Microscope design 1.7
SC865

Concepts for maximum image contrast

§ 1 Paraxial Optics

Perfect lens elements

for

Optical specifications

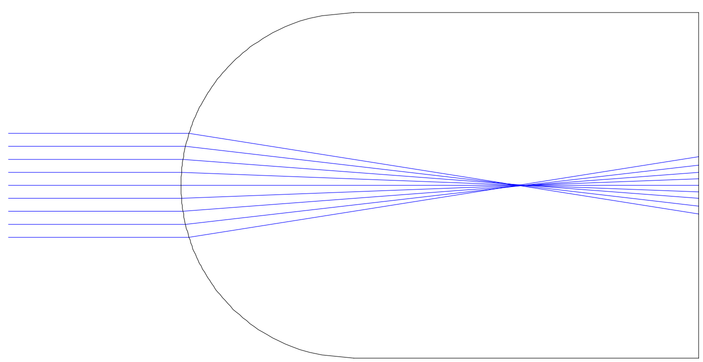
Focal length and effective focal length

$$f_n = nf$$

$$\sin\theta_n = \frac{\sin\theta}{n}$$

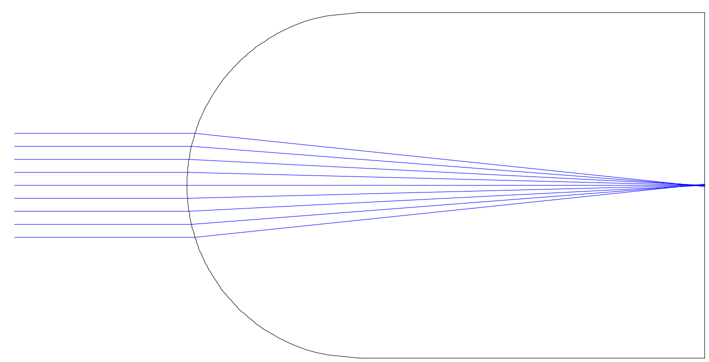
- Effective focal length EFL=f
  - Constant throughout all media
- Focal length FL=f_n
  - Scales with refractive index
- Due to Snell's Law

power of 0.1mm^{-1} within n=1.0



EFL=BFL=10

power of 0.1mm^{-1} within n=1.5



EFL=10 while BFL=15mm

Image height

$$h_I = \theta_0 f_0$$
$$h_I = \theta_n f_n$$

- Constant with EFL
- Decedent upon
  - Object height
  - EFL

power of 0.1mm^{-1} within n=1.0

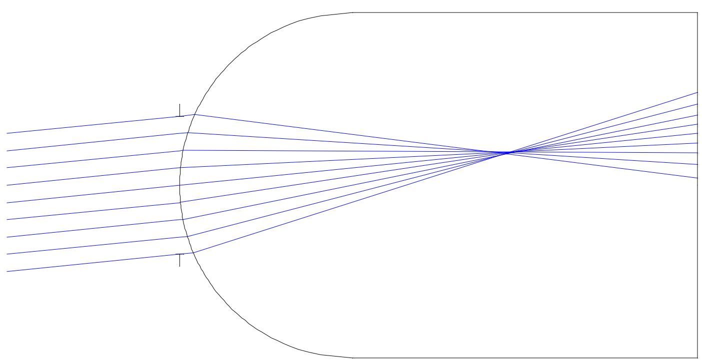


Image height = 1.0

power of 0.1mm^{-1} within n=1.5

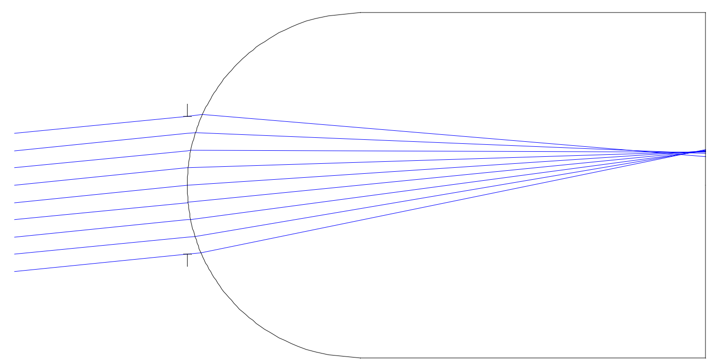
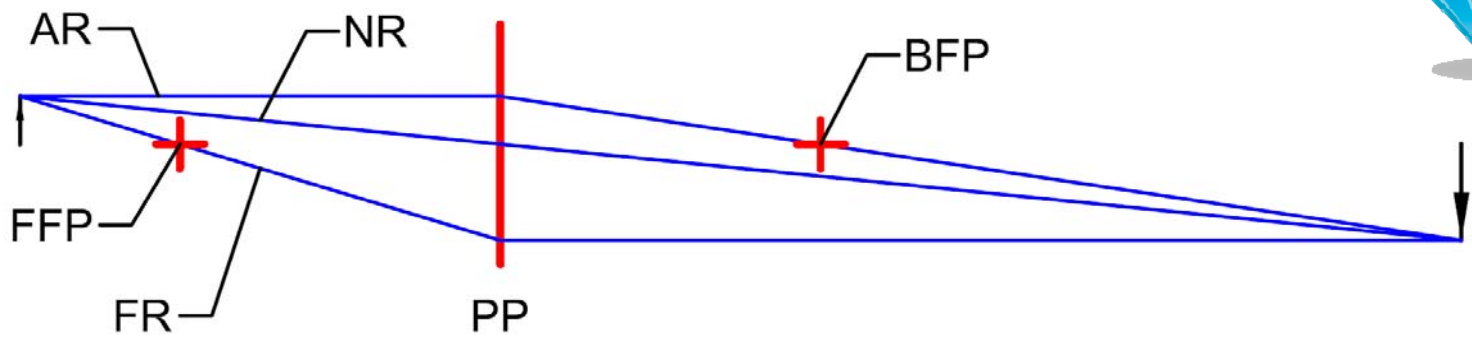


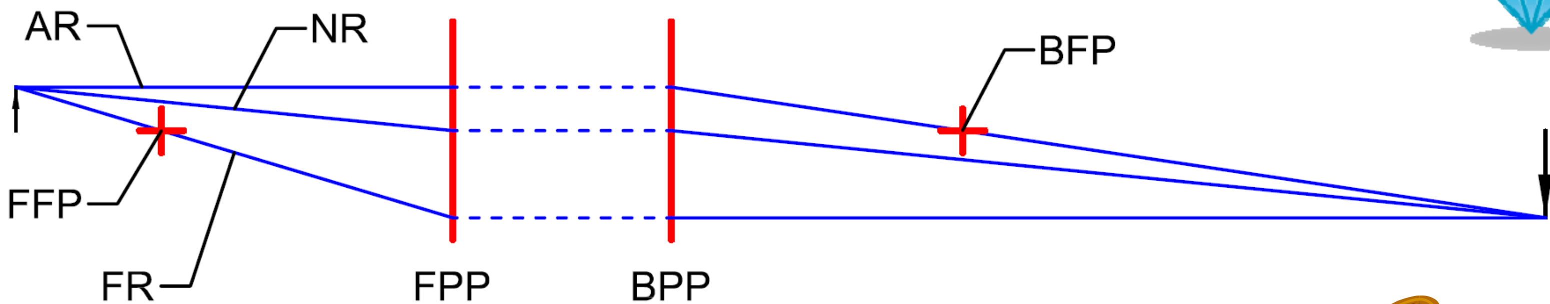
Image height = 1.0

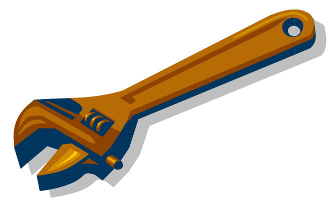
Thin lens cardinal points



- Object cardinal points
  - Front focal point FFP
  - Principle plane PP
- Object Rays
  - Axial ray AR parallel to axis
  - Nodal ray NR thru PP center
  - Focal ray FR thru FFP
- Image cardinal points
  - Back focal point BFP
  - Principle plane PP
- Image Rays
  - AR directed thru BFP
  - NR passes without bend
  - FR becomes axial

Thick lens separates PP





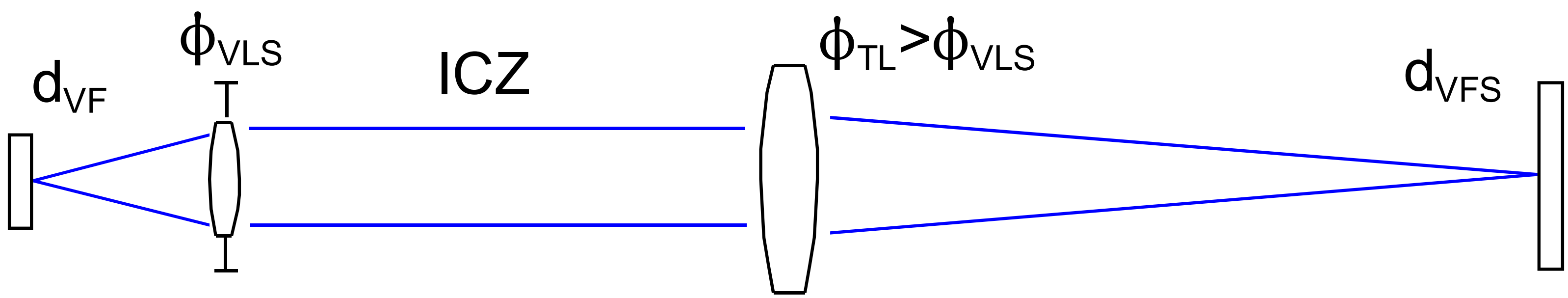
- Principle planes
  - Front principle plane FPP
  - Back principle plane BPP
  - Transformation between planes at right

$$\begin{vmatrix} y' \\ m' \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ -1/f & 1 \end{vmatrix} \cdot \begin{vmatrix} y \\ m \end{vmatrix}$$

