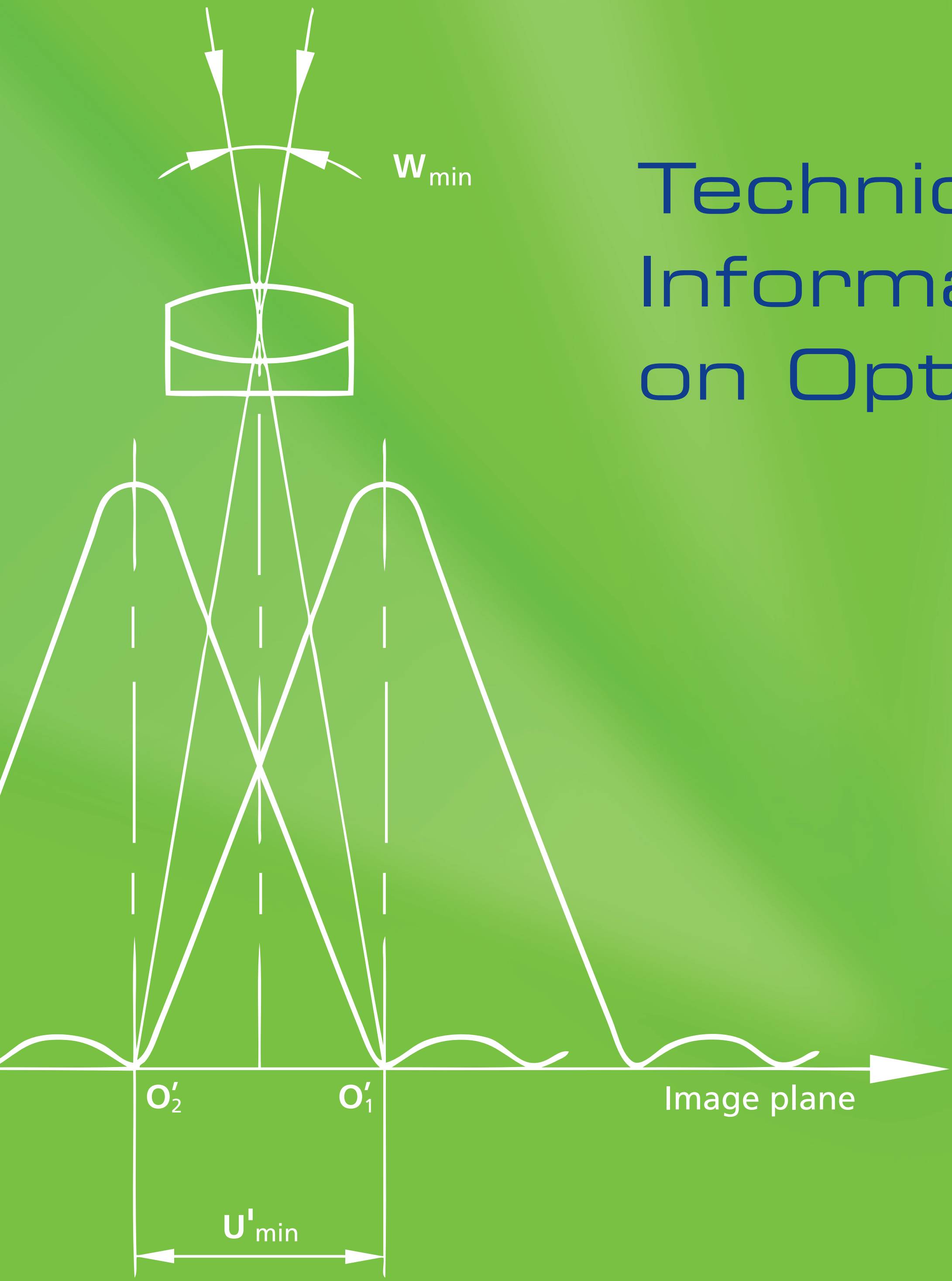
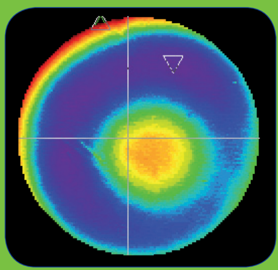
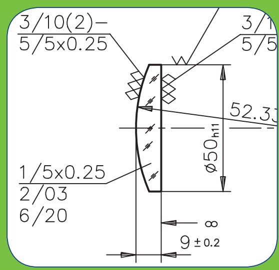
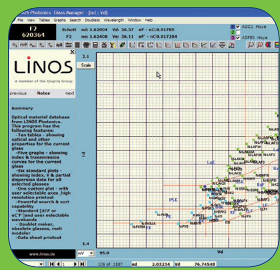


Technical Information on Optics







Technical Information on Optics

This chapter contains plenty of information on optics, from an overview of specialized optic terms to the physical principles of optical resolution, Gaussian beam optics and thin film coatings.

Furthermore, designations and measurement methods for testing optical components and properties of optical materials are explained. Valuable tips on further reading are contained in the bibliography and media index.

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Technical Information on Optics

Technical Info

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Terminology

The following list of definitions is an alphabetically sorted collection of technical terms and their definitions. The terminology provided is to promote a better understanding between customer and manufacturer. For further information you are referred to technical literature. A brief listing of literature is in the section literature. More explanations can be found in the WinLens™ help system, see chapter Optics Software, WinLens™.

Abbe number
A term introduced by Ernst Abbe to characterize the dispersion of an optical medium. The Abbe number represents the reciprocal dispersive power and is defined as:

$$v_d = \frac{n_d - 1}{n_F - n_C}$$

where n_d, n_F n_C = indices of refraction of the Fraunhofer d-, F-, and C-lines (d=587.6 nm, F=486.1 nm, C=656.3 nm). Large Abbe numbers correspond to low dispersions.

Aberrations
Aberrations occur during image formation with optical systems when the rays from the object point do not converge completely at the conjugate image point. Lens aberrations include: spherical aberrations, coma, astigmatism, distortion and chromatic aberrations.

Absorption
The conversion of light or radiation energy into another form of energy while passing through an optical medium.

Absorption factor
The ratio between the radiant flux in the optical medium and the incident radiant flux is called absorption factor. The internal absorption factor is the ratio between the radiant flux penetrating into the medium and the radiant flux absorbed in the medium.

Airy disc
The central maximum of a diffraction pattern of a circular aperture. The Airy disc is limited by the first dark ring of the diffraction pattern.

Angular dispersion
The wavelength dependence of the diffraction angle of light beams passing through a dispersive optical element. It is a function of both the dispersive power of the material and the shape of the optical element.

Anti-reflection coating
A single or multi-layer dielectric coating deposited on the surface of an optical element to reduce reflection by means of interference (see also chapter Thin Film Coatings).

Aperture stop
Mechanical device which limits the path of light rays between the object and image planes of an optical imaging forming system.

Astigmatism
Aberration which occurs in an image formation due to skew rays. Astigmatism is characterized by two different focal positions in two perpendicular planes (meridional and sagittal).

Back focal length
The distance of the paraxial focus from the last vertex of an optical system (the distance from the last surface of a lens or lens system to its image plane). Unlike the effective focal length, the back focal length can be measured directly.

Birefringence
In optical anisotropic crystals, the index of refraction is different for different levels of polarization. A non-polarized light beam is separated into two beams polarized perpendicular to each other which have two different indices of refraction. These are called ordinary and extraordinary rays. Consequently, double images occur in non-polarized light during transmission through anisotropic crystals.

Brewster angle
Angle of incidence where the reflected and the refracted rays of light striking a transparent optically isotropic medium are perpendicular to each other. The reflected component is linearly polarized and the plane of polarization is perpendicular to the plane of incidence.

$$\alpha = \arctan\frac{n'}{n}$$

with n = refractive index of the surrounding medium (i. e. air); n' = refractive index of the refracting medium

Chromatic aberration
Chromatic aberrations are functions of the dispersion characteristics of optical materials. There are two forms of chromatic aberration:
longitudinal chromatic aberrations which result in different focal points for different wavelengths and transverse chromatic aberrations, which cause different magnifications for different wavelengths.

Coherence
The constancy of phase relations between two waves. There are two types of coherence: temporal and spatial coherence.

