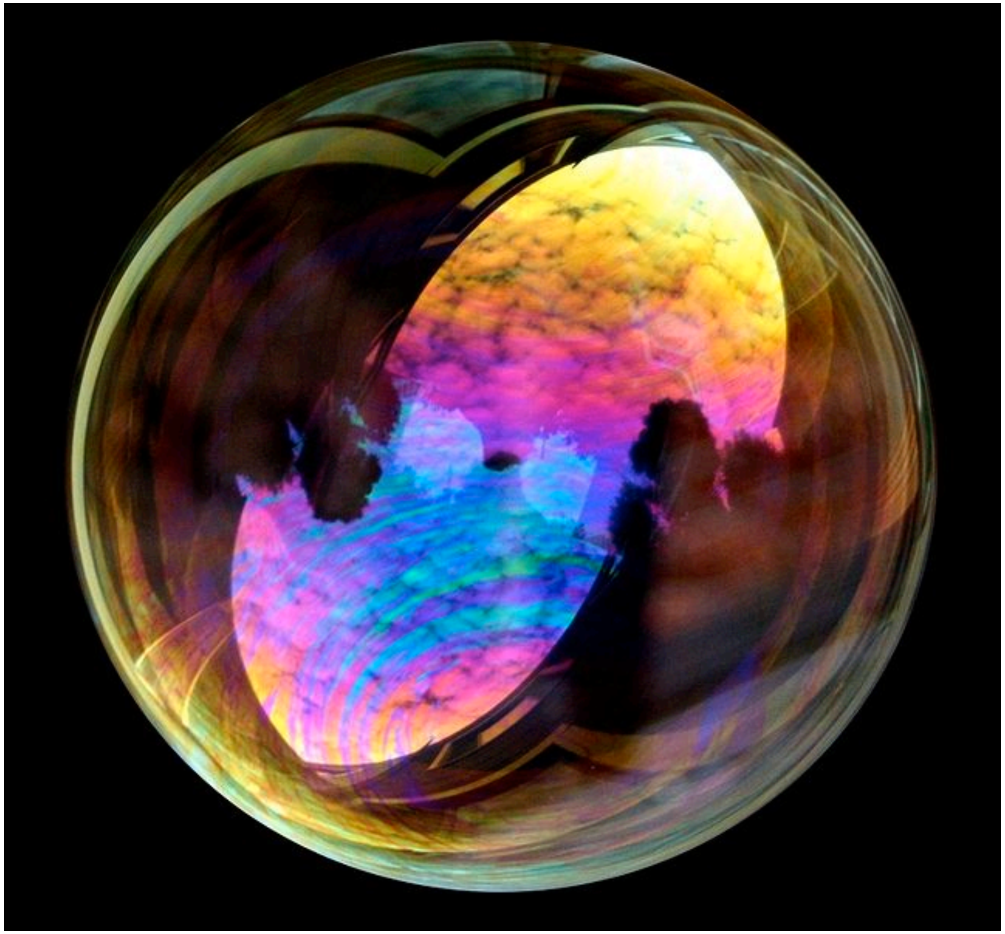
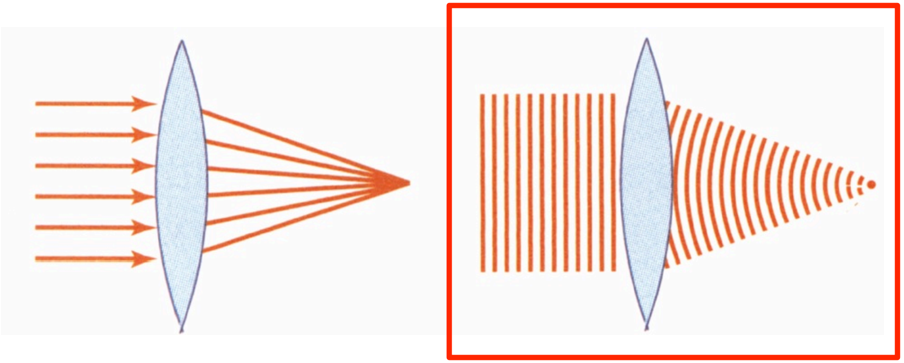
Dept. Electrical Engin.&
Computing Systems
UNIVERSITY OF Cincinnati

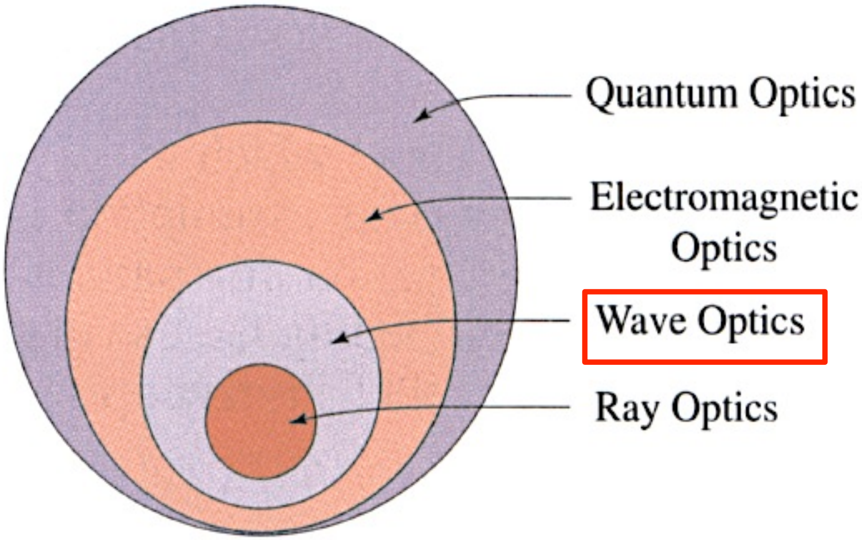
3 – Optical Interference



- Today, we will mainly use wave optics to understand thin-film interference…



Credit: Fund. Photonics – Fig. 2.3-1



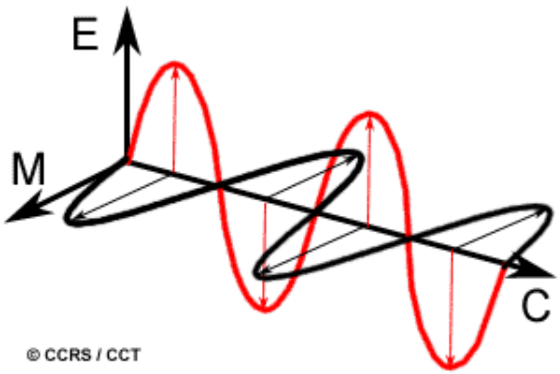
Credit: Fund. Photonics – Fig. 1.0-1

- Topics:

(1) basic principles of interference
(2) revisit refraction as a interference
(3) interferometers
(4) thin film interference and anti-reflection coatings
(5) Bragg reflectors (dielectric mirrors, photonic crystals)
(6) some advanced stuff and applications…

Figures today are mainly from CH1 of Fund. of Photonics or wiki.

