Mirror Example

- Consider a concave mirror radius r = -10 cm then

$$f = -\frac{r}{2} = -\frac{-10}{2} = 5\ cm$$

- Now consider a 1 cm candle s = 15 cm from the vertex
- Where is the image

$$\frac{1}{s} + \frac{1}{s'} = -\frac{2}{r} = \frac{1}{f}$$

$$\frac{1}{s'} = -\frac{2}{r} - \frac{1}{s} = \frac{1}{5} - \frac{1}{15} = 0.13333 \qquad s' = \frac{1}{0.1333} = 7.5\ cm$$

- Magnification $m = \frac{M'}{M} = -\frac{s'}{s} = -\frac{7.5}{15} = -0.5$
- Thus image is inverted and half size of object
- What if candle is at 10 cm (radius of curvature)

$$\frac{1}{s'} = -\frac{2}{r} - \frac{1}{s} = \frac{1}{5} - \frac{1}{10} = 0.1 \quad s' = \frac{1}{0.1} = 10\ cm \qquad m = -\frac{s'}{s} = -\frac{10}{10} = -1$$

Image is at object position (10 cm) inverted and same size (1 cm)

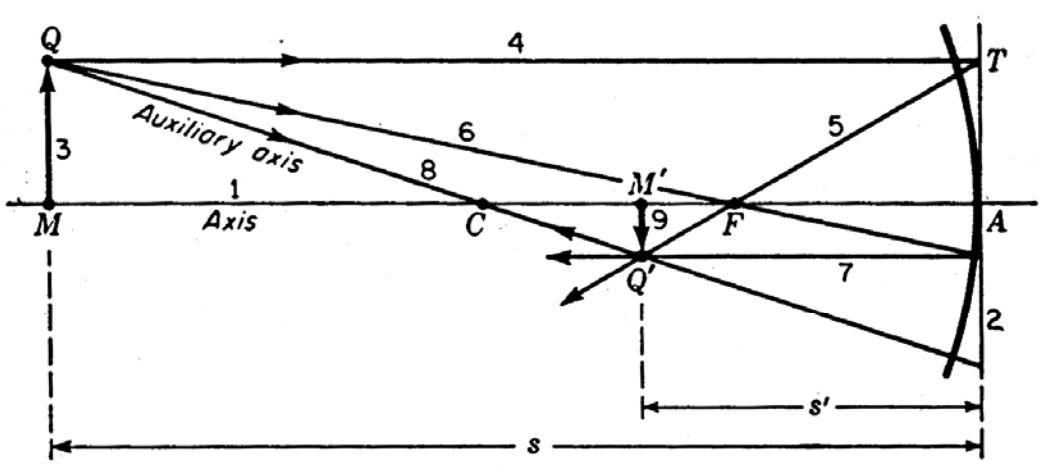


FIGURE 6E
Parallel-ray method for graphically locating the image formed by a concave mirror.

Graphic Method of Solving Optics

- Graphic method is useful in thinking about what happens
- Use some scale (graph paper good)
- Place mirror on axis line and mark radius C & focal F points
- Draw line from object top Q to mirror parallel to axis (ray 4)
- Hits vertex line at T
- Then direct ray from T through focus point F (ray 5) and beyond
- Now direct ray from object top Q through radius C (ray 8)
- This intersects ray 5 at image Q' (point 9)
- This correctly shows both position and magnification of object
- This really shows how the light rays are travelling
- Eg Ray through the focal point F (ray 6) becomes parallel (ray 7)
- Intersects ray 5 again at image Q'
- Can use graphics to solve exactly
- But often sketch this to see if optic paths make sense
- Graphics method also assumes parallax assumption
- Graphics very good with multi mirror/lens combination
- Formulas harder to see what is going on there.

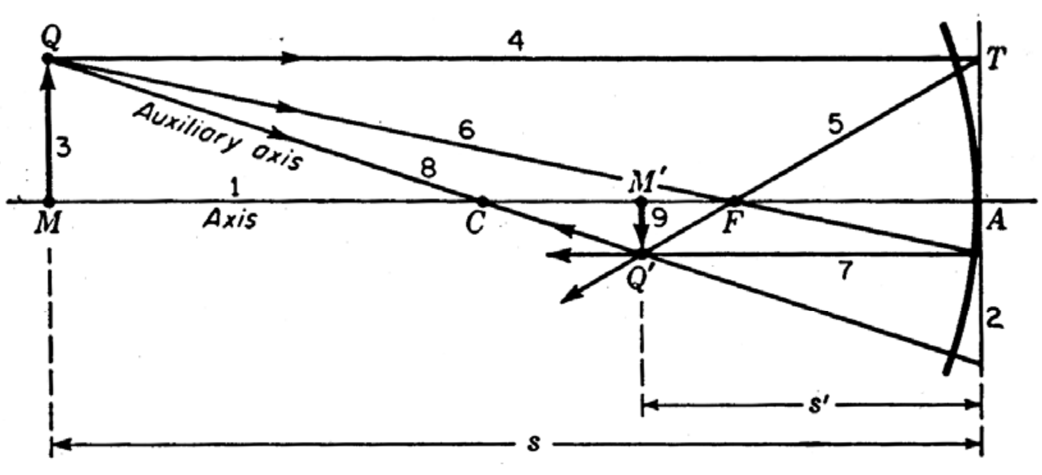


FIGURE 6E
Parallel-ray method for graphically locating the image formed by a concave mirror.

Objects at less than Focal Length Position & Convex Mirrors

- Now consider object at 2.5 cm (smaller than f = 5 cm)

$$\frac{1}{s'} = -\frac{1}{f} - \frac{1}{s} = \frac{1}{5} - \frac{1}{2.5} = -0.2 \quad s' = \frac{1}{-0.2} = -5\ cm \qquad m = -\frac{s'}{s} = -\frac{-5}{2.5} = 2$$

- Image appears to be behind the mirror by 5 cm
- Image is virtual – light is expanding from mirror
- Image is erect and twice object size
- Do not see image if place something at image position
- With graphical method must project C & F lines to right side
- Shows size of image there
- For convex mirrors (r is +) F & C on right side of mirror
- Again ray from object parallel to axis hits mirror (ray 1 below)
- Now draw ray through focus F on right (ray 1)
- Then extend to other side of mirror also
- 2^{nd} ray from object now through C on left (r+) or right (r-)
- Interception point is where virtual image is

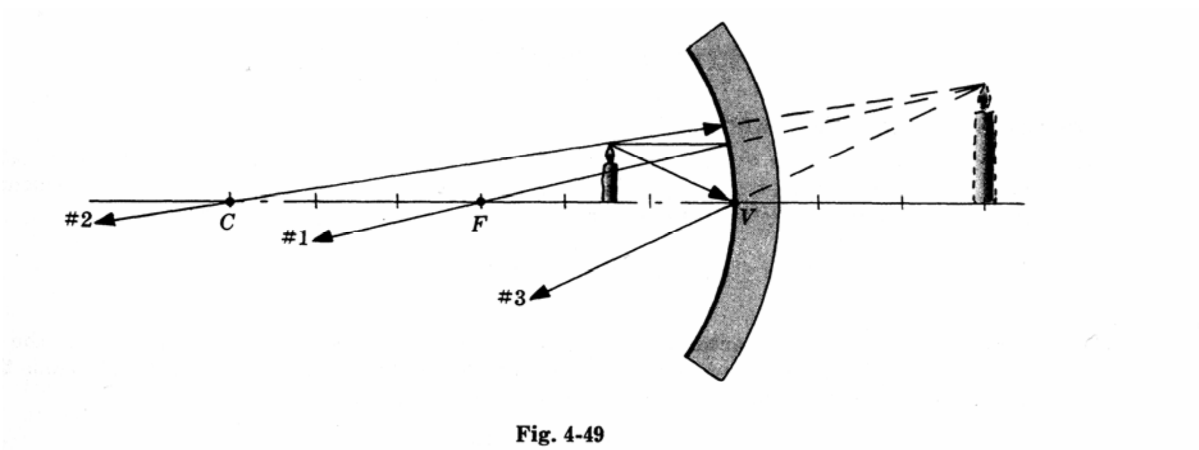
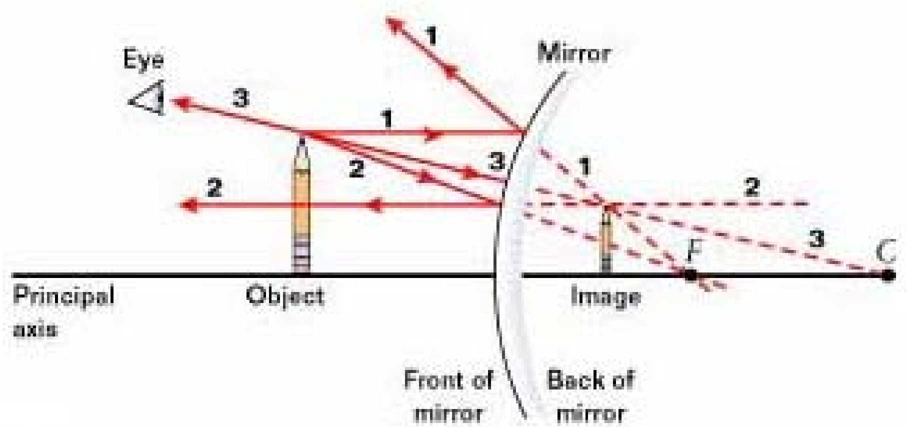
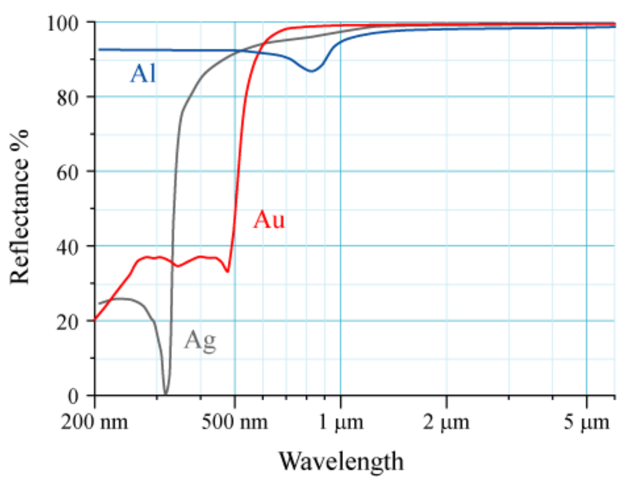


