Lecture Notes 10
Image Sensor Optics

- Imaging optics
  - Space-invariant model
  - Space-varying model
- Pixel optics
  - Transmission
  - Vignetting
- Microlens

Image Sensor Optics

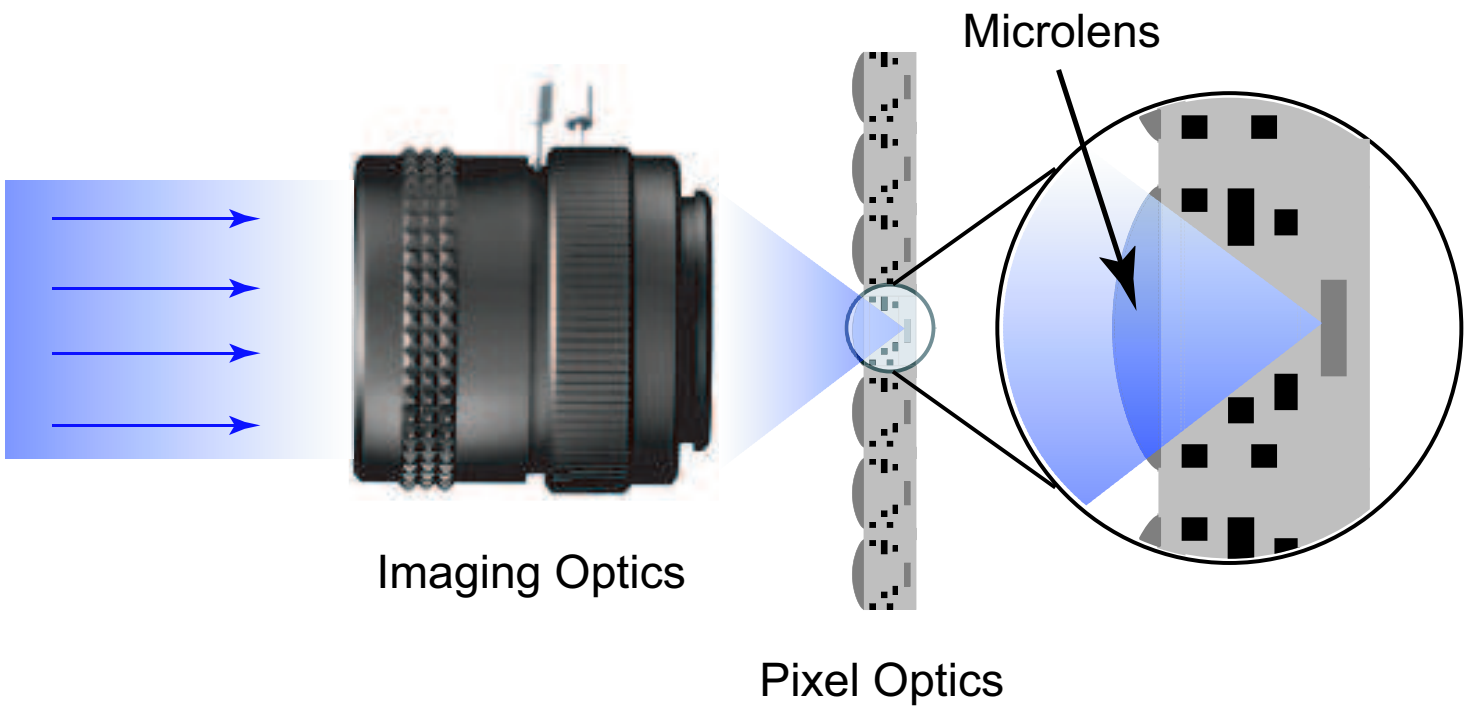
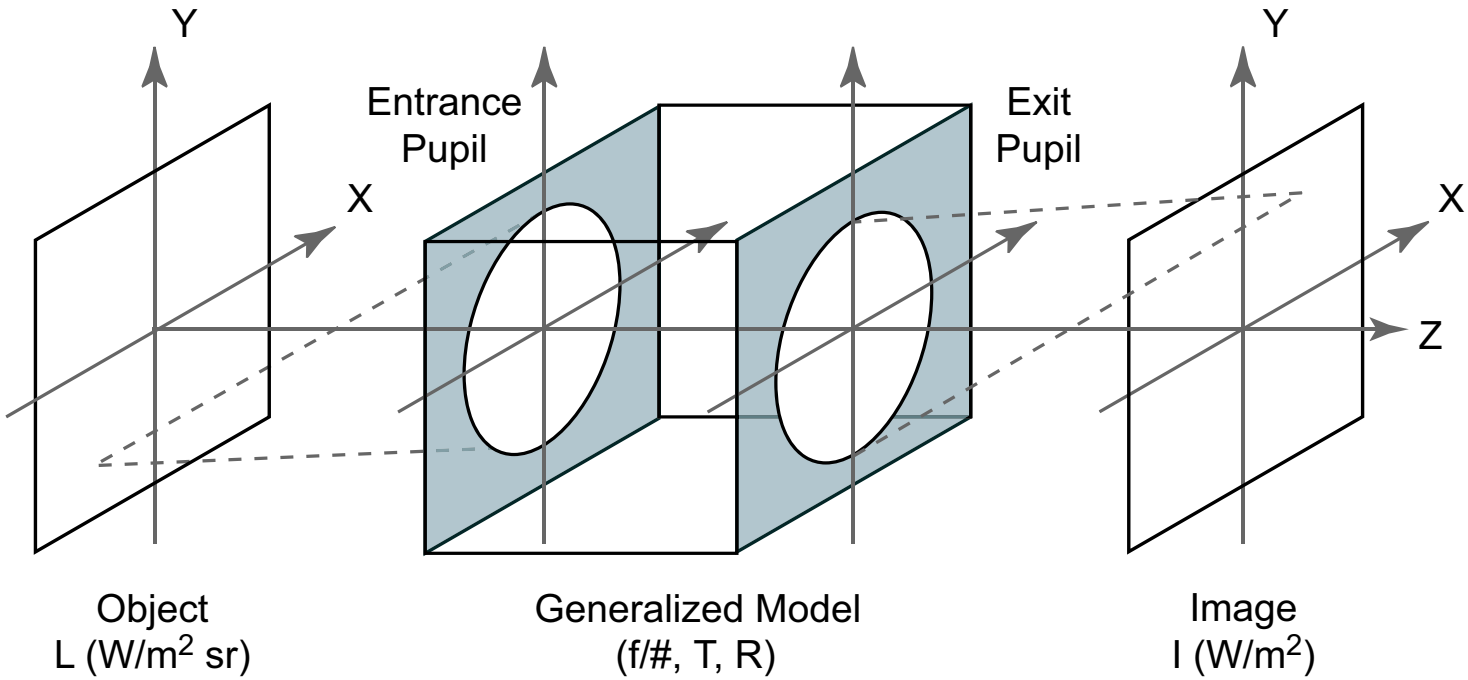


Image sensor optics consist of (a) imaging optics and (b) pixel optics

Imaging Optics: Linear Space-Invariant Model



A generalized model for rotationally symmetric imaging optics

J.W. Goodman, *Introduction to Fourier Optics*, 2nd Ed, Ch 6, pp. 126-171 (1996)

Imaging Optics: Camera Equation

$$I_{ideal}(x,y;\lambda) \cong \pi \frac{T(\lambda)R(x,y;\lambda)}{1+4(1+m)^2(f/\#)^2} L_{scene}\left(\frac{x}{m},\frac{y}{m};\lambda\right)$$

I_{ideal}: ideal, unaberrated, geometric image irradiance distribution $\left(\mathrm{W/m^2}\right)$

L_{scene}: Lambertian object radiance distribution $\left(\mathrm{W/sr\ m^2}\right)$

$m = -\left|z_i/z_o\right|$: magnification

T: transmittance

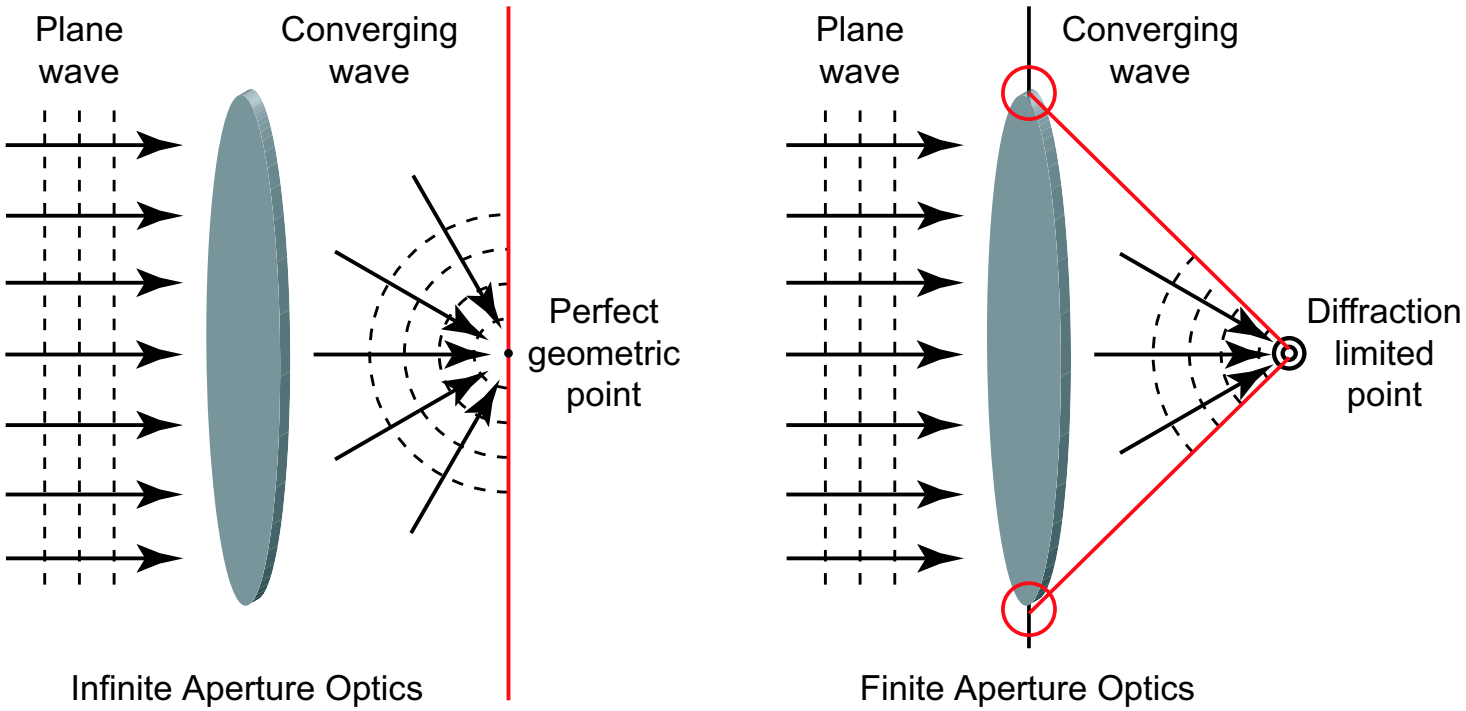
R: relative illumination factor (e.g., $\cos^4$ fall-off)

$f/\# = f/D$: f-number

Imaging optics map 2D object radiance distribution (W/sr m^2) into 2D image irradiance distribution (W/m^2)

M.V. Klein and T.E. Furtak, *Optics*, , 2nd Ed, Ch 4, pp. 193-262 (1986)

Resolution Limited by Diffraction



Diffraction, which is caused at aperture edges, is the fundamental reason why a plane wave can not be focussed into a perfect geometric point

Diffraction: Space Domain Description

Image formation process with incoherent illumination can be described in the space domain by a convolution operation

$$I_{image}(x, y; \lambda) = \mathrm{PSF}(x, y; \lambda) * I_{ideal}(x, y; \lambda)$$

I_{image}: blurred, aberrated, distorted image irradiance distribution

I_{ideal}: ideal, unaberrated, geometric image irradiance distribution

PSF: point spread function, i.e., response of optical system in image plane to a point excitation in object plane

