PH 301

ENGINEERING OPTICS

Lecture_9

Lens Design

Optical lens design is the process of designing a lens to meet a set of performance requirements & constraints, including cost & manufacturing limitations.

Parameters:

- **Surface profile types (spherical, aspheric, holographic, diffractive, etc.),**
- **Radius of curvature,**
- **Distance to next surface,**
- **Material type, &**
- **Optionally tilt & decenter.**

Lens design process is computationally intensive, using ray tracing or other techniques to model how lens affects light that passes through it.

Performance requirements

- **Optical performance (image quality): Choice of image quality metric is application specific.**

  - **Encircled energy,**
  - **Modulation transfer function,**
  - **Strehl ratio,**
  - **Ghost reflection control, &**
  - **Pupil performance (size, location & aberration control)**

- **Physical requirements: Weight, static volume, dynamic volume, centre of gravity & overall configuration requirements.**

- **Environmental requirements: ranges for temperature, pressure, vibration, & electromagnetic shielding.**

- **Design constraints include realistic lens element centre & edge thicknesses, minimum & maximum air-spaces between lenses, maximum constraints on entrance & exit angles, physically realizable glass index of refraction & dispersion properties.**

Spherical lenses

Aspheric lenses

Achromatic lenses

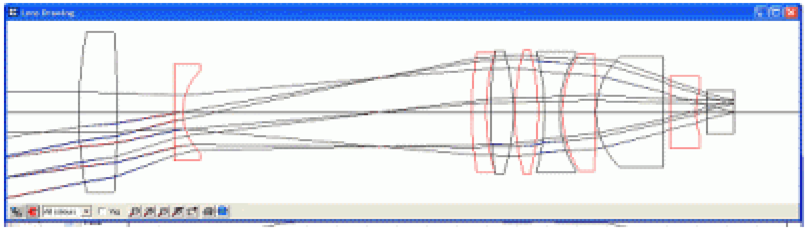
Cylindrical lenses

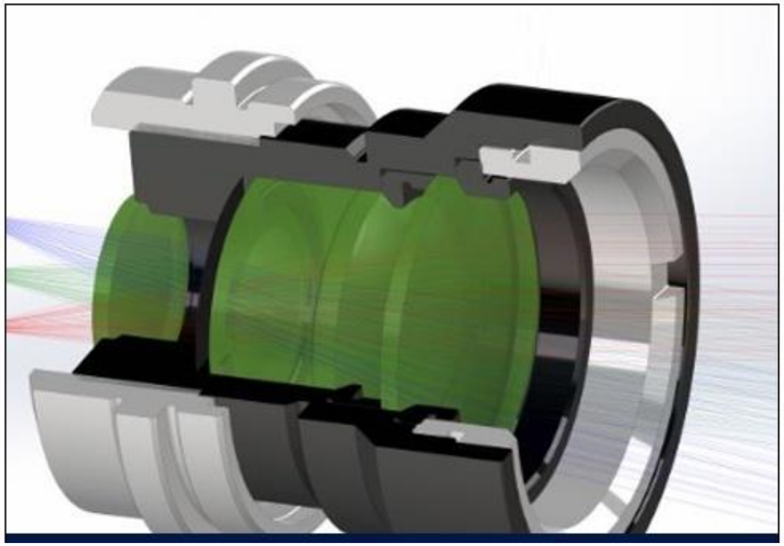
Objective lenses

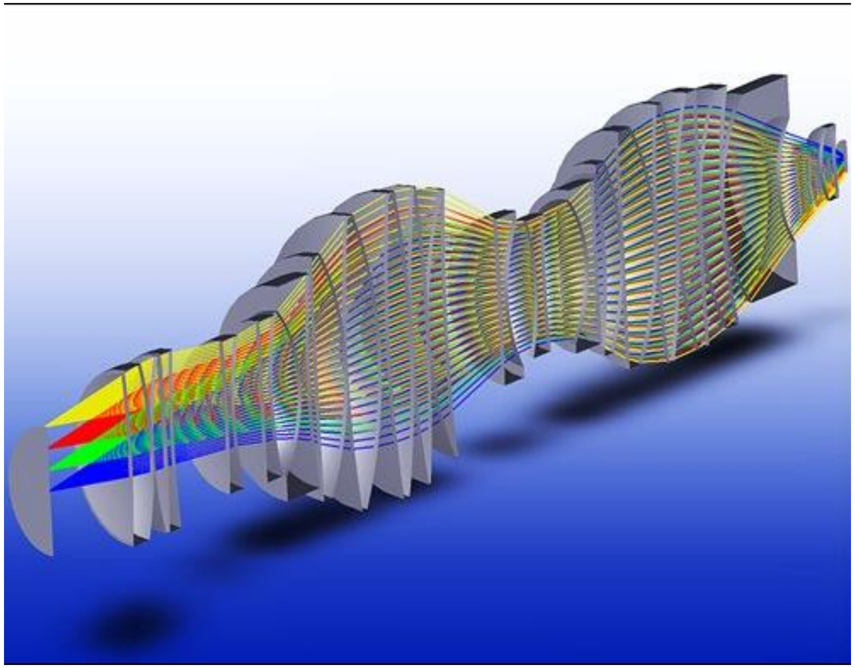
Micro lenses

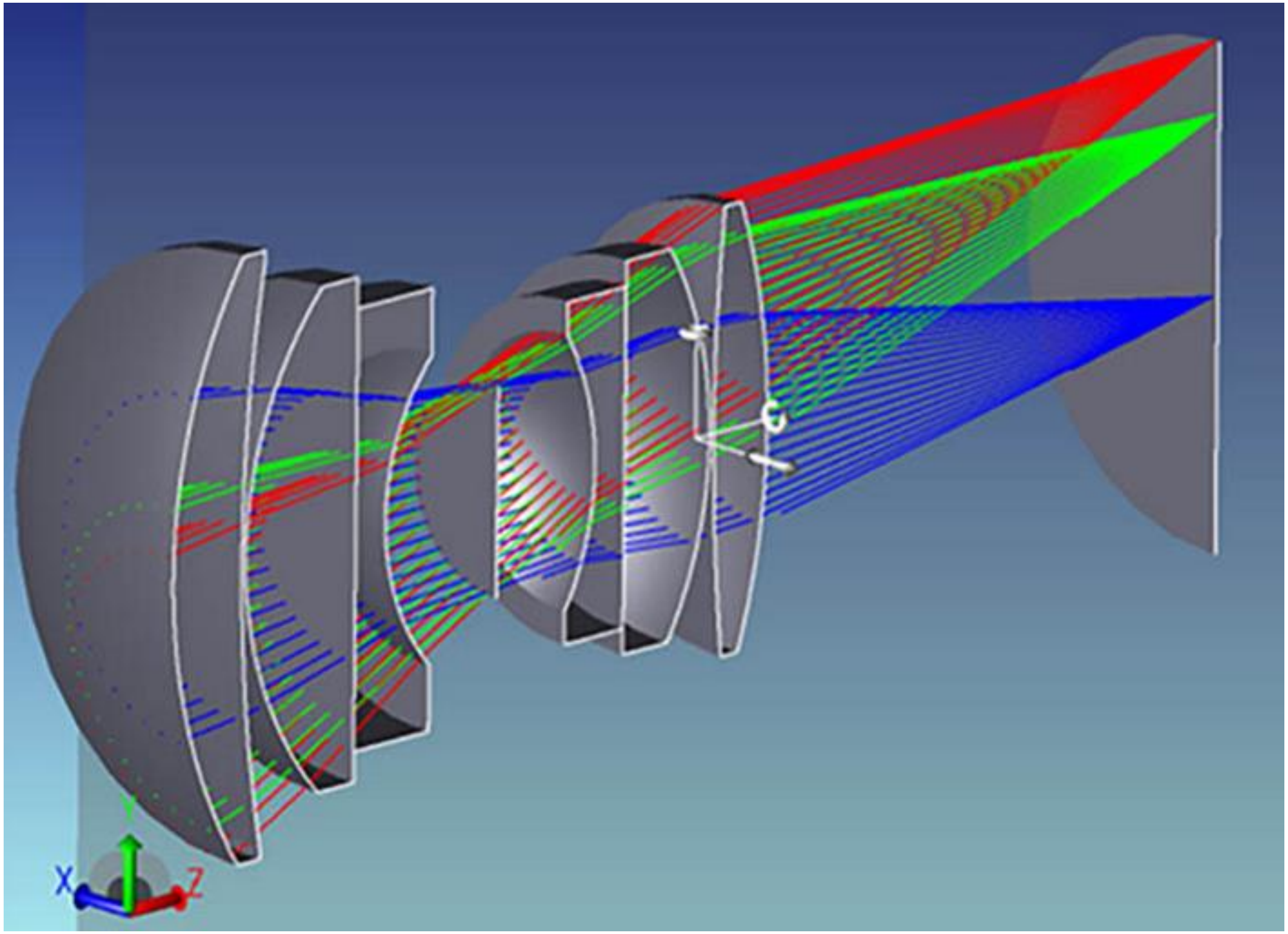
Lens Design

- Optics Software for Layout & Optimization (OSLO), Univ. Rochester
- Zemax software
- WinLens3D Basic, Qioptiq
- LightTrans GmbH