§ 2 Stops

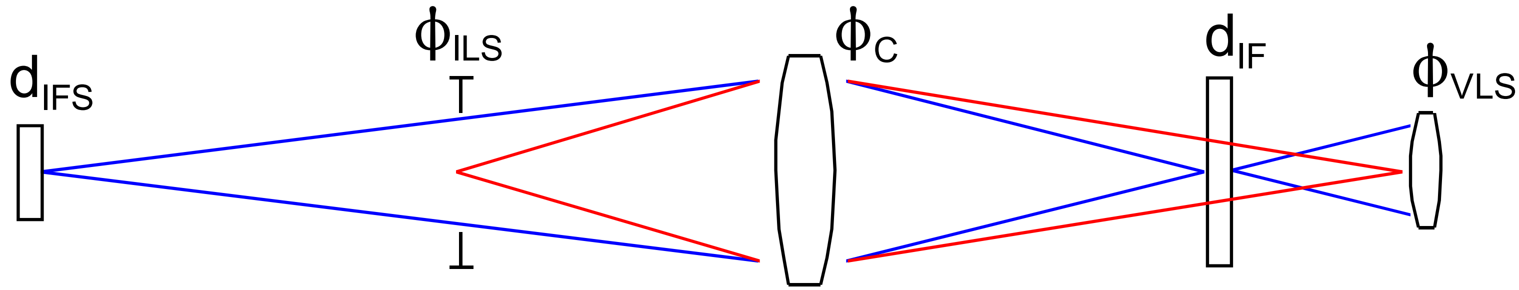
Constraints in space and angle

Vision stops



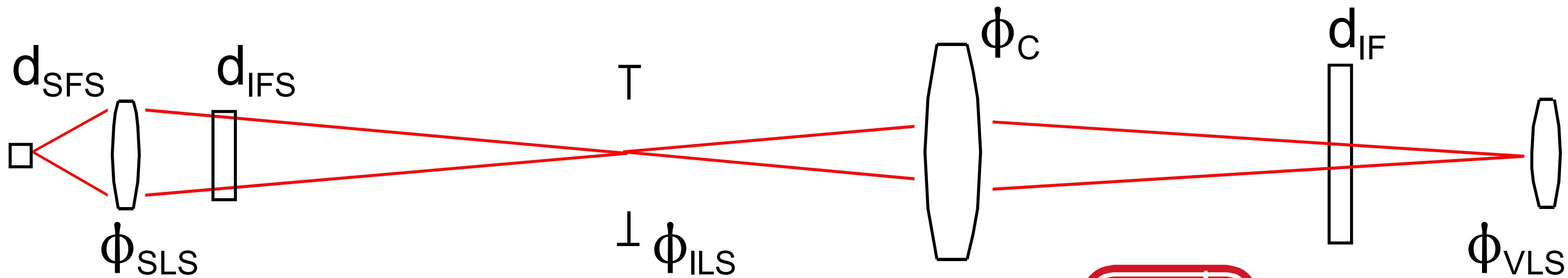
- Spatial extents
  - vision field-stop VFS
  - vision field VF
- Angular extents
  - vision lens-stop VLS
- Image conjugates
  - VF and VFS
- Other features
  - infinity correction zone ICZ
  - tube lens TL

Illumination stops



- Spatial extents
  - IFS illumination field-stop
  - IF illumination field
- Angular extents
  - ILS illumination lens-stop
- Image conjugates
  - IFS and IF
  - ILS and VLS
- Other features
  - Φ_C Diameter of condenser

Source stops



- Spatial extents
  - source field-stop SFS
- Angular extents
  - source lens-stop SLS

- Source image located at
  - illumination lens-stop ILS
  - vision lens-stop VLS
- Other features
  - Diffuser (not shown)

§ 3 Wave Optics

Propagation of electromagnetic waves

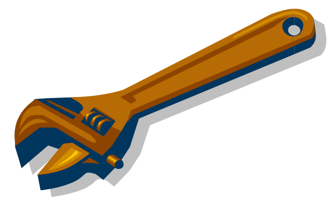
Space-angle product of waves

$$A\Omega \geq \lambda^2$$

Cannot be made smaller

without

creation of evanescent field



$$A_0\Omega_0 = A_1\Omega_1 = \cdots = A_n\Omega_n \geq \lambda^2$$

Coherence length

- Analogous to Heisenberg Uncertainty principle
- conversion of $\sigma_z \sigma_k$ of to wavelength

$$\Delta z \Delta p \geq \frac{\hbar}{2}$$

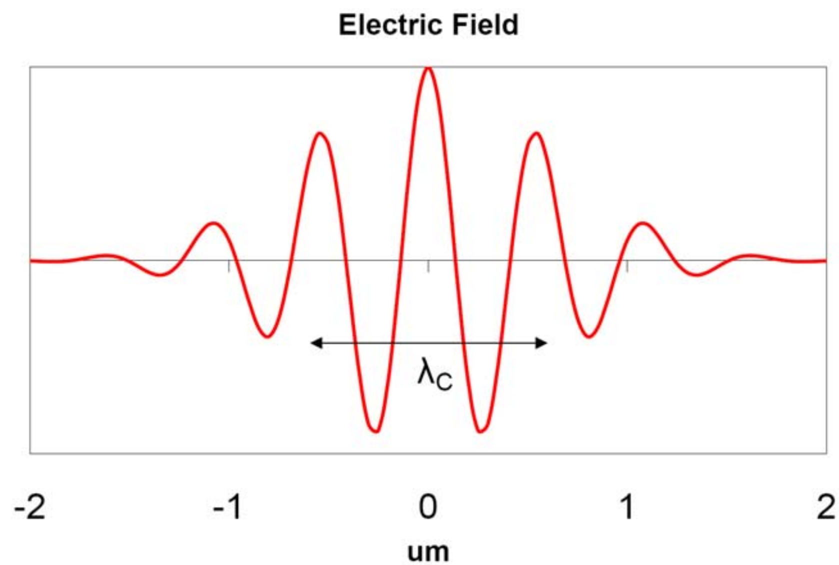
$$\sigma_z \sigma_k \geq \frac{1}{2}$$

$$\Delta\lambda = 4\sigma_\lambda$$

$$\lambda_C = 4\sigma_z$$

$$\lambda_C = \frac{\lambda^2}{\Delta\lambda}$$

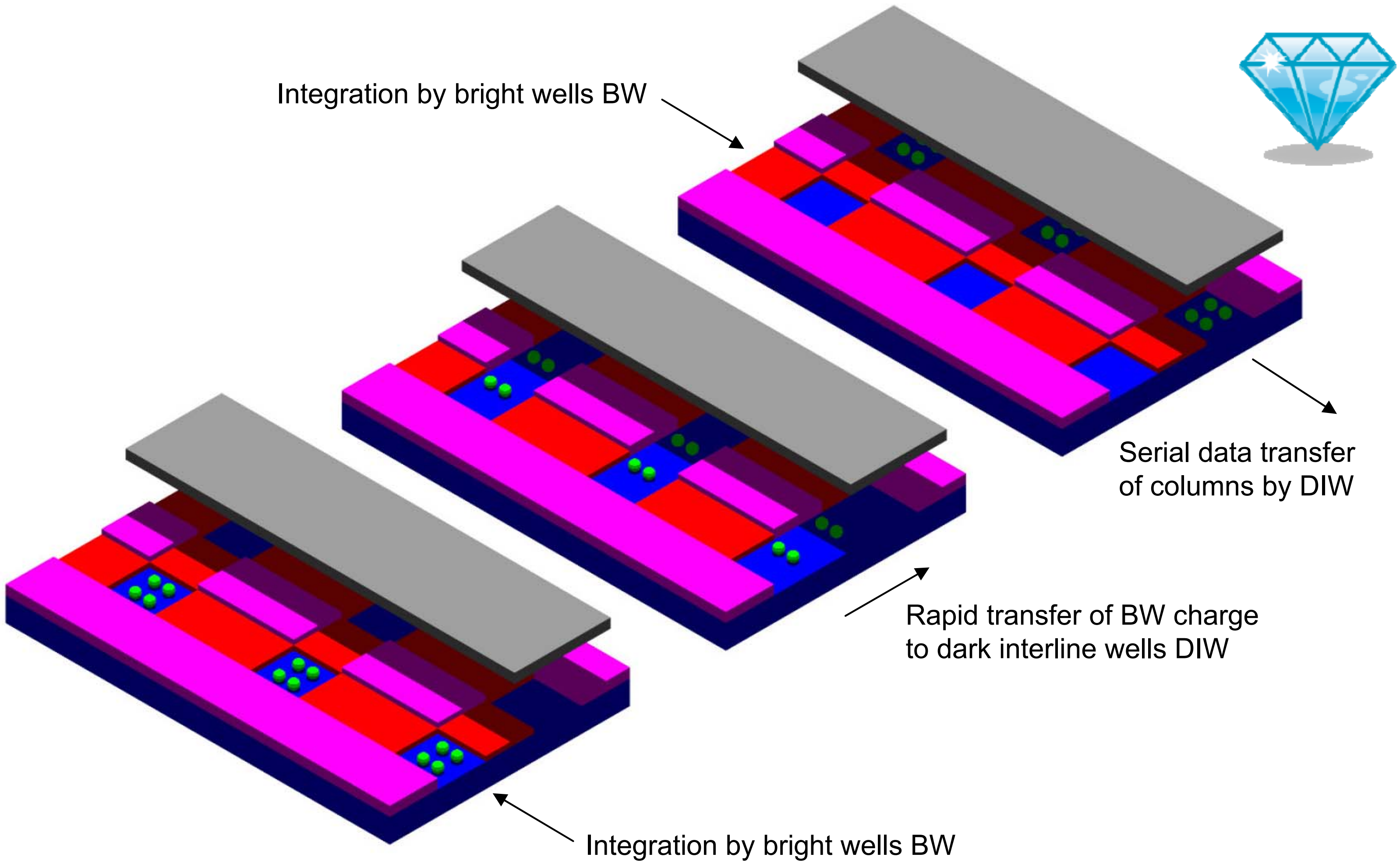
- Human vision filter
  - $\lambda = 550\text{nm}$
  - $\Delta\lambda = 650\text{nm} - 400\text{nm}$
  - $\lambda_c = 1.2\text{um} \approx 2\lambda$