$*$: convolution operator

Diffraction: Frequency Domain Description

Alternatively, image formation in shift-invariant systems can be viewed as a linear filtering process in the frequency domain

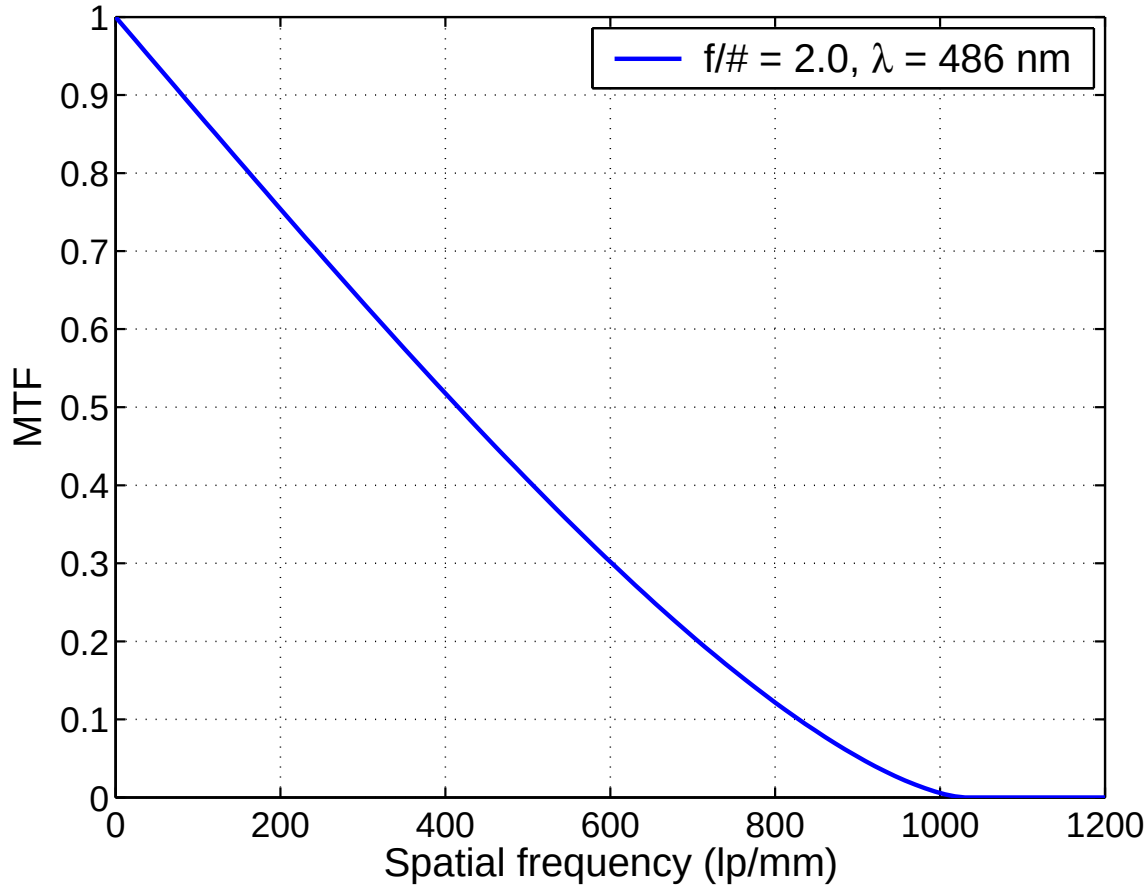
$$\begin{aligned}\mathsf{F}\left\{I_{image}(x,y;\lambda)\right\} &= \mathsf{F}\left\{\mathrm{PSF}(x,y;\lambda)\right\}\cdot\mathsf{F}\left\{I_{ideal}(x,y;\lambda)\right\}\\ &= \mathrm{OTF}\left(f_x,f_y;\lambda\right)\cdot\mathsf{F}\left\{I_{ideal}(x,y;\lambda)\right\}\end{aligned}$$

$$I_{image}(x,y;\lambda) = \mathsf{F}^{-1}\left\{\mathrm{OTF}\left(f_x,f_y;\lambda\right)\cdot\mathsf{F}\left\{I_{ideal}(x,y;\lambda)\right\}\right\}$$

The optical transfer function (OTF) is normalized to preserve radiometry. Its magnitude is the modulation transfer function (MTF)

$$\mathrm{MTF}\left(f_x,f_y;\lambda\right) = \left|\mathrm{OTF}\left(f_x,f_y;\lambda\right)\right| = \left|\frac{\mathsf{F}\left\{\mathrm{PSF}(x,y;\lambda)\right\}}{\mathsf{F}\left\{\mathrm{PSF}(x,y;\lambda)\right\}\Big|_{f_x=0,\,f_y=0}}\right|$$

Example: Diffraction-limited Lens



$\text{MTF}(f_r) = \frac{2}{\pi}(\varphi - \cos\varphi \sin\varphi)$ with $\varphi = \cos^{-1}(f_r \lambda f/\#)$ and $f_{r,cutoff} = \frac{1}{\lambda f/\#}$

System MTF

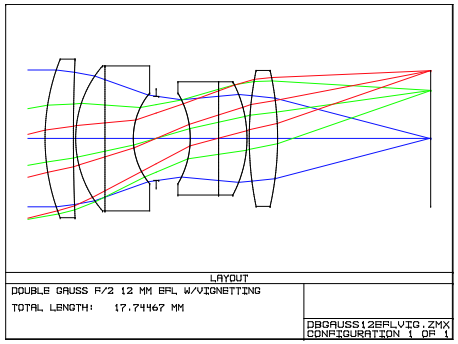
If the system is linear and space-invariant, the system MTF (optics + sensor) in the frequency domain can then be easily computed

$$\mathrm{MTF}_{system}\left(f_x, f_y; \lambda\right) = \mathrm{MTF}_{optics}\left(f_x, f_y; \lambda\right) \cdot \mathrm{MTF}_{geometric}\left(f_x, f_y\right) \cdot \mathrm{MTF}_{diffusion}\left(f_x, f_y; \lambda\right)$$

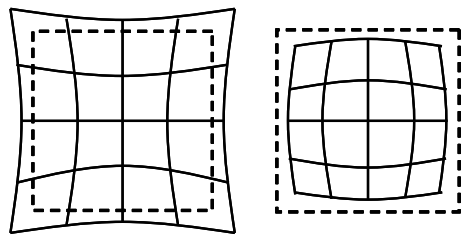
To obtain the image spectrum we apply the MTF as a linear filter

$$I_{image}\left(f_x, f_y; \lambda\right) = \mathrm{MTF}_{system}\left(f_x, f_y; \lambda\right) \cdot I_{object}\left(f_x, f_y; \lambda\right)$$

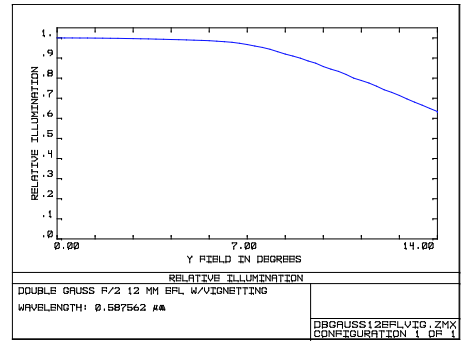
Modeling Real Imaging Lenses



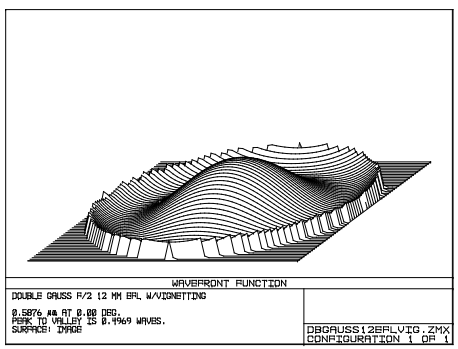
Vignetting



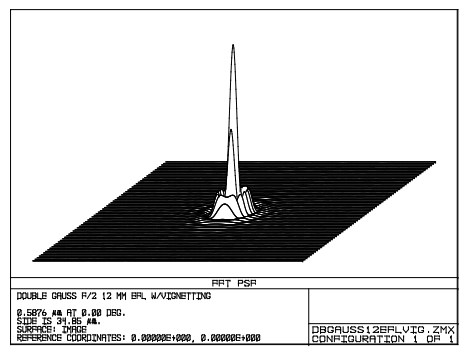
Distortion



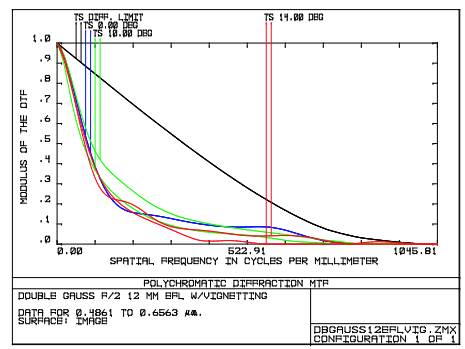
Illumination Effects



Wavefront Aberrations



Point Spread Function (PSF)



Modulation Transfer Function (MTF)

