Thin Film Optics

- Physics of thin film optics
- Important spectral features
- BaCuSF data

BaCuSF film made by Hiroshi Yanagi, Sang Moon Park

Spectra taken by Levi Kilcher

Spectrometer built by Ross Brody, Derek Tucker

Talk given to TCO group 3-11-02

Optics basics

$$E = E_0 e^{i\omega\left(t - \frac{n_c x}{c}\right)} \left[= E_0 e^{i(\omega t - kx)}\right]$$

k wave vector

$$n_c = n_r + i n_i = n - ik$$

$$E = E_0 e^{i\omega\left(t - \frac{nx}{c}\right)} e^{-\left(\frac{\omega k}{c}\right)x}$$

$$I = I_0 e^{-\alpha x} \Rightarrow \alpha = \frac{2\omega k}{c} = \frac{4\pi k}{\lambda}$$

$$\varepsilon = \varepsilon_1 - i\varepsilon_2$$

$$\varepsilon = n_c^2$$

$$\varepsilon_1 = n^2 - k^2$$

$$\varepsilon_2 = 2nk$$

n = index of refraction

α = absorption coefficient

k = extinction coefficient

ε = dielectric constant

Unfortunate double use of k as wave vector and as extinction coeff

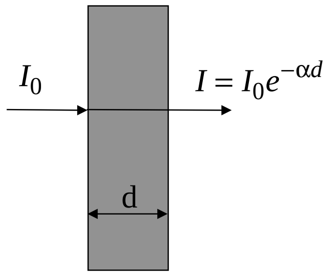
Sign of ik in n_complex depends on sign of wt-kx

Optical properties depend on 2 quantities (n, k) so generally need to measure 2 things (R,T for us, phase & amp for ellipsometry)

But can get from one to the other with Kramer's-Kronig analysis, but need full spectrum.

Absorption

Bulk sample



$x =$ thruput

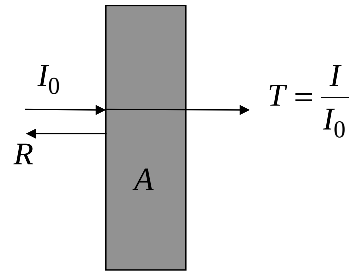
$A =$ absorption

$$x = \frac{I}{I_0} = e^{-\alpha d}$$

$$x + A = 1$$

$$x = 1 - A$$

Real sample with surfaces



$$R + T + A = 1$$

$$x \overset{?}{=} 1 - A = 1 - (1 - R - T)$$

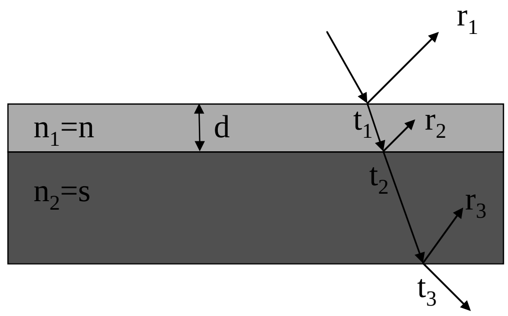
$$x \overset{?}{=} R + T$$

$$@\alpha \to \infty \begin{cases} T = 0 \\ x \neq R \end{cases}$$

Normal idea of absorption used when bulk sample absorbs, for which A+x=1. This leads one to conclude that x=1-A. If this is now applied to the case of a real sample with surfaces, then one gets x=R+T, which is not correct. X should only relate to how much light is absorbed in single pass through a slab of material, but R+T includes info about what happens at each surface and also has info about multiple passes.

We have often taken Tfilm/Tsub to get absorption, which accounts for reflection and absorption of substrate (but not reflection of film)

Thin Film on substrate



$$R_1 = r_1^2 = \frac{(n-1)^2}{(n+1)^2}$$

$$R_2 = r_2^2 = \frac{(n-s)^2}{(n+s)^2}$$

- polarization
- angle

Formulas are for normal incidence. At and angle the reflection and transmission coeffs depend upon angle and polarization of light.

Surface reflection and transmission

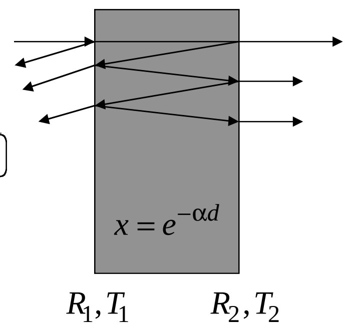
n_1	n_2	R	T
1	1.5	0.04	0.96
1.5	2.5	0.063	0.937
1	2.5	0.184	0.816

R & T for real sample(no fringes)

surface coeffs

$$R = R_1 + \frac{x^2 T_1^2 R_2}{1 - x^2 R_1 R_2}$$

multiple bounces



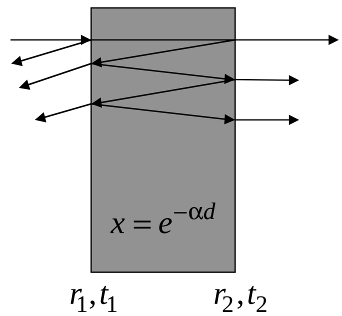
surface coeffs

$$T = \frac{x T_1 T_2}{1 - x^2 R_1 R_2}$$

multiple bounces

These coeffs are for case where we can neglect fringes from interference. This is case if film (or substrate) is thicker than the coherence length of the light.

