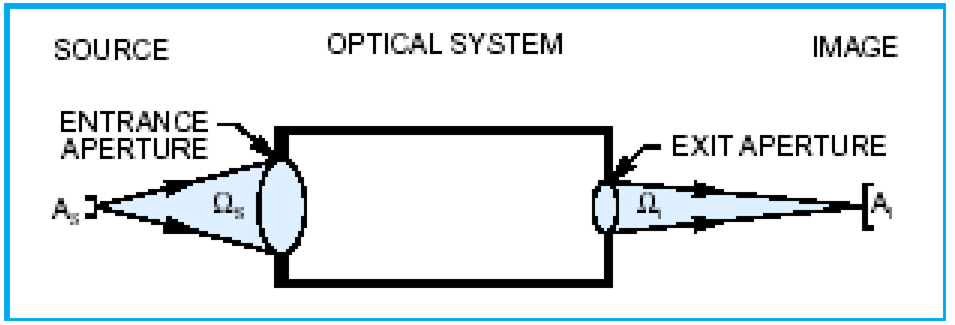
Review

The Geometrical Extent



$$A_s\Omega_s = A_i\Omega_i$$

Where:

A_s = Source area

A_i = Image area

Ω_s = Solid angle subtended at the source by the entrance aperture of the optical system

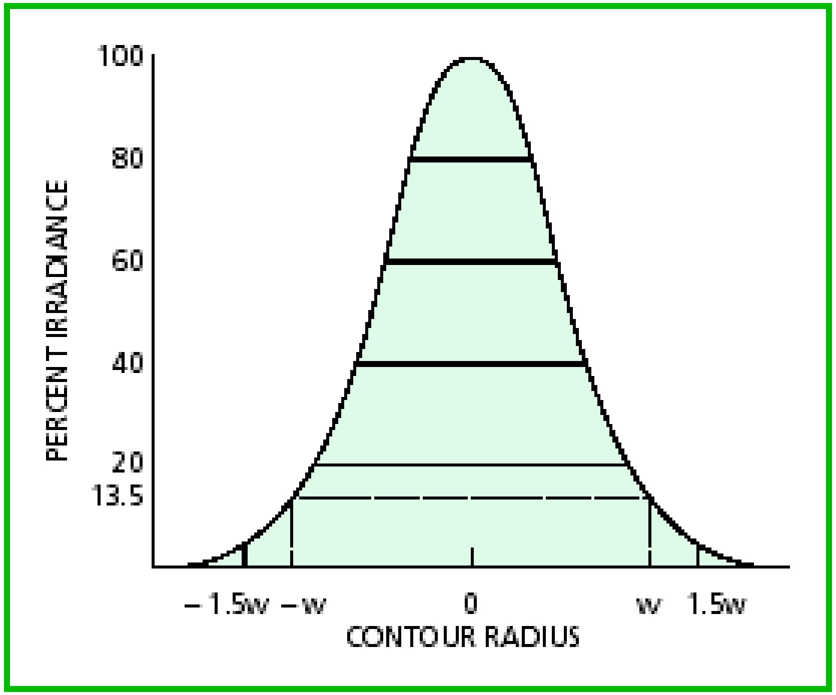
Ω_i = Solid angle subtended at the image by the exit aperture.

Power Throughput

Source Spectral Radiance L ($W\text{-}m^{-2}\text{-}sr^{-1}\text{-}nm^{-1}$)
Aperture A (m^2)
Solid angle Ω (sr) = $\pi \bullet NA^2$
Transmittance T
Geometrical Extent $G = A\Omega$

Flux across element $\Phi = TGL$

Gaussian Beam Distribution

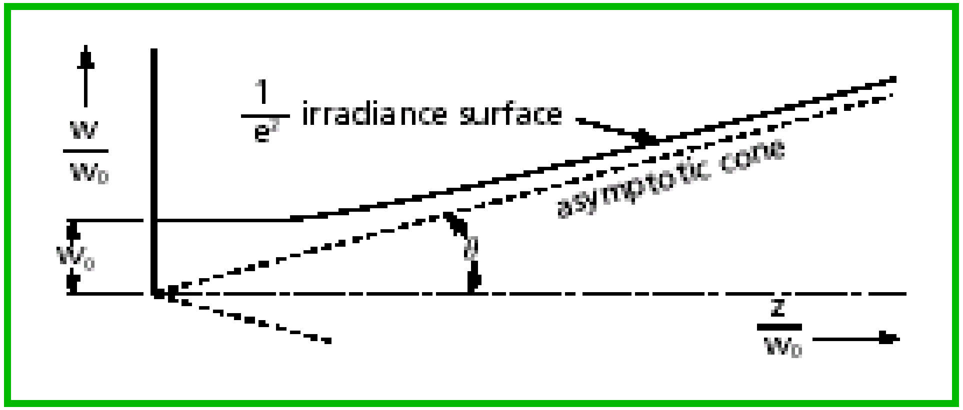


$$I(r) = I_0 \exp\left(-\frac{2r^2}{\omega^2(z)} \right)$$

Power enclosed within circle of radius r:

$$\frac{P(r)}{P(\infty)} = 1 - \exp\left[-2\frac{r^2}{\omega^2} \right]$$

Beam Waist and Divergence



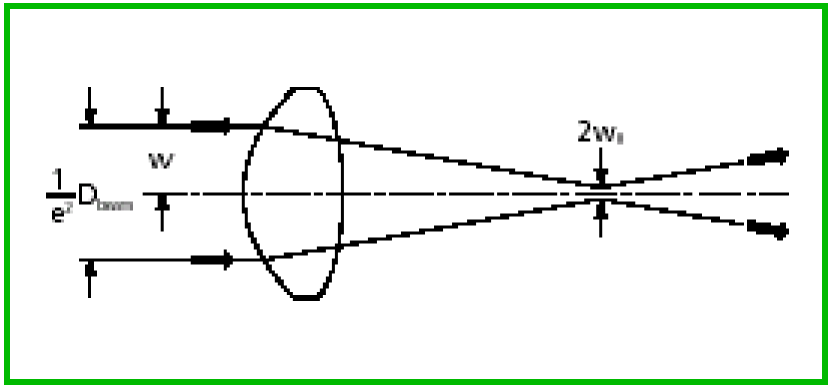
$$R(z) = z\left[1+\left(\frac{\pi\omega_0^2}{\lambda z}\right)^2\right]$$

$$\omega(z) = \omega_0\left[1+\left(\frac{\lambda z}{\pi\omega_0^2}\right)^2\right]^{1/2}$$

For large z:

$$R(z) \cong z \qquad \omega(z) \cong \frac{\lambda z}{\pi\omega_0} \qquad \theta = \frac{\omega}{z} = \frac{\lambda}{\pi\omega_0}$$

Beam Focusing



Spot diameter

$$2\omega_0 = 2\frac{\lambda f}{\pi \omega_{lens}} \approx \frac{2}{\pi}\frac{\lambda}{NA}$$

Example

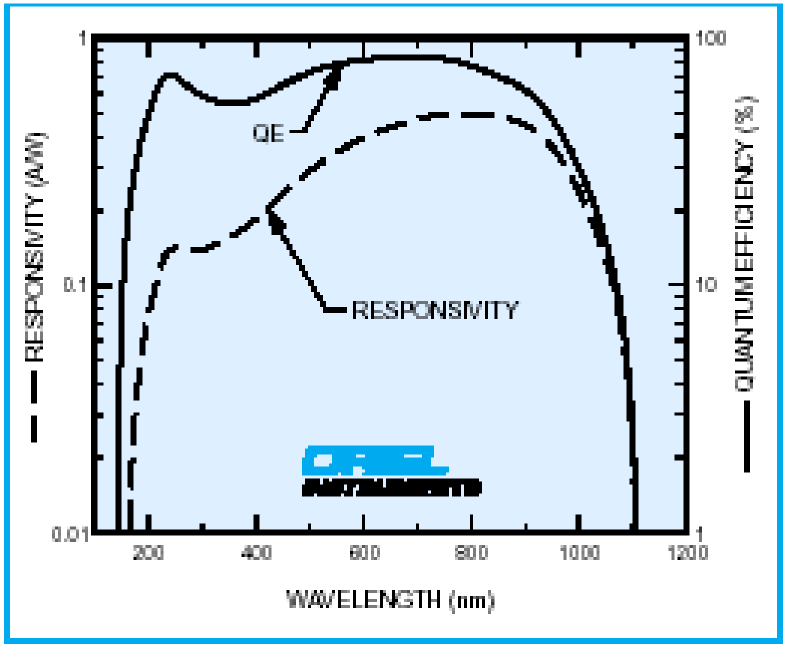
f=10 mm, $2\omega_{lens}$=5 mm, λ=1.55 μm,

spot diameter=3.9 μm

Time Domain – Frequency Domain

$$\text{Rise time} = \frac{.35}{\text{Bandwidth}}$$

Responsivity and Quantum Efficiency



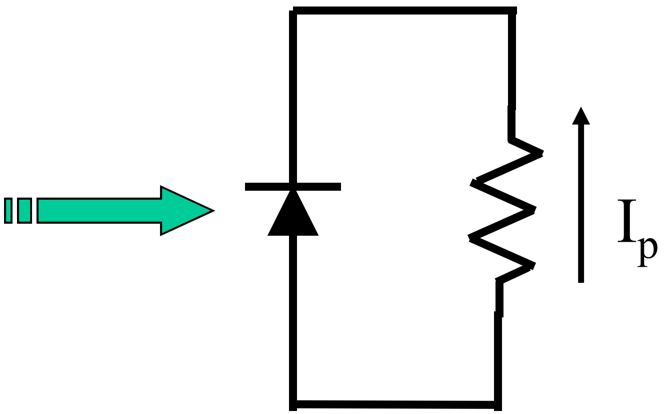
- R(λ) = Amps / Incident Watt
- Q(λ) = e⁻ / Incident Photon

