



EPFL

MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 9

25.11.2024

Ye Pu

Sciences et techniques de l'ingénieur
École Polytechnique Fédérale de Lausanne
CH-1015 Lausanne

Outline

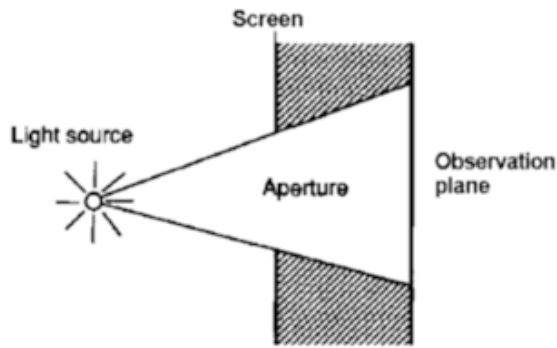
Theory

- Review of physical optics
- Physical optics modeling
 - Gaussian optics
 - Diffraction
- Imaging
 - Modulation transfer function
 - Point spread function

ZEMAX Practice

- ZEMAX physical optics modeling
 - MTF
 - PSF
 - Imaging simulation

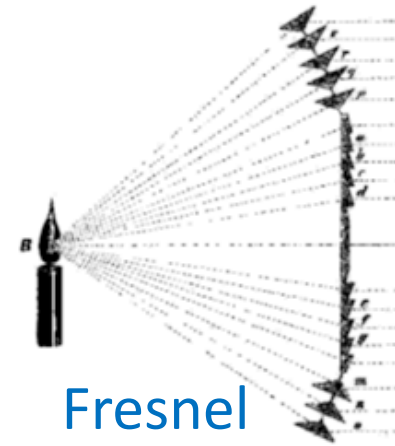
Historical Development of the Theory of Light



Grimaldi



Newton



Fresnel



Sommerfeld



Kirchhoff

1665

1678

1704

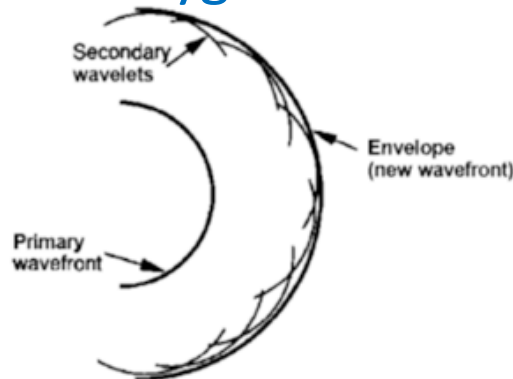
1801

1818

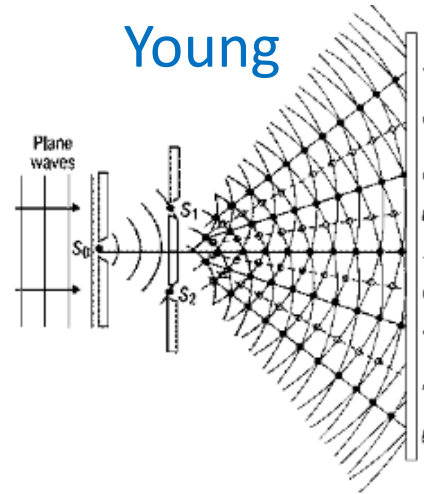
1860

1882-96

Huygens



Young



Maxwell

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}$$

Electromagnetics: From Vector to Scalar

Free-space Maxwell equation

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad \nabla \times (\nabla \times \mathbf{E}) = \nabla (\cancel{\nabla \cdot \mathbf{E}}) - \nabla^2 \mathbf{E} = -\mu \frac{\partial}{\partial t} \nabla \times \mathbf{H}$$

$$\nabla \times \mathbf{H} = \varepsilon \frac{\partial \mathbf{E}}{\partial t} \quad \nabla \times (\nabla \times \mathbf{H}) = \nabla (\cancel{\nabla \cdot \mathbf{H}}) - \nabla^2 \mathbf{H} = \varepsilon \frac{\partial}{\partial t} \nabla \times \mathbf{E}$$

$$\nabla \cdot \varepsilon \mathbf{E} = 0$$

$$\nabla \cdot \mu \mathbf{H} = 0$$

Separable variable

$$u(P, t) = A(P)T(t)$$

$$\frac{\nabla^2 A(P)}{A(P)} = -k^2$$

$$\frac{1}{c^2 T} \frac{d^2 T}{dt^2} = -k^2$$

Scalar wave equation at point P and time t

$$\nabla^2 u(P, t) = \frac{n^2}{c^2} \frac{\partial^2 u(P, t)}{\partial t^2}$$

where u represents any component in $\mathbf{E}$ or $\mathbf{H}$

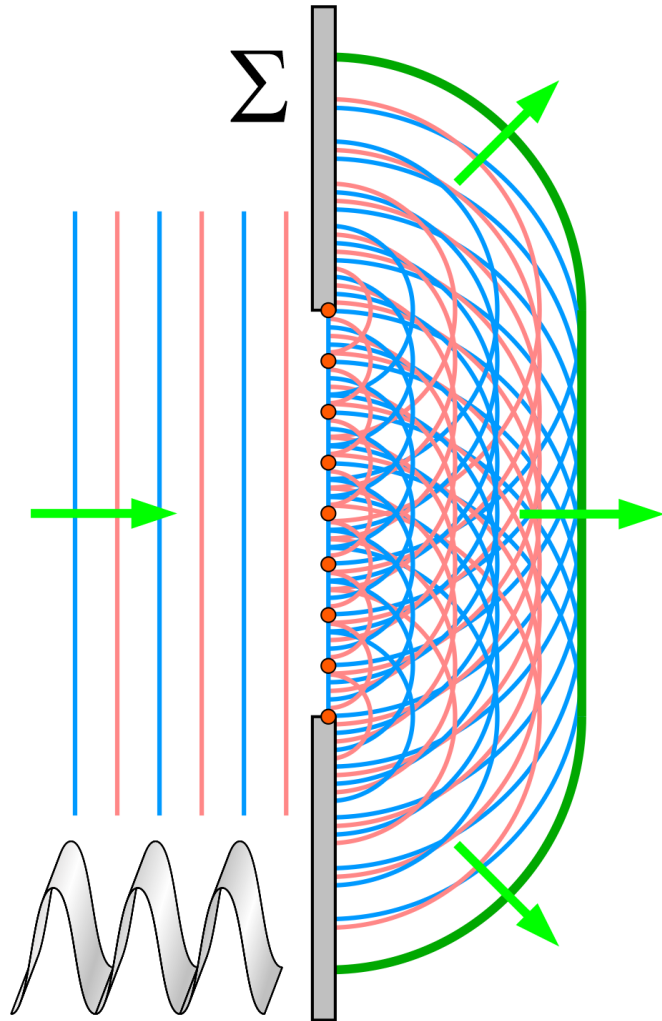
$$n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} \quad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