Y
X
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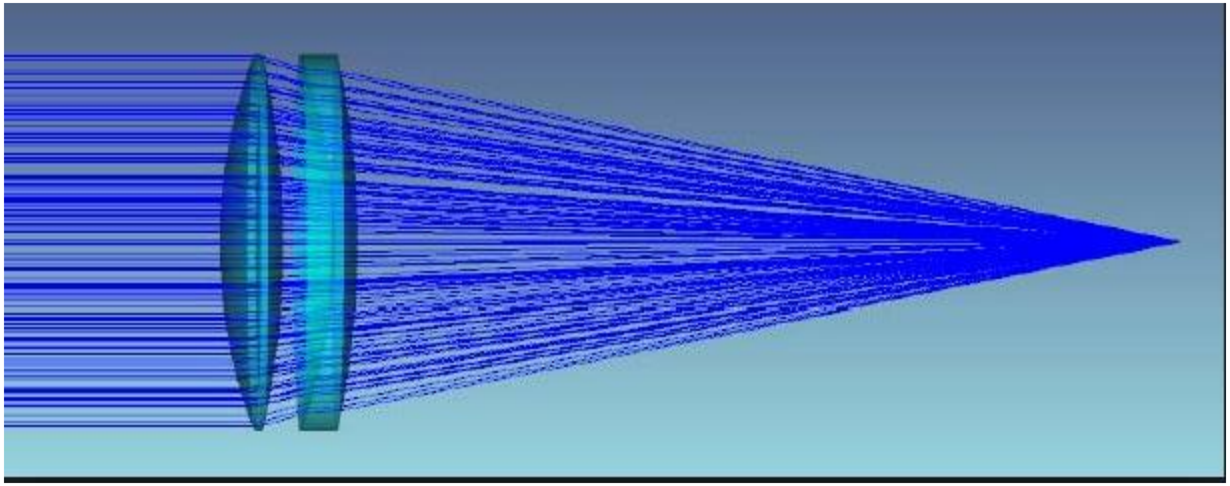
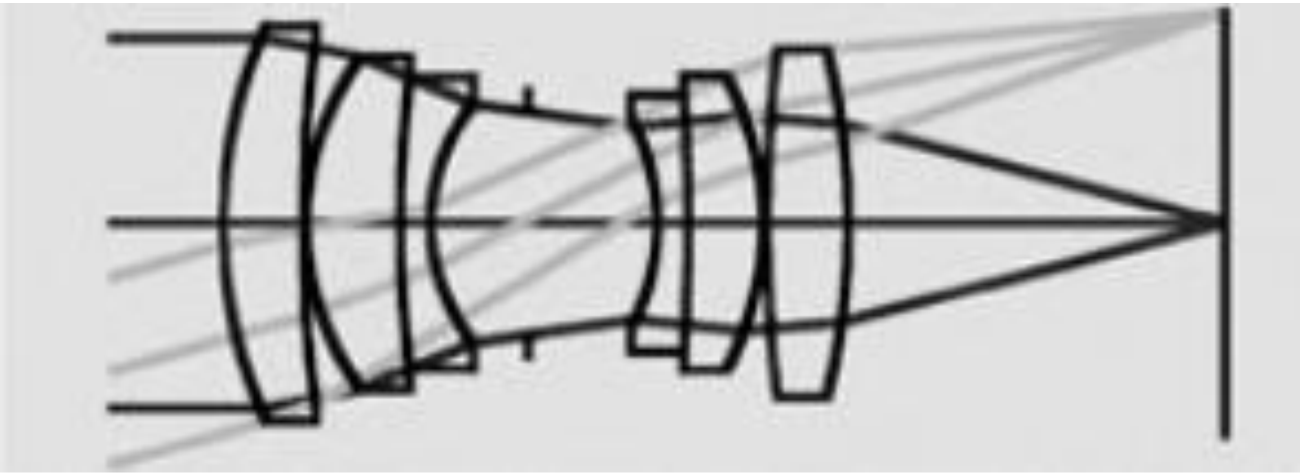
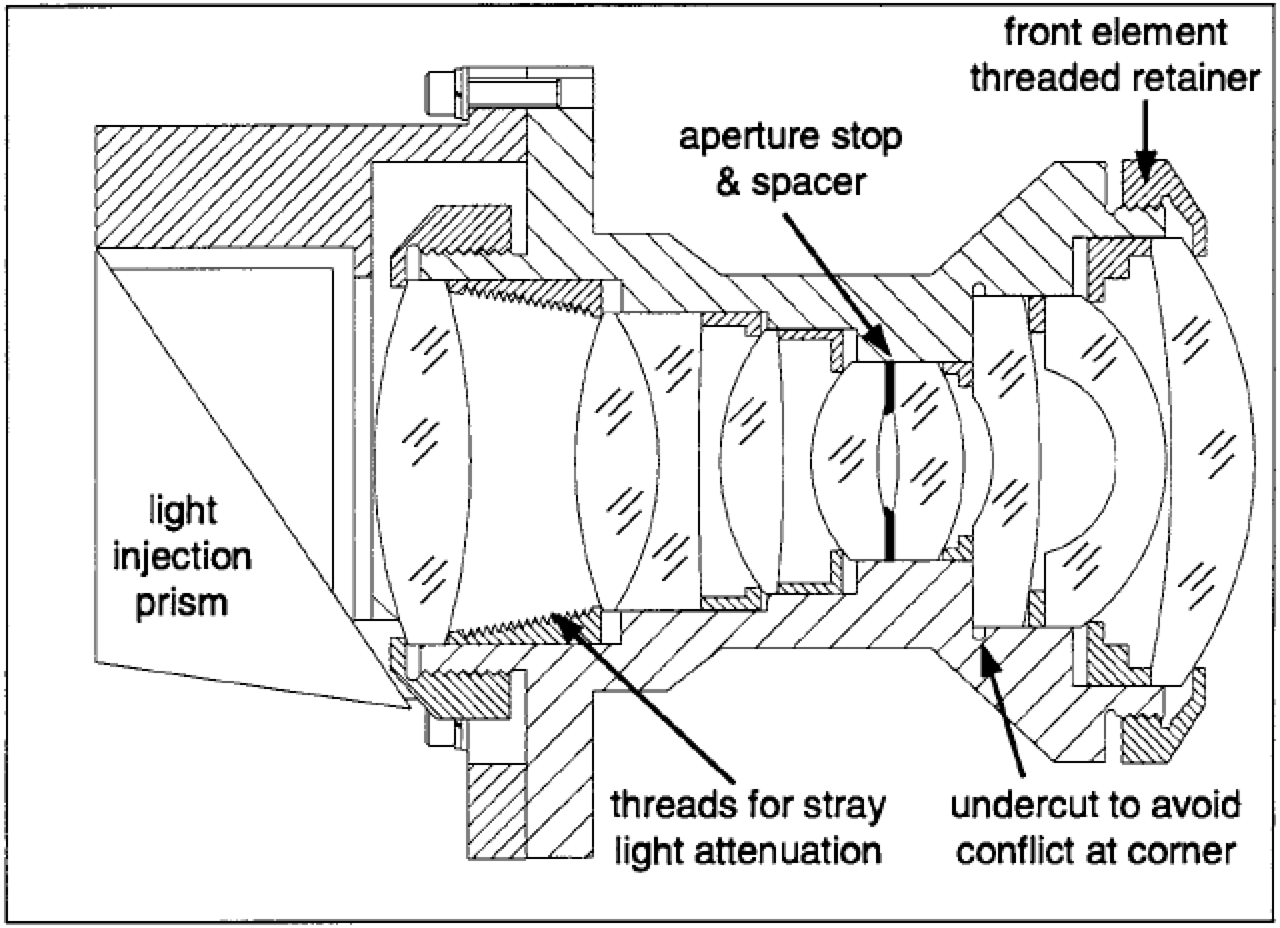
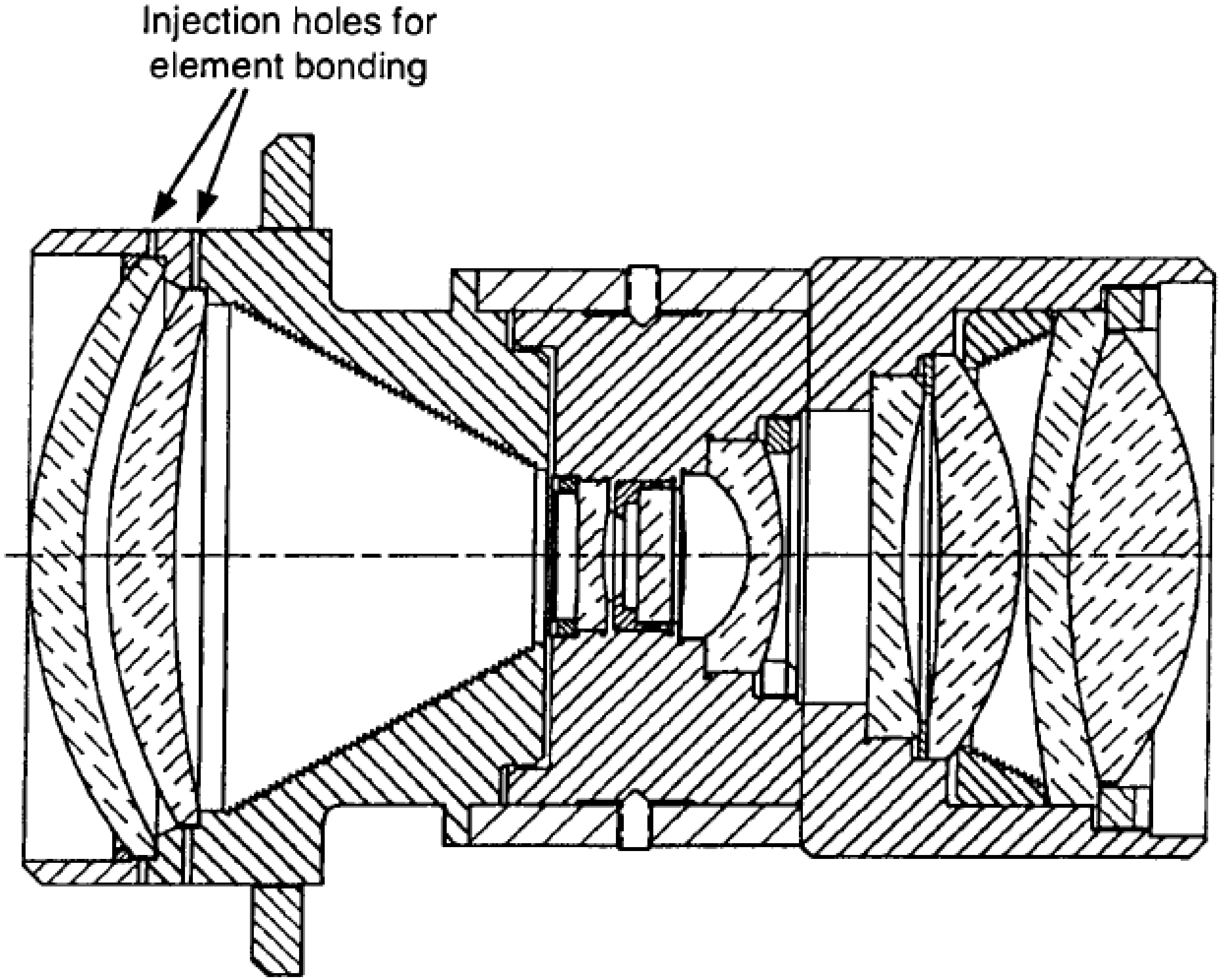
Lens Design