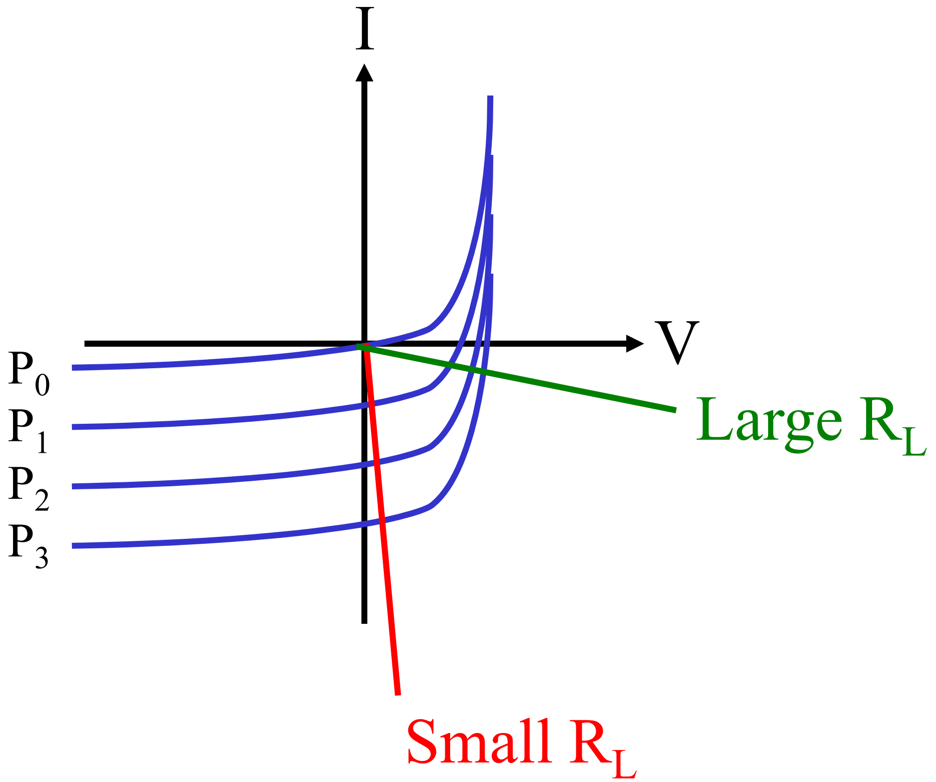
$$R = \frac{q}{h\upsilon} Q$$

Photodiode Biasing

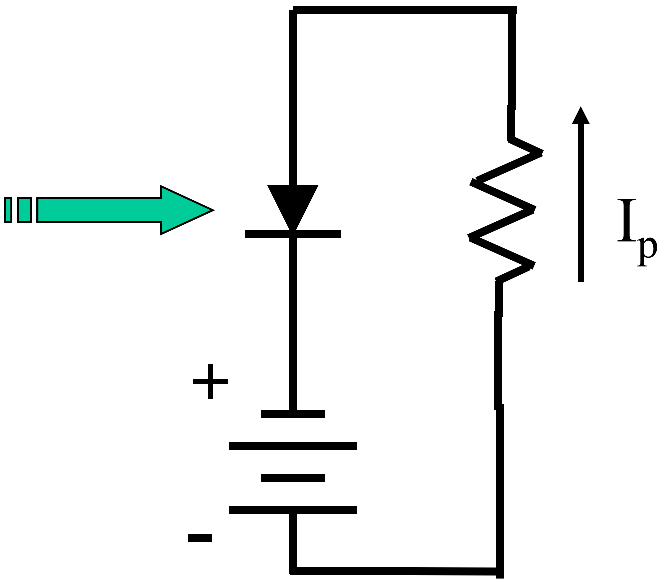
- Reverse bias improves time response and linearity
- Reverse bias induces "dark" current, which then leads to excess shot noise
- Unbiased operation requires small load resistance for linearity, but then requires amplification for adequate signal amplitude
- In practice, transimpedance amplifiers are used:
    - 10^3 – 10^8 for low level detection
    - 10^2-10^3 for high speed operation

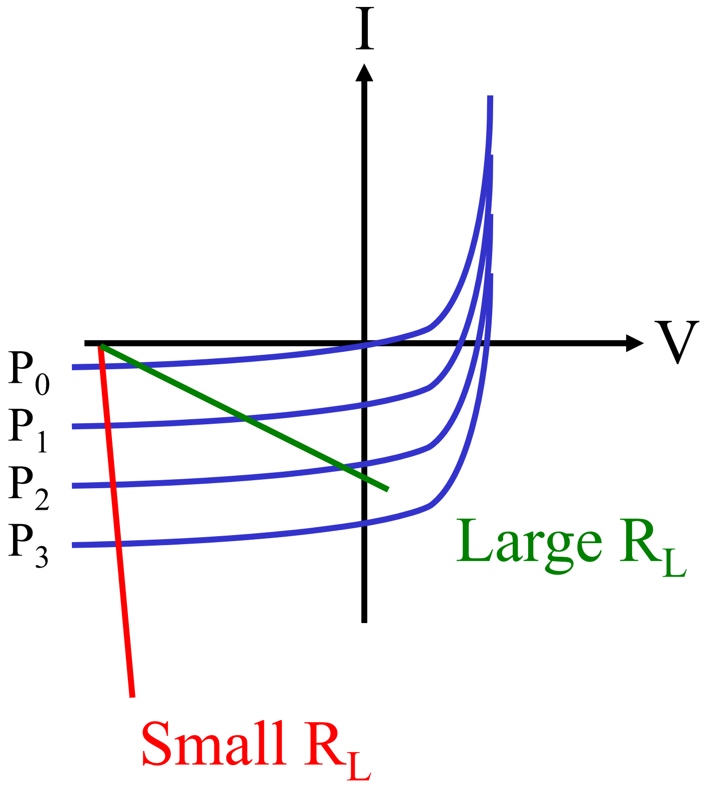
Photovoltaic Operation





Photoconductive Operation





Noise Sources

Thermal noise: $I_{th} = \sqrt{\dfrac{4k_B TB}{R_L}}$

Shot noise: $I_{shot} = \sqrt{2q(I_p + I_d)B}$

1/f noise: Thermally ionized traps, miscellaneous effects

Readout noise: Electronic circuitry associated with arrays

Noise Specifications

Noise Equivalent Power , NEP (W/Hz $^{1/2}$):

The optical power required to generate a signal equal to the noise level.

Depends on wavelength and frequency.

Normalized Detectivity, D* (cm-Hz $^{1/2}$-W $^{-1}$) :

