

New Color Filter Arrays of High Light Sensitivity and High Demosaicking Performance

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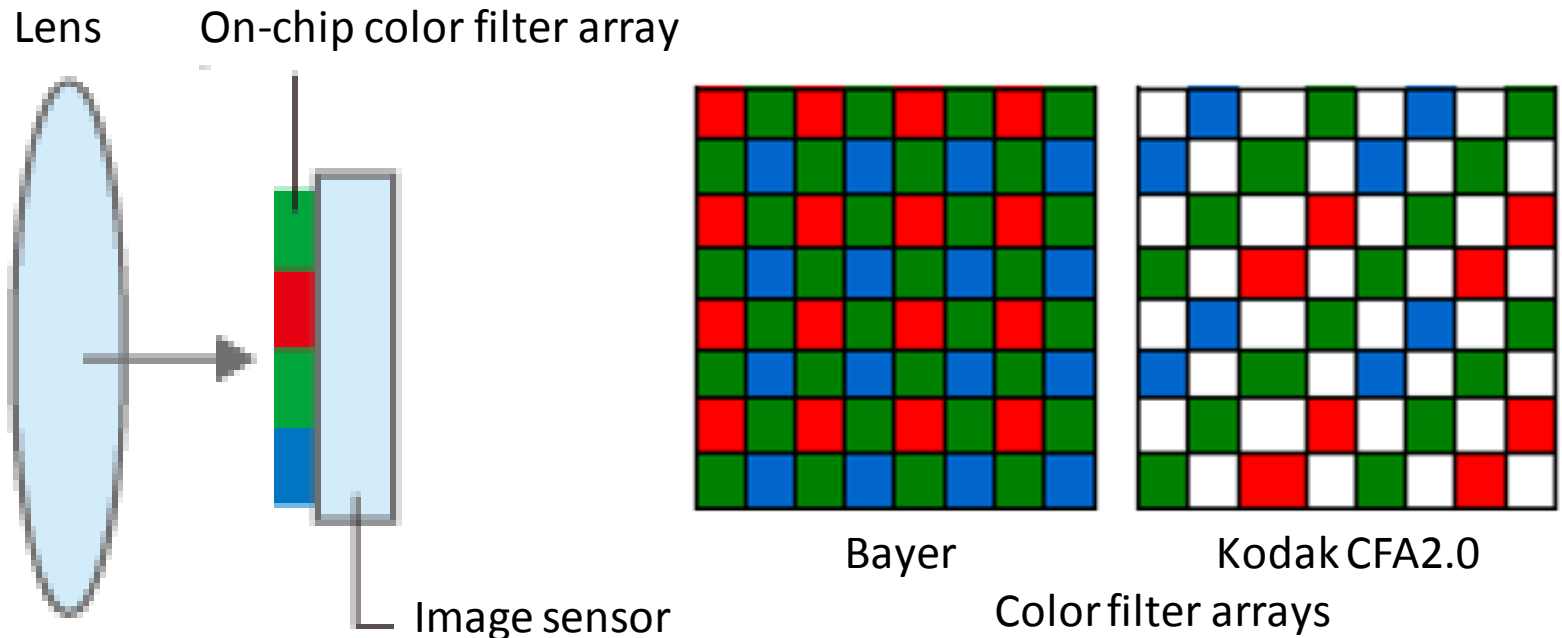
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Outline

- Introduction: What is CFA
- How CFA works: demosaicking
- CFA representation: frequency structure
- CFA design: what should be optimized
- CFA design: what constraints
- New CFA designs & Evaluation
- Conclusions