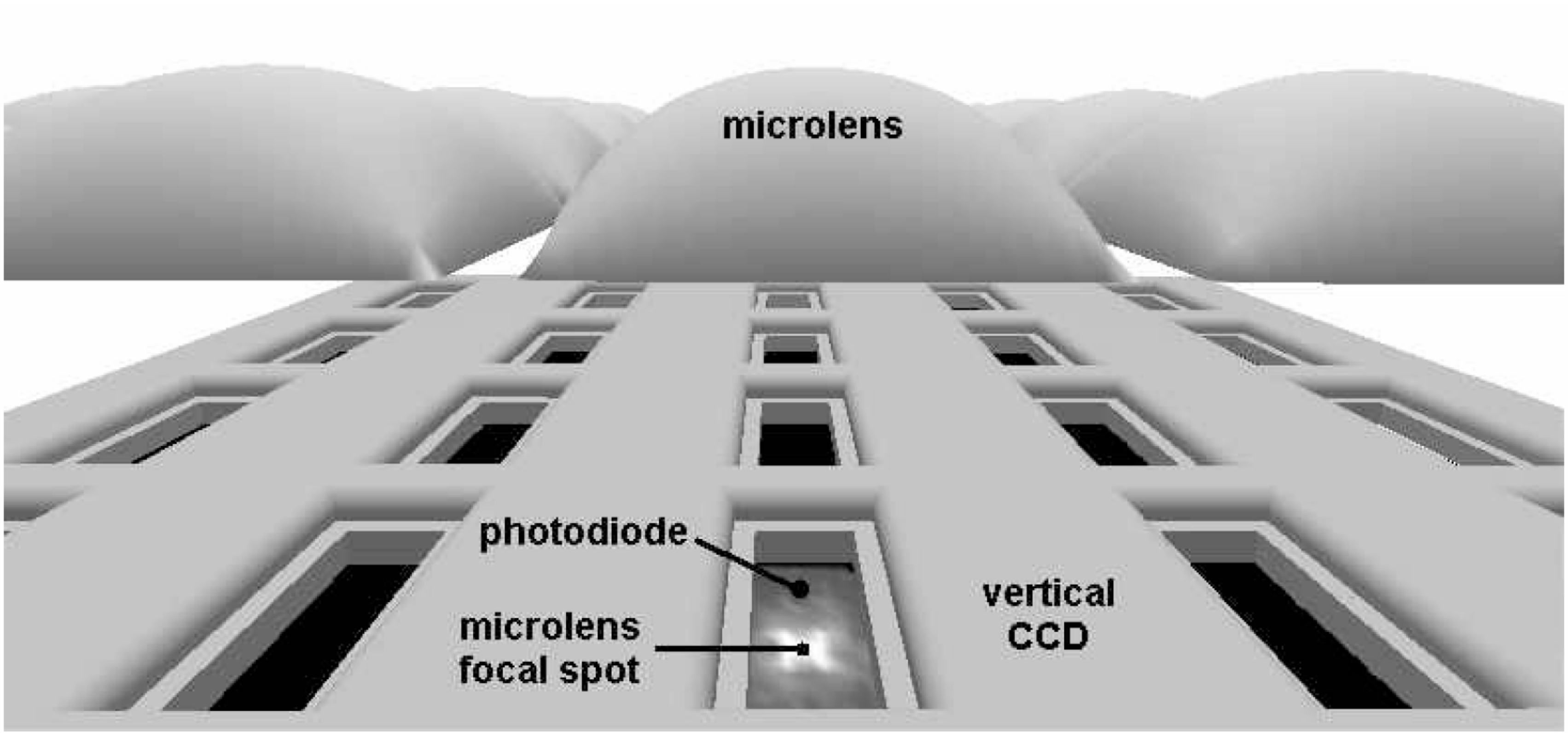
§ 4 Charge coupled devices

Space-angle product of pixel
determines
design goals for optics

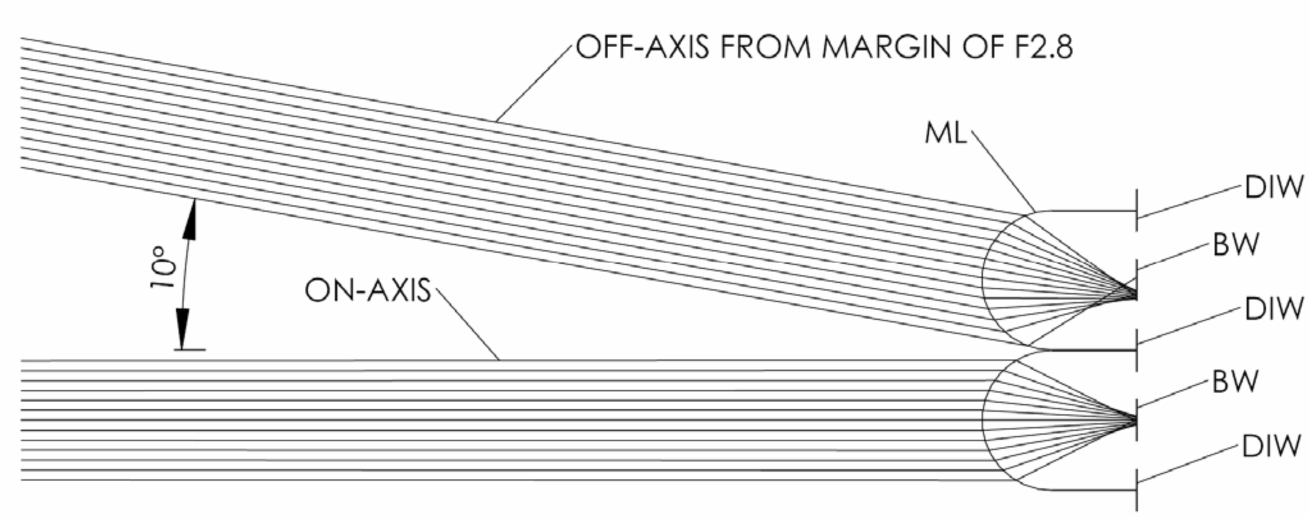
Interline transfer with sheild



CCD microlens array

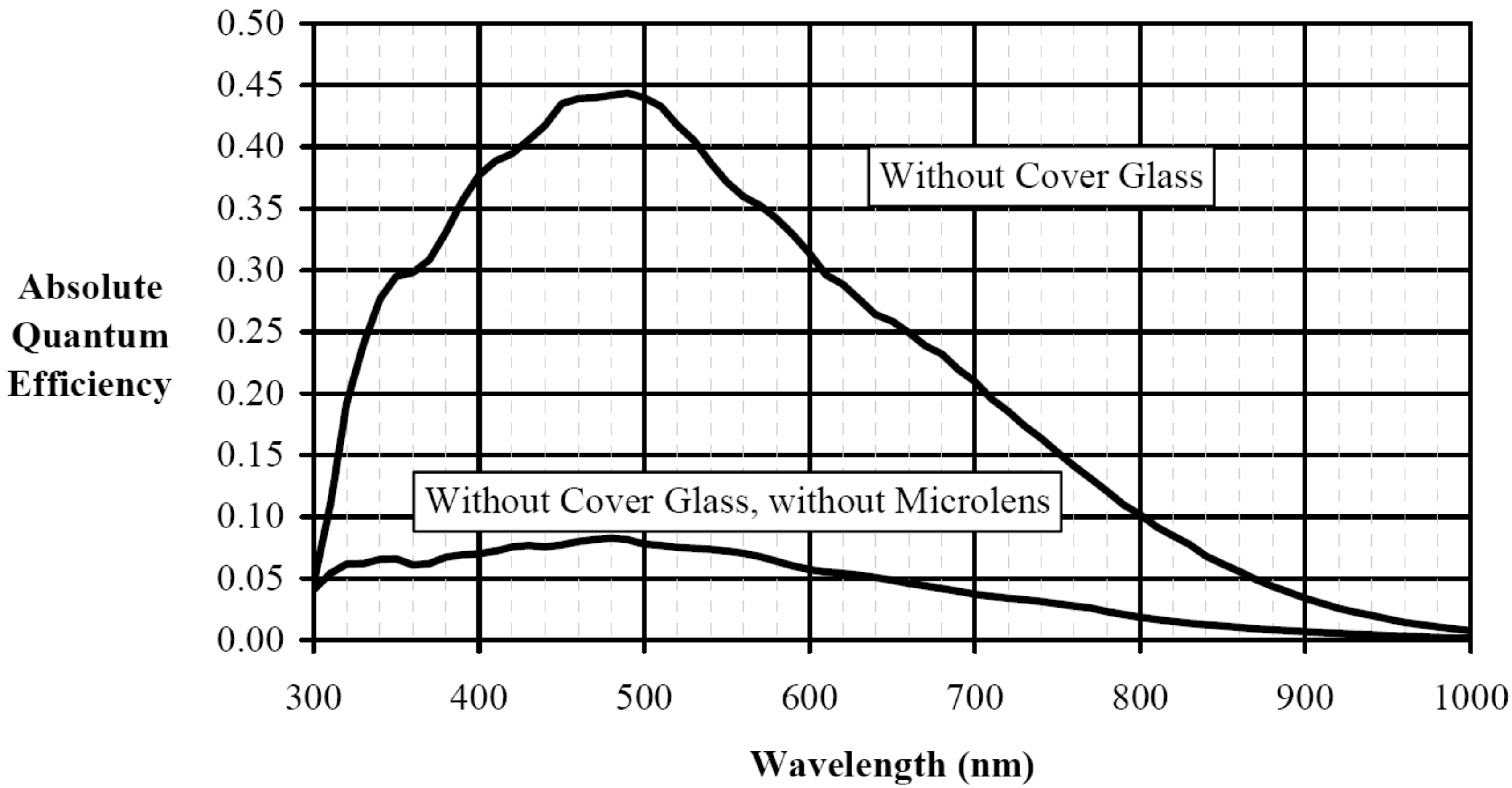


F2.8 Microlens



- Bright wells BW
  - accumulate charge during exposure
  - display less than 25% fill-factor
- Dark interline wells DIW
  - Quickly collect charge from bright wells
  - Transfer charge without further exposure
- Microlenses ML
  - Display nearly 100% fill-factor
  - Accept F2.8 rays
  - Spherical aberrations SA
  - Surface form errors SFE
  - >4X gain to quantum efficiency

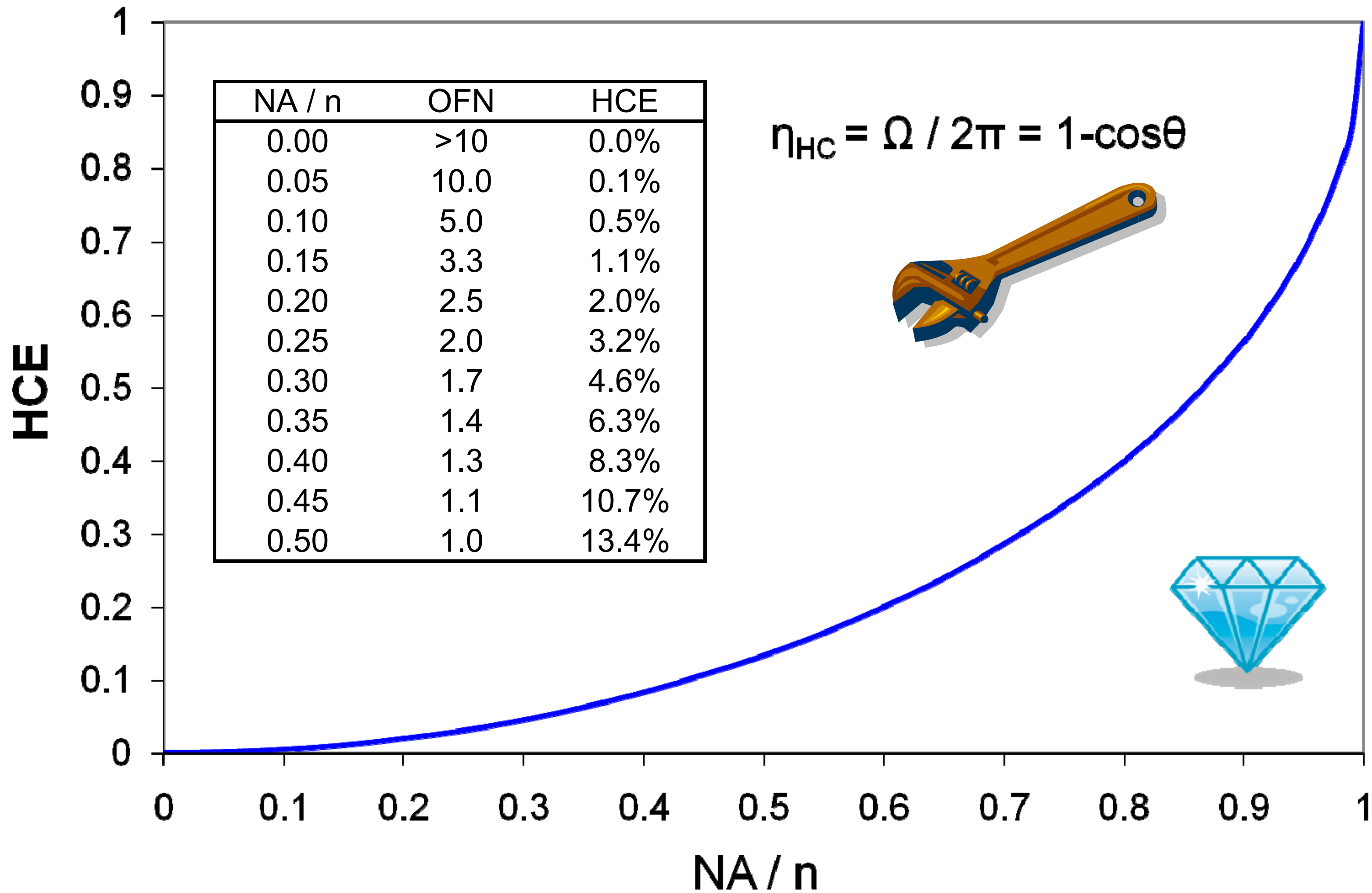
Quantum efficiency KAI-1020



§ 5 Contrast enhancement

To make a needle appear within haystack

Hemispherical Collection Efficiency η_{HC}



NA / n	OFN	HCE
0.00	>10	0.0%
0.05	10.0	0.1%
0.10	5.0	0.5%