Fig. 4-49

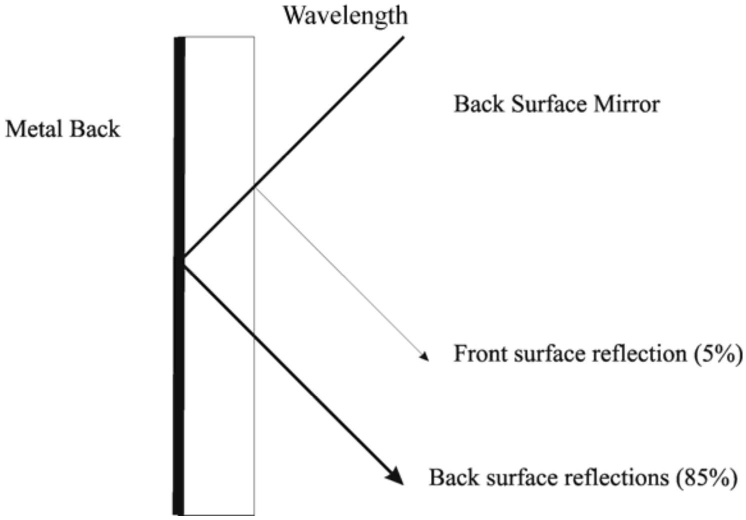


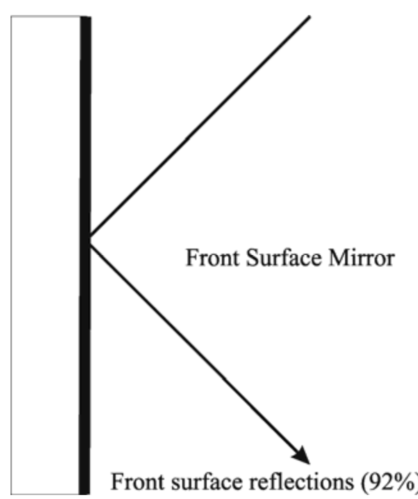
Mirror Coatings

- Classic mirrors use metallic coatings
- Most optics mirrors front surface mirror
- Regular mirrors back surface (coating on glass)
- Problem for optics (reflection both from glass & metal surface)
- Mirrors wavelength range depends on the coating
- Aluminum (Al) most common now: 90-92% reflective in optical
- Often coated for protection with transparent film (aluminium oxide)
- Silver (Ag) mirrors higher reflection 95-99% but poor in UV range
- Silver coatings must be recoated or fail in 6 months
- Gold (Au) mirrors for IR systems but poor <550 nm (yellow)
- For lasers Al mirrors problem is ~8% absorption
- Film gets damaged by laser energy absorbed
- Typical limit 50 W/cm^2 CW, 10 mJ/cm^2 for 10 nsec pulse
- Need to watch cleaning as they scratch easily




Gold mirror





Mirror Substrates

Pyrex

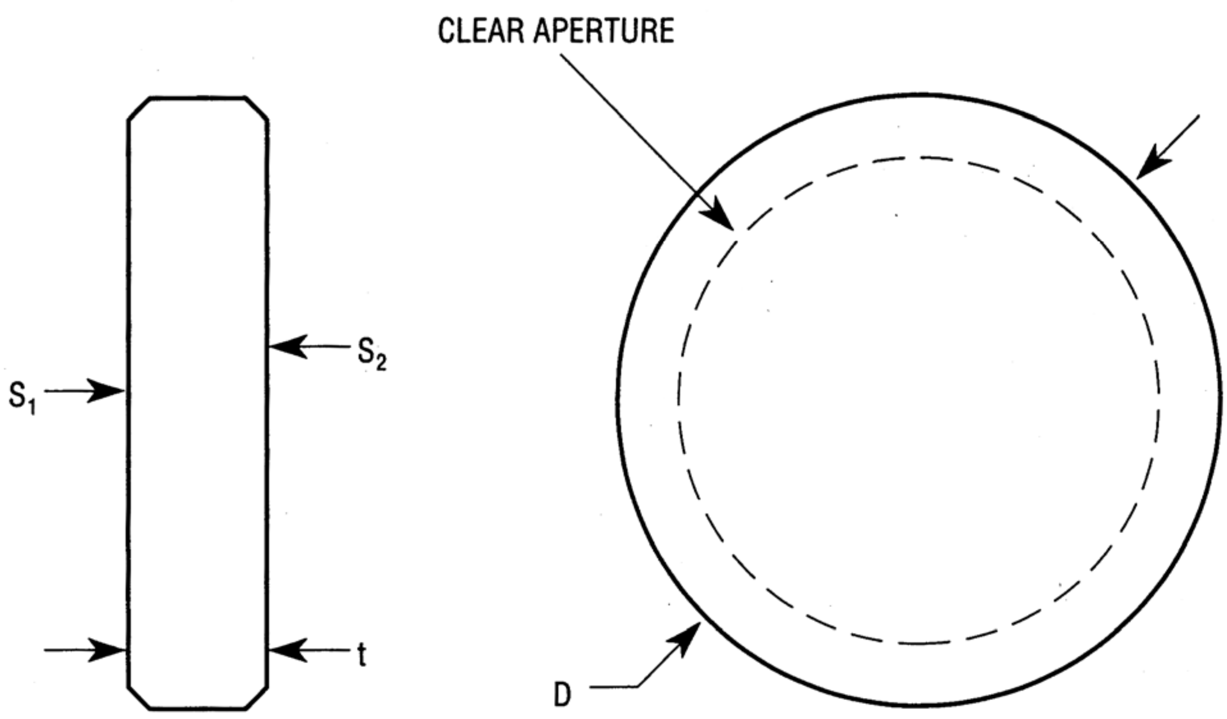
- Typical substrate pyrex: BK7
- Low deformation with heating (expansion coefficient $87x10^{-7}$)
- Good surface polish
- Typical size: 1 inch diameter, 0.5 inch thick
- Must be platinum free
- Price of substrate ~$100

Glass-Ceramic materials

- eg Newport's Zerodur
- designed for low thermal expansion
- Used were there must be not thermal changes
- Price of Substrate ~$130

Fused Silica (Quartz)

- High thermal stability (thermal expansion coef $6x10^{-7}$)
- Extremely good polishing characteristics
- 3 times price of Pyrex



Optical Interference

- Wave nature of light results in optical interference
- Consider two plane wave sources of same wavelength
- Waves are Coherent: ie waves stay with same phase
- Where wave peaks/troughs add get constructive interfrence
- e.g. Waves A & B below
- Where peaks/troughs opposite get destructive interference
- e.g. Waves A & C below
- Where waves cancel get **nulls** – areas with no waves
- Where add get crests: high intensity (bright) areas
- Many optical effects created by this.