Helmholtz Equation

$$(\nabla^2 + k^2) A(P) = 0$$

$$k = \frac{n\omega}{c} = \frac{2\pi}{\lambda}$$

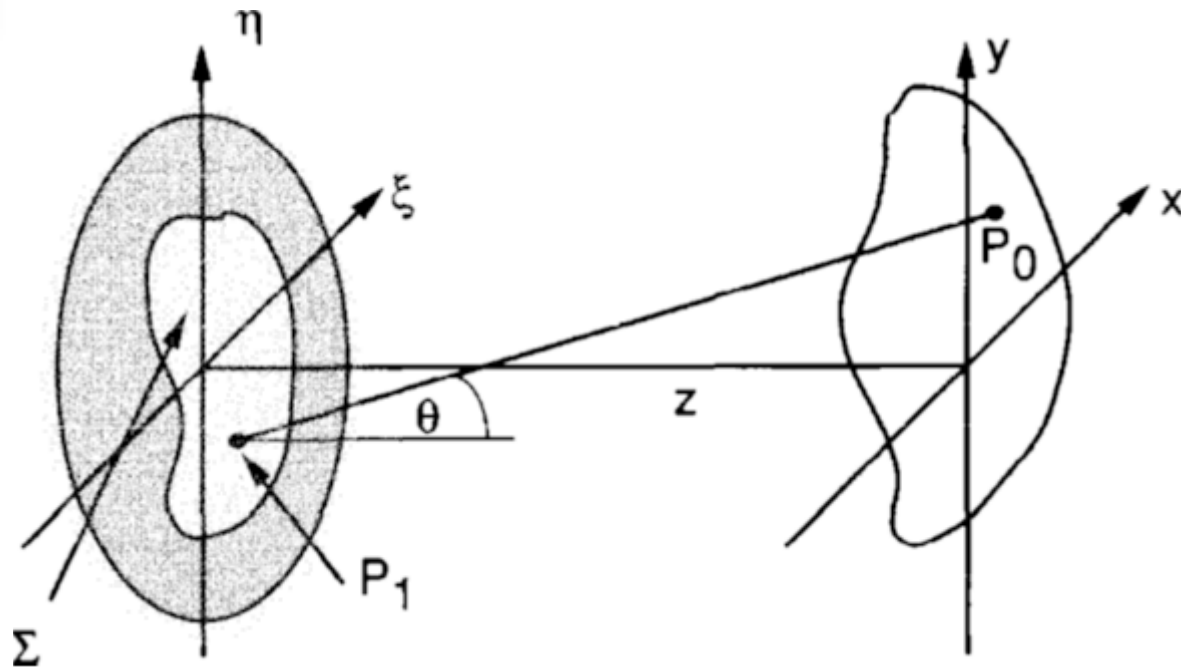
Principle of Wave Propagation



Huygens-Fresnel Principle

- Proposed by Huygens in 1678
- Every point in a light disturbance becomes a secondary source of spherical wave
- The sum of these secondary waves determines the form of the wave at subsequent times.
- Assumes the secondary waves travel only in the "forward" direction
- Qualitatively explains planar and spherical wave propagation, the laws of reflection and refraction, but not diffraction
- In 1818 Fresnel combined Huygens's principle with principle of interference
- Quantitatively explains rectilinear propagation of light and diffraction

Principle of Wave Propagation



Huygens-Fresnel Principle in
Rayleigh-Sommerfeld solution

$$U(x, y) = \frac{1}{i\lambda} \iint_{\Sigma} U(\xi, \eta) \frac{\exp(ikr_{01})}{r_{01}} \cos \theta ds$$

$$\cos \theta = \frac{z}{r_{01}} \quad r_{01} = \sqrt{(x - \xi)^2 + (y - \eta)^2 + z^2}$$



$$U(x, y) = \frac{z}{i\lambda} \iint_{\Sigma} U(\xi, \eta) \frac{\exp(ikr_{01})}{r_{01}^2} ds$$

Principle of Wave Propagation

Fresnel Approximation

$$z^3 \gg 2k \left[(x - \xi)^2 + (y - \eta)^2 \right]_{\max}^2$$

In denominator: $r_{01} \approx z$

In exponent:

$$r_{01} = \sqrt{(x - \xi)^2 + (y - \eta)^2 + z^2} = z \sqrt{1 + \left(\frac{x - \xi}{z} \right)^2 + \left(\frac{y - \eta}{z} \right)^2} \approx z \left[1 + \frac{1}{2} \left(\frac{x - \xi}{z} \right)^2 + \frac{1}{2} \left(\frac{y - \eta}{z} \right)^2 \right]$$

$$U(x, y) = \frac{e^{ikz}}{i\lambda z} \iint_{\pm\infty} U(\xi, \eta) \exp \left\{ -i \frac{2\pi}{\lambda z} \left[(x - \xi)^2 + (y - \eta)^2 \right] \right\} d\xi d\eta$$

Convolution

$$U(x, y) = \frac{e^{ikz}}{i\lambda z} e^{i \frac{k}{2z} (x^2 + y^2)} \iint_{\pm\infty} U(\xi, \eta) e^{i \frac{k}{2z} (\xi^2 + \eta^2)} \exp \left[-i \frac{2\pi}{\lambda z} (x\xi + y\eta) \right] d\xi d\eta$$

Fourier Transform

Principle of Wave Propagation

Fraunhofer Approximation

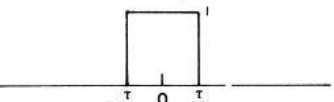
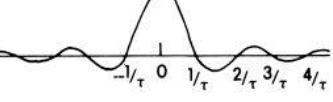
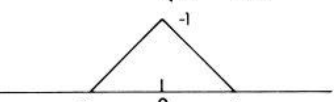
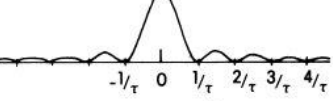
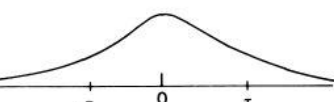
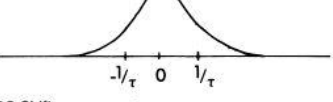
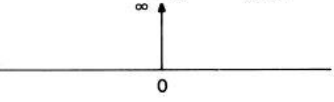
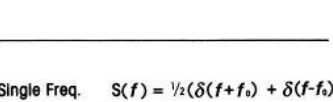
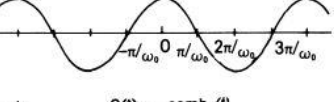
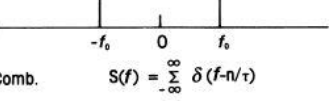
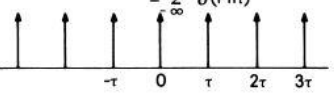
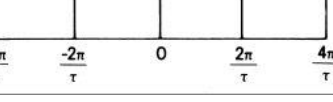
$$z \gg \frac{k}{2} (\xi^2 + \eta^2)_{\max}$$

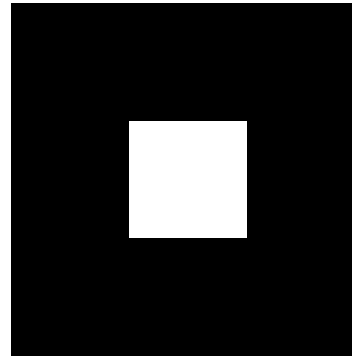
$$i \frac{k}{2z} (\xi^2 + \eta^2) \rightarrow 0$$

$$U(x, y) = \frac{e^{ikz}}{i\lambda z} e^{i \frac{k}{2z} (x^2 + y^2)} \iint_{\pm\infty} U(\xi, \eta) \exp \left[-i \frac{2\pi}{\lambda z} (x\xi + y\eta) \right] d\xi d\eta$$

