https://doi.org/10.2352/ISSN.2470-1173.2017.15.DPMI-079

Interferometric Measurement of Sensor MTF and Crosstalk

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Abstract

We have developed a laser interferometer with the goal of precise measurement of the pixel MTF and pixel crosstalk in camera sensors. One of the advantages of our interferometric method for measuring sensor MTF is that the sinusoidal illumination pattern is formed directly on the sensor rather than beamed through a lens. This allows for a precise measurement of sensor MTF and crosstalk unaltered by the lens. Another advantage is that we measure MTF in a wide range of spatial frequencies reaching high above the Nyquist frequency. We discuss the theory behind the expected and observed sensor performance, and show our experimental results. Our comparison with the Slanted Edge method shows that we have better precision and cover a wider range of frequencies.

Introduction

Sensor pixel size is getting smaller and smaller, approaching one micron. New sensors that are coming on the market need to be independently evaluated for their performance. This includes the need to measure reliably the photon transfer curve, noise, MTF [1], etc.

The "slanted edge" method is the classic method for measuring sensor MTF [2, 3]. The response of the sensor to the shadow of an edge is measured, and MTF is computed from the Fourier transform. This has worked well for large-pixel sensors. For small-pixel sensors in the one-micron range, the edge shadow is not sufficiently sharp to capture the high frequencies needed to measure the response of the micron- and submicron-size pixels.

Alternatively, a lens image of a bar or sine-wave grating can be used [4]. However, in this method, measurement of the MTF of the sensor is confounded by the MTF of the lens itself, which is typically poor exactly at the high frequencies (at and above Nyquist) that we want to capture. In addition, the lens MTF varies widely from lens to lens and also depends strongly on focusing, which makes the lens-grating method unreliable for small pixels.

By definition the MTF is the response of the sensor to a sinusoidal signal in a given range of frequencies [5]. It is expressed as contrast in the captured images. Light-wave interference naturally produces sinusoidal fringes that can reach very high frequencies, up to $\lambda/2$, where λ is the wavelength. It is for this reason that we are using interferometry as the natural and most appropriate method for measuring MTF.

For measuring the MTF in small-pixel sensors, interferometric methods have been used [6] [7] [8]. The measurements produced by these methods typically have fixed-pattern noise such as fringes due to imperfections and double reflections in glass surfaces, as well as speckle caused by the optics of the system, thus limiting their MTF-measuring usability.

The goal of the present work is to provide new tools that are specifically designed for evaluating the new, micron-sized pixels, within the context of an interferometric system. The tools we are proposing are designed to be used for

(1) Measuring sensor frequency response, its MTF
(2) Quantifying pixel crosstalk.

The experiments for this paper use a HeNe laser at λ= 633 nm to produce sinusoidal fringes that can reach deep into the submicron range. The optics are designed to avoid laser speckle and glass-surface artifacts. These fringes are formed directly on the sensor, without any lens, and make it possible to measure sensor MTF reaching high above Nyquist even for 1 μm pixels, and smaller. We show how measuring the sensor response to these fringes can be used to evaluate pixel crosstalk.

In the present paper, contrast of a single-frequency signal is defined by the formula below, where I_{max} and I_{min} are respectively the maximum and minimum intensity. This is known as Michelson contrast, fringe visibility, or Michelson visibility. (Wikipedia reference [9]),

$$Michelson\ Contrast\ = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Interferometer

We have built a system that is a combination between Young [10] and Mach-Zehnder [11] interferometers. Our main contribution compared to prior works was to produce a reliable, clean signal. We use a spatial filter to clean the beam of higher frequency components coming from the laser, and then a pair of microscope objectives with pinholes at the output to generate a smooth interferogram clean of unwanted fringes and other optical artifacts. Since there are no external surfaces or lenses after the pinholes, we are also free of speckle, something quite unusual for laser imaging. See Figure 1 for our interferometer setup.

