

ISET - Microlens Module

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Motivation

The irradiance image at the surface of a digital image sensor must travel down the pixel tunnel, passing through the sensor’s back-end technology, to the photodetector in the silicon substrate. Methods for controlling the path of the photons between sensor surface and silicon substrate, a distance usually ranging from a few to more than 10 microns, are called the pixel optics. These methods are increasingly important in image sensor design as pixel size shrinks [1, 2].

In many digital image sensors an array of microlenses is placed near each pixel aperture on the sensor surface. The position and properties of this microlens array control two important functions of the optical path from the sensor surface to the photodetector.

1. Light concentration

First, the microlenses concentrate photons incident within the pixel aperture onto a compact region at the silicon substrate. In most CMOS imagers, the photodetector only occupies a fraction of the area at within the substrate because the photodetector shares substrate area with transistors that form the pixel circuitry. For example, in the widely used active pixel sensor (APS) pixel three transistors perform tasks including selecting and resetting the pixel. Microlenses are intended to concentrate the photons onto the photodetector rather than allowing them to fall on non-photosensitive positions in the pixel floor. To concentrate photons the microlens properties must be coordinated with those of the imaging lens, as we discuss below.

2. Light redirection

Second, the microlens array redirects the light path. Consider the pixels at different positions across the sensor array. As pixel position varies from center to edge, the angular distribution of the rays arriving at the pixel changes. The angular distribution is centered on the pixel aperture for pixels in the center of the sensor. But pixels near the edge receive a bundle of rays that would normally pass through the aperture and travel to substrate positions that are displaced from the pixel floor. These rays would strike the edge of the pixel tunnel or travel to regions within the floor of adjacent pixels. The microlens must redirect these rays so that they travel through the pixel tunnel and reach the photodetector position at the substrate. The loss of light due to the failure to redirect these rays is called pixel vignetting [3]. Redirection of the rays is achieved by appropriate placement of the microlenses with respect to the pixel aperture.

Calculation examples

1. Light concentration

The light gathering efficiency of any optical system is summarized by a quantity called the geometrical extent (also known as etendue or light throughput) [4]. It is the optical equivalent of the space-bandwidth product. The geometrical extent (G) of an optical system, say one that converts the scene radiance to image irradiance at the pixel aperture, is the product of the pixel aperture area with the solid angle subtended by the exit pupil of the imaging lens as seen by the pixel. For systems with radial symmetric or systems that are xy-separable, the geometrical extent can be expressed in terms of more familiar properties, i.e., as the product of the imaging lens numerical aperture (NA) with the size of the pixel aperture. In the paraxial approximation, NA and $f/\#$ are related by $NA = n/(2f/\#)$ and G becomes,

$$G_{imaging} = w_{pixel} NA_{imaging} \cong \frac{n_{air} w_{pixel}}{2(f/\#)_{imaging}} \quad (1.1)$$

The geometrical extent of the pixel optics, that is the path from the sensor surface to the photodetector, is the product of the photodetector size and the NA of the microlens,

$$G_{pixel} = w_{detector} NA_{micro} \cong \frac{n_{detector} w_{detector}}{2(f/\#)_{micro}} \quad (1.2)$$

In a system comprising several stages, such as the imaging lens and the pixel optics, light throughput is limited by the system component with the smallest geometrical extent. Generally for CMOS imagers, pixel optics is the limiting factor, $G_{pixel} < G_{imaging}$. The microlens is intended to increase the geometrical extent of the pixel optics to that of the imaging optics, $G_{pixel} = G_{imaging}$. For pixels with a linear fill-factor of 50% ($w_{detector} = w_{pixel}/2$), the NA of the microlens should satisfy $NA_{micro} = 2NA_{imaging}$ or, expressed in terms of $f/\#$, $(f/\#)_{micro} = n_{detector}/n_{air} (f/\#)_{imaging}/2$. In summary, the microlens should have an $f/\#$ that is smaller than that of the imaging lens by a factor that depends on the desired concentration.

The dilemma in pixel scaling for CMOS imagers is the following. Small pixel sizes require imaging lenses with small $f/\#$ s to obtain a sufficient photon supply at the sensor surface. Concentration of light onto the photosensitive area in small pixels requires a microlens with even smaller $f/\#$. Given the small pixel aperture, the smaller $f/\#$ means shorter focal length. The focal length is determined by the sensor thickness (stack height). When CMOS technology scales, the lateral dimensions (e.g., transistor size and pixel size) shrink but the stack height usually increases.

What "pixel gain" (concentration) is achieved by applying a microlens array? When does the stack height become too high to permit the microlens to concentrate the light from the imaging lens onto the photodetector? These questions can be answered by the Microlens Module in ISET.

2. *Light redirection*

Given the difficulties associated with microlens design, the main purpose of the microlens array is no longer concentration. Rather, the most important function is the redirection of light onto the photodetector for off-axis pixels. To achieve proper redirection of light, the microlenses must be offset from the center of the pixel aperture.

This offset Δ , which is towards the optical axis, can be calculated to a very good approximation using first-order geometrical optics and yields

$$\Delta = f_{ML} \tan(\theta) \tag{1.3}$$

where f_{ML} is the focal length of the microlens (inside the dielectric stack) and θ is the chief ray angle (inside the dielectric stack).

How does the offset of the microlens with respect to the pixel center affect the amount of light collected by the photodetector? What “pixel gain” is achieved by applying an offset to the microlens versus a pixel-centered design? These questions can be answered by the Microlens Module in ISET.

How to

The microlens calculations are performed in the Microlens window of ISET. In this section, we show how to perform some of the calculation examples described before.