R & T for real sample(w/ fringes)



$$\delta = 2\pi \frac{d}{\lambda/n} 2 = \frac{4\pi n d}{\lambda}$$

$$R = \left| -r_1 + \frac{x e^{-i\delta} t_1 t_1' r_2}{1 - x e^{-i\delta} r_1 r_2} \right|^2$$

$$T = \left| \frac{\sqrt{x}\, t_1 t_2}{1 - x e^{-i\delta} r_1 r_2} \right|^2$$

$$R = \frac{r_1^2 + x^2 r_2^2 - 2 x r_1 r_2 \cos\delta}{1 + x^2 r_1^2 r_2^2 - 2 x r_1 r_2 \cos\delta}$$

$$T = \frac{x t_1^2 t_2^2}{1 + x^2 r_1^2 r_2^2 - 2 x r_1 r_2 \cos\delta}$$

Deduce Abs Coeff from R & T

$$R = \frac{r_1^2 + x^2 r_2^2 - 2x r_1 r_2 \cos\delta}{1 + x^2 r_1^2 r_2^2 - 2x r_1 r_2 \cos\delta} \qquad T = \frac{x t_1^2 t_2^2}{1 + x^2 r_1^2 r_2^2 - 2x r_1 r_2 \cos\delta}$$

$$1 - R = \frac{\left(1 - r_1^2\right)\left(1 - x^2 r_2^2\right)}{1 + x^2 r_1^2 r_2^2 - 2x r_1 r_2 \cos\delta} \qquad T = \frac{x\left(1 - r_1^2\right)\left(1 - r_2^2\right)}{1 + x^2 r_1^2 r_2^2 - 2x r_1 r_2 \cos\delta}$$

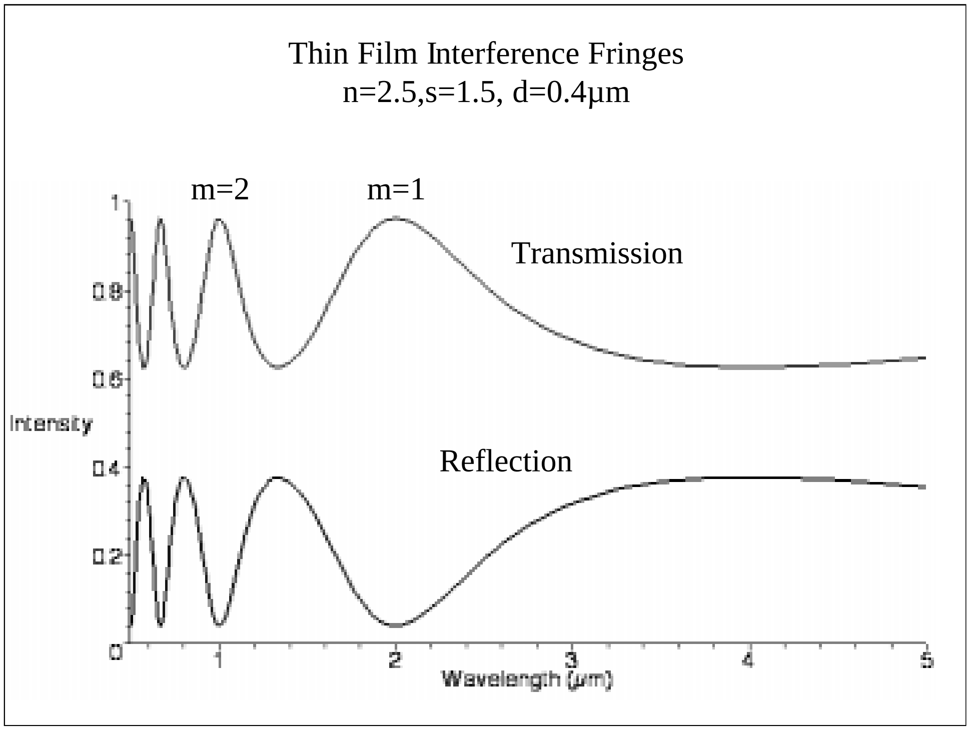
$$\frac{T}{1-R} = \frac{x\left(1 - r_1^2\right)\left(1 - r_2^2\right)}{\left(1 - r_1^2\right)\left(1 - x^2 r_2^2\right)}$$

$$\frac{T}{1-R} = x \frac{\left(1 - r_2^2\right)}{\left(1 - x^2 r_2^2\right)}$$

Transmission normalized to what it “should” have been

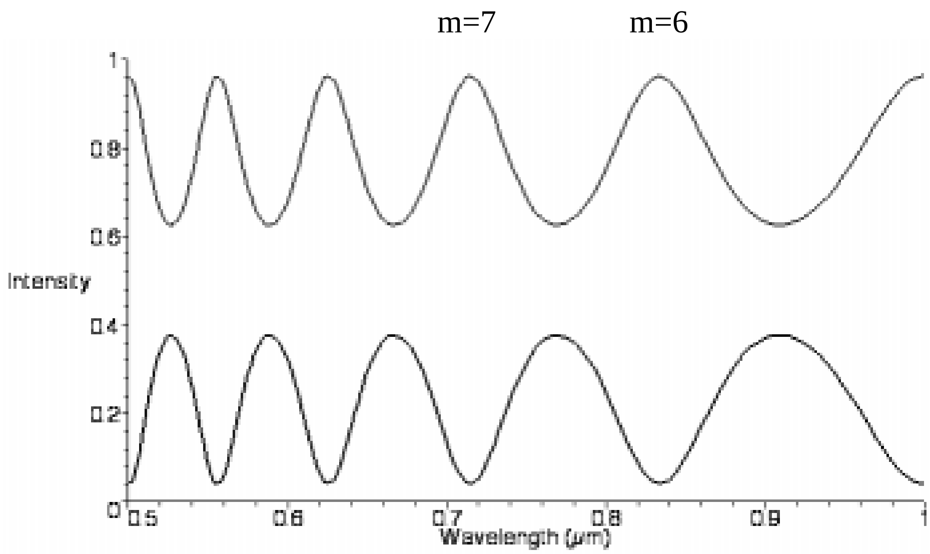
“should” have means without reflection from front surface of film,

technique also gets rid of fringes, which is important for small energy gaps which show up in fringe regime



