order matrices or 3D lookup tables.

Hence, we propose a second crosstalk metric as the RMS pre-correction color error of the 24 Color-Checker colors. This would be independent of any specific calibration methods. In our experiments, we found that larger color error always indicates higher crosstalk and poorer color performance. The range of the pre-correction color error is roughly from 7.5ΔE to 12.5ΔE.

COLOR EYE DIAGRAM

The third crosstalk metric is the normalized area of the pre-correction Color Checker gamut in CIELAB (a*, b*) plane, which could be graphically represented by the eye-diagram of 9 most saturated colors: primary R, G, B; complementary C, M, Y; yellow-green, blue-green, and orange. The area is normalized to the ideal color gamut area, value ranging between 0 (worst case) and 1 (ideal case). Smaller eye opening is an evidence of higher crosstalk, which intuitively lead to larger color error before CCM and larger CCM noise factor. Our data are in the interval of (0.08, 0.28).

F-NUMBER DEPENDENCE

As pixel shrinks, smaller f-number lenses are required to increase the incoming light flux to compensate the loss of light collecting efficiency. Accordingly, optical crosstalk may become a performance-limiting factor due to larger light entrance angles, on top of other optical system design challenges [7].

A C-mount global lens with long back focal length was used in this study to minimize the shading effect without microlens shift. A combination of neutral-density filters and electronic shutter control are used to maintain the focal plane illuminance at constant level with a fixed analog gain while taking test images using variable f-numbers.

The color eye-diagrams under different f-number lenses in Fig. 5a clearly reveal the effect of optical crosstalk in 1.1um pixel. The optical crosstalk is increasingly larger as f-number is reduced from F8.0 to F1.3. In contrast, the reference 1.4um pixel shows almost no optical crosstalk in Fig. 5b.

EQUIVALENCE OF 3 METRICS

Figs. 6a-6c show a subset of a systematic study of 1.1um pixels of various process splits (SP1-SP8), characterized by 3 crosstalk metrics under different f-number lenses. The process splits are designed to investigate the effects of photodiode and isolation implants on crosstalk. The correlation plots in Figs. 7a-7b demonstrate strong correlation among these 3 metrics and prove their equivalence. Each one should be equally well suited for quantitative specification of pixel crosstalk. In short, we showed that the complex nature of pixel crosstalk could be effectively characterized by well-defined one-number metrics.

CROSSTALK DECOMPOSITION

To minimize crosstalk, it is important to distinguish its sources. The f-number dependency discussed above is an effective way to identify the optical crosstalk. In addition, a monochrome sensor combined with RGB filters coated on glass plates is used to take 3-shot images as references, where the spatial (electrical, optical) crosstalk among neighboring pixels cancel out in a relatively uniform area of the color patches. Consequentially, only spectral crosstalk remains. Combining these two techniques, we could decompose the crosstalk components experimentally as shown in Fig 8. For SP8 1.1um pixel, we are able to clearly separate the effect of each crosstalk component. For 1.4um pixel, both of electrical and optical crosstalk is negligible. Comparing with Fig. 6a, the SP5 1.1um pixel shows almost no measurable electrical crosstalk, while its optical crosstalk still needs further improvement. Work is under way to optimize the optical path and stack height.

SUMMARY

From the initial process development phase to the mass production over extended period, key performance index like pixel crosstalk needs to be continuously monitored and tracked. RGB QE spectrum measurement is time consuming and not practical for a large number of devices. In contrast, the 3 crosstalk metrics proposed in this paper are based on one test-chart image, making them suitable for process monitoring at FT level. The CCM noise factor, combined with parameters like FPN, readout noise, and FWC, can be used to predict YSNR10 directly. The pre-correction eye-diagram area and the RMS color difference are even simpler to calculate. Both are shown strongly correlated to the CCM noise factor; therefore, indirectly to YSNR10. Using these metrics, we demonstrated an experimental method to separate and quantify the electrical, optical, and spectral crosstalk components.