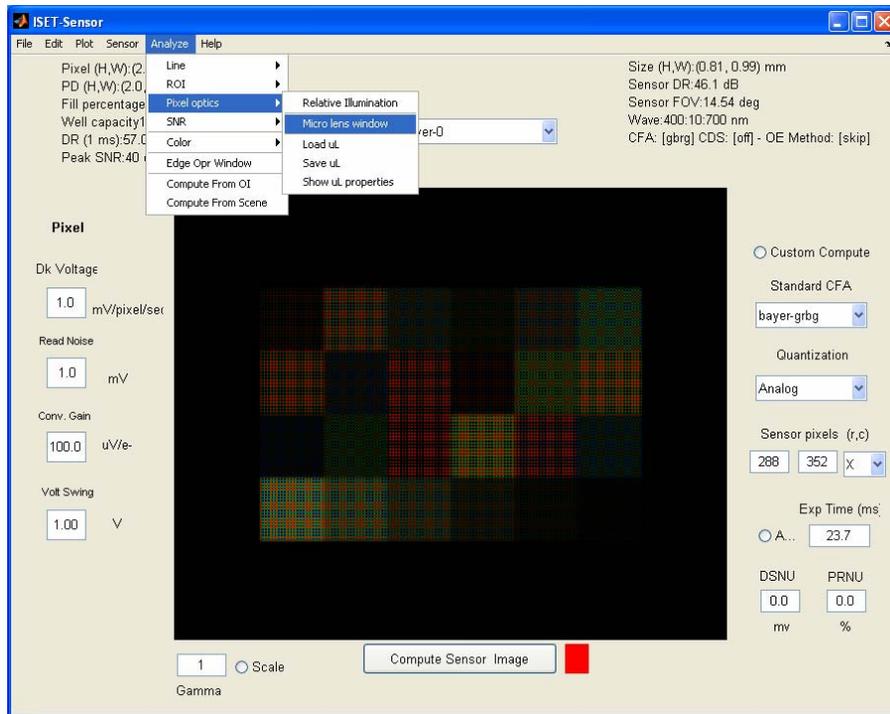


Figure 1: Selecting and opening the Microlens window from the ISET-Sensor window.

We assume that an ISET simulation has been set up, i.e., that a scene has been chosen, an imaging lens has been selected, and a particular sensor is being studied (pixel, photodetector, and dielectric stack have been defined).

To open the Microlens window, select the Analysis | Pixel optics | Microlens pulldowns in the ISET-Sensor window (Figure 1). This will also upload the required simulation parameters.

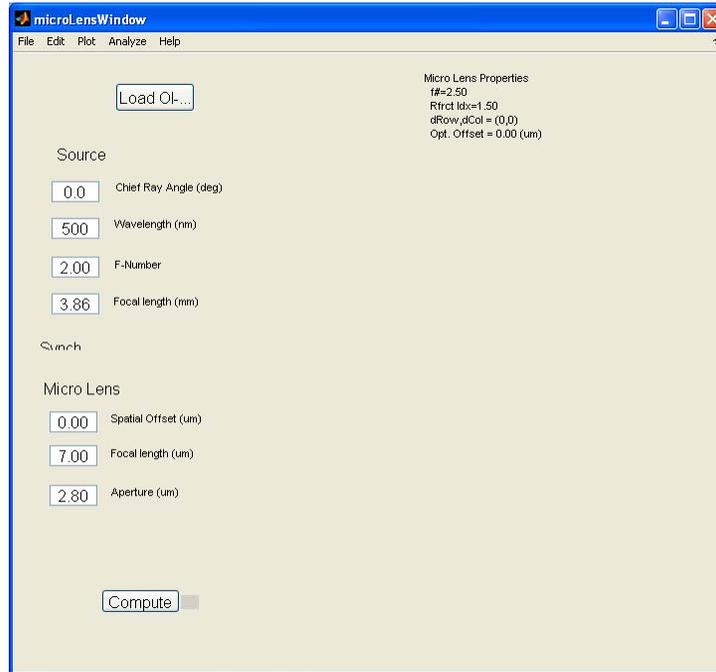
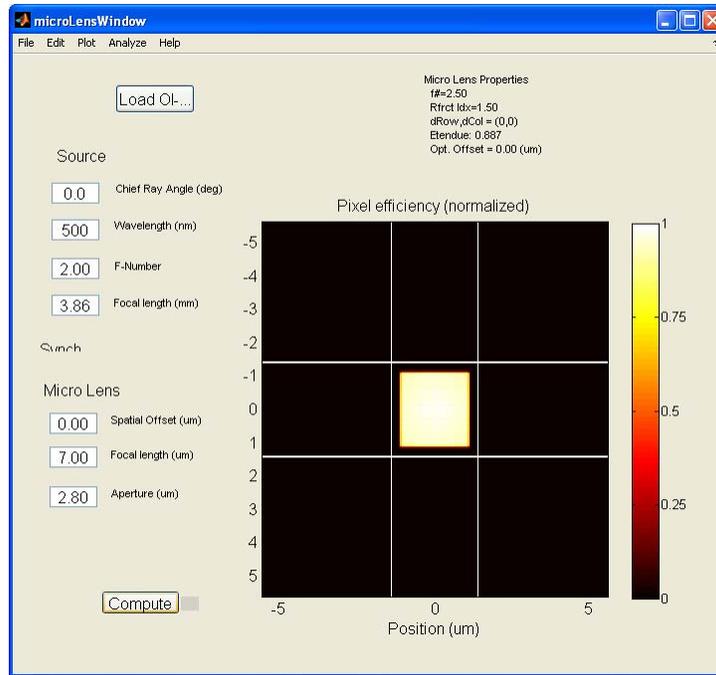