These are exact calcs from maple sheet. Later compare to approx calcs from Siegman notes

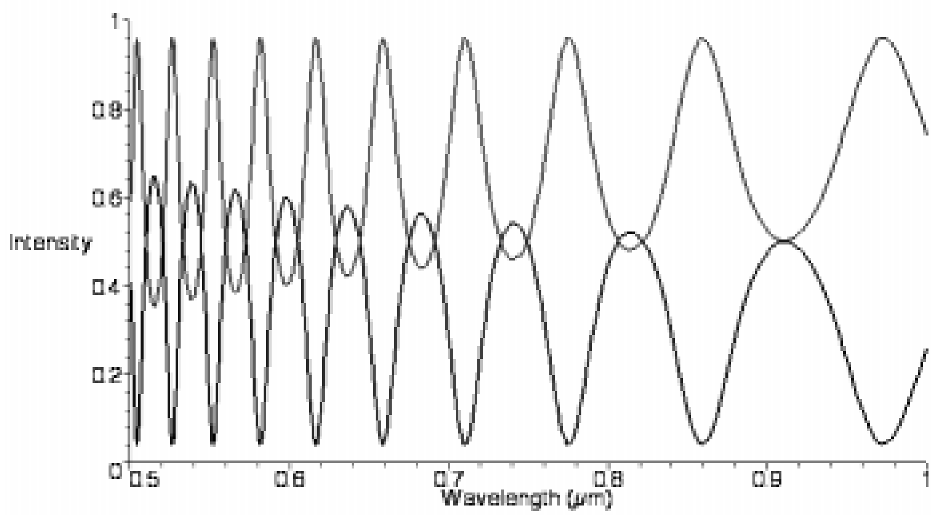
Thin Film Interference Fringes
n=2.5, s=1.5, d=1μm