0.15	3.3	1.1%
0.20	2.5	2.0%
0.25	2.0	3.2%
0.30	1.7	4.6%
0.35	1.4	6.3%
0.40	1.3	8.3%
0.45	1.1	10.7%
0.50	1.0	13.4%

$$\eta_{HC} = \Omega / 2\pi = 1-\cos\theta$$

Sub-pixel collection efficiency

- Angle at object

$$\Omega_{pp} = 4\pi \sin^2 \frac{\theta_{pp}}{2}$$

$$\approx \frac{(ONA)^2}{2} \mathrm{H}$$

A hemisphere H is reference as

$$\mathrm{H} = 2\pi$$

- Angle at image

$$\Omega_{pp} = 4\pi \sin^2 \frac{\theta_p}{2}$$

$$\approx \frac{(INA)^2}{2M^2} \mathrm{H}$$

$$\approx \frac{\mathrm{H}}{8M^2 (IFN)^2}$$

Full-pixel collection efficiency

- Space-angle product at object

$$A_{pp}\Omega_{pp} = \frac{d_p^2}{M^2} 4\pi \sin^2 \frac{\theta_{pp}}{2}$$

$$\approx \frac{d_p^2}{M^2} \frac{(ONA)^2}{2} \mathrm{H}$$

A hemisphere H is reference as

$$\mathrm{H} = 2\pi$$

- Space-angle product at image

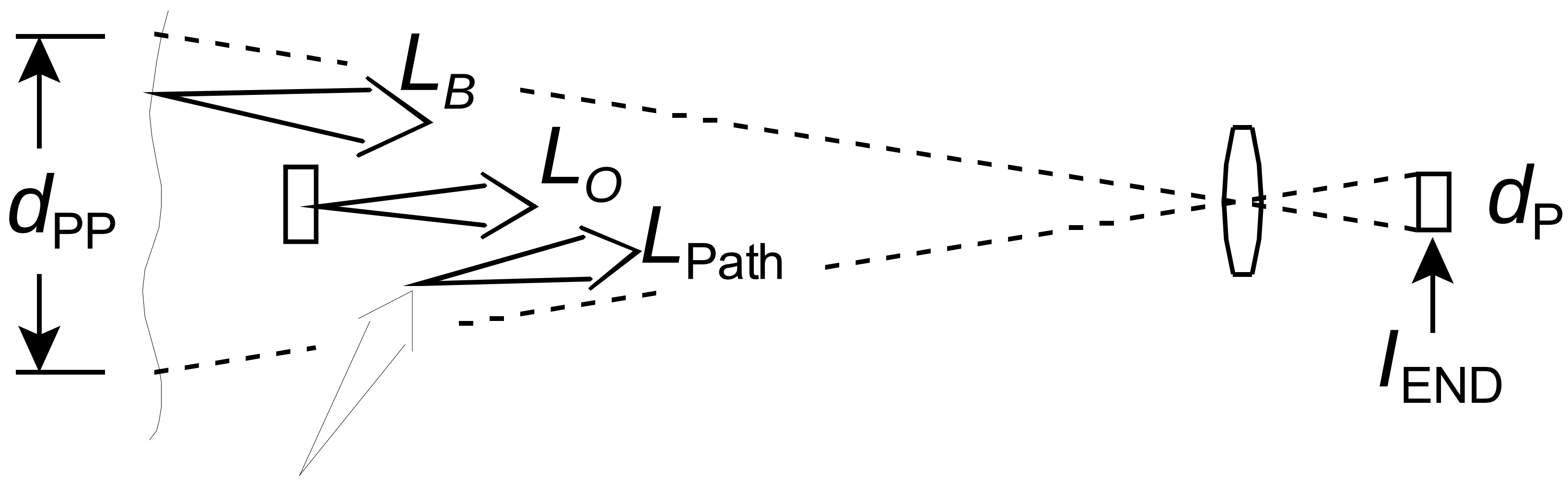
$$A_p\Omega_p = d_p^2 4\pi \sin^2 \frac{\theta_p}{2}$$