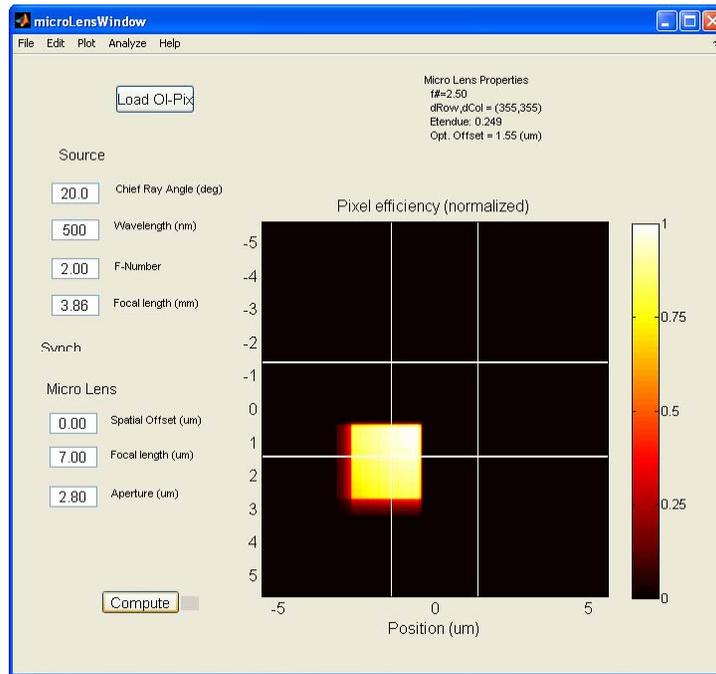
Figure 2: Microlens Window – Setup for given Source and Microlens parameters.

The Source (chief ray angle, wavelength, f/#, focal length) and Microlens parameters (spatial offset, focal length, and aperture) are shown on the left hand side of the window (Figure 2). When modified, they will be updated into the ISET structure of your simulation. In the upper right-hand corner, there are some derived Microlens Properties (f/#, refractive index, pixel index, and optimal offset) providing you feedback about the microlens analysis.

The main part of the window is the irradiance graph, which shows a zoomed-in part of the sensor array, centered on a particular pixel of interest. After a microlens simulation is run, the graph depicts the irradiance distribution inside the pixel at the photodetector [Figure 3(a)]. White lines demark the spatial extent of the pixel. This graph gives you visual feedback on the extent of the focal spot (e.g., if it is bigger than the pixel or nicely fits inside the pixel) and its location (e.g., is the microlens redirecting the rays to the photodetector or not). The qualitative visual data is also quantitatively summarized in the upper right-hand corner by the etendue value; an etendue value of 1 means that all light incident on the pixel is being redirected into the photodetector area. If the etendue is smaller than 1, you have lost some of the light incident on the pixel. This could be due to an inappropriate choice of microlens parameters or an inappropriate positioning of the microlens with respect to the pixel [Figure 3(b)].



(a)



(b)

Figure 3: Microlens Window – (a) On-axis irradiance calculation: irradiance falls entirely inside pixel, which is limited by white lines; and (b) Off-axis irradiance calculation (without spatial offset for the microlens): irradiance falls partially outside of the pixel.

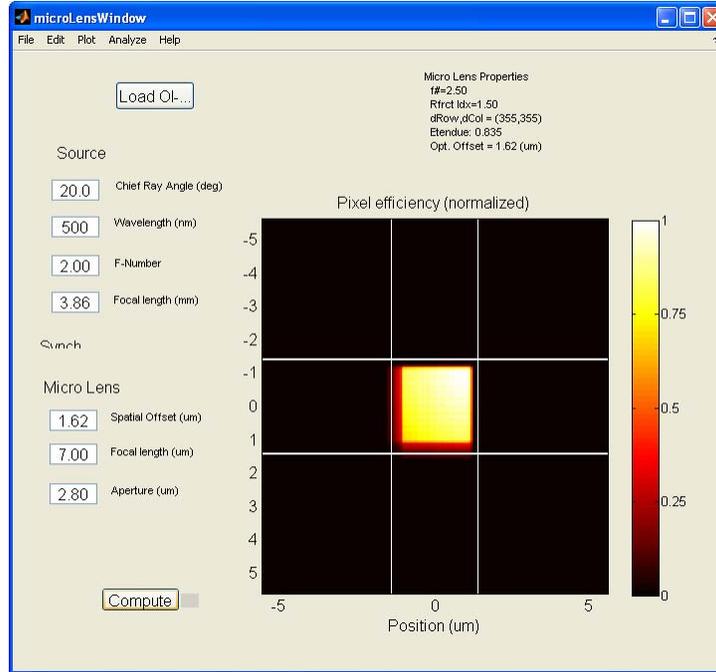


Figure 4: Microlens Window – Off-axis irradiance calculation (with spatial offset for the microlens): irradiance falls entirely inside pixel again.

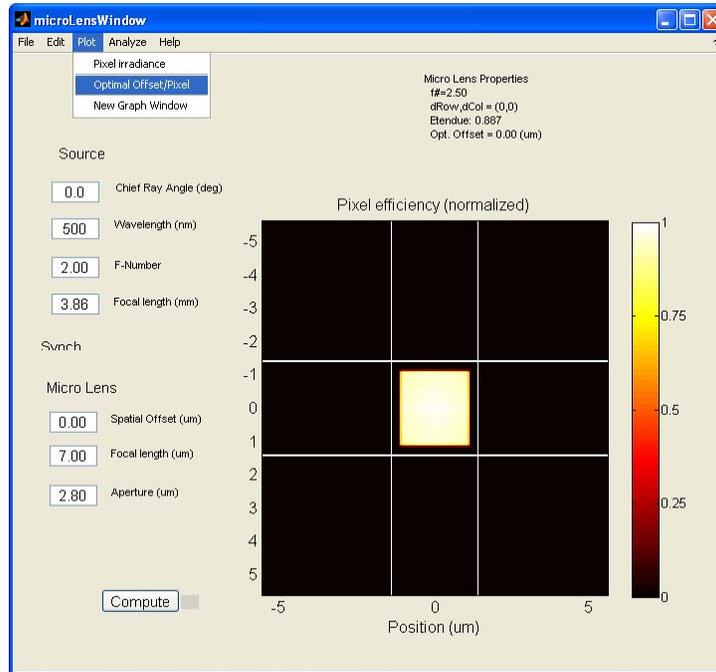


Figure 5: Microlens Window – Selecting plot functions. For example, the user can query ISET for the optimal offset for the microlens with respect to the pixel center as a function of pixel position in the array by selecting the Plot | Optimal Offset/Pixel menu.