Dispersion tightens up fringes

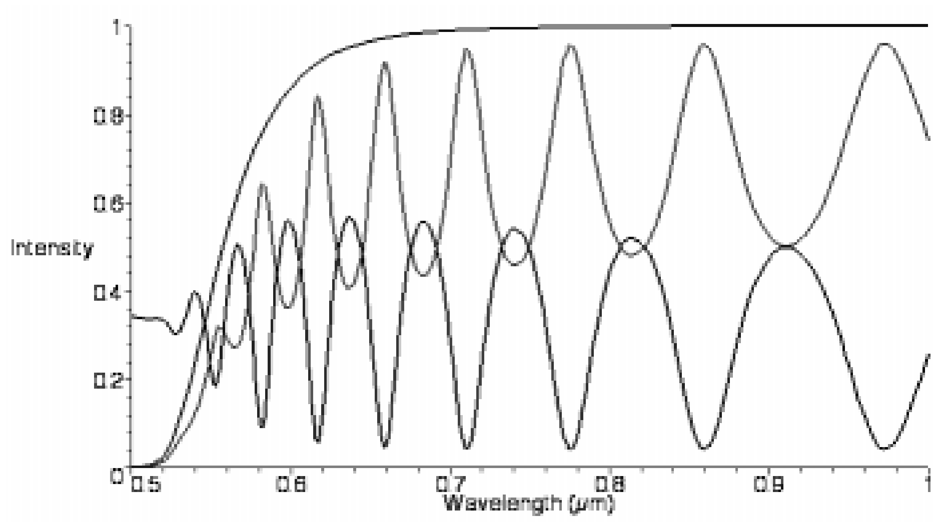
n=2.6+, s=1.51, d=1µm

$$n = 2.6 + \frac{0.3}{\lambda^2}$$

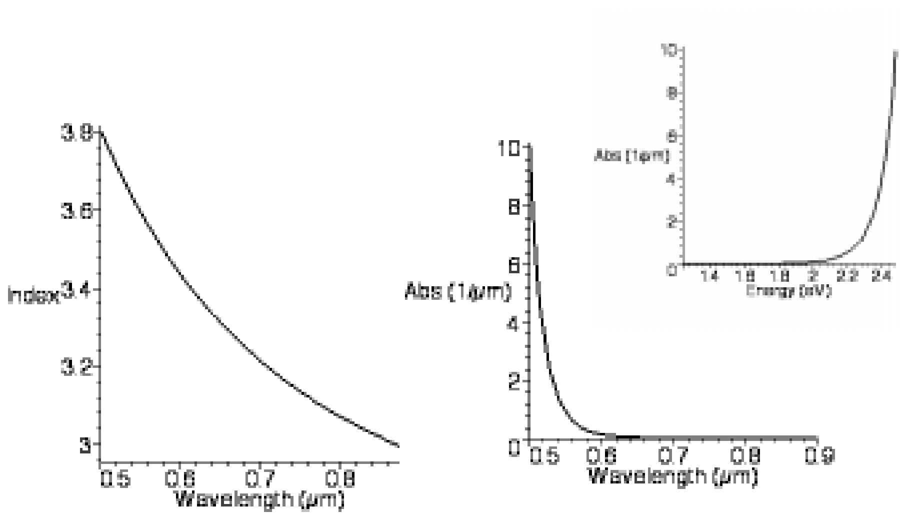


Absorption cuts transmission

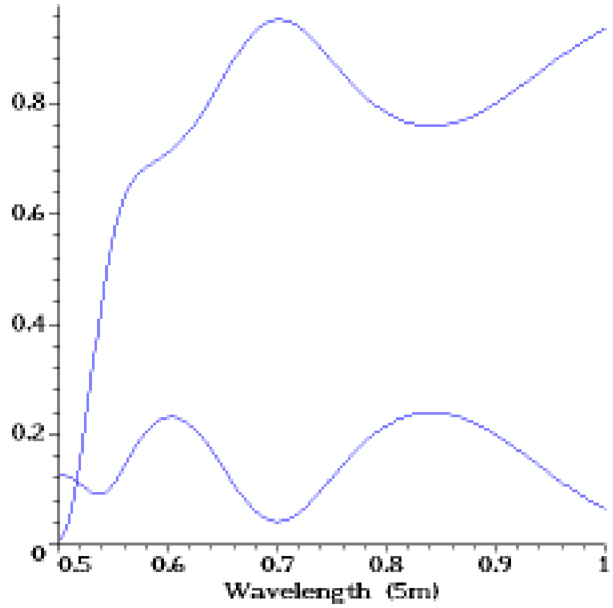
n=2.6+, s=1.51, d=1μm, absorption (blue)



Index, absorption model (amorph Si)



Fringes vs angle



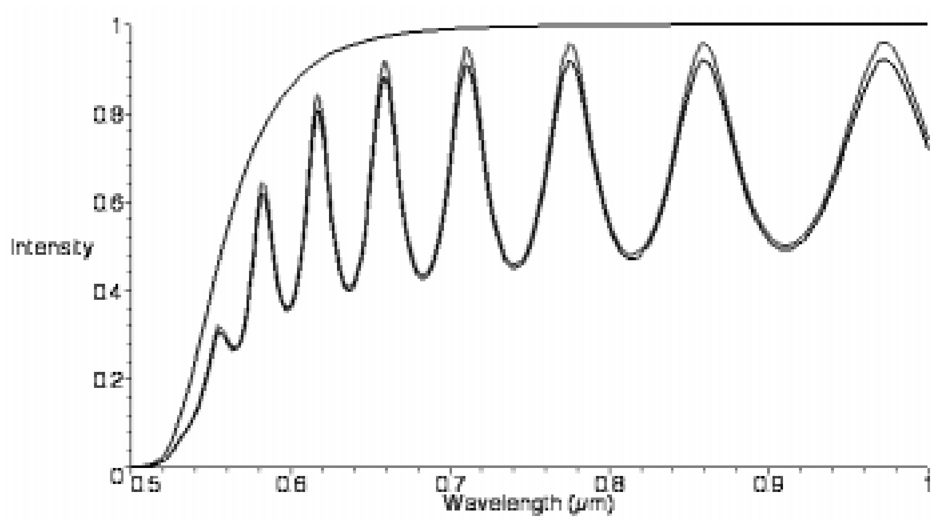
$$\delta = \frac{4\pi n d}{\lambda}\cos\theta_{\text{in film}}$$

$$\sin\theta_{\text{ext}} = n\sin\theta_{\text{in}}$$

$$m\lambda_m(\theta) = 2nd\cos\theta_{\text{in}}$$

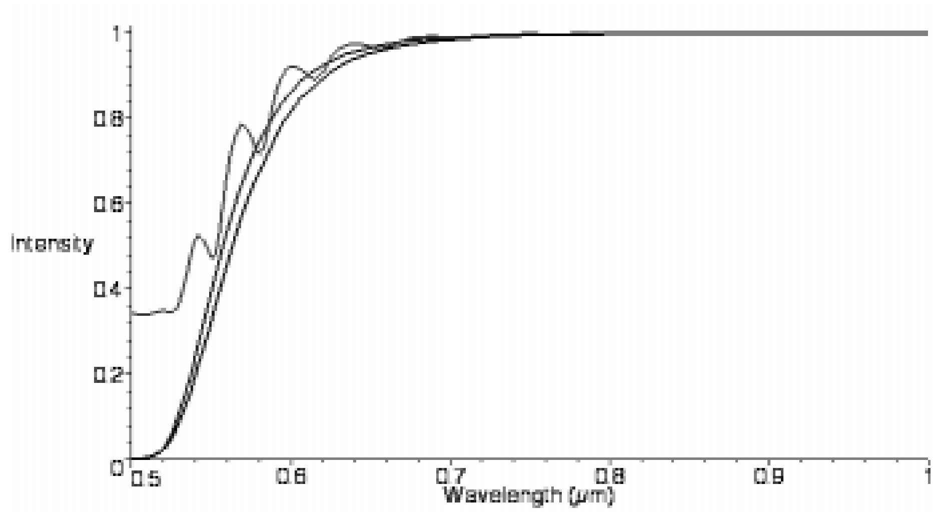
$$\lambda_m(\theta) = \lambda_m(0)\cos\theta_{\text{in}}$$