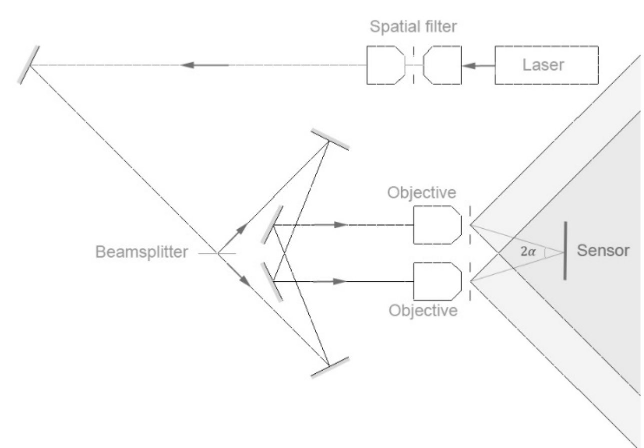

Figure 1. Our interferometer setup

A beam splitter and first-surface mirrors arranged as in a Mach-Zehnder interferometer split the laser beam 50-50. Because of the high spatial coherence of the laser, the fringes have close to 100% Michelson contrast. A microscope objective / pinhole pair is used at the end of the optical path to create fringes as in a Young interferometer.

In Figure 2, we zoom in on Figure 1, first to the pinhole and sensor region, and then further to the region immediately before the sensor. The distance d between the fringes can be computed from $2d \sin\alpha = \lambda$ as can be seen from the geometry shown in the right-hand portion.

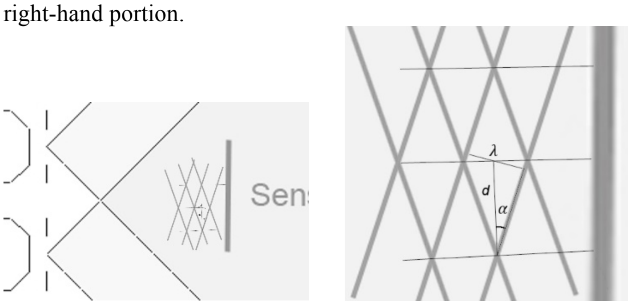

Figure 2. Computing the distance d between fringes (see the right-hand, zoomed-in drawing, where the diagonal lines represent wave crests)

Measuring the MTF

Sensor MTF is the response of the sensor to a sinusoidal signal in a given range of frequencies. It is measured by the contrast in the response signal assuming the input signal is at 100% contrast. The measured contrast function is based on a discretization that is not shift invariant (as it is with lens MTF).

For our experiments we are using a grayscale CMOS sensor MQ013RG-E2 purchased from XIMEA. Pixel pitch is 5.3µm. Figure 3 is a typical captured image from our interferometer. This particular image is captured at frequency slightly below twice the Nyquist, and strongly aliased.

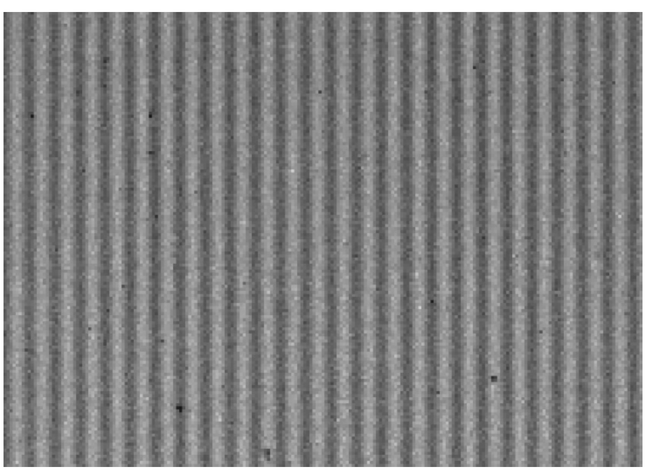

Figure 3. A crop from a typical aliased image above the Nyquist frequency

A column mean in this image reduces noise and is a function of one variable, x. Figure 4 is a plot of column means.

