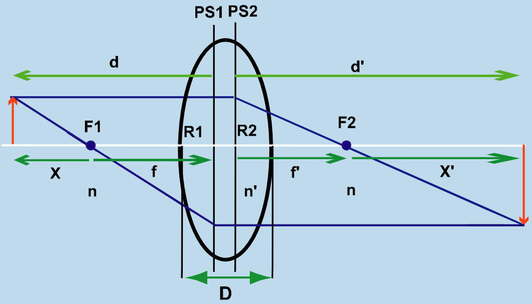
Optics Reference Chart

Geometric Optics

Definitions

Focal Point (F1,F2) : Point(s) where light rays parallel to the optical axis will come to a focus.
Paraxial Approximation: Limiting case that the rays from the object are near to the optical axis and have a small angle of deviation from being parallel to the optical axis.
Principal Surface: (PS1,PS2); Surfaces defined as the intersection points between the extended rays entering the optical system and those exiting the optical system.
Principal Points: Intersection points of the princpal surfaces with the optical axis.
Effective Focal Length (EFL): Focal length of a group of optical systems.
Backward Focal Length (BFL): Distance from last phyical surface of optical system to the exit focal point.
Working Distance: Distance from last physical optical surface to the focal point.
Numerical Aperture (NA): Sine of the angle defining the cone of acceptance for the optical system.
f/#: A parameter which is given by the focal length of a lens divided by its aperture defined by light from infinity. If light is from object at a finite distance then the working f/# is given by 1/(2*NA).
Aperture Stop: A surface which limits the angle of axial cone of rays from the object.
Exit Pupil: Image of the aperture stop as viewed image plane at the exit of the optical system.
Entrance Pupil: Image of aperture stop as viewed from an axial point on the object.
Chief Ray: A ray which passes through the center of the aperture of the optical system with no angular deflection.
Marginal Ray: A ray wich travels parallel to the optical axis and at the edge of the aperture.



Sagital Plane, Ray: Plane, and rays which travel in plane, not containing the optical axis.
Tangential or Meridonal Plane, Ray: Plane, and rays which travel in plane, containing the optical axis.
Spherical Aberration: Deviation of focus from ideal paraxial focus due to increase in aperture of system
Astigmatism: Aberration caused by different focal lengths for tangential and sagital rays.
Chromatic Aberration: Deviation of focus for different wavelengths of light cause by variations in index of refraction as a function of wavelength.
Coma: Aberration caused by the change in magnification as the aperture size is altered.
Distortion: Difference in image height from that given by paraxial ray trace for off axis point.

Some First Order Optical Relationships

Thin Lens

$$\frac{1}{f}=\left(\frac{n'}{n}-1\right)\left[\frac{1}{R1}-\frac{1}{R2}\right]$$

Thick Lens

$$\frac{1}{f}=\left(\frac{n'}{n}-1\right)\left[\frac{1}{R1}-\frac{1}{R2}+\frac{D(n-1)}{nR1*R2}\right]$$

If n=1: $\frac{1}{d'}-\frac{1}{d}=\frac{1}{f}$ $\quad xx'=f^2$

$m=\frac{d'}{d}$ $\quad m=\frac{f}{x}$ $\quad m=-\frac{x'}{f}$

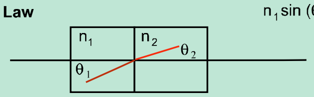
R1: Radius of Curvature of First Surface (positive if center of radius to the right of surface)
R2: Radius of Curvature of Second Surface (positive if center of radius to the right of surface)
d: Distance from principal plane to object (positive if to the right of reference point)
x: Distance from first focal point to object (positive if to the right of reference point)
d': Distance from principal plane to image (positive if to the right of reference point)
x': Distance from second focal point to image (positive if to the right of reference point)
m: Magnification of system (negative if image is inverted)
n': Index of Refraction of lens
n: Index of Refraction of surrounding medium

Useful Formulas and Approximate Relations

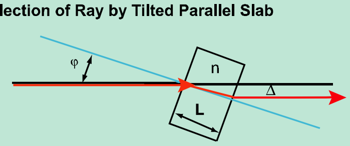
(Ray Trace and First Order Optics, Angles in Radians)

Snell's Law

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



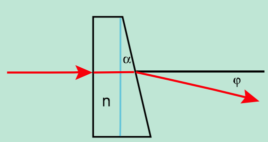
Deflection of Ray by Tilted Parallel Slab



