Investigation of Color Aliasing of High Spatial Frequencies and Edges for Bayer-Pattern Sensors and Foveon X3® Direct Image Sensors

Rudolph J. Guttosch
Foveon, Inc.
Santa Clara, CA

Abstract
The reproduction of an edge and a high frequency bar pattern is examined for image sensors employing two different color sampling technologies: Bayer RGB color filter array, and Foveon X3 solid state full color. Simulations correlate well with actual images captured using sensors representing both technologies. Color aliasing artifacts in the Bayer mosaic case depend on whether an anti-aliasing optical lowpass filter is used, and are severe without such a filter. For both the edge image and the bar pattern, the Foveon X3 direct image sensor generates few or no color aliasing artifacts associated with sampling.

1. Introduction
1.1 Bayer Background
Color image data files typically viewed on computer monitors are made up of three complete planes of red, green, and blue data. Digital capture of an image with three complete planes was often accomplished with an image capture system consisting of a color separating prism and three image sensors affixed to the exit windows of the prism. Such devices produce high quality results, but require great precision in manufacturing and are costly, requiring image sensors and a prism to construct.

The recent explosion of digital image capture devices in both the DSC (Digital Still Camera) and the cell phone markets has been fueled by the use of a less expensive alternative for color image capture. This alternative is known as the Bayer[1] CFA (Color Filter Array), named after its inventor, Dr. Bryce Bayer, of the Eastman Kodak Company.

The Bayer CFA is made up of a repeating array of red, green, and blue filter material deposited on top of each pixel in an array (Figure 1). These tiny filters enable what is normally a black-and-white sensor to create color images.

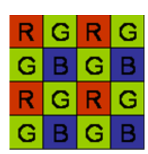


Figure 1: Typical Bayer CFA showing the alternate sampling of red, green, and blue pixels.

By using two green-filtered pixels for every red and blue, the Bayer CFA is designed to maximize the perceived sharpness in the luminance channel, which is composed mostly of green information. However, since the image plane is under-sampled by 50% to begin with, the full detail available in the optical image is not attained in the luminance sampled data. In addition, chrominance detail is lost due to the even lower sampling density of 25% in the red and blue channels in the sensor. Figure 2 shows a Bayer filter pattern decomposed into its constituent color components, showing the sparseness of the sampling. In order to create the required completely-populated image plane (i.e. three complete planes of red, green, and blue information), the Bayer CFA data must be interpolated, the process which fills in the voids shown in Figure 2.

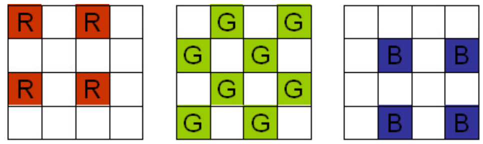


Figure 2: Decomposition of a typical Bayer CFA pattern into its components. Under-sampling in the image plane results in lower sharpness than could otherwise be achieved. Further, gaps in the image plane lead to color moiré artifacts.

Introduced in the 1970's, the Bayer CFA improved the state-of-the-art of image color image capture and reduced image capture cost. However, when considering the image quality vectors of sharpness and artifact control, the Bayer CFA represents an inefficient use of silicon area and imposes constraints on the digital camera designer. Due to the sparse nature of the sampling, the Bayer CFA imposes the need for the following:

1. interpolation of the missing color data to create three complete color image planes (R, G, & B)
2. sharpening of the image to account for the inherent reduction in the sharpness of the luminance and chrominance
3. suppression of color aliasing artifacts resulting from incomplete sampling in the image plane and the phase offsets of the color channels

To combat the third effect noted above, an optical blur filter, also known as an Anti-Aliasing filter, or an optical low-pass filter, (OLPF), is usually employed in consumer and professional digital cameras. Blur filters reduce the color aliasing artifacts caused by spatial phase differences among the color channels (i.e. the red, green, and blue filters are placed next to each other). Two blur filters are typically placed in the optical path: one to blur in the horizontal direction, the other in the vertical. The blur filters reduce color aliasing at the expense of image sharpness. In order to control costs, blur filters have not typically been used in digital cameras designed for cell phones. The effect of leaving out this component can be readily seen in images.

