Photonics and Laser Physics

Wendsday 9h15-10h45
Kleiner Hörsaal, Physikalisches Institut
http://www.mpi-hd.mpg.de/ato/amo/
http://www.atomchip.uni-hd.de/teaching/vorlesung/LasPhys03/index.html

Recommended Literature:

- **Bahaa E.A. Saleh / Malvin C. Teich:**
  Fundamentals of Photonics (John Wiley & Sons, New York, 1991).
- **Dieter Meschede:**
  Optik, Licht und Laser (Teubner, Stuttgart, 1999).
- **Wolfgang Demtröder:**
  Laserspektroskopie: Grundlagen und Techniken (Springer, Heidelberg, 1998).
- **Eugene Hecht:**
  Optics (Addison-Wesley, New York, 1997).
- **F. Graham. Smith / Terry A. King:**
  Optics and Photonics: An Introduction (John Wiley & Sons, New York, 2000).
- **Peter W. Milonni / Joseph H. Eberly:**
  Lasers (John Wiley & Sons, New York, 1988).
- **Anthony E. Siegman:**
  Lasers (University Science Books, Mill Valey, 1986).
- **Optics Guide: Melles Griot catalog**
  http://www.mellesgriot.com/products/optics/toc.htm

Course Layout

The course Photonics and Laser Physics gives an introduction in the fundamentals of modern optics from classical optics to quantum optics. The lecture will give a broard overview into the subject, with emphasis on the fundamental physics, experiment and application.

Program:

- **Classical Optics**
  - ray optics
  - wave optics
  - beam optics, gaussian optics
  - fourier optics, formation of images
  - wave guides, fiber optics, integrated optics
  - interference, coherence
- **Photon Optics**
  - light fields in resonators
  - photon detection
  - statistical optics
  - higher order coherence
  - quantum statistics of light
- **Photons and Atoms**
  - interaction between an atom and light (classical picture)
  - interaction between an atom and light (quantum picture)
- **Lasers**
  - amplification of light
  - laser theory
  - types of lasers
  - pulsed laser
- **Acousto and Electro Optics**
- **Nonlinear Optics**
- **Applications**

Ray Optics Basics

Postulates of Ray Optics

- Light travels in form of rays
- An optical medium is characterized by the *refractive index* n
  time it takes light to travel distance d: $\mathrm{d/c} = n\mathrm{d}/\mathrm{c}_{\mathrm{vac}}$
  optical path: $n\mathrm{d}$

$$n = \frac{c_{vac}}{c_{med}}$$

- An inhomogeneous optical medium: $n(\mathbf{r})$ $\mathbf{r}=(\mathrm{x,y,z})$
  time taken by the light to travel
  from A to B is proportional to
  optical path length

$$\text{Optical path length} = \int_A^B n(\vec{r})ds$$

- Fermat's Principle:
  optical rays travel between two points A, B on the path where the optical path length is an extremum
  in most cases a minimum
  light travels the path of shortest time

$$\delta \int_A^B n(\vec{r})ds = 0$$

- homogeneous medium: light travels on straight lines

Ray Optics
reflection and refraction

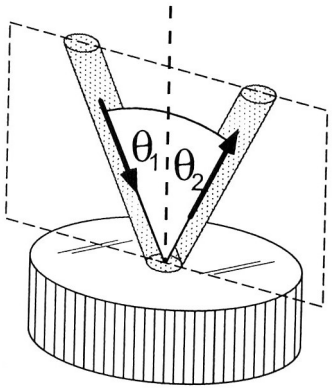


Abb. 1.2 *Reflexion am ebenen Spiegel.*

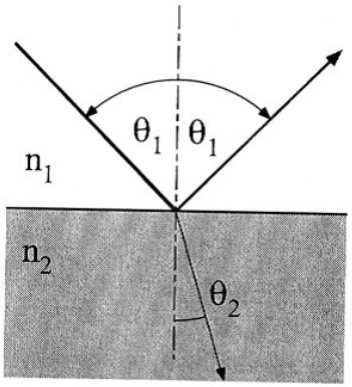


Abb. 1.3 *Brechung und Reflexion an einer dielektrischen Fläche.*

$\sin(\theta_c)=n_2/n_1$

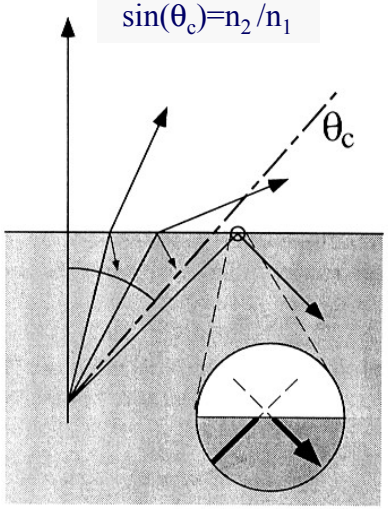


Abb. 1.4 *Totalreflexion an einer dielektrischen Fläche. Der Reflexionspunkt der Strahlen liegt nicht genau auf, sondern etwas jenseits der Grenzfläche (Goos-Hänchen-Effekt [33, 81]).*