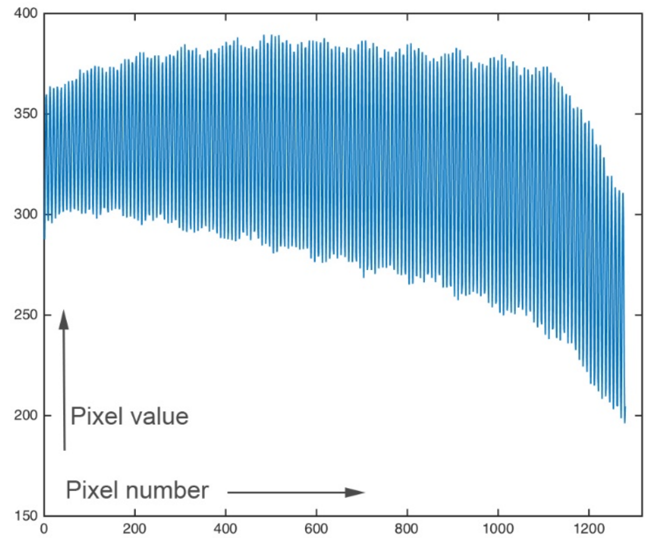

Figure 4. A graph of the pixel value variation across the whole image (a crop of which was shown in Figure 3).

In the quantized signal, at Nyquist and its odd multiples, no measure can reliably recover signal contrast, because the integrated signal varies based on the sensor alignment with the fringes. It is not shift-invariant.

In an image, Michelson contrast can be computed locally in each pixel neighborhood where a signal is present. Or, we could define overall maximum contrast with the same formula, only applied to the whole captured image. In a real captured image, overall contrast can overestimate the true contrast, and both local and overall contrast measures are susceptible to aliasing at integer-ratio harmonics of the Nyquist frequency.

A second definition of contrast, analogous to RMS contrast [12] in the spatial-domain, is derived from the 2-D Fourier transform of the image.

The Fourier contrast formula is defined as the ratio of the AC component of the signal to the DC component of the signal. See Fig.5. However, we want to use power spectral density values in the Fourier domain to evaluate the frequency components of the signal. In case of the discrete Fourier transform, power is distributed to other frequencies, as spectral leakage occurs. In this case power of a particular fundamental frequency can be calculated as the sum of all spectral leakage power around the discretized frequencies.

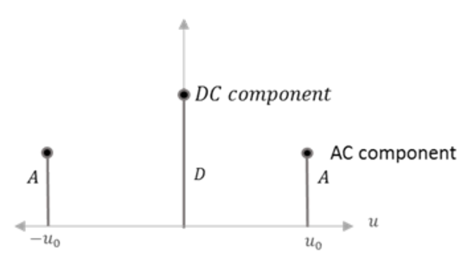

Figure 5. Single-frequency signal representation in Fourier domain.

The Fourier contrast calculated this way is proportional to Michelson contrast. Fourier contrast needs a multiplication of factor of $\sqrt{2}$ for normalized comparison with Michelson contrast. In the ideal case where we have positive and negative components for a single frequency, we can derive contrast as

$$I = D + A(e^{i\omega x} + e^{-i\omega x})$$

$$Fourier\ Contrast = \frac{2A}{D} = \sqrt{2}\frac{\sqrt{A^2 + A^2}}{D^2}$$

In an analog signal, Fourier contrast evaluated this way equals Michelson contrast.

In the discretized signal, theoretically-simulated Fourier contrast shows a "jump" in value by a factor of $\sqrt{2}$ at Nyquist frequencies. This can be explained by aliasing. At Nyquist frequency, the fundamental window and the folding window overlap. The signal value at Nyquist frequency is sum of the value at the positive frequency of the fundamental window and the negative frequency of the folded window. Similar overlap happens at negative Nyquist frequency. This results in aliased signal that is $\sqrt{2}$ times the original value. Thus, Fourier contrast defined this way differs from Michelson contrast. Fourier contrast can be thought of as a global measure of average contrast. In the presence of sensor noise, Fourier contrast will be a more robust measure compared to Michelson contrast.