Effect of ignoring last surface
n=2.6+, s=1.51, d=1μm, absorption (blue)
red=no substrate, black = w/ substrate



see small effect of including reflection of back substrate-air interface (black) vs only film on substrate (no back surface)(red)

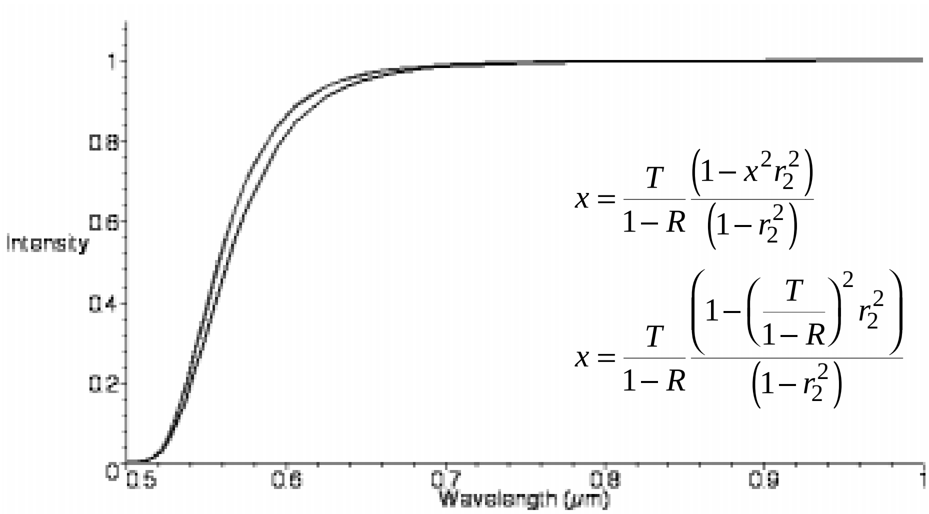
Analysis to find absorption
n =2.6+, s=1.51, d=1µm
blue=abs, red = R+T, black=T/(1-R)



blue is x=exp(-alpha d)

Determine abs
n dispersive, s=1.51, d=1µm
blue=abs, black = T/(1-R), red=expt abs

$$x = e^{-\alpha d}$$

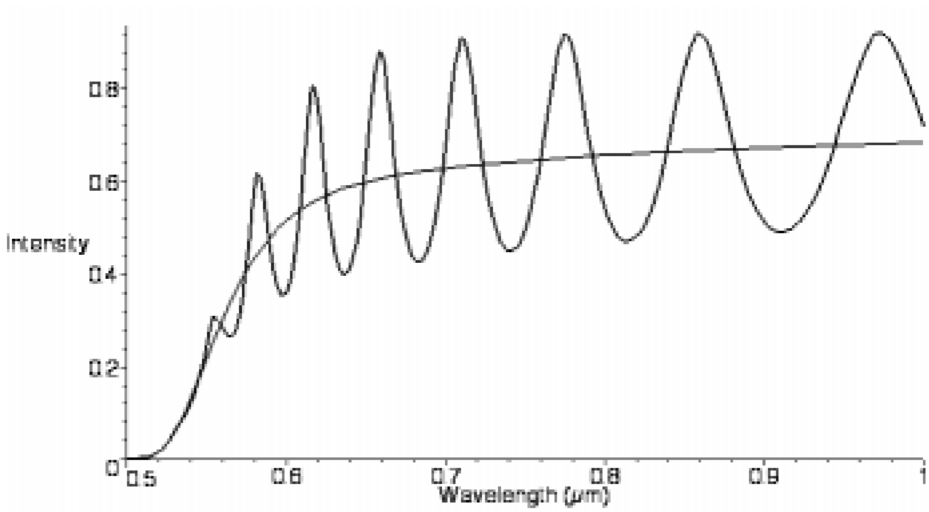


$$x = \frac{T}{1-R}\frac{\left(1-x^2 r_2^2\right)}{\left(1-r_2^2\right)}$$

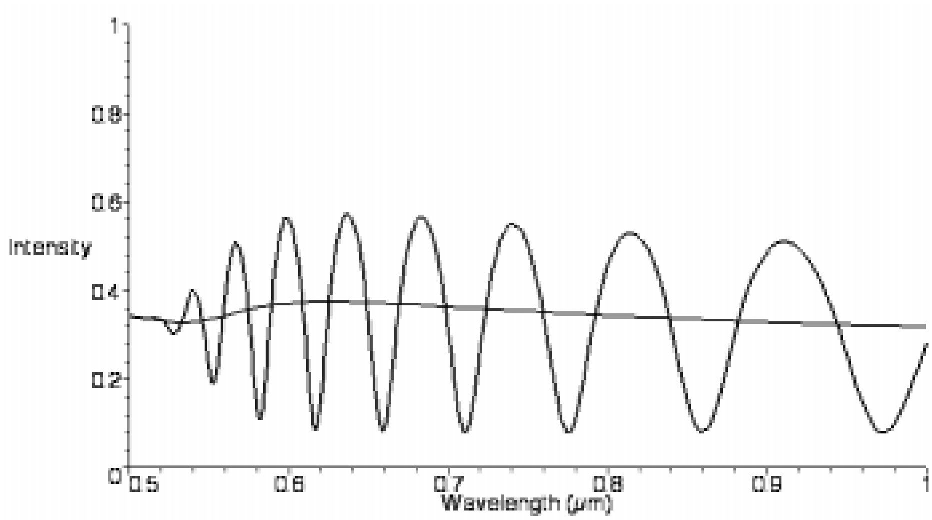
$$x = \frac{T}{1-R}\frac{\left(1-\left(\frac{T}{1-R}\right)^2 r_2^2\right)}{\left(1-r_2^2\right)}$$