Tab. 1.1 *Optische Eigenschaften ausgewählter Gläser.*

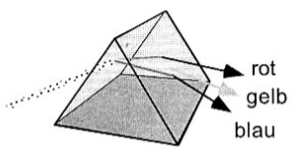
Kurzname	BK7	SF11	LaSF N9	BaK 1	F 2
Name	Borkron	Schwerflint		Barytkron	Flint
Abbe-Zahl	64,17	25,76	32,17	57,55	36,37
Brechzahl bei ausgewählten Wellenlängen					
$\lambda = 486,1nm$	1,5224	1,8065	1,8690	1,5794	1,6321
$\lambda = 587,6nm$	1.5168	1.7847	1.8503	1.5725	1.6200
$\lambda = 656,3nm$	1,5143	1,7760	1,8426	1,5695	1,6150
Dispersionskonstanten der Brechzahl (s. Gl.1.6)					
B_1	1,0396	1,7385	1,9789	1,1237	1,3453
B_2	0,2379	0,3112	0,3204	0,3093	0,2091
B_3	1,0105	1,1749	1,9290	0,8815	0,9374
C_1	0,0060	0,0136	0,0119	0,0064	0,0100
C_2	0,0200	0,0616	0,0528	0,0222	0,0470
C_3	103,56	121,92	166,26	107,30	111,89
Dichte (g/cm^{-3})					
	2,51	4,74	4,44	3,19	3,61
Ausdehnungskoeffizient (-30 C bis +70 C) $\times 10^6$					
	7,1	6,1	7,4	7,6	8,2

Spannungsdoppelbrechung: typ. 10 nm/cm
Homogenität der Brechzahl von Schmelze zu Schmelze: $\pm 1 \times 10^{-4}$

$$n^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$ λ in µm

Reflection: $\theta_{in}=\theta_{out}$ Refraction: $n_1 \sin(\theta_1)= n_2 \sin(\theta_2)$
Snell´s law

Dispersion



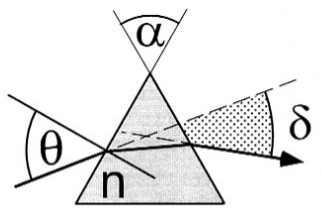


Abb. 1.9 *Brechung und Dispersion am symmetrischen Prisma. Aus dem Minimalwinkel der Ablenkung $\delta = \delta_{min}$ kann man den Brechungsindex n auf einfache Art und Weise bestimmen.*

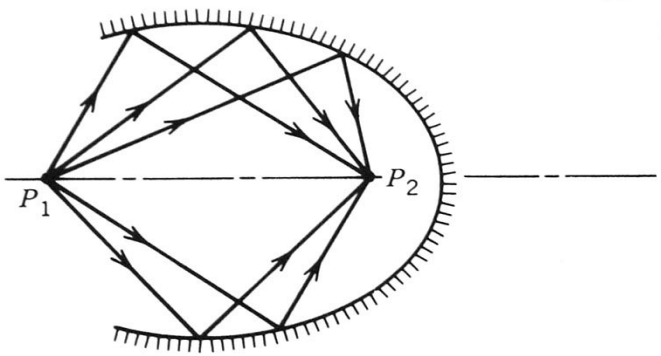
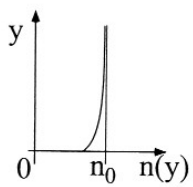


Figure 1.2-3 Reflection from an elliptical mirror.

Inhomogeneous medium



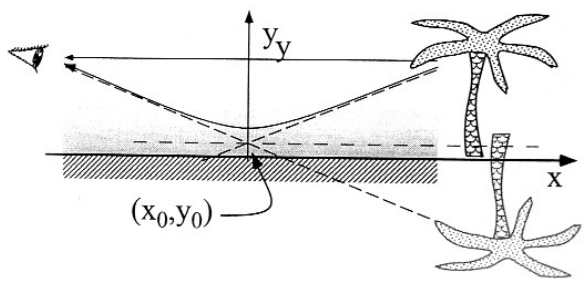


Abb. 1.6 *Brechzahlprofil und Strahlengang bei einer Luftspiegelung.*

Ray Optics

Mirrors, Lenses, paraxial approximation

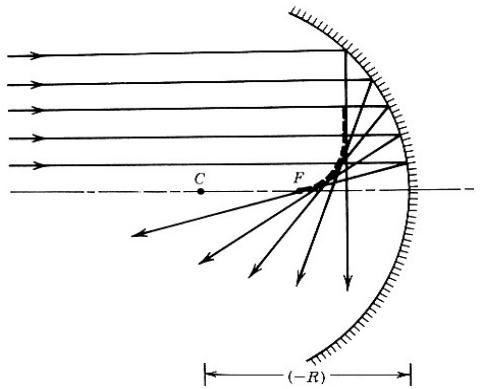


Figure 1.2-4 Reflection of parallel rays from a concave spherical mirror.