1.2 Foveon X3 Technology

An alternative method for obtaining color images from a single chip monolithic imaging array is now available:[2,3] the Foveon X3 direct image sensor. A direct image sensor is an image sensor that directly captures red, green, and blue light at each point in an image during a single exposure. Foveon X3 sensors take advantage of the natural light absorbing characteristics of silicon. Light of different wavelengths penetrating the silicon is absorbed at different depths -- high energy (blue) photons are absorbed near the surface, medium energy (green) photons in the middle, and low energy (red) photons are absorbed deeper in the material.[4] In contrast to the lateral color sensing method in the Bayer CFA, X3 image sensors enable red, green, and blue pixels to be stacked vertically. A schematic representation of this vertical arrangement is shown in Figure 3.

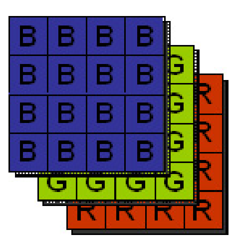


Figure 3: Schematic depiction of a Foveon X3 image sensor showing stacks of pixels, which record color channels depth-wise in silicon.

Figure 4 shows the color planes that result directly from image capture, without interpolation.

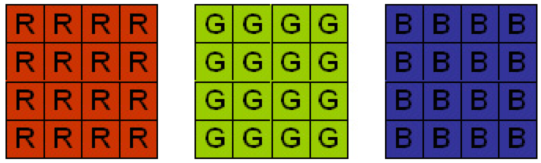
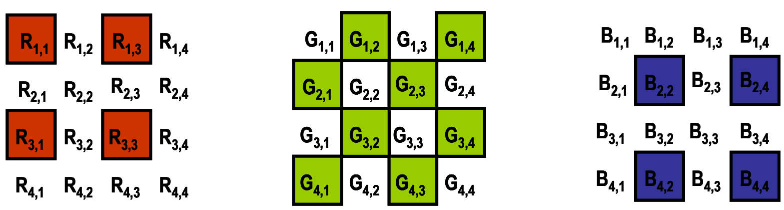


Figure 4: Fully populated image sampling found in film scanners, color-separation prism cameras, and also in Foveon X3 image sensors.

Vertical stacking increases pixel density, thereby increasing the sharpness per unit area captured in the image plane. The stacks of red, green and blue pixels also eliminate the phase differences among the samples in color planes, thus eliminating false color patterns without additional processing. Blur filters are not necessary to combat color moiré patterns and the sharpness improvement for X3 image sensors in both luminance and chrominance can be measured using industry-standard techniques.[5]

2. Method

A Bayer CFA image sensor and a Foveon X3 image sensor were each simulated using a simplified model. The two sensors were exposed to two different stimuli in the simulation: an edge and a high frequency bar target. In order to achieve a processed image from Bayer CFA data, it is first necessary to interpolate, or fill in, the missing pixel data, a step not required for Foveon X3 image sensors. For this study, color interpolation was performed on the Bayer CFA using the bi-linear method shown in Figure 5 to create three complete planes of R, G, B data.



$R_{11} = R_{11}$	$G_{22} = (G_{12} + G_{32} + G_{21} + G_{23})/4$	$B_{22} = B_{22}$
$R_{12} = (R_{11} + R_{13})/2$	$G_{23} = G_{23}$	$B_{23} = (B_{22} + B_{24})/2$
$R_{21} = (R_{11} + R_{31})/2$	$G_{32} = G_{32}$	$B_{32} = (B_{22} + B_{42})/2$
$R_{22} = (R_{11} + R_{13} + R_{31} + R_{33})/4$	$G_{33} = (G_{23} + G_{43} + G_{32} + G_{34})/4$	$B_{33} = (B_{22} + B_{24} + B_{42} + B_{44})/4$

Figure 5: Bayer CFA color sample positions and the color interpolation equations used in this investigation

Other, more complex algorithms are often used[6], and sometimes licensed[7]. With the more complex algorithms, the overall performance of the color interpolation process can be improved; however, this comes with a significant penalty in both computation time and image processing device costs. In addition, no amount of added processing complexity can eliminate the fundamental sampling disadvantages of a Bayer CFA. The simple color interpolation algorithm used in this analysis is widely applied in low-cost digital image capture systems where blur filters are also prohibitively expensive.