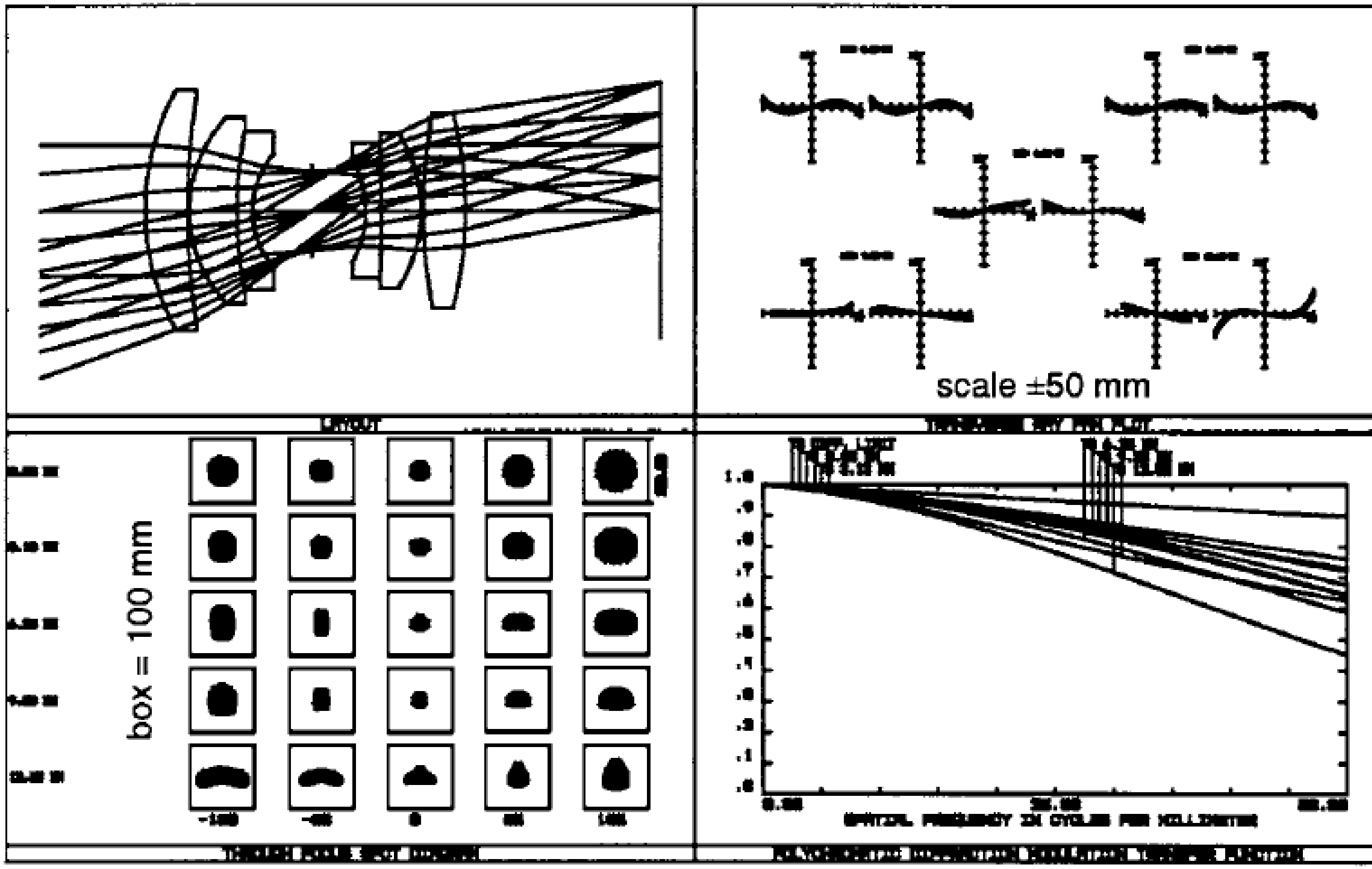


Typical lens housing

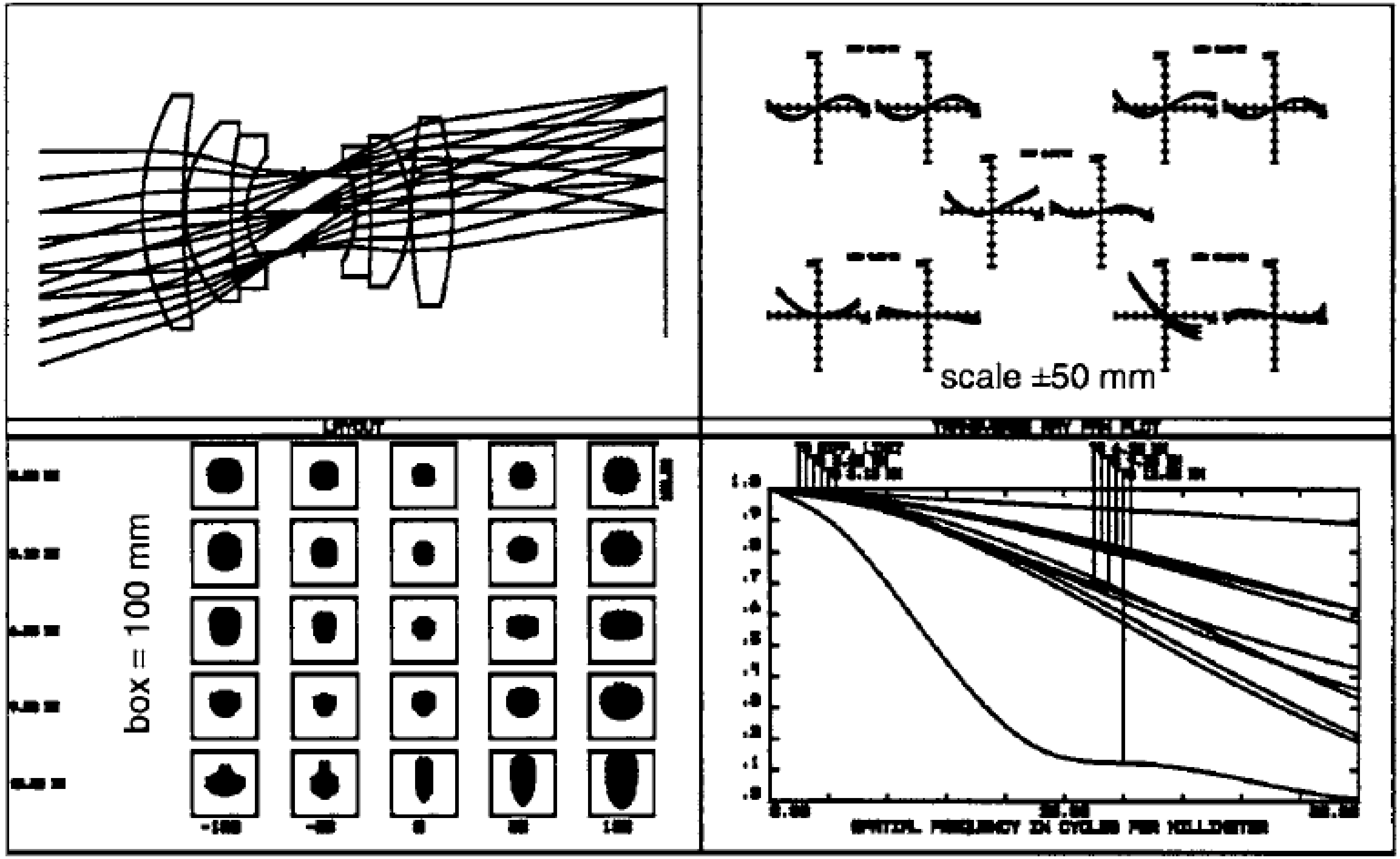


Typical lens housing

