2.1 FABRICATION OF OPTICAL SURFACES

2.1 Optical Materials [Book 4.3]

Materials with desireable optical properties are strongly application dependent (e.g. polarization optics, laser rods, etc.). Here we will focus mainly on materials for lenses, prisms and mirrors.

2.1.1 The most common materials for lenses, prisms and mirrors is glass and plastic. We are concerned with multiple properties

Optical Properties

First and foremost, we are interested in the index of refraction. However, we know index of refraction is dependent upon wavelength. We typically specify index at some standardized wavelengths.

WAVELENGTH [nm]	DESIGNATION	SPECTRAL LINE (SOURCE)
656.2725	C	Hydrogen (H)
643.8469	C'	Cadmium (Cd)
589.2938	D	Sodium (Na) center of double line
587.5618	d	Helium (He)
546.0740	e	Mercury (Hg)
486.1327	F	Hydrogen (H)
479.9914	F'	Cadmium (Cd)

For materials in the visible, d and e are common since they are in the center of the sensitivity of the eye.

Example: Glass N-SF6   SCHOTT GLASS "N-" MEANS REDUCED LEAD

$N_C = 1.79608$ $N_{C'} = 1.79749$

$N_d = 1.80518$ $N_e = 1.81266$

$N_F = 1.82783$ $N_{F'} = 1.82980$

Dispersion is a measure of this variation in refractive index

One metric to measure dispersion $\dfrac{\text{Power in middle of spectrum}}{\text{Difference in power across spectrum}}$

If difference is small, then this number is large

powers
$$\phi_F = \frac{N_F - 1}{R}$$
$$\phi_d = \frac{N_d - 1}{R}$$
$$\phi_C = \frac{N_C - 1}{R}$$

$$\frac{\phi_d}{\phi_F - \phi_C} = \frac{\frac{N_d - 1}{R}}{\frac{N_F - 1}{R} - \frac{N_C - 1}{R}} = \frac{N_d - 1}{N_F - N_C} = V_d = \text{Abbe Number}$$

V-Number

Constringence

Also see
$$V_e = \frac{N_e - 1}{N_{F'} - N_{C'}}$$

CROWN GLASS HAS HIGH $V_d \gtrsim 55$

FLINT GLASS HAS LOW $V_d \lesssim 55$

Example: Glass N-SF6

$V_d = 25.36$ $N_F - N_C = 0.031750$

$V_e = 25.16$ $N_{F'} - N_{C'} = 0.032304$

} These are large changes so Abbe # is small.

International Glass Code or MIL NUMBER

Six digit # where first 3 numbers are the three digits after the decimal place for $N_d = 1.xxx$. Last three digits are the Abbe Number $V_d = yy.y$ to the tenths place

Example: Glass N-SF6

Code = 805254

Schott adds three more digits for material density 805254.337 means 3.37 g/cm^3

Index of refraction and dispersion vary from batch to batch. Manufacturers will provide measured data upon request. Refractive index can vary within a piece of glass, so homogeneity is an issue as well.

Partial Dispersion

Relative Partial Dispersion

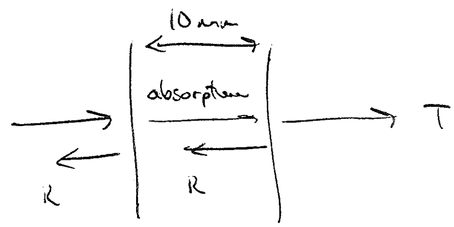
$$P_{x,y} = \frac{(N_x - N_y)}{(N_F - N_C)} \quad \text{for F, C lines}$$

$$P'_{x,y} = \frac{(N_x - N_y)}{(N_{F'} - N_{C'})}$$

Example N-SF6

$$P_{d,C} = \frac{N_d - N_C}{N_F - N_C} = 0.2867$$

Color Code



$$R = \left[\frac{N-1}{N+1}\right]^2 \quad \text{Fresnel Reflectivity}$$

Color Code describes the wavelengths ~~to~~ λ_{80} and λ_5 where the transmission T drops to 0.80 and 0.05 respectively

Example N-SF6 $\lambda_{80} / \lambda_5 = 45/37$ meaning 450 nm and 370 nm

Chemical Properties

Climatic Resistance or ~~Stai~~ Dimming - high humidity and high temp or rapid temperature changes can cause white film to develop on glass surface

Staining - lightly acidic water (e.g. sweat) causes chemical reactions which result in silica-rich surface layer to be formed creating an interference color on that layer

Acid, Alkali and Phosphate Resistance

High or low PH solutions can affect glass as well as Phosphates (e.g. detergents for cleaning). These usually lead to the surfaces dissolving

Mechanical Properties

Knoop Hardness - measures surface changes after indentation with a diamond for a standardized pressure and duration

Grindability - how much material is removed by grinding for a standard time frame and setup.