- You could freeze a photon in time (image below) and observe sinusoidal with respect to distance (kx).



$$E = E_{\max} \sin(wt - kx)$$

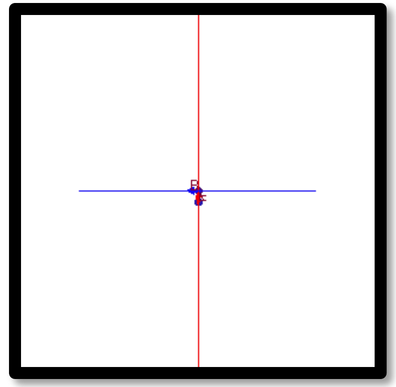
$$B = B_{\max} \sin(wt - kx)$$

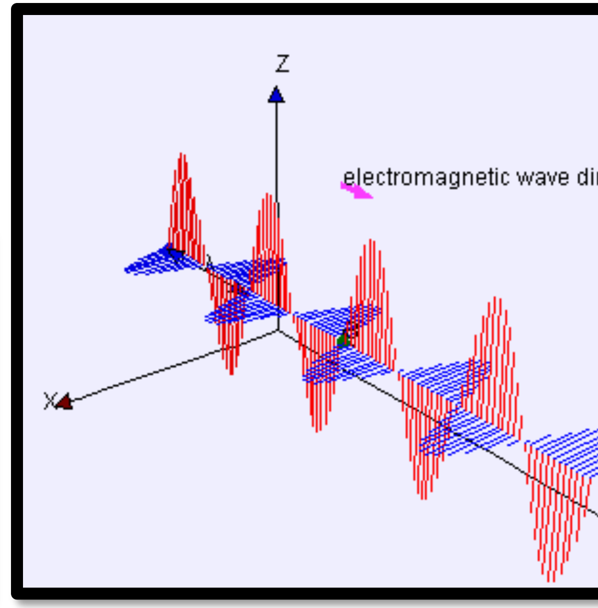
$$w = angular\ \ freq.\ \ (2\pi f, radians / s)$$

$$k = angular\ wave\ number\ (2\pi / \lambda, radians / m)$$

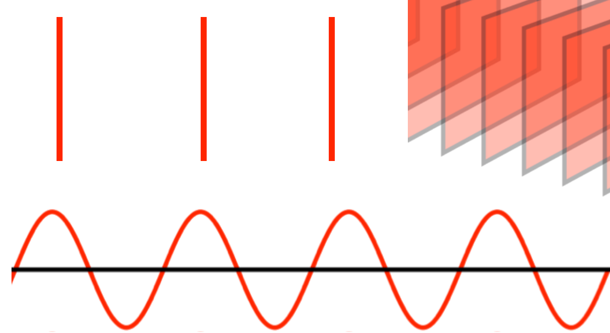
- Note, we use 2π radians by convention (make sure your calculator is set to radians mode!). Obvious we could use 360 degrees too… (degrees * π / 180).

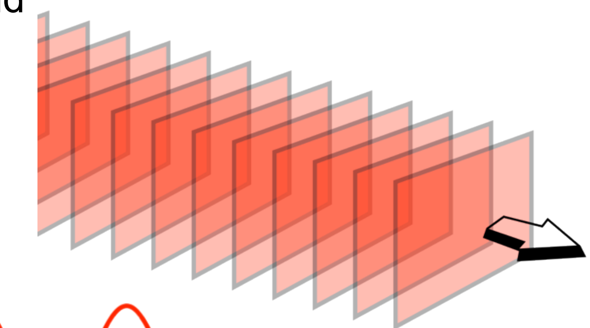
- You could also freeze your position and observe sinusoidal with respect to time (wt).



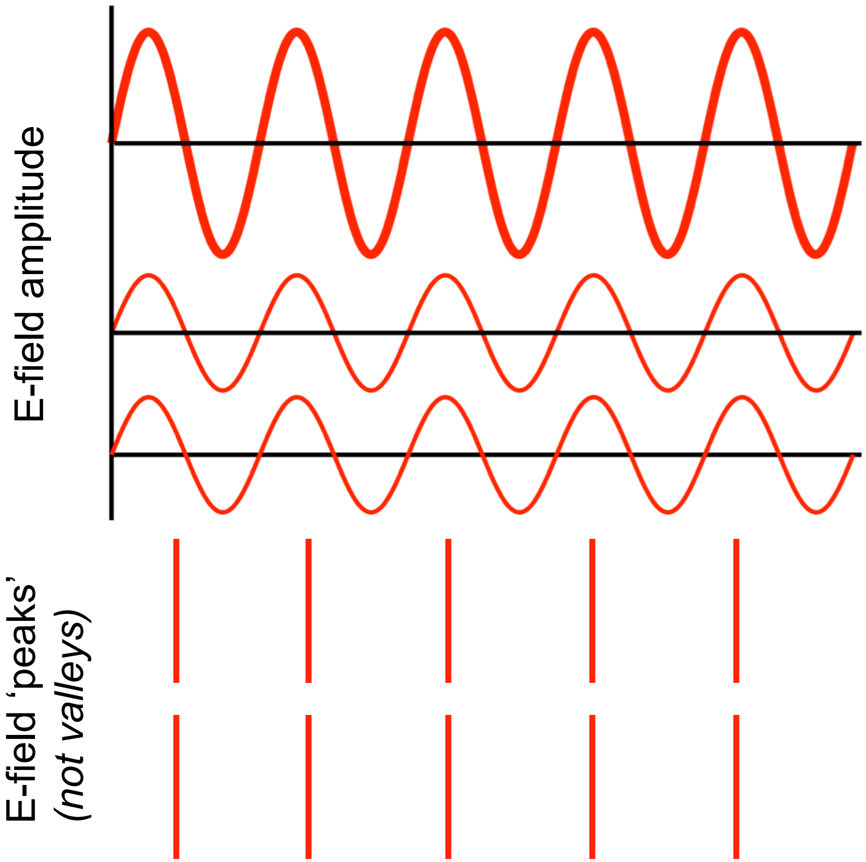


- Lastly, we can just track E, and just show peak as plane waves:





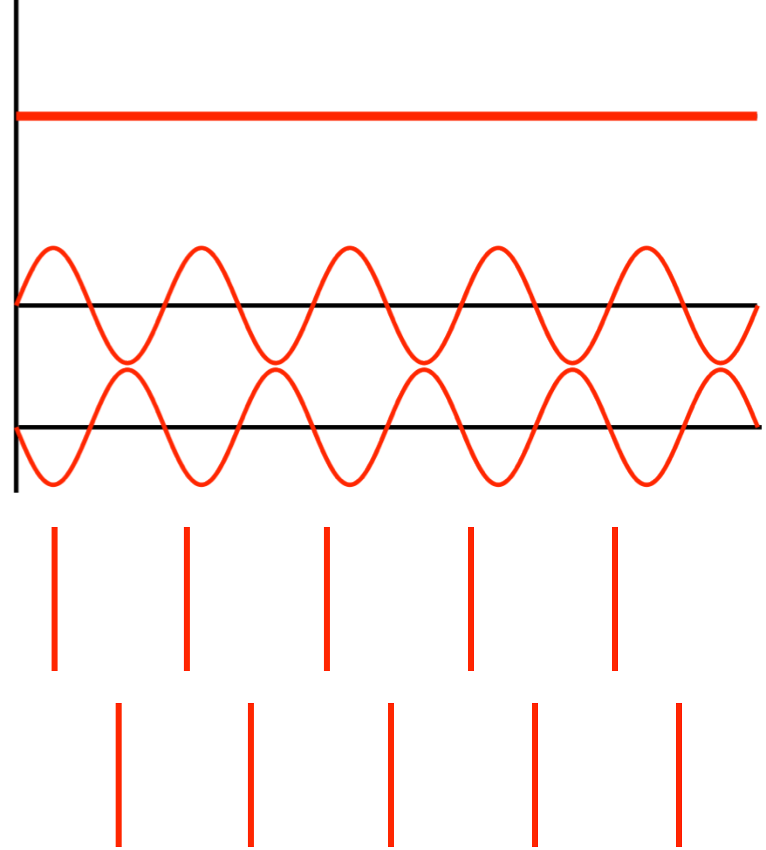
- Constructive interference of two waves… (could also be two coherent laser beams, for example).



