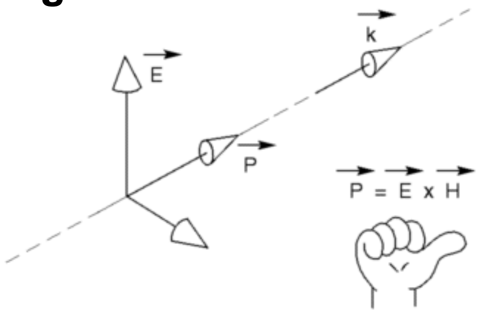
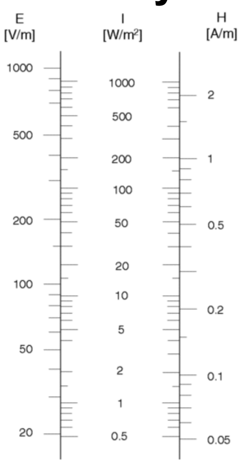
Optics Reference Guide
Newport Corporation

Light



Light is a transverse electromagnetic wave. The electric and magnetic fields are perpendicular to each other and to the propagation vector *k*, as illustrated.**Power density** is given by **Poynting's vector**, P, the vector product of E and H. You can easily remember the directions if you "curl" E into H with the fingers of the right hand: your thumb points in the direction of propagation.

Intensity Nomogram



The nomogram below relates E, H, and I in vacuum. You may also use it for other area units, for example, [V/mm], [A/mm] and [W/mm^2]. If you change the electrical units, remember to change the units of I by the product of the units of E and H: for example [V/m], [mA/m], [mW/m2] or [kV/m], [kA/m], [MW/m^2].

Wave quantity relationships

$$k = \frac{2\pi}{\lambda} = \frac{2\pi n}{\lambda_0} = \frac{2\pi n \nu}{c} = \frac{n\omega}{c}$$

$$\nu = \frac{c}{\lambda_0} = \frac{c}{n\lambda} = \frac{kc}{2\pi n} = \frac{\omega}{2\pi}$$

$$\lambda = \frac{c}{n\nu} = \frac{\lambda_0}{n} = \frac{2\pi}{k} = \frac{2\pi c}{n\omega}$$

where,
k: wave vector [radians/m]
n: frequency [Hertz]
w: angular frequency [radians/sec]
λ: wavelength [m]
λ_0: wavelength in vacuum [m]
n: refractive index

Energy Conversions

Wavenumber $(\nu)\left[cm^{-1}\right]$

$$= \frac{10^7}{\lambda_0}\left[nm\right]$$

Electron volts (eV) per photon

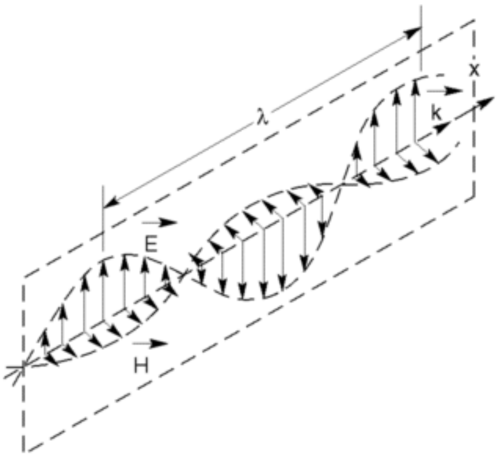
$$= \frac{1242}{\lambda_0}\left[nm\right]$$

Wavelength conversions

1 nm = 10 Angstroms(Å) = 10^{-9}m = 10^{-7}cm = 10-^{3}micron

Plane polarized light

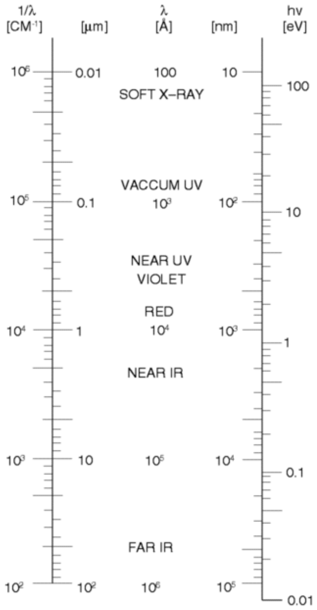
For **plane polarized light** the *E* and *H* fields remain in perpendicular planes parallel to the propagation vector *k* as shown below.



Both *E* and *H* oscillate in time and space as:

sin (wt-kx)

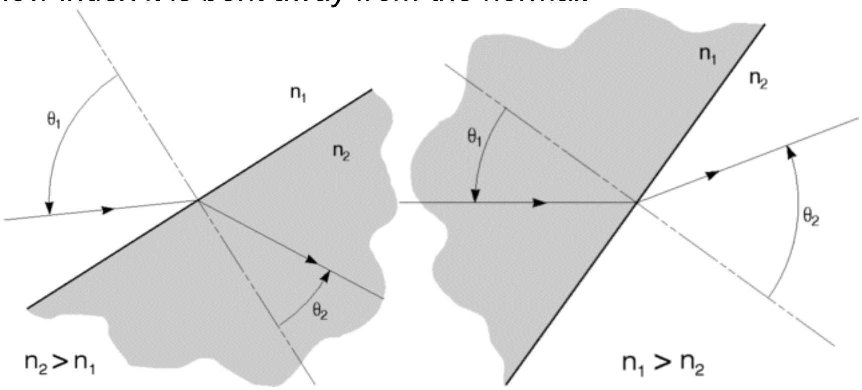
The nomogram relates wavenumber, photon energy and wavelength.



Snell's law

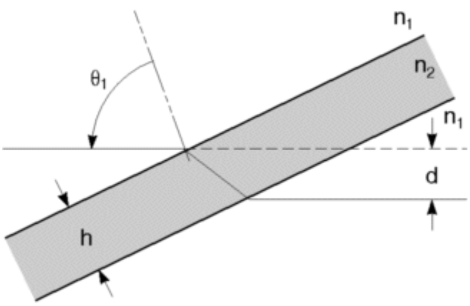
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

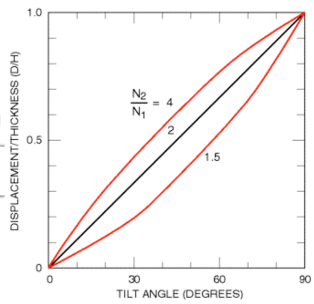
Snell's law tells how a light ray changes direction at a single surface between two media with different refractive indices. The angle of incidence, θ, is measured from the normal to the surface. A ray passing from low to high index is bent *toward* the normal; passing from high to low index it is bent *away from* the normal.



Displacement

A flat piece of glass can be used to *displace* a light ray laterally without changing its direction. The displacement varies with the angle of incidence; it is zero at normal incidence and equals the thickness of the flat at grazing incidence. The shape of the curve depends on the refractive index of the glass, as shown in the next column.

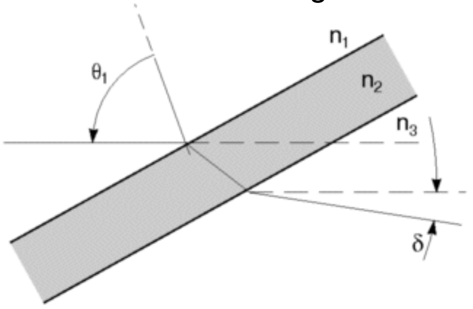




$$d = h \sin\theta_1 \left[1 - \frac{\cos\theta_1}{\sqrt{\left(\frac{n_2}{n_1}\right)^2 - \sin^2\theta_1}} \right]$$

Deviation

Both **displacement** and **deviation** occur if the media on the two sides of the tilted flat are different -- for example, a tilted window in a fish tank. The displacement is the same, but the angular deviation V is given by the formula. Note that V is independent of the index of the flat; it is the same as if a single boundary existed between media 1 and 3.



Example: The refractive index of air at STP is about 1.0003. The deviation of a light ray passing through a glass Brewster's angle window on a HeNe laser is then:

$V = (n_3 - n_1) \tan\theta$

At Brewster's angle, $\tan\theta = n_2$

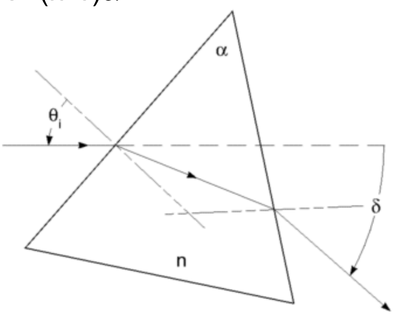
$= (0.0003) \times 1.5 = 0.45$ mrad

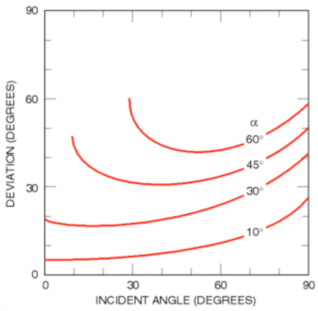
At 10,000 ft. altitude, air pressure is 2/3 that at sea level; the deviation is 0.30 mrad. This change may misalign the laser if its two windows are symmetrical rather than parallel.