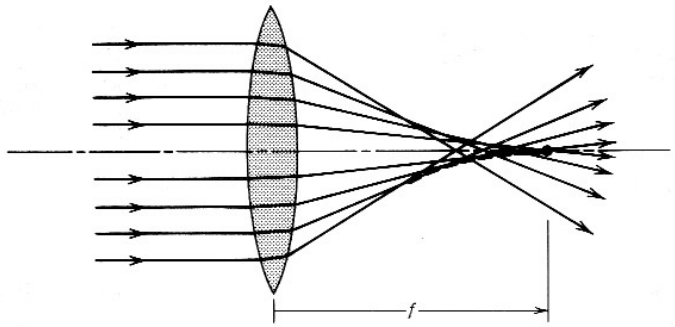


Figure 1.2-15 Nonparaxial rays do not meet at the paraxial focus. The dashed envelope of the refracted rays is called the caustic curve.

A light ray is completely defined by:

- distance from the optical axis r
- angle to the optical axis θ

Ray: (r, θ)

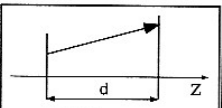
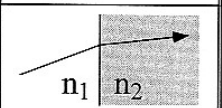
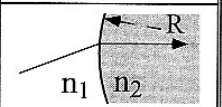
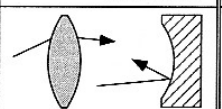
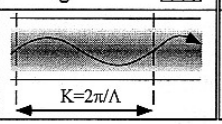
paraxial approximation:

$\sin(\theta) = \tan(\theta) = \theta$

Propagation and optical surfaces can now be described as a matrix acting on the ray

Example: thin lens $\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$

Ray propagation using matrices

Operation		ABCD-Matrix
Translation		$\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$
Brechung (ebene Fläche)		$\begin{pmatrix} 1 & 0 \\ 0 & n_1/n_2 \end{pmatrix}$
Brechung (gekr. Fläche)		$\begin{pmatrix} 1 & 0 \\ \frac{n_1-n_2}{n_2 R} & \frac{n_1}{n_2} \end{pmatrix}$
Linsen Hohlspiegel (Brennw. f)		$\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$
Glasfaser GRIN (Länge *l*)		$\begin{pmatrix} \cos Kl & K\sin Kl \\ -K\cos Kl & \cos Kl \end{pmatrix}$

Ray Optics
inhomogeneous media
Guides

GRIN (Gadient Index) lens

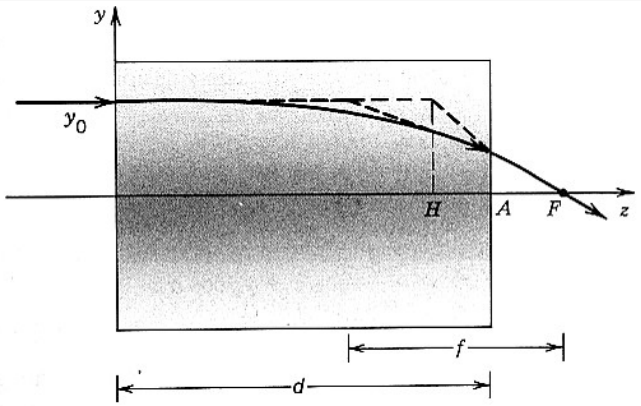


Figure 1.3-6 The SELFOC slab used as a lens; F is the focal point an principal point.

Parabolic variation of the refractive index

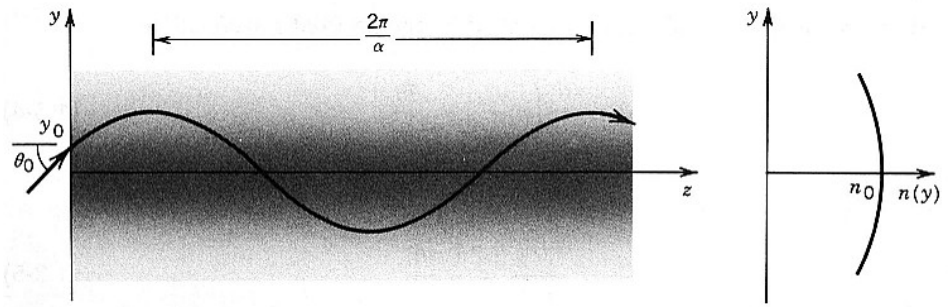


Figure 1.3-4 Trajectory of a ray in a GRIN slab of parabolic index profile (SELFOC).

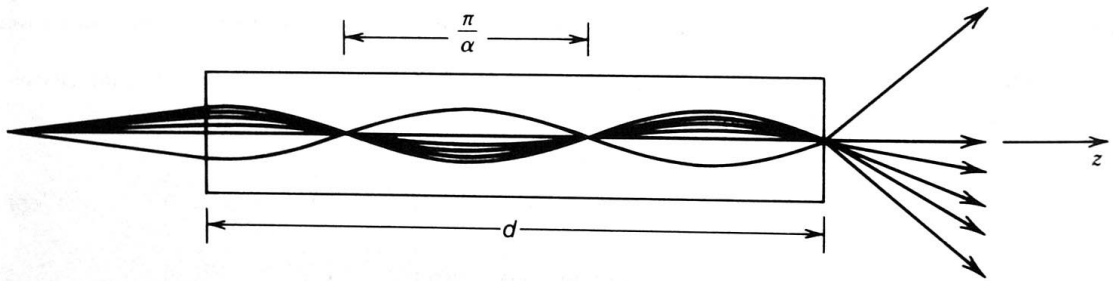


Figure 1.3-5 Trajectories of rays in a SELFOC slab.