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Fig. 1: Out-band/in-band color ratio of a 1.1u pixel

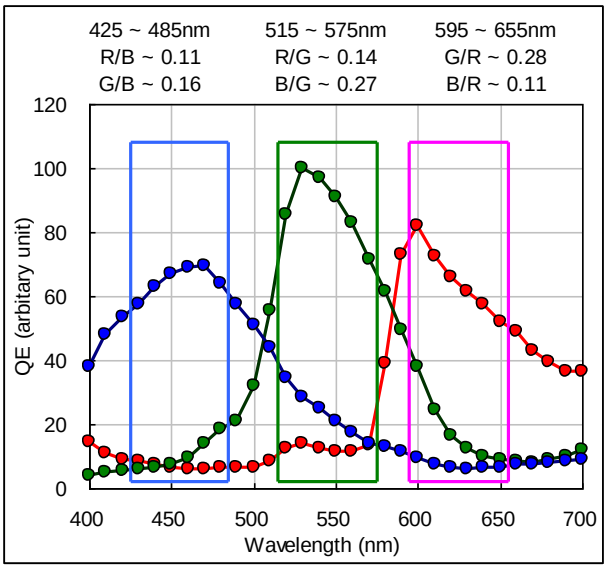

Fig. 2: (a*, b*) chromaticities before and after CCM

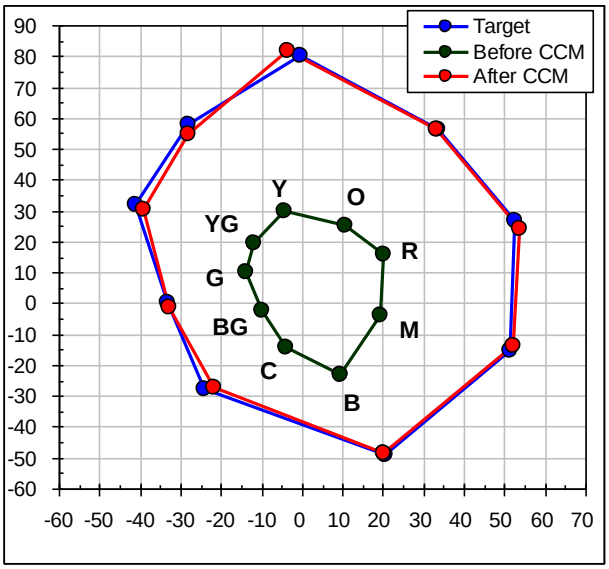

Fig. 3: RMS color difference after CCM of 1.1u DUTs

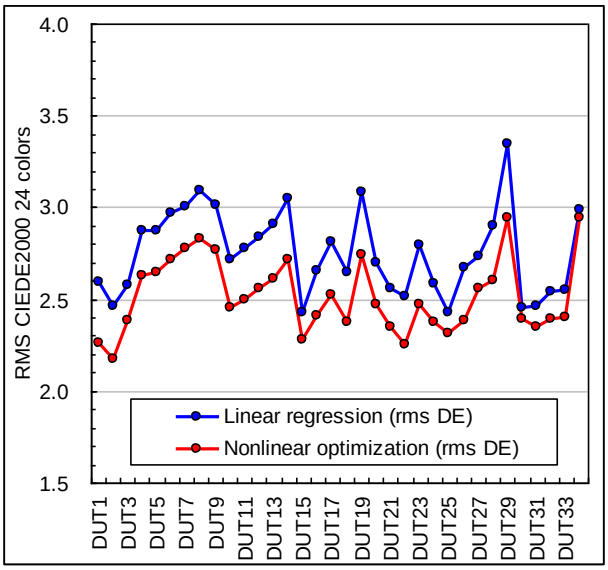

Fig. 4: YSNR comparison of 1.1u and 1.4u pixels