$$\approx d_p^2 \mathrm{H} \frac{(INA)^2}{2}$$

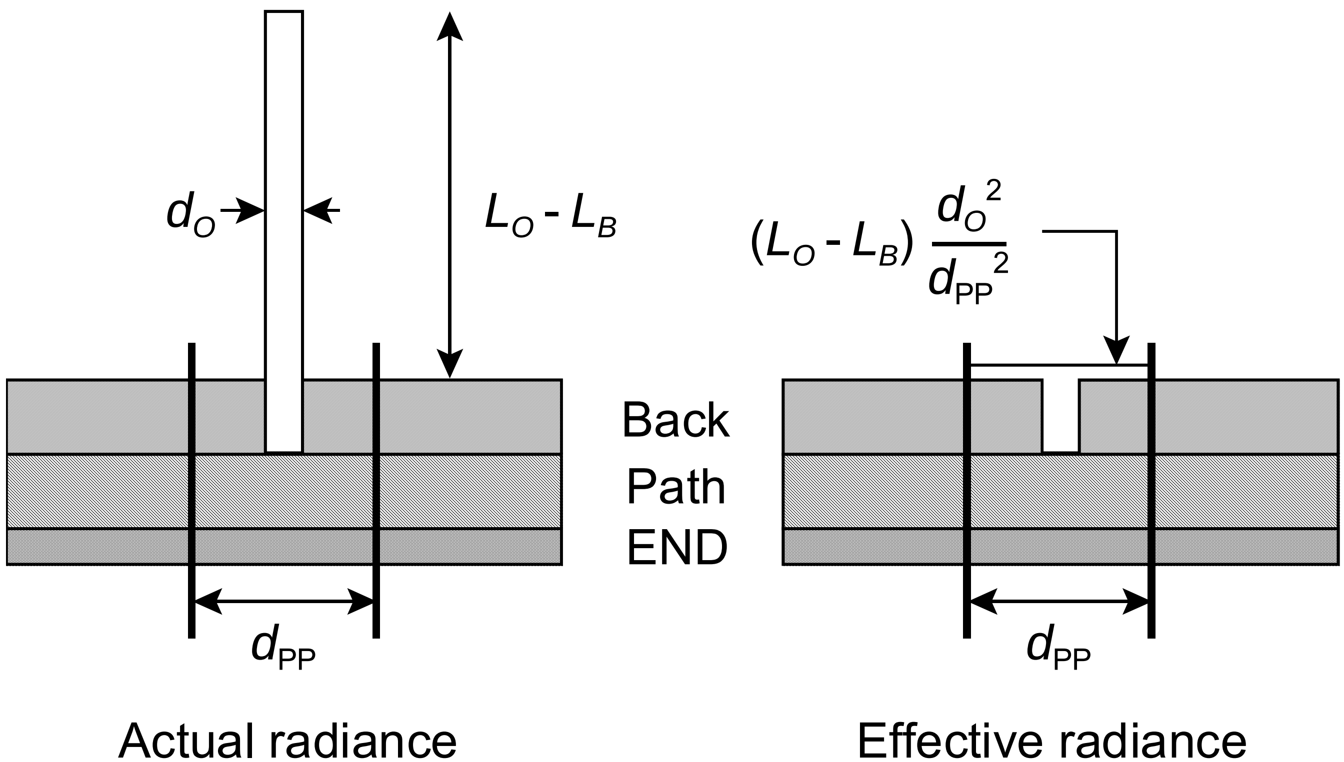
$$\approx d_p^2 \frac{\mathrm{H}}{8(IFN)^2}$$

Path Radiance

- Radiance from path of optics L_{Path}
  - Collected from background path of object
  - Collected from foreground path of object
  - Different from background radiance L_B



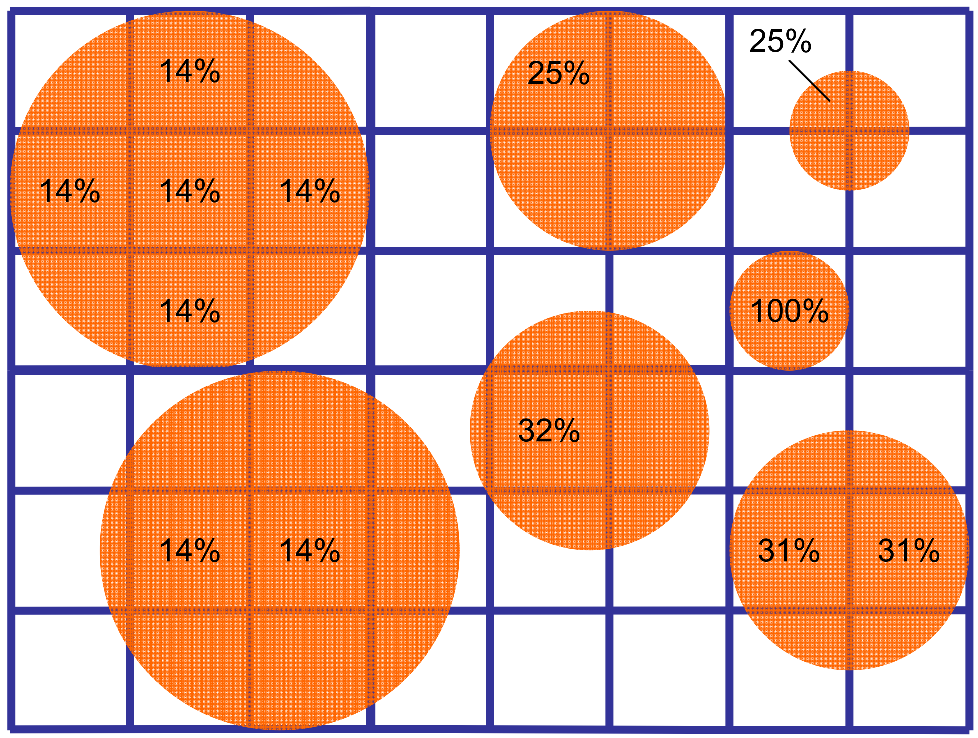
Redistribution within pixel



$$C_{SPO} = \frac{(L_O - L_B)\, d_O^2/d_{PP}^2}{L_B + L_{Path} + L_{END}}$$

Minimum Pixel Collection Efficiency

- Minimum η_{PC}
  - 14% at 3X pixel-width
  - 25% at 2X pixel-width
  - 25% at 1X pixel-width
- Minimum is at most 25%