Numerical aperture:
$NA = \sin(\theta_a)$

For a fiber with an index step:
core: n_1 cladding: n_2
$NA = \sin(\theta_a) = (n_1^2 - n_2^2)^{1/2}$

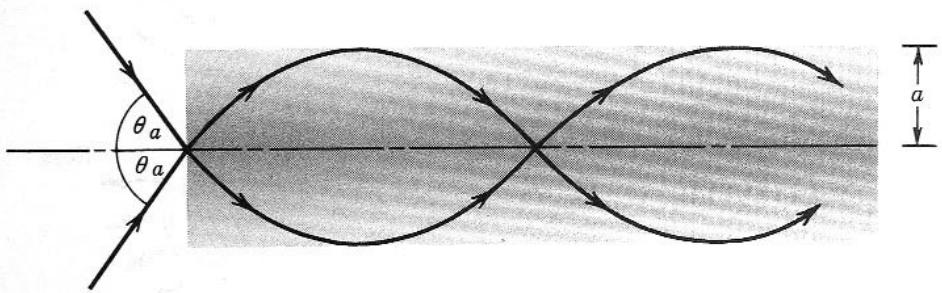
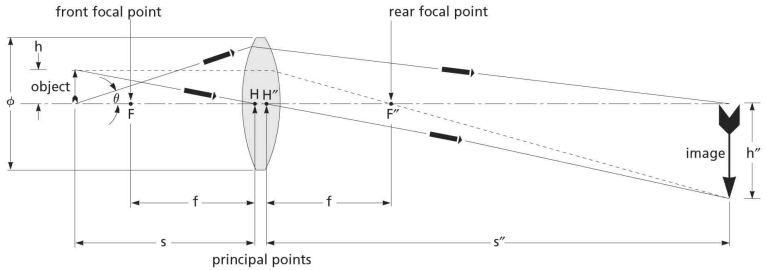


Figure 1.3-8 Acceptance angle of a graded-index optical fiber.



Note location of object and image relative to front and rear focal points.

ϕ = lens diameter

m = s″/s = h″/h = magnification or conjugate ratio, said to be infinite if either s″ or s is infinite

θ = arcsin (ϕ/2s)

h = object height

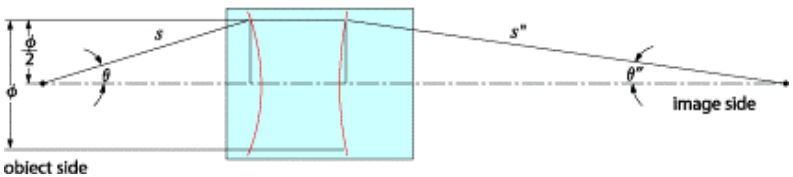
h″ = image height

s = object distance, positive for object (whether real or virtual) to the left of principal point H

s″ = image distance (s and s″ are collectively called conjugate distances, with object and image in conjugate planes), positive for image (whether real or virtual) to the right of the principal point H″

f = effective focal length (EFL) which may be positive (as shown) or negative. f represents both FH and H″F″, assuming lens to be surrounded by medium of index 1.0

Numerical Aperture and Magnification



$$NA(\text{object side}) = \sin\theta = \frac{\phi}{2s} \qquad NA''(\text{image side}) = \sin\theta'' = \frac{\phi}{2s}$$

which can be rearranged to show $\phi = 2s''\sin\theta$

and $\phi = 2s''\sin\theta''$

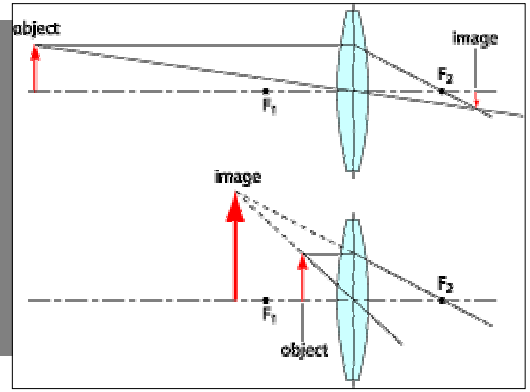
leading to $\frac{s''}{s} = \frac{\sin\theta}{\sin\theta''} = \frac{NA}{NA''}$

Since s"/s is simply the magnification of the system, we arrive at $m = \frac{NA}{NA''}$

The magnification of the system is therefore equal to the ratio of the numerical apertures on the object and image sides of the system. This powerful and useful result is completely independent of the specifics of the optical system, and it can often be used to determine the optimum lens diameter in situations involving aperture constraints.

http://www.mellesgriot.com/products/optics/toc.htm

Lens Imaging Basics



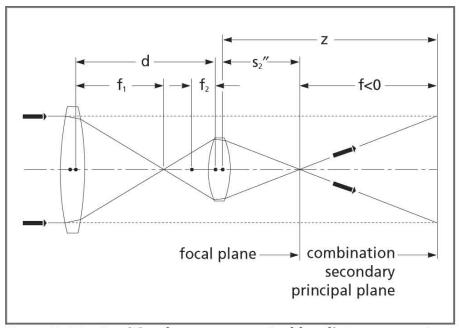


Figure 1.10 **Positive lenses separated by distance greater than $f_1 + f_2$:** f is negative, while both s_2'' and z are positive. Lens symmetry is not required.