Below, we compare our experimental MTF results to "theoretical" results that are derived through computational simulations. In each simulation, noise-free, artifact-free simulated images are generated and measured in the same manner as real images. This theoretical/real comparison will be the information ultimately used to derive the measure of crosstalk; the greater the crosstalk, the greater the reduction in the real measured contrast compared to the theoretical.

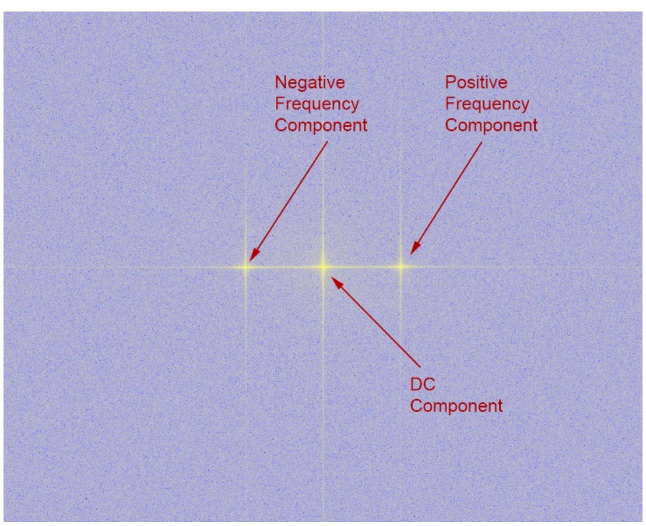

Figure 5(a). Fourier transform of the image. Amplitude squared represented (yellow) in 2D frequency space.

The Figure 6 below shows the "theoretical" simulated results and the experimental measurements of our sensor MTF. Active pixel size used in the theoretical calculations has been estimated from the measured curve. Interferometric images were captured, and contrast measured by two different methods:

(1) Michelson contrast

(2) Fourier contrast

The measured result shown in the plot is that the experimental contrast is similar in form to the theoretical, but scaled down. The reduction in contrast will be related to the effects of crosstalk, but other factors such as the presence of dark noise or unequal beam intensities produce similar results, and their influence needs to be evaluated and eliminated as much as possible through experimental or computational techniques.

In addition, the effects of discretization need to be obviated; for example, at Nyquist frequency, when the optical signal is aligned with pixel grid, a shift of fringes by half pixel size will take the contrast from the maximum possible value of $2/\pi$ down to minimum 0. Our solution to this has been to maintain consistent measurements with proper phase for all frequencies.

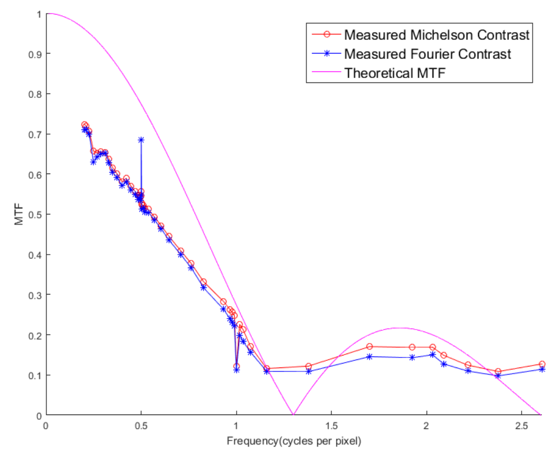

Figure 6. Sensor MTF computed from Michelson contrast and Fourier contrast compared with theoretical MTF (assuming sinc signal, with estimated active pixel width < pixel pitch)

Contrast at the Nyquist Frequency

One goal in this paper is to provide a method to measure the level of crosstalk in a camera sensor without the confounding effects of the lens MTF that is found, for instance, in knife-edge measurements. Contrast measured at the Nyquist frequency can be used to estimate pixel crosstalk.