To assist you in the design of the microlens array, the Microlens window will provide you with an optimized offset for the microlens for a given off-axis chief ray angle. This value is given in the upper right-hand corner. Try and type it into the offset box and see what happens. The irradiance image should show that the focal spot is now centered on the pixel (Figure 4).

The Microlens window also features plot and analysis functions that summarize typical calculation examples and apply them to the entire pixel array in stead of a single pixel-under-test.

For example, the user might be interested in the uniformity of the pixel irradiance, which is more clearly visible in a mesh plot (Plot | Pixel irradiance) as opposed to an image (Figure 4). By selecting the Plot | Optimal Offset/Pixel menu (Figure 5), ISET calculates the optimal offset for the microlens with respect to the pixel center as a function of pixel position in the array. The results are plotted in a separate ISET Graph window (Figure 6).

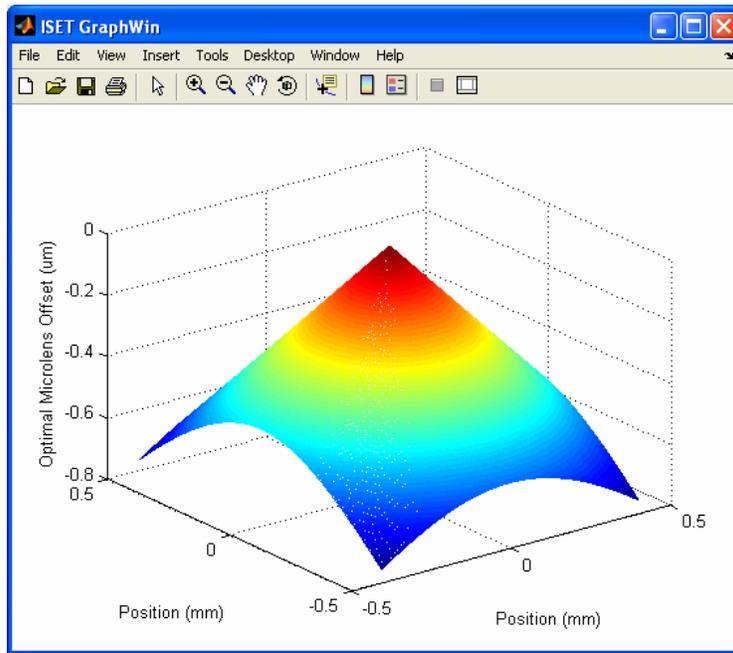
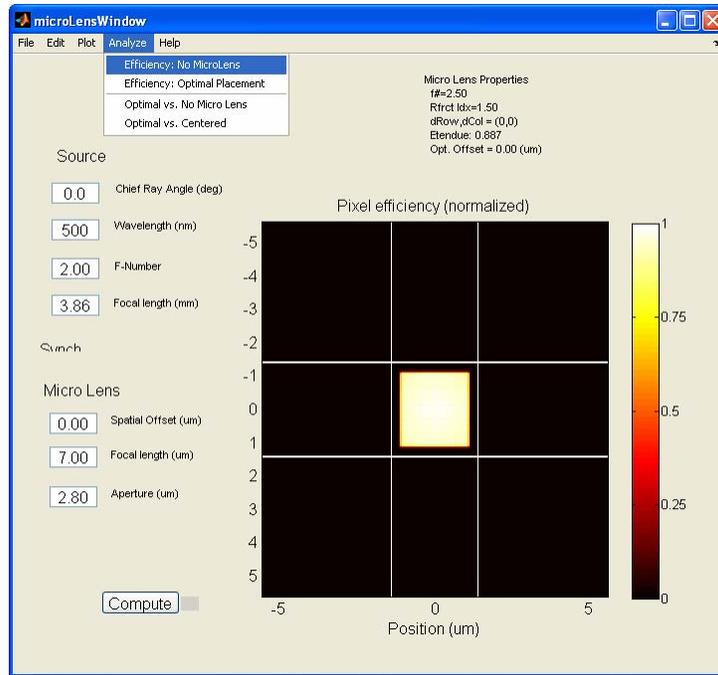
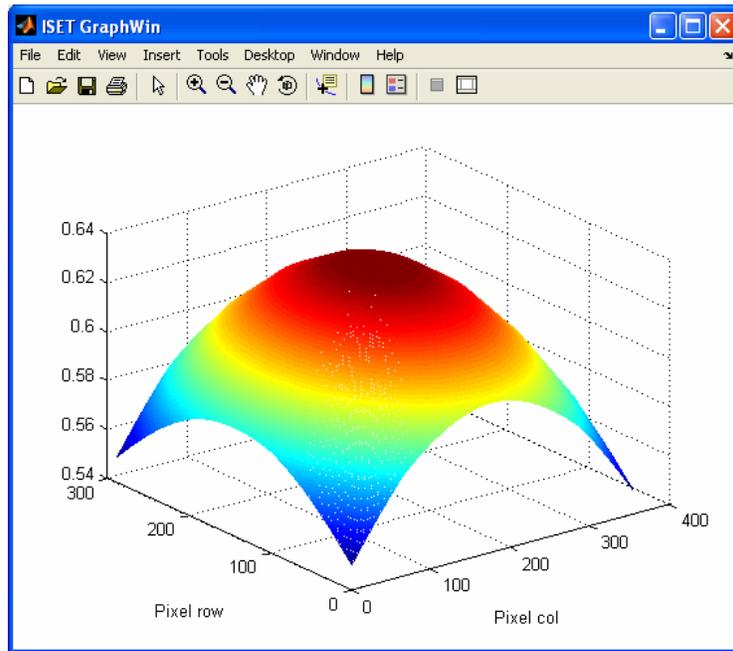


Figure 6: Optimal Microlens Offset (in μm) versus two-dimensional position in the pixel array (in mm).