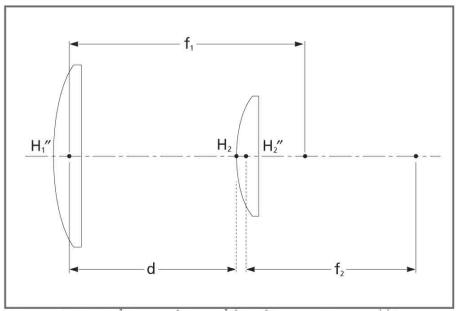


Figure 1.11 **Achromatic combinations:** Air-spaced lens combinations can be made nearly achromatic, even though both elements are made of the same material. Achieving achromatism requires that, in the thin-lens approximation,

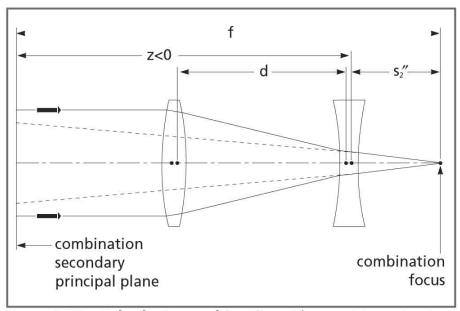


Figure 1.12 **Telephoto combination:** The most important characteristic of the telephoto is that the EFL, and hence the image size, can be made much larger than the distance from the first lens surface to the image would suggest by using a positive lens followed by a negative lens *(but not necessarily the lens shapes shown in the figure)*. For example, f_1 is positive and $f_2 = 4f_1/2$. Then f is negative for d less than $f_1/2$, infinite for $d = f_1/2$ (Galilean telescope or beam expander), and positive for d larger than $f_1/2$. To make the example even more specific, catalog lenses 01 LDX 189 and 01 LDK 021, with d = 78.2 mm, will yield $s_2'' = 2.0$ m, f = 5.2 m, and z = 43.2 m.

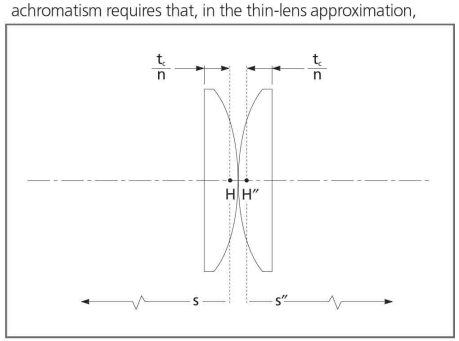
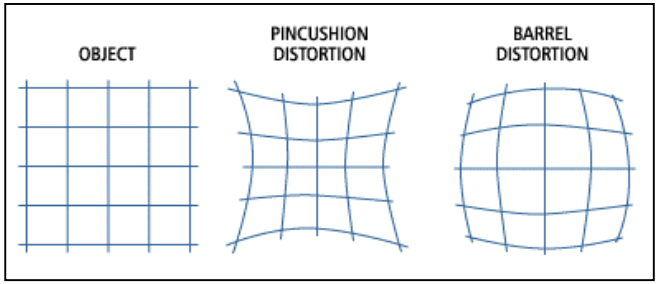
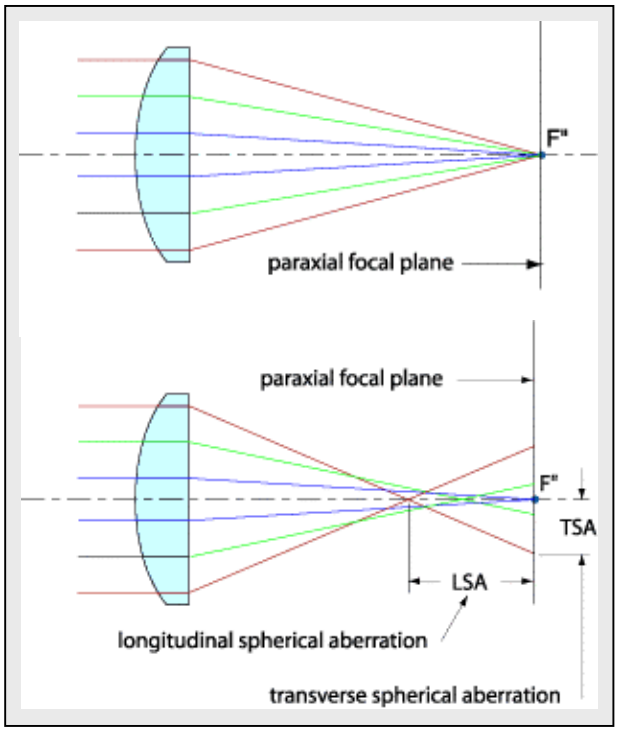