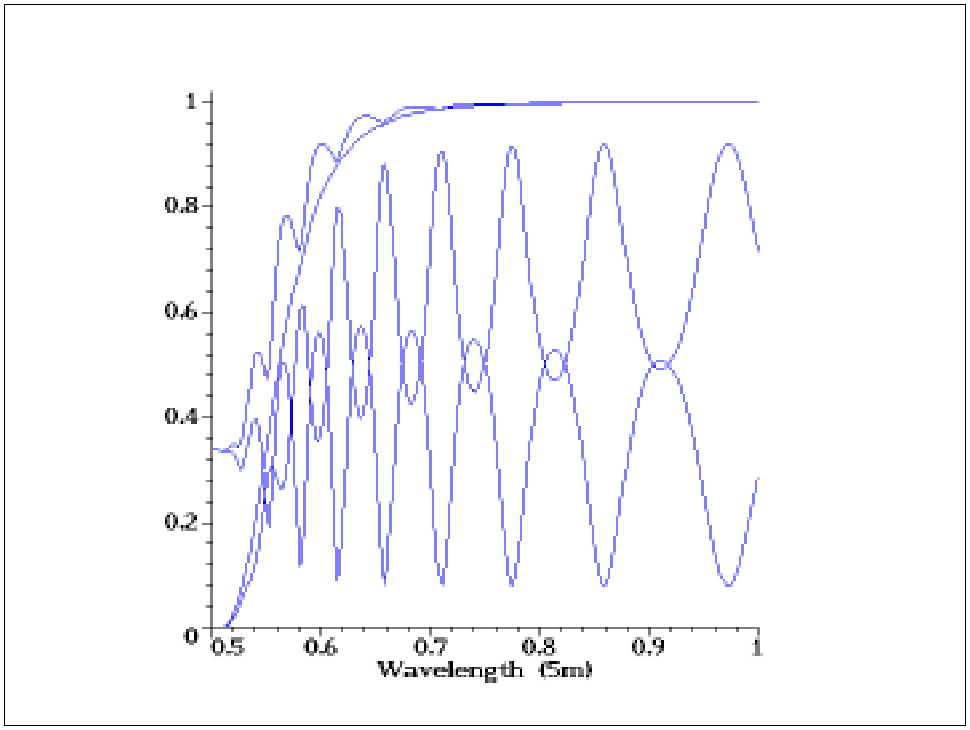
red is x obtained from eqn. Shown, which assumes that x is approx T/(1-R) to avoid solving quadratic eqn.

Average transmission fringes
n dispersive, s=1.51, d=1μm

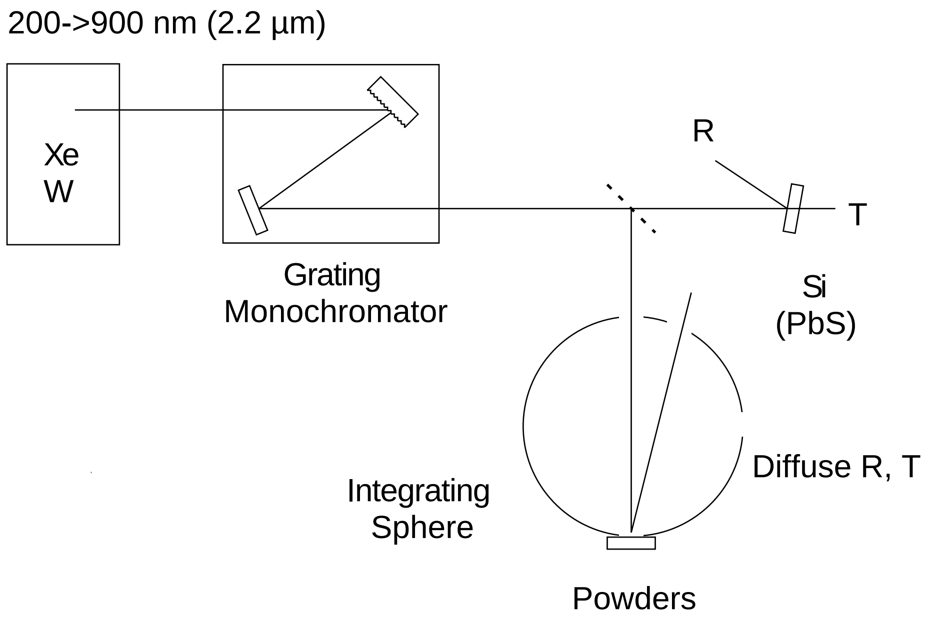


Average reflection fringes
n dispersive, s=1.51, d=1µm




1
0.8
0.6
0.4
0.2
0
0.5
0.6
0.7
0.8
0.9
1
Wavelength (5m)