$D \cdot A^{1/2} \cdot B^{1/2} / NEP$

Figure of merit to compare detector materials

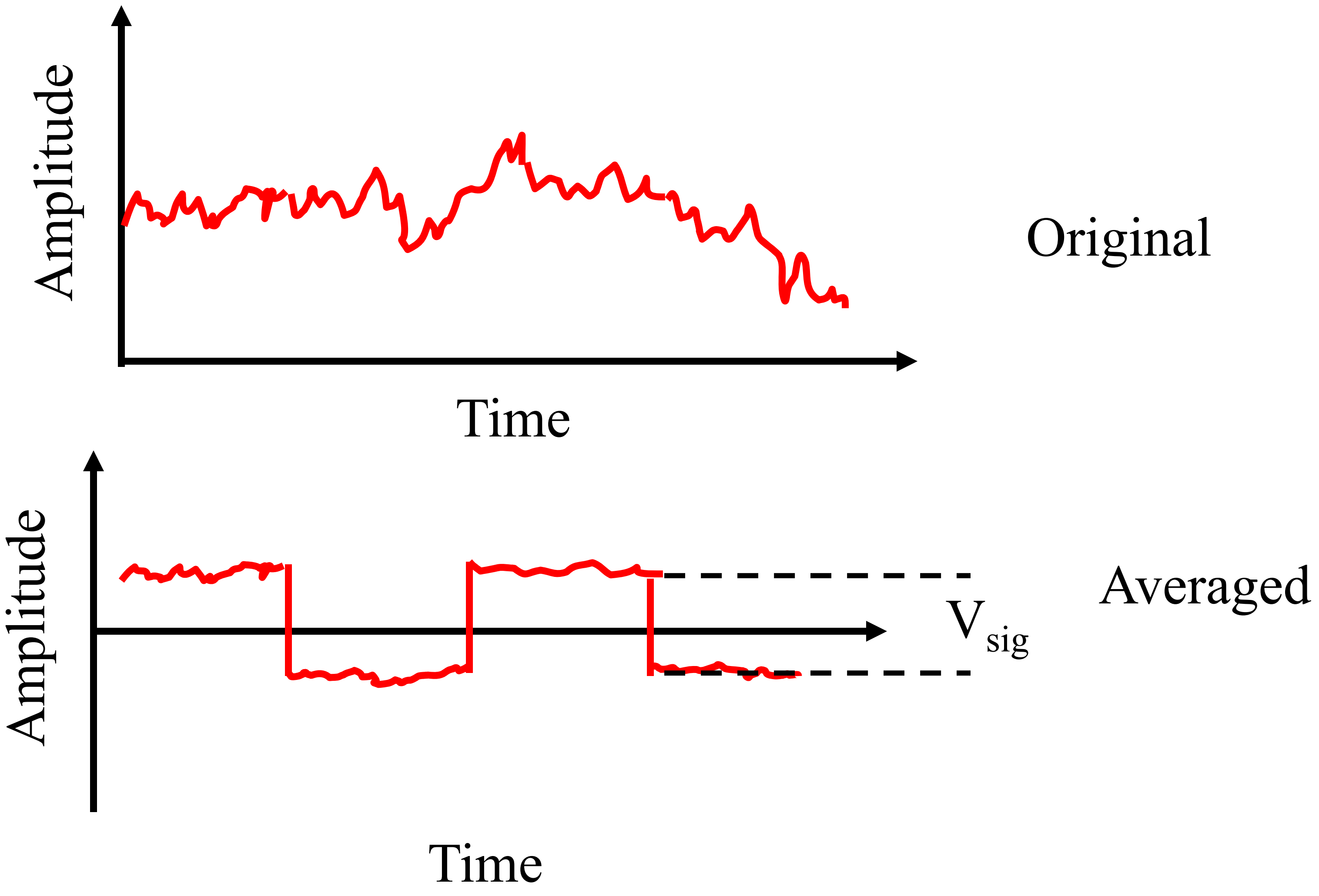
Signal Averaging

$$\frac{SNR_{out}}{SNR_{in}} = \sqrt{\text{Number of samples}}$$

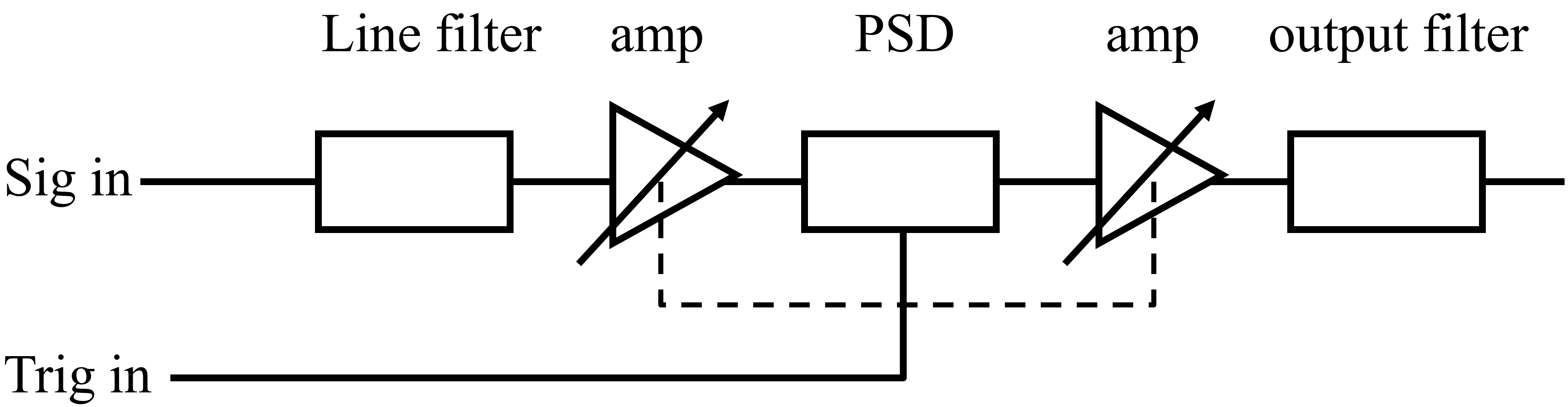
- Time-integrated signal: what “DC” instruments measure
- Example: Optical power meters with adjustable integration time
- Drift in experiment limits amount of averaging possible

  (ambient temperature drift, sample degradation…)

AC Techniques



Lock-in Amplifiers



Line Filters

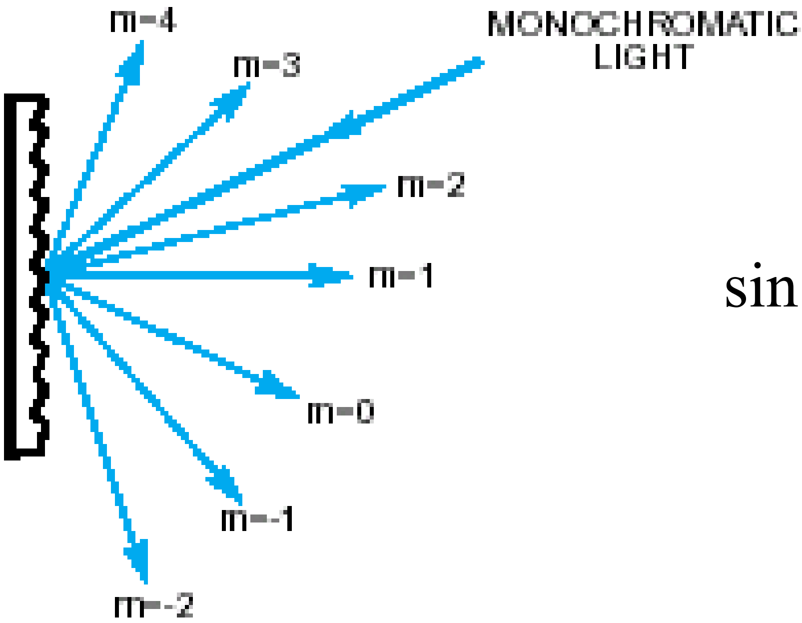
Sensitivity

Phase

Dynamic Reserve

Time Constant

Diffraction Gratings



$$\sin\theta_i + \sin\theta_d = m\frac{\lambda}{a}$$

- Ruled gratings: up to 1200 lines/mm (a = 0.83 μm)
- Holographic gratings: 1200-3600 lines/mm

Resolution

Linear Dispersion: $$\frac{dL}{d\lambda} = \frac{fm}{a\cos\theta_d}$$

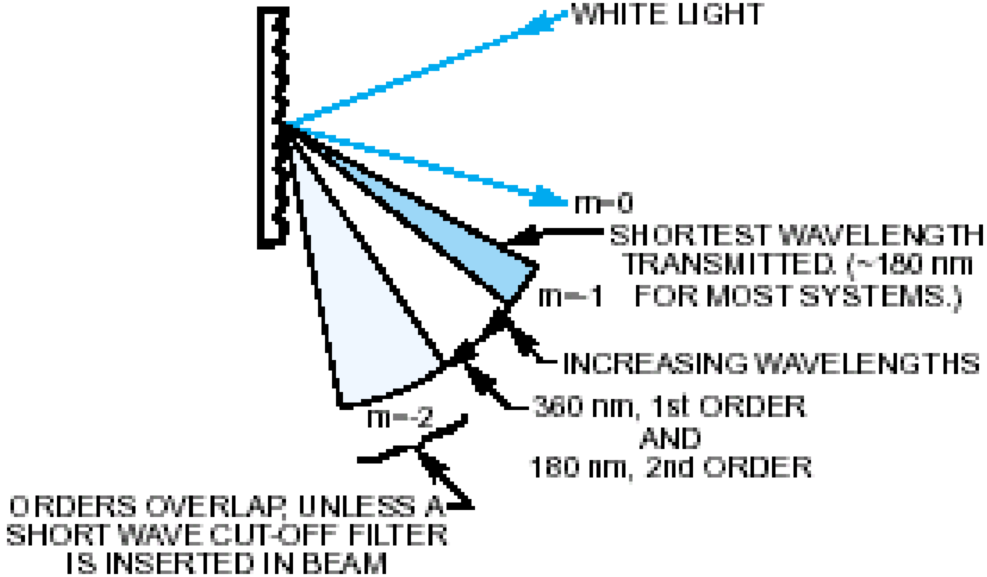
Slit-limited resolution: $$\Delta\lambda = \frac{\text{slit width}}{\text{linear dispersion}}$$

Pixel-limited resolution: $$\Delta\lambda = \frac{\text{1-3 times pixel width}}{\text{linear dispersion}}$$

Resolving Power: $$R = \frac{\lambda}{\Delta\lambda} = \frac{W\left(\sin\theta_i + \sin\theta_d\right)}{\lambda}$$