An outline of the color interpolation steps used in the simulated images is illustrated in Figure 6. As the diagram shows, going from capture to finished image requires an extra color interpolation step for Bayer image sensors.

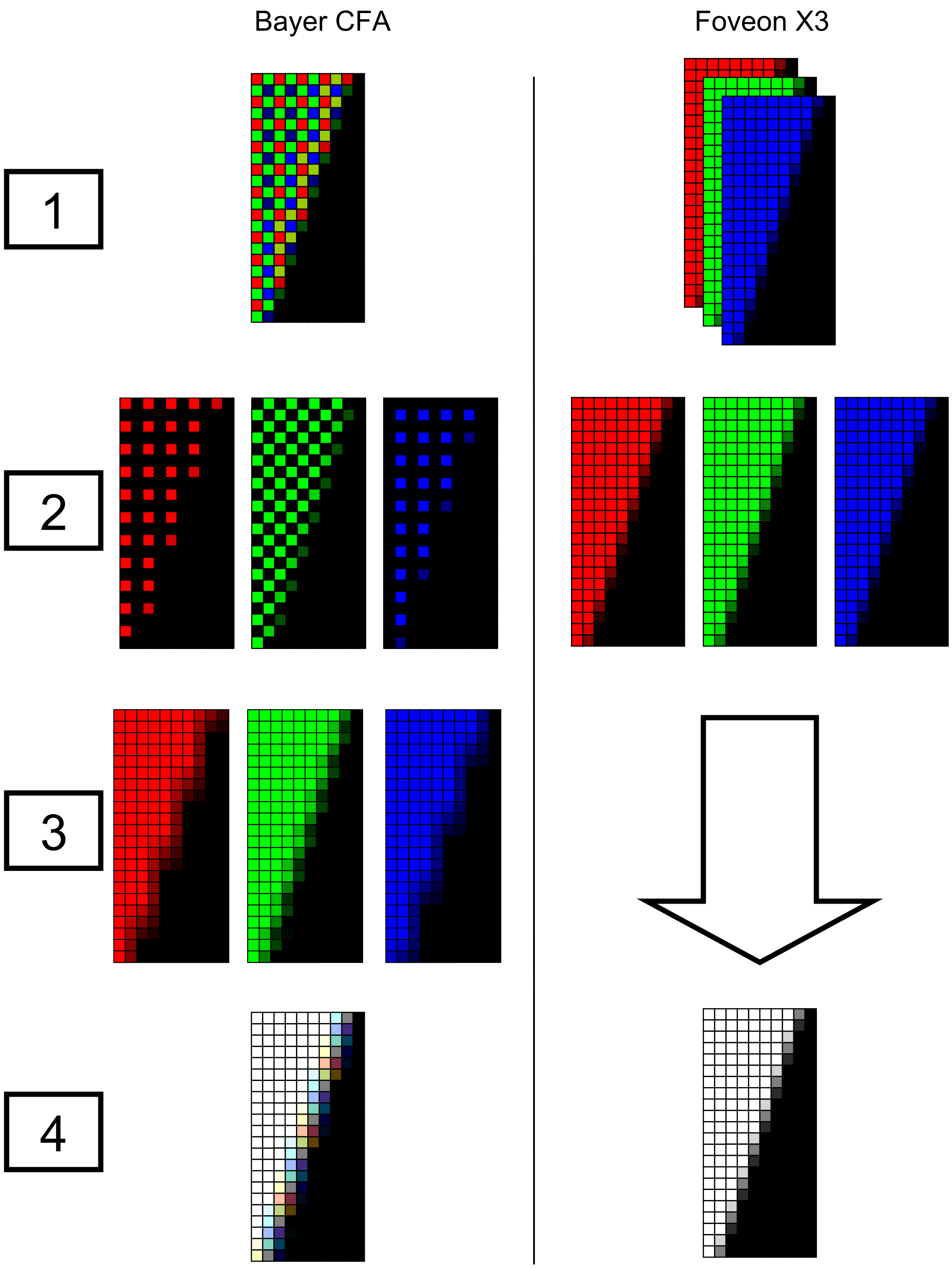


Figure 6: Comparison of color image capture planes and resulting images for a simulated edge.
1. Edge image projected onto image sensor.
2. R, G, and B planes immediately after capture. Missing data for the Bayer case is evident.
3. Bayer image planes after color interpolation, a step not required for Foveon X3 sensors.
4. Resulting edge images.