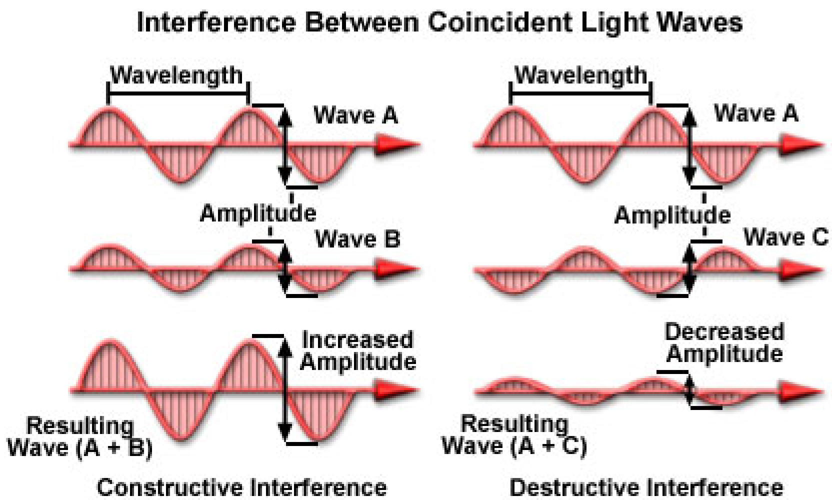
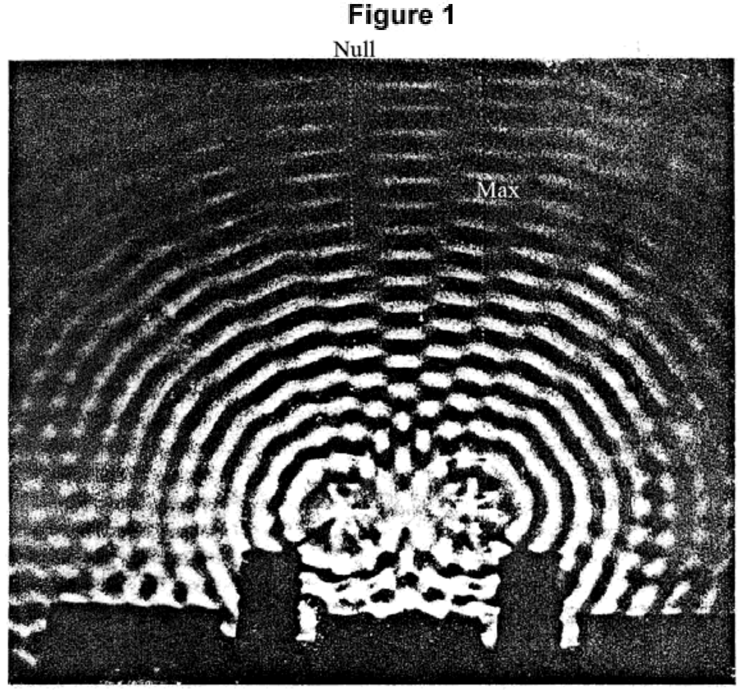
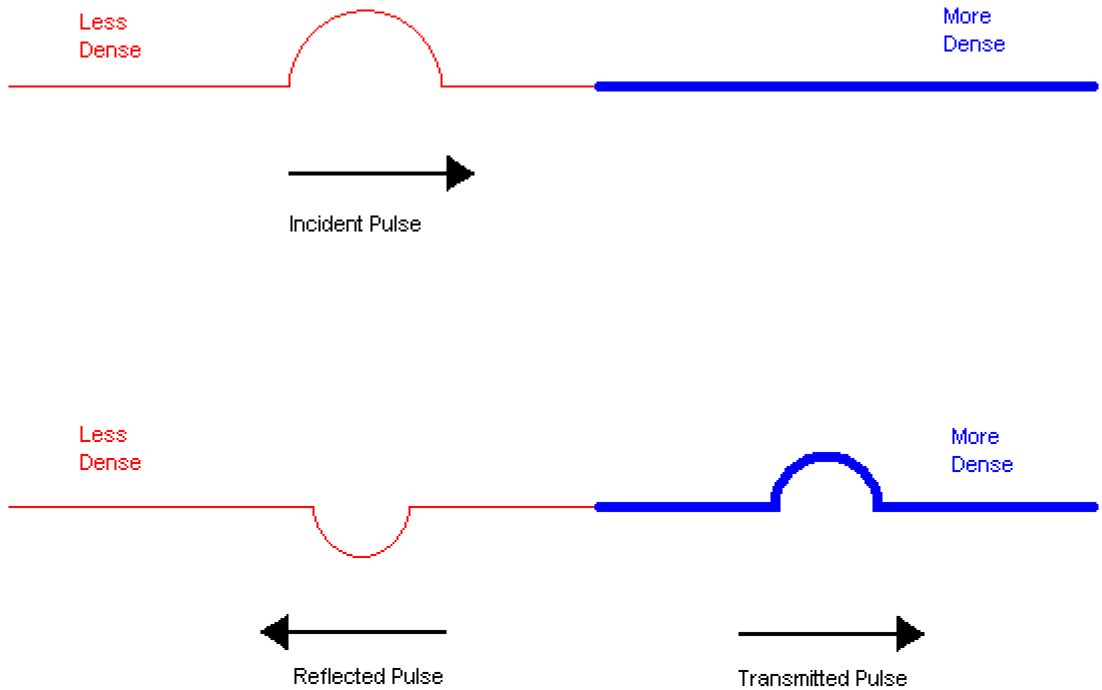


Figure 1



Wavelength and Coatings

- Consider a thin dielectric film $n_o << n_c$
- Inverting reflection from low index n_o to a high n_c
- Non-Inverting reflection from high index n_c to low
- Thus interference is going to depend on what you reflect from



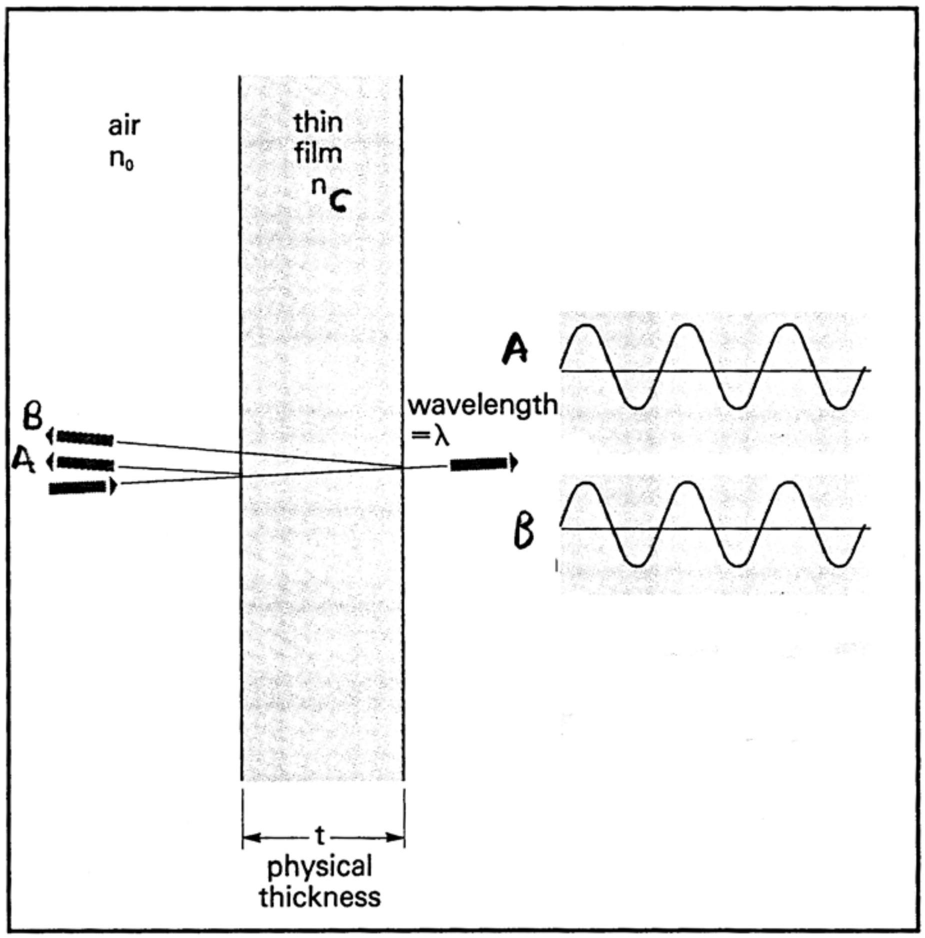
Inference in Thin Films

- Consider film of thickness

$$n_c t = \frac{\lambda}{4}$$

where t is the film thickness

- Result is a ½ wavelength path
- Consider a high index n_c between two lower index n_o and n_s
- First surface: inverting reflection from low index n_o to a high n_c
- Back surface: Non-Inverting reflection from high index n_c to low
- Result is constructive interference
- This is what happens in soap films



Wedge Interference

- Illuminate with a monochromatic light source (e.g. laser)
- Bottom surface: inverting reflection from low index n_o to a high n_c
- Front surface: Non-Inverting reflection from high index n_c to low
- Goes through destructive interference when

$$t = \frac{(2j+1)\lambda}{4}$$

- Where j is an integer >=0
- Creates parallel lines of bright and nulls space by $\lambda/2$
- If measure horizontal distance between nulls get slope
- Non-parallel lines show defects << λ (~10's nm)