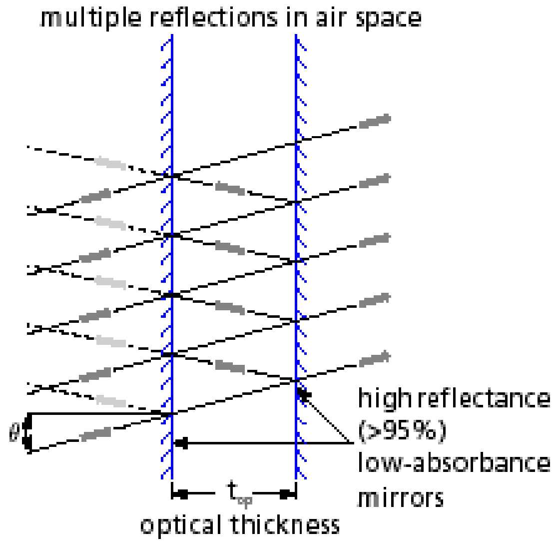
Aberration-limited resolution: coma ~ NA^3

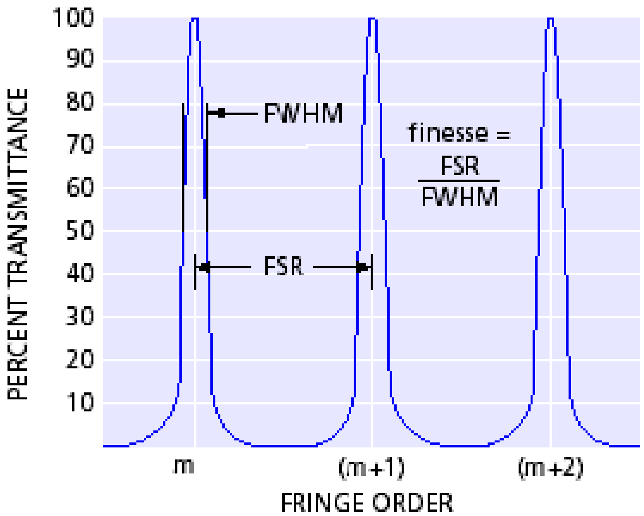
Free Spectral Range



- Spectra from different diffraction orders can overlap
- Use optical filters to narrow spectral range to single order
- Order 0 has no dispersion: useful for alignment

Fabry Perot Interferometer





$$\Delta\lambda_{1/2} = \frac{\lambda^2}{2\pi nl}\frac{1-R}{\sqrt{R}} \qquad FSR = \frac{\lambda^2}{2nl}$$

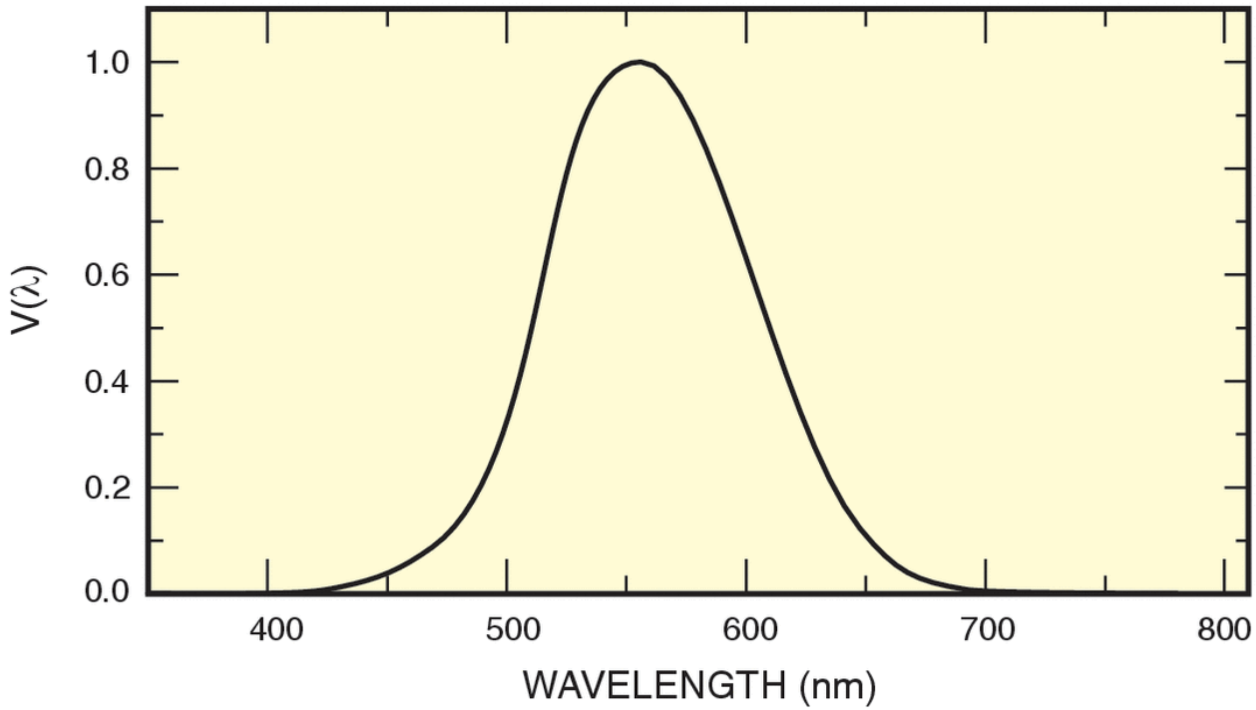
- Vary gap width to scan resonant wavelength
- Cascade 2nd FPI or grating monochromator for higher FSR

Terminology

Radiometric	**Spectral**	**Photometric**
Power (Watts)	Spectral Density (Watts-nm^{-1})	Luminous Flux (Lumens)
Irradiance (W-m^{-2})	Spectral Irradiance (W-m^{-2}-nm^{-1})	Illuminance (Lux=Lumens-m^{-2})
Radiant Intensity (W-sr^{-1})	Spectral Intensity (W-sr^{-1}-nm^{-1})	Luminous Intensity (Candela=Lumens-sr^{-1})
Radiance (W-m^{-2}-sr^{-1})	Spectral Radiance (W-m^{-2}-sr^{-1}-nm^{-1})	Luminance (nit=Lumens-m^{-2} –sr^{-1})

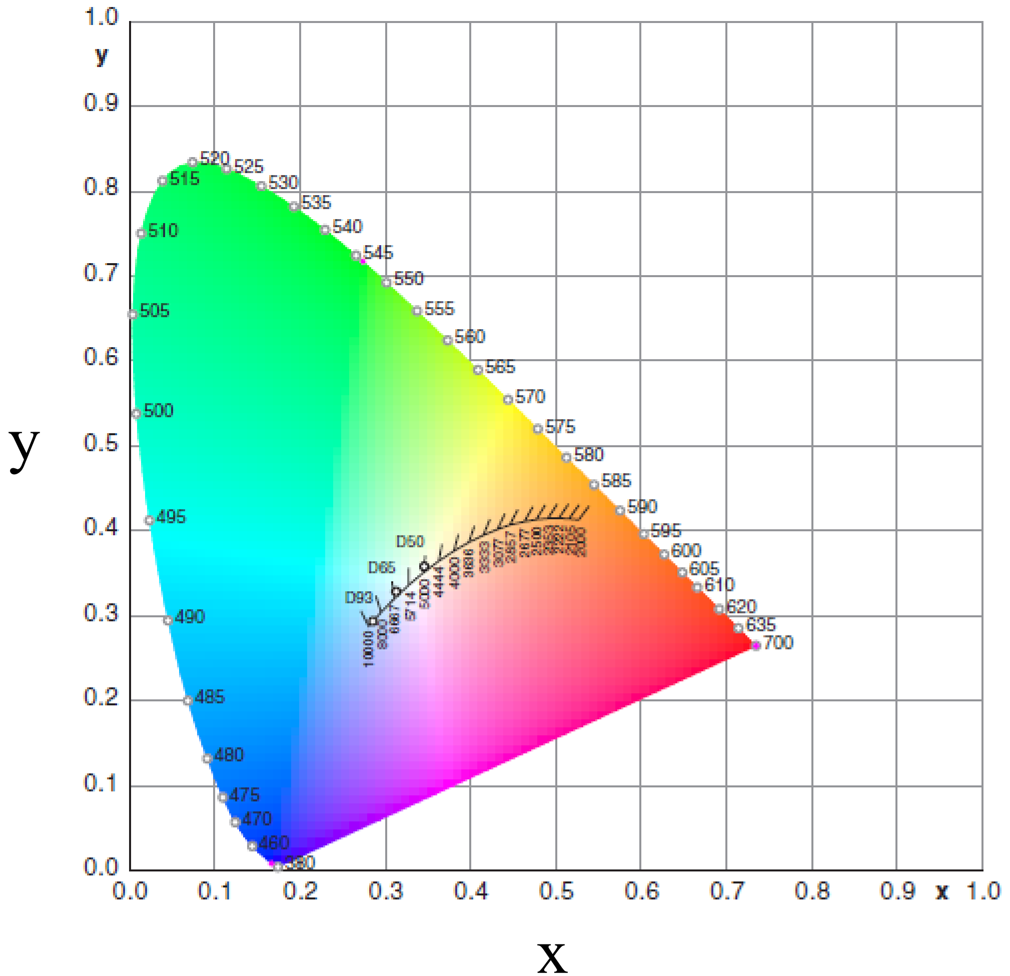
Normalized Eye Response

1924 CIE Spectral Luminous Efficiency Function



$$Luminance = \left(683\,Lumens/Watt\right)\int Radiance(\lambda)\bullet V(\lambda)\,d\lambda$$

