Method for measuring modulation transfer function of charge-coupled devices using laser speckle

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Abstract. A new method has been developed to measure the modulation transfer function (MTF) of an array out to the Nyquist frequency without high quality optical or mechanical components, without precision alignment, and with only one moving part. Test results for an infrared staring array of PtSi Schottky barrier construction show that this technique is a viable MTF measurement approach in the 3 to 5 μm spectral region.

Subject terms: modulation transfer function measurement; infrared; charge-coupled device; speckle.

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1. INTRODUCTION

Typically, the MTF of CCDs is measured by means of the system's response to bar charts or other test targets.[1-4] These tests often require complex scanning techniques and high quality imaging optics. Also, separate target data for each spatial frequency of interest are generally required. A new MTF measurement method based on laser speckle is presented that requires neither moving parts, critical alignment, nor high quality optical components. The measurement method depends on the determination of a system transfer function by means of a series of random inputs.

We can define a spatial-frequency power spectrum as the squared modulus of the Fourier transform. When this operation is applied to two-dimensional scene data, the notation $S_{in}(\xi,\eta)$ or $S_{out}(\xi,\eta)$ is used to denote the two-dimensional spatial frequency power spectrum of the scene before or after processing by the CCD, respectively, where ξ and η are the spatial frequency variables. The input $S_{in}(\xi,\eta)$ and output $S_{out}(\xi,\eta)$ power spectra of a two-dimensional system are related in the following manner:

$$S_{out}(\xi,\eta) = |H(\xi,\eta)|^2 S_{in}(\xi,\eta) , \tag{1}$$

where $H(\xi,\eta)$ is the system transfer function. In the present application, the system transfer function is the MTF of the device, since the MTF determines what the relative system transfer is, as a function of spatial frequency. Laser speckle provides an input of optical spatial noise of known spatial power spectrum into the system. The output power spectrum is computed directly from the array data.

2. SPECKLE PROPERTIES

Speckle is an interference phenomenon observed when coherent radiation is scattered from a rough surface. A point-to-point variation in optical intensity is observed at any plane beyond the scatterer. This variation of optical intensity has a spatial power spectrum described by the normalized autocorrelation of the intensity distribution in the scattering aperture.[5] Thus, the power spectrum due to the speckle, which is the input to the CCD array, is described by

$$S_{in}(\xi,\eta) = \langle I\rangle^2 \left\{ \delta(\xi,\eta) + \frac{\displaystyle\iint_{-\infty}^{\infty} |P(x_1,y_1)|^2 |P(x_1-\lambda Z\xi, y_1-\lambda Z\eta)|^2 dx_1 dy_1}{\left[\displaystyle\iint_{-\infty}^{\infty} |P(x_1,y_1)|^2 dx_1 dy_1\right]^2} \right\} , \tag{2}$$

where $P(x_1,y_1)$ is the product of the scattering aperture func-

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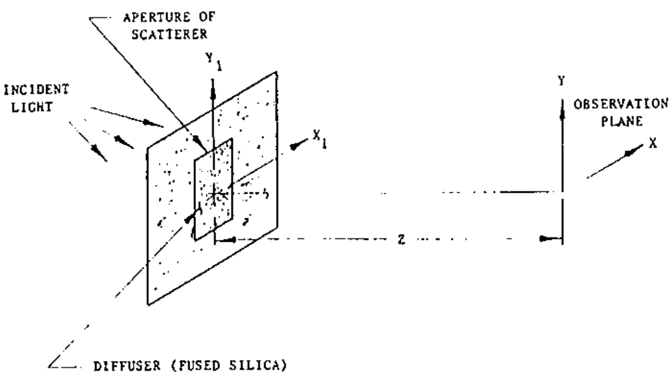

Fig. 1. Free-space propagation geometry for speckle formation.