Coherence length
The greatest optical path difference between two partial waves from a radiation source where interference can still occur.

Collimator
Optical lens system designed to image a point light source in such a way that all the emerging rays are parallel to each other. Collimation is a general term for the imaging of a focal point at infinity (in a typical laser collimator a small laser beam is transposed into an expanded beam of collimated light).

Coma
An aberration for skew rays which is not rotationally symmetrical. Coma can also be viewed as an aperture aberration in skew rays whereby the principal ray assumes the function of the optical axis.

Condenser
Optical system which is designed to collect light sources as completely as possible and transfer that light to an object point or plane.

Conjugate points
Points in both the object and image plane which are transformed into each other by the process of image formation.

Contrast
Contrast is a general term used for differences in brightness. Contrast in the context of optical transfer function is termed modulation (see also modulation).

Crown glasses
Glasses having an Abbe number > 50.

Depth of field
A term used, especially in photography, for the plus or minus distance in which an acceptable focus is attained. The depth of field (S) for a microscope lens system can be expressed simply as:

$S = \pm n \lambda / (2 \cdot NA)$

NA = numerical aperture,
n = index of refraction in object space
λ = wavelength of light.

Dielectric films
Dielectric films are typically inorganic materials which are vacuum-deposited onto the surfaces of optical components to increase or decrease reflectivity.

Diffraction
Deviation of a wavefront from its original direction of propagation as it passes by an opaque edge or through an aperture. Diffraction is not caused by refraction, reflection or scatter but by the wave nature of light.

Diffraction grating
Typically an arrangement of equi-distant parallel lines or elements on a transparent or reflecting surface which causes incident light rays to be diffracted.

DIN and ISO standards
These standards specify dimensions, tolerances and standard illustrations for industrial and scientific products. Referencing the appropriate standard used in the manufacturing process eliminates the need to prepare detailed specifications for individual components. MIL standards are mostly inactive and out of date.

Direction of polarization
Direction of the electric field vector of linearly polarized light. The plane of polarization and the polarization direction are parallel to each other. In classical optics, the plane of polarization is always perpendicular to the direction of the beam.

Dispersion
Term used to define the process in which rays of light containing different wavelengths are deviated angularly by an optical medium. More specifically, dispersion is used to indicate the dependency of the refractive index as a function of wavelength (see also Abbe number).

Dispersion curve
A graphic representation of the variation of the refractive index of a material as a function of wavelength.

Distortion
A lens system aberration characterized by the imaging of off-axis straight lines as curved lines. There are two types of distortion: pincushion, where off-axis straight lines are imaged curving towards the center and distortion barrel distortion, where off-axis straight lines are imaged curving away from the center.

Entrance pupil
The image of the aperture stop in object space.

Entrance window
The image of the field stop in object space.

Exit pupil
The image of the aperture stop in image space.

Exit window
The image of the field stop in image space.

Extinction ratio
The transmission ratio of a pair of polarizers in the crossed position to that in the parallel position.

Field angle
Angle between the optical axis and the principal ray of the object boundary point.

Field curvature
A lens aberration that causes a flat object surface to be imaged onto a curved surface rather than a plane.

Field lens
Lens which is inserted between other lenses in an optical system to intercept off-axis rays and bend them toward the optical axis thus increasing the field of view. A field lens has no effect on the magnitude or position of the image.

Field of view
The outermost point of the field angle being transmitted through a lens system to form an image. This spatial limitation can be induced by a field stop.

Field of view number
A characteristic quantity for eyepieces which gives the diameter of the field of view in millimeters by the equation:
$S = 2 \cdot f \cdot \tan w$ (field of view number)
f = eyepiece focal length
w = field angle

Field stop
Diaphragm or aperture used to restrict the useable field by limiting the angle of view. An object field stop is located in the object area and an image field stop in the image area.

Fizeau fringes
Fringe pattern which contours the variation in thickness of thin transparent objects; i. e., a wedge airgap between two glass plates viewed at normal incidence and illuminated with monochromatic light.

Flatness
The measured deviation of a surface with respect to a reference surface. Deviation in flatness of the test surface is typically given in units that are a fraction of the wavelength of the monochromatic light used for measurement.

Flint glasses
Glasses with an Abbe number < 50.

F-number
The ratio of the focal length to the entrance pupil diameter of an imaging system.

Focal length
Focal length is defined as the distance between the principal planes and the corresponding focal point for paraxial rays. For an individual lens, focal length is a function of lens radii, glass type and thickness. Focal length is the most important characteristic of any optical imaging system.

Fraunhofer lines
Fraunhofer observed dark lines in the solar spectrum. He determined that these lines were caused by the atomic absorption in specific elements found in the chromosphere of the sun. Fraunhofer realized that these lines corresponded to certain wavelengths in the spectrum and could therefore be used to measure the dispersion of optical glasses. He labeled the strongest lines A through H.

Fresnel equations
They describe the intensity of reflected and refracted unpolarized light striking a non-absorbing optical medium having a refractive index of n' at an angle of incidence α. In the process, the reflected ray at the angle of reflection becomes partially polarized. The Fresnel equation gives the intensities of these beams according to their polarization components parallel and perpendicular to the plane of the incident beam.

Fresnel lens
A Fresnel lens consists of a central thin spherical or aspherical lens surface surrounded by graduated annular rings in the form of prismatic circular zones, all of which refract light to the same point. For all practical purposes, the lens surface has a constant thickness. Fresnel lenses are commonly made from acrylic plastic and are used for simple image formation where very large apertures are required, e.g. for overhead projectors. Fresnel lenses have the advantage of being relatively inexpensive as well as thinner and lighter than an equivalent glass lens .

Fused quartz (fused silica)
Fused quartz is made by melting and forming natural or synthetic crystalline quartz. The melting process destroys the crystalline structure and there is no longer any birefringence or rotary dispersion. Fused quartz provides better transmission especially in the ultraviolet and near infrared than normal optical glasses.

Gaussian optics
Gaussian optics is the term used to describe the optics of paraxial rays and forms the basis of geometric optics.

Geometrical GOTF
See modulation transfer function.

Geometric optics
The field of optics which deals with the propagation of rays in straight lines without taking the effect of diffraction into consideration. Geometric optics only acknowledges the wave theory of light with respect to the refractive index as a function of wavelength.

Haidinger fringes
Series of curved interference fringes which are produced by a constant slope between a test and a reference plate using monochromatic light.

Half-width
Half-width refers to the full wavelength bandwidth of an interference filter at half of the maximum transmission intensity. (full-width at half maximum, FWHM)

Illuminance
Illuminance is measured as the luminous flux per unit area: lux = 1 lumen/m^2

Index of refraction
The ratio of the velocity of light in a vacuum to the velocity in an optical material at a certain wavelength.

$$n = \frac{c_V}{c_M}$$

Infrared radiation
That part of the electromagnetic spectrum having a wavelength between 0.75 and 1000 micrometers.

Interference
The combining of two or more waves in such a way that cancellation or amplification occurs. If amplification occurs it is termed constructive interference. If cancellation occurs it is termed destructive interference.

Interferometer
Optical instrument, based on the phenomenom of interference of light, that is typically used to measure length or change in length. Interferometers are among the most accurate distance and length measuring instruments available today.

Internal absorption factor
See absorption factor.

Irradiance
The radiant power per unit area in W/cm^2.

Isotropy
A medium is considered to be isotropic when its optical properties are independent of direction. Optical glass, for example, is isotropic as its index of refraction is the same in all directions. Many crystals, however, are anisotropic, as, in their case, the index of refraction is dependent on direction.

Koehler illumination
A microscope illumination system whereby the microscope lenses and the sample are illuminated uniformly.

Light flux
Power radiated by a luminous source. It is defined as the product of geometrical flux, the luminance of the light source and the transmission efficiency of the optical system. The unit of measurement is the lumen (lm).

Light ray (light beam)
Light ray is the normal to the wavefront of a wavetrain. In general, the direction of the flow of lumious energy.

Linearly polarized light
Light whose electromagnetic field vector is restricted to a single plane.