Chromaticity Diagram



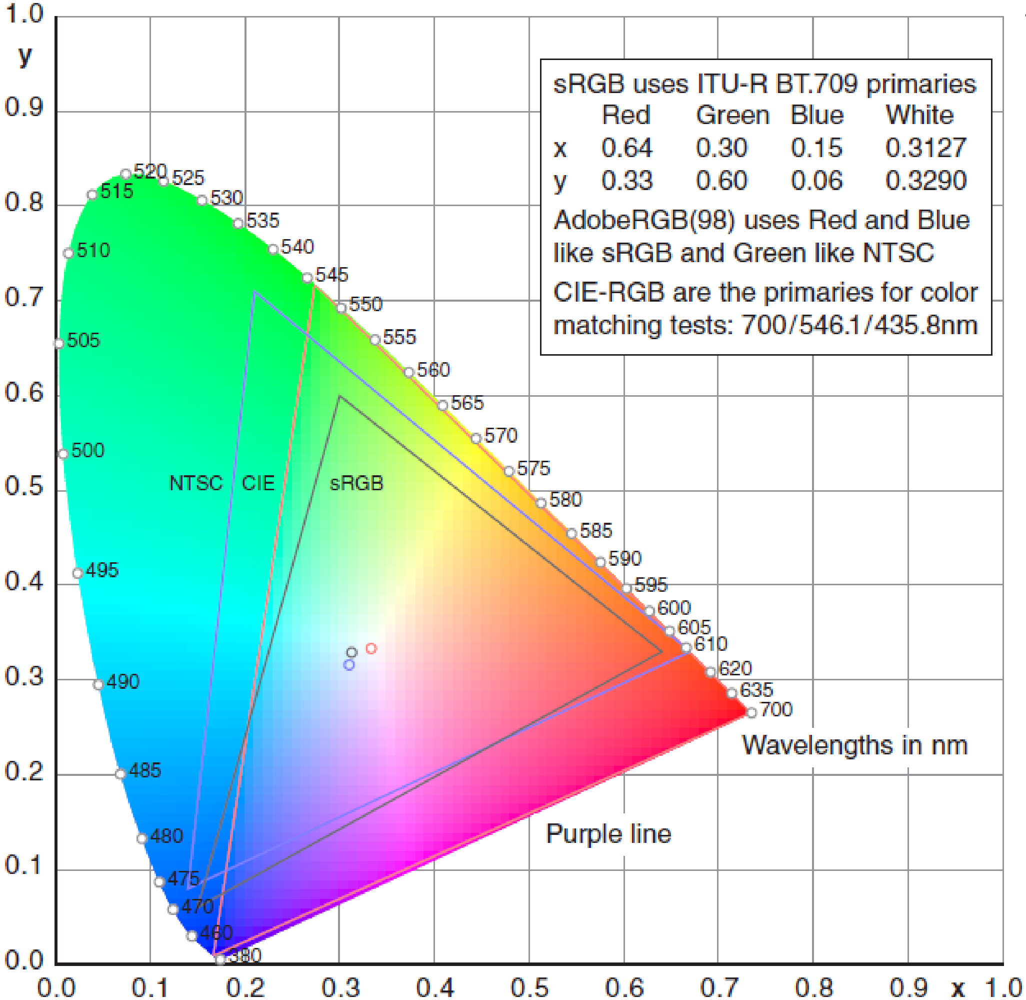
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

- X=tristimulus value

  x = color coordinate

Color Gamut



- Gamut = range of colors
- This display does not show full CIE 1931 gamut
- Various standards shown
- Various others proposed

Plankian Locus in (u’,v’) Diagram

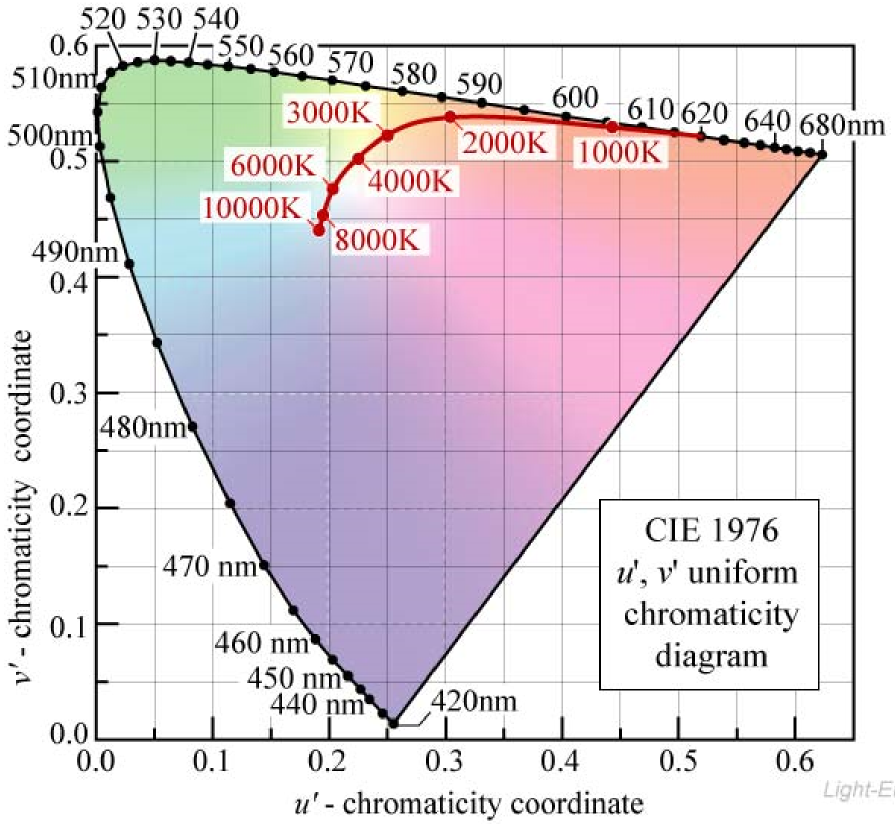


Fig. 18.4. CIE 1976 (u', v') uniform chromaticity diagram calculated using the CIE 1931 2° standard observer and planckian locus.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Color Difference in (u',v')

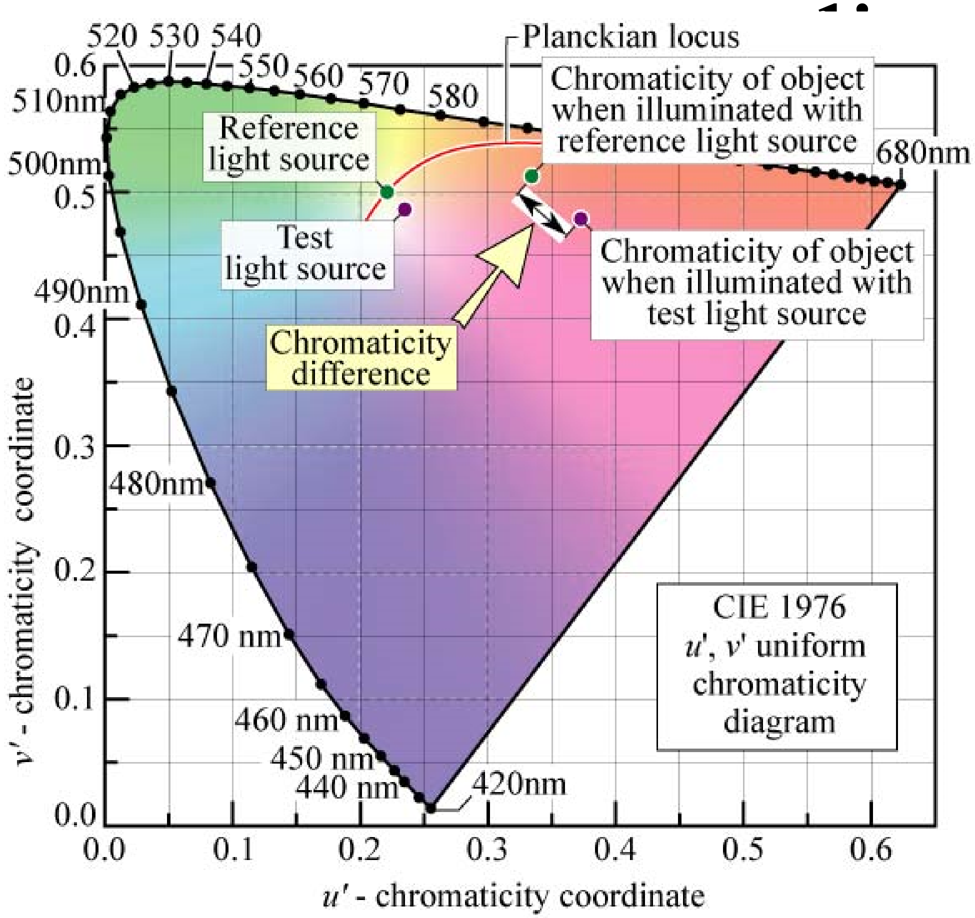


Fig. 19.6. Chromaticity difference resulting from the illumination of an object with a reference and a test light source. In the CIE 1976 *u*', *v*' uniform chromaticity diagram, the color difference is directly proportional to the geometric distance. The reference light source is located on the planckian locus at the correlated color temperature of the test light source.