Graphical representations of the edge applied to Bayer CFA and Foveon X3 image sensors are shown in figure 7; graphical representations of the high-frequency bar pattern case are given in Figure 8.

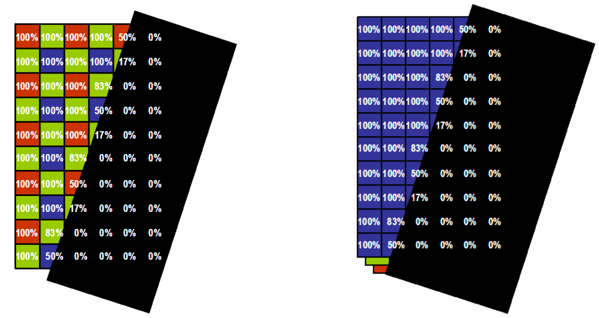


Figure 7: Bayer CFA image sensor, left, and Foveon X3 image sensor, right, with simulated edge superimposed. Percentages refer to percent response, based on percent of area exposed, equivalent to a 100% fill-factor pixel. Response normalized so that black = 0% and white = 100%. These percentages were scaled to 8 bits for simulated image output.

Image output was created and analyzed to show how each system reproduces the stimuli of interest. Optical effects and lens aberrations were specifically excluded from this analysis in order to gain a clear understanding of the contribution of the sensor sampling method on the output image quality.

The aliasing response of the Bayer CFA was also investigated visually from a simulated bar pattern with a spatial frequency of 1/3 cycle per pixel location. This frequency is below the Nyquist rate of 1/2 cycle per pixel location. Although the bar pattern used in this analysis is synthesized, such patterns are commonly found in fabrics, vertical blinds, buildings, and are used in most standard imaging system resolution tests. An example of the graphical superposition of a high-frequency bar pattern on a Bayer CFA sensor and a Foveon X3 sensor is given in Figure 8.

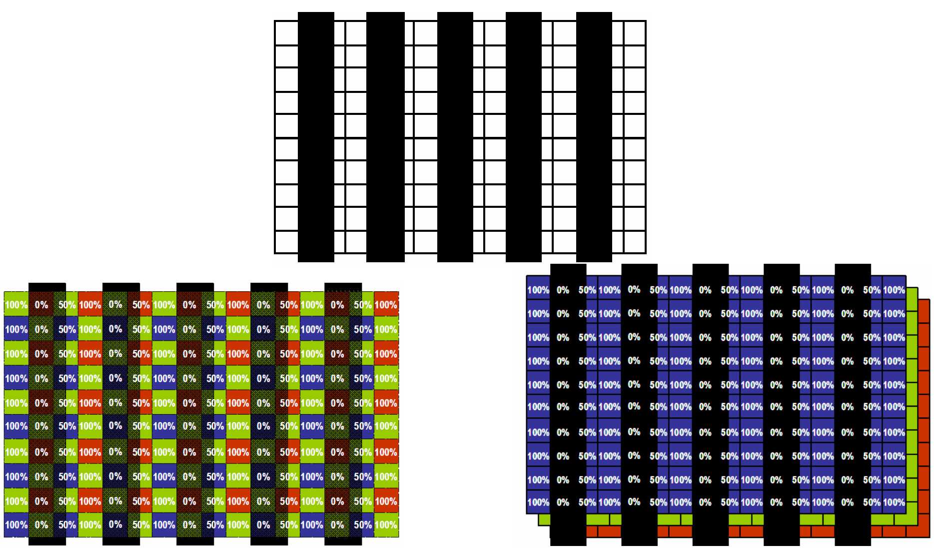


Figure 8: Bar pattern with frequency of 1/3 cycle/pixel location (top). Same bar pattern superimposed on Bayer CFA, left, and Foveon X3 sensors, right, with resulting relative responses (in percent).