P. Y. Maeda, P. B. Catrysse, and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, pp. 48-58 (2005)

Imaging Optics: Linear Space-Varying Model

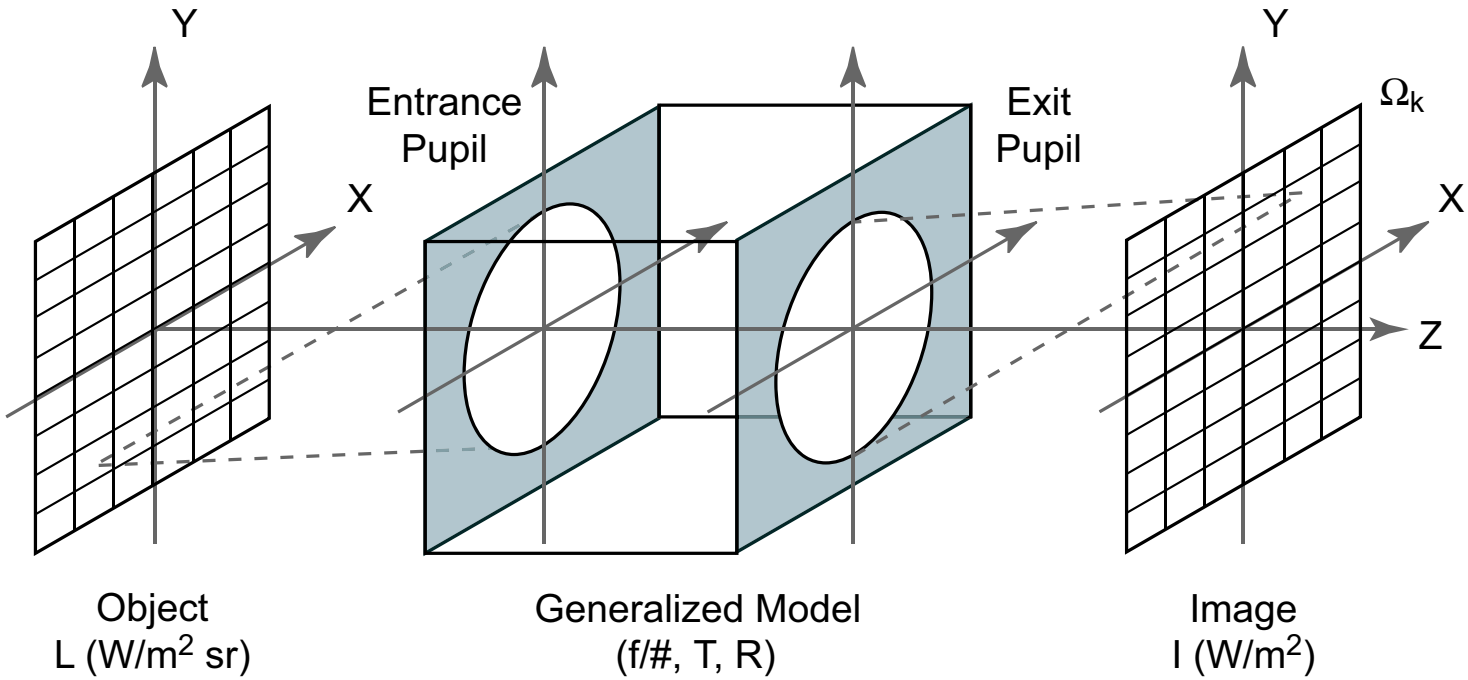


Image plane is segmented into isoplanatic regions: Ω_1, Ω_2, ..., Ω_n

P. Y. Maeda, P. B. Catrysse, and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, pp. 48-58 (2005)

Linear Space-Varying Image Formation

Let Ω_k, $k = 1, \ldots, n$ be aplanatic image segments, then

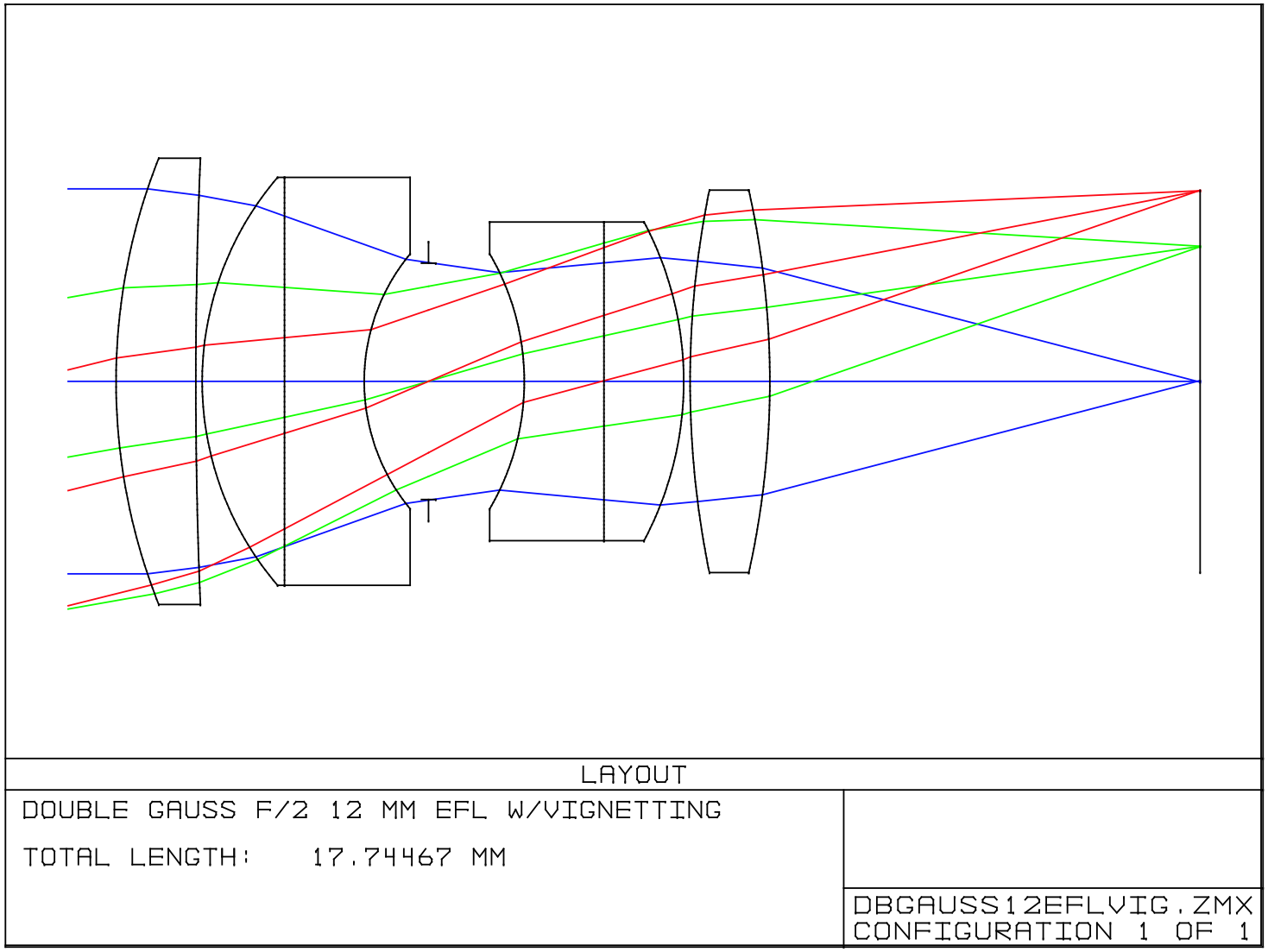
$$I_{image}(x, y; \lambda) = \sum_k \mathrm{PSF}_{\Omega_k}(x, y; \lambda) * I_{ideal,\Omega_k}(x, y; \lambda)$$

or

$$I_{image}(x, y; \lambda) = \mathsf{F}^{-1}\left\{\sum_k \mathrm{OTF}_{\Omega_k}(f_x, f_y; \lambda) \cdot \mathsf{F}\left\{I_{ideal,\Omega_k}(x, y; \lambda)\right\}\right\}$$

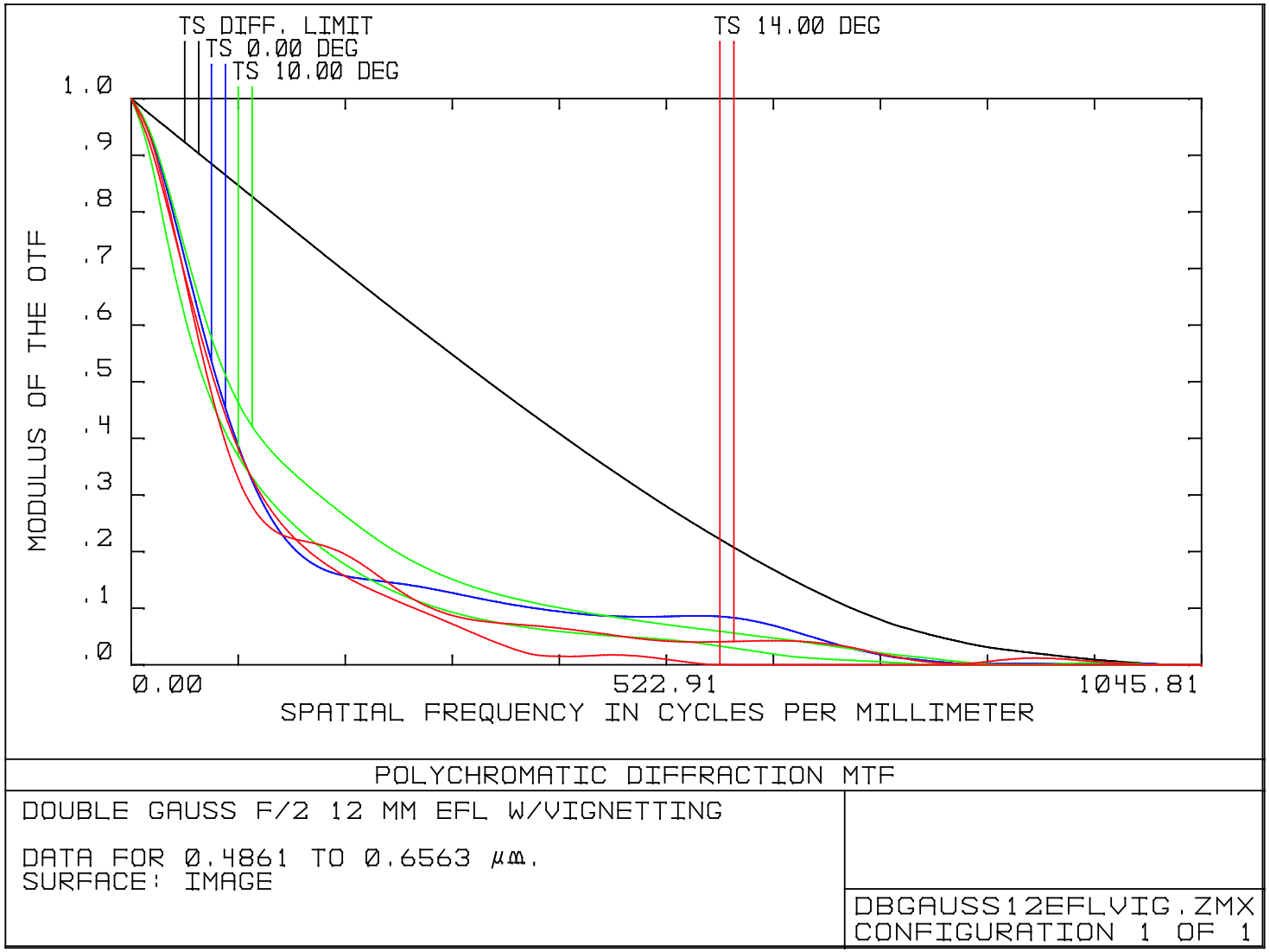
P. Y. Maeda, P. B. Catrysse, and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, pp. 48-58 (2005)

Example: Double Gauss f/2.0 Lens



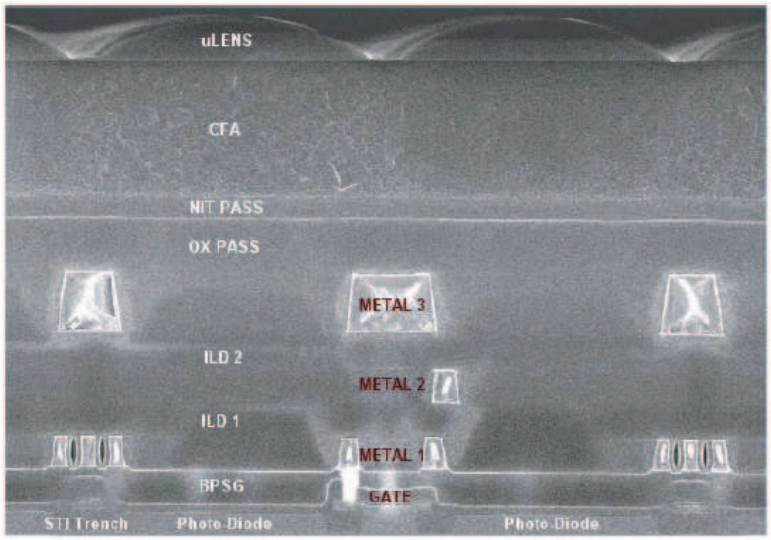
P. Y. Maeda, P. B. Catrysse, and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, p. 48-58 (2005)