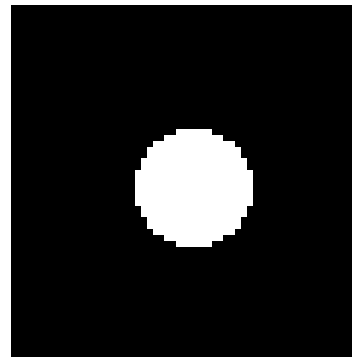
Fourier
Transform

Example 2D Fourier Transforms

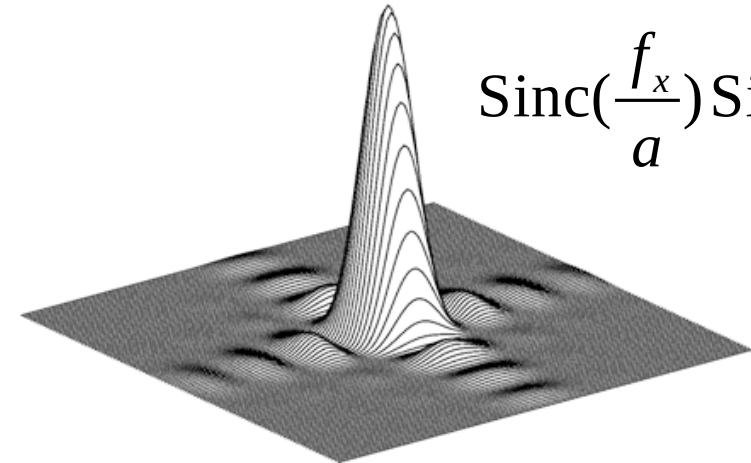
Time Function	Frequency Function
Boxcar $G(t) = \begin{cases} 1, & t < \tau/2 \\ 0, & t > \tau/2 \end{cases}$ 	Sinc $S(f) = \tau \text{sinc}(f\tau)$ $r = (1/\pi f) \sin(\pi f t)$ 
Triangle $G(t) = \begin{cases} 1- t /\tau, & t < \tau \\ 0, & t > \tau \end{cases}$ 	Sinc² $S(f) = \tau \text{sinc}^2(f\tau)$ $= (1/\pi^2 f^2 \tau) \sin^2(\pi f t)$ 
Gaussian $G(t) = e^{-1/2 t^2}$ 	Gaussian $S(f) = \tau(2\pi)^{1/2} e^{-(\pi f \tau)^2}$ 
Impulse $G(t) = \delta(t)$ $\infty, t=0$ $0, t \neq 0$ 	DC Shift $S(f) = 1$ 
Sinusoid $G(t) = \cos \omega_0 t$ 	Single Freq. $S(f) = 1/2(\delta(f+f_0) + \delta(f-f_0))$ 
Comb. $G(t) = \text{comb}(t)$ $= \sum_{n=-\infty}^{\infty} \delta(t-n\tau)$ 	Comb. $S(f) = \sum_{n=-\infty}^{\infty} \delta(f-n/\tau)$ 



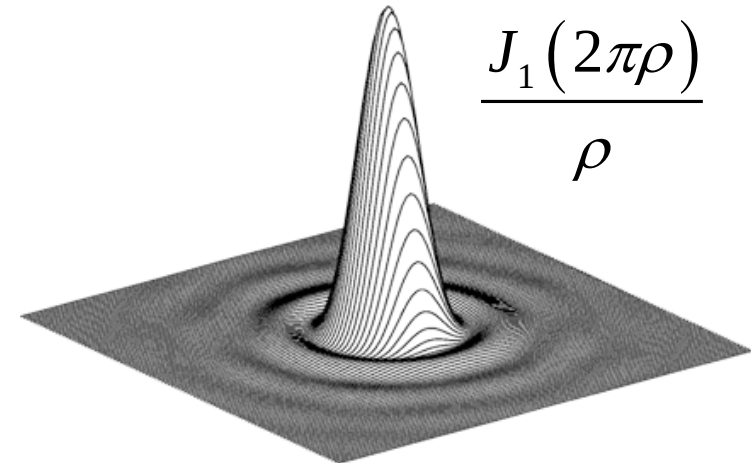
Rect(ax, by)



Circ(r)



$$\text{Sinc}\left(\frac{f_x}{a}\right) \text{Sinc}\left(\frac{f_y}{b}\right)$$



$$\frac{J_1(2\pi\rho)}{\rho}$$

Gaussian Beam Optics

Helmholtz equation $(\nabla^2 + k^2) A(P) = 0$

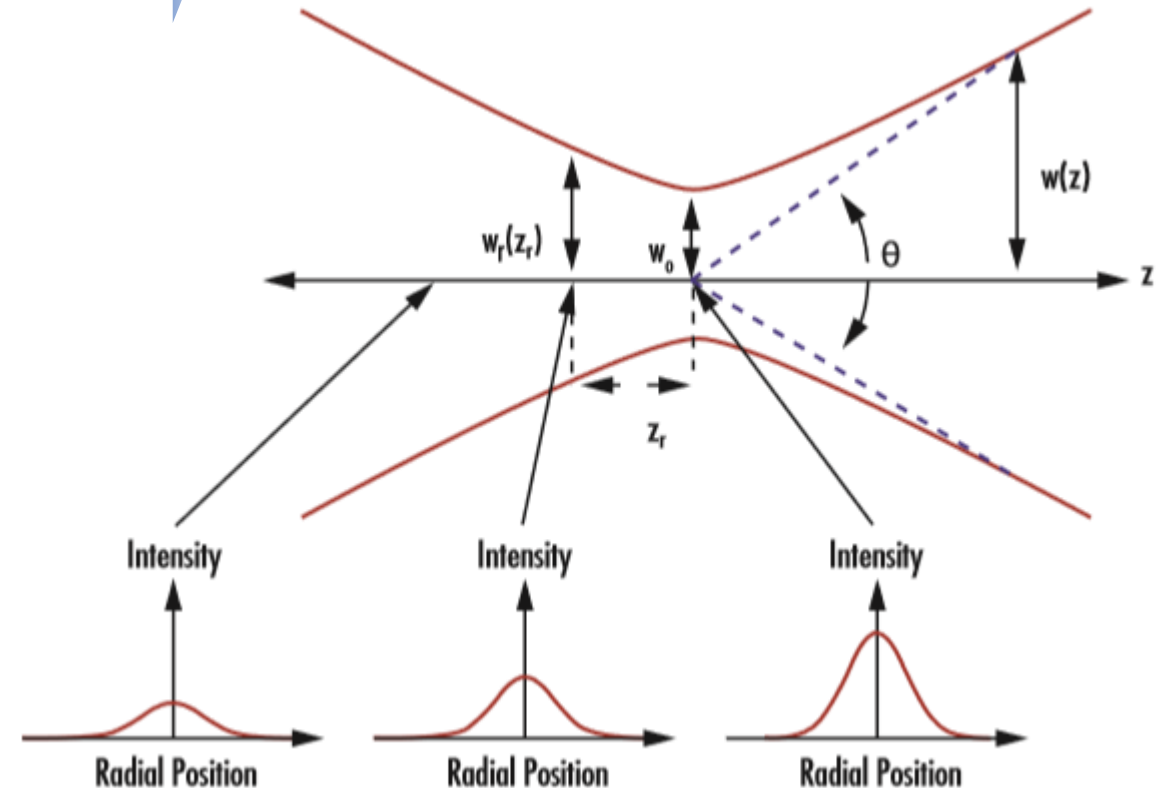
Paraxial approximation $A(P) = u(r) \exp(ikz)$



$$\nabla_{\perp}^2 u + 2ik \frac{\partial u}{\partial z} = 0 \quad \nabla_{\perp}^2 \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