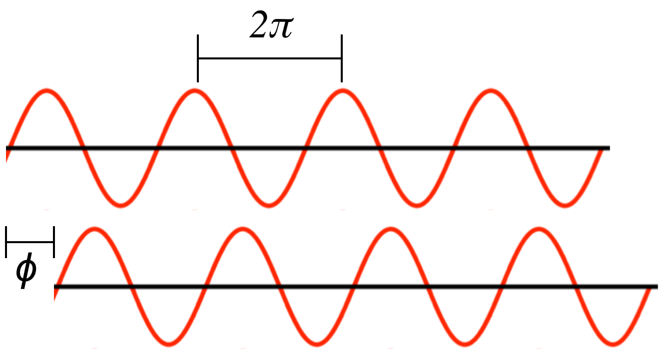
- Destructive interference of two waves…

Does this 'kill the light'?

No! It just means it must show up somewhere else where it is constructive!



- Previous slide shows perfect in phase (ϕ=0) or perfect out of phase (ϕ=π).



How do we account for phase in the wave equation?

$$E = E_{\max}\sin(wt - kx)$$

$$E = E_{\max}\sin(wt - kx + \phi)$$
$$\phi \text{ in radians}$$

$$w = angular\ \ freq.\ \ (2\pi f, radians / s)$$
$$k = angular\ wave\ number\ (2\pi / \lambda, radians / m)$$

What if $\phi=2\pi$? What $\phi=\pi$, and what about other cases like $\pi/2$? Do we just add the sum of E field?

- We typically measure the interference in terms of intensity (I):

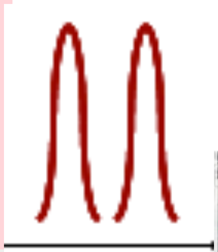
$$I \approx \frac{c\, n\, \varepsilon_0}{2} E_{\max}^2 \qquad W / m^2$$

- Which we can feed into the interference equation for two waves each of intensity I_1 and I_2:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\,\cos\phi$$

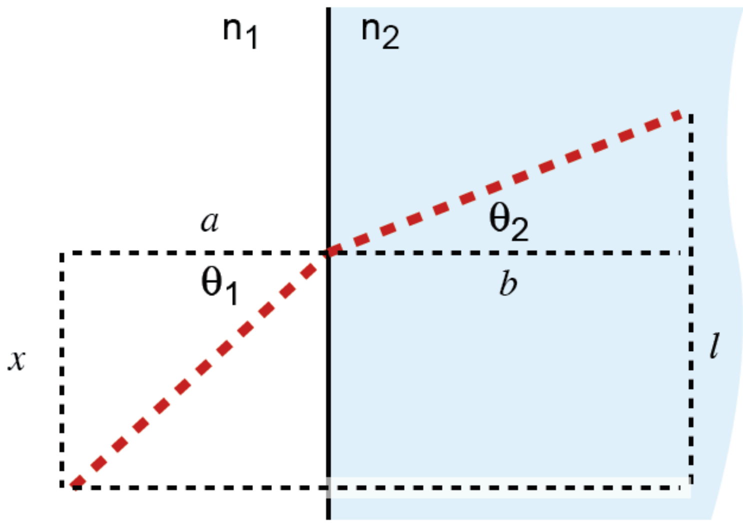
$$Ex.\quad 4+4+2\sqrt{4\times 4}\,\cos 2\pi = 16 \quad (360^\circ)$$
$$Ex.\quad 4+4+2\sqrt{4\times 4}\,\cos \pi = 0 \quad (180^\circ)$$
$$Ex.\quad 4+4+2\sqrt{4\times 4}\,\cos \pi/3 = 8 \quad (60^\circ)$$
$$Ex.\quad 4+4+2\sqrt{4\times 4}\,\cos 2\pi/3 = 4 \quad (120^\circ)$$
$$Ex.\quad 2+8+2\sqrt{2\times 8}\,\cos 2\pi = 18 \quad (not\ 10!)$$
$$Ex.\quad 2+8+2\sqrt{2\times 8}\,\cos \pi = 2 \quad (not\ 0!)$$

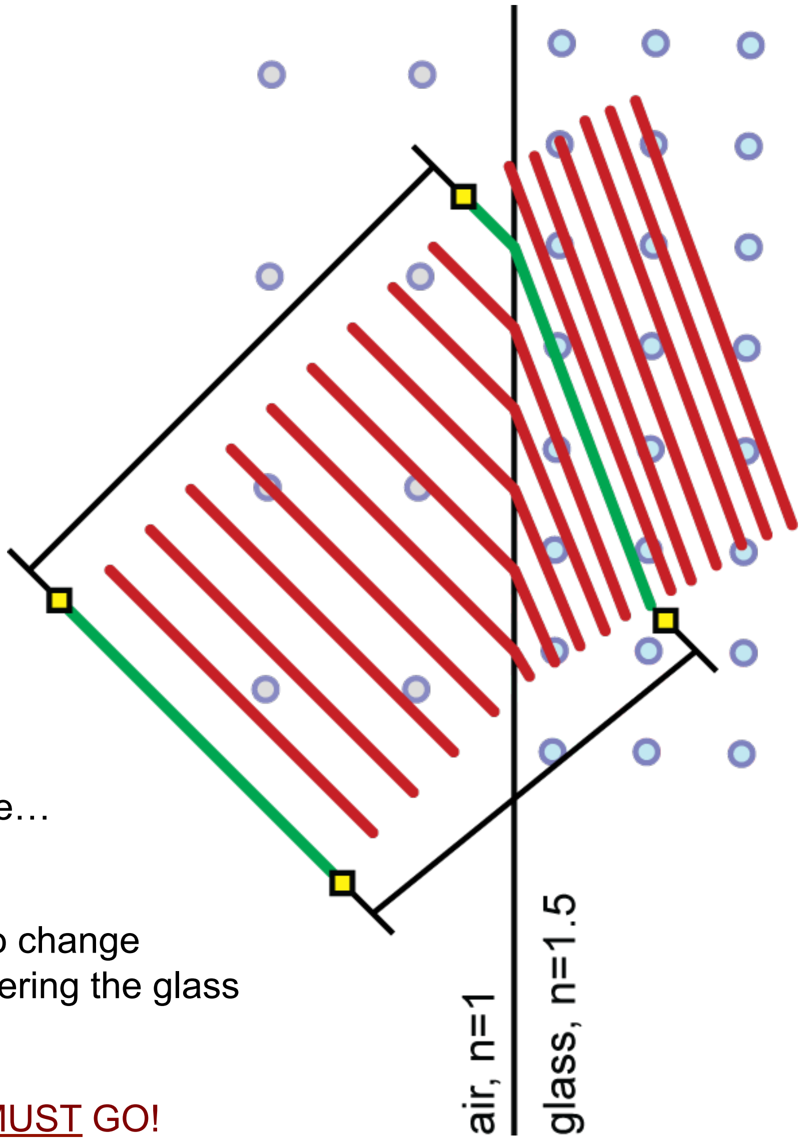
If the two beams are of equal intensity, the maxima are four times as bright as the individual beams, and the minima have zero intensity (but integrate across max/min and get same total power or average brightness).



- We derived refraction using ray optics…

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





- But we could also derive using wave optics and interference…

… the plane waves must stay in phase,
… so if the waves in the glass travel slower, then they need to change direction to stay in phase with other portions of the waves entering the glass at different times/locations.

INTERFERENCE COMMANDS THE LIGHT TO WHERE IT MUST GO!