In the Analyze menu, it is possible, for example, to calculate the attenuation that the signal undergoes as it propagates from the pixel surface to the substrate. This is typically referred to as pixel vignetting (Analyze | Efficiency – No Microlens) and results in an array of values between 0 and 1 (Figure 7). Another useful calculation (Analyze | Efficiency – Optimal Placement) involves the optimal placement of the microlens with respect to the pixel center. The result is an offset that depends on the position of the microlens in the array. The resulting optical efficiency is an array of values between 0 and 1, which are (hopefully) larger than the ones for the no-microlens case (Figure 8).

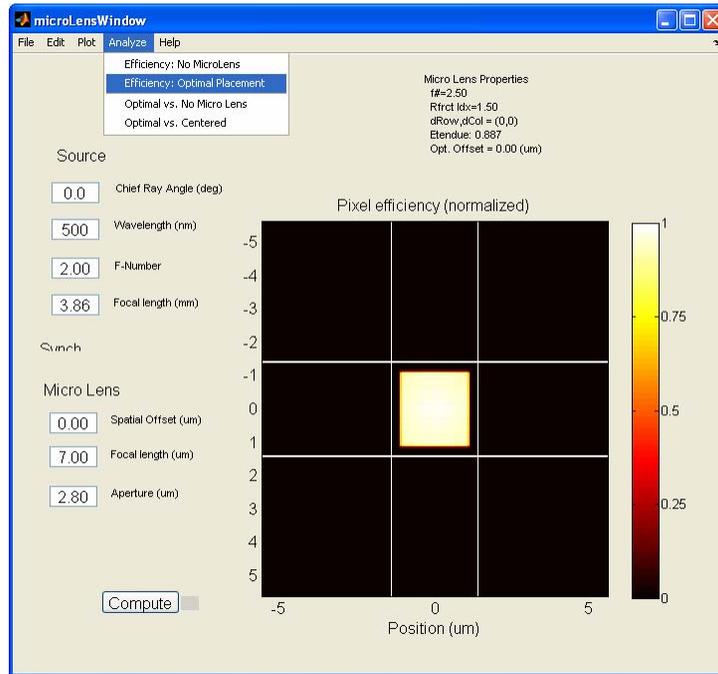


(a)

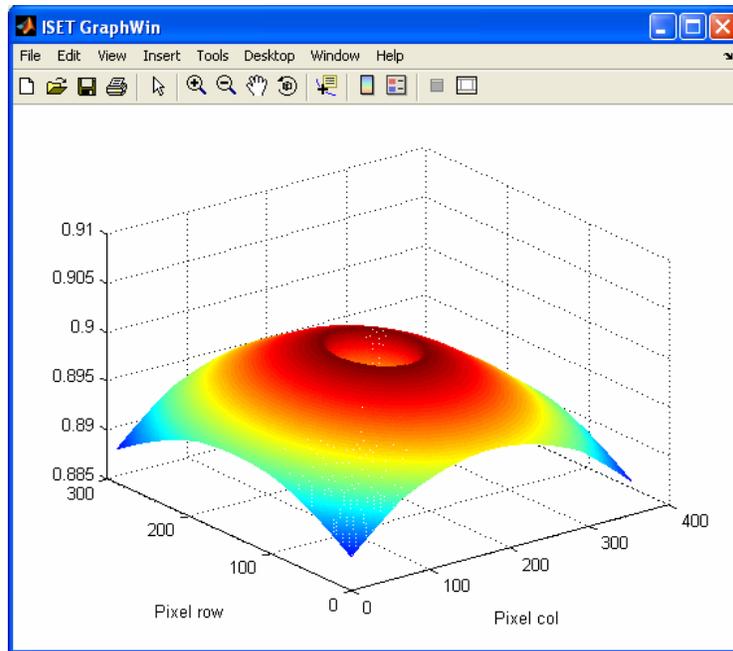


(b)

Figure 7: Microlens Window – Analyze | Efficiency: No Microlens: (a) Selecting the pixel vignetting calculation and (b) Results of the pixel vignetting calculation in a separate ISET graph window.



(a)



(b)

Figure 8: Microlens Window – Analyze|Efficiency: Optimal Placement: (a) Selecting the optimal placement calculation and (b) Efficiency of pixel in the array (on a 0-1 scale) after optimal placement calculation in a separate ISET graph window.