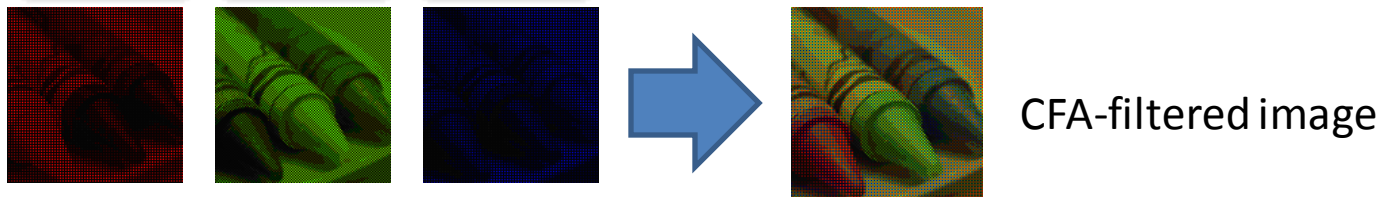
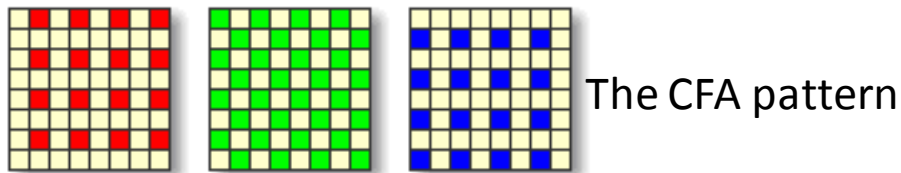
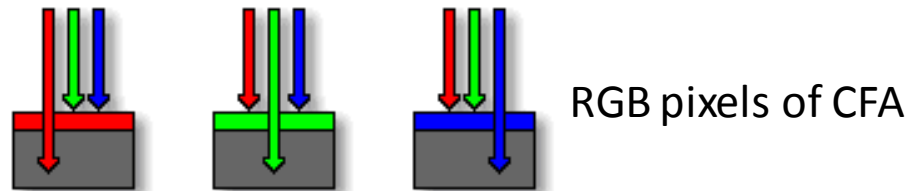
Single-chip Color Cameras

- Single-Chip Camera is based on a color filter mosaic fabricated on top of the light sensors, and the mosaic is generally an array (Color Filter Array, CFA).

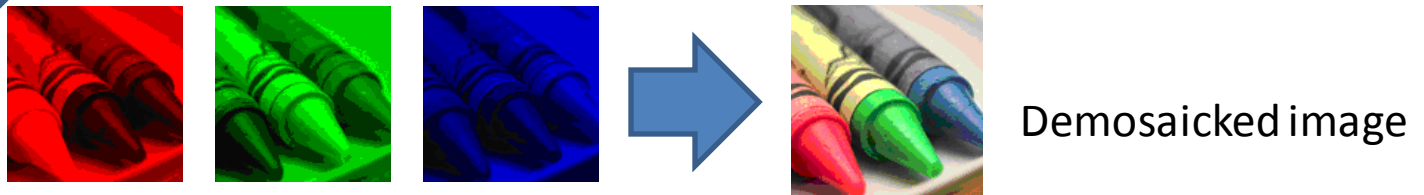


Demosaicking

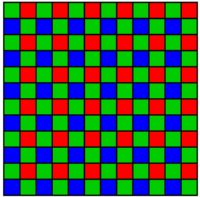
- As each individual sensor only records one color, at each pixel all the three primary colors, red, green and blue, of a color image must be reconstructed using a computational interpolation method – **demosaicking**.



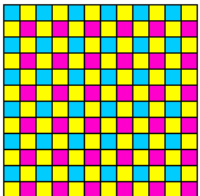
Demosaicking



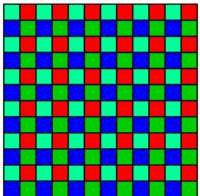
A few Commercialized CFAs



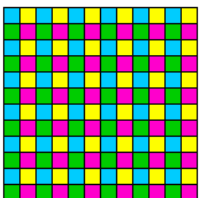
Bayer CFA pattern (Kodak, red, green, blue)



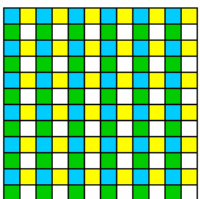
CMY CFA (Kodak, cyan, yellow, magenta)



RGBE CFA (Sony, red, green, blue, emerald)



CYGM CFA (a few, cyan, yellow, green, magenta)

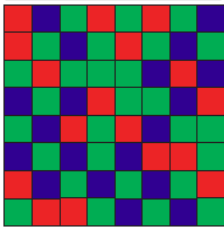


CYGW CFA (JVC, yellow, cyan, green, unfiltered)

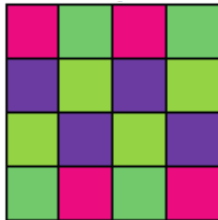
CFAs proposed by researchers



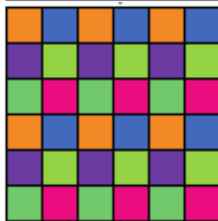
Gindele & Gallagher (with white, 2002)