Angular Deviation of a Prism

Angular deviation of a prism depends on the prism angle α, the refractive index, and the angle of incidence θ_i. Minimum deviation occurs when the ray within the prism is normal to the bisector of the prism angle. For small prism angles (optical wedges), the deviation is constant over a fairly wide range of angles around normal incidence. For such wedges the deviation is:

$V=(n-1)\alpha$





Geometric Optics

Field reflection

The **field reflection** and transmission coefficients are given by:

$r = E_r/E_i$ $t = E_t/E_i$

Non-normal incidence:

Conservation of energy:

$R + T = 1$

This relation holds for *p* and *s* components individually and for total power.

Power reflection
The **power reflection** and transmission coefficients are denoted by capital letters:

$R = r^2$ $T = t^2(n_t \cos\theta_t)/n_i \cos\theta_i)$

The refractive indices account for the different light velocities in the two media; the cosine ratio corrects for the different cross sectional areas of the beams on the two sides of the boundary.

The **intensities** [watts/area] must also be corrected by this geometric obliquity factor:

$I_t = T \times I_i (\cos\theta_i/\cos\theta_t)$

Fresnel Equations:
i - incident medium
t - transmitted medium
use Snell's law to find θ_t

Normal incidence:
$r = (n_i - n_t)/(n_i + n_t)$

$t = 2n_i/(n_i + n_t)$

Brewster's Angle
$\theta_{(beta)} = \arctan (n_t/n_i)$

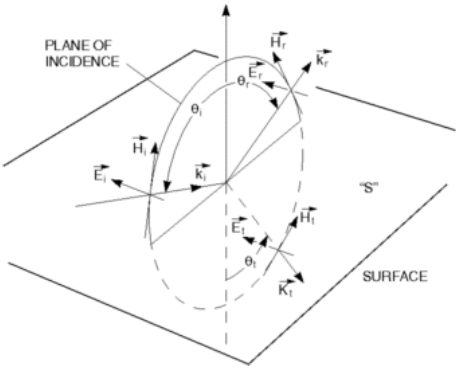
Only s-polarized light reflected.

Total Internal Reflection (TIR)
$\theta_{TIR} > \arcsin (n_t/n_i)$

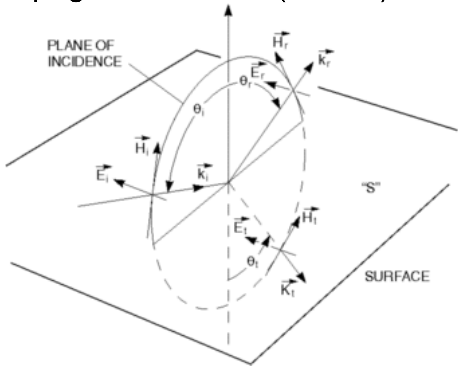
$n_t < n_i$ is required for TIR

Polarization

To simplify reflection and transmission calculations, the incident electric field is broken into two plane polarized components. The **plane of incidence** is denoted by the "wheel" in the pictures below. The normal to the surface and all propagation vectors (*k*i,*k*r,*k*t) lie in this plane.



E normal to the plane; **s-polarized.**

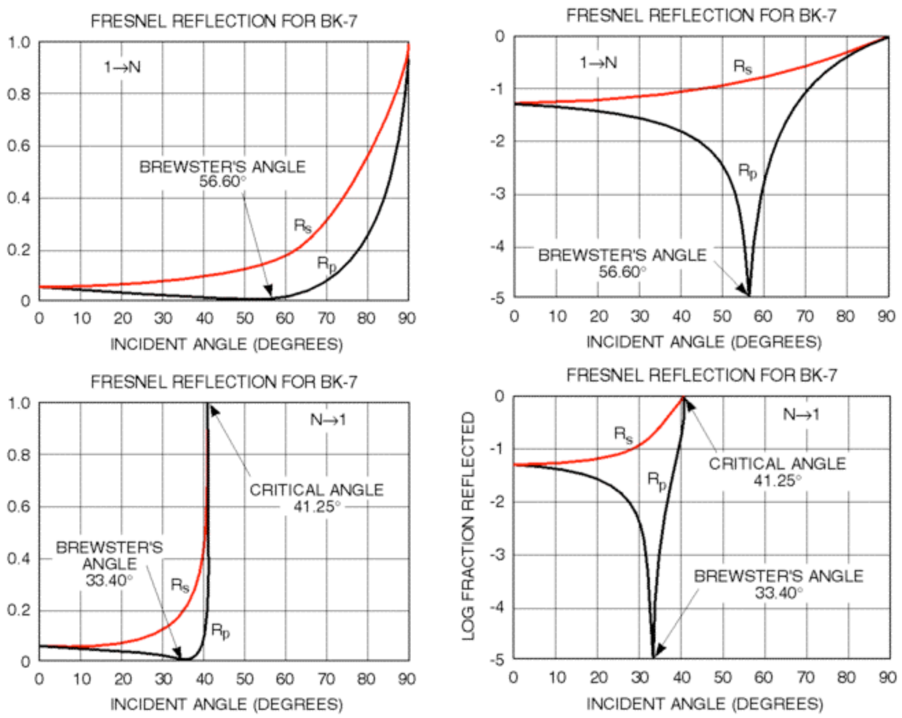


E parallel to the plane; **p-polarized.**

Power reflection coefficients

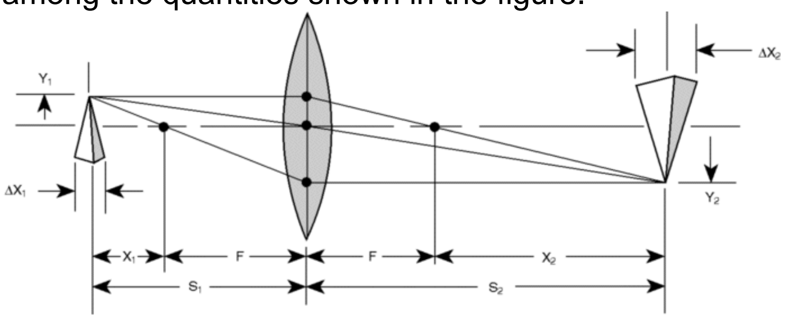
Power reflection coefficients *R*s and *R*p are plotted linearly and logarithmically for light traveling from air (ni = 1) into BK-7 glass (*n*t = 1.51673). **Brewster's angle** = 56.60°.

The corresponding reflection coefficients are shown below for light traveling from BK-7 glass into air **Brewster's angle** = 33.40°. **Critical angle (TIR angle)** = 41.25°.



Thin Lens

If a lens can be characterized by a single plane then the lens is "thin." Various relations hold among the quantities shown in the figure.



Sign conventions for images and lenses				Lens types for minimum aberration	
Quantity	+	-		$\lvert s_2/s_1 \rvert$	Best lens
s1	real	virtual		<0.2	plano-convex/concave
s2	real	virtual		>5	plano-convex/concave
F	convex lens	concave lens		>0.2 or <5	bi-convex/concave

Gaussian:

$$\frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{F}$$

Newtonian:
$x_1 x_2 = -F_2$

Magnification:
Transverse:

$$\frac{1}{s_1} + \frac{1}{s_2} = \frac{1}{F}$$

$M_t < 0$ - Image inverted

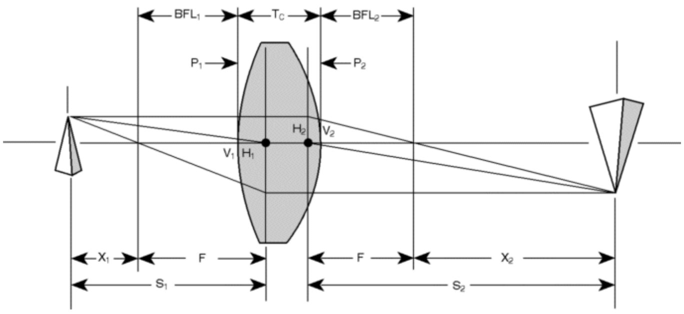
Longitudinal:

$$M_T = \frac{y_2}{y_1} = -\frac{s_2}{s_1}$$

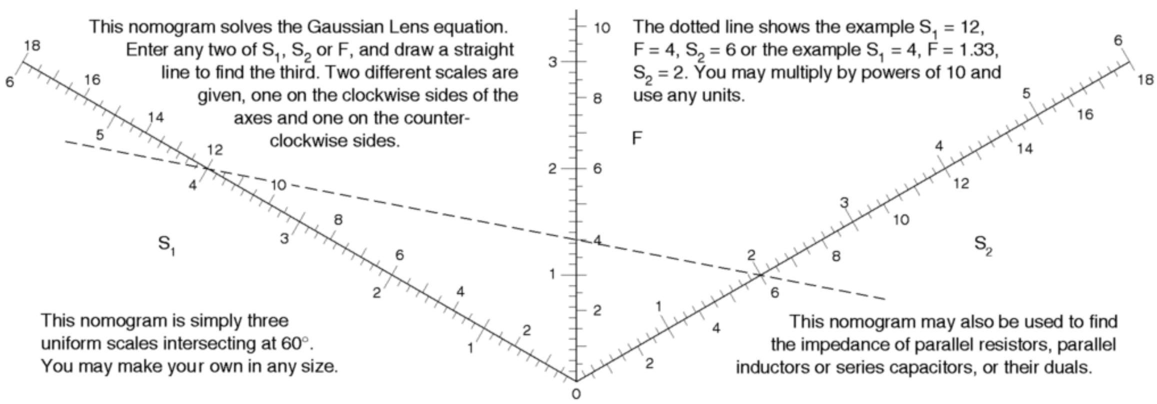
$M_l < 0$ - No front to back inversion

Thick Lens

A **thick lens** cannot be characterized by a single focal length measured from a single plane. A single focal length *F* may be retained if it is measured from two planes, *H1*, *H2*, at distances *P1*, *P2* from the vertices of the lens, *V1*, *V2*. The two back focal lengths, *BFL* and *BFL2*, are measured from the vertices. The thin lens equations may be used, provided all quantities are measured from the principal planes.



Lens Nomogram

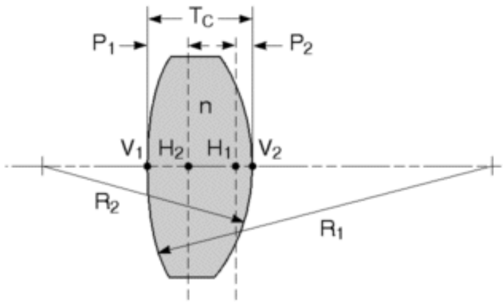


The Lensmaker's Equation

$$\frac{1}{F} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)T_c}{nR_1R_2}\right]$$

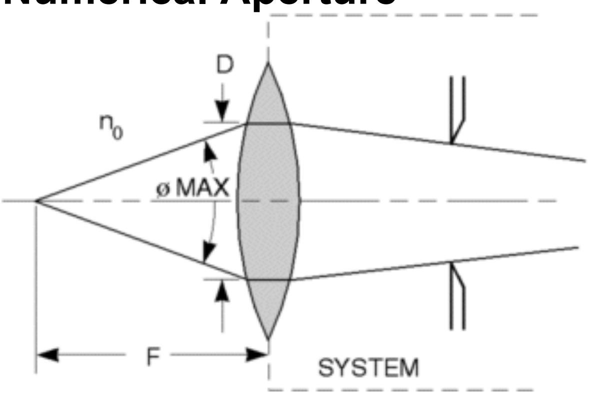
$$P_1 = -\frac{F(n-1)T_c}{nR_2}$$

$$P_2 = -\frac{F(n-1)T_c}{nR_1}$$



Convex surfaces facing left have positive radii. In the above $R_1>0$, $R_2<0$. Principal plane offsets, *P*, are positive to right. As illustrated, $P_1>0$, $P_2<0$. The thin lens focal length is given when $T_c = 0$.

Numerical Aperture



$$NA = n_0 \sin\left(\frac{\phi_{MAX}}{2}\right)$$

$ø_{MAX}$ is the full angle of the cone of light rays that can pass through the system.

For small ø

$$f/\# = \frac{F}{D} \approx \frac{1}{2\,NA}$$

Both f-number and NA refer to the *system* and not the exit lens.

Constants and Prefixes

Vacuum light vel.
c = 2.998x108 m/s

Planck's const.
h = 6.625×10^{-34} J-s

Boltzmann's const.
k = 1.3085x10-23 J/¡K

Stefan-Boltzmann
s = 5.67x108 W/m2¡K4

1 electron volt

eV = 1.602×10^{-19} J

exa (E)
10^{18}

peta (P)
10^{15}

tera (T)
10^{12}

giga (G)
10^{9}

mega (M)
10^{6}

Kilo (k)
10^{3}

milli (m)
10^{-3}

micro (u)
10^{-6}

nano (n)
10^{-9}

pico (p)
10^{-12}

femto (f)
10^{-15}

Laser Source properties
(nm)

KrF
248

NdYAG(4)
266

XeCl
308

HeCd
325, 441.6

N2
337

XeF
350

NdYAG(3)
354.7

Ar
488, 514.5, 351.1, *363.8*

Cu
510, 578

NdYAG(2)
532

HeNe
632.8, 1152, *534, 594, 604*

Kr
647

Ruby
694

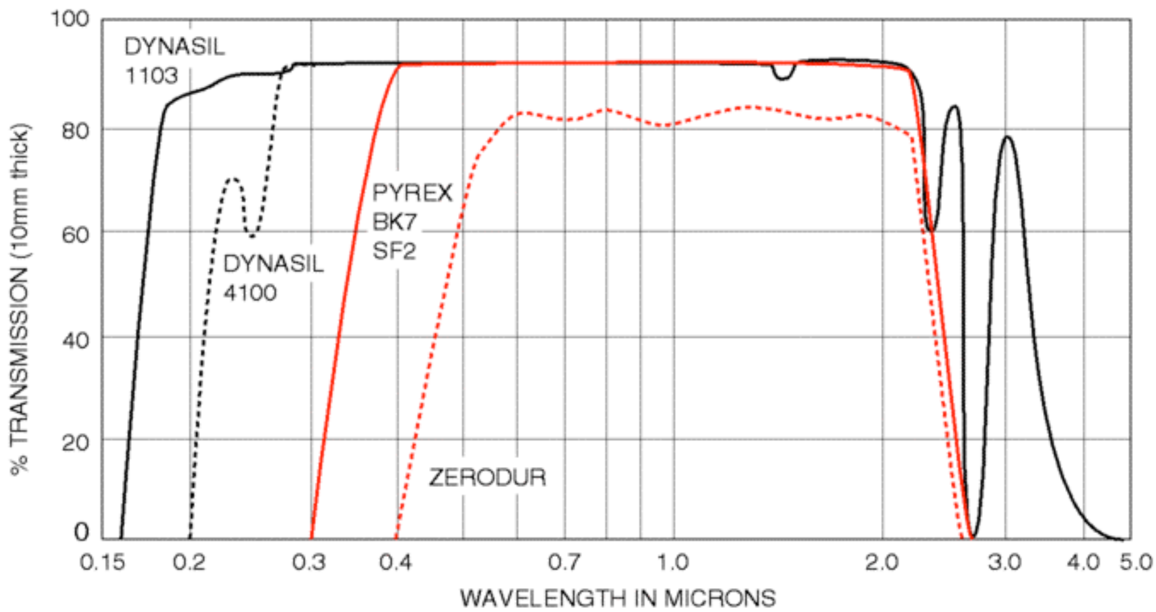
Nd:Glass
1060

Nd:YAG
1064, *1319*

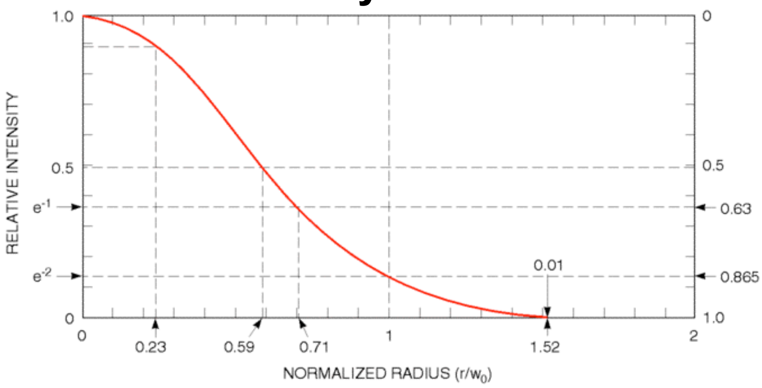
Italics indicates secondary lines.