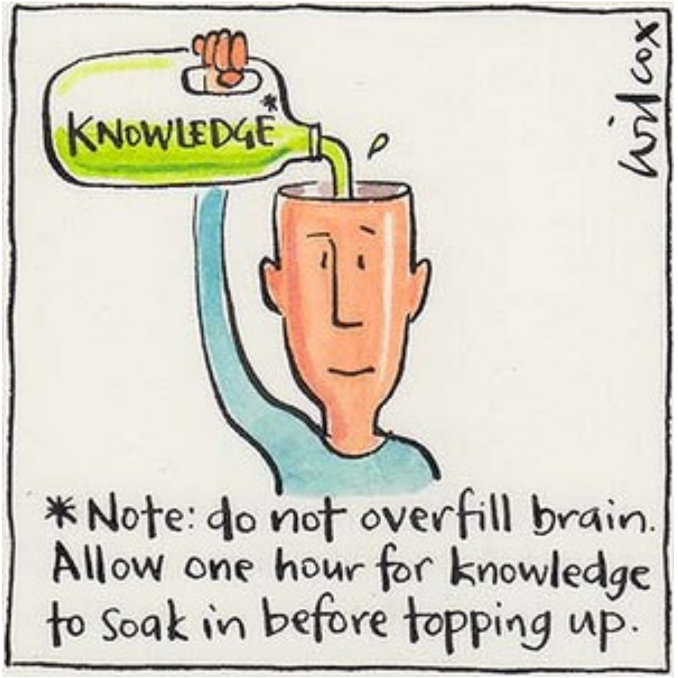
- If we interfere two waves, how do we ‘add them up’ in terms of their resulting intensity?

(a) Linearly (just a simple addition).
(b) No change at all.
(c) Non-linearly (more complex than just addition).
(d) Exponentially.

- Destructive interference:

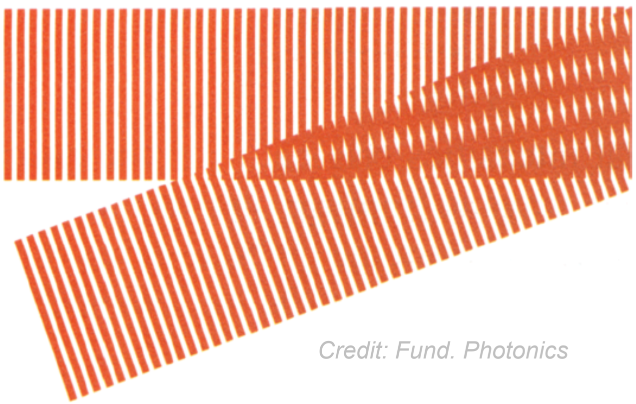
(a) destroys the energy of the light completely.
(b) simply redistributes the energy to where there is constructive interference (conservation of energy).
(c) increases the total amount of energy.
(d) none of the above.

- Whew! That’s enough. Lets take a break!



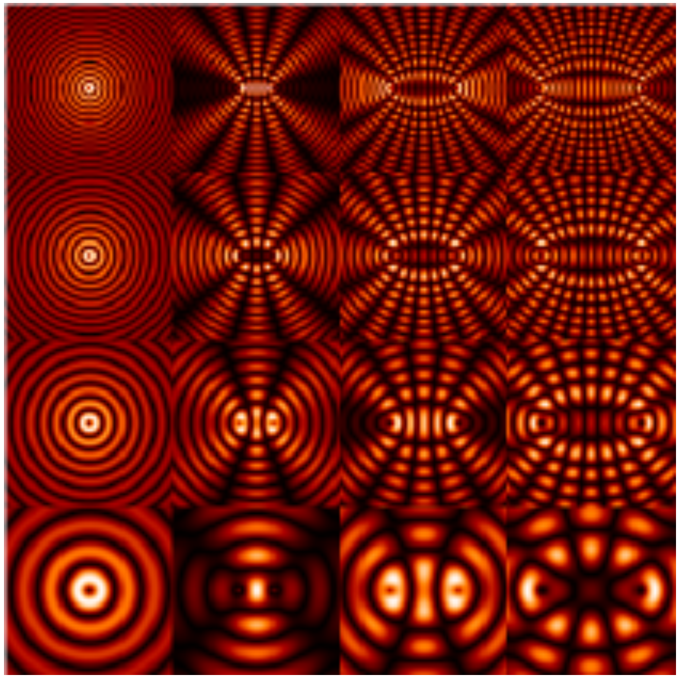
Dept. Electrical Engin.&
Computing Systems
UNIVERSITY OF Cincinnati

- The overlap of two plane waves can result in interference patterns…



Credit: Fund. Photonics

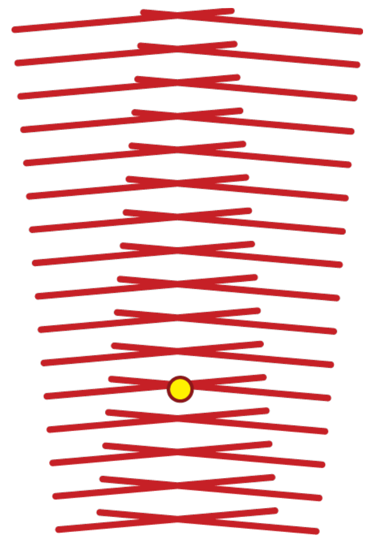
- Consider two point sources with different wavelengths and point separations (credit Wiki):

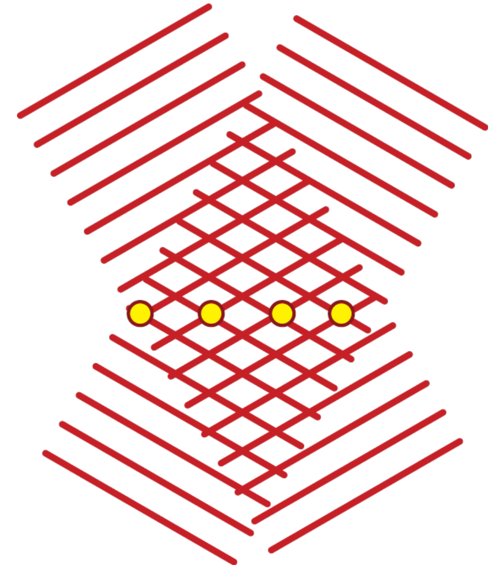


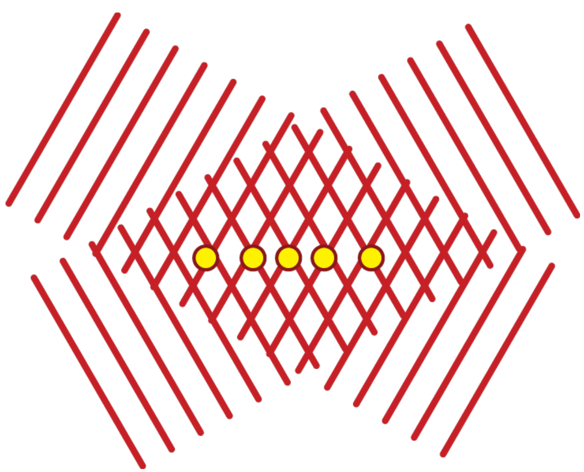
Credit: Wiki Commons

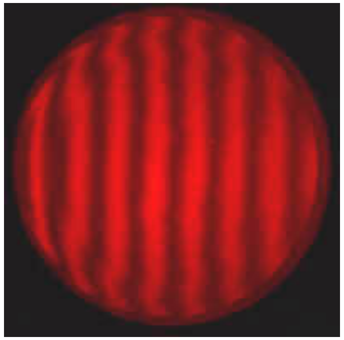
- Next week, we will talk about diffraction, which results in optical interference that can build up images …