In the current method, interference fringes are produced by splitting a laser beam into two channels that are projected directly onto the sensor; the overlapping beams will produce the sine-wave fringes at the sensor. The two-beam interference equation for monochromatic light is:

$$I(x, y) = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos(\phi_1 - \phi_2),$$

Where I_1 and I_2 are the two beam irradiances, ϕ_1 and ϕ_2 are the phases of the two beams, and I is the resulting irradiance over position (x, y). If it is assumed that I_1 and I_2 are equal, the equation becomes: $I = 2I_1(1 + \cos(\Delta\phi))$.

At the sensor, the fringe signal is integrated (spatially discretized) by the pixels, and windowed by the sensor size. We consider an optical signal that is formed on the sensor at the

Nyquist frequency. The photon integration produces a sensor signal of reduced amplitude, as shown here in Figure 7. The integration and discretization process means that the resulting sensor signal is not shift invariant.

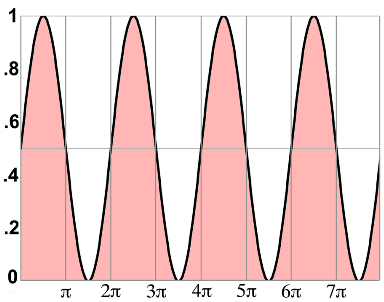

Figure 7a. Fringe signal as it will be integrated. Contrast = 1.

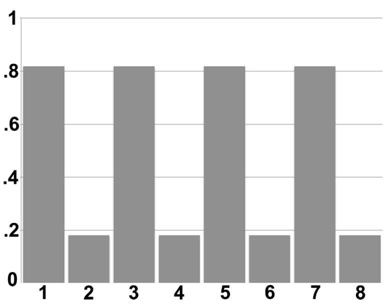

Figure 7b. Sensor signal, [0.8183, 0.1817], for the integrated fringe signal in (7a). Contrast = 2/p.

In the following example, the fringe signal will be characterized as $\sin(\omega x)$, where $\omega = 2\pi(cycles/pixel)$ for the Nyquist frequency. For this initial consideration our sensor is assumed noise-free, crosstalk-free and pixel active area has width equal to pitch. The contrast in the sensor signal in the interval is related to contrast in the fringe signal at 0 phase (sine phase) by a factor of 2/π, as will be shown.

The x values are pixel boundaries, e.g., 0-1, 1-2, 2-3, etc.:

$$\int \sin(\omega x)\, dx = -\frac{1}{\omega}\cos(\omega x) + k$$
$$\omega = 2\pi(cycles/pixel)$$
$$at\ Nyquist\ \omega = 2\pi(.5) = \pi$$
$$fringeSignal = \frac{\sin(\omega x)}{2} + .5$$

$$\int_0^1 \left(\frac{\sin(\pi x)}{2} + .5\right) dx = \frac{1}{2}\left(-\frac{1}{\pi}\cos(\pi \cdot 1) + \frac{1}{\pi}\cos(\pi \cdot 0)\right) + .5$$
$$= \frac{1}{\pi} + .5 = 0.8183$$

And

$$\int_1^2 \left(\frac{\sin(\pi x)}{2} + .5\right) dx = \frac{1}{2}\left(-\frac{1}{\pi}\cos(\pi \cdot 2) + \frac{1}{\pi}\cos(\pi \cdot 1)\right) + .5$$
$$= -\frac{1}{\pi} + .5 = 0.1817$$

That is, the amplitude of the sensor signal is 1/π, and where maximum contrast in the fringe signal equals 1, maximum contrast in the integrated sensor signal equals (1/π) / .5 = 2/π = 0.6366 for a noise-free, crosstalk-free sensor with $I_1 = I_2$.

Unequal-intensity beams: fringe signal contrast

Unequal-intensity beams affect the contrast of the fringe signal, as shown in the following derivation.

Maximum and minimum of the fringe signal are:

$$I_{max} = I_1 + I_2 + 2\sqrt{I_1 I_2}cos(0) = I_1 + I_2 + 2\sqrt{I_1 I_2}$$
$$I_{min} = I_1 + I_2 + 2\sqrt{I_1 I_2}cos(\pi) = I_1 + I_2 - 2\sqrt{I_1 I_2}$$
$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{4\sqrt{I_1 I_2}}{2(I_1 + I_2)} = \frac{2\sqrt{I_1 I_2}}{(I_1 + I_2)}$$

Clearly, the contrast *C* will equal 1 only when $I_1 = I_2$; the greater the inequality the smaller *C* will be.