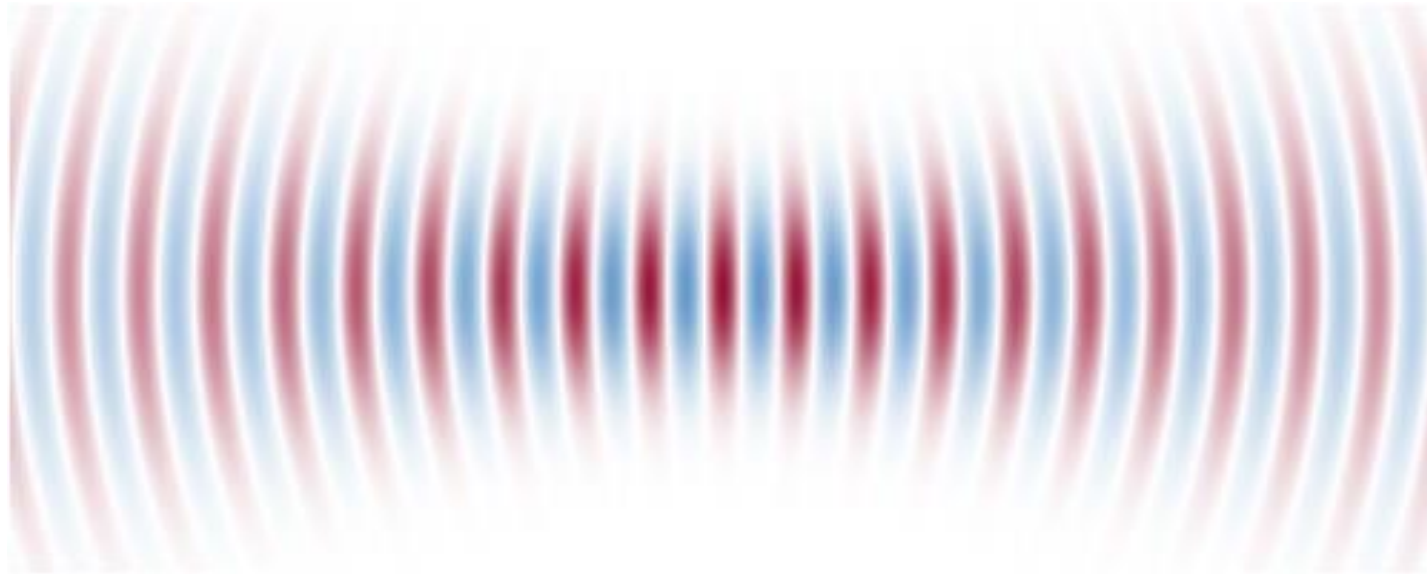
$$I(r, z) = I_0 \frac{w_0^2}{w(z)^2} \exp\left[-\frac{2r^2}{w(z)^2}\right]$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \quad z_R = \frac{\pi w_0^2}{\lambda}$$

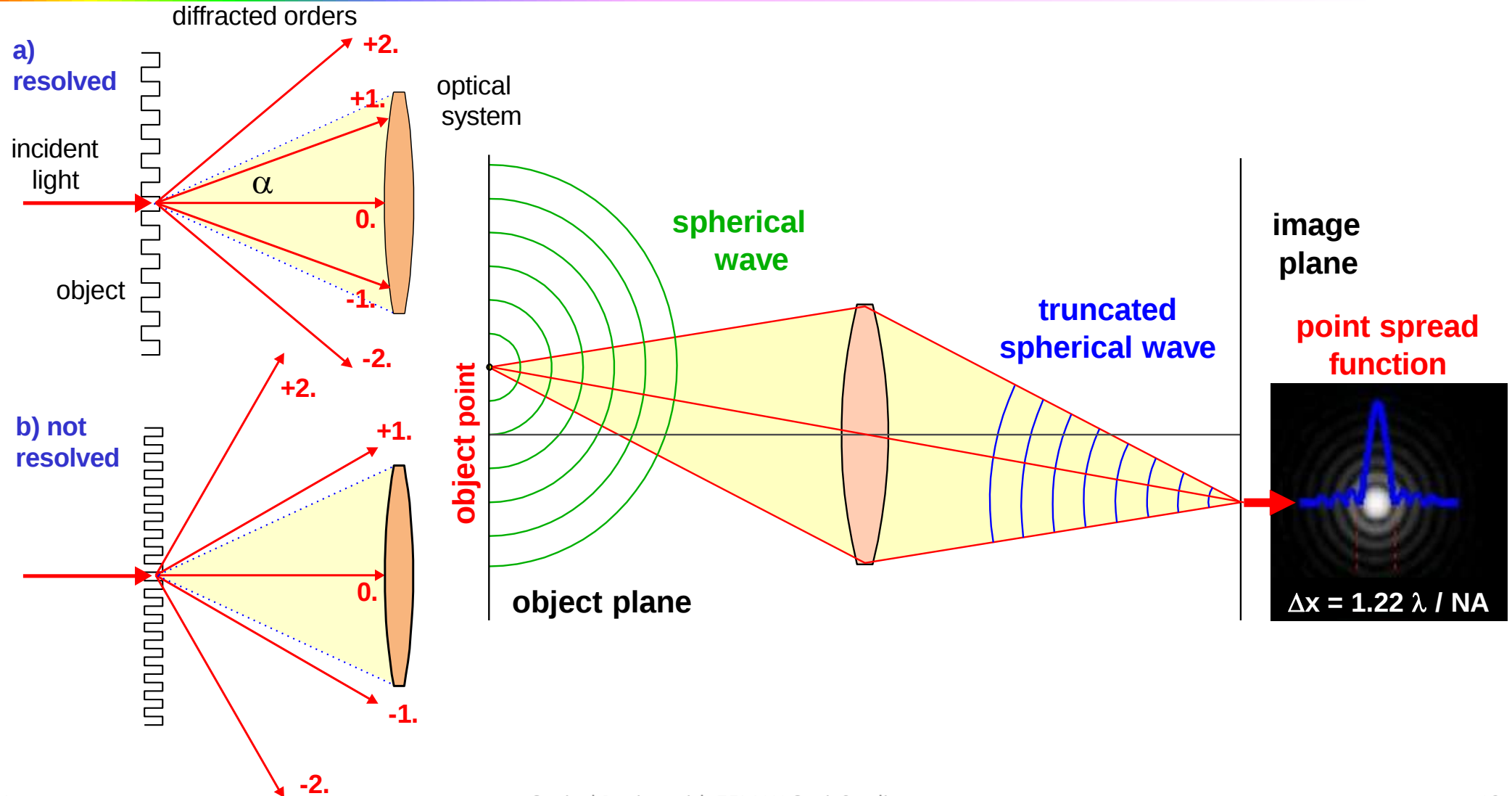


Gaussian Beam Propagation

$$\mathbf{E}(r, z) = E_0 \hat{\mathbf{e}} \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w(z)^2}\right] \exp(-ikz) \exp\left[-ik \frac{r^2}{2R(z)}\right] \exp[-i\psi(z)]$$