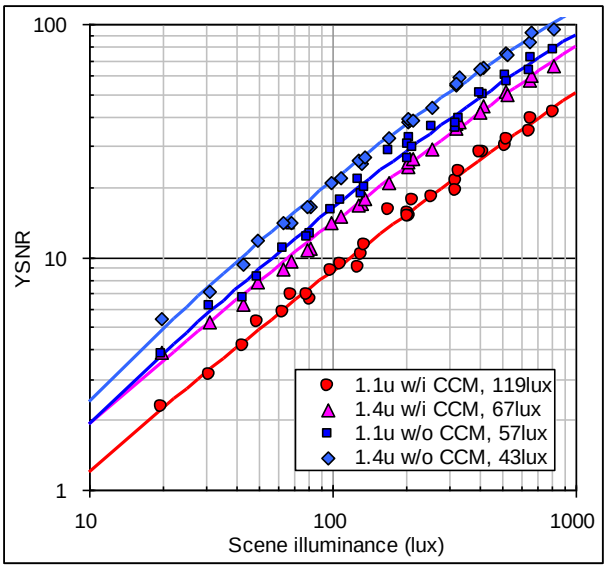

Fig. 5a: Color eye-diagram of a 1.1u pixel vs. f-numbers

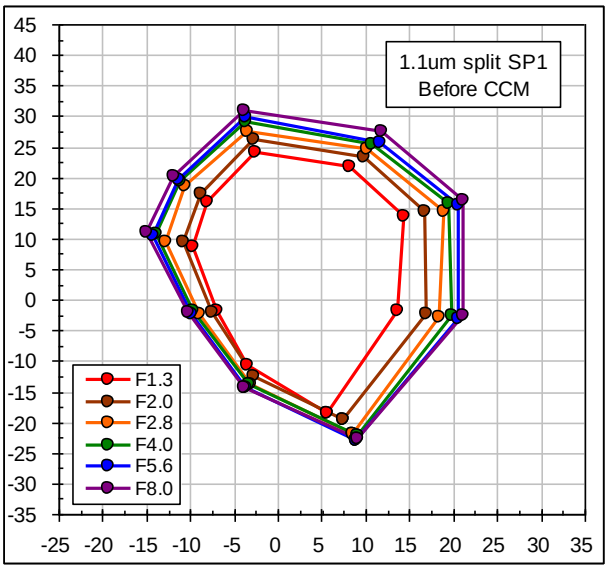

Fig. 5b: Color eye-diagram of a 1.4u pixel vs. f-numbers

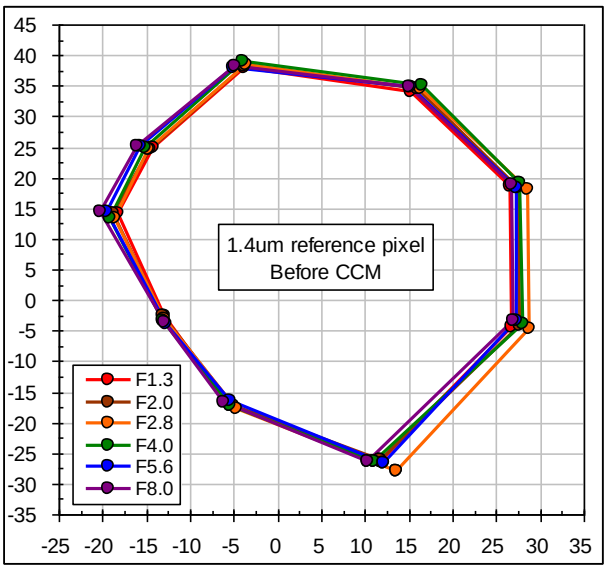

Fig. 6a: CCM-noise-factor comparison of pixel splits

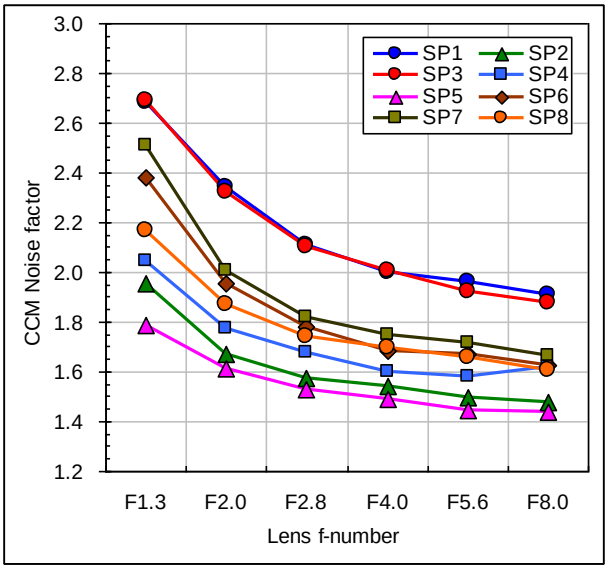

Fig. 6b: Color-error-before-CCM comparison of splits