Unequal-intensity beams: sensor signal contrast

Spatially discretized signal at Nyquist with zero sine phase:

$$\int_0^1 I\, dx = \int_0^1 I_1\, dx + \int_0^1 I_2\, dx + \int_0^1 2\sqrt{I_1 I_2}sin(\pi x)\, dx$$
$$\int_1^2 I\, dx = \int_1^2 I_1\, dx + \int_1^2 I_2\, dx + \int_1^2 2\sqrt{I_1 I_2}sin(\pi x)\, dx$$

I_1 and I_2 are constants, so

$$\int_0^1 I\, dx = I_1 + I_2 + 2\sqrt{I_1 I_2}\left(\frac{1}{\pi}\right)(-\cos(\pi) + \cos(0))$$
$$= I_1 + I_2 + 2\sqrt{I_1 I_2}\left(\frac{2}{\pi}\right)$$
$$\int_1^2 I\, dx = I_1 + I_2 + 2\sqrt{I_1 I_2}\left(\frac{1}{\pi}\right)(-\cos(2\pi) + \cos(\pi))$$
$$= I_1 + I_2 + 2\sqrt{I_1 I_2}\left(-\frac{2}{\pi}\right)$$

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{4\sqrt{I_1 I_2}\left(\frac{2}{\pi}\right)}{2(I_1 + I_2)} = \frac{2\sqrt{I_1 I_2}}{(I_1 + I_2)}\left(\frac{2}{\pi}\right)$$

Again, *C* will be largest when $I_1 = I_2$, although in this case the maximum is $2/\pi$.

A numerical example of the effect of unequal beam strength is:

$$I_2 = .5 I_1 \quad \rightarrow \quad \frac{2\sqrt{I_1 I_2}}{(I_1 + I_2)} = \frac{2\sqrt{.5}}{1.5} = 0.94$$

That is, when one beam is half the strength of the other, the maximum contrast has been reduced by 6%.

Generally, if the ratio of unequal beam intensities $I_2 : I_1 = R$, choosing for simplicity the version of the ratio that is < 1, then the maximum contrast will be reduced by a factor of $K = 2\sqrt{R}/(1 + R)$. It's easy to see that 0 < K < 1. The function K (R) is shown in Figure 9. Notice that above R = 0.5 the amount of contrast reduction is very little, for example when R=.753 the contrast is reduced by less than 1%.

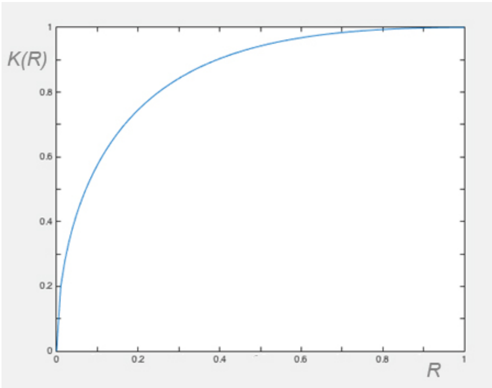

Figure 9. The function $K\,(R) = 2\sqrt{R}/(1+R)$.

When the phase is not zero for a signal at Nyquist, the amplitude and the contrast will be less, as in this example where phase is -1/4 pixel:

$$\int_{1/4}^{1+1/4}\left(\frac{\sin(\pi x)}{2}+.5\right)dx$$
$$=\frac{1}{2}\left(-\frac{1}{\pi}\cos\left(\pi\cdot\left(1+\frac{1}{4}\right)\right)+\frac{1}{\pi}\cos\left(\pi\cdot\frac{1}{4}\right)\right)$$
$$+\ .5=\frac{\sqrt{2}/2}{\pi}+.5$$

and

$$\int_{1+1/4}^{2+1/4}\left(\frac{\sin(\pi x)}{2}+.5\right)dx=\frac{-\sqrt{2}/2}{\pi}+.5$$

Amplitude = $\frac{\sqrt{2}/2}{\pi} = 0.2251$, contrast = 0.2251/.5 = 0.4502, or $\frac{\sqrt{2}}{\pi}$, compared to $\frac{2}{\pi}$ for the 0-phase fringes.