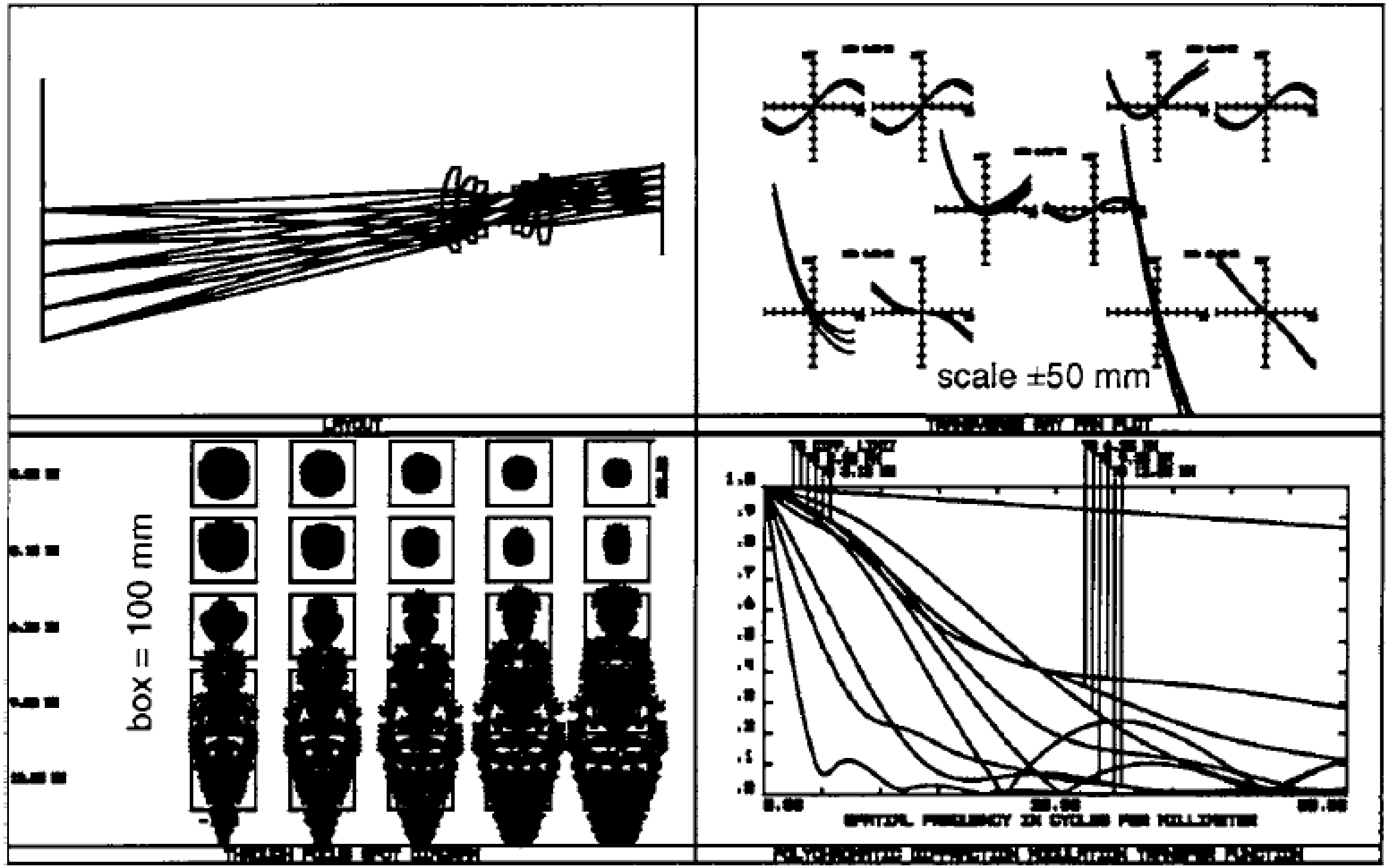
Modulation transfer function (MTF) data are plotted to 50 line pairs/mm.