Properties of optical materials

	Pyrex	Zerodur	BK-7	SF2	Fused Silica
Lambda(nm)	----------------------------	Index n (Lambda)	----------------------------	-	
1060			1.507	1.628	1.449
643.8	1.473		1.515	1.643	1.457
564.1	1.477	1.54	1.517	1.652	1.460
486	1.481		1.522	1.661	1.463
346.6					1.477
248.2					1.508
Abbe number V_d			64.2	33.8	67.8
Birefringence(nm/cm)	10	5	6	6	5
Expansivity (10^{-7}/°C)	32.5	-0.2	71	84	5.5
Conductivity (mW/cm°C)	11.3	16.3	11.3	7.3	13.8
Heat capacity (J/gm°C)	0.75	0.85	0.85	0.50	0.75
Max. Temp. (°C)	500	600	280	200	950
Density (gm/cm^3)	2.23	2.52	2.51	3.86	2.20
Hardness	460	550	510	350	500
Young's Modulus (kN/mm^2)	65.5	90.2	81.5	55	70.3



Gaussian intensity distribution



The **Gaussian intensity distribution:**
$I(r) = I(0) \exp(-2r^2/w_0^2)$

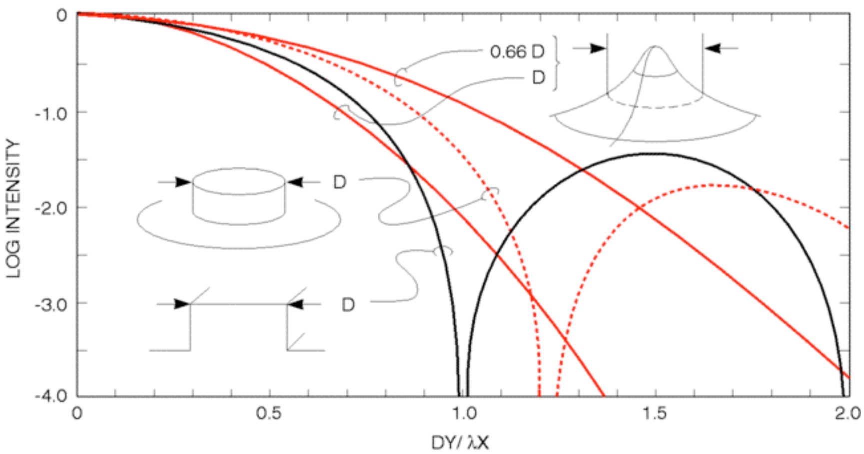
is shown at right. The right hand ordinate gives the fraction of the total power encircled at radius r:
$P(r) = P(\text{infinity})[1-\exp(-2r^2/w_0^2)]$

The total beam power, P(infinity) [watts], and the on-axis intensity I(0) [watts/area] are related by:
$P(\text{infinity}) = \{(\pi)w_0^2/2\}\, I(0)$

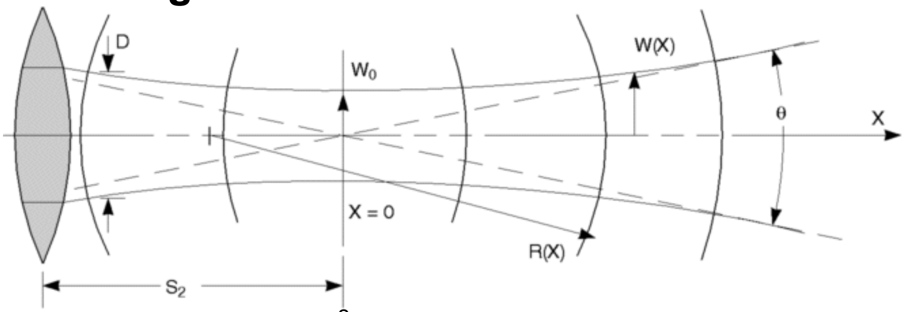
$I(0) = (2/(\pi)w_0^2)\, P(\text{infinity})$

Diffraction

The second figure compares the far-field intensity distributions of a uniformly illuminated slit, a circular hole, and Gaussian distributions with e^{-2} diameters of D and 0.66D. (99% of a 0.66D Gaussian will pass through an aperture of diameter D.) The point of observation is Y off axis at a distance X>>Y from the source.



Focusing a Collimated Gaussian Beam



In the third figure the e^{-2} radius, w(*x*), and the wavefront curvature, R(*x*), change with *x* through a beam waist at *x* = 0. The governing equations are:

$w^2(x) = w_0^2[1 + ((\text{lambda})x/(\text{pi})w_0^2)^2]$

$R(x) = x[1 + ((\text{pi})w_0^2/(\text{Lambda})x)^2]$

$2w_0$ is the waist diameter at the e^{-2} intensity points. The wavefronts are plane at the waist [R(0) = infinity].
At the waist, the distance from the lens will be approximately the focal length: s_2=F.

D = collimated beam diameter or diameter illuminated on lens.

$$\text{f} - \text{number} \equiv \text{f}/\# = \frac{F}{D}$$

Depth of focus (DOF)

$DOF = (8(\text{lambda})/(\text{pi}))(f/\#)^2$

Only if DOF <F, then:

New waist diameter

$$2w_0 = \left(\frac{4\lambda}{\pi}\right)(f/\#)$$

Beam spread

$$\theta = (f/\#)^{-1}$$

Optimal pinhole diameter for spatial filtering

$$D_{OPT} = 2\lambda(f/\#)$$

This aperture passes 99.3% of total beam energy and blocks spatial wavelengths smaller than the diameter of the initial beam. No diffraction effects will be caused by this aperture.

Cleaning

Cleaning of any precision optic risks degrading the surface. The need for cleaning should be minimized by returning optics to their case or covering the optic and mount with a protective bag when not in use. If cleaning is required, we recommend one of the following procedures:

Cleaning Materials

Polyethylene lab gloves. Please wear them. Solvents are harsh to the skin.

Dust free tissue. Lens tissue or equivalent.

Dust free blower. Filtered dry nitrogen blown through an antistatic nozzle (Simco Inc., Hatfield, PA) is best. Bulb type blowers and brushes must be very clean to prevent redistribution of dirt.

Mild, neutral soap, 1% in water. Avoid perfumed, alkali or colored products. Several drops of green soap (available in any pharmacy) per 100 cc of distilled water is acceptable.

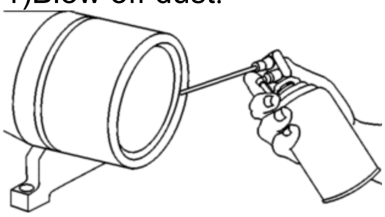
Spectroscopic grade ***isopropyl alcohol and acetone***.

Cotton swabs. Avoid plastic stems which can dissolve in alcohol or acetone.

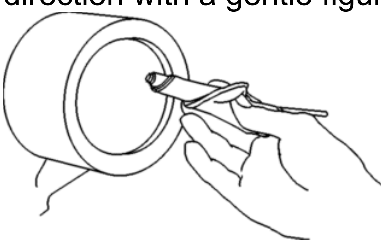
Cleaning Procedures

Dust on optics can be very tightly bound by static electricity. Blowing removes some dirt; the remainder can be collected by the surface tension of a wet alcohol swab. Acetone promotes rapid drying of the optic to eliminate streaks.

1)Blow off dust.



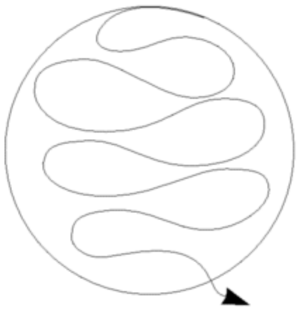
2)If any dust remains, twist tissue around a swab, soak in alcohol and wipe the optic in one direction with a gentle figure-eight motion. Repeat.



3)Repeat Step (2) with acetone soaked swabs.

Fingerprints, oil or water spots should be cleaned immediately. Skin acids attack coatings and glass. Cleaning with solvents alone tends to redistribute grime. These contaminants must be lifted from an optical surface with soap or other wetting agent. The part is then rinsed in water and the water removed with alcohol. Acetone speeds drying and eliminates streaks.

1)Blow off dust.



2)Using a soap saturated lens tissue around a swab, wipe the optic gently in the same figure 8 motion. Repeat.

3)Repeat (2) with distilled water only.

4)Repeat (2) with alcohol.

5)Repeat (2) with acetone.

Delicate optics such as UV aluminum mirrors are most safely cleaned by immersion. ***Do not immerse cemented optics***. Washing solutions should be used only once to prevent recontamination.

1. Blow off dust.
2. Prepare petri dishes filled with soap solution, distilled water, alcohol, and acetone. Line the bottom of each with tissue to prevent blemishing an optic.
3. Immerse the optic in soap solution. Agitate gently.
4. Immerse in distilled water. Agitate.
5. Immerse in alcohol. Agitate.
6. Immerse in acetone. Agitate.
7. Blow dry.

Military Specifications

Military specifications are used by Newport to communicate the durability of optical coatings in an industry consistent manner. The primary MILSPECS used are:

MIL-C-675 specifies that the coating will not show degradation to the naked eye after 20 strokes with a rubber pumice eraser. Coatings meeting MIL-C-675 can be cleaned repeatedly and survive moderate to severe handling.

MIL-M-13508 sets durability standards for metallic coatings. Coatings will not peel away from the substrate when pulled with cellophane tape. Further, no damage visible to the naked eye will appear after 50 strokes with a dry cheesecloth pad. Gentle, nonabrasive cleaning is advised.