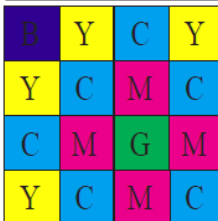
Parmar & Reeves (random, 2004)



Hirakawa & Wolfe (better recovery, 2008)



Condat (robust to noise, 2009)



Hao, Li, Lin & Dubois (better demosaicking, 2011)

Kodak's CFA2.0

- Second generation CFA for high-light sensitivity

W	B	W	G
B	W	G	W
W	G	W	R
G	W	R	W

G	W	R	W
G	W	R	W
B	W	G	W
B	W	G	W

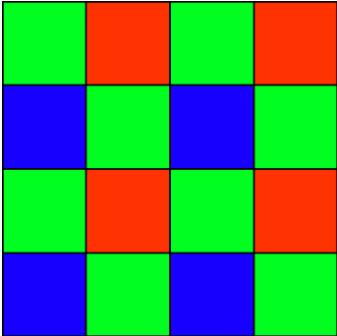
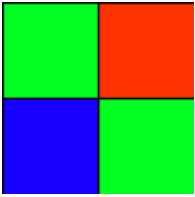
with 50% unfiltered pixels (2007)
(aka panchromatic or white pixels)

Periodical CFAs: Representation

- Matrix representation in the spatial domain

just use one period

Bayer CFA

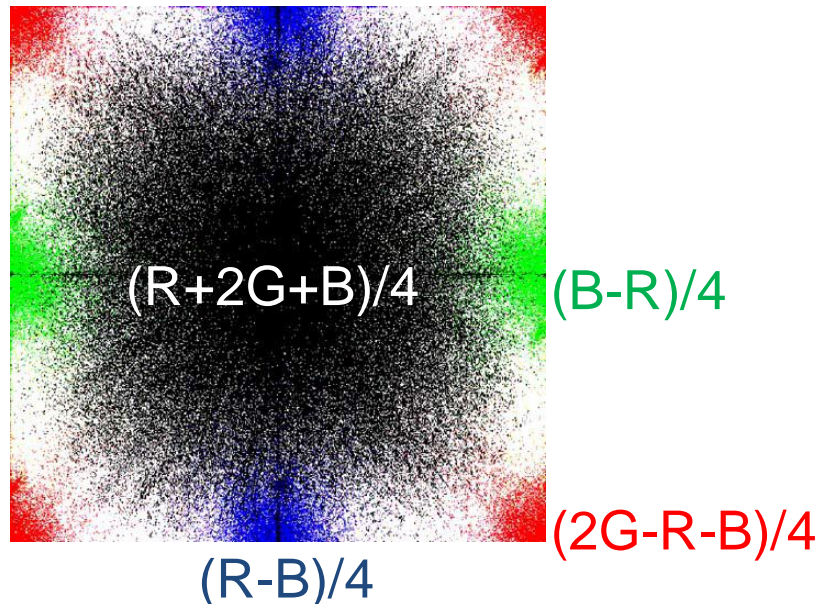
$$\begin{aligned}
 &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \cdot \begin{matrix} \color{red}{r} \end{matrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{matrix} \color{green}{g} \end{matrix} + \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \cdot \begin{matrix} \color{blue}{b} \end{matrix} \\
 &= \begin{bmatrix} G & R \\ B & G \end{bmatrix}
 \end{aligned}$$

The Frequency Structure

- Apply symbolic DFT to the one period matrix representation in the spatial domain

$$DFT \begin{bmatrix} G & R \\ B & G \end{bmatrix} = \frac{1}{4} \begin{bmatrix} R + 2G + B & B - R \\ R - B & 2G - R - B \end{bmatrix} = \begin{bmatrix} F_L & F_{C2} \\ -F_{C2} & F_{C1} \end{bmatrix}$$