For phase = ½ pixel, the integral for pixel 1 will equal .5, for pixel 2 will also equal .5, so amplitude will be 0; dc will be .5; that is, contrast will equal 0. The sensor sees a uniform gray with no contrast. This non-shift-invariance of the signal is an important confounding factor that must be dealt with.

Contrast at Nyquist

The contrast at Nyquist frequency can be computed reliably if we shift slightly away from that frequency in both directions, and average. This avoids the phase (shift) dependence. The signal can also be corrected for the unequal beam intensities using the coefficient K derived from sensor outputs for single-beam illumination. We can also apply a method that directly computes average contrast instead of maximum contrast.

One of the two captured "near-Nyquist" images is shown in Fig 10 for illustration:

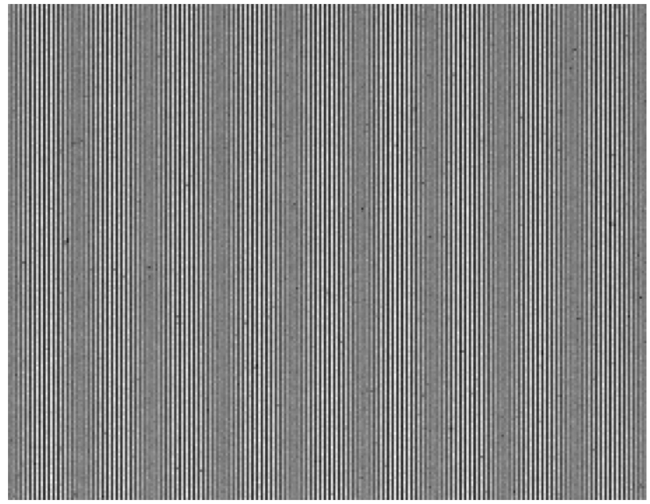

Figure 10. Image captured close to Nyquist

To directly compute average contrast, we first compute $C = (I_i - I_{i+1})/(I_i + I_{i+1})$ for every pixel, where the increment is in the horizontal direction. This gives us per pixel contrast for the whole image. Then we compute the average contrast for the first image, say the one slightly below Nyquist. The same is computed for the image at slightly above Nyquist.

The two average contrasts are 0.5018 and 0.4786.

Next we compute the correction factor $K = 2\sqrt{R}/(1+R)$, where R is computed from the two beam intensities. The correction factors are 0.92 and 0.91. The corrected contrasts are 0.5454 and 0.5259, and their average is 0.5356, which is our final result for contrast at Nyquist.

The Fourier contrast at Nyquist using the nearest measurements above and below the Nyquist frequencies are 0.5382and 0.5122, averaging to 0.5252.

If there were no crosstalk or other factors, the contrast would have to be 2/π = 0.637, assuming fill factor equal to 1. Knowledge of pixel shape or other methods can be used to estimate fill factor and theoretical MTF at Nyquist.

As a final result, the pixel crosstalk results in a contrast between 0.536 and 0.523 according to our two different methods, while the theoretical no-crosstalk contrast would be 0.637.

Comparison with Slanted Edge Method

In order to validate our results in relation to established prior work [2, 3, 4], we performed a lens-free slanted edge experiment with our sensor. A razor blade, carefully cut as a short piece, was placed on the sensor such that the sharp edge touches the silicon die. As in the previous sections, a XIMEA CMOS sensor MQ013RG-E2 was used. The sensor was illuminated using a parallel beam produced with the same 633 nm HeNe laser. We have captured 6 images of the shadow of the sharp edge rotated to different angles relative to the vertical axis of the sensor (0.8º, 2º, 10º, 92º, -8º, and -101º).