MIL-C-14806 specifies durability of surfaces under environmental stress. Coatings are tested at high humidity, or in brine solutions to determine resistance to chemical attack. These coatings can survive in humid or vapor filled areas.

Surface quality of an optical element ultimately determines the performance of a system. Even the highest quality material, if finished poorly, will cause distortion, loss or at elevated power levels, failure of the optic. In order to communicate optical surface quality, Newport has adopted the following standards.

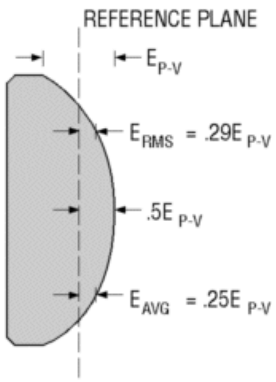
A clear aperture is specified for all Newport optical components. It indicates a minimum area over which specifications are guaranteed. Although typical optics will meet or exceed their ratings to the edge of the component, a clear aperture specification allows sufficient area for safe handling of the optic during manufacture.

Scratch-dig ratings measure the visibility of large surface defects as defined by U.S. military standard MIL-O-13830. Ratings consist of two numbers, the first denoting the visibility of scratches, the second, of digs (small pits). A 0/0 scratch-dig number indicates a surface free of visible defects. Numbers increase as the visibility of blemishes increases. Scratch numbers are linear with a #10 scratch *appearing* identical to a 10 micron wide standard scratch on glass. Similarly, a #1 dig *appears* identical to a 0.01 mm diameter standard pit. ***Please note that no absolute measurement of defect size is made or implied by the scratch-dig standard***.

Components with small scratch-dig numbers will have increased damage thresholds, reduced scatter, and will eliminate unwanted diffraction effects. Newport recommends the following guidelines in selecting surface finish:

Scratch-Dig Applications >60-40 Non-laser optics
60-40 Low-power, unfocused beams
40-20 Collimated laser beams
<40-20 High-energy, focused beams

Figure is a measure of how closely the surface of an optical element matches a reference surface. Since geometrical errors will cause distortion of a transmitted or reflected wave, deviations from the ideal are measured in terms of wavelengths of light.



Spherical Error comprises the majority of figure deviations. Optical polishing relies on circular strokes to finish a surface. For this reason, deviations from the ideal are usually spherical, either concave or convex. Newport computes spherical error as the maximum peak-to-valley deviation from a best fittings reference surface. Mathematically, the ideal surface is halfway between the points of maximum deviation. Practically, this represents the point of best alignment. Figure errors are represented by E, with Ep-v corresponding to the maximum peak-to-valley deviation from the reference surface. Although less frequently used, the root mean square error, ERMS, and the average error, EAVG, may also be defined.

Irregularity, denoted by , refers to figure deviations that are not spherical in nature. It is usually caused by warpage due to internal material stress or mishandling. By means of careful processing of the highest quality optical materials, this error is negligible in magnitude.

The wavelength used in testing all Newport optics is 632.8 nm, consistent with modern laser interferometers. When used at longer wavelengths than 632.8 nm, an optic will have a smaller relative error. Similarly shorter wavelengths will accentuate the relative error. The following may be used to convert figure errors:

$$E = E_{p-v} \times \frac{632.8\,(\text{nm})}{\text{wavelength of use}\,(\text{nm})}$$

Laser Damage

Certified Damage Threshold optics are available from Newport. Testing on a lot basis enables Newport to certify damage resistance to the rated fluence.

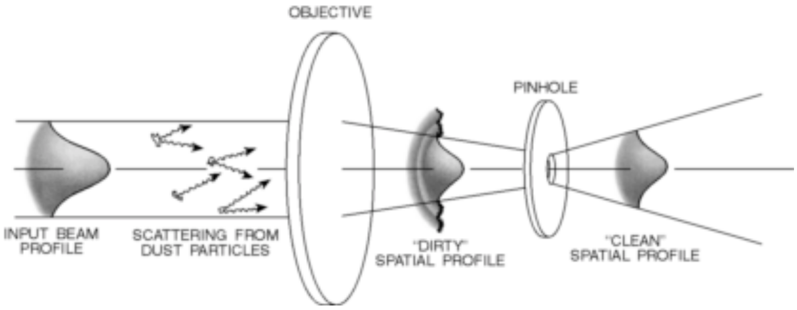
Safe Energy Levels are listed for a majority of Newport optical components. Although these carry no certification, the levels published are conservative and derived from laboratory use tests.

Orders are shipped from our main plant in Irvine, California. Unless otherwise noted, all optics are in stock and ready for delivery.

Items whose prices appear in brackets [$XXX] are high accuracy, material intensive products. They are offered on a limited stock basis. Please contact Newport for exact delivery times.

Unlisted (=) prices or starred (*) part numbers indicate high accuracy optics with very specific applications. They are stocked as uncoated substrates and coated as needed. Please contact Newport for price and delivery.

SPATIAL FILTERS



Spatial filters provide a convenient way to remove random fluctuations from the intensity profile of a laser beam. This greatly improves resolution - especially critical for applications like holography and optical data processing.Laser beams pick up intensity variations from scattering by optical defects and particles in the air. You can view this by expanding a laser beam onto a card: the whorls, holes and rings superimposed on the ideal pattern of uniform speckles are spatial noise.Spatial filtering is conceptually simple: an ideal coherent, collimated laser beam behaves as if generated by a distant point source. Spatial filtering involves focusing the beam, producing an image of the "source" with all imperfections in the optical path defocused in an annulus about the axis. A pinhole blocks most of the noise.The ideal Gaussian laser beam profile, I(r), is contaminated by intensity fluctuations, dI, caused by scattering. dI varies rapidly over an average distance dn, which is much smaller than the beam radius, a. The distance dn is then known as the average spatial wavelength of the laser beam noise.When a Gaussian beam is focused by a positive lens of focal length F, the image at the focal plane (the Optical Power Spectrum [OPS]) will be an inverted "map" of spatial wavelengths present in the beam. Short wavelength noise (dn) will appear in an annulus of radius Fl/dn centered on the optic axis. The long spatial wavelength of an ideal Gaussian profile will form an image directly on the optic axis.A pinhole centered on the axis can block the unwanted noise annulus while passing most of the laser's energy. The fraction of power passed by a pinhole of diameter D is:

$$\frac{P(D)}{\text{Total Power}} = 1 - e^{-\frac{1}{2}\left(\frac{\pi a D}{\lambda F}\right)^2}$$

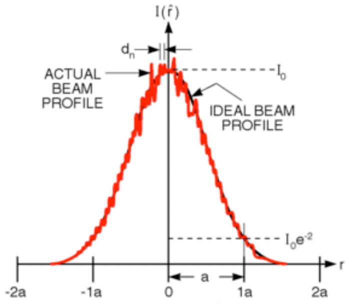
and the minimum noise wavelength transmitted by the pinhole is

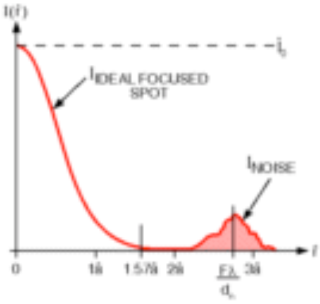
$$D_{opt} = \frac{F\lambda}{a}$$

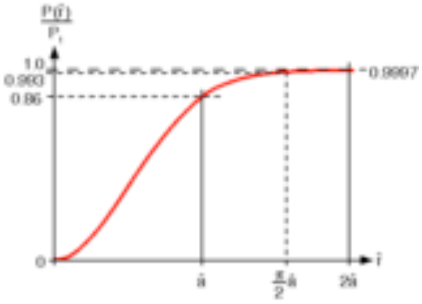
Newport recommends a pinhole of diameter Dopt:

$$d_{n(min)} = 2\frac{F\lambda}{D}$$

This passes 99.3% of the total beam energy and blocks spatial wavelengths smaller than 2a, the diameter of the initial beam. Since dn is always much smaller than the beam diameter, the filtered beam is very close to the ideal profile.For convenience, optimal pinhole/objective combinations have been tabulated in the Selection Guide shown on page 1. 15.







$$I(r) = I_0 e^{-2\left(\frac{r}{a}\right)^2} \quad \text{where } I_0 = \frac{2P_t}{\pi a^2},$$

$$I_{ACTUAL} = I(r) + \Delta I_{NOISE}$$

$$I(\hat{r}) = \hat{I}_0 e^{-2\left(\frac{\hat{r}}{\hat{a}}\right)^2} \quad \hat{a} = \frac{\lambda F}{\pi a}$$

$$D_{opt} = \frac{\lambda F}{a}$$

where F = Objective Lens Focal Length
λ = Laser Wavelength
$\hat{r}$ = Radius Distance within OPS
$\hat{a}$ = Radius of OPS Gaussian at $I(\hat{r}) = \hat{I}_0 e^{-2}$

where F = Objective Lens Focal Length
λ = Laser Wavelength
$\hat{r}$ = Radius Distance within OPS
$\hat{a}$ = Radius of OPS Gaussian at $I(\hat{r}) = \hat{I}_0 e^{-2}$

D = Pinhole Diameter
F = Objective Lens Focal Length
a = Beam Radius Input to Lens

WAVE PLATES

The interaction of light with the atoms or molecules of a material is wavelength dependent. A consequence of this dependence is the resonant interactions related to material **dispersion**. Another consequence of such **resonant interaction** is **birefringence**, the change in refractive index with the polarization of light. The orderly arrangement of atoms in some crystals results in different resonant frequencies for different orientations of the electric vector relative to the crystalline axes. This, in turn, results in different refractive indices for different polarizations. Unlike dispersion, birefringence is easy to avoid: use amorphous materials such as glass, or crystals that have simple symmetries, such as NaCl or GaAs. On the other hand we can "use" birefringence to modify the polarization state of light, a useful thing to do in many situations. The optical components that do this trick are called **birefringent wave plates** or **retardation plates** (or just wave plates or retarders for short).