Grating Spectrometer



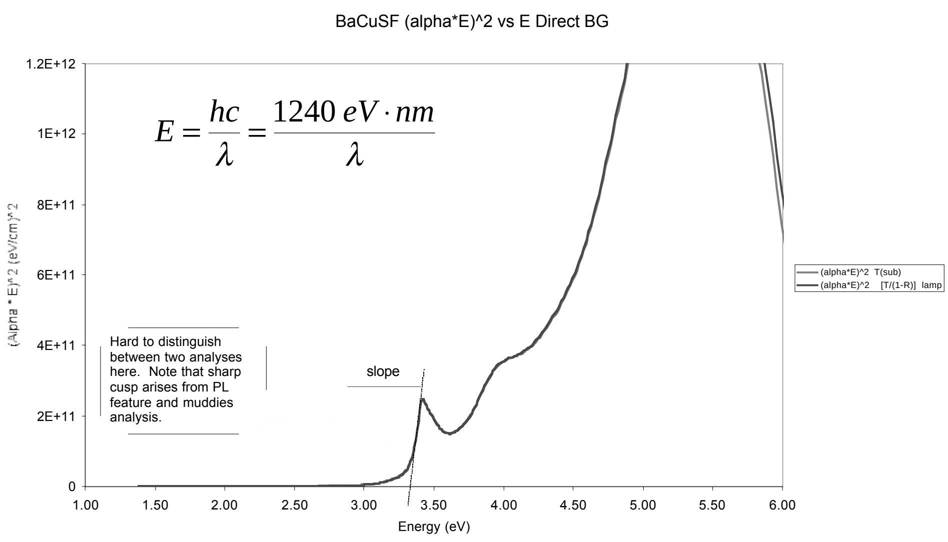
BaCuSF Transmission

T here is T-normalized on ly to lamp spectrum (not normalized to substrate)

Point out possible photoluminescence above gap (orange)

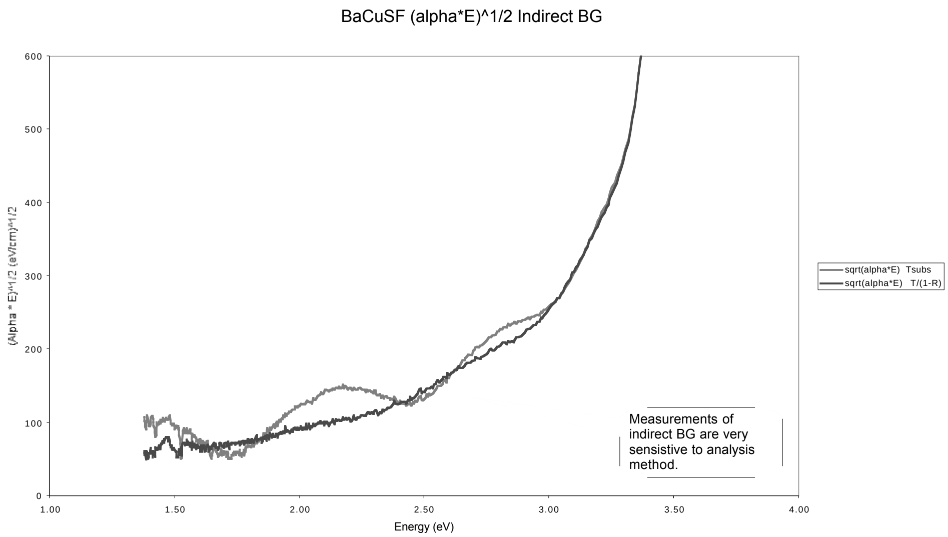
Ignore wavelength in legend (due to MS excel oddity)