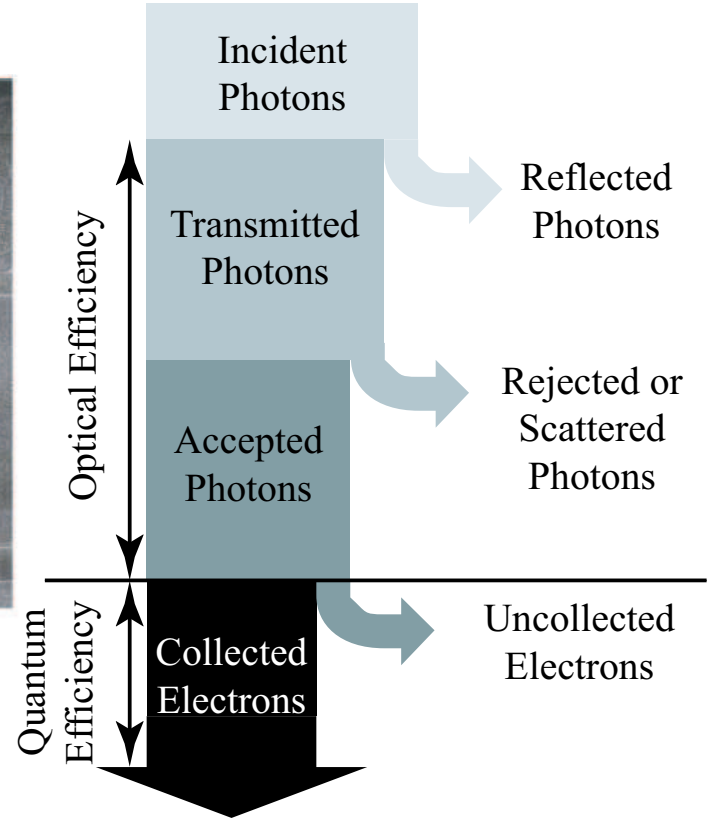
Double Gauss f/2.0 Lens: MTF



P. Y. Maeda, P. B. Catrysse, and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, p. 48-58 (2005)

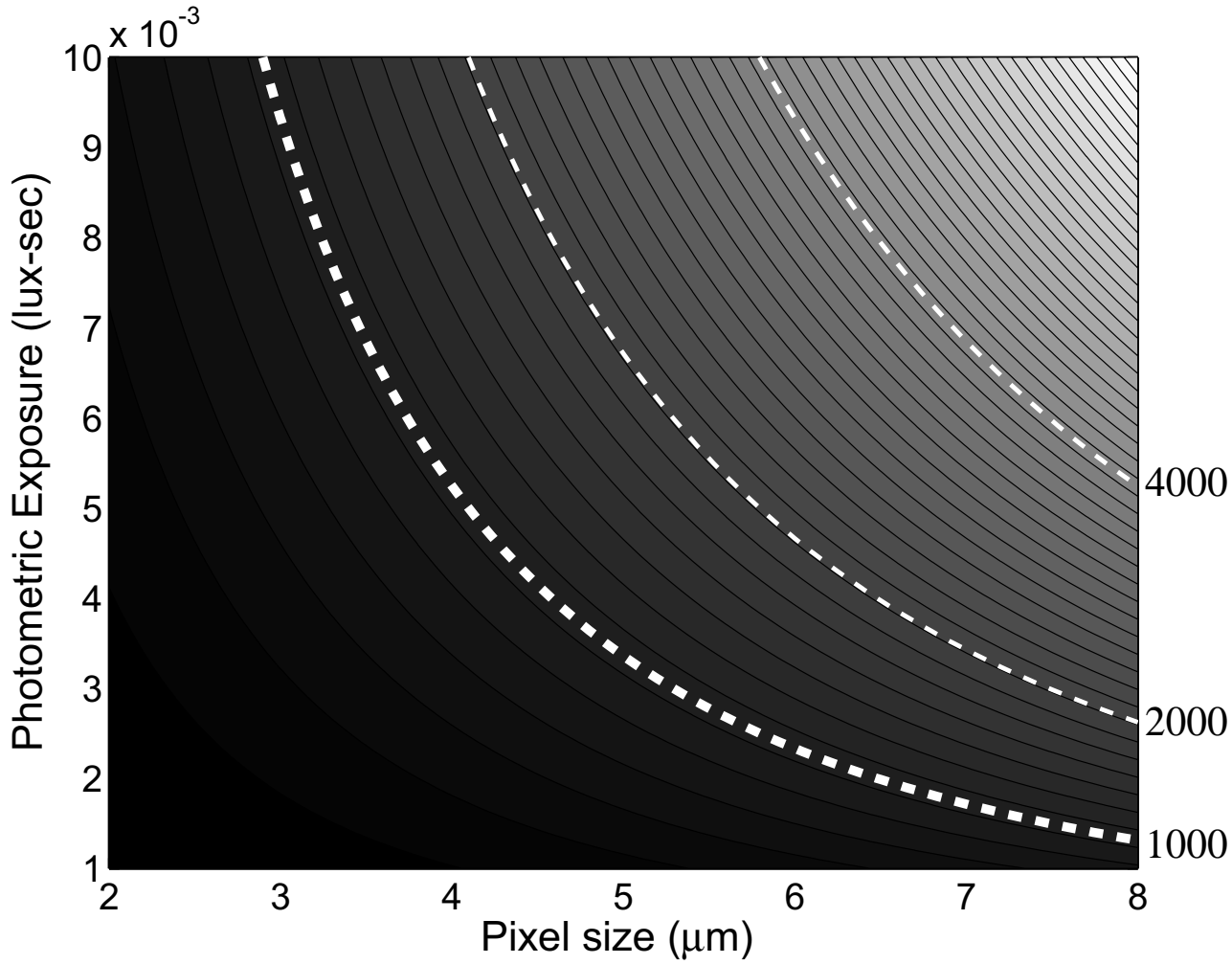
Pixel Optics





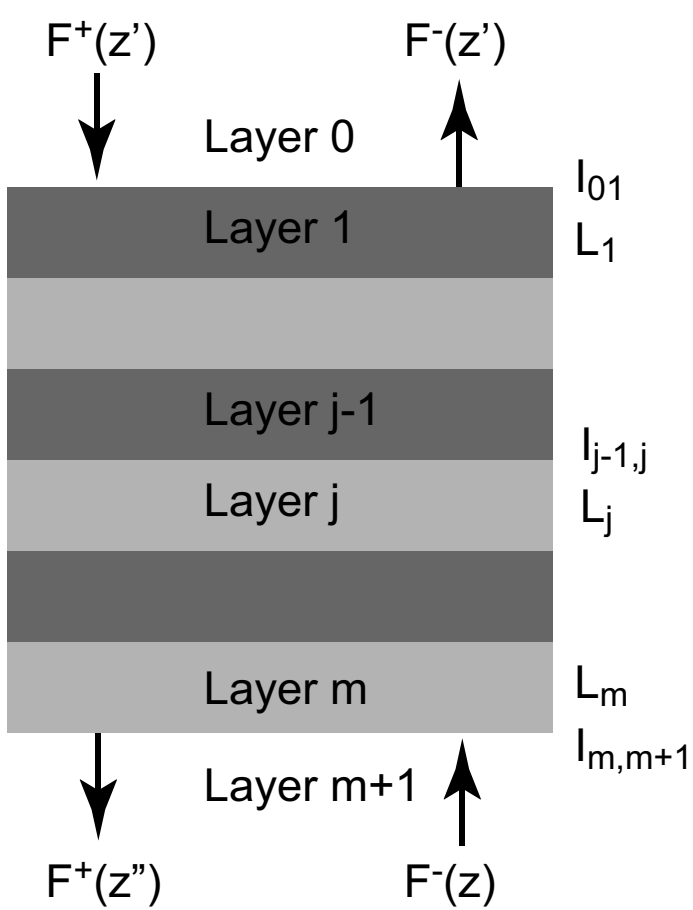
P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A **19**, pp. 1610-1620 (2002)
H. Rhodes et al., IEEE Workshop on Microelectronics and Electron Devices, pp. 7-18 (2004)

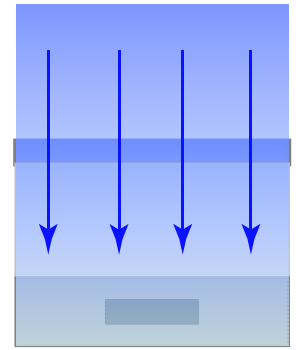
Incident Photons



P. B. Catrysse and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, pp. 1-13 (2005)

Pixel Transmittance



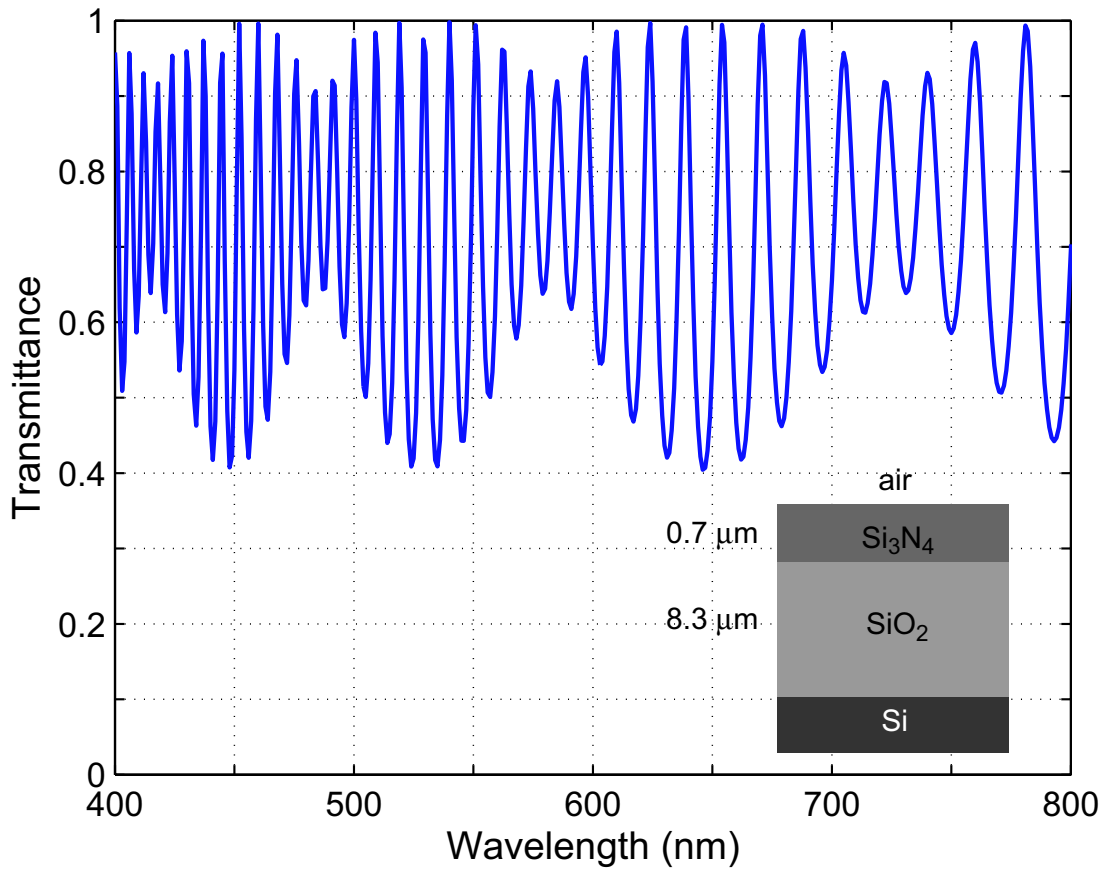


Transmission

F. Abeles, Ann. de Phys. **5**, pp. 596-640 (1950)

P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A **19**, pp. 1610-1620 (2002)

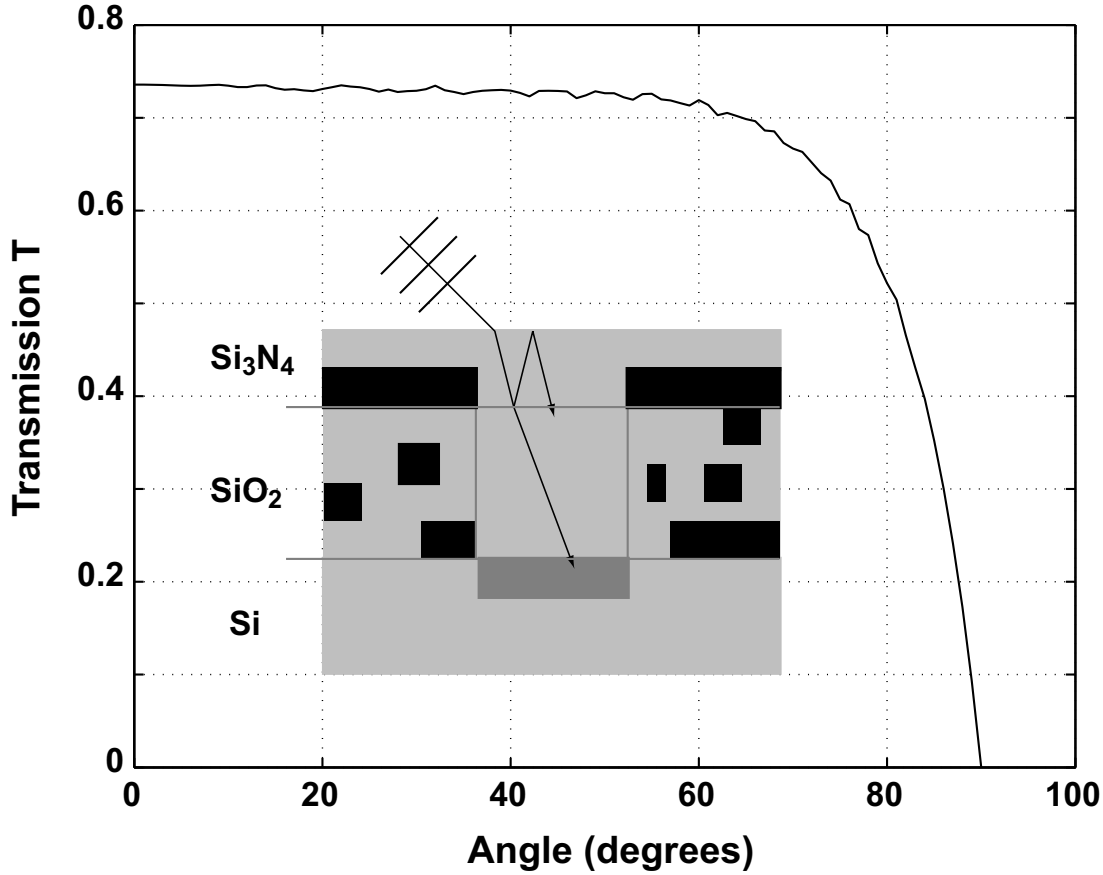
Example: Transmittance 0.18μm CMOS



Pixel transmittance is λ-dependent (even for dispersion-free materials)