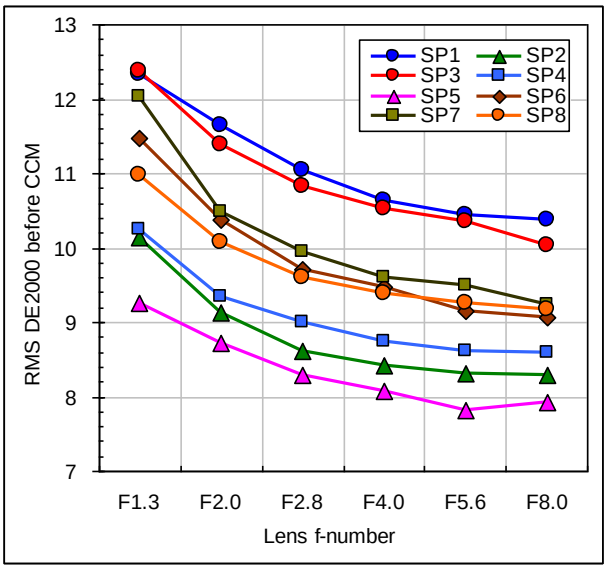

Fig. 6c: Eye-diagram-area comparison of pixel splits

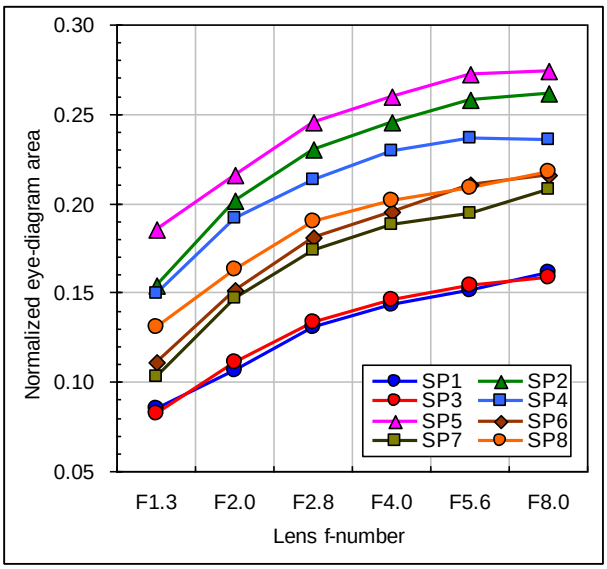

Fig. 7a: Color error before CCM vs. CCM noise factor

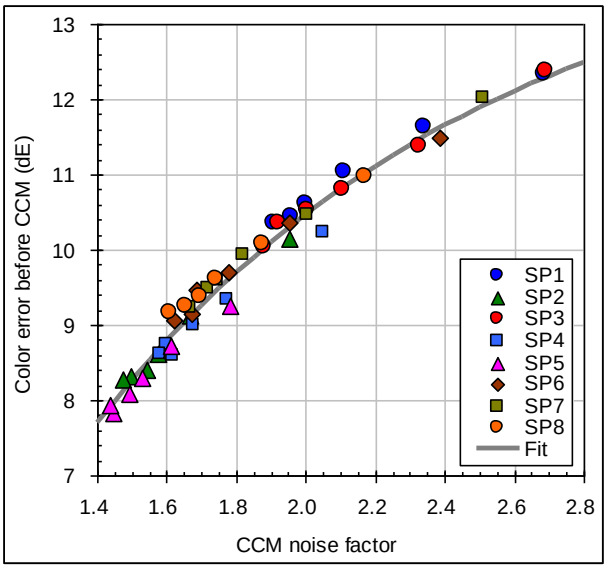

Fig. 7b: Eye-diagram before CCM vs. CCM noise factor

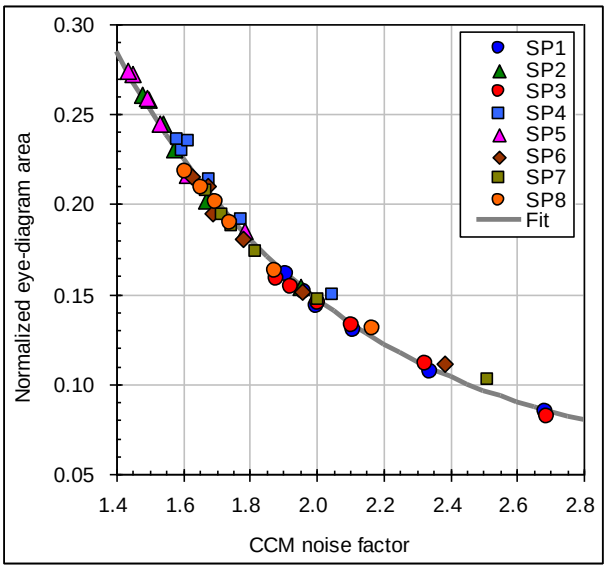

Fig. 8: Crosstalk decomposition