Lens as a Filter

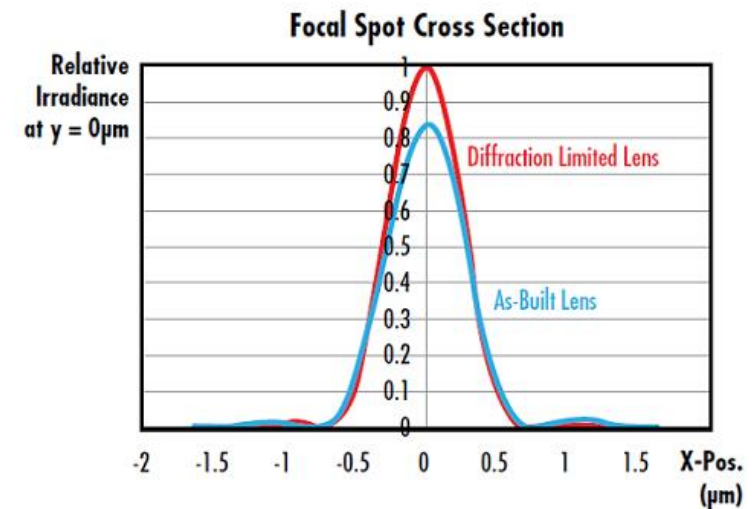
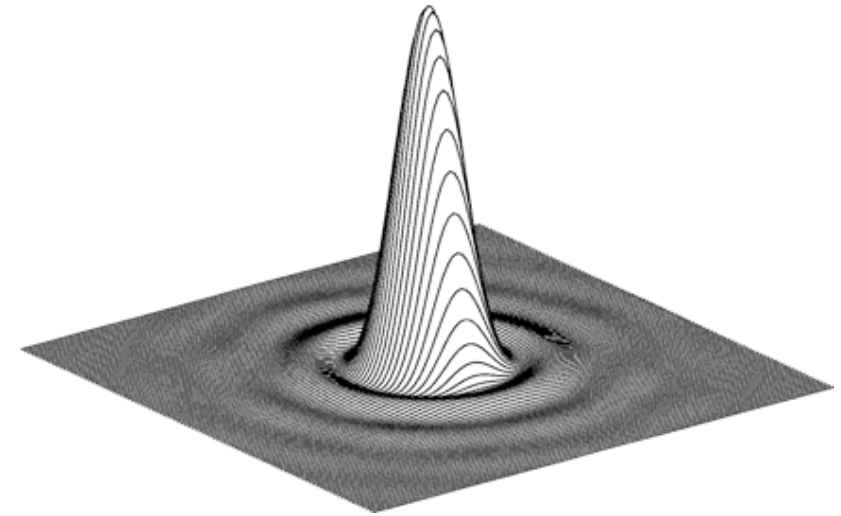


Modulation Transfer Function

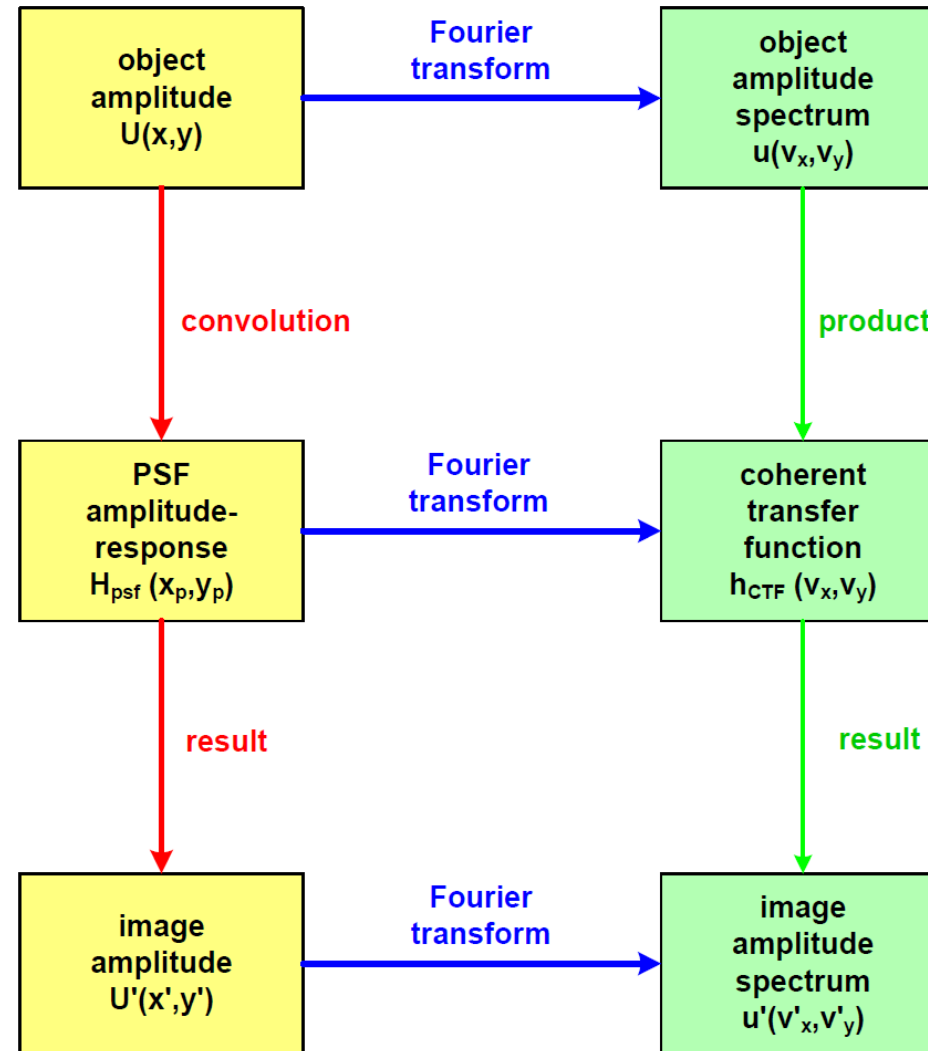
- **MTF:** Quotient of the **contrast** (or **modulation depth**) in the image plane and the contrast in the object plane, for an object with a sinusoidal intensity distribution, as a function of **spatial frequency**
- Display modes of MTF often used in optical design:
 - MTF for different wavelengths, or an average over the spectrum
 - MTF for frequencies in radial (denoted by S) and tangential direction (denoted by T)
 - MTF (S and T) values for discrete frequencies as functions of defocus; this shows astigmatism and defocus
 - MTF (S and T) values for discrete frequencies as functions of the field height
 - The MTF of a system without aberrations is used as a benchmark

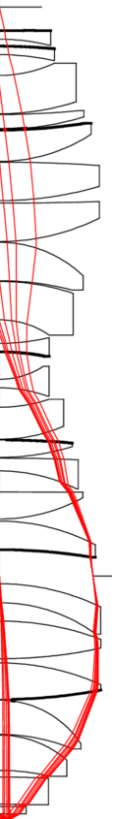
Point Spread Function

- **PSF:** Normalized intensity of the diffraction image pattern of a point object
- Useful diagnostic for optical systems with small aberrations
- Strehl number: the quotient of the intensity at the center of the PSF divided by the central intensity of an ideal PSF