P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A **19**, pp. 1610-1620 (2002)

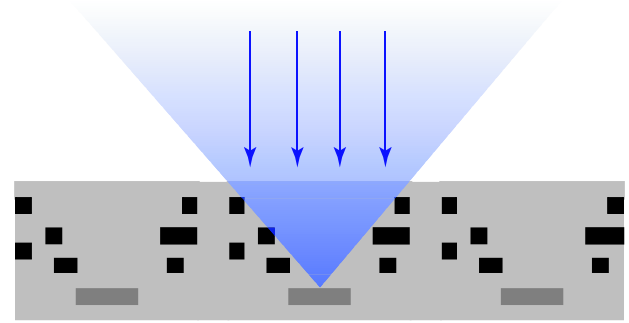
Example: Transmittance 0.18μm CMOS



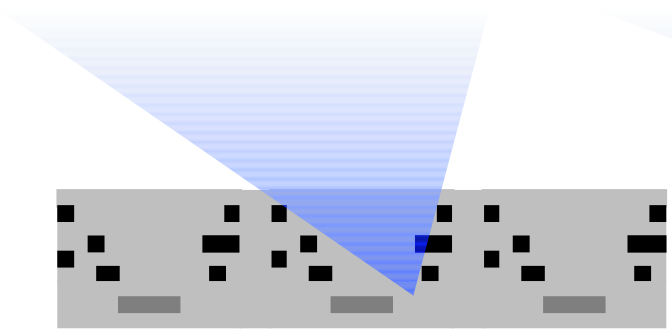
Pixel transmittance (λ-averaged) is approximately independent of angle

P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A **19**, pp. 1610-1620 (2002)

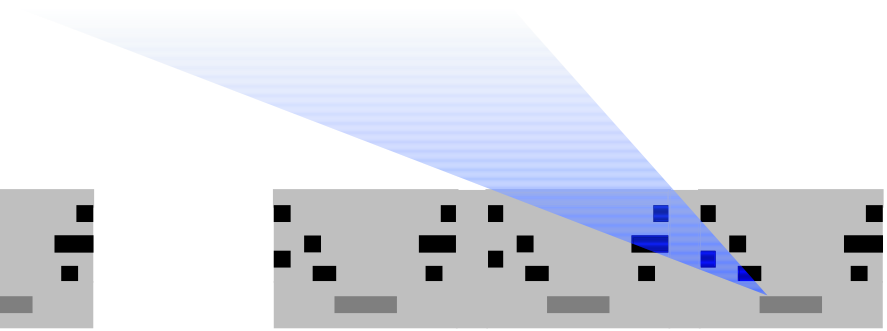
Pixel Vignetting



No Vignetting



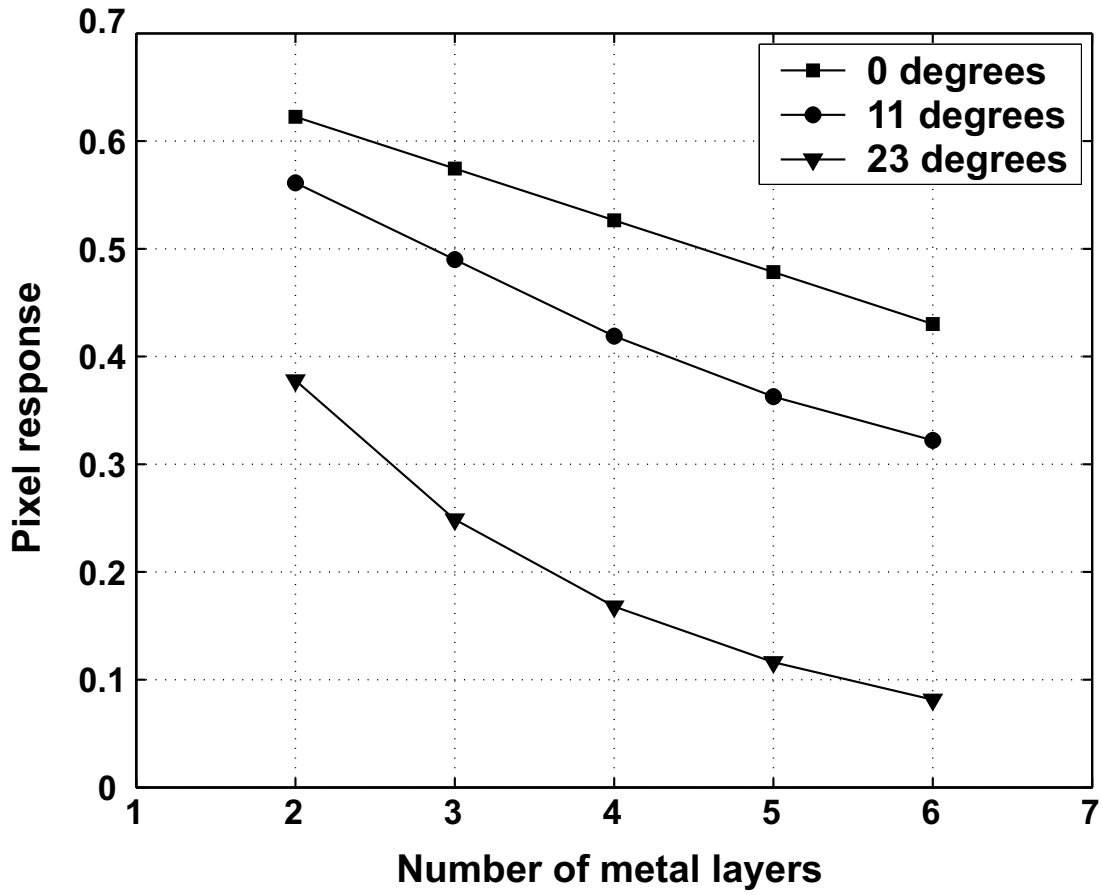
Pixel Vignetting



Pixel Cross-talk

P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A **19**, pp. 1610-1620 (2002)

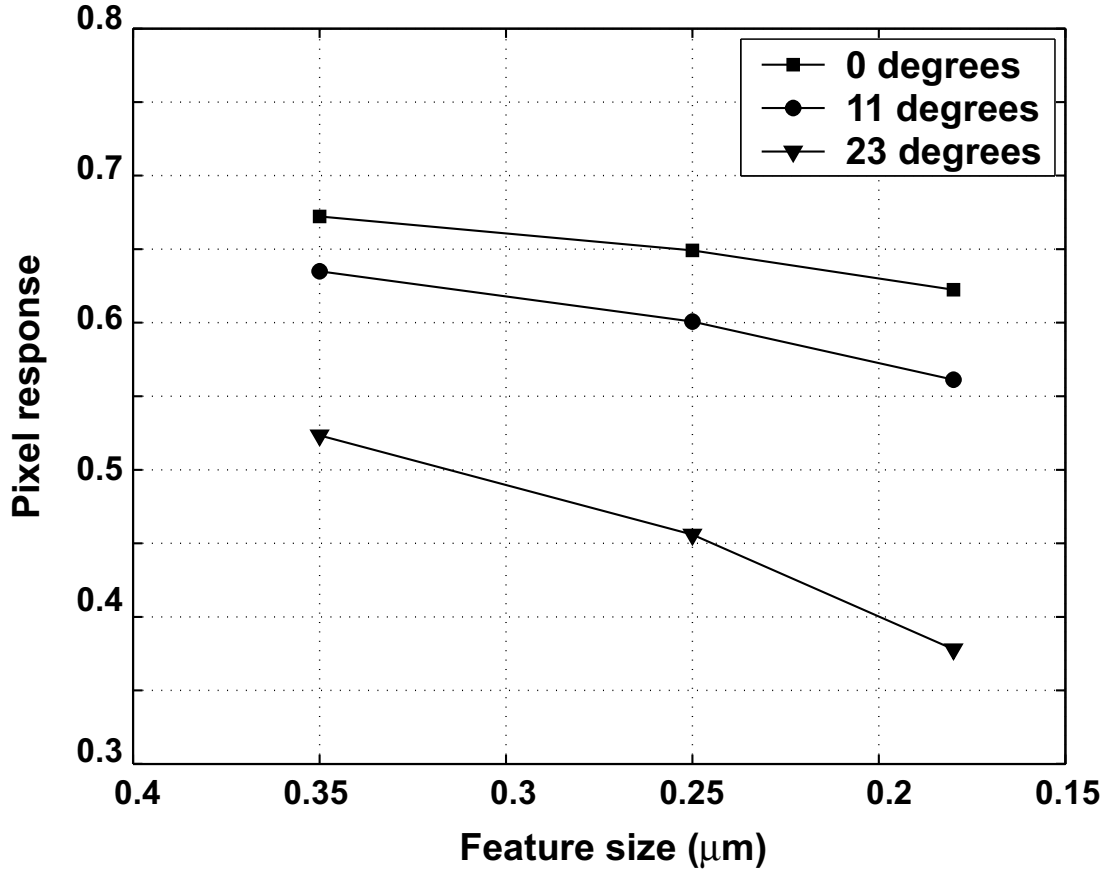
Pixel Vignetting: Effect of Pixel Height



Reduction in optical efficiency as a function of the number of metal layers in a 0.18μm standard CMOS process (f/1.8 imaging lens)

P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A **19**, pp. 1610-1620 (2002)

Pixel Vignetting: Effect of Technology Scaling



Reduction in optical efficiency for a standard APS pixel with a 30% fill-factor using 2 metal layers as a function of the feature size of CMOS technology

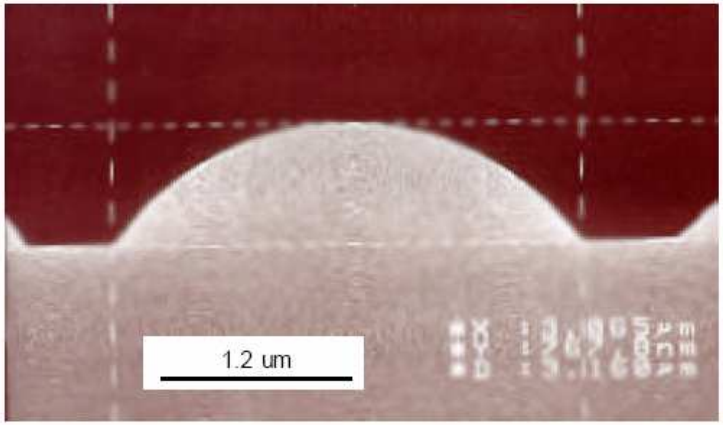
P. B. Catrysse and B. A. Wandell, J. Opt. Soc. Am. A **19**, pp. 1610-1620 (2002)