By taking just the right slice of a crystal with respect to the crystalline axes, we can arrange it so that the minimum index of refraction is exhibited for one polarization of the electric vector of a plane-polarized wave, as shown in Figure 1.

We say that wave is polarized along the fast axis, since its phase velocity will be a maximum. A plane-polarized wave with its plane rotated 90° will propagate with the maximum index of refraction and minimum phase velocity, as shown in Figure 1.

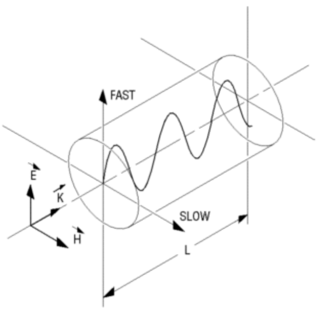


Fig. 1.

We say it is polarized along the slow axis. The difference in the number of wavelengths shown in Figures 1 and 2 (2 2/3, and 4 respectively) would imply a ratio of the two indices of refraction nfast/nslow = 2/3, a much larger difference than in typical natural crystals; we have exaggerated the ratio for clarity.

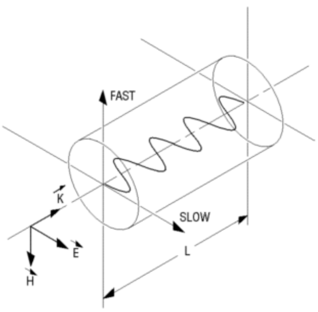


Fig. 2.

The propagation phase constant k can be written as 2pfn/c radians per meter, so that a wave of frequency f will experience a phase shift of ø = 2pfnL/c radians in travelling a distance L through the crystal. Thus, the phase shift for the wave in Figure 1 will be øfast = 2pfnfastL/c, and for the wave in Figure 2, øslow = 2pnslowfL/c (8p radians as shown.) The difference between these two phase shifts is termed the **retardation** G = 2pf(nslow -nfast)L/c. The value of G in this formula is in radians, but is more common to express in "wavelengths" or "waves", with a "full wave" meaning G = 2p, a "half-wave" meaning G = p, a "quarter-wave" meaning G = p/2, and so forth. Thus, we would term the crystal shown in the Figures a "4/3 wave plate"; that is, it retards the phase of the slow wave by 4/3 of a wave (cycle) relative to the fast wave.

Since waves repeat themselves every 2p radians, we could just as well subtract out an integral number of 2ps or waves and call the crystal shown a 2p/3 radian or 13 wave plate. We would never know the difference, provided we only used it at exactly the optical frequency shown in the Figures. However, if we change the frequency we will quickly note that the retardation will change at a rate faster than it would for a plate that had really only 13 wave retardation. We can note this difference by calling it a "**multiple order** 13 wave plate."

Half-wave Plates

By far the most commonly used wave plates are the half-wave plate
(G = p) and the quarter-wave plate
(G = p/2). The half-wave plate can be used to rotate the plane of plane polarized light as shown in Figure 3.

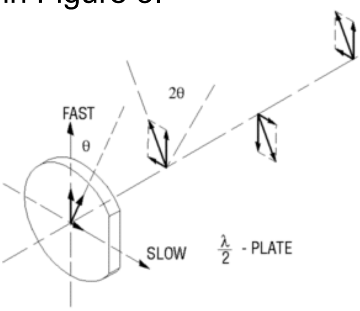


Fig. 3.

Suppose a plane-polarized wave is normally incident on a wave plate, and the plane of polarization is at an angle q with respect to the fast axis. To see what happens, resolve the incident field into components polarized along the fast and slow axes, as shown. After passing through the plate, pick a point in the wave where the fast component passes through a maximum. Since the slow component is retarded by one half-wave, it will also be a maximum, but 180° out of phase, or pointing along the negative slow axis. If we follow the wave further, we see that the slow component remains exactly 180° out of phase with the original slow component, relative to the fast component. This describes a plane-polarized wave, but making an angle q on the opposite side of the fast axis. Our original plane wave has been rotated through an angle 2q. You can satisfy yourself that you will find the same result if the incident wave makes an angle q with respect to the slow axis.

A half-wave plate is very handy in rotating the plane of polarization from a polarized laser to any other desired plane (especially if the laser is too large to rotate). Most large ion lasers are vertically polarized, for example, so to obtain horizontal polarization, simply place a half-wave plate in the beam with its fast (or slow) axis 45° to the vertical. If it happens that your half-wave plate does not have marked axes (or if the markings are obscured by the mount), put a polarizer in the beam first and orient it for extinction (horizontally polarized), then interpose the half-wave plate normal to the beam and rotate it around the beam axis so that the beam remains extinct, you have found one of the axes. Then rotate the half-wave plate exactly 45° around the beam axis (in either direction) from this position, and you will have rotated the polarization of the beam by 90°. You may check this by rotating the polarizer 90° to see that extinction occurs again. If you need some other angle, instead of 90° polarization rotation, simply rotate the wave plate by half the angle you desire. A convenient wave plate mount calibrated in angle is the **RSP-1T** (section 6).

Incidentally, if the polarizer doesn't give you as good an extinction as you had before you inserted the wave plate, it likely means your wave-plate isn't exactly a half-wave plate at your operating wavelength. You can correct for small errors in retardation by rotating the wave plate a small amount around its fast or slow axes. Rotation around the fast axis decreases the retardation while rotation around the slow axis increases the retardation. Try it both ways and use your polarizer to check for improvement in extinction ratio.

Quarter-wave Plates

Quarter-wave plates are used to turn plane-polarized light into circularly-polarized light and vice versa. To do this, we must orient the wave plate so that equal amounts of fast and slow waves are excited. We may do this by orienting an incident plane-polarized wave at 45° to the fast (or slow) axis, as shown in Figure 4.

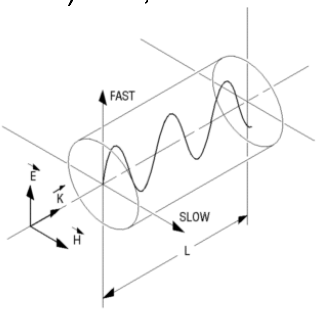


Fig. 4.

On the other side of the plate, we again examine the wave at a point where the fast-polarized component is maximum. At this point, the slow-polarized component will be passing through zero, since it has been retarded by a quarter-wave or 90° in phase. If we move an eighth wavelength farther, we will note that the two are the same magnitude, but the fast component is decreasing and the slow component is increasing. Moving another eighth wave, we find the slow component is maximum and the fast component is zero. If we trace the tip of the total electric vector, we find it traces out a **helix**, with a period of just one wavelength. This describes **circularly polarized light**. Right-hand light is shown in the Figure; the helix wraps in the opposite sense for left-hand polarized light. You may produce left-hand polarized light by rotating either the wave plate or the plane of polarization of the incident light 90° in the Figure.

Setting up a wave plate to produce circularly polarized light proceeds exactly as we described for rotating 90° with a half-wave plate: first, cross a polarizer in the beam to find the plane of polarization. Next, insert the quarter-wave plate between the source and the polarizer and rotate the wave plate around the beam axis to find the orientation that **retains**the extinction. Then rotate the wave-plate 45° from this position. You should now have half the incident light passing through the polarizer (the other half being absorbed or deflected, depending on which kind of polarizer you are using). You can check the quality of the circularly polarized light by rotating the polarizer -- the intensity of light passing through the polarizer should remain unchanged. If it varies somewhat, it means the light is actually **elliptically polarized**, and your wave plate isn't exactly a quarter-wave plate at your operating wavelength. You may correct this as with the half-wave plate by tilting the wave-plate about its fast or slow axes slightly, while rotating the polarizer to check for constancy.