- Interferometry typically involves splitting a laser beam (coherent / plane waves) and bringing the beams back together to produce interference fringes…

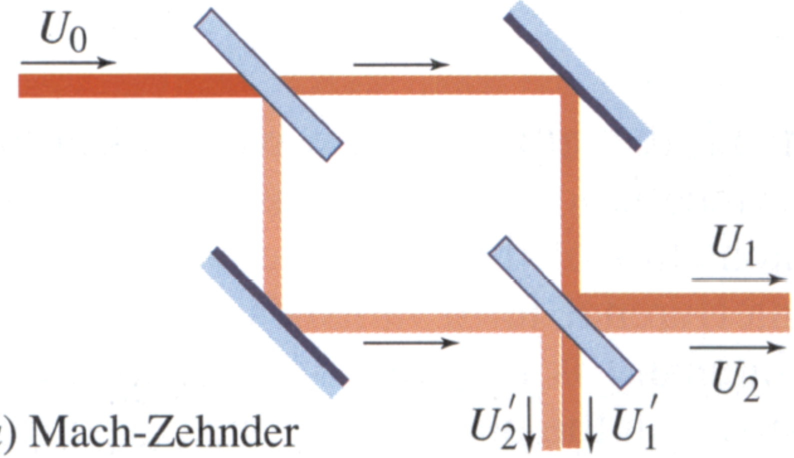




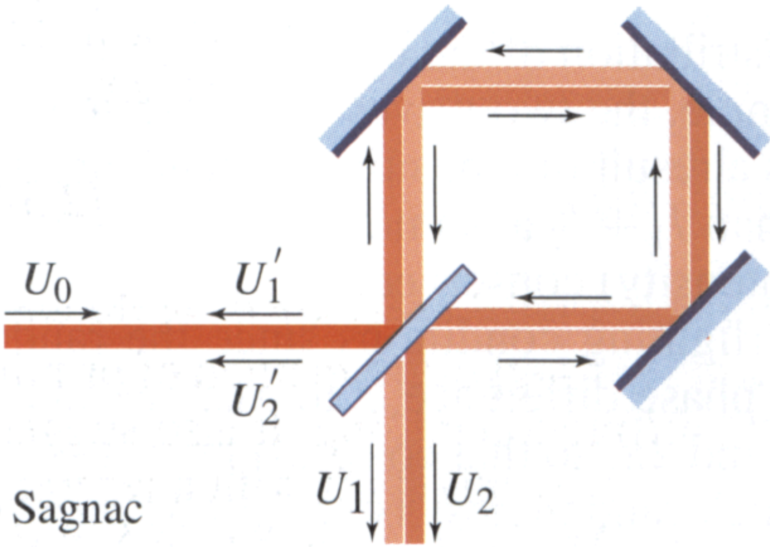




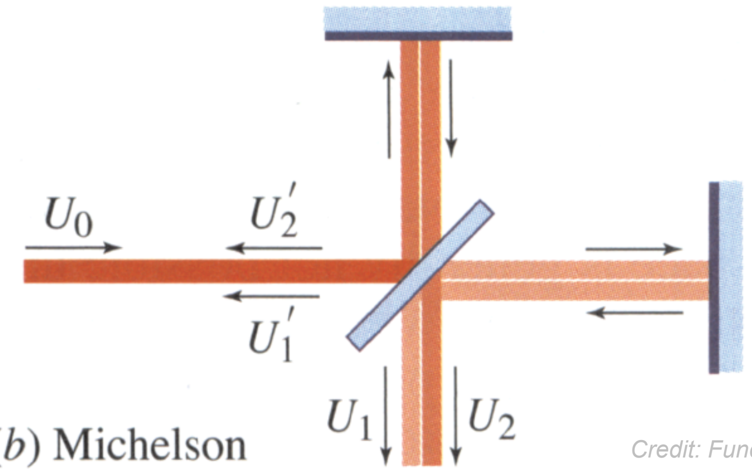
If you place a paper card in the region of interference, you will observe fringes!



(a) Mach-Zehnder



(c) Sagnac



(b) Michelson

Credit: Fund. Photonics

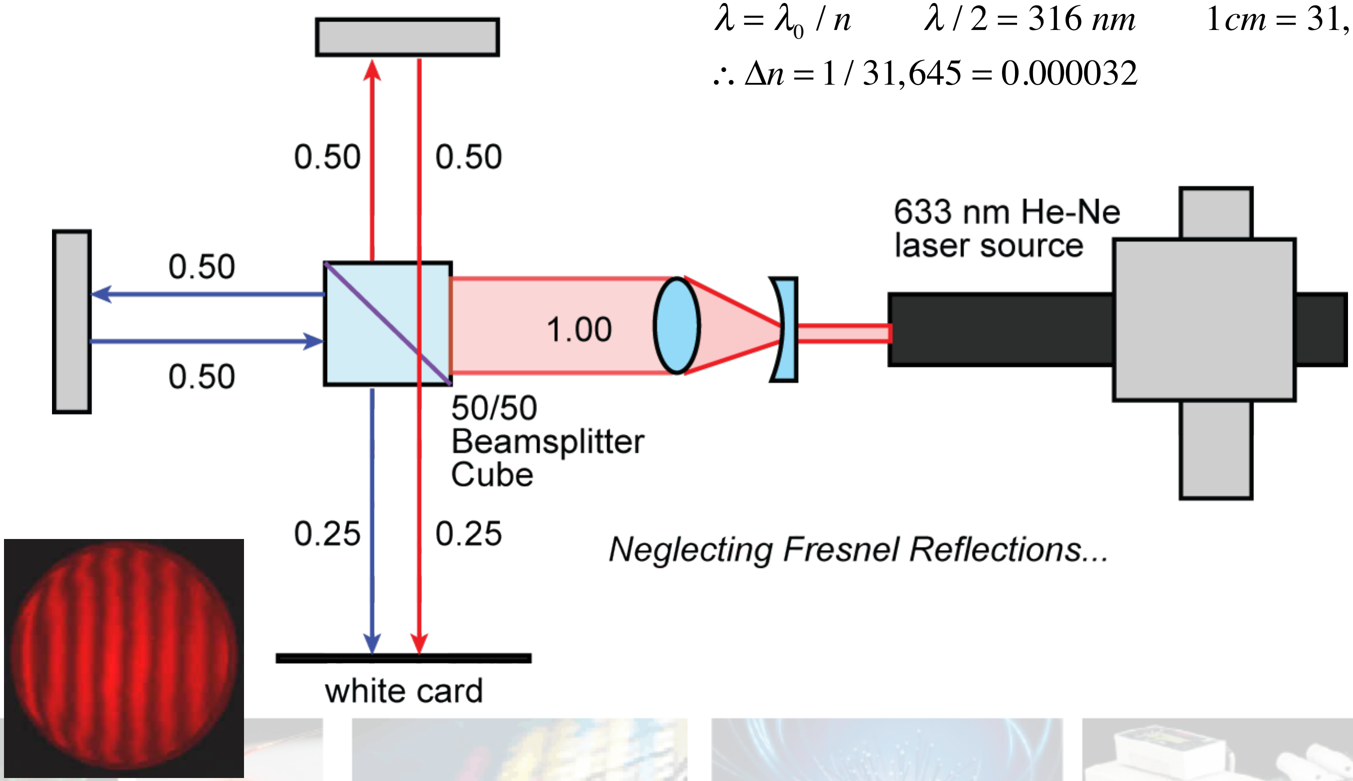
- If everything was PERFECTLY flat and the blue vs. red path length was one half wavelength different in length, what would I see at the card? Can you get it in the lab this week?