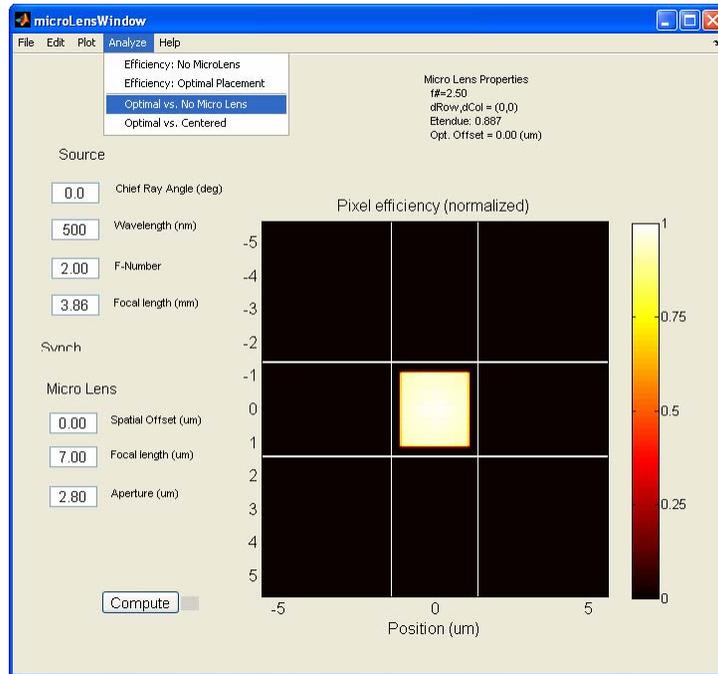
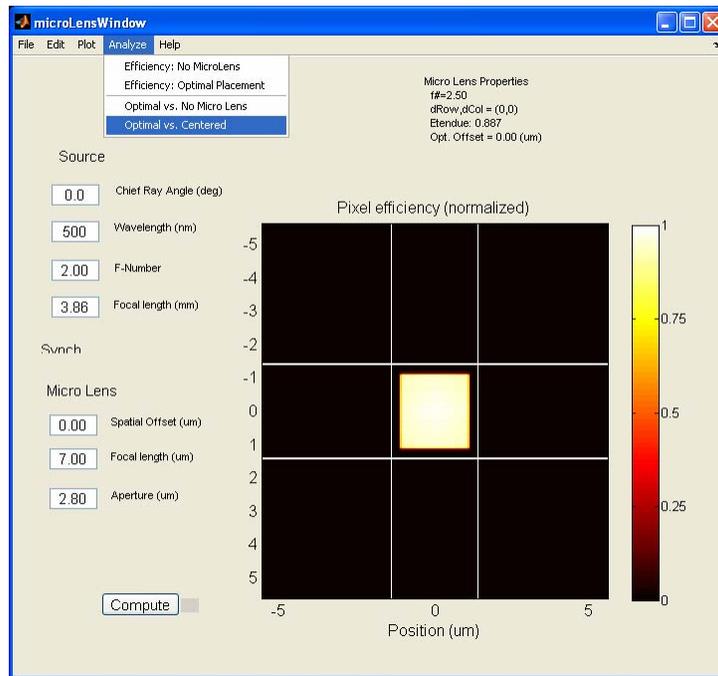
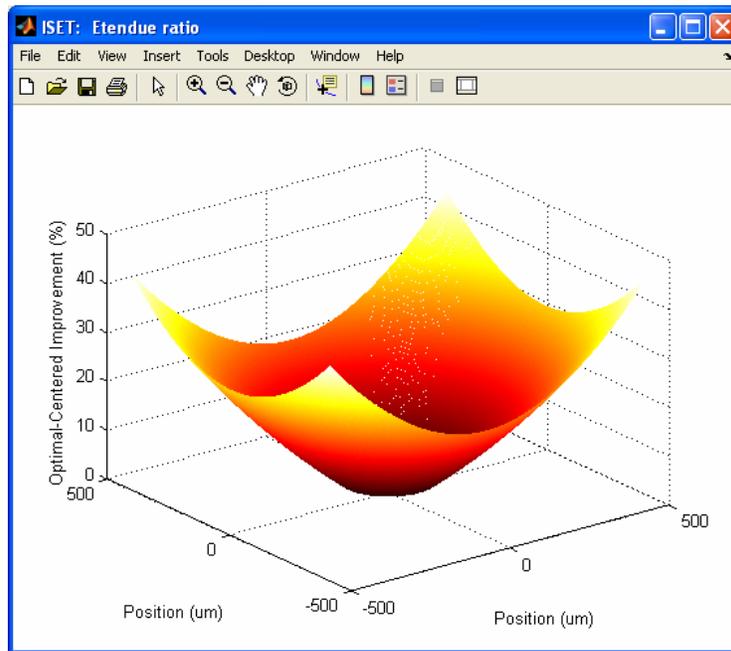


Figure 9: Microlens Window – Analyze | Optimal vs. No Microlens.



(a)



(b)

Figure 10: Microlens Window – Analyze | Optimal vs. Centered Microlens: (a) Selecting the optimal-versus-centered microlens calculation and (b) Improvement (in %) of the optimal-versus-centered calculation in a separate ISET graph window.

Finally, it is also possible to compare the relative improvement that can be achieved, say, by adding an optimal microlens array (Analyze | Optimal vs. No Microlens) or by off-setting the microlens array from the pixel centers (Analyze | Optimal vs. Centered). In these cases, the result is an array of percentage values that represent the improvement over the reference case, i.e., no microlens and centered, respectively (Figures 9 and 10).

Methods

The microlens calculations in ISET are performed using a Phase Space (PS) Toolbox that we developed specifically to predict the optical efficiency (OE) of CMOS image sensor pixels [1].

As currently implemented, geometrical optics PS comprises 4-dimensional functions whose entries describe the relationship between each geometrical light ray and a plane, which is typically perpendicular to the optical axis or axis of propagation. Two of the four dimensions define the location of the ray intersection with the plane, (x, y) ; the other two dimensions describe the angles between the ray and the optical axis at the intersection point, (θ_x, θ_y) . In the geometrical optics PS representation, these angles are usually measured in terms of (p, q) given by

$$p = n \sin \theta_x, \quad q = n \sin \theta_y \tag{1.4}$$

where n is the index of refraction of the material at the plane. We call (p, q) “generalized reduced angles,” because they are a non-paraxial generalization of the reduced angles defined by Goodman [5]. The spatial dimensions (x, y) are unbounded; the angular dimensions (p, q) fall within a range of $-n$ to n , i.e. the PS representation is limited to forward propagating rays.