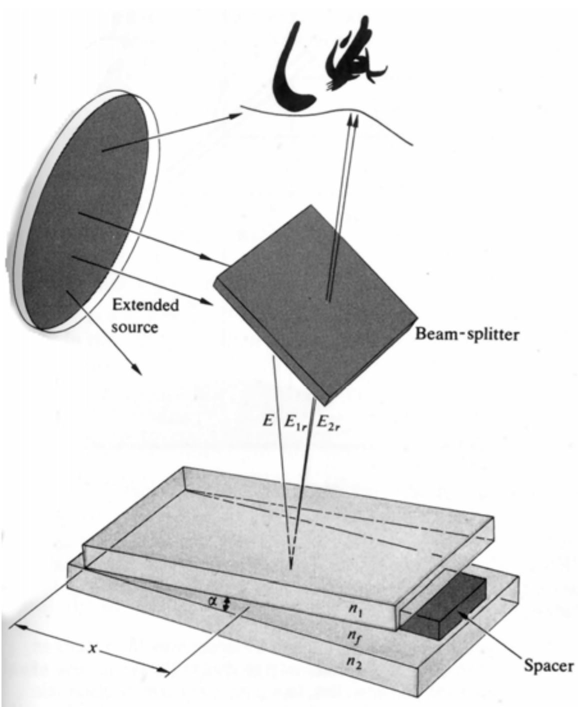
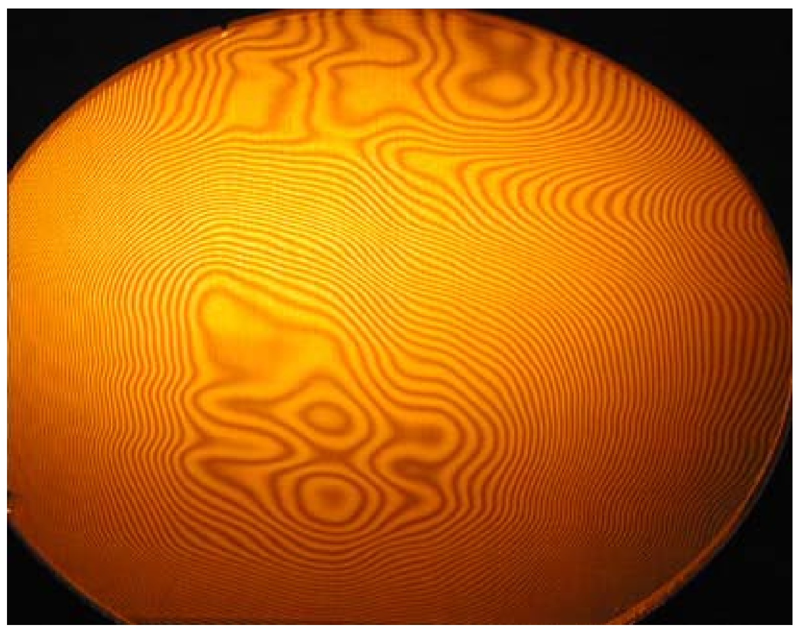
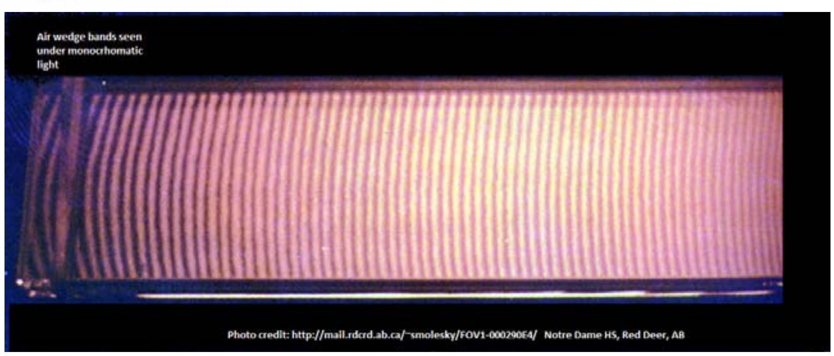


Figure 9.22 Fringes from a wedge-shaped film.



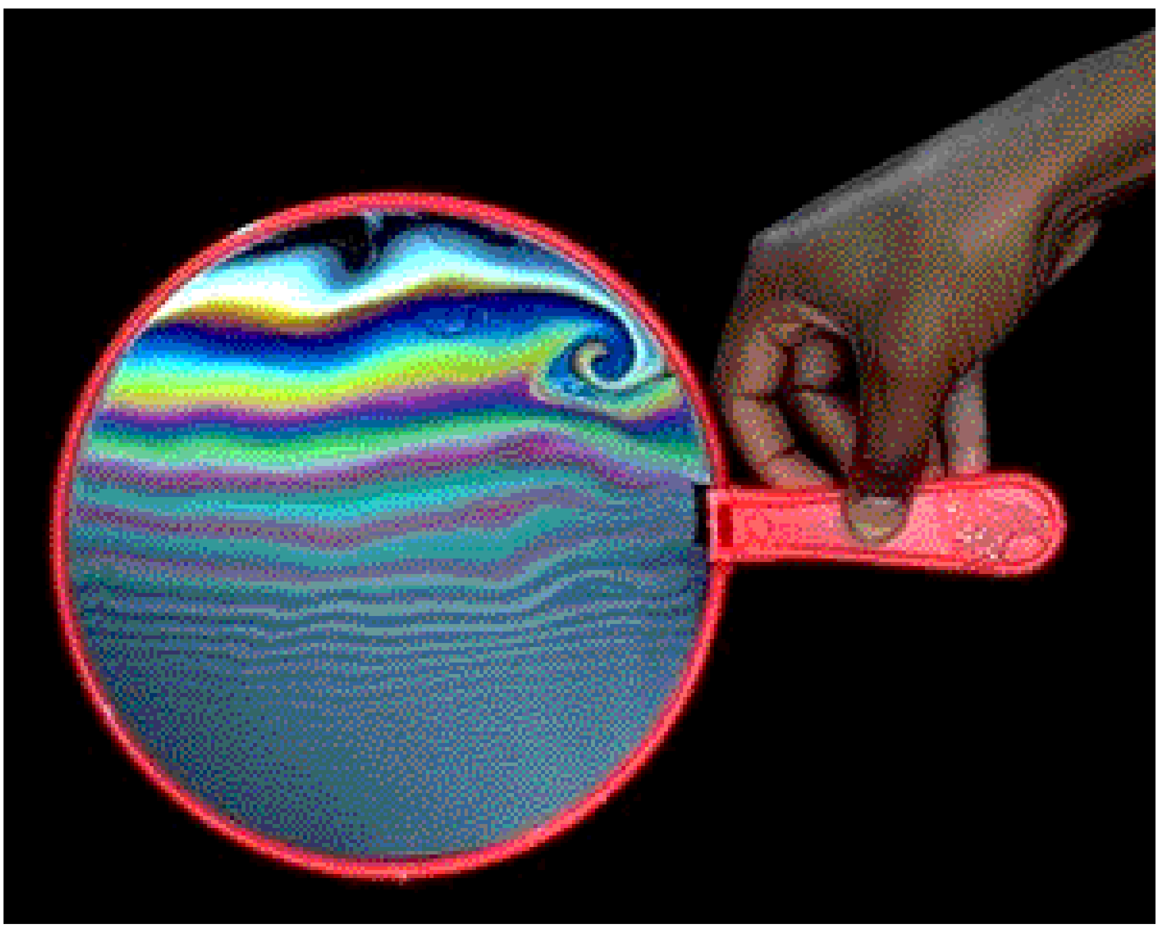


Soap Bubbles

- In soap bubbles film changes thickness from thin (top)
- to thick bottom
- Thickness few wavelengths
- As wavelengths go through constructive interference see that colour

$$n_c t = \frac{(2j+1)\lambda}{4}$$

- Where j is an integer >=0
- Get a spectrum as each colour hits max while others decline
- Wide spaced colours at top as thickness changes slowly there
- Towards bottom thick area get overlap of interference



Newton's Rings

- Now put lens on flat plat and illuminate with monochromatic light
- Get Newton's Rings: circles of light
- Consider a lens of Radius of Curvature R
- Let x = distance from center
- Let d = distance between lens surface and plate
- Now relationship between these is