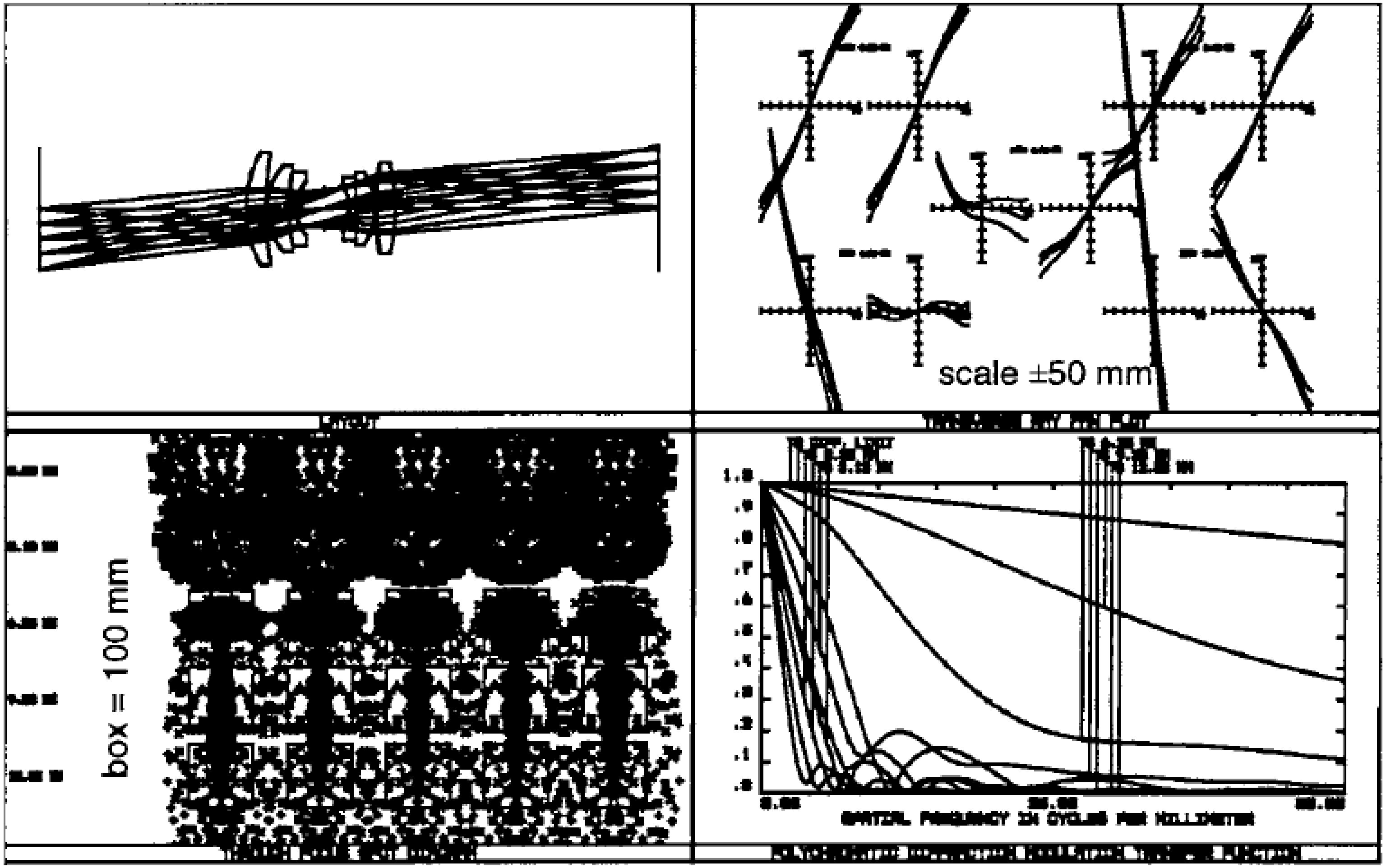
A 35 mm focal length *f*/2.8 lens at infinity



A 35 mm focal length *f*/2.8 lens at 500 mm object distance

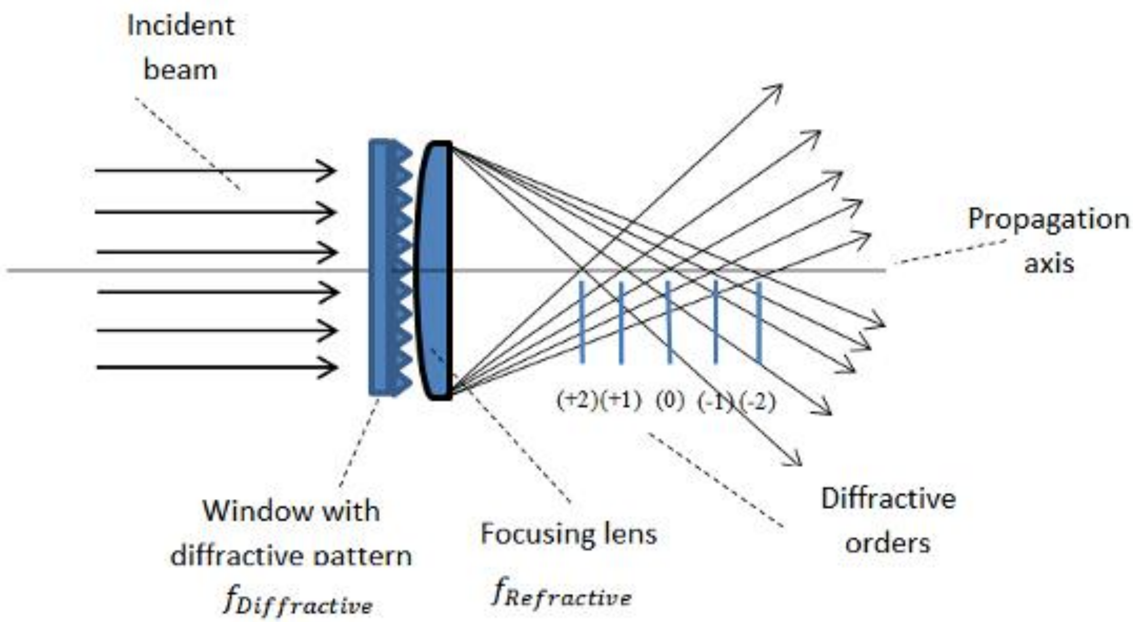


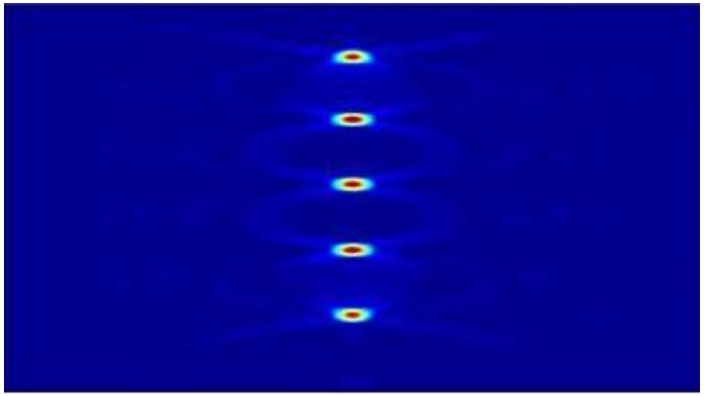
A 35 mm focal length *f*/2.8 lens at 100 mm object distance



A 35 mm focal length *f*/2.8 lens at unit magnification (32.41 mm object distance)

Multifocal Diffractive Lens





The distance between the focal spots can be described by the equation

$$\frac{1}{f_m} = \frac{1}{f_{\text{Refractive}}} + \frac{m}{f_{\text{Diffractive}}}, \text{ for } m = \pm 1, \pm 2, \pm 3\ldots,$$

where f_m is the focal Length for the mth diffractive order,

$f_{\text{Refractive}}$ is the focal length of the refractive lens, and

$f_{\text{Diffractive}}$ is the focal length of the diffractive lens.

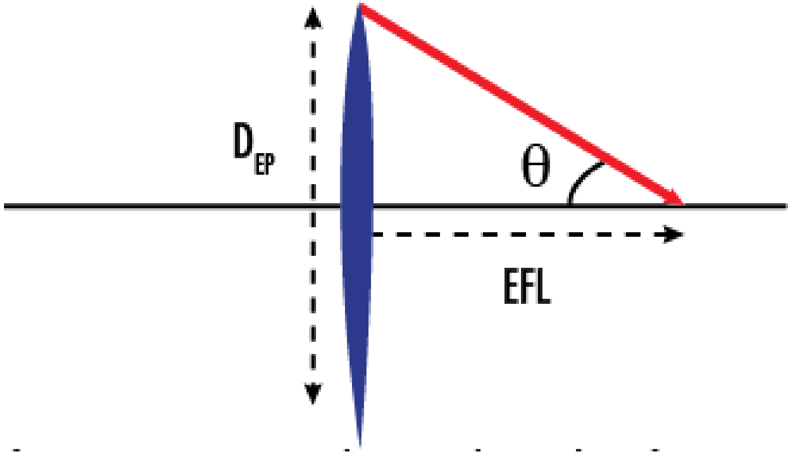
f/# (Lens Iris/Aperture Setting)

f/# **setting on a lens controls many of lens's parameters:**

- **overall light throughput**
- **depth of field**
- **ability to produce contrast at a given resolution**

f/# **is defined as ratio of effective focal length (EFL) of lens to effective aperture diameter.**