We used Imatest Software [4] following ISO 12233 standard [3] to compute the sensor MTF. The software produced 6 different MTF plots covering spatial frequencies from zero to 2*Nyquist frequency. Figure 11 summarizes the results, where the bars on the Slanted Edge plot indicate standard deviation error computed from those 6 measurements. The bars on our interferometric Michelson contrast plot indicate the errors of our method.

We see that the error in our interferometric method was similar to or smaller than the error in the Slanted Edge method, especially at high frequencies. We actually cover frequencies much above Nyquist, which are not computed by the Imatest software. In general, the Slanted edge method has noise and interpolates the results at high frequencies. We do not measure very low frequencies in our current experimental setup.

At low and high frequencies we observe a match between the two methods within the error. However, around Nyquist our method tends to have higher contrast values than the Slanted Edge method. We can suggest two reasons for this discrepancy. (1) The slanted Edge method underestimates contrast when working with signal with high signal to noise ratio. The drop in MTF could be up to 10% [2]. (2) A dust particle or some curvature of the razor blade could bring it a few microns above the silicon die and produce soft shadow which would be interpreted as lower MTF.

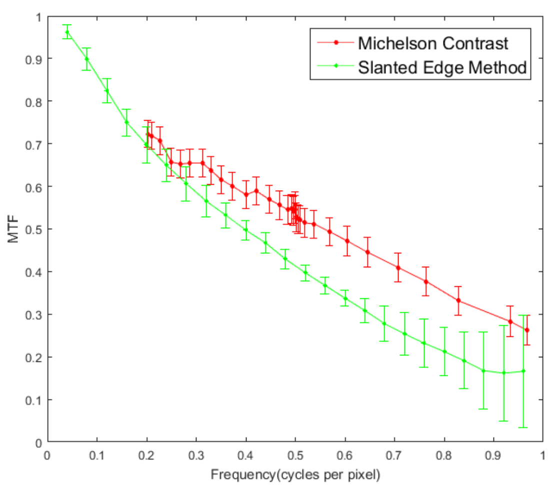

Figure 11. Comparison of the MTF measured with Michelson contrast and Slanted Edge methods.

Conclusion

We have built an interferometer for measuring sensor MTF. The interferometer creates fringes projecting light from pinholes directly on the sensor without passing through any optics. In this way we remove speckle and ghost fringes occurring from multiple reflections in glass elements.

The slanted edge method uses a razor edge that is projected by a lens system onto the sensor. With this approach, the lens influences the MTF. Our interferometric method is lens free, and in this way it is much more precise, not involving any lens MTF or issues of focusing. Also, we cover much wider range of frequencies, reaching several times the Nyquist.

Alternatively, the slanted edge method may use an edge physically touching the surface of the sensor (as above) or depositing metal mask on the surface of the sensor. This runs the risk of destroying or rendering the sensor not useful for capturing images. In comparison, our interferometric setup is non-destructive, as we do not use physical edges and do not touch the surface of the silicon.

Two computational methods of measuring MTF were proposed: Michelson contrast and Fourier contrast. Independently, we have developed a computational method for contrast at the Nyquist that will be most useful for evaluating crosstalk. Our results for a CMOS sensor suggest substantial crosstalk that reduces the contrast at Nyquist from the ideal 0.637 to 0.536.

Sensor MTF is affected by both optical crosstalk and electrical crosstalk, each of which we want to quantify independently. For future work we are planning measurement of contrast based on radioactive sources which would single out the electrical crosstalk. Preliminary results with two radioactive sources suggest little or no electrical crosstalk, which would indicate that for our sensor crosstalk is mainly optical. Separation between electrical and optical crosstalk can also be achieved with measurements using lasers at different wavelengths, since penetration of light into silicon depends on the wavelength.

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Todor Georgiev received his PhD in Molecular Science from Southern Illinois University. He worked at Adobe Photoshop where he authored some of the Photoshop features, for example, the Healing Brush. He is currently Principal Engineer at Qualcomm.