The spectrum
with Bayer CFA

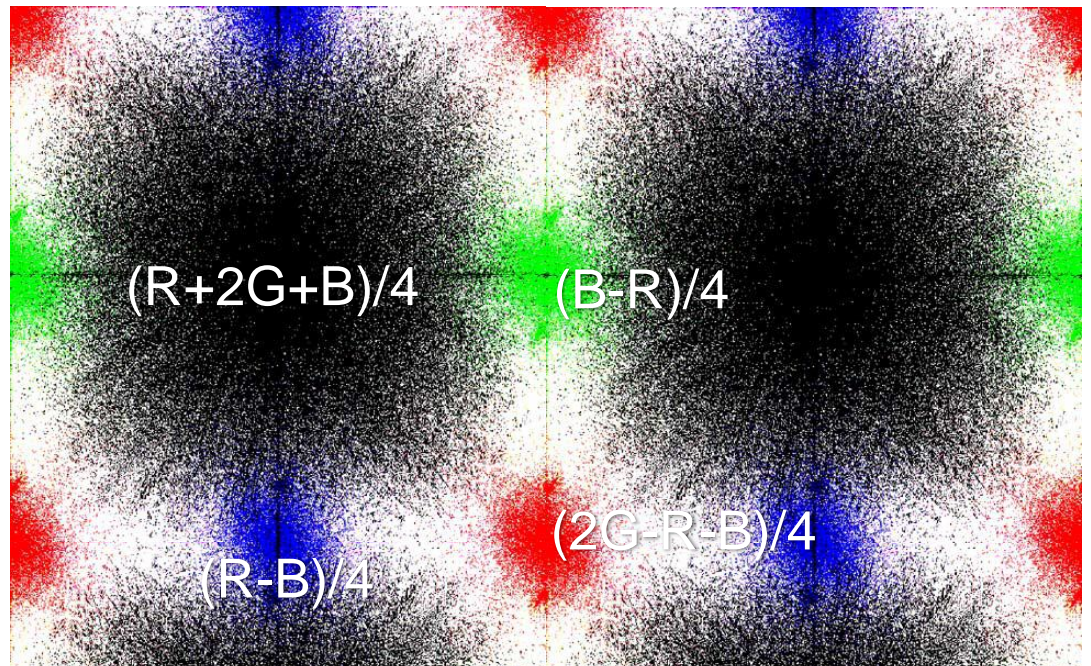


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The spectrum
with Bayer CFA
(periodical)



Relations: luma&chromas and RGB

- It is a linear transform:

$$DFT \begin{bmatrix} G & R \\ B & G \end{bmatrix} = \frac{1}{4} \begin{bmatrix} R + 2G + B & B - R \\ R - B & 2G - R - B \end{bmatrix} = \begin{bmatrix} F_L & F_{C2} \\ -F_{C2} & F_{C1} \end{bmatrix}$$