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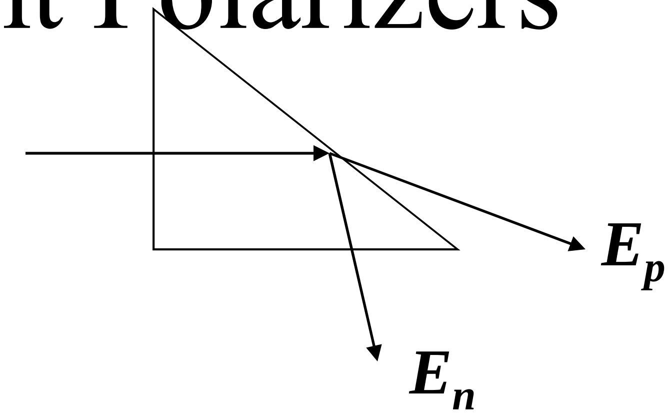
Polarizers

- Birefringent
  - Polarization- dependent refractive index
  - Redirects one polarization component
- Dichroic
  - Polarization-dependent absorption
  - Absorbs one polarization component

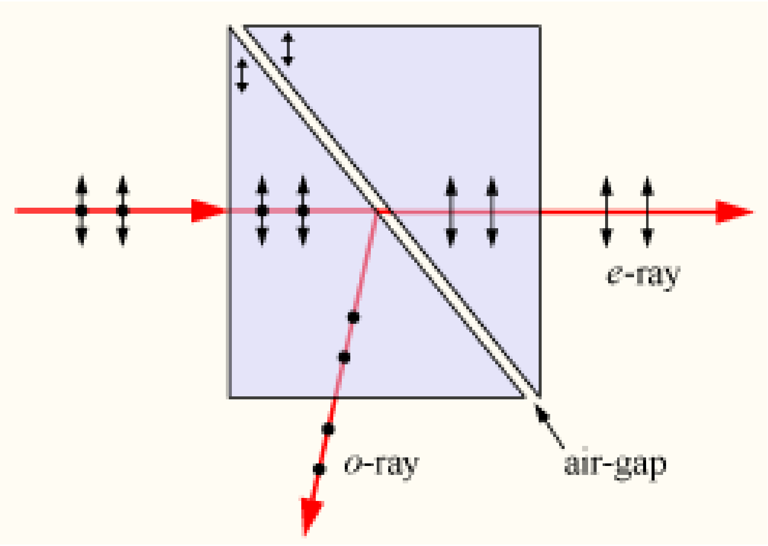
Birefringent Polarizers

$\boldsymbol{E_n}$ undergoes total internal reflection, $\boldsymbol{E_p}$ does not.



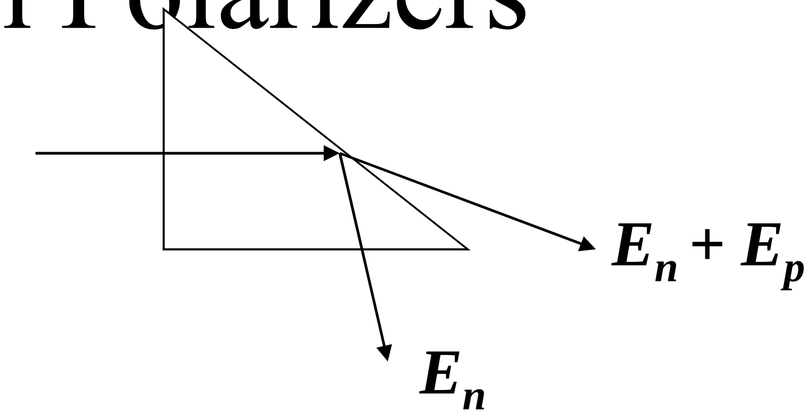
Glan Taylor Polarizer

2nd prism straightens beam



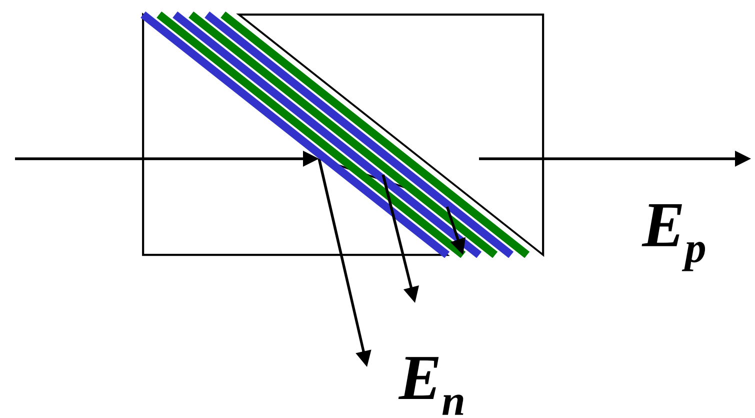
Reflection Polarizers

Brewster's angle: $R_p = 0$

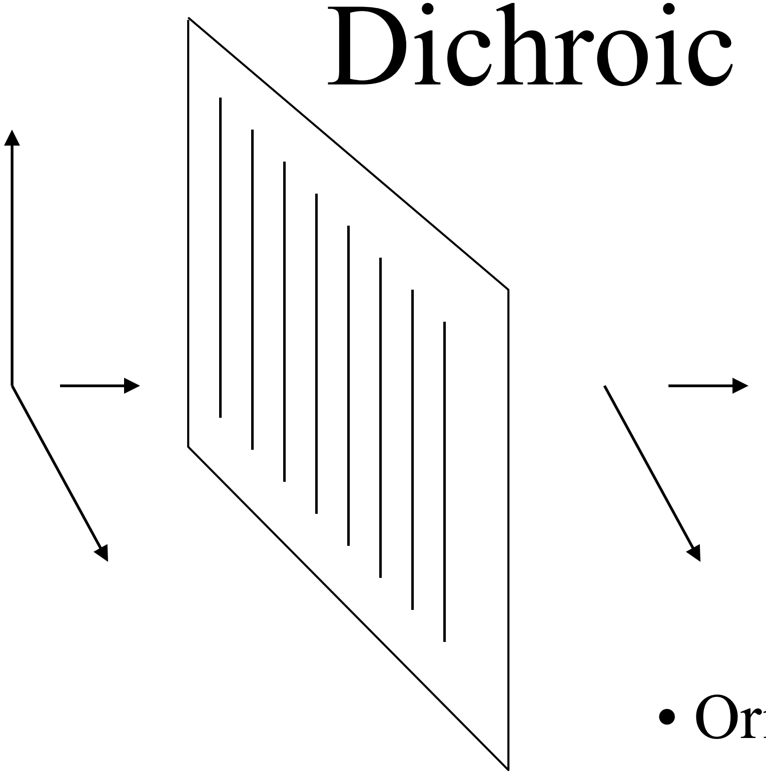


Dielectric stack

Polarizing beamsplitter cube

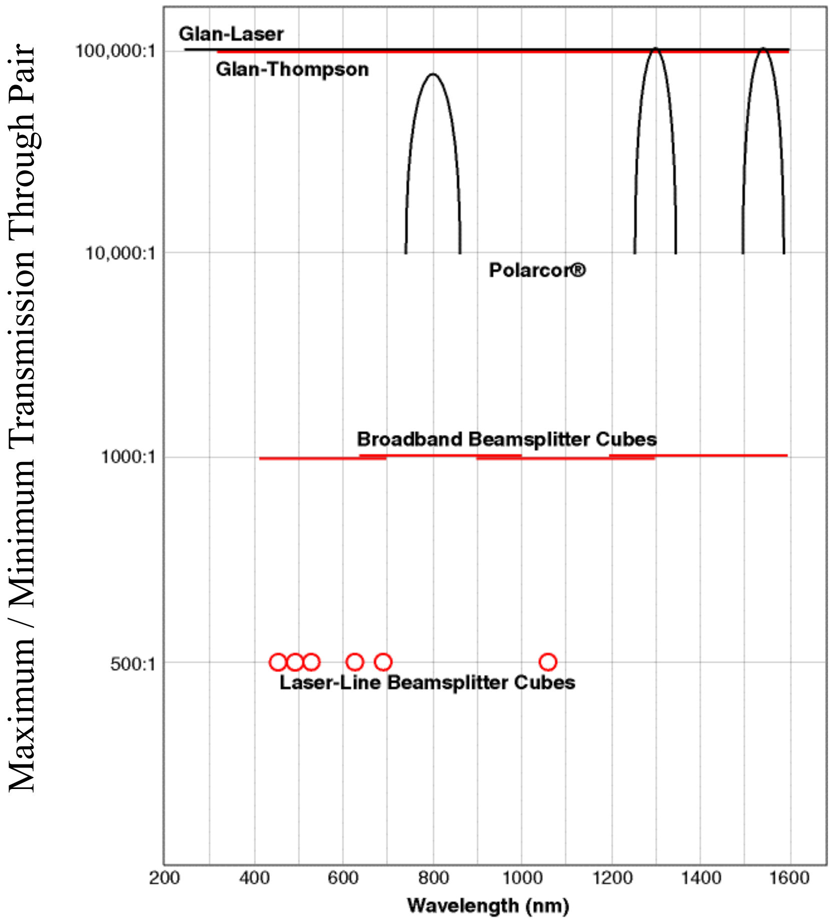


Dichroic Polarizers



- Oriented molecules or nanoparticles
- Absorption depends on field direction
- Example: polaroid lenses