PSF vs MTF

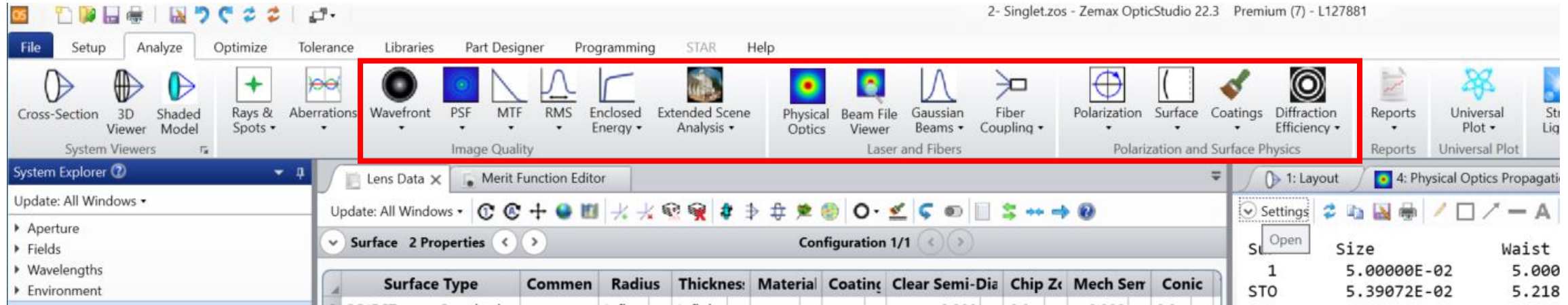




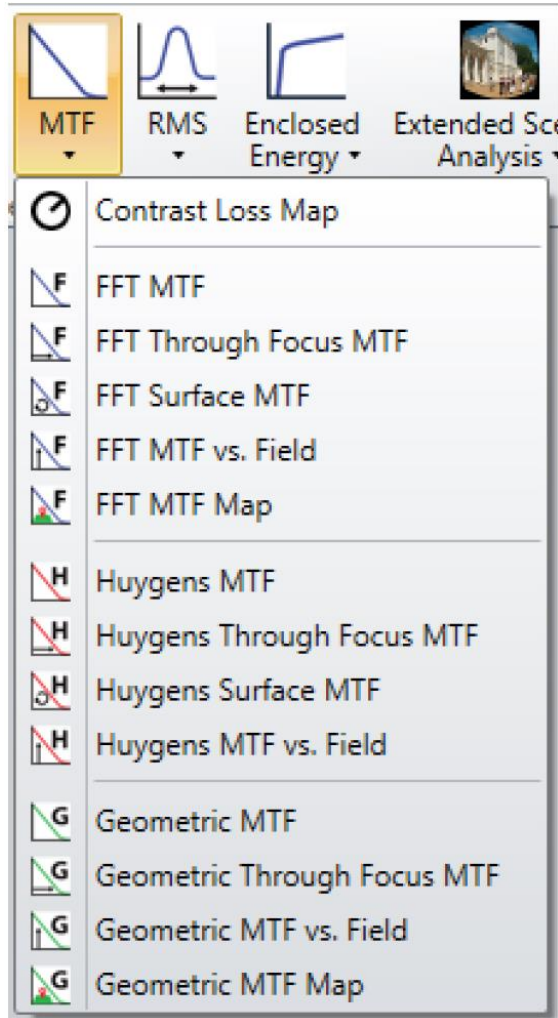
ZEMAX

OpticStudio

ZEMAX OpticStudio: Physical Optics



ZEMAX OpticStudio: MTF



FFT MTF

- Computes the diffraction MTF for all field positions using an FFT algorithm
- Fast
- With assumptions
- Only accurate at $F/\# > 1.5$

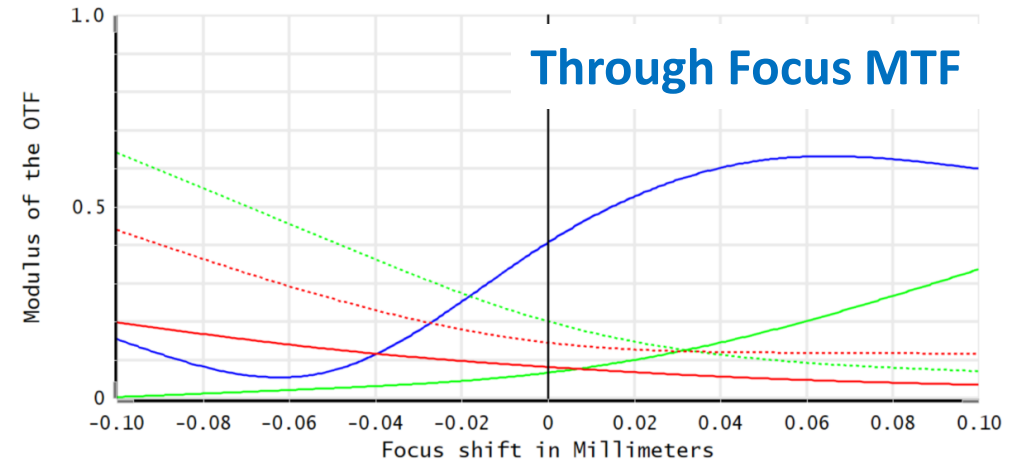
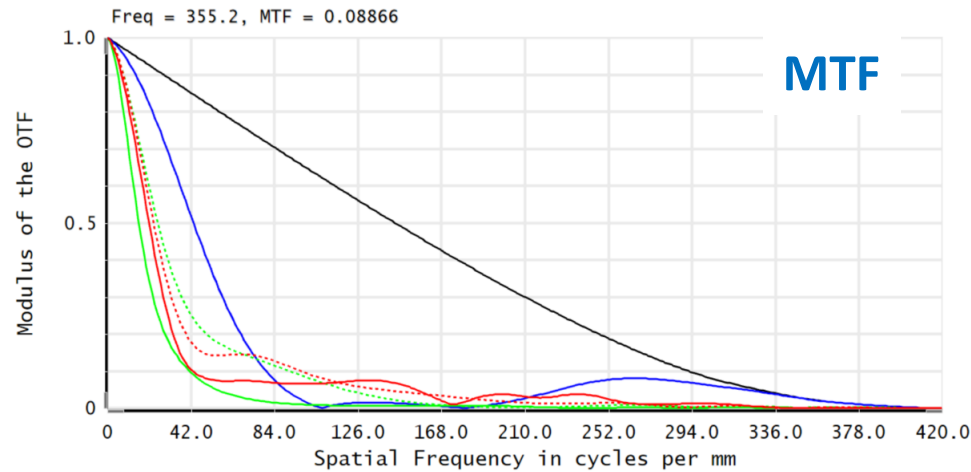
Huygens MTF

- Computes the diffraction MTF using a Huygens direct integration algorithm
- More accurate in most cases
- Slower