Viscosity - Three stages of cooling melting range, super cooled melt range and solidification range. (Liquid ⇒ Plastic ⇒ solid). Surface shape and/or refraction indices may change if the transformation temperature Tg is reached.

Thermal Expansion - Thermal Coefficient of Expansion (TCE) describes change in dimension with temperature

$$L' = L(1 + \alpha(TCE)\Delta T)$$

AFFECTS THICKNESSES AND RADII

Change in Index

$\alpha_{-30/+70°C}$ $\alpha_{+20/+300°C}$

$$\frac{dn_{abs}(\lambda,T)}{dT} = \frac{n^2(\lambda,T_0)-1}{2\cdot n(\lambda,T_0)}\cdot\left(D_0 + 2\cdot D_1\cdot\Delta T + 3\cdot D_2\cdot\Delta T^2 + \frac{E_0 + 2\cdot E_1\cdot\Delta T}{\lambda^2-\lambda_{TK}^2}\right)$$

Definitions:

T_0	Reference temperature (20°C)
T	Temperature (in °C)
ΔT	Temperature difference versus T_0
λ	Wavelength of the electromagnetic wave in a vacuum (in µm)

D_0, D_1, D_2, E_0, E_1 and λ_{TK}: constants depending on glass type

Plastics - Plastic materials offer advantages and disadvantages compared to glass

ADVANTAGES - low cost, low cost manufacturing, light weight, high impact resistance, easier to mold, easier to integrate mounts.

DISADVANTAGES - Melt at much lower temps, less resistance to abrasion & chemicals. Coatings don't stick as well. Limited choice of materials.

Common Plastic optical materials

<u>PMMA</u> (Polymethyl methacrylate, acrylic, perspex, plexiglass, lucite)

good clarity and transmission in visible

high Abbe # (55.3)

Good mechanical stability

Easy to machine, polish and mold

<u>Polystyrene</u> higher absorption in blue

high index, low Abbe 1.59/30.9

lower resistance to UV/scratches than PMMA

<u>Polycarbonate</u> (CR39)

more expensive

higher impact resistance - eyeglasses

<u>COC</u> (cyclo olefin copolymers, Zeonex)

Similar to PMMA, but lower water absorption

[2.1.2] <u>Dispersion Formulas</u> - Empirical fit to refractive index data [Book 4.3.2]

<u>Cauchy Formula</u>

$$N(\lambda) = A_0 + \frac{A_1}{\lambda^2} + \frac{A_2}{\lambda^4} + \dots$$ usually only two terms used

OK Fit in visible but <u>inaccurate</u> in IR and UV

<u>Schott Formula</u>

$$N^2 = A_0 + A_1\lambda^2 + \frac{A_2}{\lambda^2} + \frac{A_3}{\lambda^4} + \frac{A_4}{\lambda^6} + \frac{A_5}{\lambda^8}$$

Schott no longer uses this formula, but it is common for other glass manufacturers to use this. Hoya

Sellmeier Dispersion Formula

$$N^2 - 1 = \frac{B_1 \lambda^2}{\lambda^2 - C_1} + \frac{B_2 \lambda^2}{\lambda^2 - C_2} + \frac{B_3 \lambda^2}{\lambda^2 - C_3}$$

Schott now uses this formula   Ohara

Many other dispersion formulas exist, but these are the most common

2.1.3 Infrared and Ultraviolet Materials [Book 4.3.3]

Limited material choices outside of visible range. Short wavelength in UV makes scatter big issue

MWIR → λ = 3 to 5 um
LWIR → λ = 8 to 14um

reasonably high transmission through atmosphere

IR Materials (INCOMPLETE LIST)

Germanium   Crown in LWIR; Flint in MWIR

N= 4.0243 @ 4um   Expensive
N= 4.0032 @ 10um   large dN/dT

ZINC SULFIDE (CLEARTRAN)

N = 2.252 @ 4um
N= 2.2005 @ 10um

SAPPHIRE   N : 1.6753 @ 4um

Very hard (means difficult/expensive to fabricate)

Doesn't transmit @ 10um   low emissivity at high temps

Make good windows when you look at something hot in IR

Supersonic windows

UV Materials (INCOMPLETE LIST)