In order to compare the results of the image simulations with those obtained by commercially available image sensors, real-world images of an edge and a high-frequency bar target were captured using the cameras listed in the table below:

	Bayer CFA Camera	Foveon X3 Camera
Camera	Roper Scientific Coolsnap	Foveon F19 Reference Design Kit
Image Sensor	Sony ICX 205 1392 x 1040 x 1	Foveon F19 X3 Sensor 1440 x 1088 x 3
Pixel Size	4.65 µm	5.00 µm
Lens	Pentax Cosmicar C-Mount	Pentax Cosmicar C-Mount

Table 1: Cameras and sensors used to capture real-world images

3. Results

The simulated edge target results are shown in Figure 9, and bar target results are shown in Figure 11. In order to validate the model and results of this study, real images of a slanted edge and bar pattern target were captured using both a Bayer CFA sensor and a Foveon X3 sensor. Those results are shown in Figures 10 and 13. Visual comparisons of the results clearly show that the model predicts the performance of real camera systems very accurately. Figure 12 shows a section of an IT-10 resolution chart captured with cameras and sensors from Table 1.

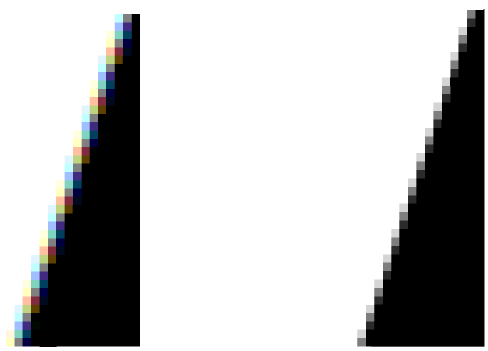


Figure 9: Simulated Bayer CFA (left) and Foveon X3 image sensor (right) responses to slanted edge. Note lack of colored artifacts and sharper edge in the X3 sensor example.

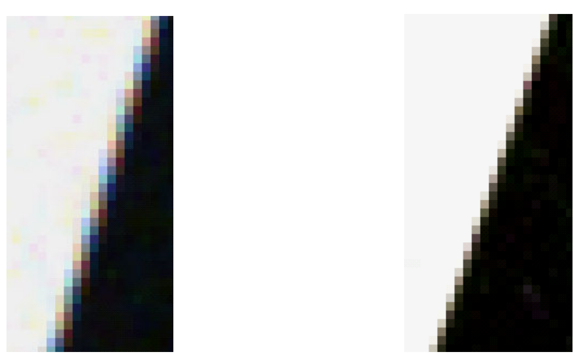


Figure 10: Real-world images obtained from cameras using, the Bayer CFA on a CCD image sensor, (left) and the Foveon X3 image sensor (right).

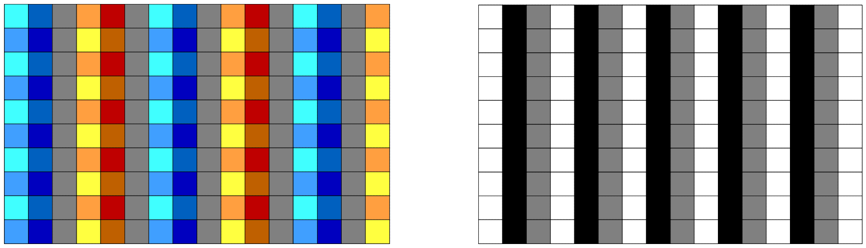


Figure 11: Simulated result of imaging a high frequency bar pattern on a Bayer CFA (left) and a Foveon X3 sensor (right).