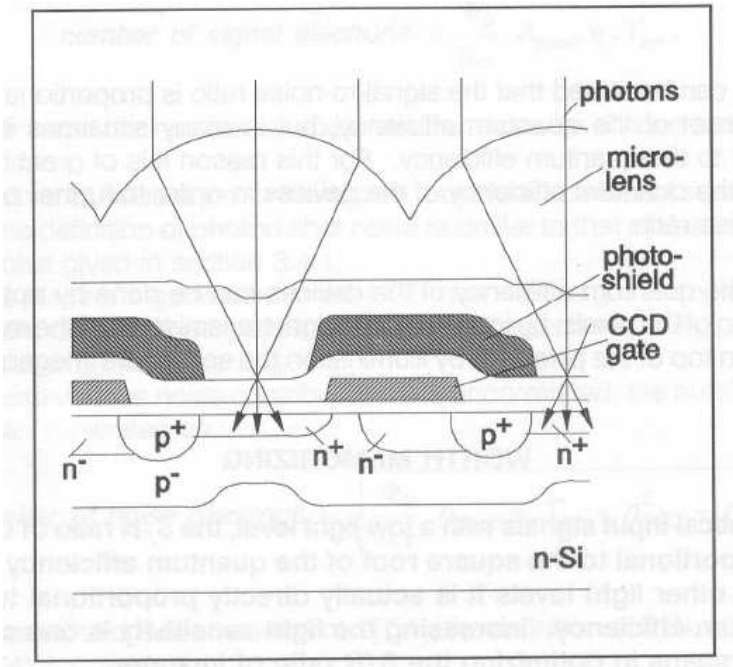
Optical Efficiency

- Definition:
  - Optical efficiency (OE) is the ratio of the photons incident of the substrate and the photons incident on the pixel surface
- Sources of photon loss:
  - Back-reflections in dielectric stack (air-SiO_2, SiO_2-Si)
  - Photons absorbed in dielectric stack (SiON)
    $\Rightarrow$ Pixel transmittance $T(\lambda,\theta)$
  - Photons scattered away from pixel (pixel cross-talk)
  - Photons rejected by metal
    $\Rightarrow$ Pixel vignetting $V(x,y,\theta)$
- Description:
  - $OE(x,y,\lambda,\theta) = T(\lambda,\theta)\ V(x,y,\theta)$

Microlens

- Focus light onto photo-sensitive region – increases effective fill factor from 25-40% to 60-80% (and sensitivity by $\geq$ 2X)
- Less effective if photosensitive area is irregularly shaped

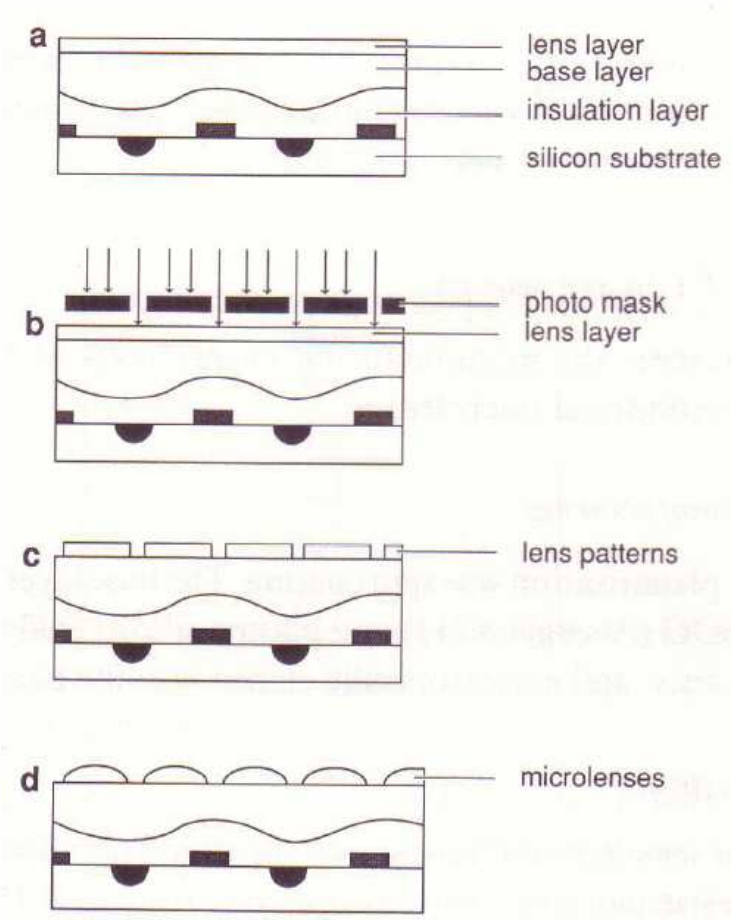




A. Theuwissen, "Solid State Imaging with Charge-Coupled Devices," Kluwer (1995) S.G. Wuu et al., "High performance 0.25 μm CMOS color imager technology with non-silicide source/drain pixel," IEDM Tech. Dig., pp. 705-708 (2000)

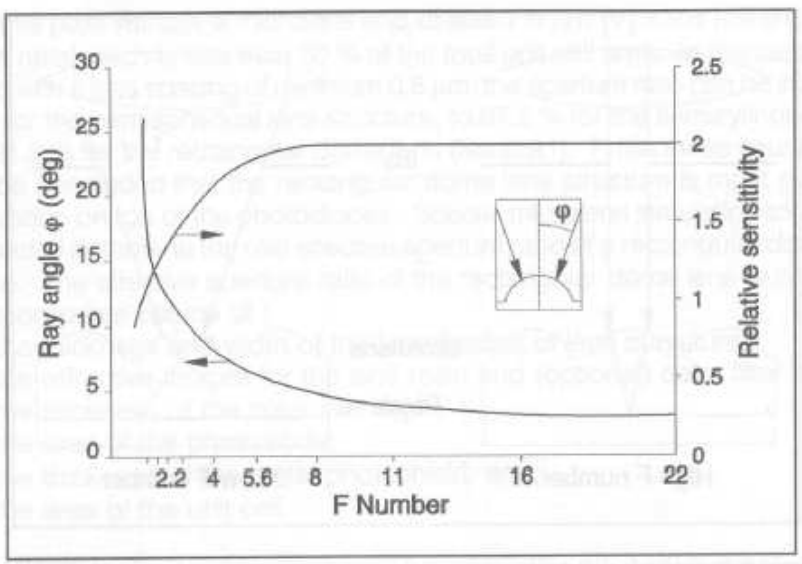
Microlens Fabrication

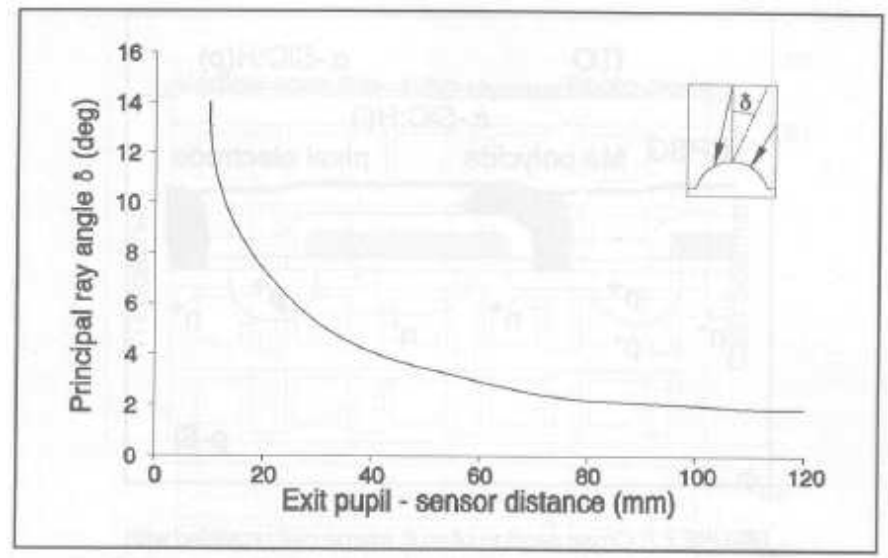
- Lens material requirements:
  - Highly transparent in the visible light region
  - Index of refraction > 1.59
  - Can be applied below 500C
  - No degradation or aging
  - Semiconductor processing compatible
  - Can be patterned with feature size commensurate with the pixel size
- Lens materials are typically i-line or DUV resists
- Base materials are acrylic-based resists, polyimide resists, epoxy resists, polyorganosiloxane, polyorganosilicate



Microlens and the Main Lens

- Microlens is optimized for a specific main lens system
- Rays incident on the microlens form a cone with NA $= \sin\varphi$
- NA varies as a function of the size and position of the exit pupil
- Principle ray at the periphery of the sensor has an angle δ, chief ray angle (CRA), between the ray and the optical axis (δ depends on the position of the pixel on the sensor)