$$f/\# = \frac{EFL}{D_{EP}}$$



Projection of image space marginal ray angle to edge of exit pupil

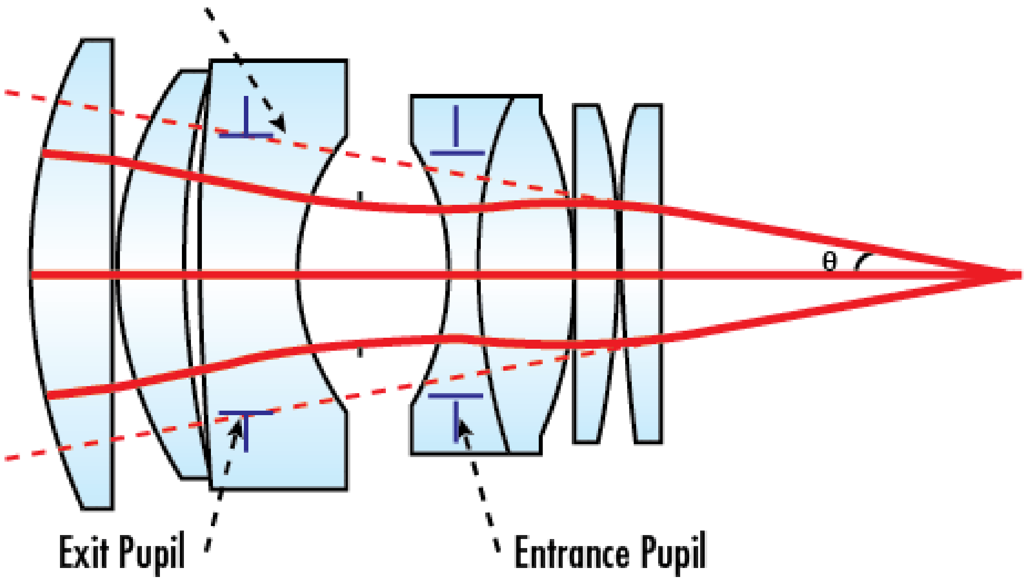
f/#	Lens Aperture Diameter (mm)	Aperture Opening Area (mm^2)
1	25.0	490.8
1.4	17.9	251.6
2	12.5	122.7
2.8	8.9	62.2
4	6.3	31.2
5.6	4.5	15.9
8	3.1	7.5

Relationship between *f/#* & effective area for a 25 mm singlet lens

f/# & Numerical Aperture

Numerical aperture (NA) or cone angle of a lens is defined as sine of the marginal ray angle in image space.

$$NA = \frac{1}{2(f/\#)}$$



Visual representation of f/#

Numerical Aperture

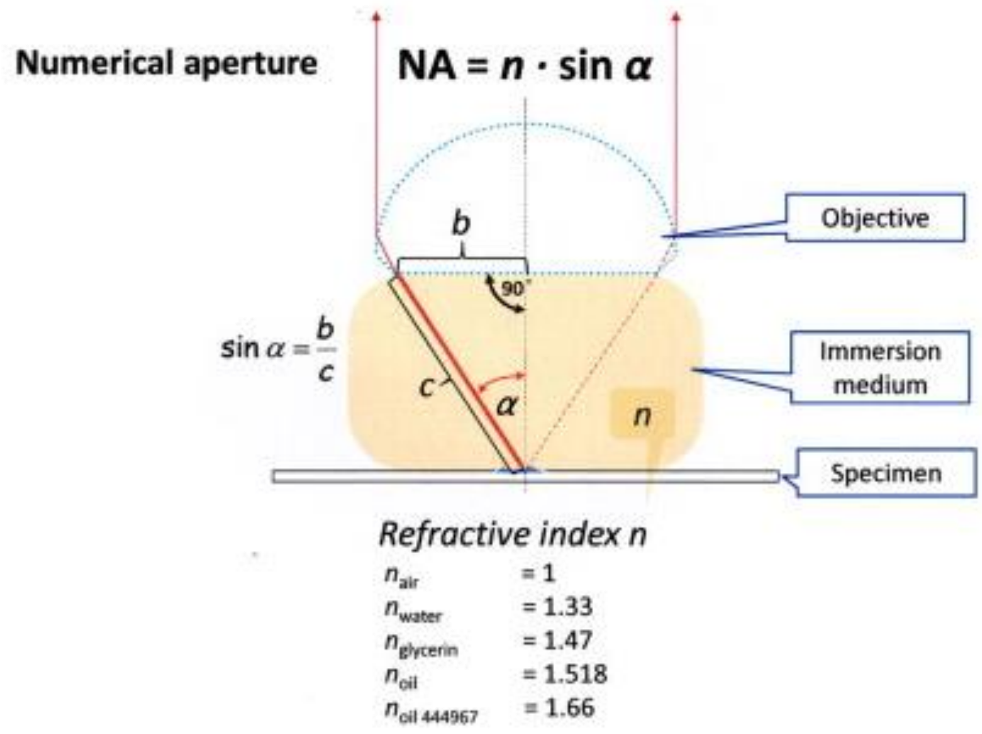
f/#	Numerical Aperture
1.4	0.36
2	0.25
2.8	0.18
4	0.13
5.6	0.09
8	0.06
11	0.05
16	0.03

Relationship between *f/#* & numerical aperture

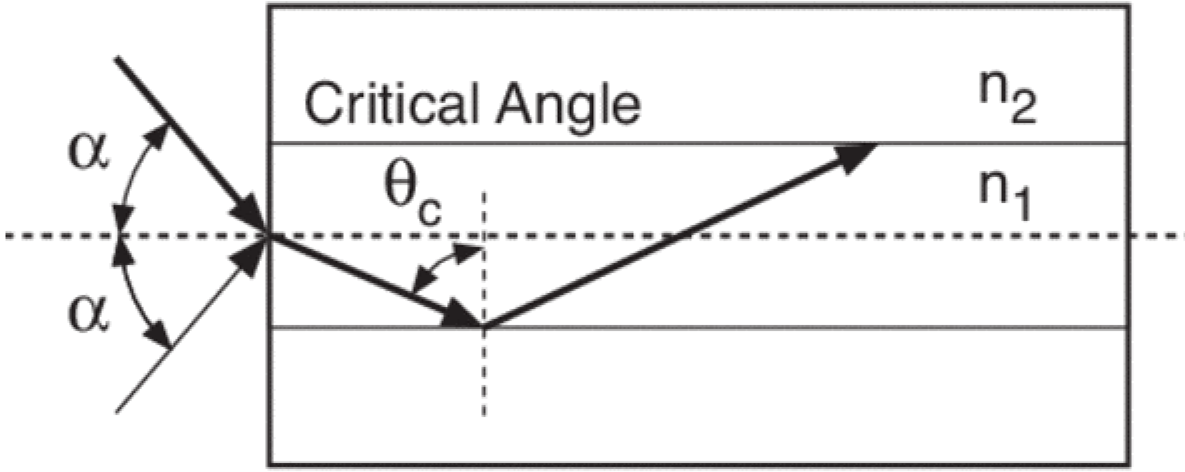
Numbers usually increase by multiples of √2. Increasing *f/#* by a factor of √2 will halve the area of aperture, effectively decreasing the light throughput of lens by a factor of 2.

Numerical Aperture

It is the light gathering ability of an objective or condenser.



Numerical Aperture



$$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2}$$

Full Acceptance Angle = 2α

Modulation Transfer Function

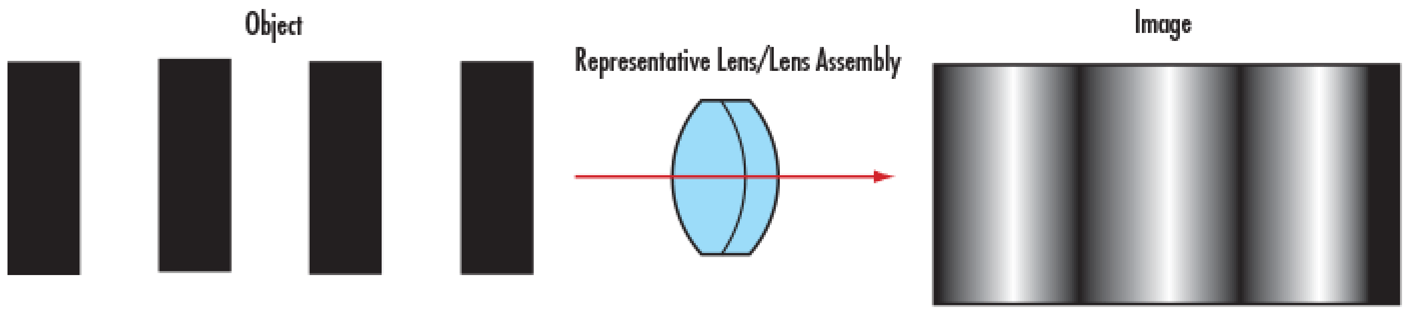
- MTF is a measure to compare performance of optical systems.
- Components of MTF: Resolution & Contrast

Resolution

- Imaging system's ability to distinguish object detail.
- Expressed in terms of line-pairs per millimeter (where a line-pair is a sequence of one black line & one white line).
- Measure of line-pairs per millimeter (lp/mm) is also known as frequency.
- Inverse of frequency yields the spacing in millimeters between two resolved lines.