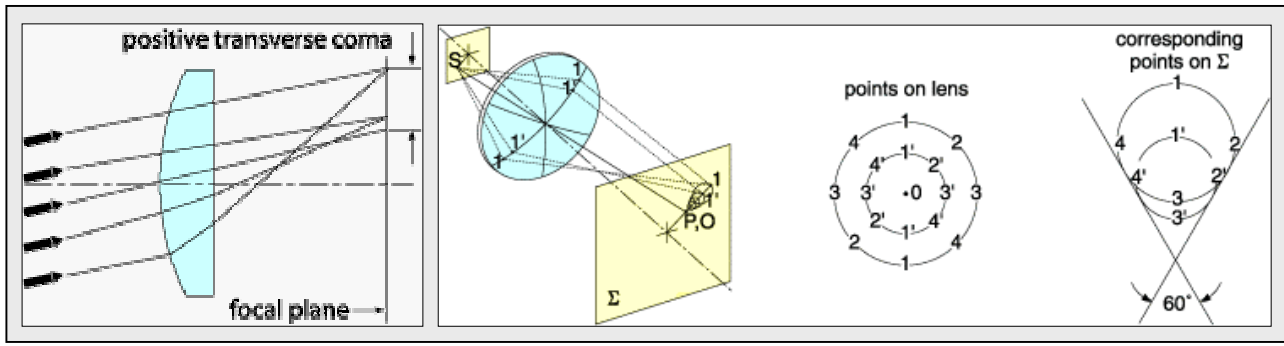
Figure 1.13 **Condenser configuration:** A pair of identical plano-convex lenses have their convex vertices in contact. (The lenses could also be plano aspheres.) Because d = 0, $f = f_1/2 = f_2/2$, $f_1/2 = s_2''$, and z = 0. The secondary principal point of the second element and the secondary principal point of the combination coincide at H″, at depth t_c/n beneath the vertex of the plano surface of the second element, where t_c is the element center thickness and n is the refractive index of the element. By symmetry, the primary principal point of the combination is similarly located in the first element. Combination conjugate distances must be measured from these points.

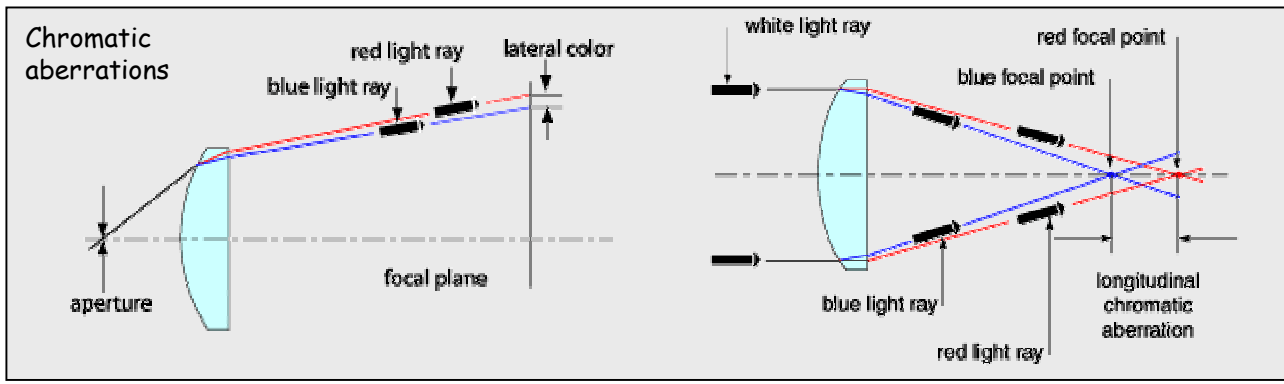
Lens Aberrations

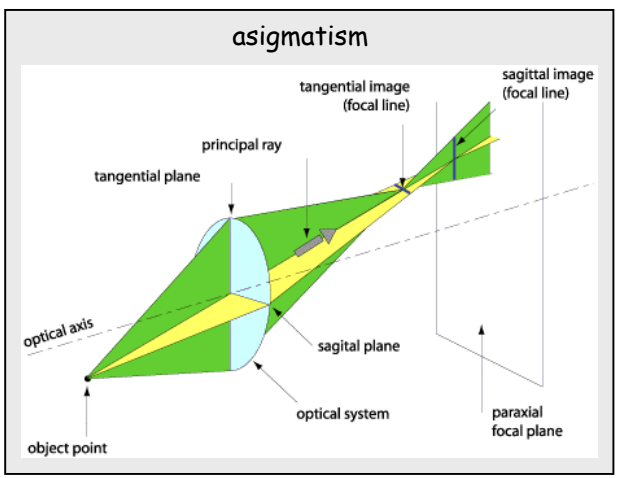
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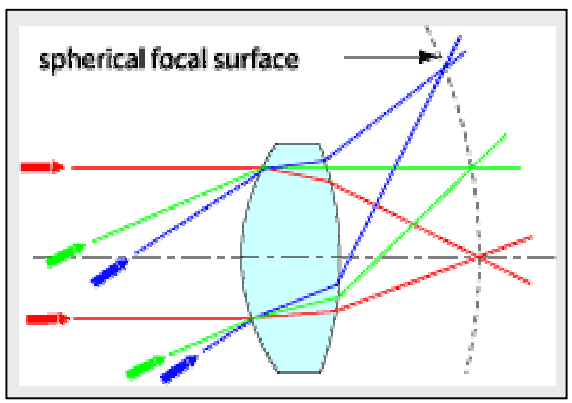