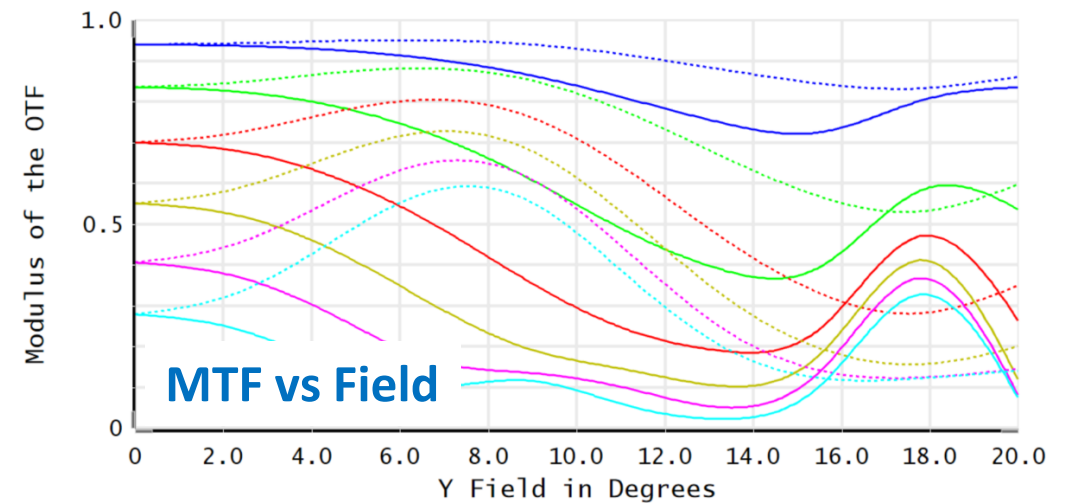
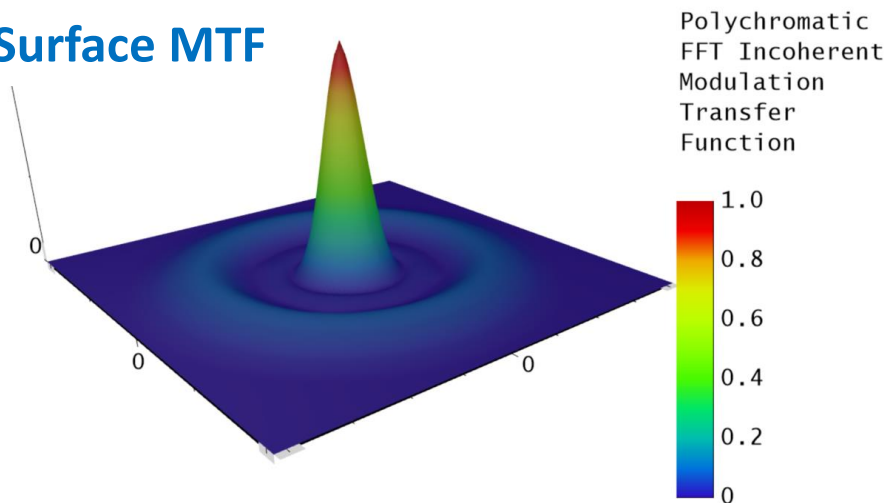
Geometric MTF

- Computes the geometric MTF, which is an approximation to the diffraction MTF based upon ray aberration data
- Very accurate for systems with large aberrations

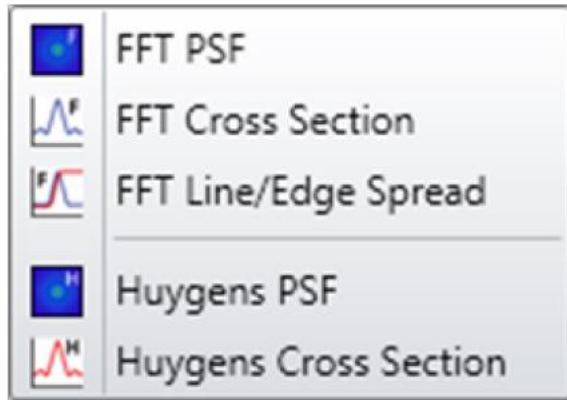
ZEMAX OpticStudio: MTF



Surface MTF



ZEMAX OpticStudio: PSF

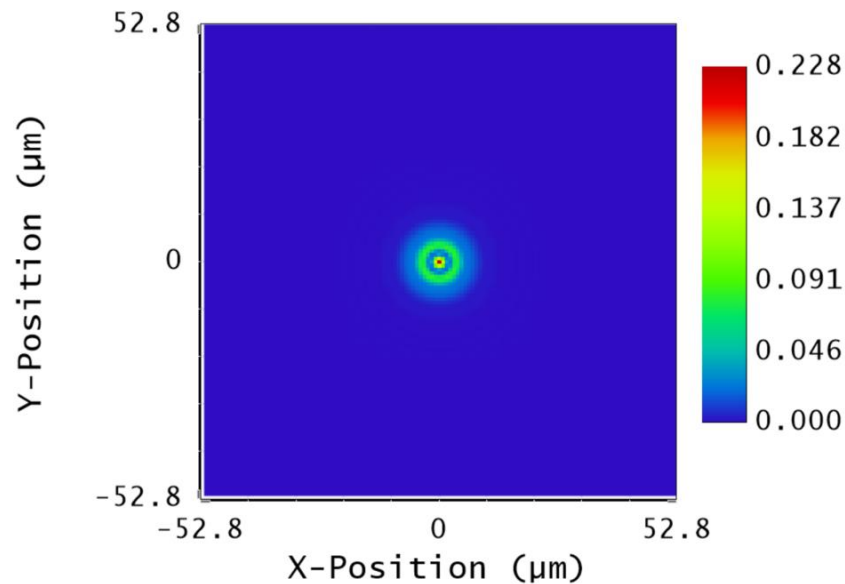


FFT PSF

- Computes the diffraction point spread function (PSF) using the Fast Fourier Transform (FFT) method
- Fast
- With assumptions
- Only accurate at $F/\# > 1.5$

Huygens PSF

- Computes the diffraction PSF using direct integration of Huygens wavelets method
- Strehl ratio also computed
- More accurate
- More general
- Slower



ZEMAX OpticStudio: Gaussian Beams

Paraxial Gaussian Beam

Paraxial Gaussian Beam



Compute ideal and M-squared-mixed-mode Gaussian beam data, such as beam size, beam divergence, and waist locations, as a given input beam propagates through the lens system