Line filter
An optical interference filter exhibiting high transmission for atomic or laser lines. Line filters are usually characterized by a small half-bandwidth (typically on the order of 1.0 nm)

Luminance
The luminous intensity per unit area. Luminance is measured in candela per m^2 (cd/m^2).

Luminance indicatrix
The spatial distribution of a luminous area as a function of the luminous intensity distribution.

Luminous intensity
The luminous flow relative to the solid angle.

$$I = \frac{\Phi}{\Omega}\left(cd = \frac{lm}{sr}\right)$$

Magnification
The ratio of image size u' to object size u measured perpendicular to the optical axis: ß' = u'/u

Media plane
Plane between two directly adjacent optical mediums.

Medium
Medium is a general term to describe any material or space through which light can pass.

Meridional plane
Plane through an optical system containing the optical axis and the object point.

Metal films
Thin films of metals designed to increase reflectivity and/or conductivity.

Minimum deviation
The smallest angle that light is deviated by an optical component or system.

Modulation
In optics modulation is defined as the ratio of the differences and the sum of the maximum and minimum illuminance of a series of lines and spaces imaged by a lens system. Modulation M is defined as:

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Modulation is usually considered a synonym for contrast.

Modulation transfer function (MTF)
MTF is a quantitative description of the image forming power of an imaging system. In determining MTF, increasingly fine lines of known contrast are imaged by the optical system and the image modulation is measured in the image plane. The ratio of the image modulation to the object modulation for different degrees of fineness of lines and separations (spatial frequency) yields the modulation factor. The MTF is a plot of this factor versus spatial frequency. An MTF calculated by ray tracing is called a geometrical optical transfer function (GOTF).

Monochromatic radiation
Radiation having a very narrow bandwidth (for example, laser radiation).

Newton rings
Circular series of interference fringes of equal thickness (i. e. Fizeau fringes) seen when two polished surfaces (at least one of which is slightly spherical) are brought together with a thin film or air between them.

Nodal point
Any ray transversing a lens through its optical center will emerge parallel to the incident direction. The extensions of the incoming and outgoing rays will cross the optical axis at two points called the nodal points. If the lens is surrounded by the same medium (i. e. air), then the nodal points coincide with the principal points.

Numerical aperture
Numerical aperture is defined as the sine of the half angle of the widest ray-bundle capable of entering a lens σ', multiplied by the index of refraction of the medium n through which the ray-bundle passes. $NA = n \cdot \sin \sigma'$. Numerical aperture has special significance for microscope lenses, see chapter "Zoom and Microscope Lenses".

Optical activity
A property of certain crystals and liquids. The polarization level of an incident beam rotates proportional to the path traversed in the crystal. One distinguishes between substances which rotate clockwise and those which rotate counterclockwise.

Optical axis
1. The symmetrical axis of optical imaging systems.
2. The direction where no birefringence occurs in optically birefringent non-cubic crystals.

Optical contact
The joining of two optical surfaces without the use of an adhesive. When the air between the two surfaces has been completely eliminated, they are said to be in optical contact. The contact is permanent and can just be separated through heat.

Optical density
Optical density D=log (1 / T), where T is the transmission. If neutral density filters are placed in series, the optical density of the combination is the sum of the individual density values.

Optical glass
Optical glasses are transparent, usually amorphous, and essentially homogeneous materials whose manufacturing processes are controlled in such a way as to create desired variation in characteristics such as refractive index, transmission range, dispersion etc..

Optical image formation
In an optical system, optical image formation is the process of transforming a light beam that emerges from an object point into a corresponding beam that creates an image point.

Optical path difference (OPD)
The difference of two optical path lengths, e.g. between the optical path length of a beam travelling through a medium and that of a beam travelling in vacuum.

Optical path length (OPL)
The optical path length of a light ray passing through a medium of constant refractive index is the product of the geometrical distance d and the index of refraction n. $OPL = n \cdot d$.

Optical transfer function (OTF)
OTF is the total optical transfer function which includes both the MTF and the phase transfer function. Usually, only the modulation transfer function (MTF) is used to describe the imaging performance of a lens system.

Optical tube length
A measure used to calculate the distance from the image focal plane of a lens to the object focal plane of an eyepiece. It is calculated as $t = -\beta' f$, with β' = magnification of the lens, and f = focal length of the lens.

Parallel shift
The shifting of the emergent beam parallel to the incoming beam which is observed when radiation passes through plane plates obliquely.

Paraxial space
The space close to the axis where all angle functions can be replaced by the angle itself ($\sin \alpha = \tan \alpha = \alpha$, $\cos \alpha = 1$). The optics in paraxial space are also called Gaussian optics.

Phase shift
When light travels through a low index medium and is incident on a medium with a higher index, a phase shift is observed in the component reflected from the surface. An additional phase shift is observed in the component passing through the denser medium.

Plane of polarization
Plane which is perpendicular to the electric field vector of linearly polarized light.

Point spread function (PSF)
The energy distribution in an image point P' formed by an illuminated object point P.

Polarization
A state of oscillation of light waves where the electric or magnetic field vector vibrations of the wave are restricted to oscillate in a single plane. The specific state of oscillation is determined by the position of the electric field vector. There are three forms of polarization: linear, elliptical and circular.

Polarization factor
The ratio of the intensity of polarized light to that of unpolarized light is called the polarization factor.

Principal planes
Planes drawn through the principal points perpendicular to the optical axis are the principal planes. The approximation of a principal plane is applicable only for the paraxial area.

Principal points
Those points of a lens which are imaged onto each other at a magnification of $\beta'=1$. The principal point represents the cardinal point from which the focal length, object distance or image distance is measured.

Principal ray
The principal, or chief ray, is a ray from an object point which passes through the center of an aperture stop. The ray assumes the function of the optical axis for skew rays.

Pupil
General term used for the paraxial image of the aperture stop. There are two types of pupils, entrance and exit pupil.

Radiant power
Radiant power is the energy emitted by a radiation source per second and is measured in Watts.

Rayleigh criterion
Two Airy interference discs are created by the image formation of two object points separated by an angular difference. The Rayleigh criterion states that the limit of the resolving power of the optical system is reached when the maximum of one Airy disc coincides with the corresponding first minimum of the other disc.

Reflection
The return of radiation upon contact with a boundary between two different media. There are two types of reflection: diffuse (from a rough surface) or direct (from a smooth surface). The characteristics of reflection at the boundary of a weakly or non-absorbing medium are summarized by Fresnel's equations.

Refracting power
Reciprocal value of the focal length of an optical imaging system relative to air. Refracting power is measured in dpt.

Refraction
The change in direction of an oblique light ray which passes from one medium to another having different refractive indices.

Resolving power
The measure of the ability of an optical component or instrument to image two closely adjacent object details as two separate details. In general, the resolving power is given as the angular distance at which these details appear or as the number of resolvable lines per mm.

Sagittal plane
Plane through an optical imaging system which contains the object point and the principle ray of skew rays. It is perpendicular to the meridional plane which contains the object point and the optical axis of the system. The sagittal plane cannot be explained as an independent concept beyond the context of a reference system.

Scattering
Scattering refers to the deflection of light by its interaction with a heterogeneous medium.

Secondary spectrum
In a simple achromatic optical imaging system, the focal points of two different wavelengths will coincide. The remaining wavelengths constitute the secondary spectrum.

Seidel aberrations
Theory of aberrations developed by Seidel went beyond Gaussian optics by no longer equating the sine of an angle to the angle itself in cases where light rays were refracted in an area outside the paraxial region. Instead, he represented a trigonometric function by power series and carried the expansion out to a third order approximation of the function. The aberrations which Seidel went on to describe by his theory were spherical aberration, coma, astigmatism, field curvature, and distortion. The Seidel zone covers that part of the ray space which can be approximated by this third order theory. The Seidel error sums and coefficients allow for a detailed analysis of an imaging system and play an important part in the design of optical components.

Sine condition
Established by Abbe to describe the quality of the image formation of surface elements lateral to the optical axis. A satisfactory quality can only be attained if the magnification is constant for all object zones. In other words, the focal length must be constant over the entire aperture of the lens. For an infinitely distant object, the sine condition is: $f = const = h / \sin \sigma'$ (h = incident height, σ' = angle of intersection with the optical axis).