- No! The mirrors and optics are not perfect! To get 5 fringes/cm only need 5x0.633 μm or 3 μm tilt in the mirror or non-flatness! You will build a NANO (λ/2 ~ 300 nm) sensor this week!

- You will see that even the heat off your finger, if placed near the beam, can cause fringes due to change in refractive index of air (hotter = lower index = faster light travel).

$$\lambda = \lambda_0 / n \qquad \lambda / 2 = 316\ nm \qquad 1cm = 31{,}645\ half\ wavelenghts$$

$$\therefore \Delta n = 1 / 31{,}645 = 0.000032$$

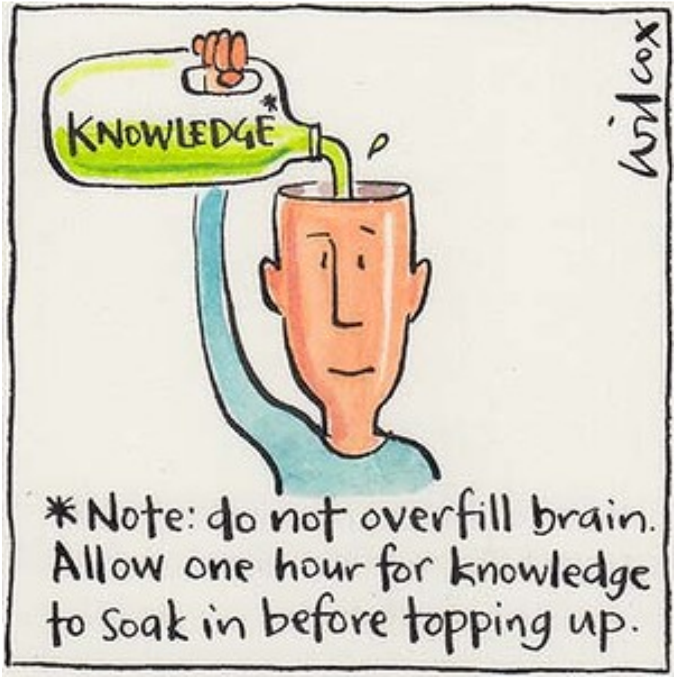


Neglecting Fresnel Reflections...

- You are going to MAKE an interferometer with red laser light, using your bare hands this week. How precise will your mirrors need to be aligned, roughly, for <10 fringes to appear?

(a) Alignment does not matter, it will work anyway.
(b) Less than 1 wavelength of the light.
(c) Less than 5 wavelengths of the light.
(d) Less than 10 wavelengths of the light.

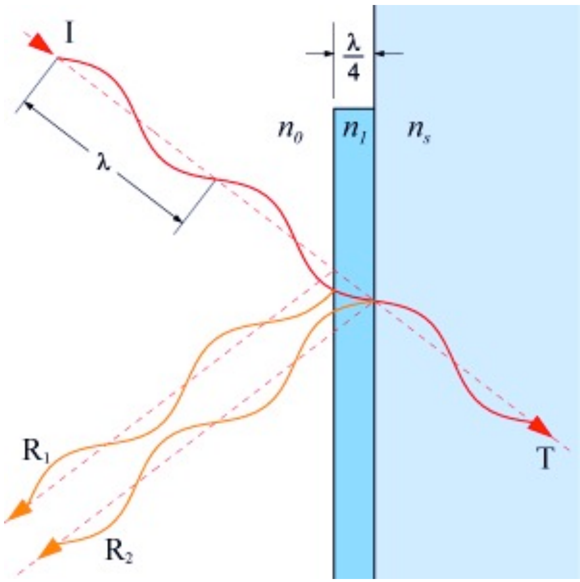
- Whew! That's enough. Lets take a break!



Dept. Electrical Engin.&
Computing Systems
UNIVERSITY OF Cincinnati

- We will also explore thin-film interference this week… which has a strong effect on Fresnel reflection.

'Quarter Wavelength' Coating



Credit: Wiki

- Assume we add a thin film and therefore get TWO Fresnel reflections (R_1, R_2)… and setup refractive indices such that R_1=R_2.

$$\%R_1 = \left(\frac{n_0 - n_1}{n_0 + n_1}\right)^2 = \%R_2 = \left(\frac{n_1 - n_s}{n_1 + n_s}\right)^2$$

Typically n_0<n_1<n_s and already helps us, how?

- Next, assume that we use the incident angle and thickness of n_1 layer to create a film that is λ/4 thick…

What will be the phase difference between R_1 and R_2?

Okay, since R_1=R_2 how much is reflected (total)? Transmitted?

INTERFERENCE COMMANDS THE LIGHT TO WHERE IT MUST GO!

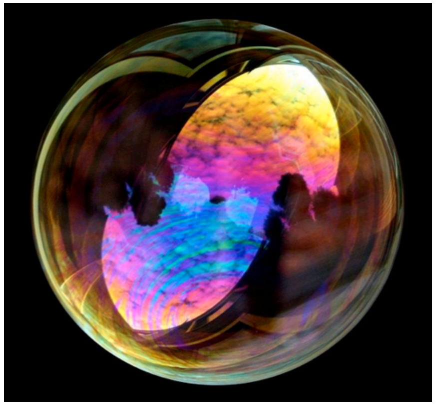
- Some well-known applications for anti-reflection coatings…

- Practical limitations… for visible white light, what limits do you have on this simple single layer approach? What about angle of incidence?

- For n_s= 1.5, n_1 ideally is 1.28, but few materials have this… practically often use a nice hard coating of MgF_2 with a non-ideal n_1 of 1.38 which still reduces 4% Fresnel reflection to <1 %, typically.

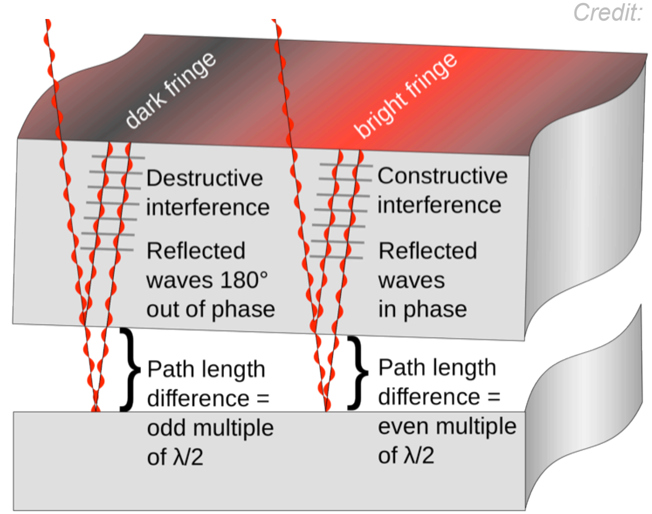
- There are other single layer examples (next slide…)

- Any single thin film can achieve thin film interference…



- The system also can have a single layer that is the lower refractive index one…

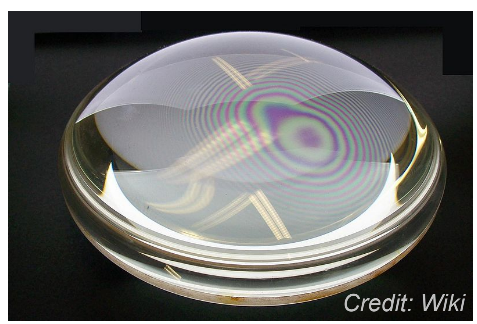
Credit: Wiki



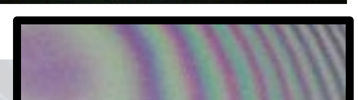
- Thin air-gaps between plates of glass are often used to test the flatness or the smoothness of radius of curvature in optics…