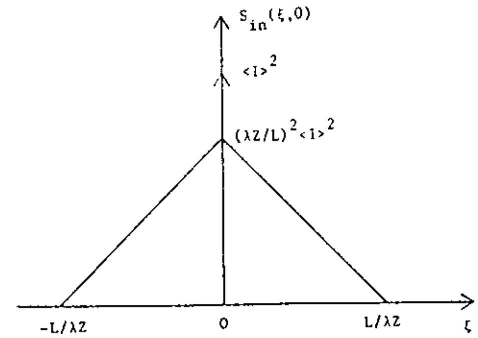

Fig. 2. ξ profile of input power spectrum of speckle.

tion and the illuminating amplitude distribution, x_1 and y_1 are the aperture coordinates, Z is the range, and λ is the wavelength of the radiation used. This expression assumes that the range Z places the observation plane in the Fresnel region of the aperture, that the phase variation introduced by the scatterer is greater than 2π, and that the smallest scatterer is unresolvable in the observation plane. Furthermore, the equal distribution of power between the delta function and the extended-frequency component of the spectrum assumes that the radiation exiting the scatterer is polarized. This was not the case in the actual experiment, so that the MTF was not normalized at zero frequency. Hence, for a scattering geometry as shown in Fig. 1, with uniform illumination on the aperture, the input power spectrum is a triangle function for spatial frequencies greater than zero, as shown in Fig. 2. For nonuniform illumination of the aperture, the power spectrum is no longer a perfect triangle function but can still be described by the autocorrelation function of the aperture. Thus, a known input power spectrum is provided that allows the MTF of the CCD to be inferred from the array data.

3. INSTRUMENT DESIGN

The instrument, shown in Fig. 3, was designed to measure the MTF of an infrared CCD at 3.39 μm under the following conditions: The upper frequency limit of the input power spectrum was chosen to be the Nyquist frequency for the array so as to avoid problems of aliasing in the output array data. To express the power spectrum of the speckle as an autocorrelation of the aperture intensity function, the structure on the diffuser surface had to be unresolvable at the detector plane. It was thus implied that

$$\Delta < \frac{\lambda Z}{D} , \tag{3}$$

where Δ is the surface correlation distance on the scatterer, λ is the laser wavelength, Z is the distance from the CCD array to the scatterer, and D is the CCD linear dimension. This condition was satisfied by the sandblasted surface of the fused silica diffuser. Another configuration of the apparatus was used to image the scattering aperture onto the array plane so that the autocorrelation of the aperture intensity function, and hence the input power spectrum, could be computed. A typical frame of speckle data with the background subtracted is shown in Fig. 4.

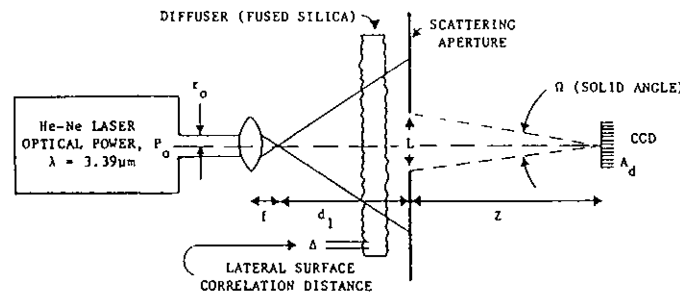

Fig. 3. Speckle MTF measuring instrument. P_o = 5 mW; r_o = 1 mm; f = 12.7 mm; d_1 = 200 mm; L_x = 4.25 mm; L_y = 8.5 mm; Z = 300 mm; $\Delta <$ 0.25 mm; and A_d = 14.75 mm^2.

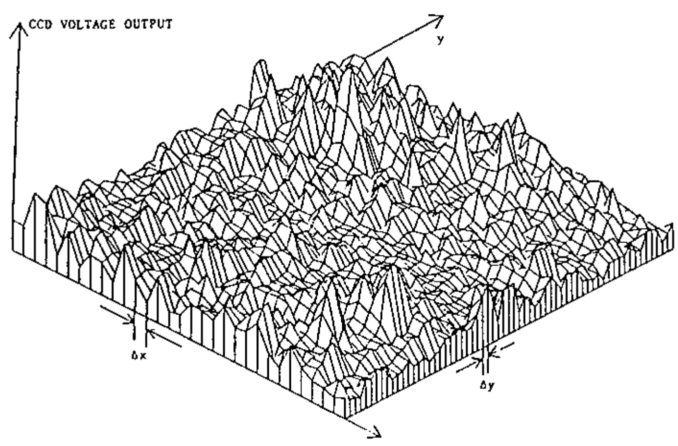

Fig. 4. Typical frame of speckle data.