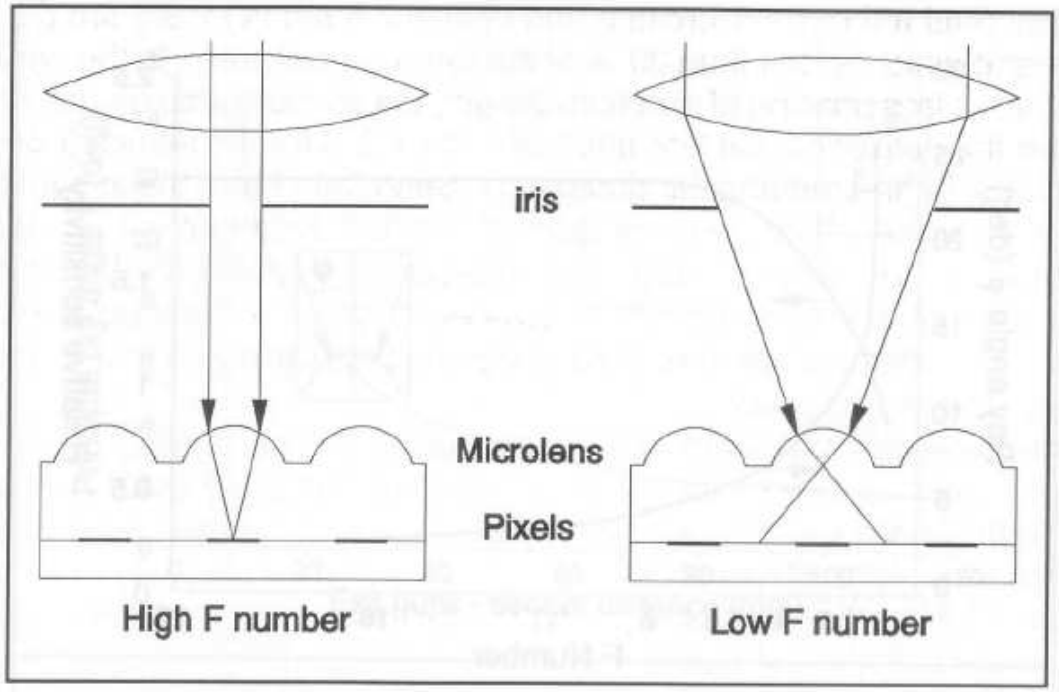




A. Theuwissen, "Solid State Imaging with Charge-Coupled Devices," Kluwer (1995)

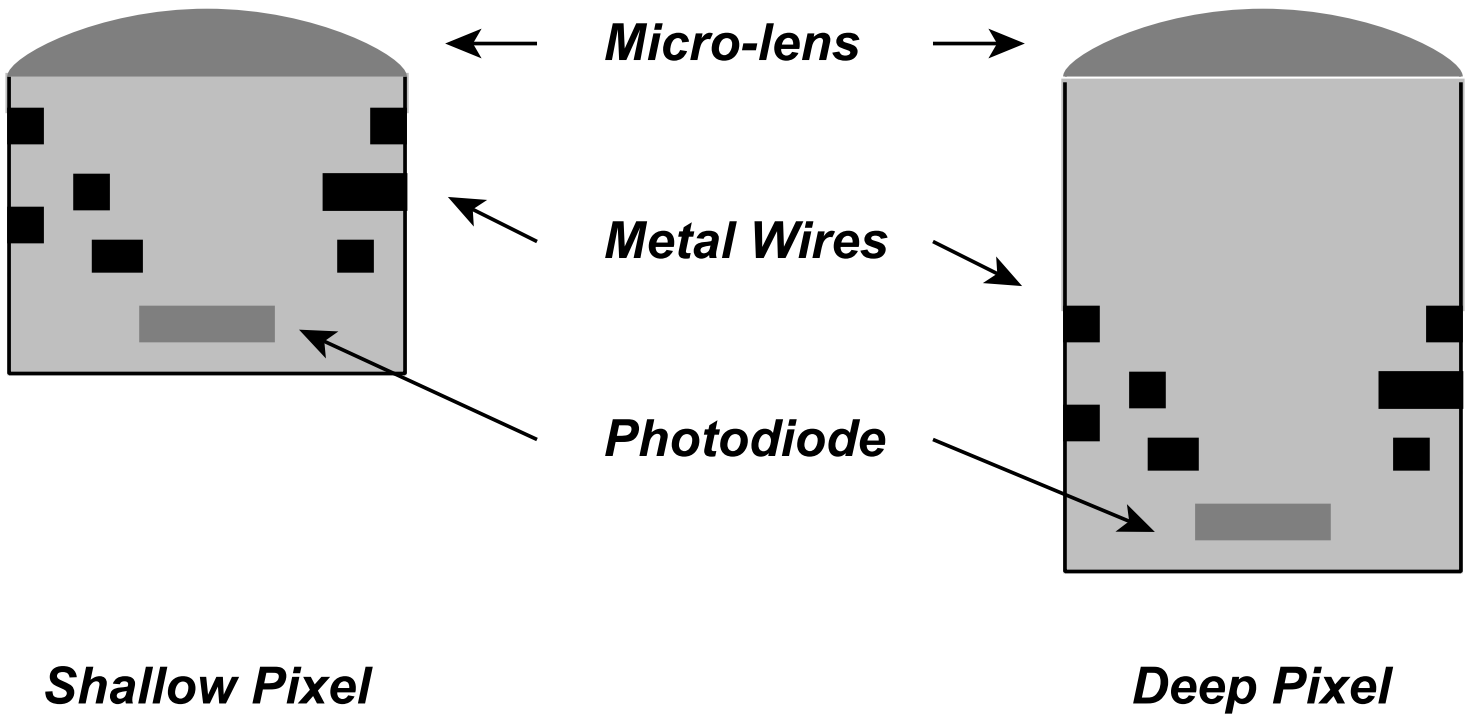
Microlens and F-Number

- High F-number: rays are parallel (NA ≈ 0)
- Low F-number: rays arrive at an angle (NA large) – microlens effectiveness low

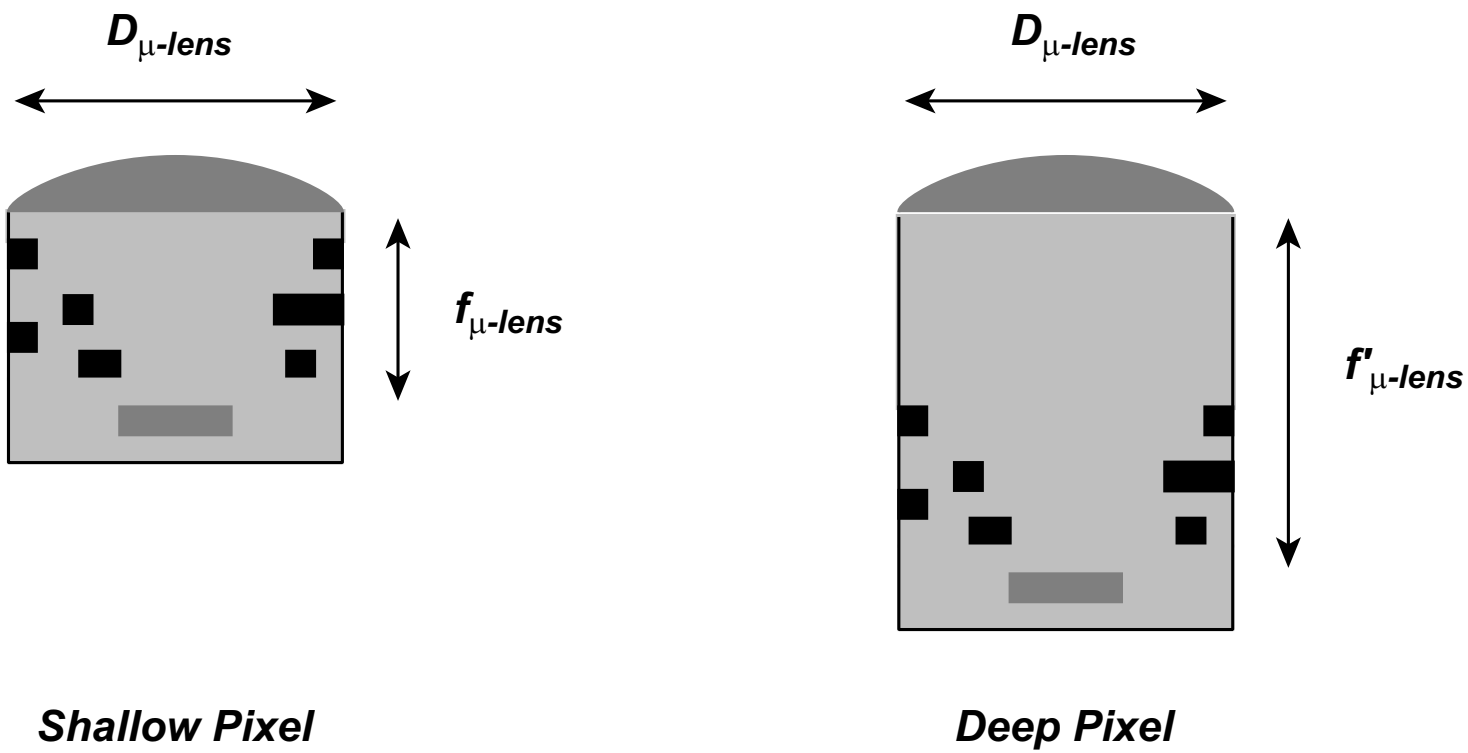


A. Theuwissen, "Solid State Imaging with Charge-Coupled Devices," Kluwer (1995)

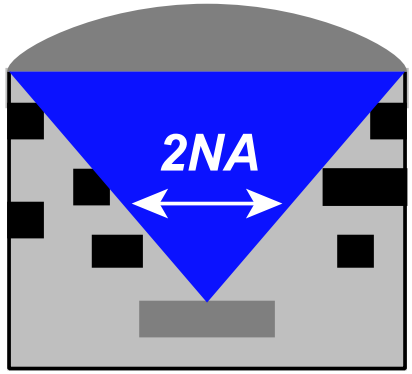
Micro lens: How to concentrate photons

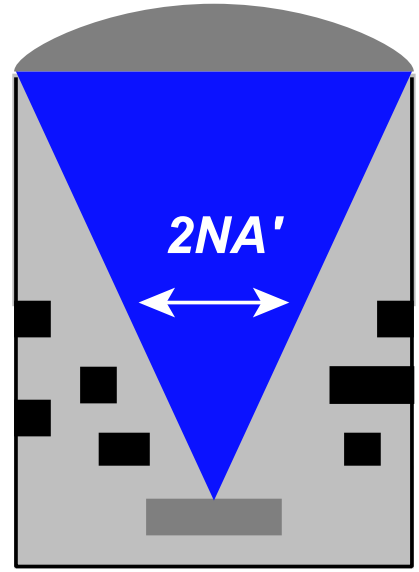


Micro lens: How to concentrate photons



Micro lens: How to concentrate photons





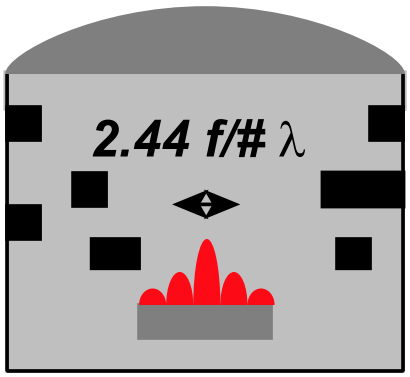
Shallow Pixel

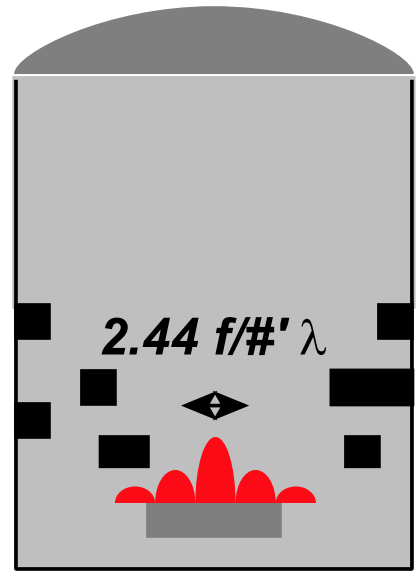
Deep Pixel

$$NA = \sqrt{\frac{1}{1+4(f/\#)^2}}$$

$$NA' = \sqrt{\frac{1}{1+4(f/\#')^2}}$$

Micro lens: How to concentrate photons





Shallow Pixel

Deep Pixel

$$f/\# = \frac{f_{\mu Lens}}{D_{\mu Lens}}$$

$$f/\#' = \frac{f'_{\mu Lens}}{D_{\mu Lens}}$$

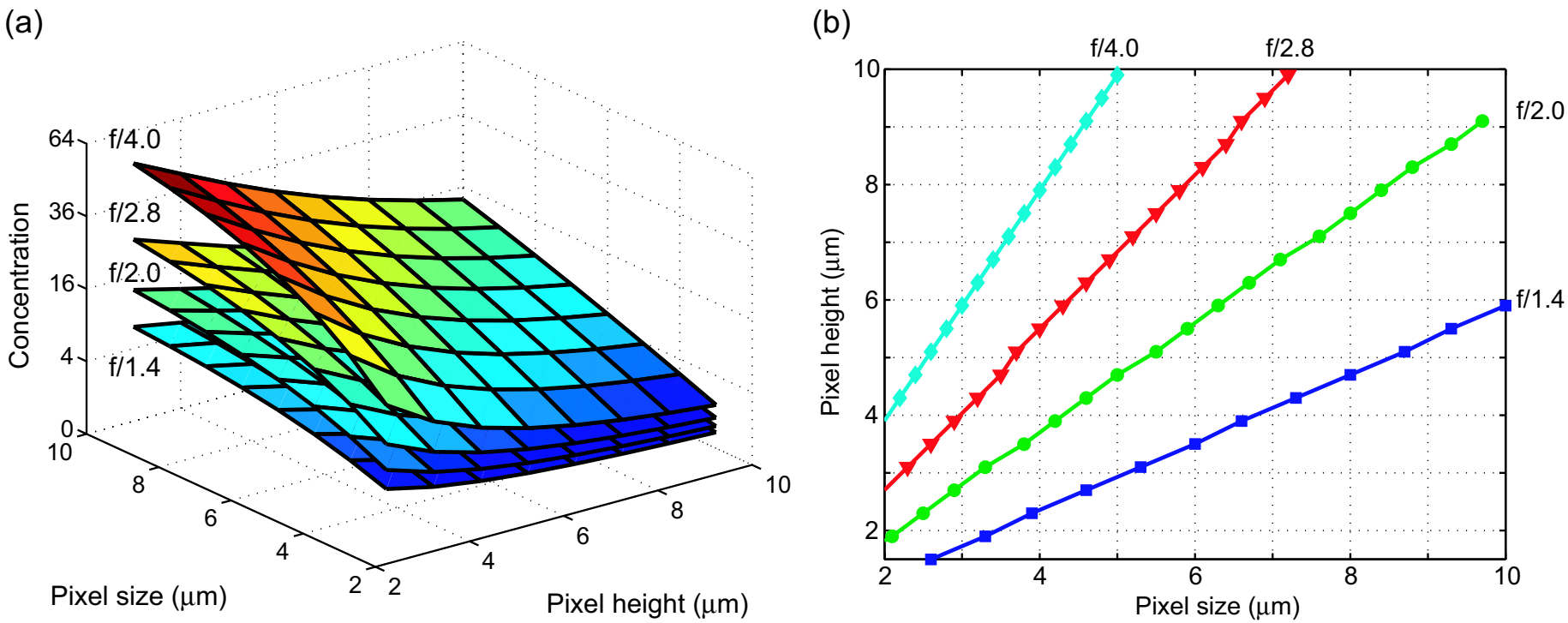
Micro lens: How to concentrate photons

- Conservation of etendue
  $\Rightarrow G = 2NA_{imaging} w_{pixel} = 2NA_{\mu lens} w_{diode}$