Spatial frequency
A term used to describe the density of regular structures (such as lines of an optical grating) and is given in lines per mm.

Spectrum
A spectrum is the entirety of emitted or absorbed radiation arranged according to wavelength. There are many different types of spectra including continuous band and line spectra.

Spherical aberration
Aberrations which occur in widely spread beams originating from an object point on the optical axis. They appear as follows: the outer circular lens zones allow image points to develop which do not coincide with the paraxial image point. What results is a rotationally symmetric diversion around the paraxial image point.

Stop
Diaphragm or aperture used to limit the ray bundles in optical imaging.

Strehl intensity ratio
The ratio of the maximum intensity I of an aberrated image in a point P to the intensity I_0 of an aberration free image in the same point: $D = I / I_0$

Surface accuracy errors
Deviations of a spherical or plane optical test surface to a reference surface (test plate) are known as surface accuracy errors. They are usually given in units of wavelength. The non-contact methods employed in today's interferometers eliminate the possibility of surface damage.

Telecentric system
An optical system where the entrance or/ and exit pupil is imaged to infinity caused by locating the aperture stop at the front or back focal point of the system. Because of that, the principal rays are parallel to the optical axis in the image or/and object space.

Test plate
A test plate is a comparison surface of extreme precision used to test for surface accuracy errors. Deviation from the test plate profile can be interpreted by careful analysis of the fringe pattern created by the close contact, in monochromatic light, of the two surfaces.

Thin films
Thin film is a term used to describe either a metal or dielectric film applied to optical components to increase or decrease reflection.

Total internal reflection
If light is incident on a boundary between two optical media of different optical densities and is incident from the denser medium, it will experience total internal reflection. The critical angle for the two materials is described from Snell's law as $\alpha c = \arcsin (n'/n)$, where n' is the index of the denser medium.

Transmission
The passage without frequency change of radiation through an optical medium.

Transmission curves
In general a transmission curve is a graphical representation of the transmission factor over a given spectral range.

Transmission factor
The ratio of transmitted to incident radiation intensity.

Vignetting
A mechanical limitation of oblique light rays passing through an optical system. This effect cannot be caused by the aperture stop.

Visible light
Radiation which has the capacity to generate visual sensation. The spectral range lies between 380 nm and 780 nm.

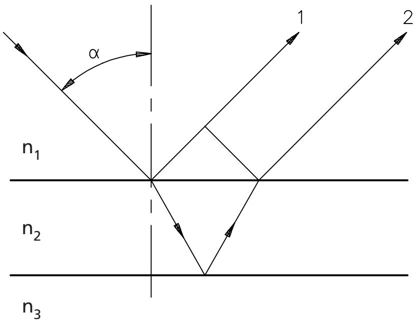
Wave optics
Description of optical image formation taking into account the wave nature of light. This branch of optics leads to the investigation of interference.

Zonal aberrations
Zonal aberrations are Seidel aberrations which occur in zones concentric to the optical axis where the effect due to the change of refractive power has not been corrected to minimize these aberrations.

Thin Films

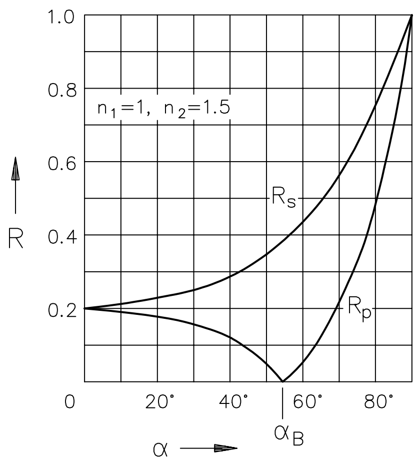
The properties of reflection and transmission of optical surfaces can be affected by thin film deposition. This is accomplished by evaporating a metal or a dielectric onto a substrate surface in a high vacuum.

The thin film on the boundary of the substrate, and a suitable choice of film thickness, produces interference. The drawing shows the path difference and the effects of the reflected beams of each boundary layer resulting in either constructive or destructive interference. This is how an increase or decrease in reflection is achieved.



Reflection on a Thin Film Surface

The reflection of the perpendicular (s) and parallel (p) components of light entering at an angle of incidence, $\alpha \neq 0$, is different. For the air-glass transition we show the following curve of the reflection coefficient R for perpendicular and parallel light as a function of the angle of incidence:



Reflection as a Function of the Angle of Incidence

At the Brewster angle α_B, the p-polarized component goes to a null position, and is transmitted without losses. The reflected beam is completely s-polarized.

The reflection properties depend on the following parameters:

- Refractive index of the surrounding medium
- Refractive index of the substrate
- Refractive index of the vacuum deposited material
- Absorption of the vacuum deposited material
- Film thickness
- Wavelength of the light source
- Angle of incidence of the light source
- Polarization of the light source

The following is a reference of the primary thin film coating letter designation (see also chapter Thin Film Coatings):

Antireflection Coatings
to minimize reflection for certain wavelengths or wavelength regions. Catalog designation **AR...**

Metallic Mirror Coatings
reflective coating, including optional over coating. Catalog designation **R...**

Dielectric Mirror Coatings
achieves maximum reflection, predominantly for laser applications, high damage threshold. Catalog designation **DL...**

Beamsplitter Coatings
for beamsplitters with a defined reflection and transmission ratio. Catalog designation **T...**

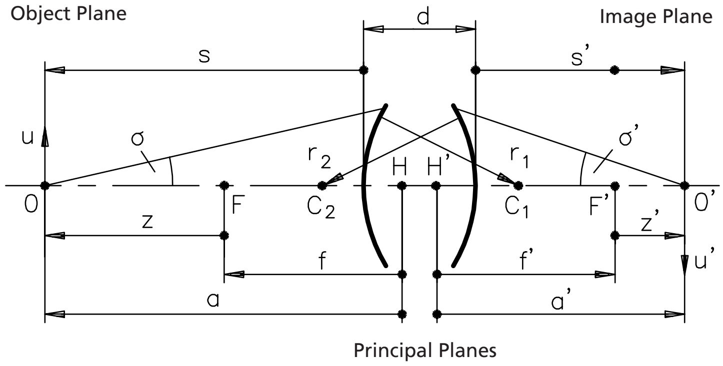
The transmission of an optical component is not just a function of coated surfaces, but also the transmission of the substrate material. We manufacture optical components from many standard materials and also many special materials.

Symbols and Sign Convention

The symbols used to describe optical components, systems and basic optical quantities in this catalog are listed below:

- The sign for paths parallel to the optical axis are determined by the light direction that travels from right to left.
- Paths measured in the direction of light are positive. Paths which are counter to the direction of light are negative. (lens thickness and system lengths are always positive).
- Symbols in object space are not primed. Symbols in image space are primed.
- The radius of curvature is measured from the surface to the center of curvature. That is why convex surfaces in the light direction appear to have a positive radius and concave surfaces appear to have a negative radius.
- Paths perpendicular to the optical axis are positive above the axis and negative below the axis.

In the drawing, we show the system parameters and image sizes for an optical component composed of two surfaces. The arrows indicate the direction of the paths. In this example and according to the sign convention, f < 0, while f' > 0. These symbols are also valid for more complex systems composed of many surfaces. The table defines the individual symbols:

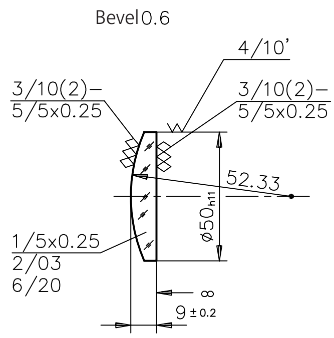


F	focal point in object space	F'	focal point in image space
H	principal point in object space	H'	principal point in image space
f	focal length	f'	focal length
s	object to front surface distance	s'	image to back surface distance
a	object distance	a'	image distance
z	object to focal point distance	z'	image to focal point distance
C_1	center of curvature, surface 1	C_2	center of curvature, surface 2
r_1	radius, surface 1	r_2	radius, surface 2
O	object point	O'	image point
u	object size	u'	image size
σ	object aperture angle	σ'	image aperture angle
d	lens thickness or system length		

Explanation of the Legends on Optical Component Drawings

Optical components and optical component drawings are characterised by code numbers found in the german standard DIN 3140 and the new international standard ISO 10110, see Literature. Outside of the pure geometrical tolerances for thickness and diameter, there are other properties corresponding to similar code numbers. Material properties of glass and form deviations are quantified.