Bar targets with a series of equally spaced, alternating white & black bars (i.e. a 1951 USAF target or a Ronchi grating) are ideal for testing system performance.

For all imaging optics, when imaging such a pattern, perfect line edges become blurred to a degree. High-resolution images are those which exhibit a large amount of detail as a result of minimal blurring. Conversely, low-resolution images lack fine detail.

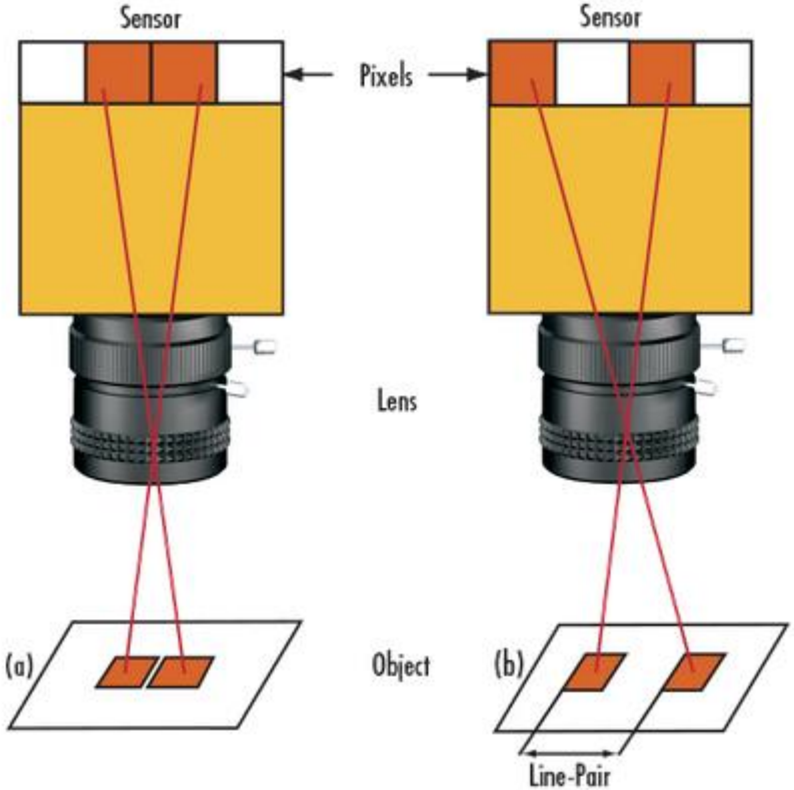


Perfect line edges before (left) & after (right) passing through a low resolution imaging lens.

A practical way of understanding line-pairs is to think of them as pixels on a camera sensor, where a single line-pair corresponds to two pixels.

Two camera sensor pixels are needed for each line-pair of resolution: one pixel is dedicated to red line & other to blank space between pixels.

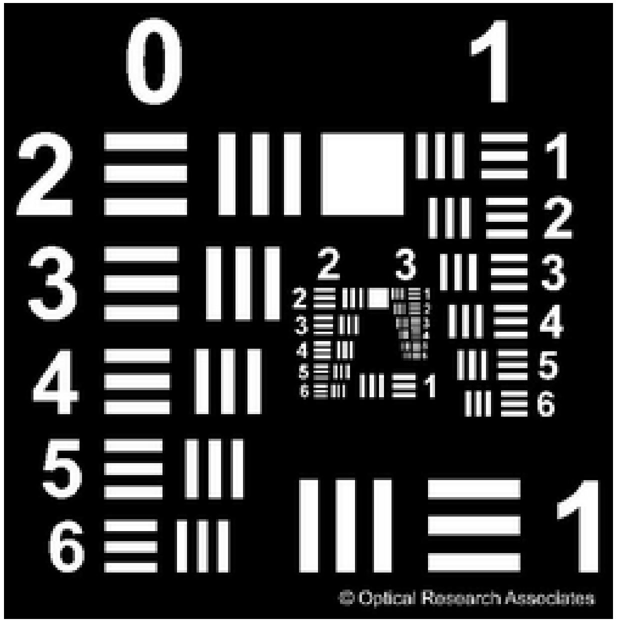
Image resolution of camera can be specified as equal to twice its pixel size.



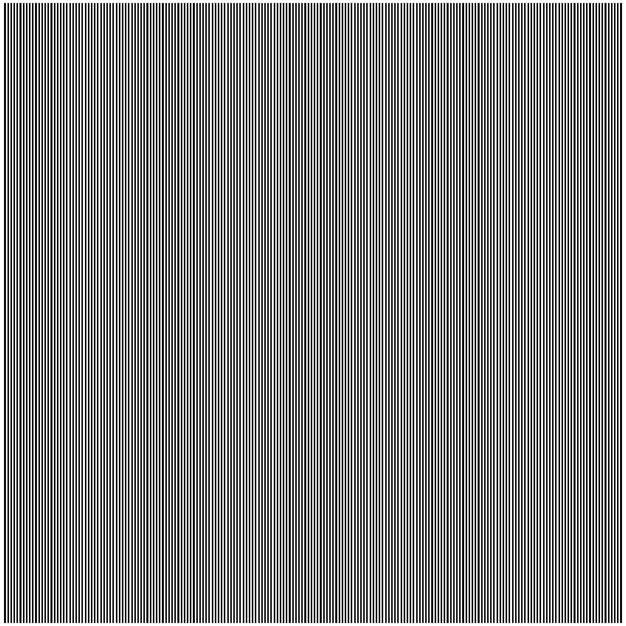
Imaging scenarios where (a) line-pair is NOT resolved & (b) line-pair is resolved

$$Object\ resolution\ (\mu m) = \frac{Camera\ resolution\ (\mu m)}{\mathrm{Pr}imary\ magnification\ (PMAG)}$$

$$Object\ resolution\ (lp/mm) = PMAG \times Camera\ resolution\ (lp/mm)$$



1951 USAF target

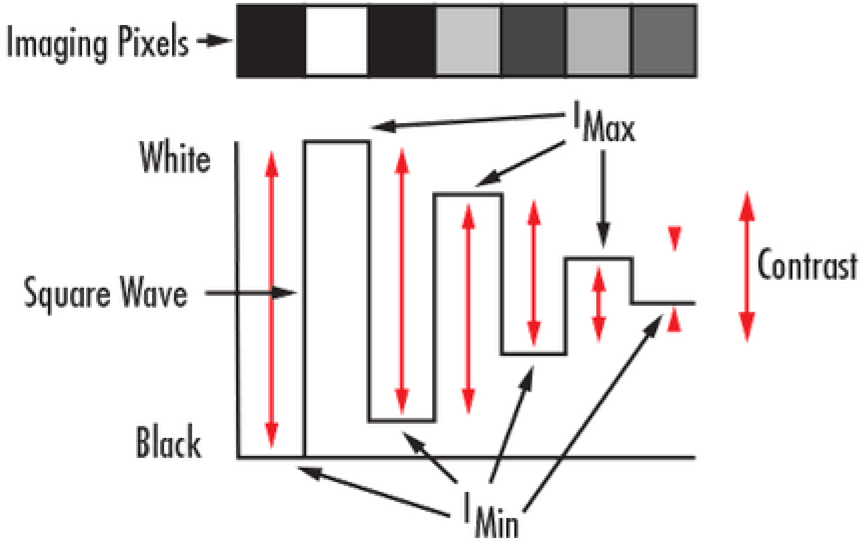


Ronchi grating

Contrast/Modulation

- Consider normalizing intensity of a bar target by assigning a maximum value to white bars & zero value to black bars. Plotting these values results in a square wave, from which the notion of contrast can be more easily seen.