You may wonder what effect retardations other than a half-wave or a quarter-wave have on linearly polarized light. Figure 5 shows the effect of retardation on plane polarized light with the plane of polarization making an arbitrary angle with respect to the fast axis.

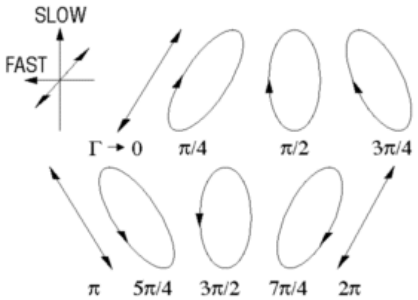


Fig. 5.

The result is elliptically polarized light, with the amount of ellipticity and the tilt of the axis of the ellipse a function of the retardation and the tilt of the incident plane wave. The exception is a half-wave retardation, in which case the ellipse degenerates into a plane wave making an angle of 2q with the fast axis. Note that the quarter-wave plate does not produce circularly polarized light here, because equal amounts of fast and slow wave components were not used; the incident tilt angle must be exactly 45° with respect to the fast (or slow) axis to make these components equal.

Wave Plate Applications

We have already mentioned the two most common applications of wave plates: rotating the plane of polarization with a half-wave plate and creating circular polarization with a quarter-wave plate. Obviously, you can also use a quarter-wave plate to create plane polarization from circular polar-ization -- just reverse the direction of light propagation in Figure 4.

Optical Isolation --

We can use a quarter-wave plate as an optical isolator, that is, a device that eliminates undesired reflections. Such a device uses a quarter-wave plate and a polarizing beamsplitter cube. The diagram on page 1. 20 shows how to construct an isolator in this manner.

Polarization Cleanup --

Often an optical system will require several reflections from metal or dielectric mirrors. There is no change in the polarization state of the reflection if the beam is incident normally on the mirrors, or if the plane of polarization lies in or normal to the plane of incidence. However, if the polarization direction makes some angle with the plane of incidence, then the reflection often makes a small phase shift between the parallel and perpendicular components. This is particularly true for metal mirrors, which always have some loss. The resulting reflected wave is no longer plane polarized, but will be slightly elliptically polarized, as you can easily determine by its degraded extinction when you insert a polarizer and rotate it. This small ellipticity can often be removed by inserting a **full wave plate** (which ordinarily does nothing) and tilting it slightly about either fast or slow axes to change the retardation slightly to just cancel the ellipticity.

Wave Plate Material and Practice

Materials --

Many natural occurring crystals exhibit birefringence, and could, in principle, be used for wave plates. Calcite and crystalline quartz are typical materials. They are durable and of high optical quality. However, the refractive index difference, nslow - nfast is so large that a true half-wave plate would be impractically thin to polish.

It is also possible to induce small amounts of birefringence into a normally isotropic material through stress. For example, most plastics exhibit birefringence from stress applied in the manufacture. Plastic wave plate material is available in half- or quarter-wave retardation values in very large sheets. It is inexpensive, but not of the highest optical quality or durability.

Multiple-order wave plates --

One alternative to polishing or cleaving very thin plates is to use a practical thickness of a durable material such as crystalline quartz and obtain a high-order wave plate, say a 15.5 wave plate for a 1 mm thickness. Such a plate will behave exactly the same as a half-wave plate at the design wavelength. However, as the optical wavelength is changed, the retardation will change much more rapidly than it would for a true half-wave plate. The formula for this change is easily derived from the definition of G:

$$\Gamma = (2m + 1)\pi \left(\frac{\delta f}{f_0} \right)$$

$$\approx -(2m + 1)\pi \left(\frac{\delta \lambda}{\lambda_0} \right)$$

where f0 and l0 are the design frequency and wavelength, and m is the order of the wave plate. Thus, the rate of change of retardation with frequency dG/df will be 2m + 1 times as large for an mth order plate as a true half-wave plate, (m = 0, or "zero order" plate). This would be 31 times larger for our 1 mm "15.5-wave" plate! You should calculate the frequency or wavelength range your system requires, and see if the error in retardation will be tolerable over that range with a multiple order wave plate.

By like reasoning, the sensitivity of the retardation to rotation about the fast and slow axes is found to be about (2m + 1) times larger for a multiple order plate than a true zero-order half-wave plate. This means much smaller rotations are required to correct for retardation errors. But it also means that light rays not parallel to the optical axis will see a (2m + 1) larger change in retardation. Multiple order wave plates are not recommended in strongly converging or diverging beam portions of your optical system. Similarly, the sensitivity of retardation to changes in length caused by changes in temperature are multiplied by (2m + 1), so that tighter temperature control will be required. A typical temperature sensitivity is 0.0015 wave per degree C for a visible 1 mm thick half-wave plate.

Multiple-order wave plates can be used to advantage if you require a wave plate that can be used at two discrete wavelengths, for example the 488 and 514 nm wavelengths of an argon-ion laser or the 532 and 1064 nm wavelengths from a Nd:YAG laser. By choosing the thickness to give a
(2m1 + 1) plate at one wavelength and a (2m2 + 1) plate at the other, both wavelengths will see a "half-wave" plate (but not the wavelengths in between)! The integers have to be chosen by a computer program, since the dispersion in index has to be accounted for also, but it is usually possible to find a plate of reasonable thickness provided the two wavelengths are not too close together.

Zero-order wave plates --

Fortunately, a technique is available for realizing true half-wave plate performance, while retaining the high optical quality and rugged construction of crystalline quartz wave plates. By combining two wave plates whose retardations differ by exactly half a wave, a true half-wave plate results. The fast axis of one plate is aligned with the slow axis of the other, so that the net retardation is the difference of the two retardations. The change in retardation with frequency (or wave-length) is minimized. Temperature sensitivity is also reduced; a typical value is 0.0001-wave per degree C. The change in retardation with rotation is highly dependent on manufacturing conditions and may be equal to greater than that of a multiple order wave plate.

These wave plates are recommended for use in systems using tunable radiation sources, such as a dye laser or white light sources.

Optomechanics Glossary

Abbe Error

Sideways motion due to angular deviation (q below) coupled with a significant mechanical lever-arm. This looks like runout (dx) but unlike true runout can be minimized by reducing the lever arm, to which it is linearly related. A stage placed atop a mounting rod will exhibit less of this sideways motion than when the rod is mounted on the stage and the measurement is repeated at the same optical axis height. Similarly, XYZ stages incorporating an angle bracket between the moving elements will exhibit apparent runout due to the lever-arm this introduces. Abbe error results in apparent runout which can be reduced by minimizing the lever-arm.

Absolute Accuracy

The output of a system versus the commanded or ideal input; it is more correctly called inaccuracy. When a motion system is commanded to move 10 mm actually moves 9.99 mm as measured by a perfect ruler, the inaccuracy is 0.01 mm. Misalignment of the stage axis versus the ruler's axis will result in a monotonic inaccuracy proportional to the cosine of the misalignment. See cosine error.

Angular deviation

Cone angle which determines the angular range of motion of the stage. This is an important definition because the measured runout will depend on the height at which the measuring device is mounted upon the stage.

Runout is often specified for the motion at the surface of the stage, but you will find that the angular deviation dominates the actual variations in straight line travel of a device mounted at a height above the stage. The angular deviation is specified in terms of roll, pitch, and yaw.

Backlash

Non-responsiveness on reversal of input. For example, a simple motorizer with motor-mounted encoder might exhibit several microns of position display change on reversal before its output position actually begins to change. Other terms frequently used to describe this or similar behavior include dead zone, stiction, looseness, slop and free play. It can be compensated by various controller schemes. The best is when the controller allows the user to specify the measured backlash of a motion assembly; this amount of extra drivetrain input is then added upon each reversal. This can provide submicron repeatabilities without over- or under-shoot. A less-desirable approach is when the controller automatically overshoots reverse motions and re-approaches the desired position so that the target position is approached from a consistent direction. This is often unacceptable in applications like fiber coupling and micro-ablation.

Cosine Error

Cumulative, monotonic inaccuracy due to misalignment of an actuator axis versus a stage's axis or a stage's axis versus an external optical axis such as an interferometer's. This is proportional to the cosine of the misalignment. This effect is very small; even a very bad misalignment of 2° -- easily discerned by the eye -- results in less than 0.1% cumulative inaccuracy. (This is quite a bit less than the 3.5% apparent transverse motion component proportional to the sine of the same misalignment.) It is evident that the inaccuracy introduced by mounting a micrometer-replacement actuator or direct-metrology encoder with reasonable care is negligible.

Cross-Coupling

Amount of motion in one axis due to the adjustment of a different axis in multiple axis devices, such as X-Y stages or kinematic mirror mounts. For example, the amount of X motion when the Y drive is adjusted in an X-Y stage. Also known as cross-talk.