In technical drawings the code number is followed by a slash (/) and then by the allowable tolerances. The following example shows the code numbers of a planoconvex lens.



Technical Drawing of a Single Lens

Code number 1 addresses the size and number of bubbles and inclusions in the medium. The smaller the value, the higher the material requirements. For further information please refer to DIN 3140 part 2.

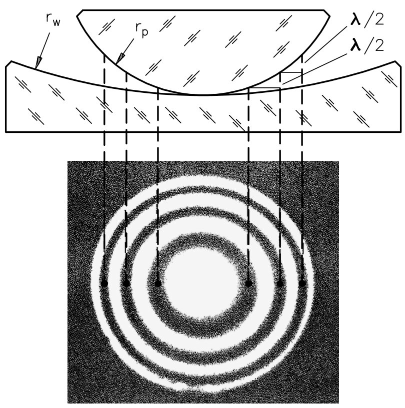
Code number 2 quantifies cords and inhomogenities in glass with the ratio of the cords size to that of the entire test area. For further information please refer to DIN 3140, part 3.

Code number 3 minimizes the allowable form error of the effective optical surfaces.

Form errors describe the deviations from plane and spherical surfaces. The testing occurs inside a predetermined test area. There are also additional form errors inside these areas which are characterised as fine form errors.

Because these form errors deal with very small deviation, the testing is accomplished with an interferometer. The wavelength of light is used as the unit of measurement; typically 546 nm or 633 nm (HeNe Laser).

Frequently the testing is done with test glasses. It is a comparative measuring procedure and relies on subjective evaluation. A reference glass is placed over the test surface and the resulting interference pattern is observed (Newton Rings). The number and the deformation of the resulting interference rings are measurements of the deviation between the reference glass and the glass under test. The distance between two interference lines signifies a half wavelength. The accuracy which can be obtained with a visual test is in the region of a 100 nm form error. For further information please refer to DIN 3140, part 5.



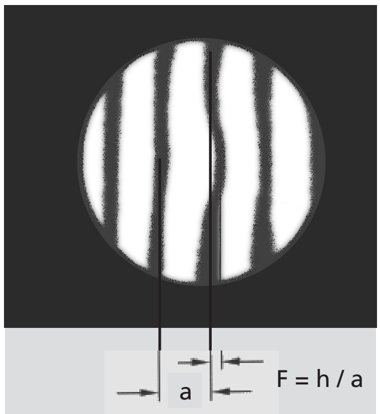
Form error testing with a test glass

Computer controlled interferometers provide a vibration free measurement with a much higher accuracy. The entire surface can be measured at one time and the "Peak-to-Valley" value determined. From this value we can understand the minimum and maximum deviation from a reference surface. On a flat surface it is the deviation of a plane and on a curved surface the relationship is with a spherical surface.

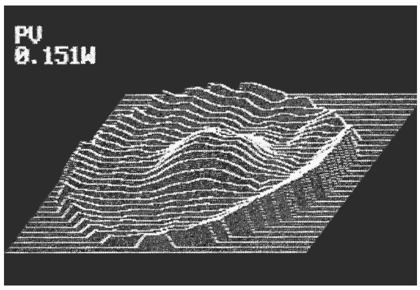
The spherical test produces mostly asymmetrical deviations, which have a particular negative effect on optical images, and are detected in the Peak-to-Valley value.

These written procedures deal with comparative measurements, always referring to a reference flat. Through a combination of many measurements and corresponding calculations absolute testing is possible.

The following illustration shows the evaluation of a fine form error obtained with an interferometer. The test component and the reference surface are slightly tilted to generate fringes. From the quantitative representation of the measured deviations of a surface from the nominal form we can determine and calculate the effects on the image quality.



Fine Form Error Interferogram (top)



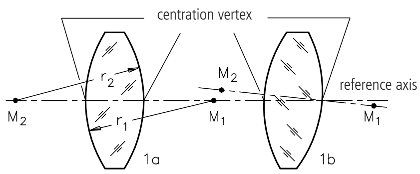
Fine Form Error Contours (bottom)

Code Number 4 addresses centration errors.

The centration error is a measurement of the deviation from the optical axis of a lens to its form axis. Frequently, the axis of the boundary cylinder is the reference axis of a lens, because the so called "Optical Axis" exists as a virtual quantity.

If the centers of curvature of the lens surface are on the reference axis, the lens is centered. Centration errors are normally stated in arc minutes.

For further information please refer to DIN 3140, part 6.



Lens Centering Error

Code Number 5 addresses the tolerances for surface defects.

Scratches and digs are considered surface defects and are classified by number and size. The smaller the value, the cleaner the surface.

For further information please refer to DIN 3140, part 7.

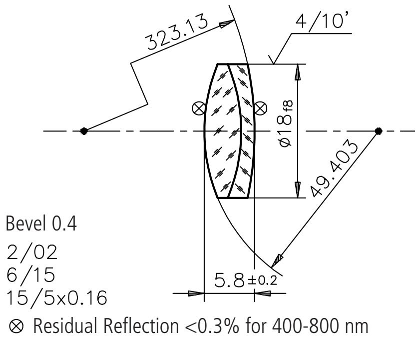
Code Number 6 classifies the effects of strains inside optical glass or optical systems.

This also applies to strains that are a result of cementing lenses. The errors are stated as the optical path difference in the glass. The defect is stated as the allowable difference in nanometers per 10 mm glass path. For further information please refer to DIN 3140, part 4.

Code number 15 addresses the purity of cement layers and bonded surfaces.

The purity of a cemented optical component is treated like code numbers 1 for flaws and code number 2 for schlieren. If the purity has not been explicitly specified, then it may not exceed the total value of the acceptable surface defects of both cemented surfaces.

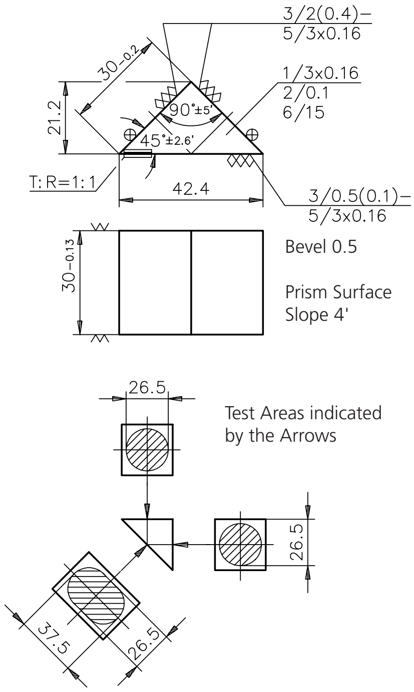
For further information please refer to DIN 58170, part 54.



Technical Drawing of a Cemented Component

Symbols for plane optical components

All the previous code number examples are also valid for plane optical components such as mirrors, plane plates, prisms and cemented beamsplitter cubes. In addition, the angle tolerances are specified.



Technical Drawing for a 90°-Prism

In this example, the prism surface slope angle is toleranced to s'. This error is also known as the "Pyramid Error". The prism hypotenuse also has a partially transmitting coating as is specified in the drawing with a special symbol. This symbol also references the transmission and reflection ratio.

The shaded areas in the lower part of the drawing shows the test area of the prism for which the code numbers and tolerances are valid.

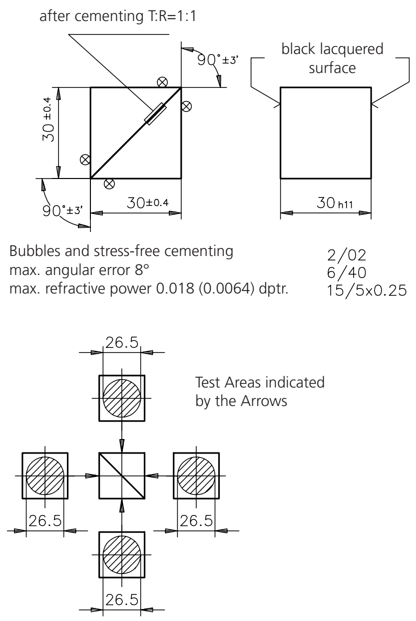
Symbols for Polished Surfaces

All optical surfaces are identified with a symbol for surface finish (roughness). The three-diamond symbol signifies a surface that has minimum stray light. For special applications the roughness can be further reduced and this surface finish is shown with 4 diamonds signifying a super fine polish.