An 'optical flat':

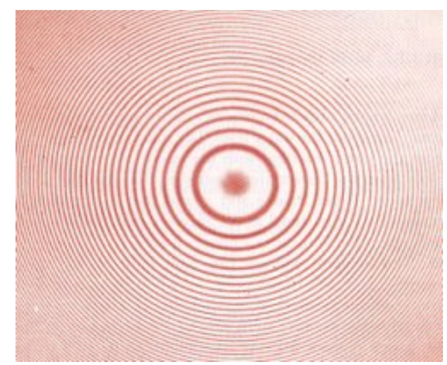
Flat side of plano-convex lens being tested in white light… *where is the gap the smallest? Colors cycle blue/green/red, why?*



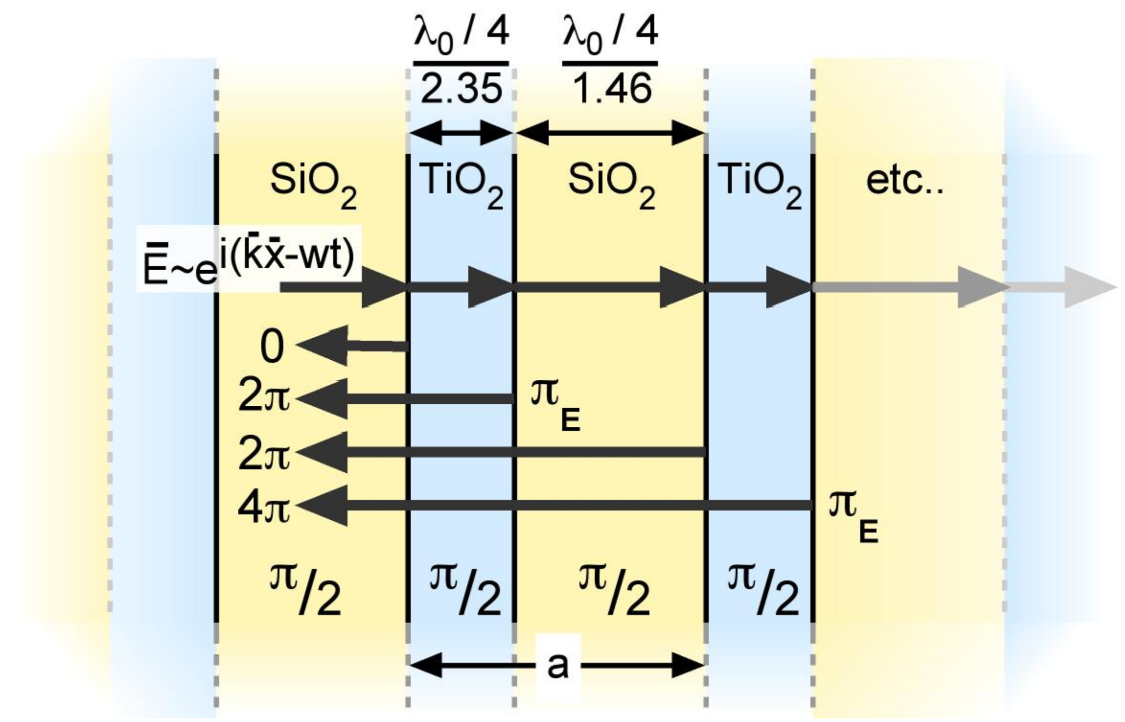
Credit: Wiki



Curved side of a plano-convex lens being tested in red light… *how use to measure curvature?*



- Multiple layers can be used, and be even more powerful… (you will simulate for homework this week).



What if layers are λ/2 thick?

Example Pi + Pi + Pi = 3 Pi, all out of phase! So becomes a perfect transmitter!

- You can also make a near perfect reflector by stacking up a bunch of Fresnel reflections (similar to what makes paper white), however, this has to be a lot thicker (and is diffuse unless it is a bunch of glass plates, for example).

- There are numerous names for the type of reflector above… dielectric mirror, Bragg reflector, 1D Photonic Crystal (why that name?).

- In a simple design where all the layers are the same thickness d, then the angular dependence for maximum reflection is as follows… *why integer number of wavelengths?*

$$m\lambda = 2d\sin\theta \quad m = \text{int}.$$

- 3M Vikuity ESR Reflector is made up of 300 layers of alternating refractive index polymer. See the sample in the lab this week (it has NO metal layers in it at all)…

- I knew it was a dielectric reflector when I tried to us it for UV and it failed miserably, why?

RESEARCH ARTICLE

Giant Birefringent Optics in Multilayer Polymer Mirrors

Michael F. Weber, Carl A. Stover, Larry R. Gilbert, Timothy J. Nevitt, Andrew J. Ouderkirk*

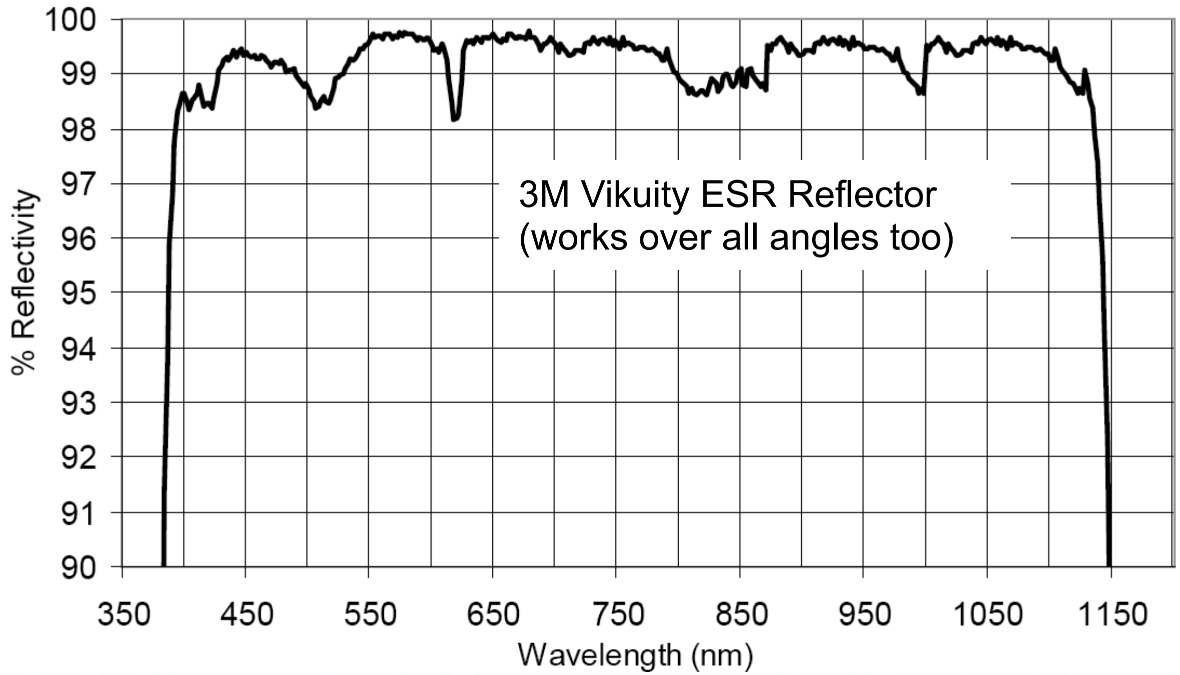
Multilayer mirrors that maintain or increase their reflectivity with increasing incidence angle can be constructed using polymers that exhibit large birefringence in their indices of refraction. The most important feature of these multilayer interference stacks is the index difference in the thickness direction (z axis) relative to the in-plane directions of the film. This z-axis refractive index difference provides a variable that determines the existence and value of the Brewster's angle at layer interfaces, and it controls both the interfacial Fresnel reflection coefficient and the phase relations that determine the optics of multilayer stacks. These films can yield optical results that are difficult or impossible to achieve with conventional multilayer optical designs. The materials and processes necessary to fabricate such films are amenable to large-scale manufacturing.