Shortcut Key: Ctrl+B

1: Paraxial Gaussian Beam Data

Settings

Wavelength: 2 M2 Factor: 1

Waist Size: 0.05 Surf 1 to Waist: 0

----- Interactive Analysis -----

Orient: Y-Z Update

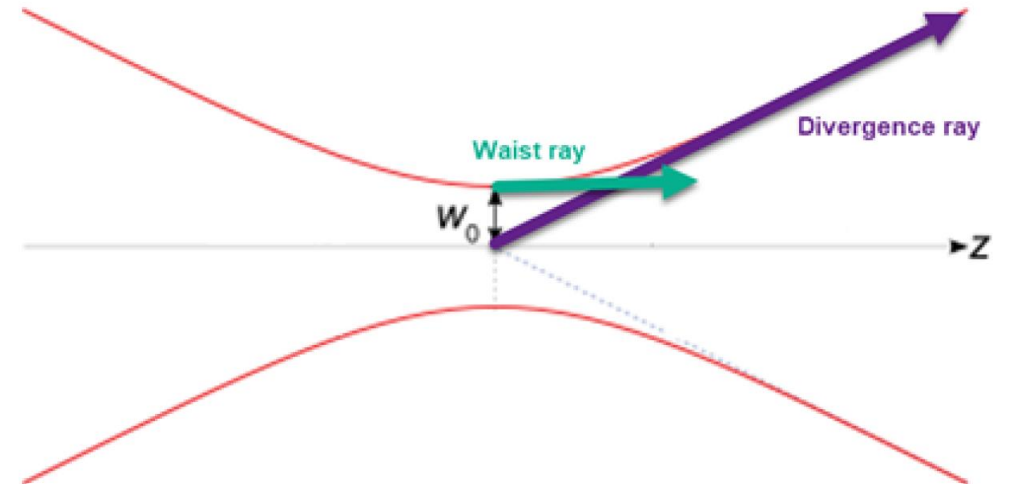
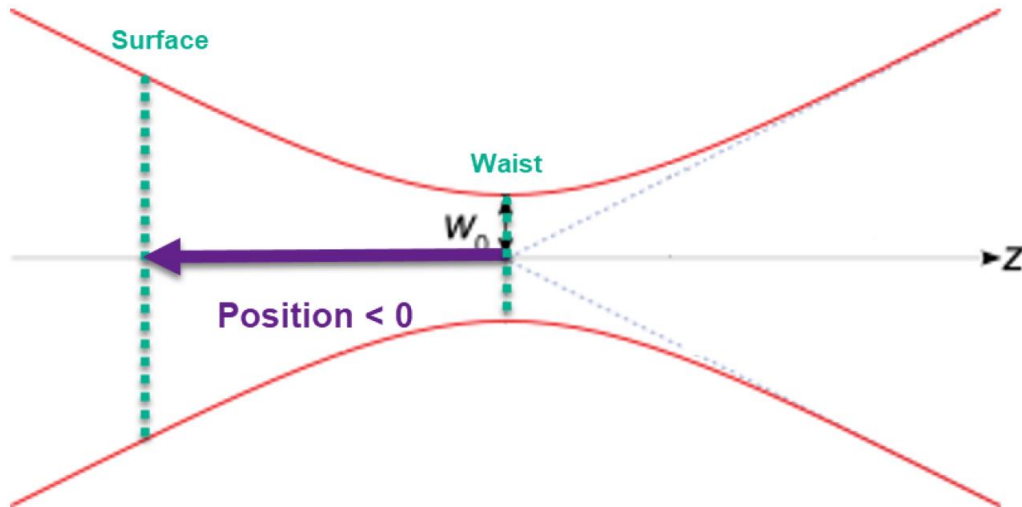
Surface: 13

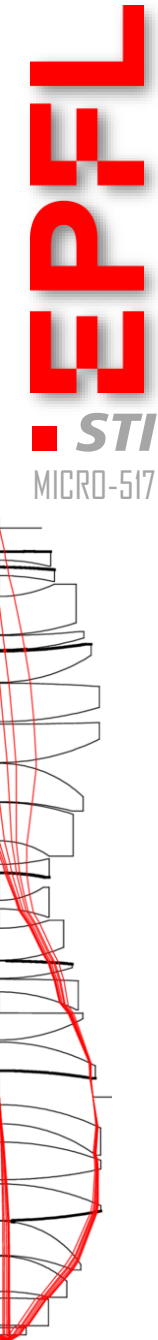
Size	3.720546E-001	Radius	4.394163E+002
Waist	1.899454E-001	Rayleigh	1.928971E+002
Position	3.248860E+002	Divergence	9.846978E-004
Wavelength	5.876000E-001	M2 Factor	1.000000E+000

☒ Auto Apply Apply OK Cancel Save Load Reset

Paraxial Gaussian Beam Parameters

ZEMAX OpticStudio: Gaussian Beams





ZEMAX OpticStudio: Image Simulation

Example 1, A singlet eyepiece.zos - Zemax OpticStudio 22.3 Premium (7) - L127881

File Setup Analyze Optimize Tolerance Libraries Part Designer Programming STAR Help

Cross-Section 3D Shaded Model Rays & Spots Aberrations Wavefront PSF MTF RMS Enclosed Energy Extended Scene Analysis Physical Optics Beam File Viewer Gaussian Beams Fiber Coupling Polarization Surface Coatings Diffraction Efficiency Reports Universal Plot Stray Light Biocular Systems PAL/Freeform NSC Raytracing Applications

System Explorer Update: All Windows

- Aperture
- Fields
- Wavelengths
- Environment
- Polarization
 - ☒ Convert Thin Film Phase To Ray Equivalent
 - ☒ Unpolarized
 - Method: X Axis Reference
- Advanced
- Ray Aiming
- Material Catalogs
- Title/Notes
- Files
- Units
- Cost Estimator

Surface Properties

Update: All Windows

Surface Type

Surface	Type	Coatir	Clear Semi	Chip Z	Mech Se	Conic	TCE x 1E-6
0	OBJE Standard	11.500	0.0...	11.500	0.0...	0.000	0.000
1	Standard	11.500	0.0...	11.500	0.0...	0.000	0.000
2	(aper Standard	8.000	U 0.0...	8.000	0.0...	0.000	-
3	(aper Standard	8.000	U 0.0...	8.000	0.0...	0.000	0.000
4	STOP Standard	2.500	U 0.0...	2.500	0.0...	0.000	0.000
5	IMAG Standard	582.780	0.0...	582.780	0.0...	0.000	0.000

Image Simulation

- Geometric Image Analysis
- Geometric Bitmap Image Analysis
- Light Source Analysis
- Partially Coherent Image Analysis
- Extended Diffraction Image Analysis
- Relative Illumination
- IMA and BIM File Viewer
- Bitmap File Viewer

Configuration 1/1

4: Prescription Data

Settings

System/Prescription Data

File : C:\Users\Ye Pu\Documents\Zemax\Samples\Sequential\Image Simulation\Example 1, A si
Title: Simulating the image formed by a singlet eyepiece
Date : 11/21/2022

LENS NOTES:

An input bitmap (left) is convolved with a PSF Grid (middle) to form the output image (right). Note that screen resolution may mean that not all elements in the 7x7 grid appear in the middle window: simply maximize the window to see the entire grid.

Note the distortion, and the variation of focus over the field of view.

This lens is so highly aberrated that the relative illumination (variation of brightness)

2: Image Simulation 1

Settings

Standard

Image Simulation: PSF Grid

Simulating the image formed by a singlet eyepiece
11/21/2022
Field height is 13.8000 Millimeters.
Field position: 0.00 mm
Surface: 5

Zemax
Zemax OpticStudio 22.2.1
Example 1, A singlet eyepiece.zos
Configuration 1 of 1

3: Image Simulation 2

Settings

Standard

Image Simulation: Diffraction Aberrations

Simulating the image formed by a singlet eyepiece
11/21/2022
Object height is 13.8000 Millimeters.
Field position: 0.00 mm
Center: chief ray
Image size is 832.0000 W x 624.0000 H (Millimeters)

Zemax
Zemax OpticStudio 22.2.1
Example 1, A singlet eyepiece.zos
Configuration 1 of 1

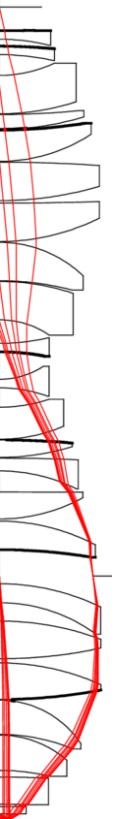
1: 3D Layout

Settings

Line Thickness

10 mm

Simulating the image formed by a singlet eyepiece | EFFL: 25.1062 | WFNO: 200 | ENPD: 10.3408 | TOTR: 1000



ZEMAX

OpticStudio

Hands-on Time

Homework

To be announced