Other Symbols for Plane Optical Components

All the previous codes are also valid for beamsplitter cubes. However, there is one new factor: the maximum refractive power. The first value indicates the spherical wavefront distortion and the bracketed value astigmatism. Both values are given in diopters.

Furthermore, the deflection angle and the maximum allowable deviation is also stated. For beamsplitter coatings the split ratio of the transmitted and reflected beam is also specified.



Technical Drawing for a Beamsplitter Cube

Quality Testing of Optical Components and Systems

The quality of optical components and systems are tested using objective measurement methods. This includes diameter and thickness measurements with precision apparatuses; surface finish with microscopes and the measurement of image performance with interferometers. The optics presented in our catalog generally meet or exceed the quality standards specified by DIN ISO.

Imaging systems are tested for their image forming quality by measuring the wavefront distortion. As a rule, the testing is done at a wavelength of 633 nm (HeNe Laser) and with an accuracy of a fraction of that wavelength. One of the quality features is the optical path difference which is detected when a wave passes through an optical system and is presented as an interferogram taken over the effective aperture (exit pupil) of the component under test. This test procedure presents a clear cut conclusion on the image formation and the identification of a possible out of tolerance component in the production process, especially when the resultant wavefront is not rotationally symmetric.

Precision optics can exhibit a wavefront distortion smaller than a quarter wavelength (160 nm). If the beam path is limited by an aperture, such as an iris diaphragm, the wavefront distortion decreases and the imaging performance becomes stronger through the influence of the diffraction of light on the iris. This is called a diffraction limited optical system.

In an imaging system there are normally many optical surfaces. The establishment of allowable tolerances of each individual surface must also be considered for the total system in order to achieve total performance.

Additional information on testing optical components and systems is available in the recommended literature section in this catalog.

Minimum Spot Size and Resolving Power

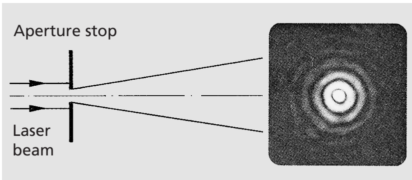
In geometric optics, the wavelength of light is ignored as the wave theory consideration which lead to diffraction and interference phenomena are not part of geometric optics. That is why it is possible, on the basis of geometrical calculation, to generate an infinitely defined image point with a perfect lens. Theoretically, this would result in an infinitely high resolving power. If this were actually possible, electron microscopes, for example, would be absolutely unnecessary.

The fact is, however, that this is not possible. Even the most flawless lens has a finite resolving power determined by wavelength-dependent diffraction.

Optical diffraction is defined as the deviation of a wave from its original direction of propagation along the normal of the wave surface which is not caused by refraction, reflection or scattering but by the wave nature of the wavetrain.

For example, if you illuminate an obstacle such as an iris diaphragm, then light will no longer propagate in a parallel manner behind the obstacle. Instead, its propagation will change in accordance with the shape of the obstacle.

The following drawing shows the result of light propagation behind a circular stop which is illuminated by a laser beam (HeNe Laser). The diameter of the stop is about 0.5 mm. As you can see, little remains of the straight parallel propagation of the light from the original laser beam.

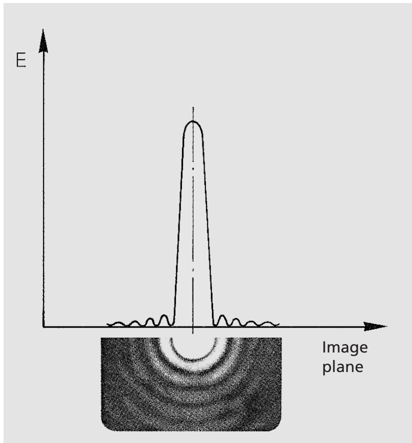


Light Propagation behind a Circular Stop

Naturally, this re-distribution of the luminous intensity resulting from the diffraction of light occurs in all optical systems which, of course, represent obstacles (usually of a circular nature) in the path of the light. If you imagine a circular aperture filled with glass (as, for example with a lens), then diffraction will be superimposed, for the most part, by refraction.

As can be seen in the following photograph, the brightness distribution of the diffraction pattern, when focussed through a lens, will re-appear in the focal or image plane. The principal feature of this brightness distribution is a very distinct central maximum surrounded by additional maxima of decreasing brightness. Between each of these maxima, there is a brightness minimum in the form of dark rings.

84 % of the total light is concentrated in the central maximum. Only 16 % is distributed among the secondary maxima.



Brightness Distribution of the Diffraction Pattern

The diameter of the first ring is also called the diameter of the diffraction (i. e. Airy disc). This diameter is given by:
$D_{Airy} = 2.44\,\lambda \cdot k$

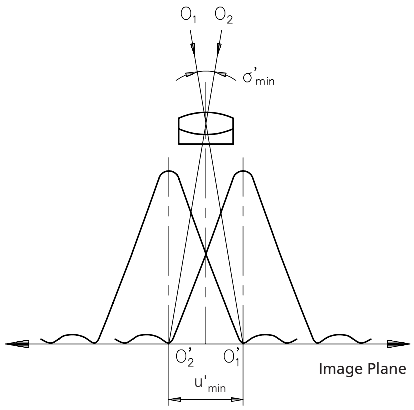
with f-number $k = \frac{f'}{\varnothing_{EP}}$

λ Wavelength
f' focal length
$\varnothing_{EP}$ Diameter of the free opening

Diffraction discs limit the resolving power of optical imaging systems. Resolving power can generally be defined as the ability of an optical system to separate object points in the image plane. For example, in a telescope, the resolving power limits the eye's ability to recognize two close stars as really two separate stars. One can calculate the resolving power from the size of the diffraction pattern.

In the following illustration, we have an optical image formation system being acted upon by the light of two separate object points O_1 and O_2, characterized by the two principal rays which pass through the imaging lens at an angular distance w.

Each object point now produces its own Airy disc in the image plane. The smaller the angle σ' or the greater the diameter of the Airy disc, the more these discs will overlap. The diameter of the disc is determined by the f-number of the lens.



Resolving Power of two separate Object Points

The resolution limit is reached when the Airy discs exhibit a 50 % overlap in the image plane. This is illustrated in the drawing on this page. In this case, the two object points can just barely be recognized as two separate points in the image plane because the maximum of the one disc will coincide with the minimum of the other. From this, the size of the smallest structure that can be resolved in the image is given by:

$$u'_{min} = 1.22\, \lambda \cdot k$$

This determines the minimum angular distance of the two object points which is generally defined as the resolving power of an optical imaging system:

$$w_{min} = 1.22 \frac{\lambda}{\varnothing_{EP}}$$

(assuming small angles, such that $\sin w_{min} \approx \tan w_{min} \approx w_{min}$)

Consequently, two object points can be recognized as separate points when their angular distance is $w \geq w_{min}$.

Furthermore, it follows that it is useless to try to raise the resolving power by increasing the magnification with the aid of focal length f', without simultaniously reducing the f-number, $k = f' / \varnothing_{EP}$.

The resolving power of optical instruments is rarely ever reached, because the theoretical limit imposed by diffraction is usually further reduced by geometrical effects. It is, of an optical imaging system. For lasers, the diffraction limit is a real measure for the efficiency of achromats because of the favorable properties of laser light (monochromaticity, parallelism).

In laser use, the laser beam itself must be considered as a "diffracting" aperture. This means that the diameter of the laser beam must be included in equations for minimum spot size and resolving power if the optical system in question is not completely illuminated.