4. DATA PROCESSING

The output power spectrum, necessary for the calculation of the MTF, is determined in the following manner: A fast Fourier transform (FFT) was performed on each row of speckle data, and the squared magnitude was taken to produce a power spectrum. Each of the row spectra was normalized individually by dividing the strength of each frequency component by the sum of all components up to the Nyquist frequency in that particular spectrum. This procedure weighted each row of data equally, rather than by the amount of power in that row. Similar procedures were applied to data in the y-direction to obtain η spectra. These

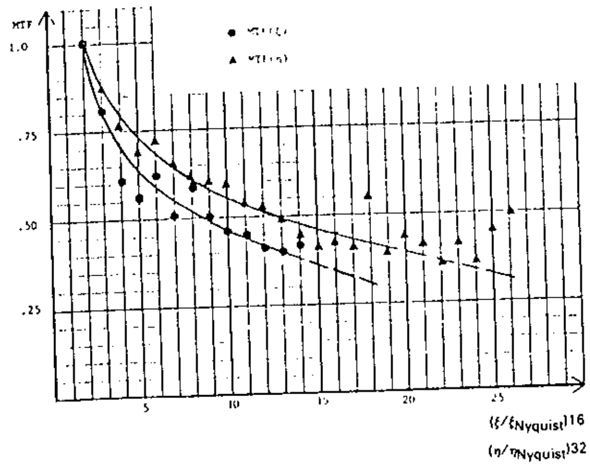

Fig. 5. MTF results from the speckle method.

normalization procedures were helpful in the reduction of the number of frame averages required for convergence of the spectra. The normalized spectra were averaged over the rows and columns of each frame and over 10 frames of speckle data. The ensemble averaging over different frames of speckle data is necessary to reduce the variance in the estimate of the output power spectrum.[6] The diffuser was moved between the acquisition of successive frames of speckle data.

The input power spectrum is also necessary for the calculation of the MTF and was calculated from the normalized autocorrelation of the aperture intensity function. The procedure used consisted of an FFT operation and squaring, then an inverse FFT to obtain the autocorrelation of the real-valued aperture intensity function.

5. RESULTS

The MTF results in both the ξ and η directions for the infrared CCD array tested are seen in Fig. 5, in which the solid lines indicate the best smooth fit to the data in each direction. Results are plotted as a function of spatial frequency variables that have been normalized to their appropriate Nyquist frequency. Since the actual array tested had a pixel spacing in the x-direction that was twice that in the y-direction, there results a different normalized representation of the same spatial frequency, depending on its orientation with respect to the array axes.

There is seen an eventual rise in the calculated MTF values as the Nyquist frequency is approached. The origin of this artifact is that the input power spectrum goes to zero at that frequency, while the output spectrum still has a finite baseline value due to noise. The lower MTF values in the ξ direction are a result of the architecture for the particular array under test. There was a higher charge transfer speed in the x-direction than in the y-direction, so the MTF was lower in the direction of faster charge transfer primarily due to the effects of charge transfer inefficiency. These results were closely corroborated by interferometric and impulse response tests on the same device.

6. CONCLUSIONS

The advantages of this method of MTF measurement are that it does not require high precision optical or mechanical components, nor is precise alignment needed. There is only one moving part in the system (the diffuser), and its motion is not critical. From each frame of data, an estimate of the MTF for the device as a whole is available at all frequencies less than the Nyquist in both the ξ and η directions. These factors make the system an ideal candidate for the automated testing of CCDs in a production environment.

7. ACKNOWLEDGMENTS

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