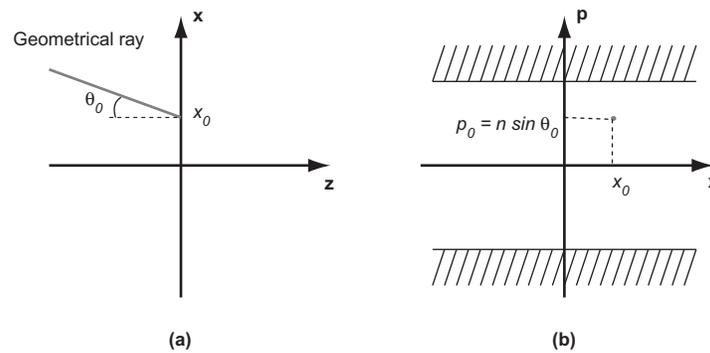


Figure 11: Geometrical optics PS: The parameters (x_0, p_0) define a geometrical ray incident on a surface in (a) 1-dimensional real space and (b) 2-dimensional phase space.

Two-dimensional signals and systems, $u(x, y)$, such as imaging systems, have 4-dimensional PS representations, $W(x, y, p, q)$. In certain cases, the 4-dimensional representation can be

reduced to a 2-dimensional PS, $W(x, p)$. This reduction is possible whenever the two-dimensional system can be represented by a simpler one-dimensional system, for example in the case of rotational symmetry. In this case, the position along one spatial dimension x_0 and one angle θ_0 are enough to characterize each light ray. Figure 11 shows the two-dimensional PS representation of a geometrical ray: a point (x_0, p_0) in PS where the generalized reduced angle is $p_0 = n \sin \theta_0$. To provide an intuitive explanation of PS representations and their use in determining pixel OE, we will rely on one-dimensional signals and systems, $u(x)$, and 2-dimensional PS, $W(x, p)$.

In general, the relationship between a one-dimensional signal or system and its two-dimensional PS representation is obtained by the Wigner transform [6, 7]:

$$W(x, \nu) = \int u(x + x'/2) u^*(x - x'/2) \exp(-2\pi i \nu x') dx'. \quad (1.5)$$

The Wigner transformation from $u(x)$ to $W(x, \nu)$ is reversible up to a constant phase factor:

$$\int W(x/2, \nu) \exp(2\pi i \nu x) d\nu = u(x) u^*(0), \quad |u(0)|^2 = \int W(0, \nu) d\nu. \quad (1.6)$$

We now define geometrical optics PS as a binary function of two variables,

$$W_{\text{geom}}(x, p) = \begin{cases} 1 & W(x, \nu) > W_{\text{thresh}} \\ 0 & \text{otherwise} \end{cases}, \quad (1.7)$$

using a threshold value, W_{thresh} , and we relate the spatial frequency, $\nu = n \sin \theta / \lambda$, to the generalized reduced angle p by

$$p = \lambda \nu. \quad (1.8)$$

In what follows, we replace the subscript ‘geom’ in order to distinguish between PS representations of optical signals, $W_I(x, p)$, and systems, $W_Y(x, p)$, respectively.

1. PS representation of optical signals

Consider the PS representation $W_I(x, p)$ of a typical optical signal that can be used as input to an image sensor. An incoherent area source consists of the image produced by a lens filled with light [8] centered on the optical axis x_0 in position. The rays are confined in space by the finite diameter of the lens’ field stop, Δ , and confined in angle by the lens’ numerical aperture, NA: A closed area represents the area source in PS (Fig. 12),

$$W_I(x, p) = \Pi\left(\frac{x - x_0}{\Delta}, \frac{p - p_0}{2NA}\right) = \Pi\left(\frac{x - x_0}{\Delta}\right) \Pi\left(\frac{p - p_0}{2NA}\right). \quad (1.9)$$

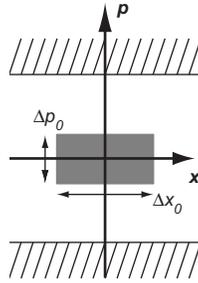


Figure 12: PS representation of a typical optical signal: The image produced by a lens filled with light is an incoherent area source with finite spatial (e.g., lens diameter) and finite directional extent (e.g., lens numerical aperture).

We define Π as the rectangle function [9]:

$$\Pi\left(\frac{x-x_0}{\Delta x_0}\right) = \begin{cases} 1 & x_0 - \frac{\Delta x_0}{2} \leq x \leq x_0 + \frac{\Delta x_0}{2} \\ 0 & \text{else} \end{cases} \quad (1.10)$$

Finally, the photon flux of the optical signal is the integral of the geometrical optics PS representation,

$$\Phi = \iint W_r(x, p) dx dp \quad (1.11)$$

2. PS representation of optical systems

PS representations can also be used to describe the acceptance range of signals incident on an optical system, such as a CMOS image sensor pixel. We denote system representations by $W_y(x, p)$. Here, the axes are unchanged from the signal diagram; but the value assigned to each location in the representation defines the system's relative responsivity to a ray at that position and angle. In many applications, it is sufficient to summarize this responsivity using a binary value, in which we treat each ray as either falling in or out of the system's acceptance range,

$$W_y(x, p) = \begin{cases} 1 & \text{within acceptance range} \\ 0 & \text{else} \end{cases} \quad (1.12)$$

The system's responsivity can now be described graphically using shaded PS graphs (Fig. 13). The PS representation of the lens-pixel system at the pixel aperture plane depends jointly on the lens and the pixel PS representations. The PS representation of the system is necessarily the intersection of the two PS representations. On the horizontal axis, the PS of the lens spans the width of the field stop Δ ; the pixel is bounded by the width w of the pixel. On the vertical axis, the pixel accepts a full hemisphere; the lens, however, is bounded by its numerical aperture NA,

$$W_Y(x, p) = \Pi\left(\frac{x}{w}\right) \Pi\left(\frac{p}{2 NA}\right). \tag{1.13}$$