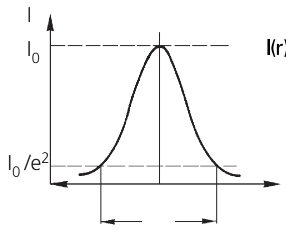
Focusing and Expanding Laser Beams

Beam Profile

Laser beams, like other radiation fields, are composed of one or more beam modes. In laser technology the radiation field develops a transverse electromagnetic mode (TEM). Lasers emit in one single mode (SM) or in multi-mode operation. The TEM Modes are distinguished by two indices which indicate how many null positions the electro-magnetic field in the x and y direction exhibits and z is the direction of the beam propagation. A TEM_{mn} mode has also m null positions in the x direction and n null positions in the y direction.

Beams in the TEM_{00} mode do not exhibit null positions in the transverse direction. This beam mode is diffraction limited; that means that the product of the beam divergence and the minimum beam radius takes the smallest possible value compared to any other beam mode. This is why lasers, whenever possible, are constructed to emit in the TEM_{00} mode. Most gas lasers such as HeNe and Ion lasers, and many low power solid state lasers emit these modes. Diode lasers frequently in asymmetrical (astigmatic) form, compared to high intensity laser beams and special material processing lasers, in general have higher beam modes. The TEM_{00} mode has also considerable meaning in practice and is frequently used as an approximation for higher beam modes.

The intensity distribution of the TEM_{00} mode is described by the Gaussian distribution (Gaussian beam):



$$I(r) = I_0 \cdot e^{\frac{-2 \cdot r^2}{w^2}}$$

Beam Profile

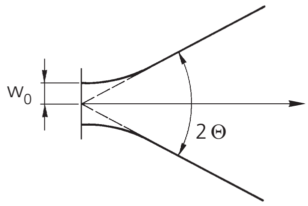
Whereby I_0 is the intensity on the optical axis, also the maximum intensity, and r is the distance from the optical axis. The beam radius w (beam diameter 2w) is defined as the distance from the optical axis where the intensity has fallen to $1/e^2$ of the maximum intensity.

The optical design program WinLens™ is especially useful to calculate the expansion and formation of Gaussian beams. A concise treatment of the expansion and formation of laser beams is also available by H. Kogelnik, T. Li: Appl. Optics 5 (1966) 1550-1567.

Beam Expansion

Every Gaussian beam has a beam waist in the direction of propagation where the beam radius takes a minimum value w_0. The beam waist can be a virtual beam waist or it can be found beyond the beam source. On both sides of the beam waist the beam radius increases with increasing distance z:

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



Beam Divergence

Where λ is the laser wavelength, z the distance from the beam waist and Θ the beam divergence defined as:

$$\Theta = \frac{\lambda}{\pi \cdot w_0}$$

In the vicinity of the beam waist the Gaussian beam maintains an approximation of a parallel beam bundle with the smallest possible cross section. Farther away from the beam waist it approximates a spherical wave with the smallest possible angular aperture; the transition between the two regions results in the distance z_R (Rayleigh Range):

$$z_R = \frac{\pi \cdot w_0^2}{\lambda}$$

For larger distances the following is valid:

$$w(z) = \Theta \cdot z$$

Beam Focusing

If a TEM_{00} beam is transmitted through a lens, a new beam waist (real or virtual) is produced in the location z' by:

$$z' = \frac{z \cdot f^2}{z^2 + z_R^2}$$

Special Cases:

1. If the beam waist of the incoming beam lies in the incoming focal point of the lens (z=0), the new beam waist lies in the image side focal point (z'=0). On the contrary in geometrical optics an object in the focal plane is imaged to infinity.

2. In the case $z_R << z$, where z_R is the Rayleigh Range in front of the lens, $z' = f^2/z$. This is also valid for imagery in geometrical optics. This case occurs, when the beam waist of an already strongly focussed beam is far away from the lens.

3. If $z_R >> z$ then $z' = z \cdot f^2/z^2_R$. This case is frequently encountered, when a highly collimated beam is focused through a lens.

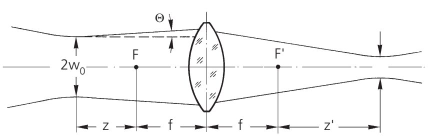
4. In addition, if $z_R >> z$ and $z_R >> f$, then z' = 0 is valid. Focusing a highly collimated laser beam through a short focal length lens the beam waist lies again in the image side focal point.

The radius of the image side beam waist, w_f, can be calculated with the following formula:

$$w_f^2 = w_0^2 \cdot \frac{z'}{z} = w_0^2 \cdot \frac{f^2}{z^2 + z_R^2}$$

In practice case 4 is very important and the following is valid:

$$w_f = \frac{\lambda \cdot f}{\pi \cdot w_0}$$



Beam Focusing

Collimating Laser Beams

Laser beams are collimated to produce plane waves or to maintain a constant diameter over a large distance. This is achieved by telescopes, where two lenses are separated by the sum of their focal lengths.

In principle this is possible using the beam focusing formula and a single lens. In most cases this method results in impractical focal lengths and beam waist positions as well as extremely high demands on the beam waist length tolerance. That is why in practice and in classical optics the predominant telescope (two lenses separated by their focal lengths) is used when collimating light.

The beam parameters of the exiting laser beam can be determined by using the two focusing formulas. For most applications it is sufficient to use the telescope expansion formula:

$$A = \frac{f_1}{f_2} \quad ,$$

where f_2 is the focal length of the exit lens and f_1 the focal length of the entrance lens. In practical terms, in case 3 and 4 the beam waist is expanded by this factor and the divergence is decreased by the same factor. The exit beam waist position can be adjusted by minor changes of the lens separation in the telescope.

Depth of Field

The depth of field Δz is the region around the beam waist length where the beam waist radius moves within a defined region:

$$\Delta z = \pm \frac{\pi \cdot w_f^2}{\lambda} \cdot \sqrt{\left(\frac{w}{w_f}\right)^2 - 1} \quad ,$$

where w/w_f is the allowable change of the beam waist radius. If $w >> w_f$ this approximation is valid:

$$\Delta z = \pm \frac{\pi \cdot w \cdot w_f}{\lambda} \quad .$$

Higher Modes

For a Gaussian beam (TEM_{00}), the product of the beam waist radius and divergence is determined by:

$$w_0 \cdot \Theta = \frac{\lambda}{\pi} \quad .$$

For correspondingly larger TEM_{mn} we use:

$$w_{0,x} \cdot \Theta_x = \frac{\lambda}{\pi} \cdot (2 \cdot m + 1) \quad \text{and}$$

$$w_{0,y} \cdot \Theta_y = \frac{\lambda}{\pi} \cdot (2 \cdot n + 1) \quad .$$

The product of the radius and divergence is larger than the product for the TEM_{00} mode and can be different in the x and y direction. It then follows that higher modes under the same conditions cannot be focussed or collimated as well as Gaussian TEM_{00} beams.

Literature and Software

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b) Technical Articles

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N. Henze, Optische Tischsysteme I-III: "Die Schwingungsisolation", "Design optischer Tischplatten" und "Tischplatten - thermisches Verhalten", Optolines - LINOS Fachmagazin für Optomechanik und Optoelektronik, 7-9, 2005-2006

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M. Schulz-Grosser, R. Schuhmann "Neue Laserspiegel für hohe Ansprüche", Laser 3, 1999, 32-36

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c) Software

(see chapter "Optics Software" regarding more information)

WinLens^{TM}
LINOS Photonics optical analysis program

WinLens Tolerancer
LINOS Photonics optic tolerance calculation program

Glass Manager
LINOS Photonics database program for glass types

Material Editor
LINOS Photonics utility to create, edit and manage custom materials data

PreDesigner
LINOS Photonics software to determine and display key parameters of optical systems

Lens Library
LINOS Photonics database including optical systems and modified LINOS components