$$x^2 = R^2 - (R-d)^2 \approx 2Rd$$

- Since R>>d
- Thus the mth order maximum occurs when

$$2d_m = \left(m + \frac{1}{2}\right)\lambda$$

- And the position of the mth bright ring is

$$x_m = \sqrt{\left(m + \frac{1}{2}\right)\lambda R}$$

- And the dark rings are at $x_m = \sqrt{m\lambda R}$

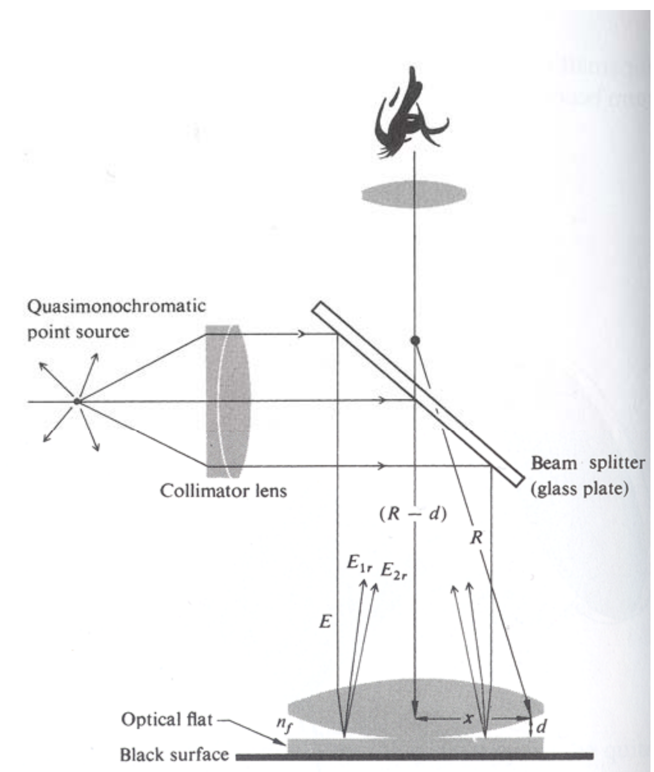
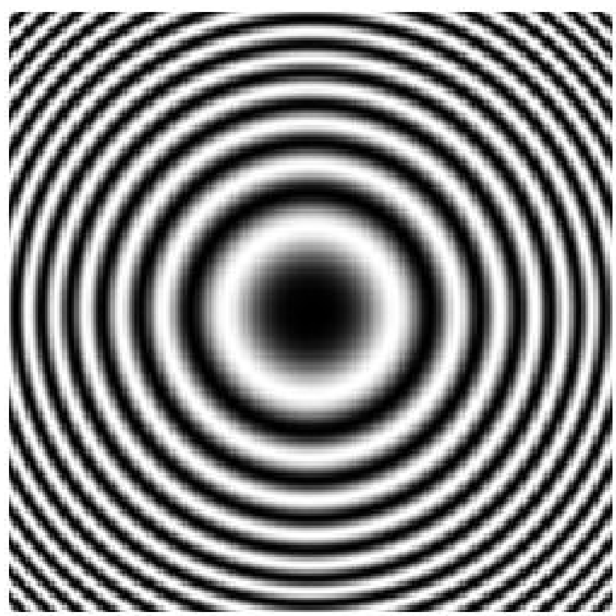


Figure 9.23 A standard setup to observe Newton's rings



Quarter Wavelength Anti Reflection Coatings

- Thin dielectric layers on substrate with even higher n
- $n_o << n_c << n_s$
- Front surface Inverting reflection from low index n_o to a high n_c
- Back surface: Inverting reflection from high index n_c to a high n_s
- Destructive interference of waves due to added path when

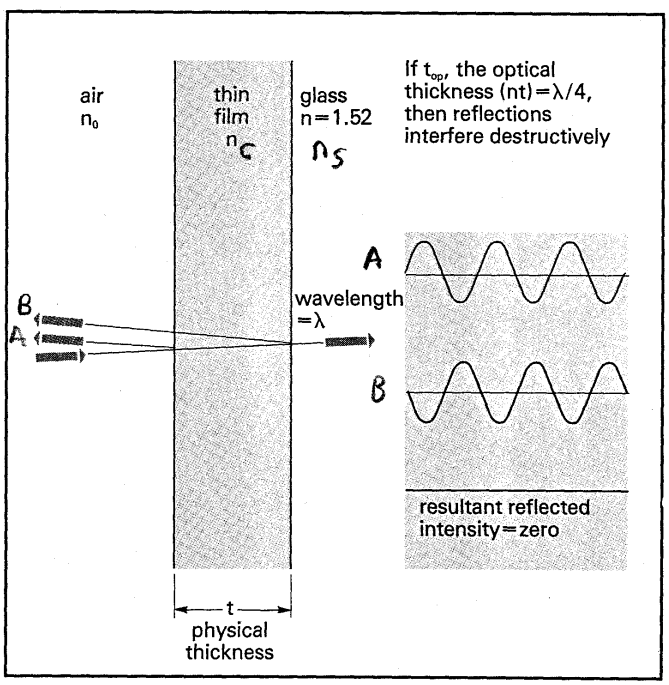
$$n_c t = \frac{\lambda}{4}$$

where t is the film thickness

- Called Anti-reflection (AR) Coating
- Equal reflections (full compensation) when

$$n_c = \sqrt{n_s}$$

- Often put AR coatings on eyeglasses
- Note this is the opposite of soap film where n_c is the highest n



SCHEMATIC REPRESENTATION of a single layer anti-reflection coating.

Enhanced Dielectric Mirrors

- If have multiple layers of alternating high/low index
- Enhanced Reflectance (ER) Coating

$$R = \left[\frac{(1-p)}{(1+p)} \right]^2$$

$$p = \left(\frac{n_h}{n_l} \right)^{N-1} \left(\frac{n_h^2}{n_s} \right)$$

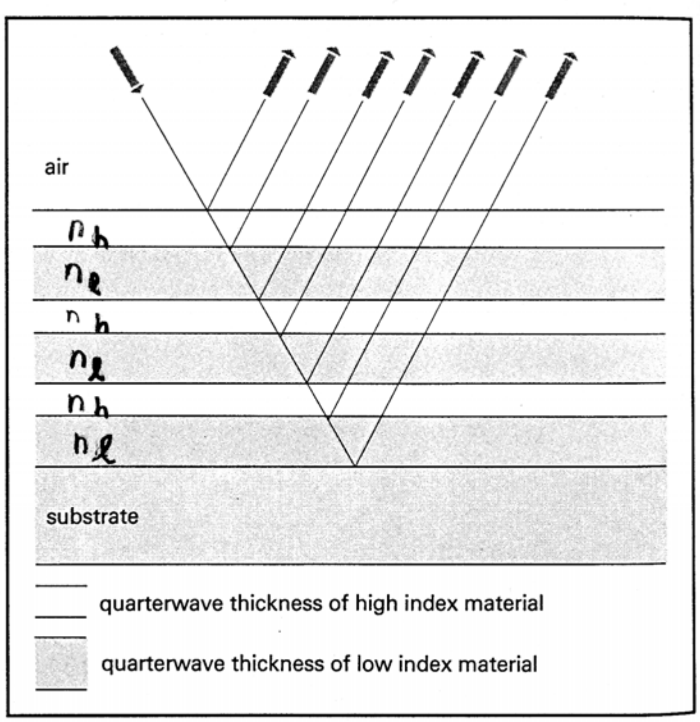
where n_s = substrate index

n_h = high index layer

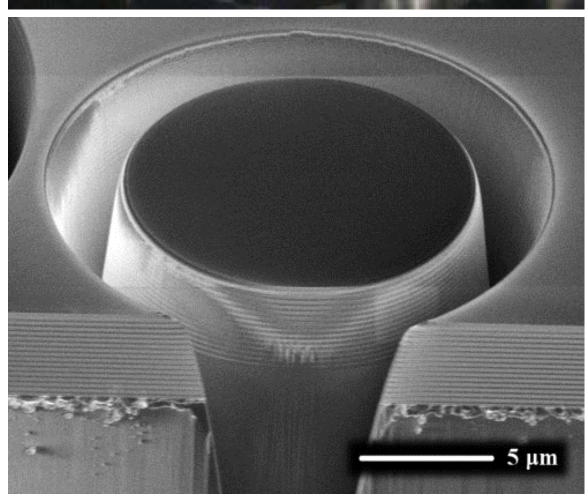
n_l = low index layer ($n_o << n_l << n_s << n_h$)

N = total number of layers (even number in mirrors)

- Greater power than metal: 1000 W/cm^2 CW, 0.5 J/cm^2 10nsec pulse
- Note: dielectric mirrors transmit wavelengths not reflected