Extinction Ratio



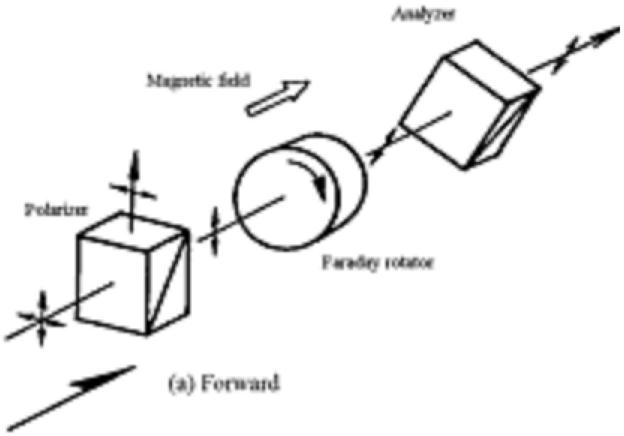
Extinction ratio measured with pair of polarizers aligned for max. then min. transmission

Malus' Law:

$I = I_0 \cos^2\theta$

where θ is angle between polarizers

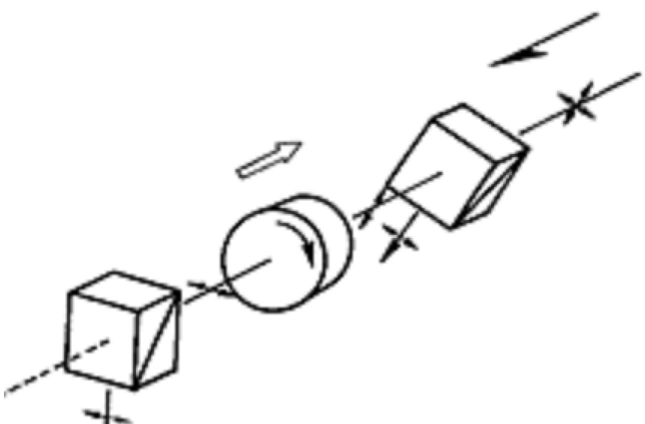
Faraday Isolator Operation



(a) Forward

Forward direction:

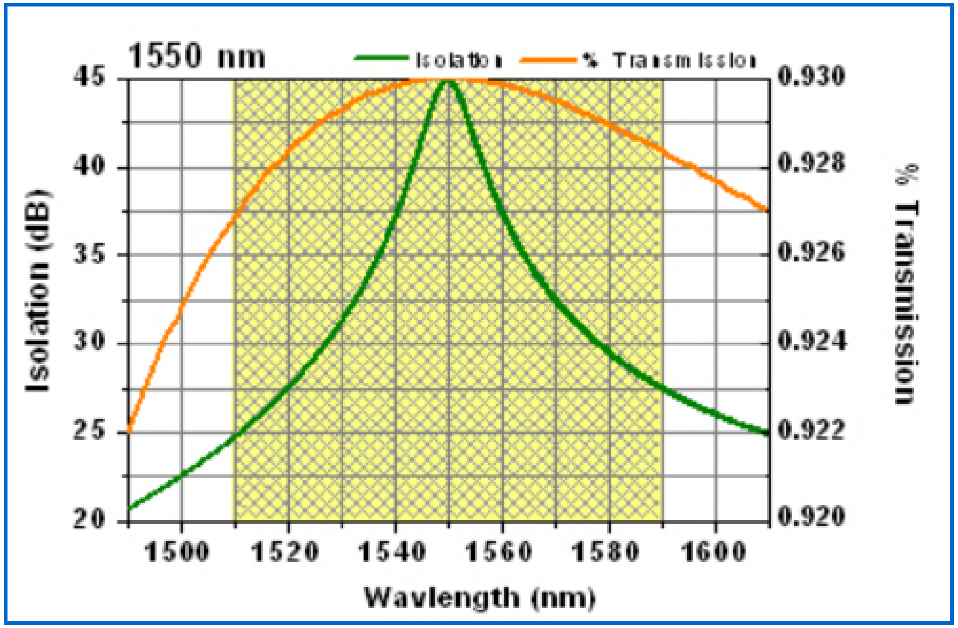
- Input polarizer selects linear component
- Faraday rotator rotates E field 45º
- Output polarizer oriented to pass 45º beam


(b) Backward

Reverse direction:

- Output polarizer selects linear component
- Faraday rotator adds <u>additional</u> 45º
- Input polarizer blocks backward transmission

Isolator Performance

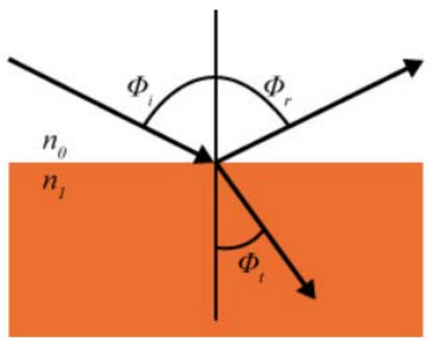


- Faraday rotation is dispersive
- Tune via magnetic field
- Compensate with quartz plate

Item#	Wavelength[a]	Max Power	Isolation	Insertion Loss	PDL	PER[b]	Return Loss	Fiber
250 - 300 mW Polarization-Independent Fiber Isolators								
IO-H-1064	1064 +20/-4 nm	250 mW	≥33 dB[c]	1.4 - 2.0 dB	≤0.20 dB	–	>55 dB	HI1060
IO-H-1310	1310 ± 15 nm	300 mW	35 - 40 dB	0.3 - 0.7 dB	≤0.1 dB	–	>55 dB	SMF-28e
IO-H-1550	1550 ± 15 nm	300 mW	35 - 40 dB	0.3 - 0.7 dB	≤0.1 dB	–	>55 dB	SMF-28e

Snell's Law and Fresnel Equa

$$n_0 \sin(\Phi_i) = n_1 \sin(\Phi_t)$$



$$r_s = \left(\frac{E_{0r}}{E_{0i}}\right)_s = \frac{n_i \cos(\Phi_i) - n_t \cos(\Phi_t)}{n_i \cos(\Phi_i) + n_t \cos(\Phi_t)}$$