Optical Glass Data

Refractive Indices and Internal Transmittances

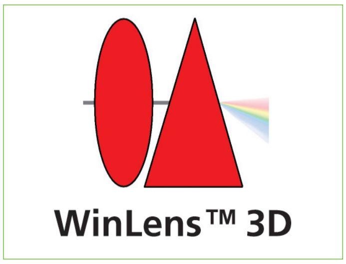
- The tables list the internal transmittances, τ_i , and the refractive indices, n, of the major types of optical glass and other fused silica used in fabricating components appearing in this catalog
- Abbe constants may be computed from the following relation:

$$v_d = \frac{n_d - 1}{n_F - n_C}$$

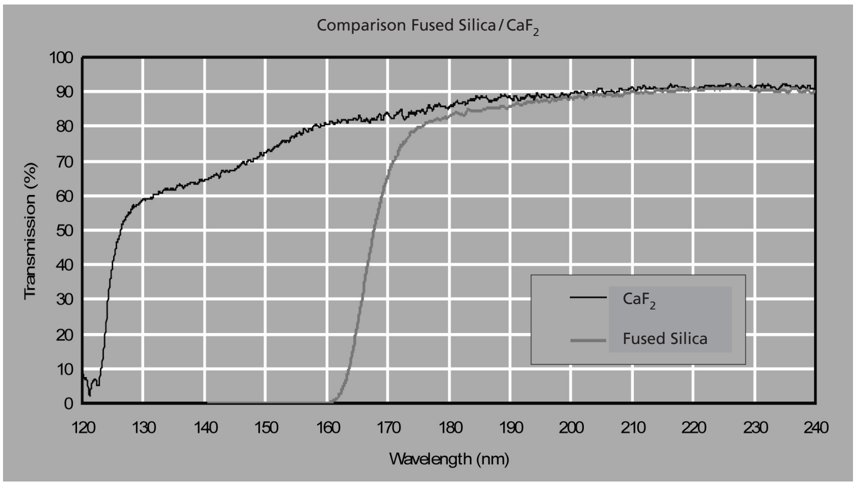
- Refer to Glass Manager on page 592 for further information on the optical glasses listed above and glass data of all main suppliers.

A closer look

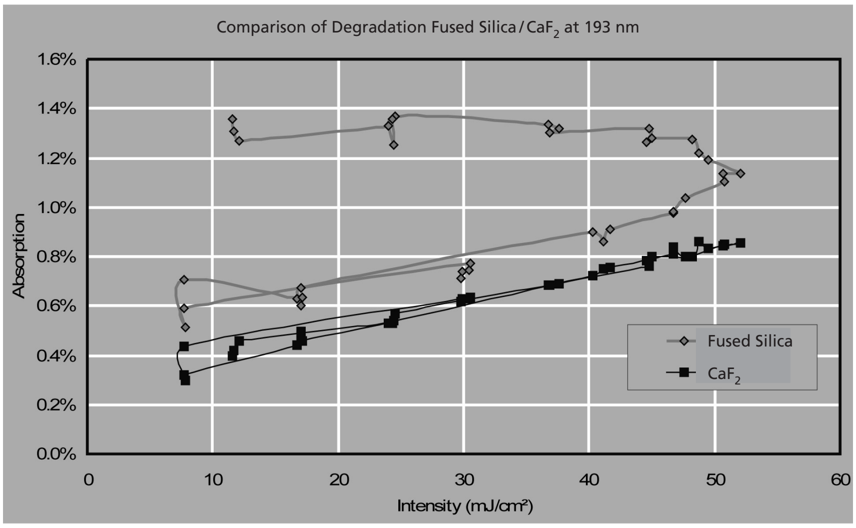
All relevant specifications of most of our optics, such as materials, radii and transmittances, are included in the database of the LINOS WinLens optical design software. A freeware version of this program is available for download at www.winlens.de.



λ (nm)		N-BK7 τ_i d=5mm	N-BK7 n	N-BaK4 τ_i d=5mm	N-BaK4 n	N-F2 τ_i d=5mm	N-F2 n	N-SF10 τ_i d=5mm	N-SF10 n	Fused Silica τ_i d=5mm	Fused Silica n
280.0		-	1.5612	-	1.6289	-	1.7474	-	-	0.990	1.4940
290.0		-	1.5567	-	1.6224	-	1.7307	-	-	0.993	1.4905
300.0		0.260	1.5529	-	1.6169	-	1.7170	-	-	0.997	1.4875
310.0		0.590	1.5495	0.240	1.6121	-	1.7055	-	-	0.999	1.4848
320.0		0.810	1.5465	0.530	1.6079	0.200	1.6959	-	-	0.999	1.4824
334.1		0.950	1.5427	0.750	1.6028	0.760	1.6845	-	-	0.999	1.4795
350.0		0.986	1.5392	0.940	1.5980	0.940	1.6742	-	-	0.999	1.4766
365.0	n_i	0.994	1.5363	0.981	1.5941	0.981	1.6662	0.060	-	0.999	1.4743
370.0		0.995	1.5354	0.988	1.5929	0.986	1.6639	0.210	1.7978	0.999	1.4736
380.0		0.996	1.5337	0.992	1.5907	0.992	1.6595	0.590	1.7905	0.999	1.4723
390.0		0.998	1.5322	0.995	1.5887	0.995	1.6557	0.830	1.7840	0.999	1.4711
400.0		0.998	1.5308	0.997	1.5869	0.998	1.6521	0.930	1.7783	0.999	1.4700
404.7	n_h	0.998	1.5302	0.997	1.5861	0.999	1.6506	0.952	1.7758	0.999	1.4695
420.0		0.998	1.5284	0.998	1.5837	0.999	1.6461	0.981	1.7685	0.999	1.4681
435.8	n_g	0.999	1.5267	0.998	1.5815	0.999	1.6420	0.990	1.7620	0.999	1.4667
460.0		0.999	1.5244	0.998	1.5785	0.999	1.6368	0.995	1.7537	0.999	1.4649
480.0	$n_{F'}$	0.999	1.5228	0.998	1.5765	0.999	1.6331	0.996	1.7480	0.999	1.4636
486.1	n_F	0.999	1.5224	0.999	1.5759	0.999	1.6321	0.997	1.7465	0.999	1.4632
500.0		0.999	1.5214	0.999	1.5747	0.999	1.6299	0.998	1.7432	0.999	1.4625
546.1	n_e	0.999	1.5187	0.999	1.5712	0.999	1.6241	0.999	1.7343	0.999	1.4603
580.0		0.999	1.5171	0.999	1.5692	0.999	1.6207	0.999	1.7292	0.999	1.4589
587.6	n_d	0.999	1.5168	0.999	1.5688	0.999	1.6200	0.999	1.7282	0.999	1.4587
620.0		0.999	1.5155	0.999	1.5673	0.999	1.6175	0.999	1.7244	0.999	1.4576
632.8	$n_{632.8}$	0.999	1.5151	0.999	1.5667	0.999	1.6166	0.999	1.7231	0.999	1.4572
643.8	$n_{C'}$	0.999	1.5147	0.999	1.5662	0.999	1.6158	0.999	1.7220	0.999	1.4569
656.3	n_C	0.999	1.5143	0.999	1.5658	0.999	1.6150	0.999	1.7209	0.999	1.4566
660.0		0.999	1.5142	0.999	1.5656	0.999	1.6148	0.999	1.7205	0.999	1.4565
700.0		0.999	1.5131	0.999	1.5642	0.999	1.6126	0.999	1.7173	0.999	1.4555
1060.0	$n_{1060.0}$	0.999	1.5067	0.999	1.5569	0.999	1.6019	0.999	1.7023	0.999	1.4498
1529.6	$n_{1529.6}$	0.997	1.5009	0.998	1.5512	0.998	1.5951	0.999	1.6938	-	1.4442
1970.1	$n_{1970.1}$	0.968	1.4951	0.983	1.5458	0.975	1.5896	0.990	1.6875	-	1.4384
2325.4	$n_{2325.4}$	0.890	1.4897	0.940	1.5410	0.930	1.5848	0.959	1.6822	-	1.4330



Measured transmission of CaF_2 and Fused Silica in the UV



Degradation after 8 000 J/cm^2 respectively 250 000 pulses

Unlike in the visible spectral region (VIS), at even shorter UV wavelengths (VUV), the absorption increases proportionally to the intensity (for intensities < 150 mJ/ cm^2). This is due to the 2-photon absorption. A degradation test (simple long-term test), starts at medium intensity, and the intensity is then increased and decreased.

In this test, optical glass made of fused silica typically shows early signs of damage (for example, caused by the formation of colored points), whereas the absorption of CaF_2 remains unchanged even after a few million pulses.