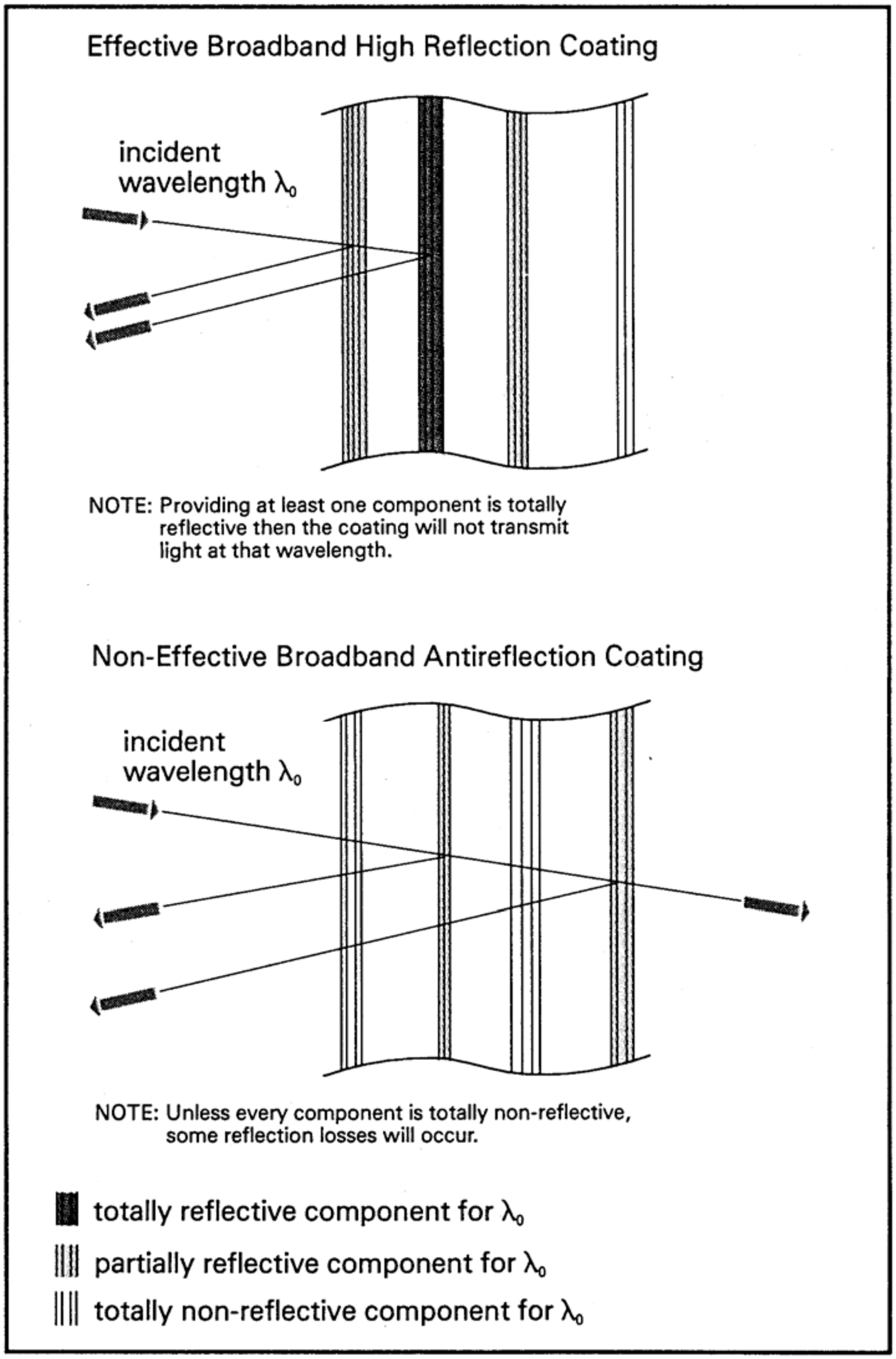


A SIMPLE QUARTERWAVE STACK.



Broadband ER Mirrors

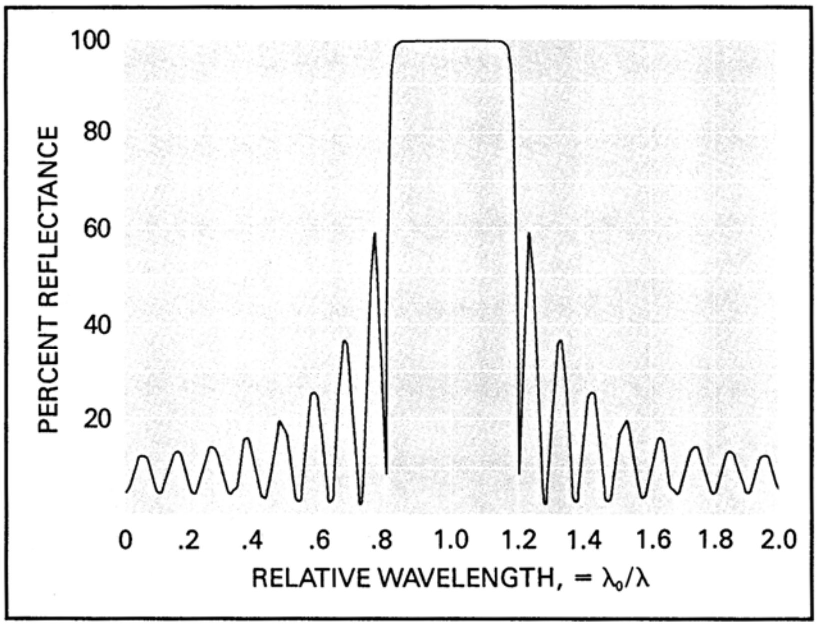
- Can broaden width of reflectance stack
- Make two stacks tuned to different wavelengths
- Alternately modify layer thicknesses to tune



SCHEMATIC MULTICOMPONENT COATINGS with only one component exactly matched to the incident wavelength, λ_0.

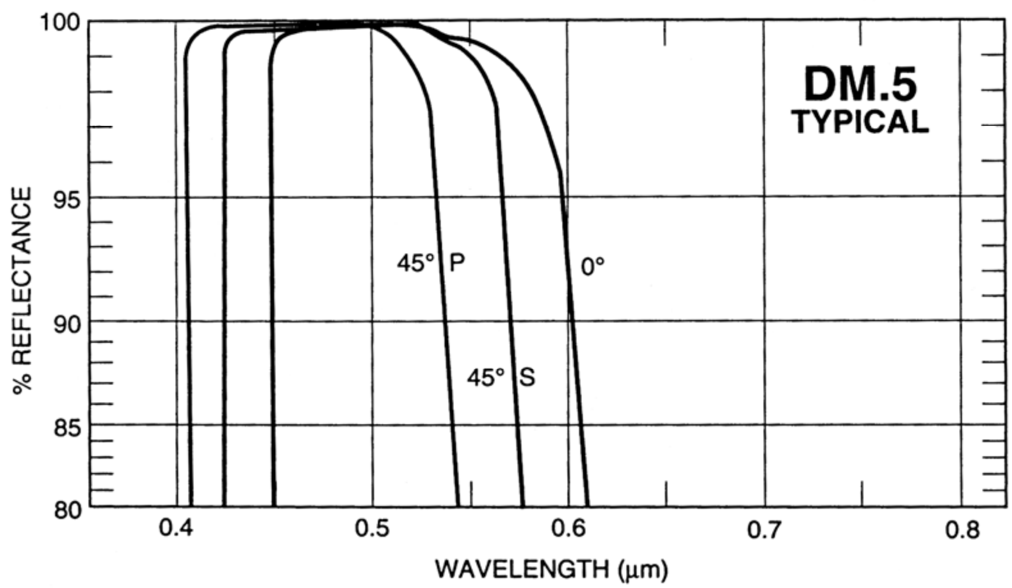
Broadband Dielectric Mirrors

- Important for lasers that emit many wavelengths
  eg Argon from 514 nm to 400 nm
- Note: different coatings for 45^o or perpendicular
- Mirrors Degrade with organic coats
- Must be cleaned with solvent eg acetone



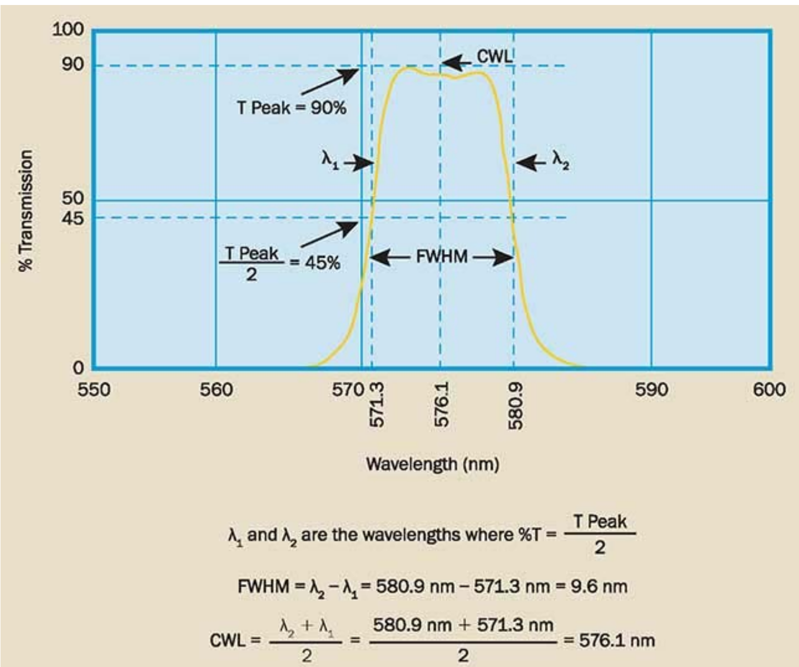
TYPICAL REFLECTANCE CURVE of an unmodified quarter-wave stack.