DC Servo Motor

An analog motor designed to be an active element in a servo circuit. A broad range of such motors are used in precision motion systems, from micro-motors the size of a sugar cube to high-duty-cycle, high-torque units bigger than a fist. Very smooth running, broad speed range without resonance, and good stability are characteristics of DC servo motors if reasonably modern controllers are employed. Poor examples abound, however, and are plagued with drift, overshoot and inaccuracies. (Also, some controllers run DC servo motors in a pulsed fashion that can be noisy.)

Being active elements of an analog servo, there are a host of servo parameters and settings that must be correct for a DC servo motor to perform crisply and stably. From a user's perspective, the manner in which these settings are handled can make a huge difference in a controller's ease-of-use. In some controllers, the parameters are set (and even fine-tuned) automatically and transparently to the user. In others, the user must enter a list of parameters appropriate to their motion device, motor and load before it can be used at all, and then the fine-tuning must be done manually for optimum performance.

Direct Output Motion Metrology

Used in closed-loop systems which perform motion control based on drivetrain output -- the stage platform or actuator shaft position. This eliminates drivetrain errors and is reserved for top-of-the-line motion systems.

Eccentricity

Displacement of the geometric center of the stage from the center of rotation.

Hysteresis

Non-repeatability on reversal of input. For most motion devices, backlash and stiction are the most significant contributors. However, non-recovery of static deflection is possible, with greatest consequence for some submicron applications when inappropriate materials are used in a motion device's design. In piezo devices, hysteresis is a characteristic property of the material.

Interferometer

An instrument which utilizes the interference property of light to measure distances. Resolution to a few nano-meters is achieved by the most advanced units. In addition to many applications in measuring position, they have been incorporated into motion devices for direct-motion-metrology. However, air is the working fluid for the optical path, rendering even a perfectly vibration-isolated interferometer sensitive to air currents, acoustic noise, changes in barometric pressure, humidity and temperature, etc.

Interpolator

An electrical circuit which divides a periodic analog signal into divisions of much higher period. Very often used in interferometers (to divide fringes) and glass scale encoders (to resolve moirŽ activity). Interpolation allows use of inherently noise-resistant, slowly-varying analog signals. The quality and internal noise level of the interpolator define a lower limit to its resolution and repeatability.

Glass Scale Encoder

A position measuring device upon which a grating has been applied. Various types exist; most utilize a stationary element in optical series with an identical moving element (reticle). As the reticle translates, a moirŽ effect causes a periodic change in the optical throughput. The pitch or spacing of the grating defines the basic resolution of the device; interpolation can greatly multiply this. Holographically-generated gratings with micron-scale pitch are a recent innovation.

Leadscrew Pitch Error

There are two sources: sinusoidal errors, which are periodic variations of the leadscrew pitch from nominal, and overall departures from the specified pitch. Both are of concern only in closed-loop devices in which the motion metrology is performed on the drive-train input via a motor- or leadscrew-mounted encoder or via a stepper-motor pulse-counting scheme. Overall pitch errors can be compensated by some controllers; the measured lead-screw pitch of a specific motion device can be programmed into such controllers. Using this feature, the user can eliminate all but the sinusoidal and other non-monotonic errors. Lookup tables and error modeling are also used.

Minimum Incremental Motion

The smallest motion a device is capable of delivering -- not to be confused with resolution claims, which are typically based on the smallest display increment and which can be more than an order of magnitude more impressive than the actual motion a system is capable of producing. This is a key specification but, unfortunately, is rarely disclosed.

MTBF

Mean Time Between Failures. This is a prediction of the lifetime between major service of the device. It does not preclude maintenance or adjustment. For precision motion devices, the MTBF ranges from as little as a few hundred hours to over 20,000 hours for industrial-class devices.

Pitch

Rotation about the transverse, or y, axis. This is also known as elevation, particularly in gimbal-type mounts used in astronomy and ranging.

Play

Uncontrolled movement due to looseness of mechanical parts. Very small in a well-built component, it can increase as a component grows older, especially if it is roughly handled or overloaded.

Precision

Range of deviations in output position that will occur for the same error-free input. Precision is also known as repeatability. Although often confused in common parlance, accuracy and precision are not the same. Figure 4 shows graphically the difference between these two parameters.

Repeatability

The ability of a motion system to achieve a commanded position over many attempts. Manufacturers often specify unidirectional repeatability, meaning the ability to repeat a motion increment in one direction. This side-steps issues of backlash, hysteresis, etc., and therefore is fundamentally irrelevant. A much more significant specification is bi-directional repeatability. Unfortunately, few manufacturers publicize this much tougher measure of motion performance.

Resolution, Display

The smallest incremental step which can be displayed or read from an actuator. The display resolution is not necessarily the same as the position resolution. An example of display resolution is the number of digits on the readout of a motor controller. Differences between display and position resolution can be caused by a variety of reasons including friction and backlash in the system.

Resolution, Position

Smallest difference in movements that can be discriminated. Often confused with display resolution. Your finger tips are sensitive enough to be able to distinguish 1° rotations of an adjustment screw. Therefore, when you see a resolution quoted for an AJS adjustment screw, it is the travel associated with a 1° turn of the screw.

Reversal Error

Small forward motions when a drive is reversed, and vice versa. It is caused by drivetrain wind-up in systems with high internal friction.

Roll

Rotation about the longitudinal, or x, axis of travel.

Runout

Motion other than motion in a straight line in a linear stage. Also called straightness of travel (deviations in the plane of travel) and flatness of travel (deviations out of the plane of travel). Cross-coupling refers to orthogonality errors in multiple axis systems. Runout is the deviation from straight line travel for a single axis.

Sensitivity

Ratio of output motion to input drive. Resolution and sensitivity are again terms that are sometimes confused. As an example of the difference between the two, for the 80 thread-per-inch adjustment screw the resolution is better than one micron (using our 1° turn definition, see position resolution), while the sensitivity is 0.0125 inch or 0.318 mm per turn.

Sinusoidal Errors

Non-cumulative periodic inaccuracies frequently found in leadscrew- or worm-gear-driven devices unless direct output motion metrology is employed.

Static Deflection

Bending of a structural component due to loading. This has little or no effect on most devices' performance as long as component design limits are not exceeded. For example, placing a 5 kg load on a steel crossed-roller-bearing stage will cause little or no measurable change in performance, since such stages are often rated to over 70 kg. Similarly, replacing a 100 g micrometer with a 600 g actuator should not seriously affect the performance or longevity of most stages.

Stepper motor

One of several motor types which increment in discrete steps. Continuous motions are performed by rapid sequences of steps. Small motions can be facilitated by dividing the steps into many discrete parts, a technique called mini-stepping.

Full-stepping motor controllers are fairly straightforward, digital devices -- requiring somewhat less of the fuss and bother encountered with certain DC servo-motor implementations -- and are consequently quite popular among controller designers and users alike. Mini-stepper controllers are somewhat more complex. Unfortunately, poorly-designed stepper devices can run hot and have loud resonances at particular speeds. Advanced electrical drive techniques have mitigated the heat problem, and viscous or ferrofluidic dampers have proven valuable in reducing noise and resonance problems.

Many open-loop stepper-motor systems are marketed as though they were closed-loop -- the controllerÕs count of pulses is taken on faith, though no motion metrology is incorporated. In predictable applications, well-engineered open-loop stepper systems can indeed provide faithful, repeatable motion.

Stiction

Occurs because the coefficient of static friction is always greater than the coefficient of moving friction. When a stage is at rest and force is first applied and slowly increased, no motion occurs. At some threshold, motion suddenly begins, so that the first move of the component will be a jump, giving non-linear and non-repeatable motion. This effect is what limits the smallest incremental movement.

Trapezoidal Motion Profile

Graphing an advanced motion deviceÕs velocity versus time or distance results in a trapezoidal plot: first, there is an acceleration phase, terminating at the commanded velocity, then a deceleration phase. Advanced controllers allow user control of acceleration/deceleration -- valuable for positioning items such as optical fibers which can vibrate if motion is too violent. More advanced controllers allow individual setting of acceleration and deceleration. Even more desirable is the ability of a few controllers to specify these parameters separately for long- and short-motion regimes. The latest advance is user-programmable ÒjerkÓ -- the time rate of change of acceleration. This allows vibration-prone loads to be moved gently but with exceptional efficiency.

Wander

Translation of the axis during rotation. Also known as eccentricity.

Wind-Up

Lost motion due to friction and deflections in the drivetrain. Along with backlash and stiction, this is a major cause of the distinction between display resolution and minimum incremental motion: the drivetrain input may apply a force to the drivetrain and imply that motion has occurred, but the drivetrain absorbs the input (or deflects slightly) because of friction, causing no motion to occur. In this manner, drivetrain friction forms a fundamental limit to incremental motion.

Wobble

Tilt of the axis during rotation.

Yaw

In-plane rotation about the vertical, or z, axis. This is also known as azimuth. This term is also used to refer to the rotation of optics in optic mounts.