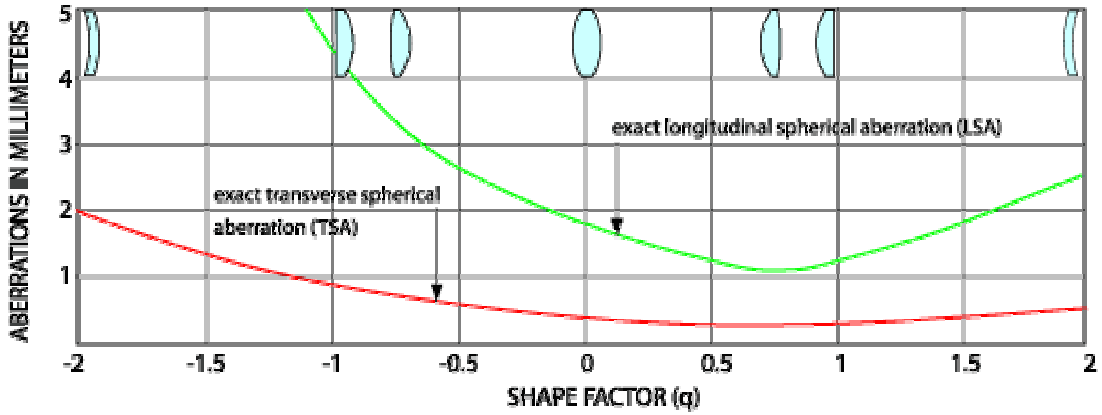
Variations of Aberrations with Aperture, Field Angle, and Image Height

Aberration	Aperture (ϕ)	Field Angle (θ)	Image Height (y)
Lateral Spherical	ϕ^3	—	—
Longitudinal Spherical	ϕ^2	—	—
Coma	ϕ^2	θ	y
Astigmatism	—	θ^2	y^2
Field Curvature	—	θ^2	y^2
Distortion	—	θ^3	y^3
Chromatic	—	—	—

Lens Aberrations

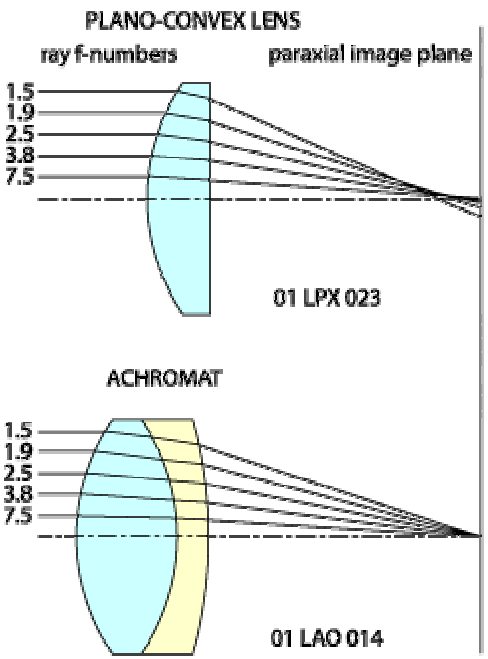
examples simple lenses

Form and orientation of a single lens is important

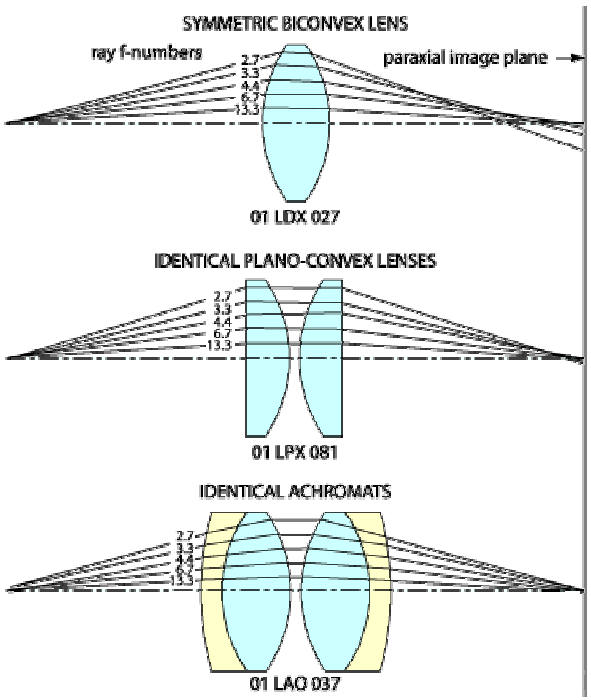


Aberrations of positive singlets as a function of shape for infinite conjugate ratio