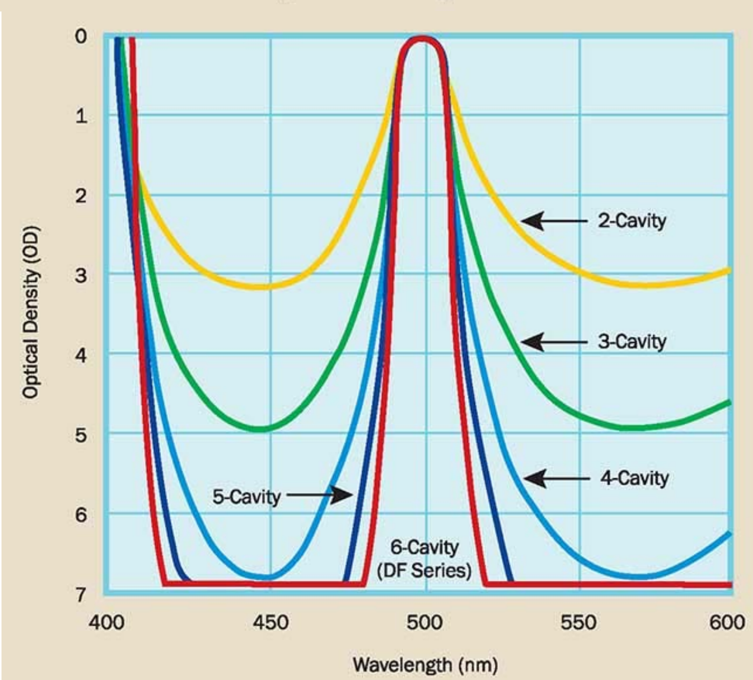
Broadband (Argon Mirror)



Optical Bandpass Filters

- Related to Anti-reflection – multi layer to pass only a narrow band
- , and odd number of layers, Top n_l, next n_h, bottom is n_l
- Also called optical notch, laser line or Fabri-Perot (FP) filters
- Used were only want to see a narrow band of light
- More layers higher rejection and narrower line
- Can get up 20 OD rejection of other waveleng





Lenses & Prism

- Consider light entering a prism
- At the plane surface perpendicular light is unrefracted
- Moving from the glass to the slope side
  light is bent away from the normal of the slope
- Using Snell's law

$$n\, sin(\varphi) = n'\, sin(\varphi')$$

$$1\, sin(\varphi') = 1.75\, sin(30^o) = 0.875$$

$$\varphi' = arcsin(0.875) = 61^o$$

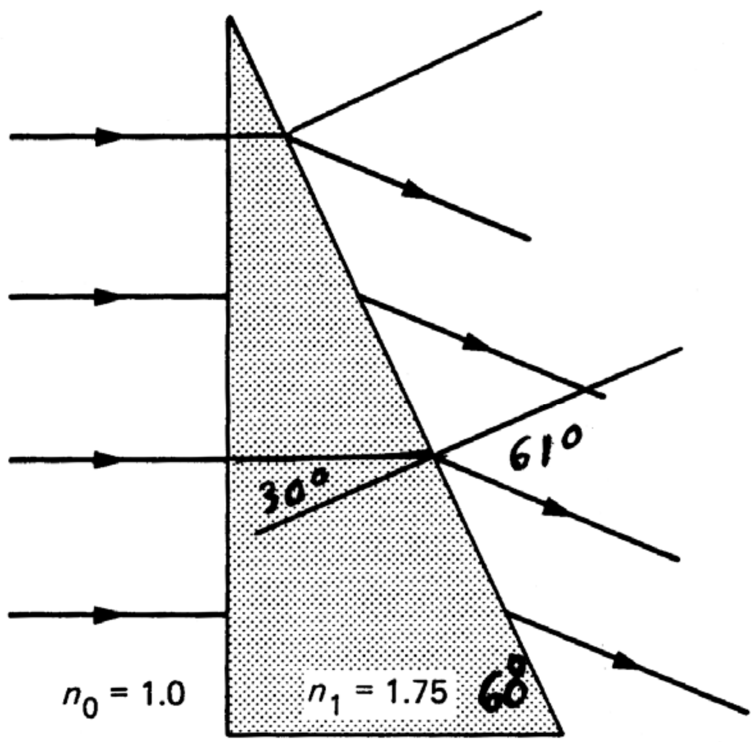


Figure 2.5 A translation into the ray language of Figure 2.3

Prisms & Index of Refraction with Wavelength

- Different wavelengths have different index of refraction
- Index change is what makes prism colour spectrum
- Generally higher index at shorter wavelengths
- Most effect if use both sides to get max deviation & long distance
- Angle change is ~ only ratio of index change – 1-2%
- Eg BSC glass red 1.5, violet 1.51, assume light leaves at 30^o

Red ϕ_R = arcsin [1.5 sin(60)] = 48.59^o
Violet ϕ_v = arcsin [1.51 sin(60)] = 49.03^o

- This 0.43^o difference spreads spectrum 7.6 mm at 1 m distance

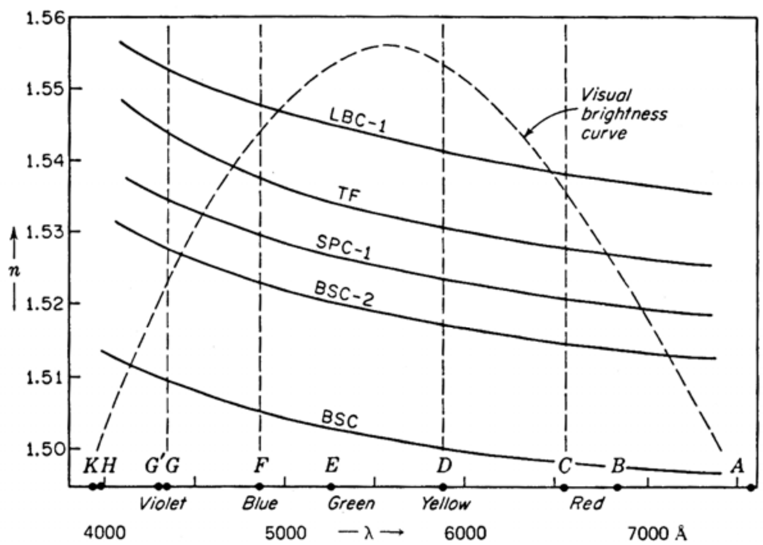
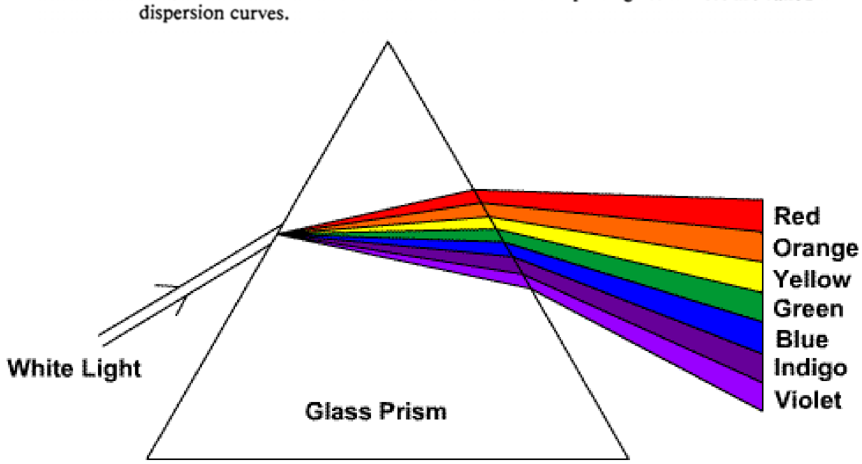


FIGURE 9Y
Graphs of the refractive indices of several kinds of optical glass. These are called dispersion curves.



Lens

- Lens is like a series of prisms
- Straight through at the centre
- Sharper wedge angles further out
- More focusing further out
- Snell's law applied to get the lens operation