- Etendue limits light collection efficiency (NA)
  $\Rightarrow$ Bigger NA allows bigger etendue
- Concentration depends on ratio of NA of microlens and imaging lens
  $\Rightarrow$ For a 2x space concentration ($w_{diode} = w_{pixel}/2$)
  $\Rightarrow 2NA_{\mu lens} > NA_{imaging}$

- Diffraction limits spot size (f-number)
  $\Rightarrow$ Smaller f-number allows smaller spot size

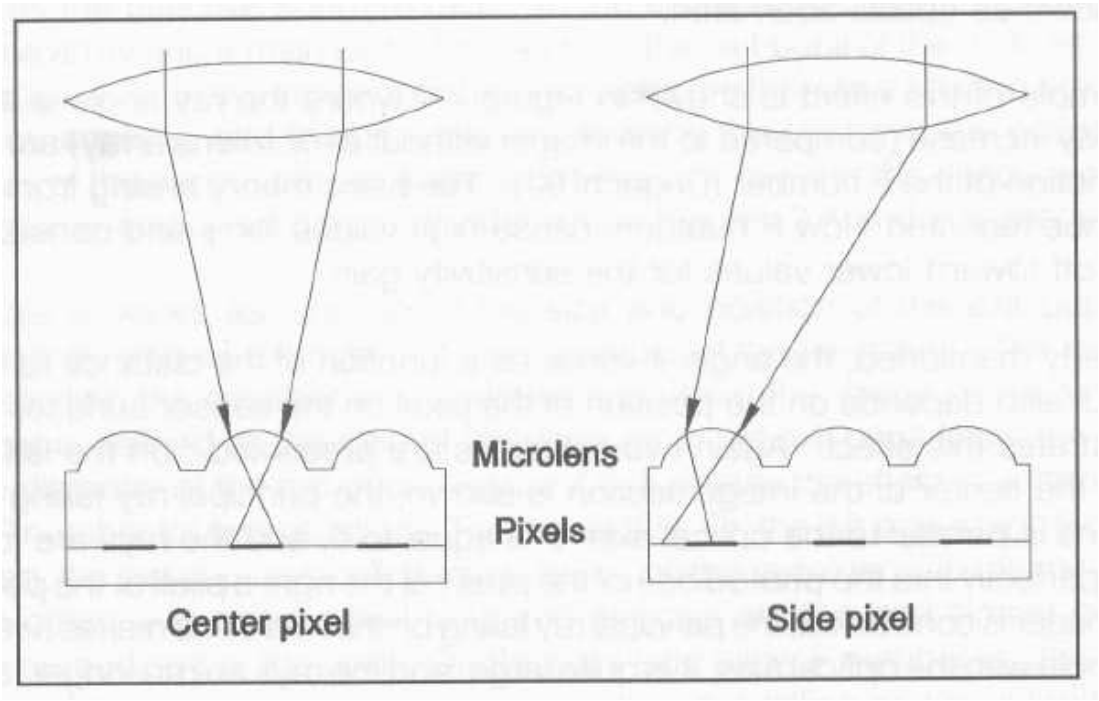
Micro lens: Concentration



P. B. Catrysse and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, p. 1-13 (2005)

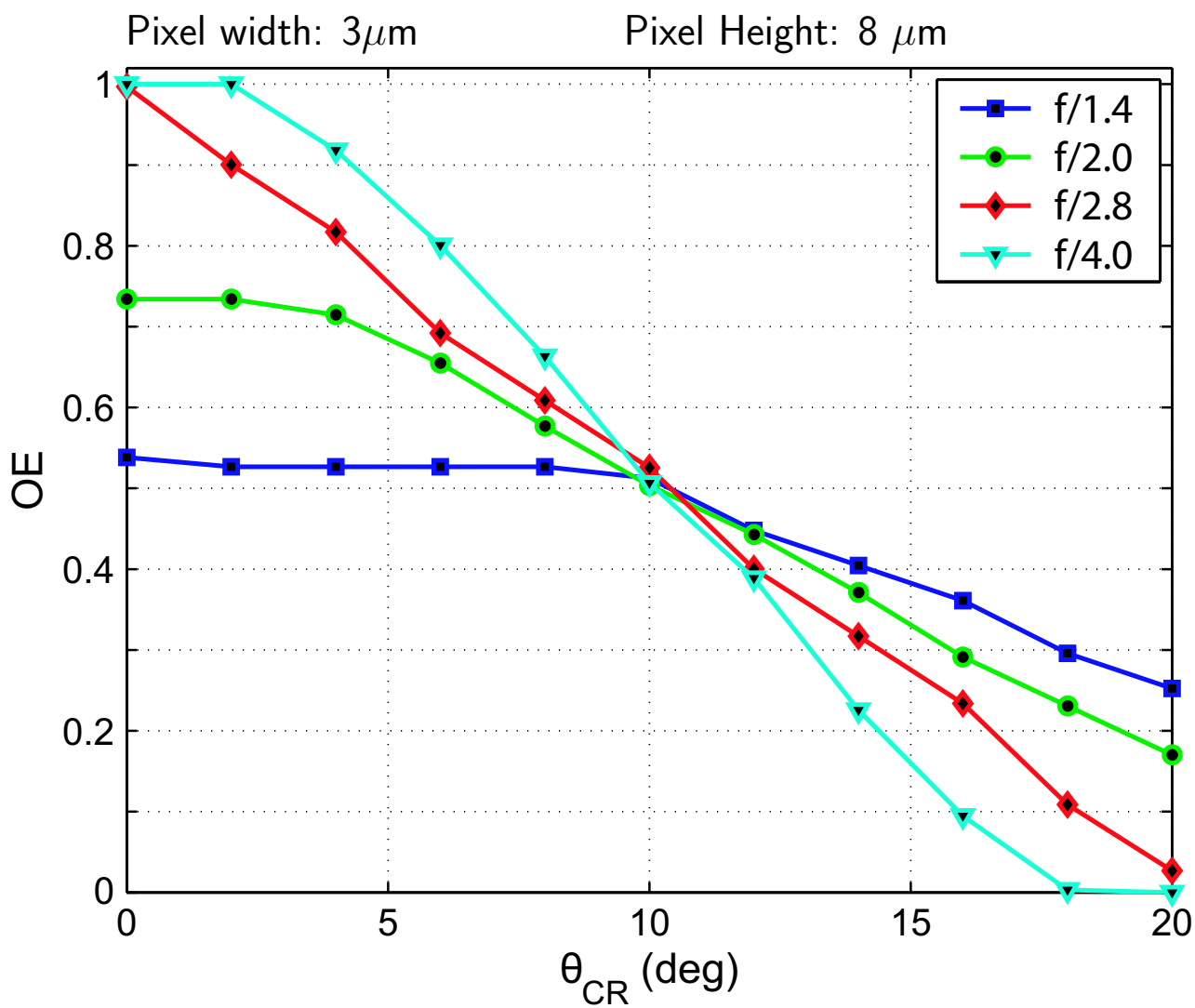
Pixel Position

- For large CRA (pixel away from the center of the lens, or exit pupil close to the sensor), ray may not focus on the photo-sensitive region
- Effect: non-uniform sensitivity profile across image sensor



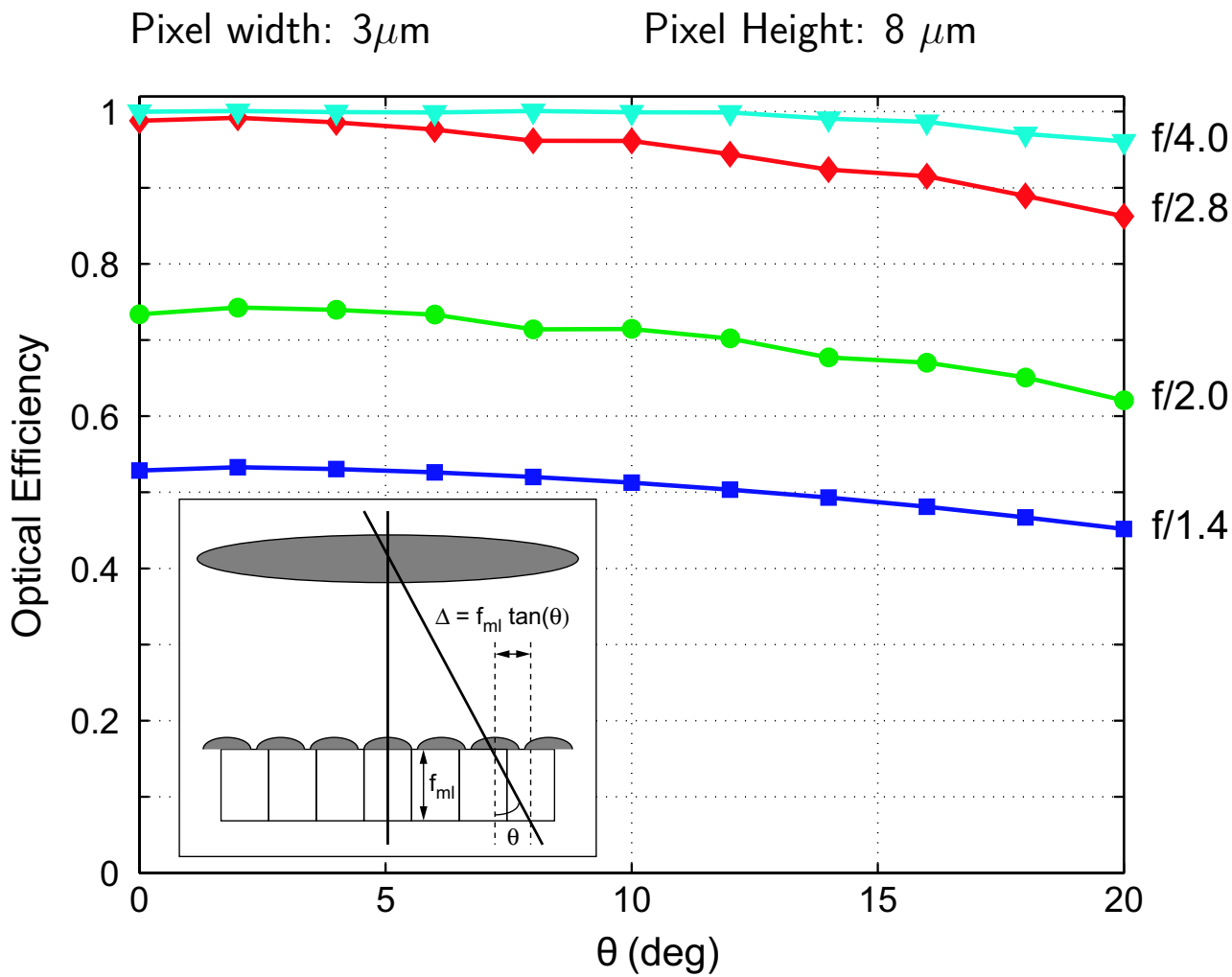
A. Theuwissen, "Solid State Imaging with Charge-Coupled Devices," Kluwer (1995)

Micro lens: Redirection (w/o offset)



P. B. Catrysse and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, p. 1-13 (2005)

Micro lens: Redirection (with offset)



P. B. Catrysse and B. A. Wandell, Proc. SPIE Int. Soc. Opt. Eng. **5678**, p. 1-13 (2005)

Optical Efficiency: Summary

- Without microlens:
  - $\mathrm{OE}(x,y,\lambda,\theta) = \mathrm{T}(\lambda,\theta)\ \mathrm{V}(x,y,\theta)$
- With microlens:
  - $\mathrm{OE}(x,y,\lambda,\theta) = \mathrm{T}(\lambda,\theta)\ \mathrm{V}(x,y,\theta)\ \mathrm{ML}(x,y,\theta)$
    - where $\mathrm{ML}(x,y,\theta)$ represents a correction factor to account for the concentration and/or redirection performed by the microlens

Improving OE

- Optimizing dielectric stack thickness
- Make sure dielectrics are not light absorbing
- Utilize different dielectric materials to achieve total internal reflection
- Add an airgap between pixels (total internal reflection)