BaCuSF Gap analysis

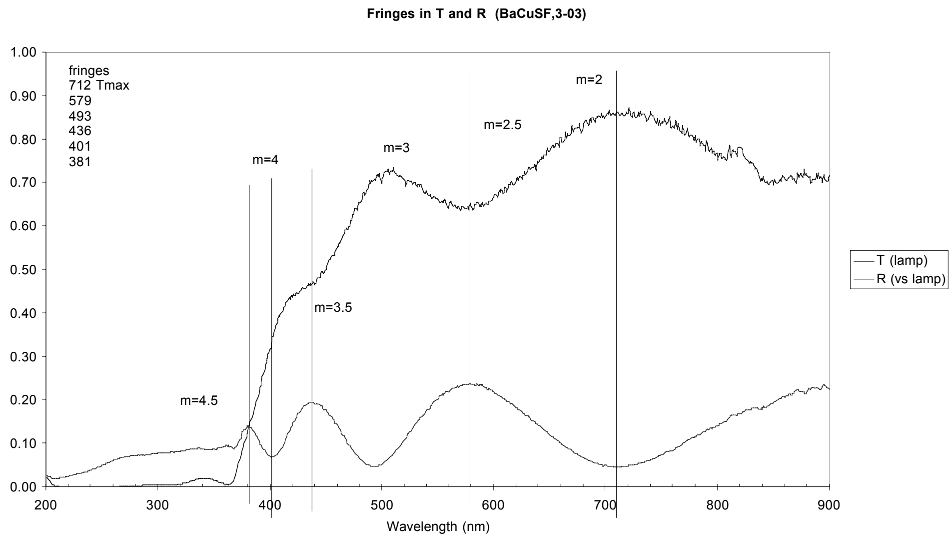


Direct gap estimate = 3.3 eV

BaCuSF Gap analysis

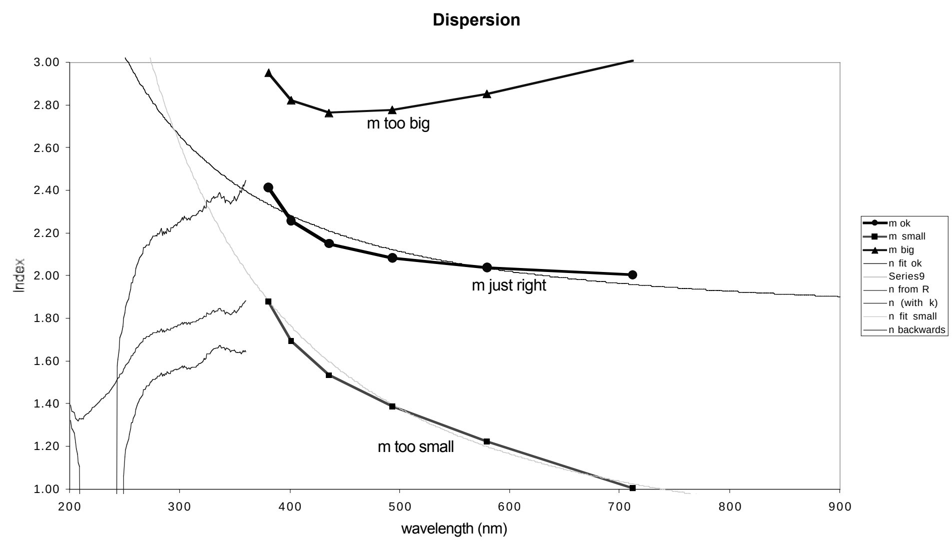


BaCuSF R, T Spectra



Locations of fringes used to estimate index of film

BaCuSF Index



m too big (3) gives index increasing with wavelength, which is abnormal

m too small gives index that appears too small

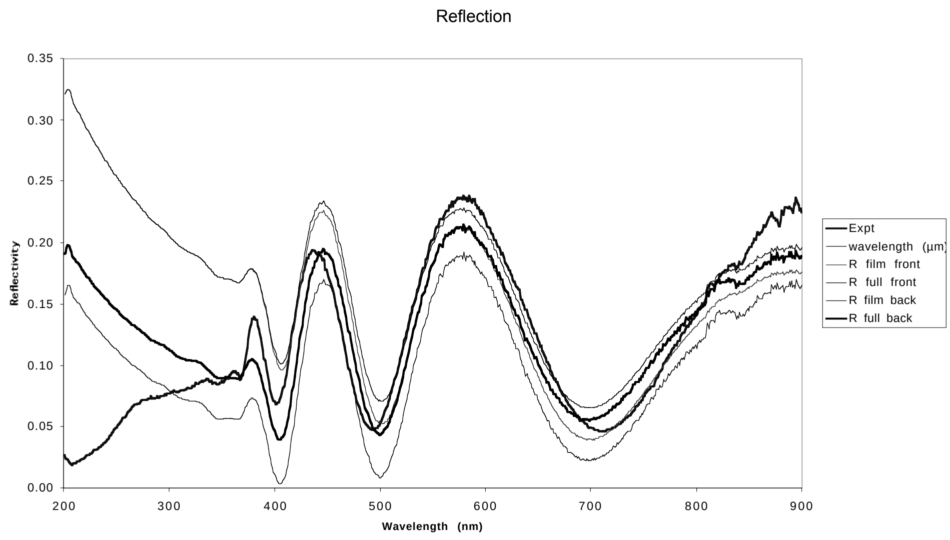
Index calcs on left come from considering amplitude of reflection from film above gap. 3ways:

1) simple R from film only

2) R using n and k from film only (k from abs)

3) R assuming light incident on substrate first, so have subs and film-subs surface reflections (blue curve)

BaCuSF Reflection (th vs expt)



Expt R compared with R calculated with theory using abs coeef from expt and index n from fit to 6 points obtained from fringe locations

4 ways

1) R from film only from film side

2) R from film and subs from film side

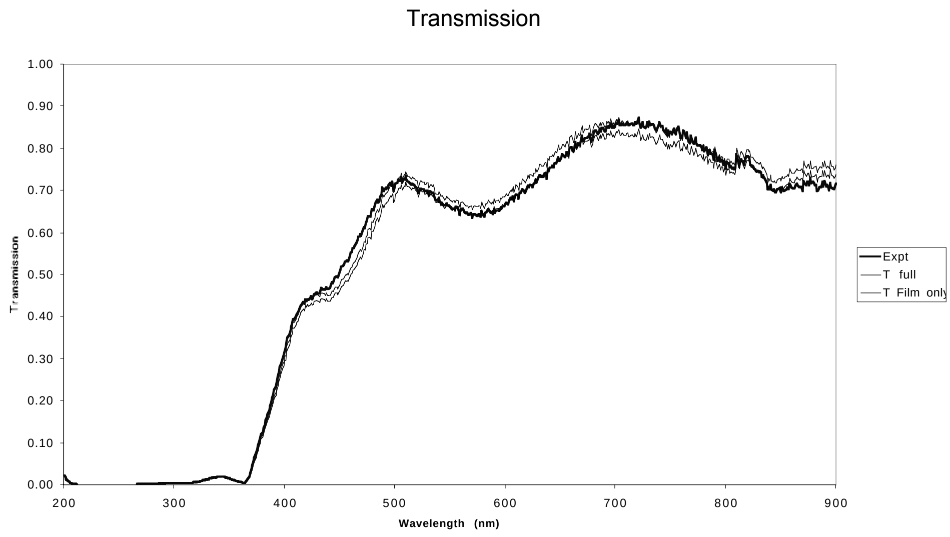
3) R from film-substrate surface only

4) R from whole system from subs side

Again ignore wavelength in legend

Shows that R very sensitive to value of n, and which way film mounted

BaCuSF Transmission (th vs expt)



T calculated from theory using alpha from expt and n from fit to 6 points from fringe locations

Shows that T mostly sensitive to alpha, not too much to n