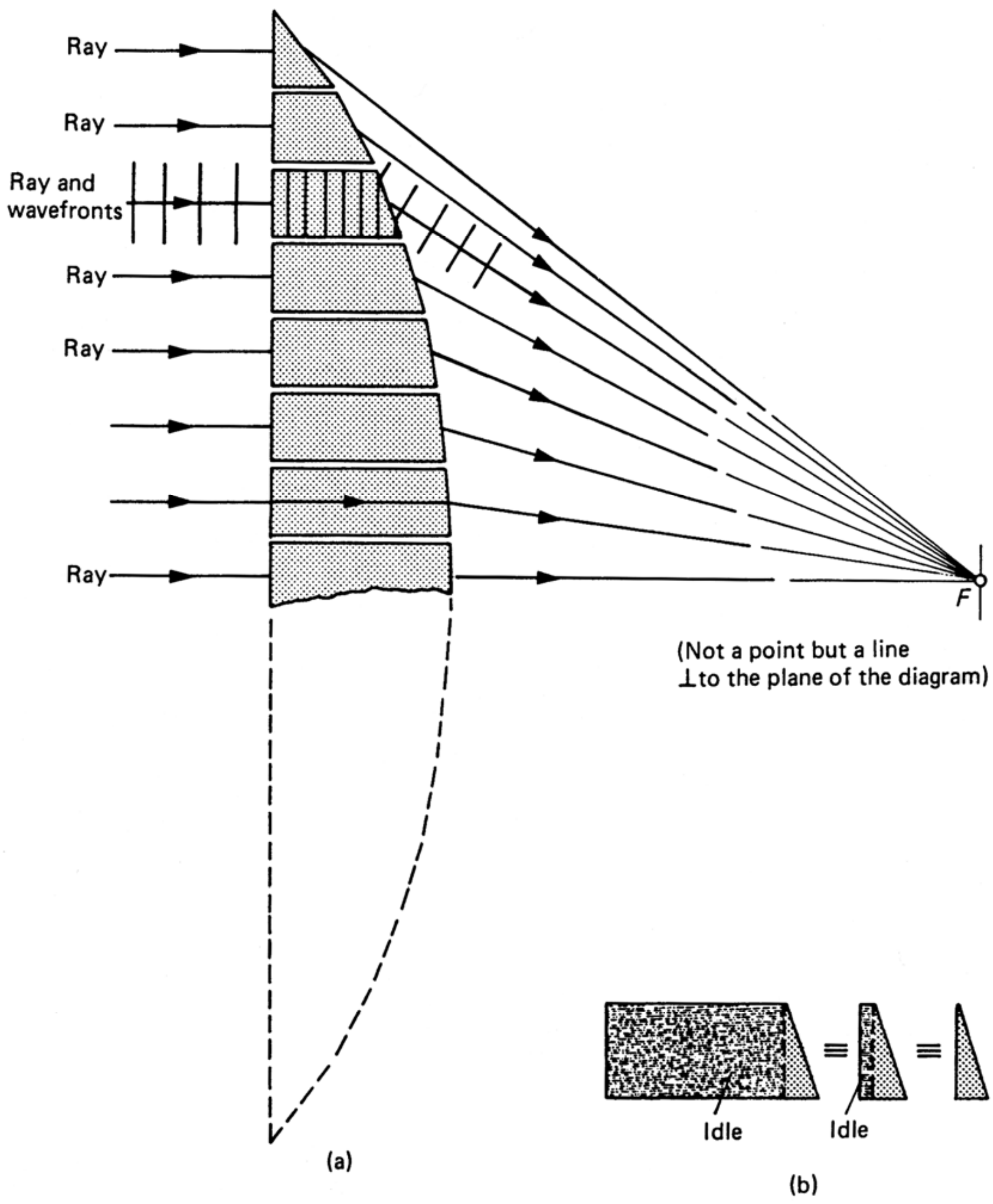


Figure 2.6 Rays corresponding to wavefronts incident upon a succession of small prisms

Focal Points

- Two focal points depending on surface & where light comes from
- **Primary Focal Points** are
- Convex (a) where diverge beam forms parallel light
- Concave surface (b) where light appears to converge when it is converted into a parallel beam
- **Secondary Focal Points**
- Convex (c) where parallel beam is focused
- Concave surface (d) where parallel light coming in appears to diverge from.

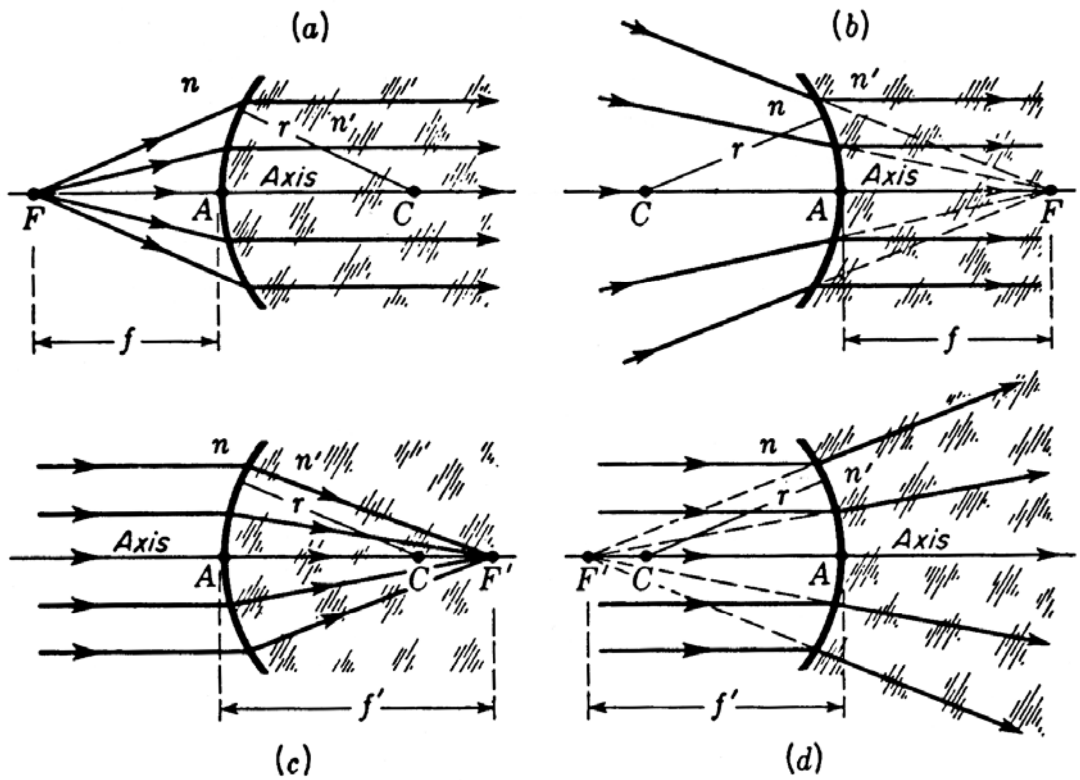


FIGURE 3B

The focal points F and F' and focal lengths f and f' associated with a single spherical refracting surface of radius r separating two media of index n and n'.

Types of Lenses

Convex

- (a) Biconvex or equiconvex
- (b) Planoconvex
- (c) positive meniscus

Concave

- (d) biconcave or equiconve
- (e) Planoconcave
- (f) negative meniscus

- Primary and secondary focal points very dependent on type
- Planoconvex/Panloconcave easiest to make
- Two surface lenses about twice the price

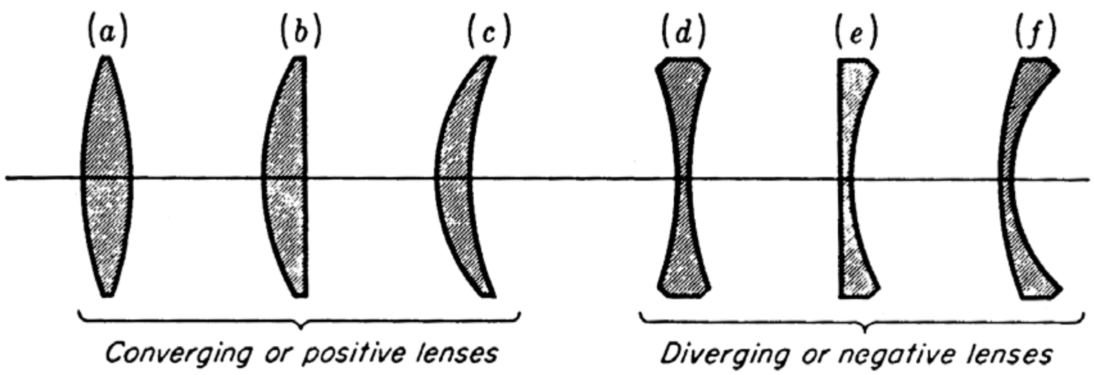


FIGURE 3A
Cross sections of common types of thin lenses.

Fresnel Lens

- Classic lenses are are spherical
- Lens with thickness remove are Fresnel lenses
- Cheaper, but can be lower quality
- Reason: diffraction effects at step boundries
- Often made of low cost moulded plastic for that reason
- Biggest ones use for large lighting systems
- eg lighthouse lamp optics (made of glass)

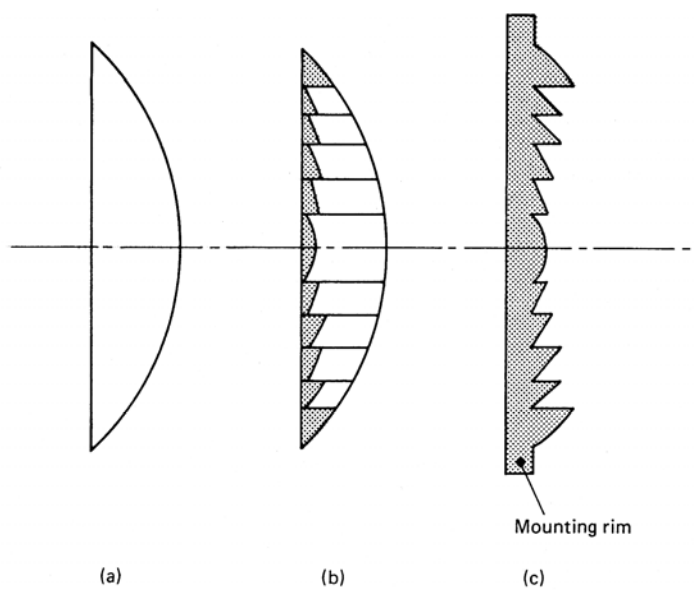


Figure 2.8 Metamorphosis of a succession of prismlets into a Fresnel lens

Light house
fresnel lamp lens