FUSED SILICA

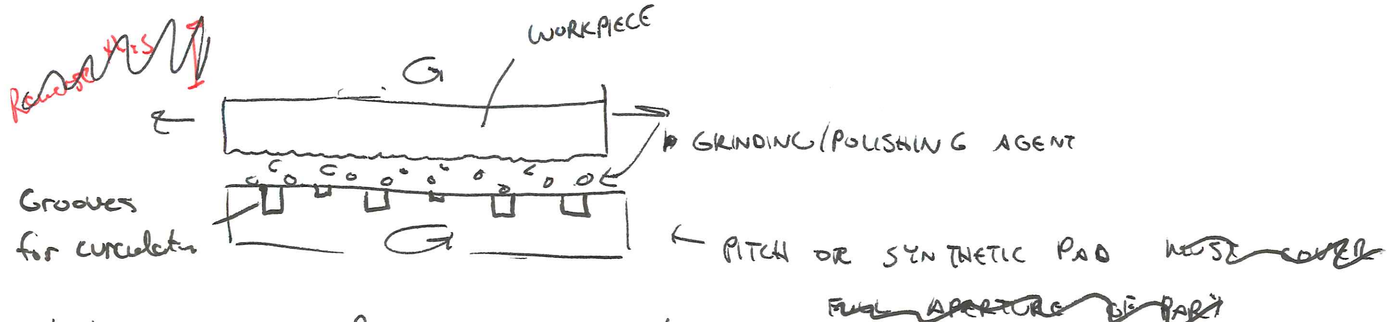
Transmission down to 160nm
very low thermal expansion

CALCIUM FL

High transmission from 350nm - 7um
Low absorption / high damage threshold

SAPPHIRE - See above

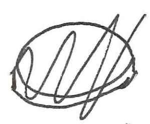
2.2 Grinding and Polishing Flats, Windows and Prisms [Book 4.4.1]



High spots on surface get worn down.

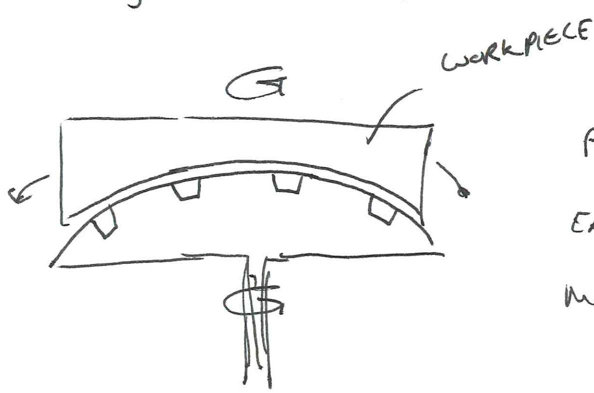
Grinding particles 5 - 30 um in diameter

Polishing particles 0.5 - 5 um in diameter



High quality Surface Figure	Low Surface Roughness
$\lambda/4$ is relatively "easy"	1 nm RMS is "easy"
$\lambda/10$ is routinely achievable	1 Å is possible
$\lambda/20$ is possible	

2.3 Grinding and Polishing Spherical Surfaces

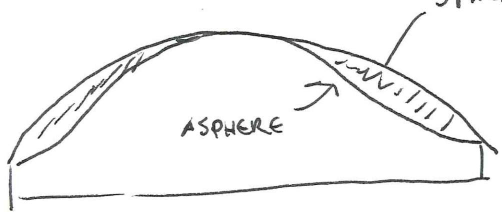


POLISHER IS LARGER THAN WORKPIECE

EACH TOOL HAS DESIRED RADIUS SO MANY ~~PIECES~~ TOOLS NEEDED

2.4 GRINDING AND POLISHING ASPHERES [Book 4.4.2]

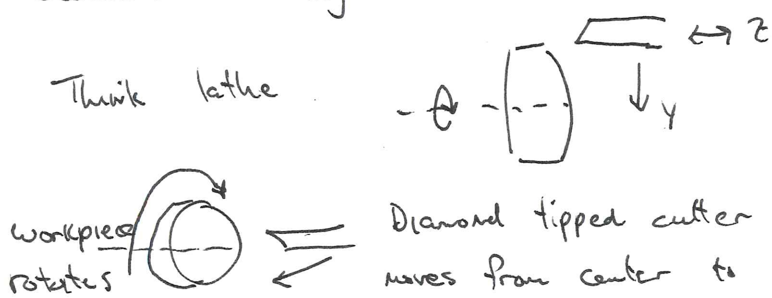
Traditional Pitch polishing won't work since shape of tool needs to change depending on position on part.



∴ Need to polish/grind over sub-apertures of workpiece

2.5 Diamond Turning and Fast Tool Servo [Book 4.4.3]

Think lathe



Diamond tipped cutter moves from center to edge of part

Fast tool servo allows cutter to vary z position during a single rotation

Limited to certain optical materials: Nickel, Aluminum, CaF_2, Ge, ZnSe, ZnS, Si, PMMA

Causes circular grooves which lead to diffraction

2.6 Magnetorheological Finishing [Book 4.4.4]

Fluid with ~~mat~~ iron and abrasive bits. Electromagnet used to shape the fluid to conform to surface

SHOW SLIDES
SHOW MOVIES (17 minutes)

2.7 PLASTIC INJECTION MOLDING

2.8 GLASS MOLDING

} SHOW SLIDES [Book 4.4.6]

ION BEAM FIGURING