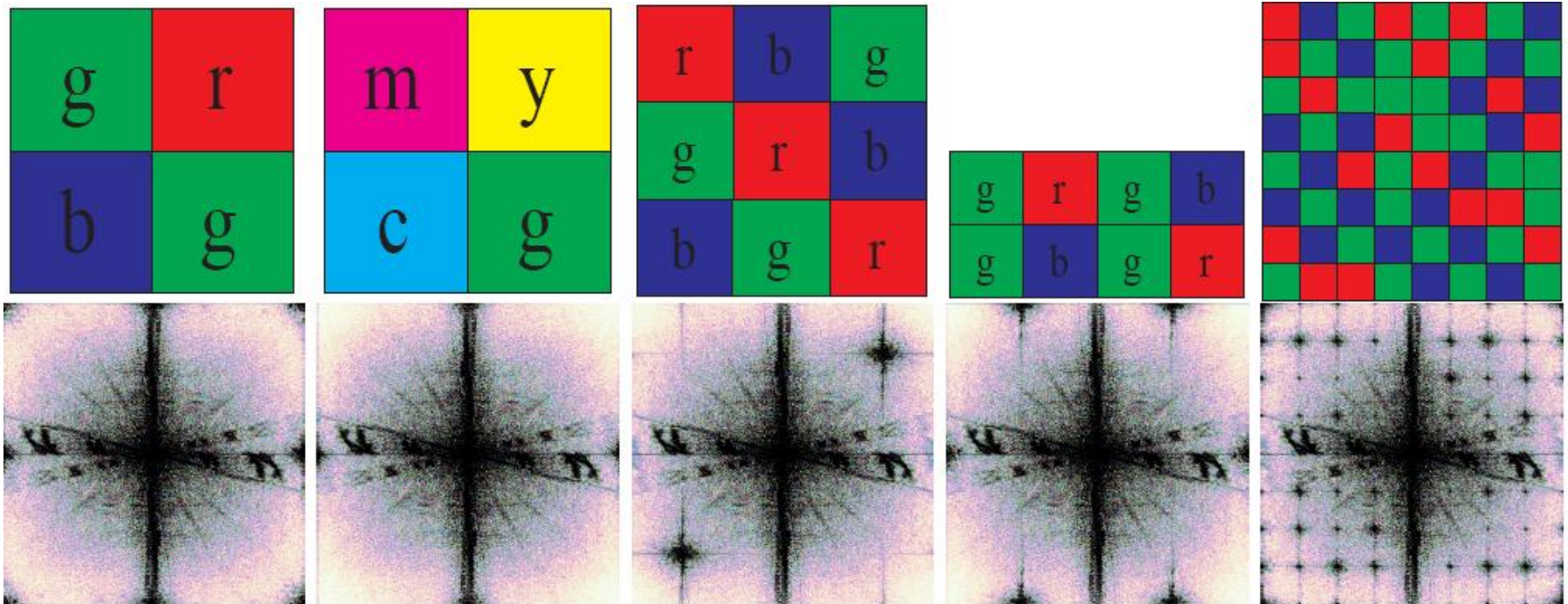


$$\begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix} = \frac{1}{4} \begin{bmatrix} 1 & 2 & 1 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} = T \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

where T is a multiplexing matrix

Spectra and Frequency Structures

- DFT of the CFA-filtered image and CFA patterns



$$\begin{bmatrix} F_L & F_{C_2} \\ -F_{C_2} & F_{C_1} \end{bmatrix}$$

$$\begin{bmatrix} F_L & F_{C_1} \\ F_{C_2} & 0 \end{bmatrix}$$

$$\begin{bmatrix} F_L & 0 & 0 \\ 0 & 0 & F_{C_1} \\ 0 & F_{C_2} & 0 \end{bmatrix}$$

$$\begin{bmatrix} F_L & 0 & F_{C_1} & 0 \\ 0 & F_{C_2} & 0 & -F_{C_2} \end{bmatrix}$$

$$\begin{bmatrix} F_L & \dots & F_{C_?} \\ \vdots & \ddots & \vdots \\ F_{C_?} & \dots & F_{C_?} \end{bmatrix}$$

$$T = \frac{1}{4} \begin{bmatrix} 1 & 2 & 1 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$\frac{1}{4} \begin{bmatrix} 1 & 2 & 1 \\ 0 & -1 & 1 \\ 1 & -1 & 0 \end{bmatrix}$$

$$\frac{1}{6} \begin{bmatrix} 2 & 2 & 2 \\ 2 & -1-i\sqrt{3} & -1+i\sqrt{3} \\ 2 & -1+i\sqrt{3} & -1-i\sqrt{3} \end{bmatrix}$$

$$\frac{1}{4} \begin{bmatrix} 1 & 2 & 1 \\ -1 & 2 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \dots & \dots & \dots \\ \vdots & \vdots & \vdots \\ \dots & \dots & \dots \end{bmatrix}$$

Demosaicking

- First: to find the luma and the chromas by filtering/interpolation: F_L , F_{C1} and F_{C2} .
- Second: to find the RGB values by the inverse :

$$\begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix} = T \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \Rightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = T^{-1} \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix} = D \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \end{bmatrix}$$

or

$$\begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix} = T \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \Rightarrow \begin{bmatrix} R \\ G \\ B \end{bmatrix} = T^+ \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix} = D \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix}$$

where D is a demosaicking matrix

Demosaicking Optimization

- First: to find more accurate luma and chromas: F_L, F_{C1} and $F_{C2} \rightarrow$ further distance (less cross-talk) \rightarrow to choose a good frequency structure.
- Second: to find accurate RGB values from the inverse :

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = D \cdot \begin{bmatrix} F_L \\ F_{C1} \\ F_{C2} \\ \vdots \end{bmatrix} \Rightarrow \min \|D\|$$

$\|D\|$ is an objective function to be minimized.

Constraints for High Light Sensitivity

- Some pixels are prescribed as unfiltered pixels, aka panchromatic or white pixels (W).
- Pixels are only of primary colors, red, green and blue, and white: $\forall(i, j), CFA(i, j) \in \{R, G, B, W\}$
- Then to optimize for high demosaicking performance.
- Not all frequency structures satisfy all the constraints – this makes the problem hard.