$\varphi \ll 1$

$\Delta \sim \frac{(n-1)L\varphi}{n}$

Angular Deflection of Ray by Wedge (Normal Incidence)

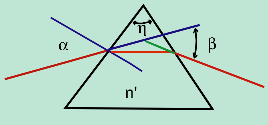


$n \sin(\alpha)=\sin(\alpha+\varphi)$

$\alpha \ll 1,\ \varphi \ll 1$

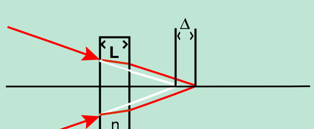
$\varphi \sim (n-1)\alpha$

Minimum Deviation Angle of Ray by Prism Occurs For:



$$n'=n\,\frac{\sin\left[\frac{\eta+\beta}{2}\right]}{\sin\left[\frac{\beta}{2}\right]}$$

Focus Shift Produced by Parallel Slab Perpendicular to Optical Axis



$\Delta \sim \frac{(n-1)L}{n}$

Physical Optics

Fraunhofer Diffraction: Diffraction in the limit when the object point and image point are far from the aperture and the optical path difference can be expressed as a linear function of the aperture coordinates.

Rayleigh Criterion: Relation for specifying the limiting resolution of an optical system due to the wave nature of light.

Minimum Resolvable Angular Separation= $\frac{1.22\lambda}{a}$

a=diameter of aperture

Also used as a limit in the maximum opitcal path difference (OPD) being less than λ/4 as a measure of the image quality of an optical system.

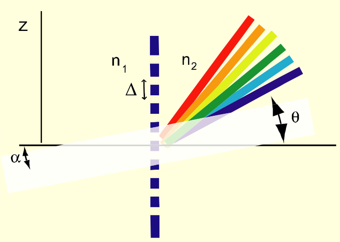
Airy Disk: The central illuminated region of the diffraction pattern formed by an ideal imaging system from a circular aperture.

Strehl Ratio: Ratio of the illumination of the center peak of the Airy Disk for an optical system relative to that of a perfect imaging system.

Strehl Ratio ~ $\exp(-(2\pi\varphi)^2)$ $\quad$ φ: RMS Optical Path Difference of optical system

Diffraction Gratings (Fraunhofer, Planar Case)

Standard Grating



Diffraction Angle

Maxima for mth Order:

$n_1 \sin(\alpha) - n_2 \sin(\theta)=(m\lambda/\Delta)$

Diffraction Efficiency(ε)

$\varepsilon_m = \gamma_m \gamma^*_m$

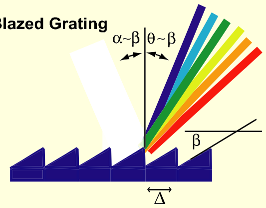
$\gamma_m = \frac{1}{\Delta}\int \tau(z)\exp\left(\frac{-i2\pi mz}{\Delta}\right)dz$

Resolving Power

$\delta\lambda = \frac{\lambda}{Nm}$

τ(z): Transmission of grating as function of z
N: Number of periods, N >>1

Blazed Grating



Diffraction Efficiency

$\lambda \sim \lambda_b$ $\quad m=1\ \ \varepsilon \sim 1$

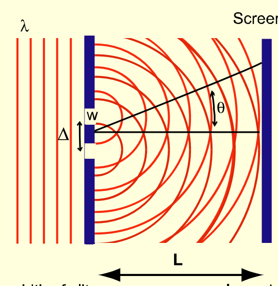
$m \neq 1,\ \varepsilon \sim 0$

Angular Dispersion

$\frac{d(\lambda)}{d\theta} = \frac{m}{\Delta\cos(\theta)}$

α: Angle of incidence
θ: Angle of diffraction
β: Blaze Angle
λ_b: Blaze Wavelength=2Δsin(β)

Diffraction and Two Slit Interference (Fraunhofer Limit)



w: width of slit
Δ: Separation Between slits
I_o: Intensity at center

Intensity at Screen as Function of θ

Single Slit

$$\frac{I_\theta}{I_o} = \left[\frac{\sin\left[\frac{\pi w \sin(\theta)}{\lambda}\right]}{\frac{\pi w \sin(\theta)}{\lambda}}\right]^2$$