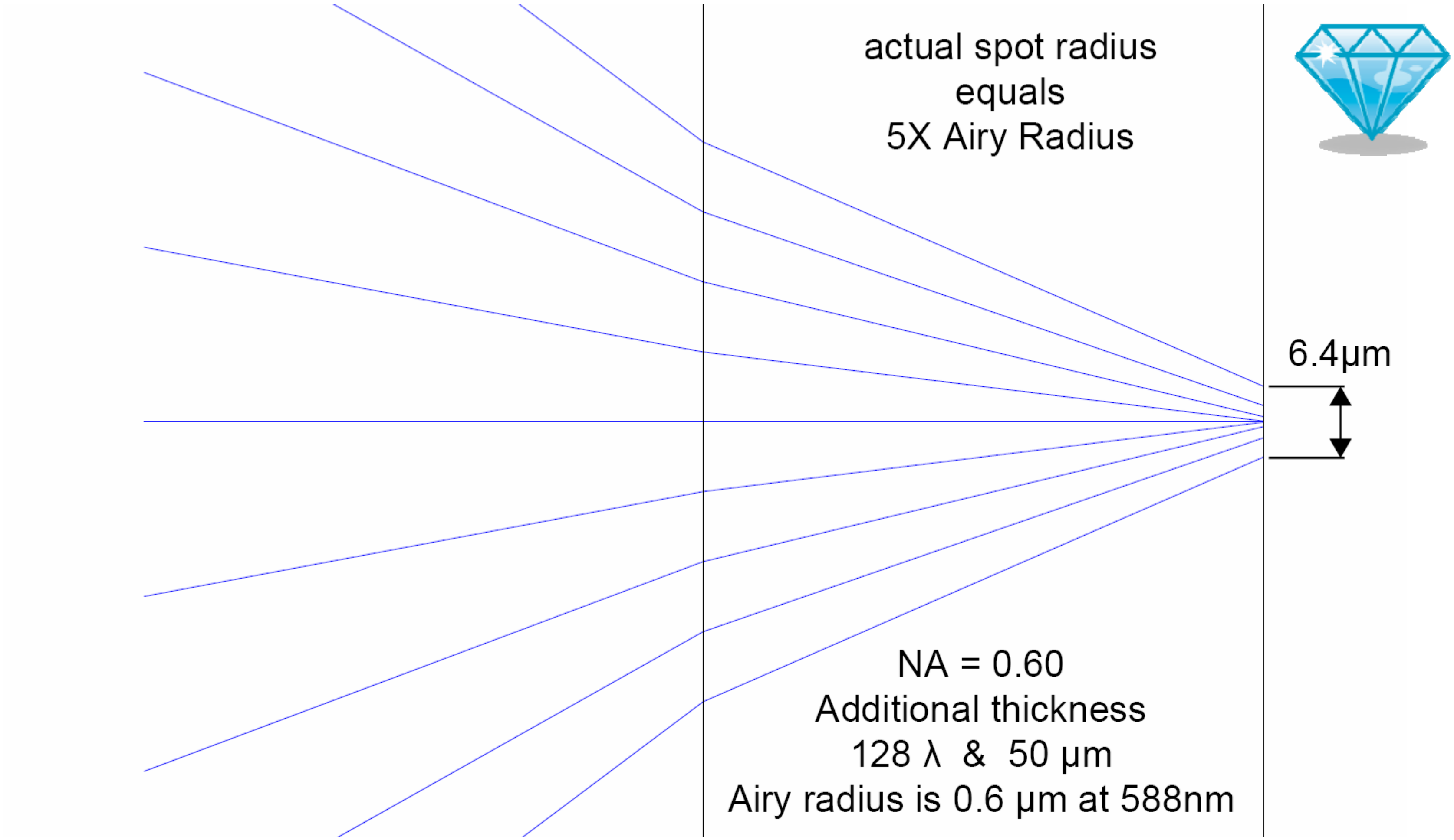
§ 6 Aberrations

Aberrations convert signal
into in background

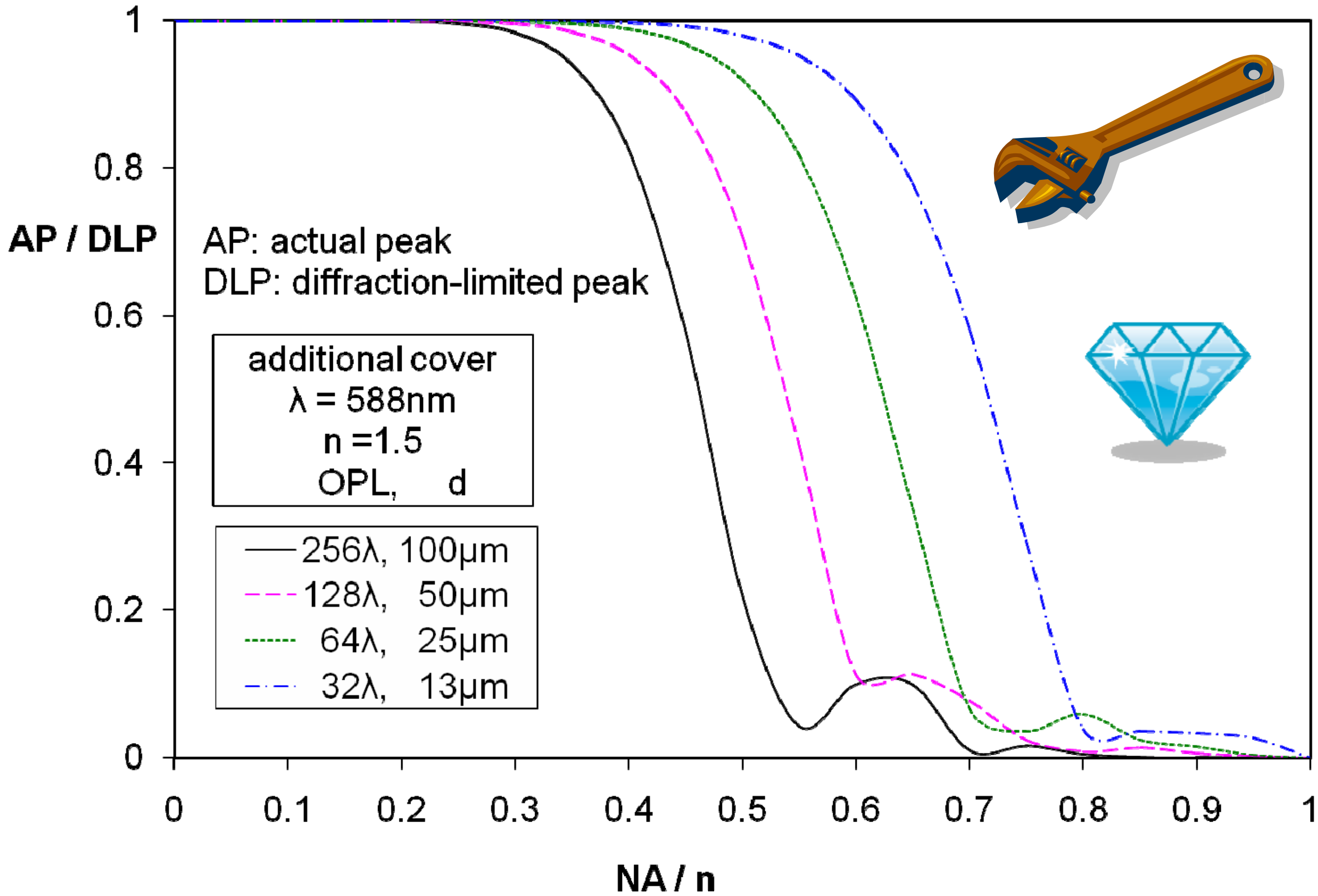
§ 7 Cover aberrations

So much trouble
created by
so little thickness

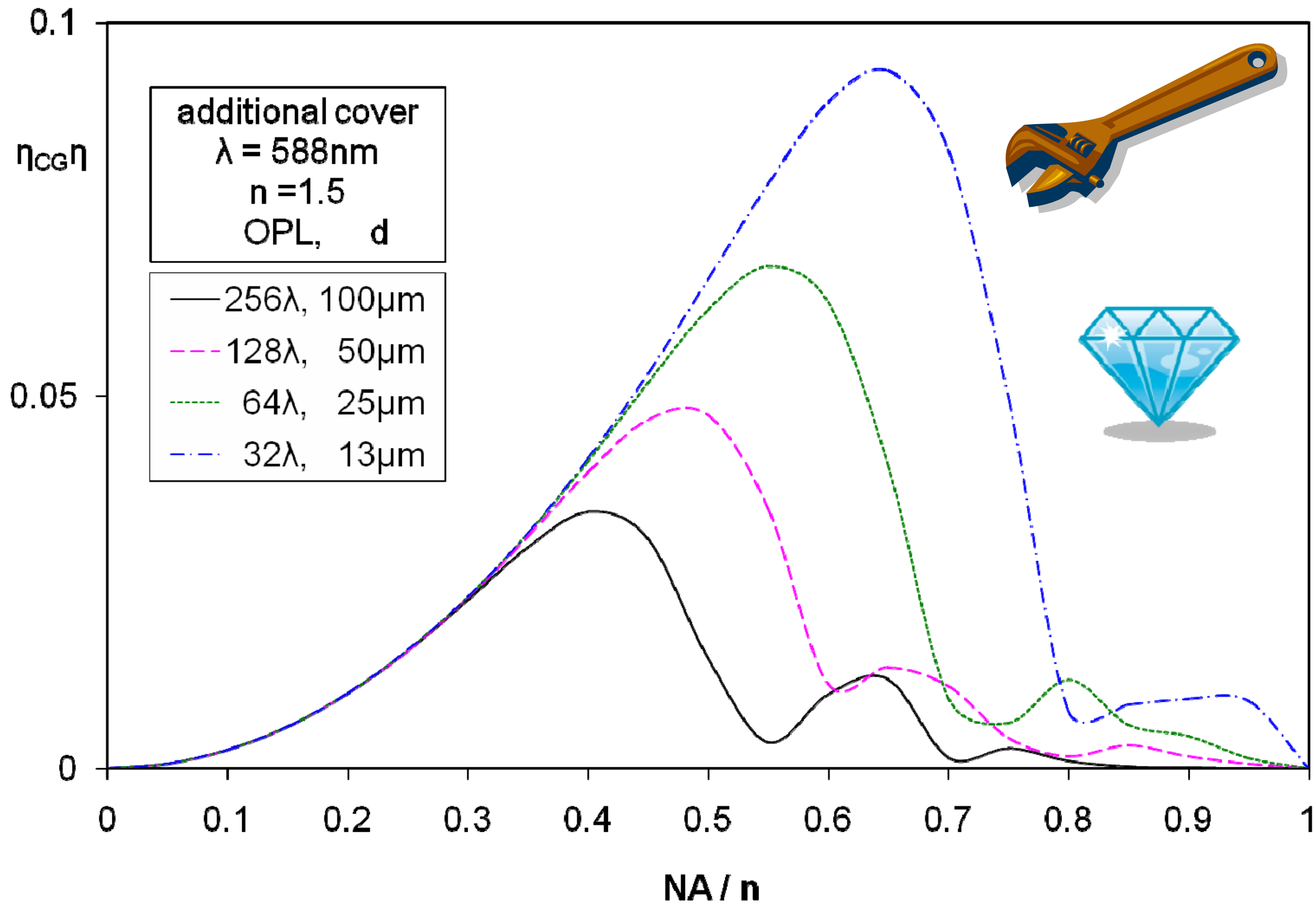
Cover spherical aberration



Cover glass efficiency η_{CG}



Combined efficiency $\eta_{CG}\ \eta_{SC}$



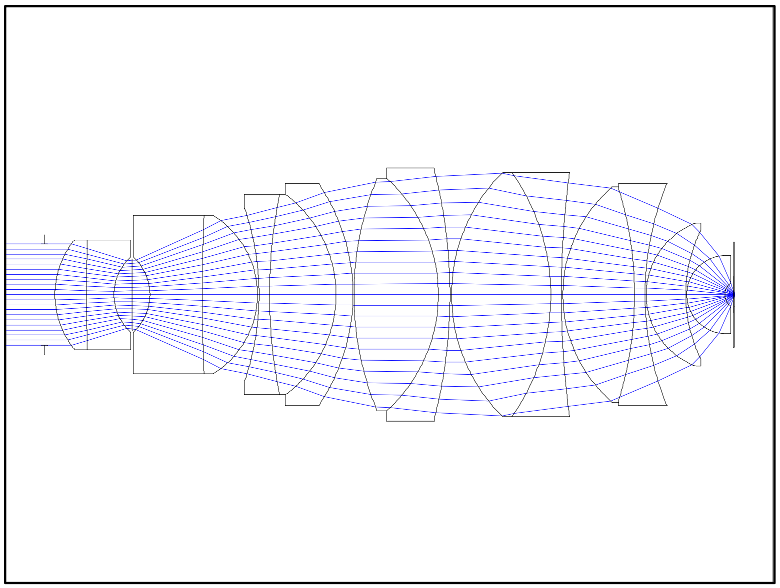
§ 8 Objective aberrations

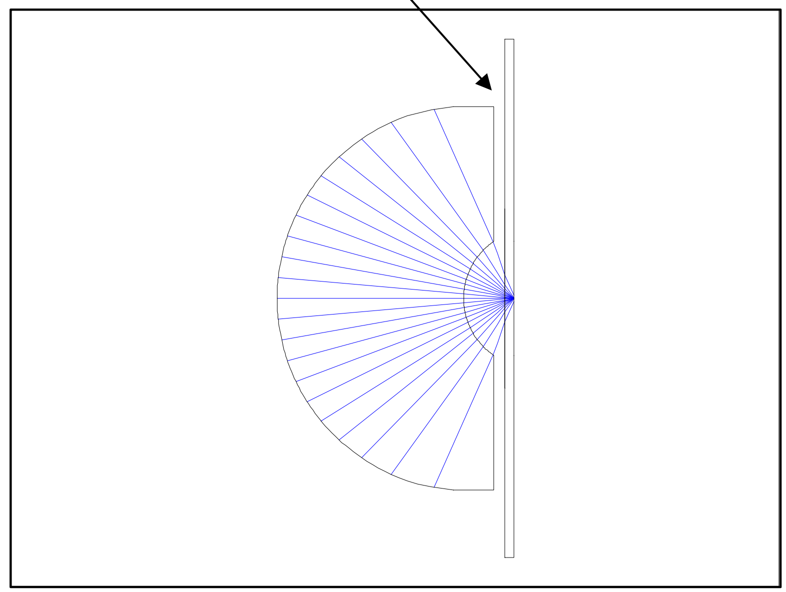
NA indicates marginal ray