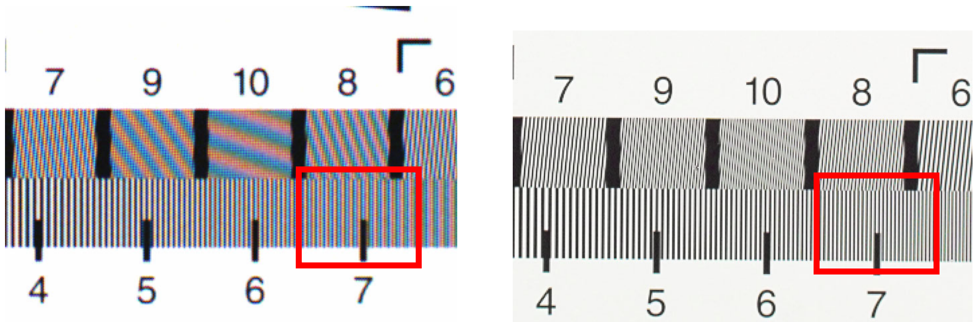


Figure 12: Section of an IT10 resolution chart captured with Bayer CFA (left) and Foveon X3 (right) image sensors. Note the various color artifact patterns in the Bayer CFA case that depend on the input frequency. The numbers in the chart refer to the spatial frequency (multiply x100 to obtain Line Widths per Picture Height, LW/PH). The region of interest for 1/3 cycle/pixel location (~700 LW/PH for both sensors) is shown in the red boxes. Detail from portions of these regions is shown in Figure 13.

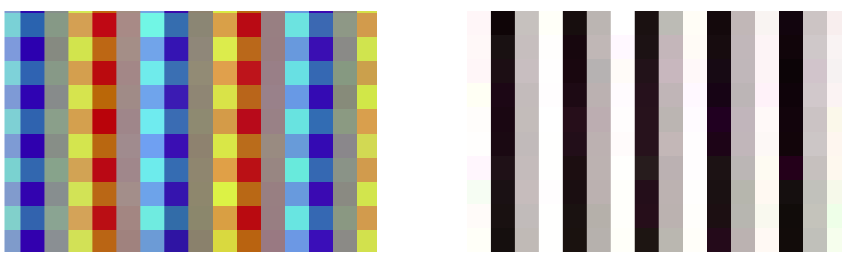


Figure 13: Digital camera output of a high frequency bar target (1/3 cycle/pixel location) for a Bayer image sensor (left) and a Foveon X3 image sensor (right).

4. Discussion

Both the simulated and actual edge response for the Bayer CFA clearly show both sharpness reduction in the edge and false-color artifacts. Complete color sampling of the image plane, as demonstrated by the Foveon X3 direct image sensor, can eliminate the source of the image artifacts. The results can be obtained using a Foveon X3 sensor without the need for optical blur filters which would reduce image sharpness and add cost to the image capture system.

In Figure 12, a comparison of the reproduction of an IT10 resolution chart is shown. In the Bayer case, interesting false color Moiré patterns crop up that are a function of the input frequency. For the Foveon X3 sensor, some luminance (i.e. not false color) Moiré, which is typical of sampled data systems, is visible.

The bar pattern results show that even at frequencies lower than Nyquist, the Bayer CFA imager will add color artifacts to black-and-white subjects. Using a bar pattern, it is quite simple to produce color artifacts both in simulations and in actual use. Again, by completely sampling the image plane, the Foveon X3 sensor provides a black-and-white reproduction of a black-and-white subject.

5. Conclusion

The performance of traditional Bayer CFA image sensor technology was compared to Foveon X3 image sensor technology using both a simple simulation and real-world image capture. The results of both the simulation and the test images clearly show the advantages of Foveon technology with respect to color artifacts and sharpness. A Bayer CFA image sensor without a blur filter shows significant color artifacts resulting from the improper sampling. While the combination of a blur filter and increased color interpolation complexity can be used to partially compensate for the deficiencies in the Bayer sensor, the underlying problem is inherent and comes from undersampling in the image plane. The costs of the attempts at working around the problems with Bayer CFA technology are direct: added component costs due to blur filter, a more advanced image processor device as well as additional compute time. In applications where cost, power, and size are critical, decreasing performance in these key areas is not an acceptable tradeoff to make in order to ensure good image quality.

By fully sampling color in the image plane, Foveon X3 direct image sensors avoid the color artifacts and provide increased sharpness without adding cost to the digital camera system.

References

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