Double Slit

$$\frac{I_\theta}{I_o} = \left[\cos\left(\frac{\pi\Delta\sin(\theta)}{\lambda}\right)\right]^2\left[\frac{\sin\left[\frac{\pi w \sin(\theta)}{\lambda}\right]}{\frac{\pi w \sin(\theta)}{\lambda}}\right]^2$$

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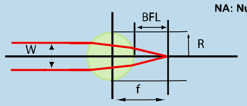
Microoptics and Fibers

Ball Lens

W: Input Diameter or Aperture
R: Radius of Ball Lens
n: Index of Refraction of Lens
NA: Numerical Aperture



$f=\frac{nR}{2(n-1)}$ BFL=f-R $NA=W\frac{(n-1)}{nR}$

Gradient Index Rods and Lens

Eqaution of ray in gradient index material

$\frac{d}{dl}\left[n(r)\frac{dr}{dl}\right]=gradient(n(\mathbf{r}))$ *l*: Arc distance parameter

Gradient Index Rod

Parabolic Index Profile
$n(r)=n_c(1-kr^2/2)$

n_c : Index of refraction of rod on axis

$f_{rod}=\frac{1}{n_c(k)^{1/2}\tan[L(k)^{1/2}]}$

L=Length of Gradient Index Rod

Diffractive Lens

Kineform (Fresnel Lens): Surface with curved or sawtooth profiles used to shape the phase response of the wavefront. Used as diffractive lenses.

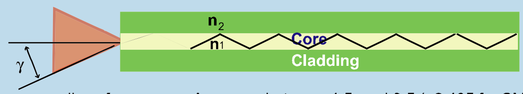
Kineform surface corresping to refractive lens

Binary Surface: Stepped surface used in diffractive lens design to simulate a kineform surface. Number of levels impacts diffraction efficiency of lens

Three level binary surface

Optical Fibers

$n_1 > n_2$



r=radius of core ν_c: A numner between 1.5 and 3.5 (=2.405 for SMF)

Critical Angle for Total Internal Reflection $(\theta_c)=\text{Arcsin}(\frac{n_2}{n_1})$

$NA=\sin[(n_1^2-n_2^2)^{1/2}]=\sin(\gamma)$ Mode Volume Number $(V)=2\pi\frac{r}{\lambda}NA$

Mode Cutoff Radius
$\lambda_c=2\pi NA(\frac{r}{\nu_c})$

Number of Modes $(N)=\frac{V^2}{4}$

Fiber Coupling Efficiency

$$\varepsilon=\frac{\iint U(x,y)\Phi^*(x,y)dxdy}{[\iint U(x,y)U^*(x,y)dxdy\iint \Phi(x,y)\Phi^*(x,y)dxdy]^{1/2}}$$

ε: Coupling Efficiency
U: Intensity pattern of
Φ: Fiber Mode Pattern

Standard Core/Cladding in µm	Type	Typical Optical Loss @1550 nm (dB/km)
9/125	SMF	~0.25
50/125	MMF	~2.0
62.5/125	MMF	~2.5
100/140	MMF	~3.2
110/125	MMF	Not Used

SMF: SIngle Mode Fiber MMF: Multimode Fiber

Optical Properties

Material or Crystal	Approximate λ Range	Index of Refraction	Coefficient of Thermal Expansion (10^{-6}/K)	Thermo-optic Coefficient (dn/dt) (10^{-6}/K)
Crown Glass	0.4 µm---1.8 µm	1.50 @ 1.6 µm	7.1	2.3 @ 1.06 µm
CaF_2	0.15 µm--8.0 µm	1.42 @ 2.6 µm	18.9	-10.4 @ 0.66 µm
Fused Silica (IR Grade)	0.2 µm---2.5 µm	1.43 @ 1.8 µm	0.51	---
GaAs	1.0 µm---16.0 µm	3.31 @ 3.1 µm	5.0	250 @ 1.15 µm
Ge	2.0 µm---12.0 µm	4.09 @ 2.15 µm	5.7	462 @ 2.50 µm
GeO_2	0.3 µm---4.9 µm	1.61 @ 2.15 µm	---	---
InAs	3.9 µm---19.0 µm	3.44	4.4	500 @ 4.0 µm
InP	0.95 µm---19.0 µm	3.09	4.5	83 @ 5.0 µm
KBr	0.3 µm---20.0 µm	1.54 @ 1.5 µm	38.5	-41.9 @ 1.15 µm
KCl	0.3 µm---15.0 µm	1.48 @ 0.98 µm	36.5	-36.2 @ 1.15 µm
LiF	0.12 µm---5.0 µm	1.75 @ 1.38 µm	34.4	-16.9 @ 1.15 µm
$LiNbO_3$	0.5 µm---5.0 µm	2.214(o) 2.140(e)	14.8 ||a, 4.1 ||c	4.4 @ 0.66 µm (o) 37.9 @ 0.66 µm (e)
MgF_2	0.2 µm---7.0 µm	1.38 @ 0.56 µm (o) 1.39 @ 0.56 µm (e)	9.4 ||a , 13.6 ||c	0.88 @ 1.15 µm (o) 0.32 @ 1.15 µm (e)
Si	1.2 µm---6.5 µm	3.48 @ 1.5 µm	2.62	166 @ 2.5 µm
β-ZnS	0.6 µm---16.0 µm	2.258	6.8	49.8 @ 1.15 µm
ZnSe	0.5 µm---16.0 µm	2.44 @ 2.8 µm	7.1	59.7 @ 1.15 µm