A Frequency Structure and Optimization

- The frequency structure:

$$\begin{bmatrix} F_L & 0 & 0 & 0 & 0 \\ 0 & 0 & F_{C2} & 0 & 0 \\ 0 & 0 & 0 & 0 & F_{C1}^* \\ 0 & F_{C1} & 0 & 0 & 0 \\ 0 & 0 & 0 & F_{C2}^* & 0 \end{bmatrix}$$

- By optimization : $\min \| D \|$

$$F_L = (R + G + B)/3,$$

$$F_{C1} = ((\sqrt{5} - i\sqrt{25 - 2\sqrt{5}})R + \sqrt{5}(1 + i\sqrt{5 + 2\sqrt{5}})G - (2\sqrt{5} + i\sqrt{10 - 2\sqrt{5}})B)/30,$$

$$F_{C2} = (- (\sqrt{5} + i\sqrt{25 + 2\sqrt{5}})R + i\sqrt{5}(i + \sqrt{5 - 2\sqrt{5}})G + (2\sqrt{5} + i\sqrt{2(5 + \sqrt{5})})B)/30.$$

New High Light Sensitivity CFA

- The corresponding CFA pattern (40% white, 5x5):

$$\begin{bmatrix} F_L & 0 & 0 & 0 & 0 \\ 0 & 0 & F_{C2} & 0 & 0 \\ 0 & 0 & 0 & 0 & F_{C1}^* \\ 0 & F_{C1} & 0 & 0 & 0 \\ 0 & 0 & 0 & F_{C2}^* & 0 \end{bmatrix} \xrightarrow{\text{Symbolic IDFT}} \begin{bmatrix} W & R & B & W & G \\ W & G & W & R & B \\ R & B & W & G & W \\ G & W & R & B & W \\ B & W & G & W & R \end{bmatrix}$$

- The multiplexing matrix $T =$

$$\begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ (\sqrt{5} - i\sqrt{25 - 2\sqrt{5}})/30 & \sqrt{5}(1 + i\sqrt{5 + 2\sqrt{5}})/30 & -(2\sqrt{5} + i\sqrt{10 - 2\sqrt{5}})/30 \\ -(\sqrt{5} + i\sqrt{25 + 2\sqrt{5}})/30 & i\sqrt{5}(i + \sqrt{5 - 2\sqrt{5}})/30 & (2\sqrt{5} + i\sqrt{2(5 + \sqrt{5})})/30 \end{bmatrix}$$

Demosaicking Performance

Image	Dubois's method [15]		Condat's method [16]	
	Kodak	Proposed	Kodak	Proposed
1	23.18	35.23	34.21	35.35
2	30.94	37.49	36.80	38.11
3	32.68	37.46	38.23	38.40
4	32.75	37.32	36.95	38.32
5	25.89	32.96	32.41	33.62
6	25.34	36.56	35.52	36.74
7	31.71	38.22	37.47	38.83
8	22.21	33.28	31.69	33.37
9	29.50	38.78	38.13	39.33
10	32.00	36.63	38.87	38.12
11	27.56	36.13	35.62	36.77
12	31.62	40.18	39.68	40.61
13	23.52	30.91	31.37	31.75
14	27.21	32.24	32.01	33.30
15	32.86	36.29	36.83	37.60
16	28.81	39.58	39.20	39.89
17	32.25	37.90	38.09	39.11
18	27.17	33.87	33.91	34.83
19	24.37	37.53	35.72	37.63
20	30.57	36.71	37.33	38.02
21	26.13	36.14	35.14	36.69
22	29.25	35.59	35.33	36.55
23	32.59	38.86	37.29	39.20
24	26.60	31.90	33.01	33.23
Avg.	27.30	35.42	35.17	36.19

Demosaicking Performance



Original image



(a) Kodak CFA with [15]



(b) Proposed CFA with [15]

Dubois's demosaicking method



(c) Kodak CFA with [16]



(d) Proposed CFA with [16]

Condat's demosaicking method

More Challenges

- High light sensitivity
- High noise tolerance
- High dynamic range
- Good color matching
- Low manufacture costs
- Easy and fast demosaicking
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Thank you