The integral of the geometrical optics PS representation, measures the geometric etendue G , i.e. the maximum incident photon flux transmittable by the optical system [4],

$$G = \iint W_Y(x, p) dx dp. \tag{1.14}$$

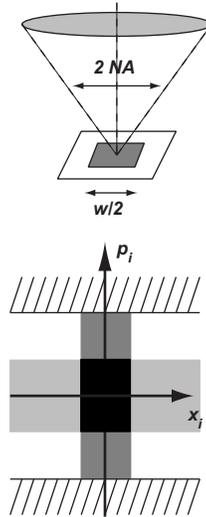


Figure 13: PS representation of lens-pixel system for pixel placed on-axis in the imaging plane of a lens. The light shaded areas indicate the PS representation of the lens at the image plane and the PS representation of the pixel; the black rectangle represents the intersection of the pixel PS and the lens PS.

Geometric etendue is the energetic equivalent of the optical space-bandwidth product described in Lohmann *et al.* [10] It is a limiting function of system throughput and is determined by the least optimized segment of the entire system. For the example system shown above, the etendue is $G = NA w$. This is the maximum achievable etendue for an image sensor pixel illuminated by an imaging lens and usually serves as a reference in many of the calculations performed with the Microlens Module in ISET.

3. Combining Signals and Systems

We now define the combined signal-system PS representation, which defines all the angles and positions of incident signal rays that are accepted by the system,

$$W_{IY}(x, p) = W_I(x, p) W_Y(x, p). \tag{1.15}$$

The integral of the signal-system PS representation, $\iint W_{IY}(x, p) dx dp$, defines an upper bound on the fraction of incident light transmitted by the optical system.

4. PS transformation: Canonical planes

To characterize an optical system in PS and to calculate its etendue, we must choose a suitable reference plane that we call the canonical plane. Using a canonical plane simplifies combining signal and system PS representations because one can compute quantities in a convenient plane and then refer them to the canonical plane.

The procedure of converting the PS representations between planes, when the paraxial approximation is valid, is described by ray transfer matrix rules [11]. Each ray in the pixel aperture plane is assigned a corresponding ray at the pixel floor by application of the following ray transfer matrix:

$$\begin{pmatrix} x_o \\ p_o \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x_i \\ p_i \end{pmatrix}. \tag{1.16}$$

We typically apply a succession of ray transfer matrices for more complex systems; for a pixel, we apply one for each dielectric layer in the tunnel. In general, the transformation for each layer comprises the product of two matrices, a free space propagation matrix and an interface transformation matrix. The free space propagation matrix is

$$\begin{pmatrix} x_o \\ p_o \end{pmatrix} = \begin{pmatrix} 1 & -d/n \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_i \\ p_i \end{pmatrix}, \tag{1.17}$$

where d is the distance of the free space propagation and n the refractive index of the dielectric layer. The free space propagation changes the position coordinate, x , without affecting the direction coordinate, p . By using generalized reduced angles, the interface transformation matrix is simplified and becomes the identity matrix.

The paraxial formulae in the previous paragraph are included to provide an intuitive discussion. In general, however, we use non-paraxial formulae. These cannot be accurately modeled using a cascade of ray transfer matrices, and their complexity quickly grows as the number of layers increases. The formulae for a single layer with index n and depth d are given by,

$$x_o = x_i - d \frac{\frac{p_i}{n}}{\sqrt{1 - \left(\frac{p_i}{n}\right)^2}} \tag{1.18}$$

$$p_o = p_i$$

The non-paraxial formulae reduce to the paraxial case for small angles.

5. PS transformation: Phase and amplitude changes

A CMOS image sensor pixel typically includes a microlens and several metal apertures inside the dielectric stack. These components each modify the PS representation by applying a phase and amplitude change, respectively.

The microlens can be described by the ray transfer matrix rules established in the previous section. The (micro)lens matrix, when the paraxial approximation is valid, is given by

$$\begin{pmatrix} x_o \\ p_o \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 1/f & 1 \end{pmatrix} \begin{pmatrix} x_i \\ p_i \end{pmatrix}, \quad (1.19)$$

where f is the focal length of the (micro)lens. The microlens changes the direction coordinate, p , without affecting the position coordinate, x . The paraxial formulae are included to provide an intuitive discussion. In general, however, we use non-paraxial formulae,

$$\begin{aligned} x_o &= x_i \\ p_o &= p_i + \frac{\frac{x_i}{f}}{\sqrt{1 - \left(\frac{x_i}{f}\right)^2}}. \end{aligned} \quad (1.20)$$

As before, the non-paraxial formulae reduce to the paraxial case for small angles.

The apertures formed by the different metal layers, patterned into wires, truncates the PS representation as it passes the layer planes. The truncation acts as a hard mask and either accepts or rejects the ray, depending on whether its position coordinate, x , falls within the linear extent of the clear part of the aperture or not. If the ray is accepted, neither the position coordinate, x , or the direction coordinate, p , are modified. If the ray is rejected, it ceases to exist and the optical power represented by that ray is lost.

6. Optical efficiency (OE)

We now show how to calculate the OE, η_{optical} , of a CMOS image sensor pixel. The OE includes the finite numerical aperture of the imaging lens, the microlens properties, the geometrical effects of the finite apertures formed by the wires in the metal layers, and the bending of the light due to the different dielectric media in the tunnel. It is calculated using the PS approach as,

$$\eta_{\text{optical}} = \frac{G_{\text{detector}}}{G_{\text{aperture}}} \quad (1.21)$$

where G_{detector} is the etendue captured by buried photodetector and G_{aperture} the etendue available at the pixel aperture (surface).

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