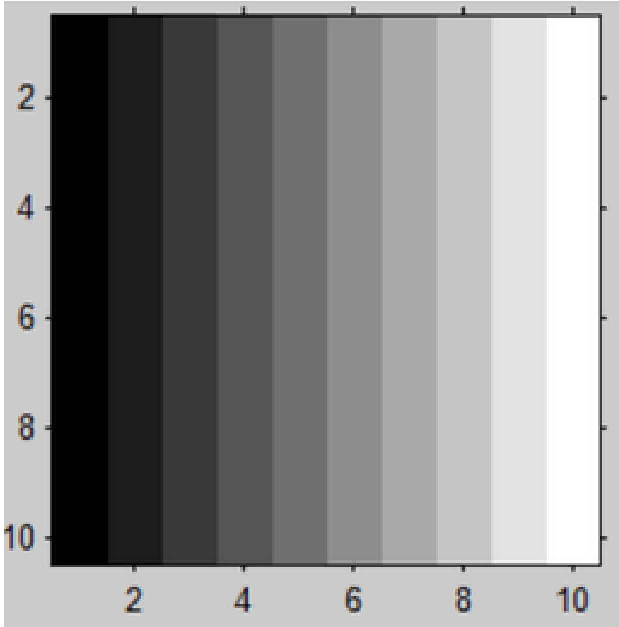
$$\% \, Contrast = \left[\frac{(I_{\max} - I_{\min})}{(I_{\max} + I_{\min})} \right] \times 100$$

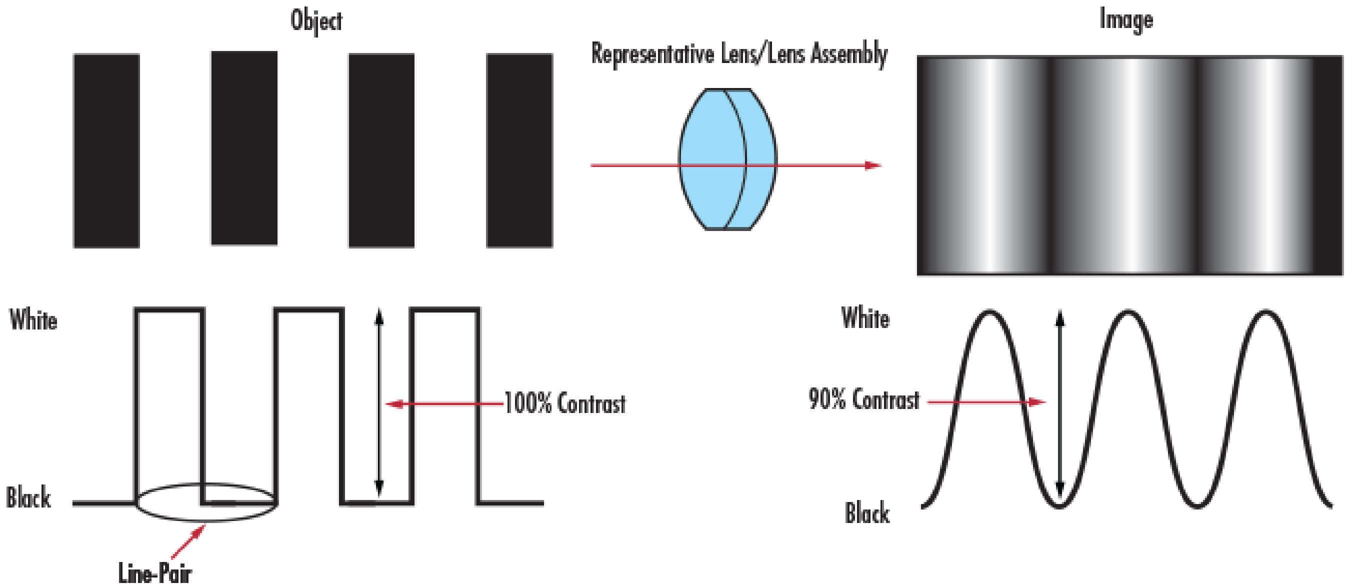


Contrast expressed as a square wave

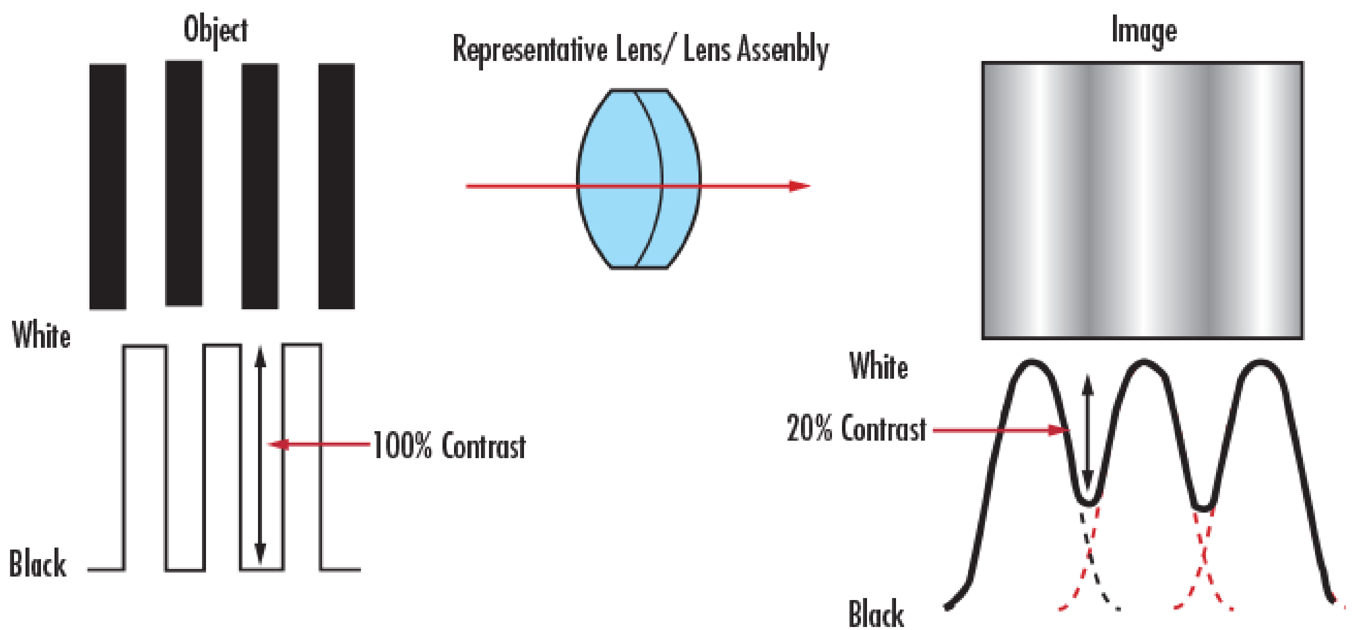
Contrast/Modulation

- Contrast means difference.
- Photography: most common differences are achieved by changes in the tones (light) or colors that compose the image.
- Contrast is the degree of difference between the elements that forms an image.
- Higher contrast will give your image a different feel than lower contrast.





Contrast of a bar target & its image

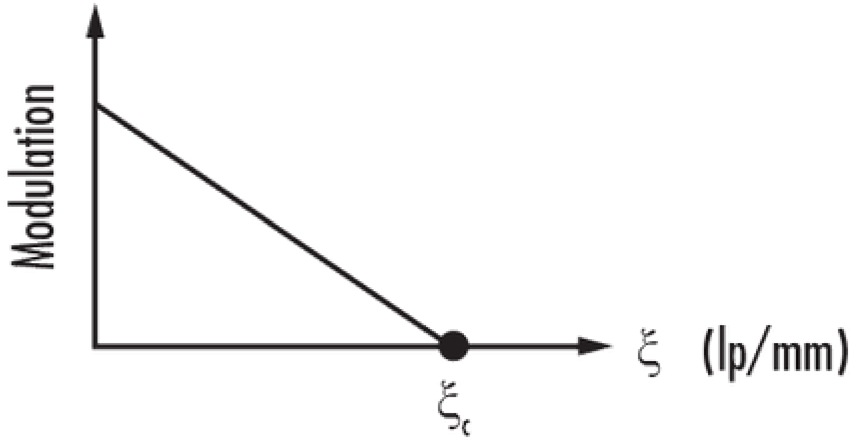


Contrast comparison at object & image planes

- **Contrast/modulation:** How faithfully the minimum & maximum intensity values are transferred from object plane to image plane.
- Spatial frequency of lines increases, contrast of the image decreases. This effect is always present when working with imaging lenses of the same resolution. For the image to appear defined, black must be truly black & white truly white, with a minimal amount of grayscale between.
- In imaging applications, imaging lens, camera sensor, & illumination play key roles in determining resulting image contrast.
- Lens contrast is typically defined in terms of percentage of the object contrast that is reproduced.
- Sensor's ability to reproduce contrast is usually specified in terms of decibels (dB) in analog cameras & bits in digital cameras.

Modulation Transfer Function

- **MTF of a lens: Ability to transfer contrast at a particular resolution from the object to the image.**
- **MTF is a way to incorporate resolution & contrast into a single specification. It is a function of spatial resolution (ξ), which refers to smallest line-pair the system can resolve.**
- **As line spacing decreases (i.e. frequency increases) on test target, it becomes increasingly difficult for the lens to efficiently transfer this decrease in contrast; as a result, MTF decreases.**



MTF for an aberration-free lens with a rectangular aperture