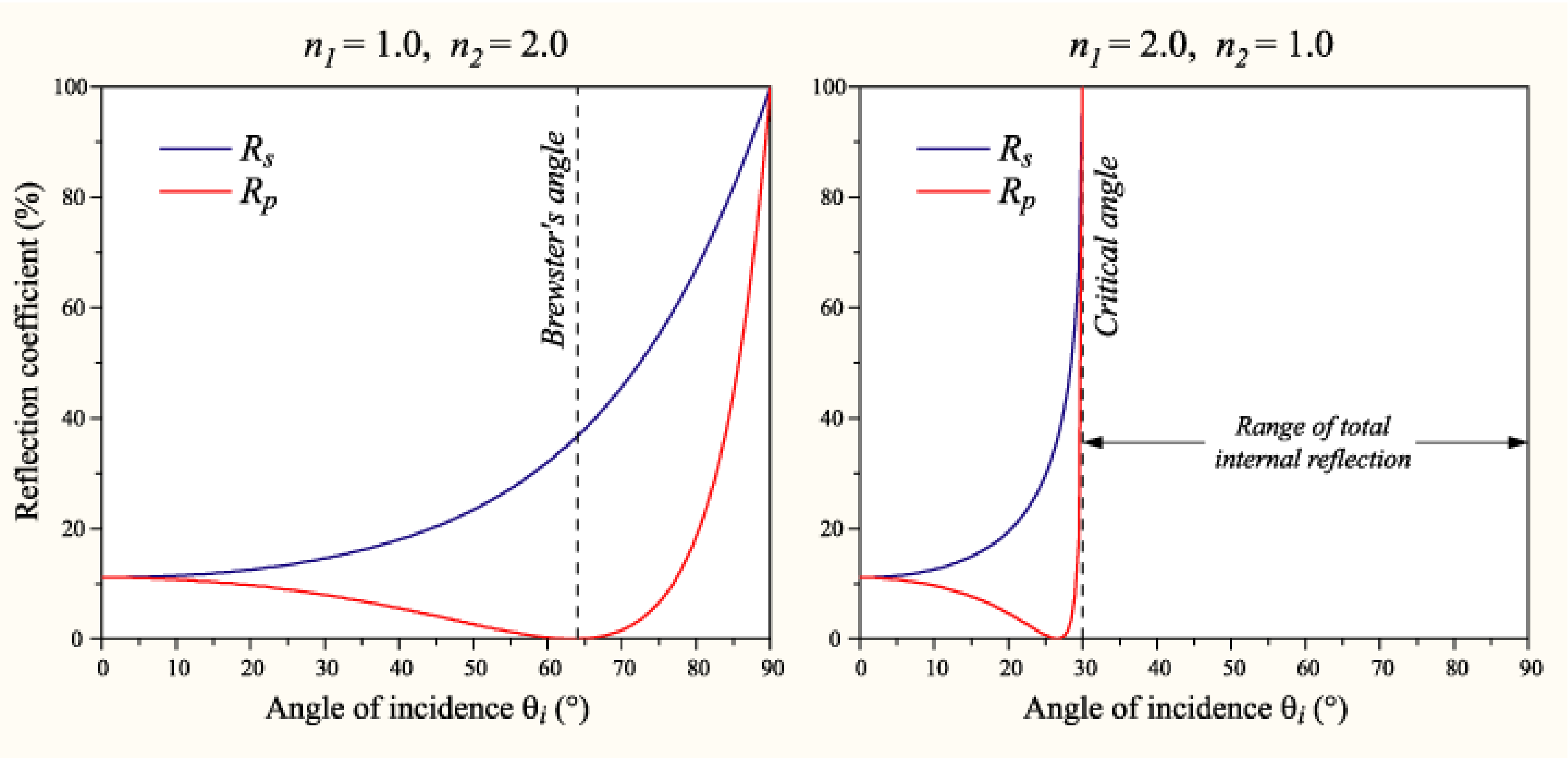
$$r_p = \left(\frac{E_{0r}}{E_{0i}}\right)_p = \frac{n_t \cos(\Phi_i) - n_i \cos(\Phi_t)}{n_i \cos(\Phi_t) + n_t \cos(\Phi_i)}$$

$$t_s = \left(\frac{E_{0t}}{E_{0i}}\right)_s = \frac{2 n_i \cos(\Phi_i)}{n_i \cos(\Phi_i) + n_t \cos(\Phi_t)}$$

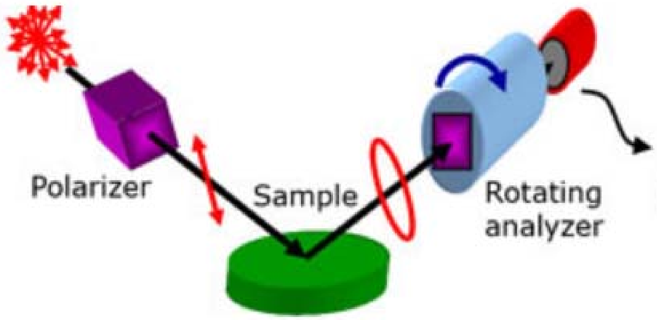
$$t_p = \left(\frac{E_{0t}}{E_{0i}}\right)_p = \frac{2 n_i \cos(\Phi_i)}{n_i \cos(\Phi_t) + n_t \cos(\Phi_i)}$$

- Govern magnitude and phase of reflection or transmission
- Complex: magnitude and phase
- "plane of incidence" defined by incident and reflected beams
- "p-polarization" in the plane of incidence; "s- or n-pol" is ⊥

Fresnel Equations Graphed



Ellipsometry



Complex reflectance ratio, ρ

$$\rho = \frac{\tilde{r}_p}{\tilde{r}_s} = \tan(\Psi)\exp(i\Delta)$$

- Illuminate with linear polarization at an angle to surface
- Choose angle of incidence and polarization for max sensitivity
- Measure ellipticity of reflected beam, then calculate ρ

Model Fitting

- In general, ρ cannot be inverted to obtain optical constants
- Build model and fit to data

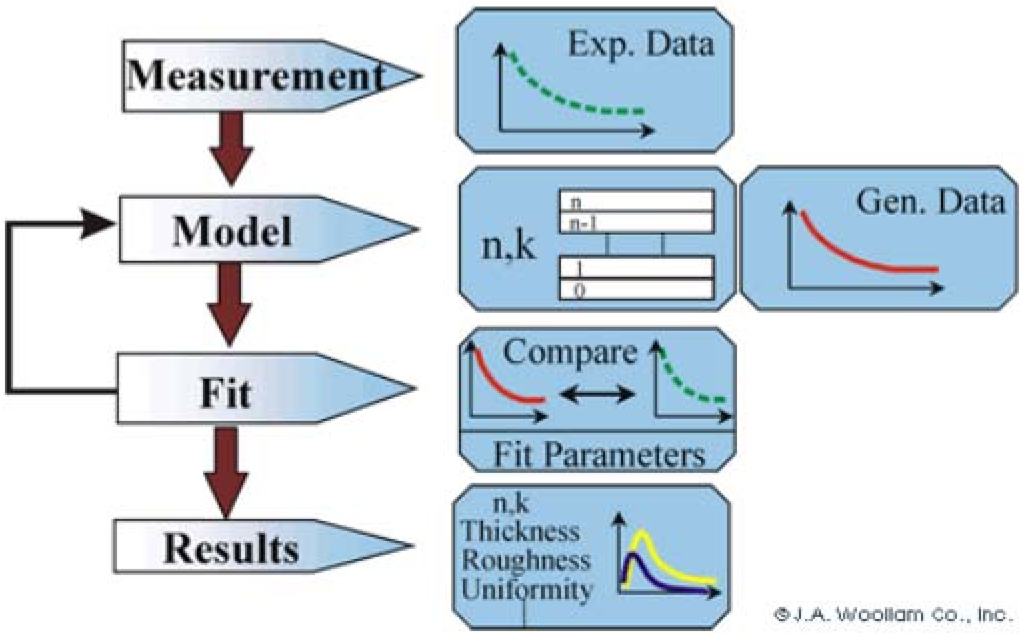


Figure 10 Flowchart for ellipsometry data analysis.

Common Material Models

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$$

- Cauchy: Purely empirical, diverges at short λ

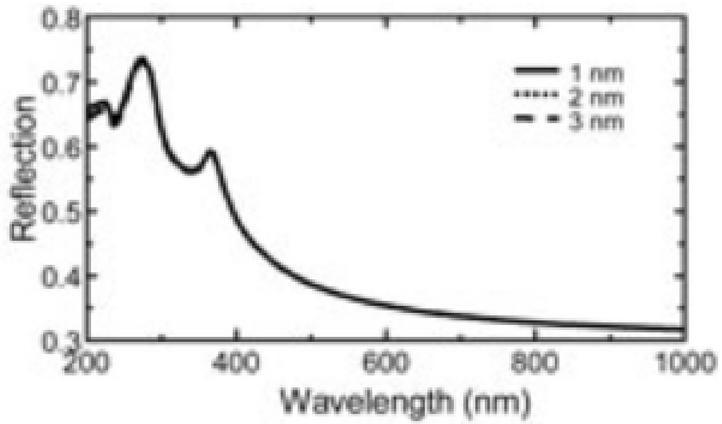
$$\varepsilon_1 = \frac{A\lambda^2 \lambda_0^2}{(\lambda^2 - \lambda_0^2)}$$

- Sellmeir: K-K consistent, but diverges at band edge

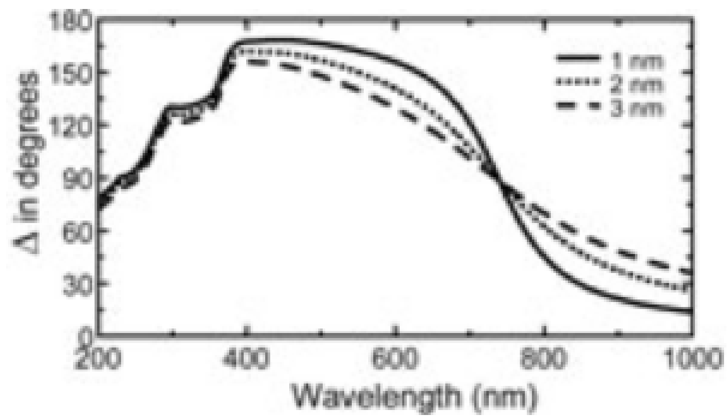
$$\varepsilon_{1,\text{offset}} + \frac{AE_c}{E_c^2 - E^2 - \mathrm{i}BE}$$

- Lorentz Oscillator: Some physical basis and reasonable response above band edge

Thickness Sensitivity



Power Reflectivity



Phase, Δ

- Δ can be measured precisely, and is sensitive to small film changes
- Measures thickness to 0.1nm; n to 0.005; k to 1E-3 (α~250 cm^{-1})