But not diffraction limit

60X 1.4NA Immersion Objective

Yamaguchi US pat. 6,519,092 B2



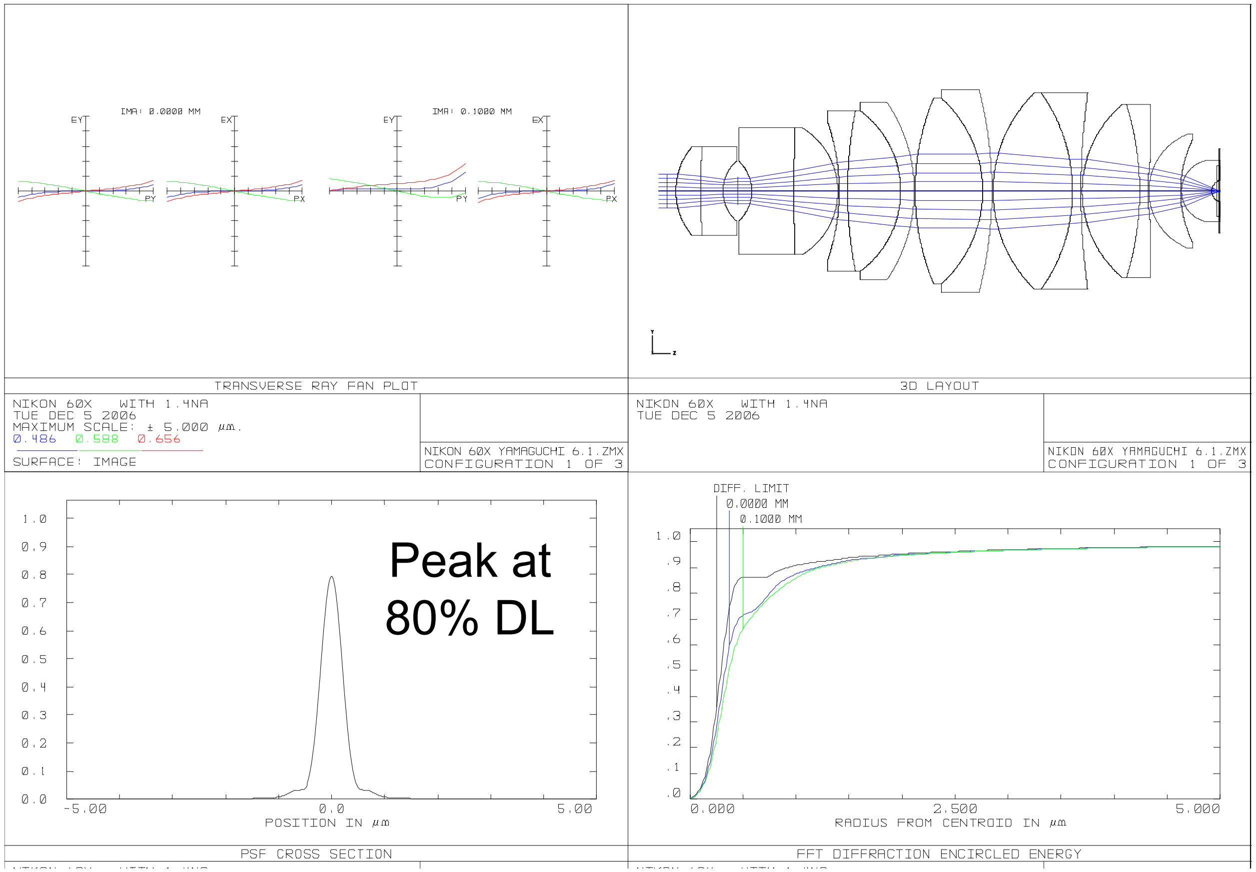


Uniform linear spacing in tube

nearly corresponds to

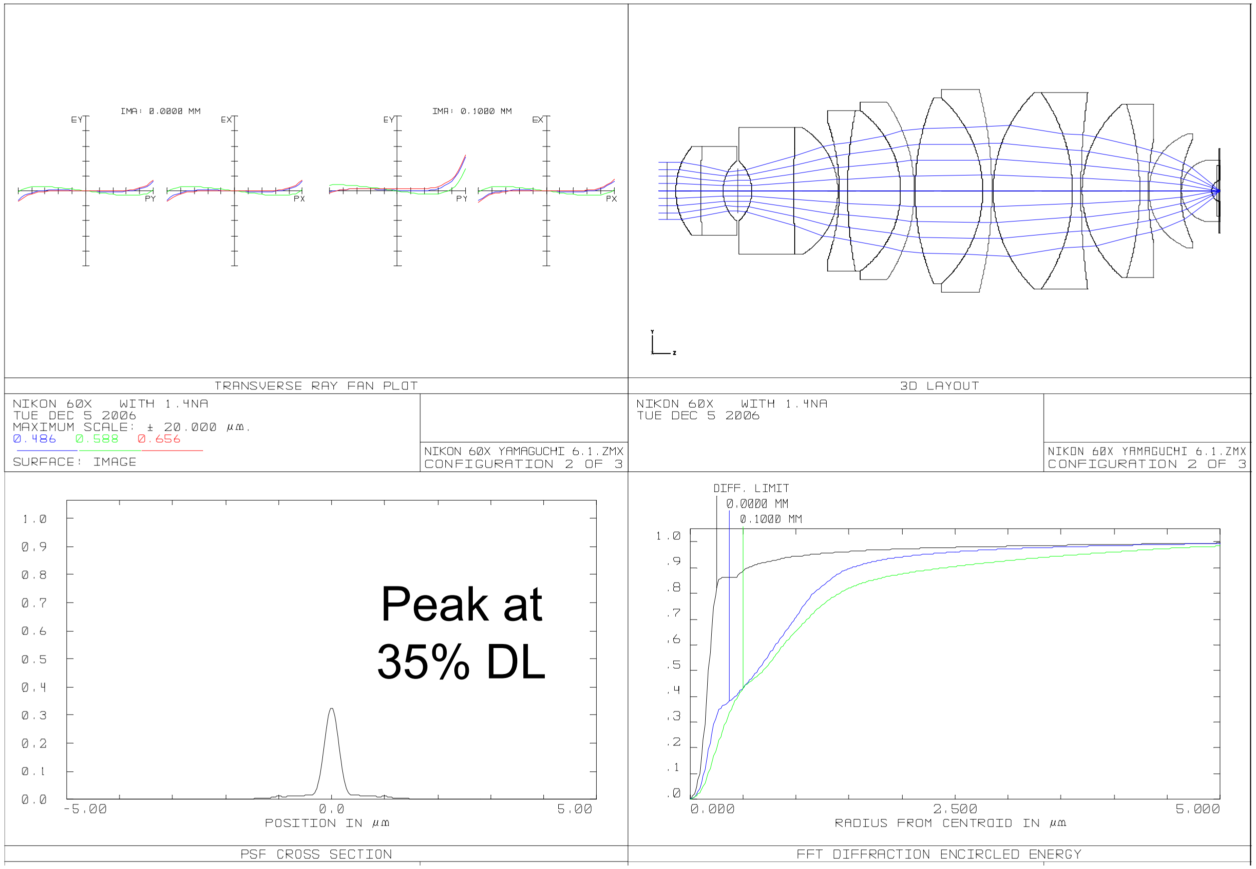
uniform angular spacing at object

60X/1.4 at 0.60NA



Yamaguchi US pat. 6,519,092 B2

60X/1.4 at 1.00NA



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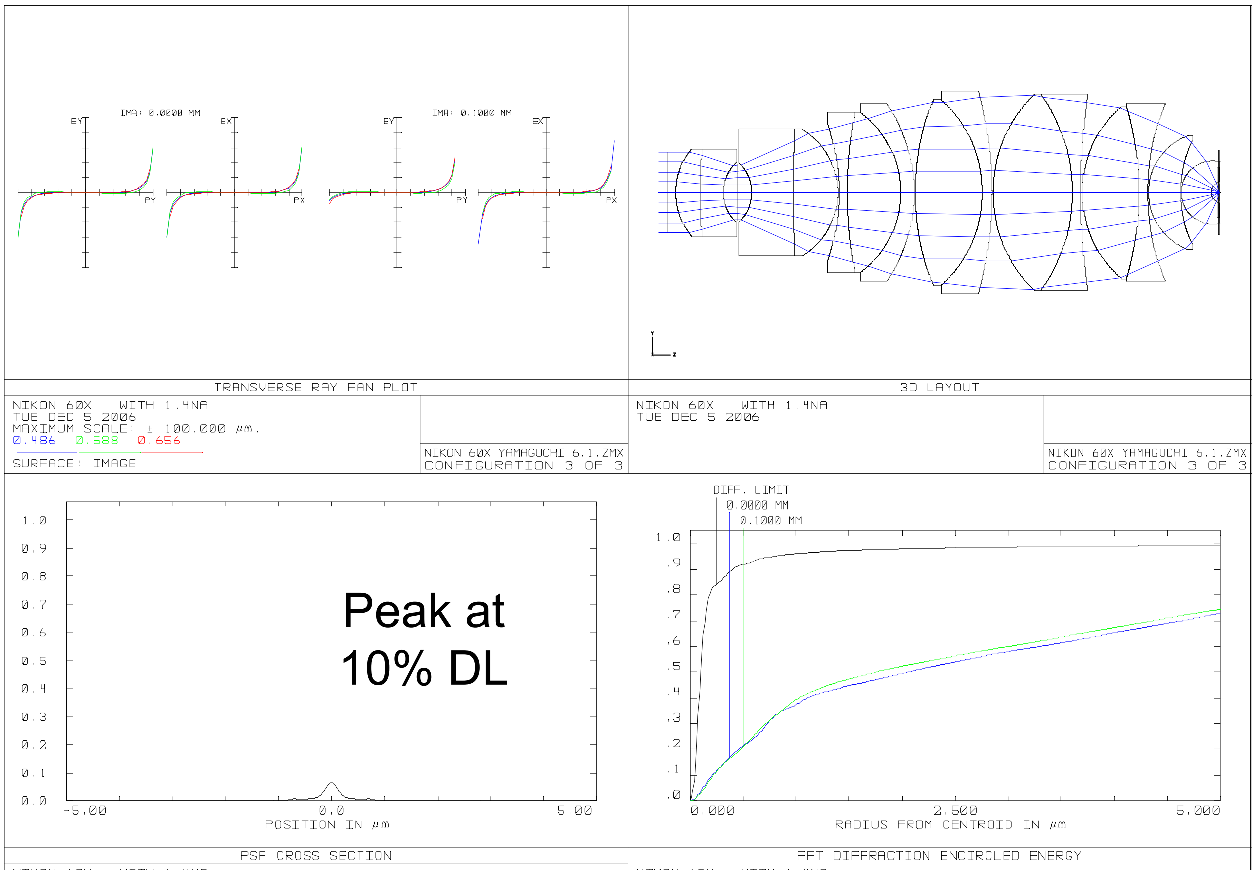
60X/1.4 at 1.40NA

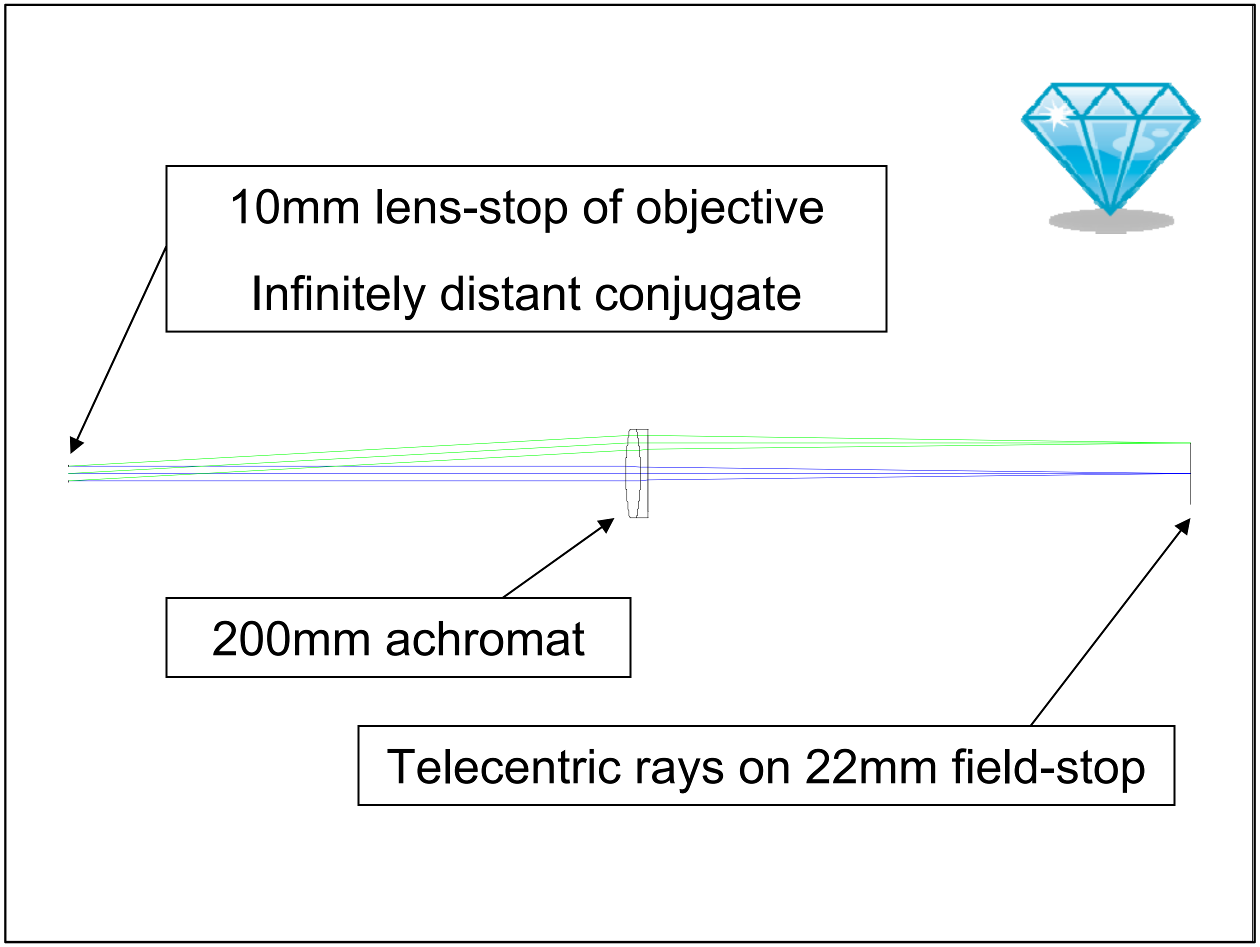


Yamaguchi US pat. 6,519,092 B2

§ 9 Design Example

A custom tube-lens
for
an off-the-shelf objective

Tube lens: Off-the-shelf OTS



§ 10 Conclusion

Closing remarks

Knowledge is power

- Comprehension of knowledge
  - Promotes maximum quality
  - Yields lasting value
- Application of knowledge without comprehension
  - Promotes application of sound ideas
  - But not in optimum combination

- Confidence without comprehension
  - Yields trouble!!!

$$C\text{-}C = T$$