balance aberrations by combining lenses

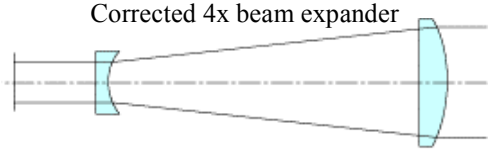


Single element plano-convex lens compared with a two-element achromat



Three possible systems for use at the unit conjugate ratio

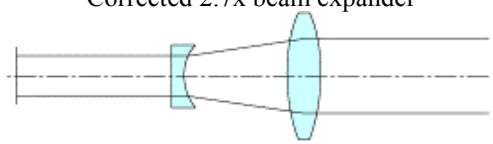
Corrected 4x beam expander



$f = -20$ mm
10-mm diameter
plano-concave
01 LPK 001

$f = 80$ mm
22.4-mm diameter
plano-convex
01 LPX 149

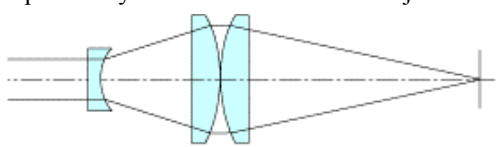
Corrected 2.7x beam expander



$f = -20$ mm
10-mm diameter
plano-concave
01 LPK 001

$f = 54$ mm
32-mm diameter
symmetric-convex
01 LDX 119

Spherically-corrected 25mm f/2.0 objective



$f = -25$ mm
25-mm diameter
plano-concave
01 LPK 003

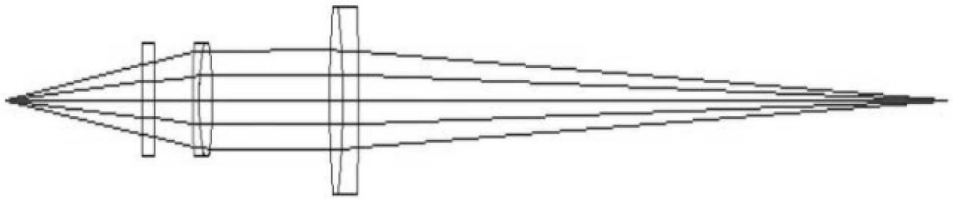
$f = 50$ mm (2)
27-mm diameter
plano-convex
01 LPX 108

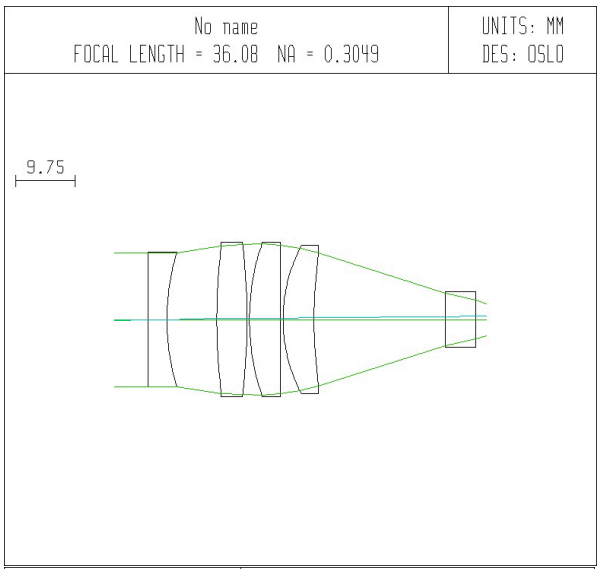
http://www.mellesgriot.com/products/optics/toc.htm

Lens Aberrations

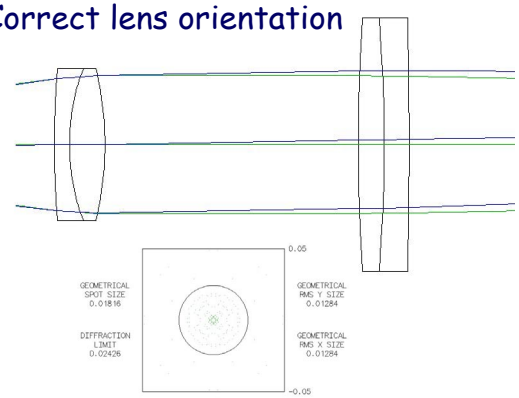
an example imaging system (for BEC)

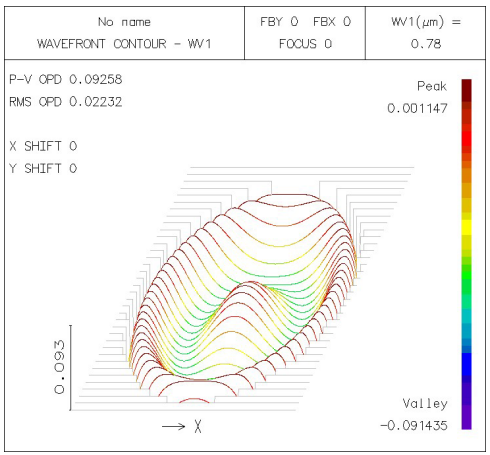
Example imaging lens due to Wolf Alt Off the shelf combination of lenses. Coma and asigmatism is low but some field curvature remains





Correct lens orientation





1st lens reversed