Thin Films

Antireflection (AR) Coating (Normal Incidence) **Thin Film**

Condition for Interference at Reflection

n_o
n_1
n_2

$n_0 < n_1 < n_2$ m=0,1,2,.... $n_0 < n_1 > n_2$

$d=\frac{(m+1/2)\lambda}{2n_1}$ $d=\frac{m\lambda}{2n_1}$

Quarter Wave Optical Thickness (QWOT)= $\frac{4nd}{\lambda}$

Reflection and Transmission

$\rho=\frac{n_0(\lambda)-n_1(\lambda)}{n_0(\lambda)+n_1(\lambda)}$

$R=\frac{(n_0-n_1)^2}{(n_0+n_1)^2}$

Reflection ond Transmission Coefficients
(no absorbtion)

$T(\lambda)=1-|\rho|^2$ $R(\lambda)=|\rho|^2$ R+T=1

Definition of Symbols

τ: Transmitivity of material
ρ: Reflectivity of material
µ: Magnetic susceptibility of material
ε: Dielectric permitivity
η: Intrinsic Impedance
λ: Wavelength of light in vacuum
n: Index of refraction for material
d: Thickness of film

Impedance: The ratio of the amplitude of the electric field to the magnetic field for an electromagnetic wave. In a non magnetic dielectric media with no reflected wave, the intrinsic impedance is defined $\eta=\eta_o/n$ where η_o is the intrinsic impedance of the vacuum

n_o
n_1
n_2
n...
n_k

$\rho=\frac{Z_m-\eta}{Z_m+\eta}$

$\tau=\frac{2Z_m}{Z_m+\eta}$

$\rho=\frac{\eta_0-\eta_1}{\eta_0+\eta_1}$

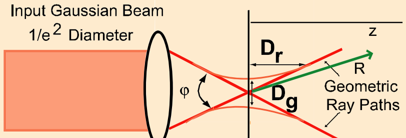
$Z_q=\eta\left(\frac{Z_m\cos(2\pi ns/\lambda)+i\eta\sin(2\pi ns/\lambda)}{\eta\cos(2\pi ns/\lambda)+iZ_m\sin(2\pi ns/\lambda)}\right)$

s: Thickness of dielectric film

Z_m: Load Impedance at plane
Z_q: Input impedance at a distance s in front of Z_m

Gaussian Beam Optics

R: Radius of curvature of wavefront
φ: Far field divergence angle is in radians



Radius of Curvature of Wavefront Growth

$R(z)=z\left[1+\left(\frac{\pi D_g^2}{4\lambda z}\right)^2\right]$

Beam Diameter Growth

$D(z)=D_g\left[1+\left(\frac{4\lambda z}{\pi D_g^2}\right)^2\right]^{1/2}$

Beam Waist Diameter (D_g)

$D_g=\frac{4\lambda}{\pi\varphi}$

Rayleigh Range (D_r)

$D_r=\frac{4\lambda}{\pi\varphi^2}$

Complex Beam Propagation Parameter

$\frac{1}{Q}=\frac{1}{R}-\frac{i4\lambda}{\pi D_g^2}$ $Q(z)=\frac{i\pi D_g^2}{4\lambda}+z$

Confocal Parameter (B)

$B=2D_r$

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