3M Film/Light Management Technology Center, 3M Center, St. Paul, MN 55144, USA.

*To whom correspondence should be addressed. E-mail: 3mopticalfilm@mmm.com

www.sciencemag.org SCIENCE VOL 287 31 MARCH 2000

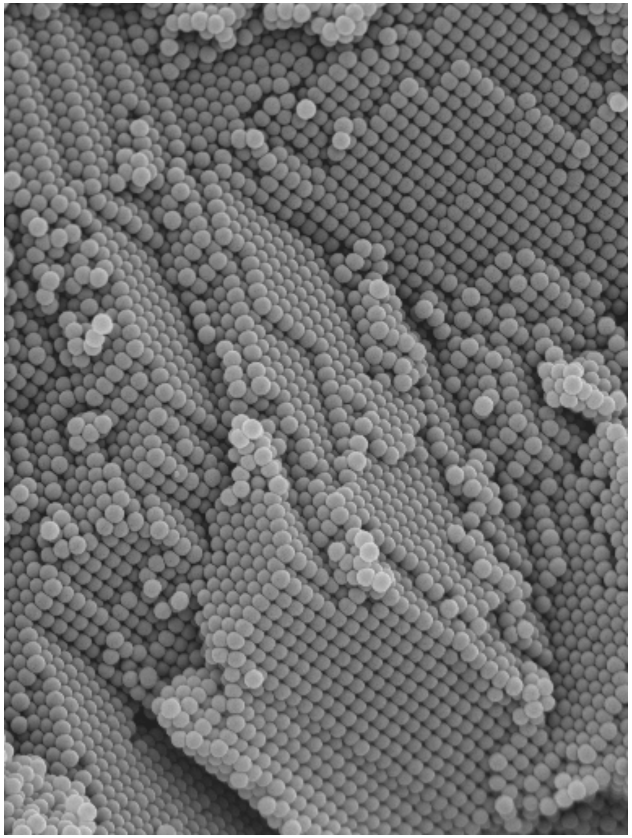
Coating	Wavelength (nm)	Avg. Reflect
Aluminum	400-1200	90
Protected Aluminum	400-800	87 Protected Silver
	400-20k	95



- Previous 2 slides have 1D periodicity, but what about 2D or 3D periodicity?

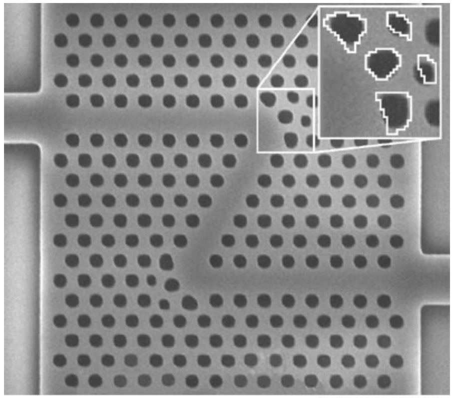
- These types of 'Photonic Crystals' have powerful application and impact!

- Go 3D (opal structure!):

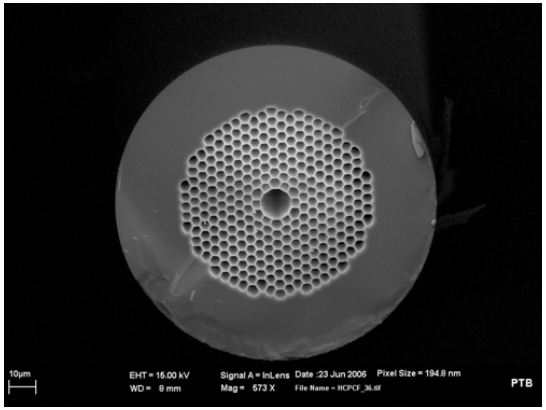


- How do you make an optical computer chip? You better at least be able to make 'wires' for the light that operate without loss and route light around super tight corners…

- Dispersion broadens/ blurs optical data signals, and is due to refractive index between core and cladding in an optical fiber. How about a fiber based mainly on air with ZERO dispersion (cladding and core are same index)?



Source: Technical University of Denmark



- Ch 7 in 'Fund of Photonics' provides numerous matrix (MATLAB) techniques for analyzing Photonic Crystals… If you are interested…

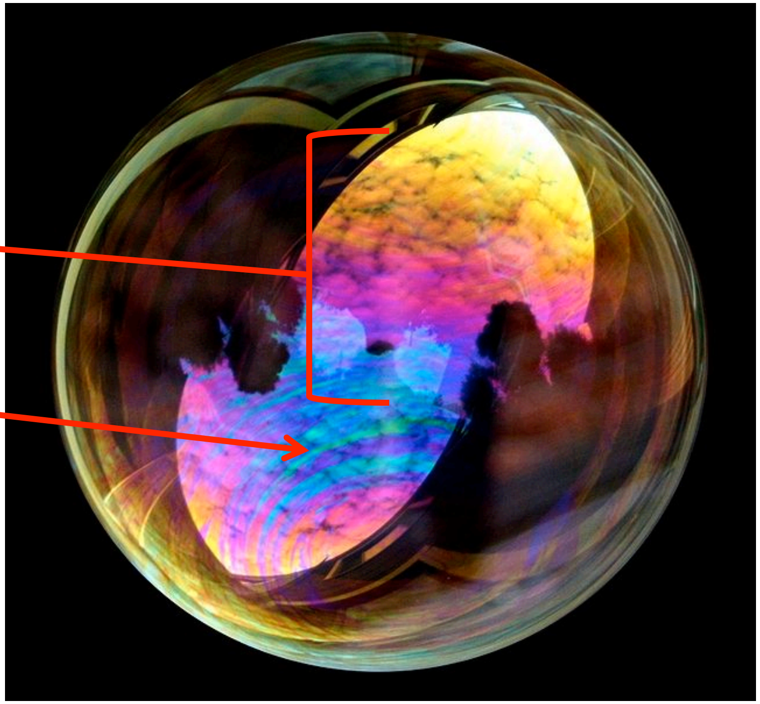
- The soap bubble at right looks like it is reflecting an image of white clouds or white popcorn. There are TWO factors at play causing the variations in color (one is gradual, the other has a few streaks), which below is correct.

(a) The gradual change is a change in the optical path length through the film due to a gradual change in the incidence angle for the light.
(b) The streaks are a change in thickness of the soap bubble film, from when it was blown.
(c) Both (a) and (b).
(d) Neither (a) nor (b).

- A 'quarter wavelength coating':

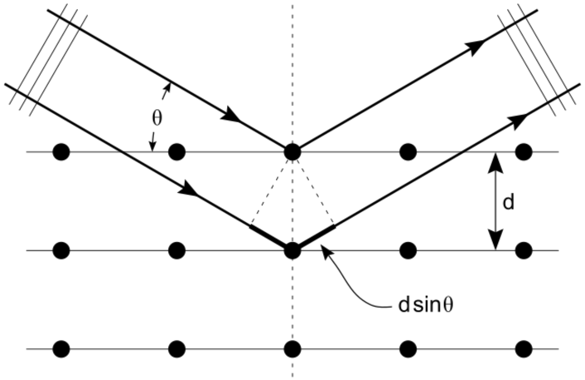
(a) Reduces reflection for that wavelength.
(b) Reduces reflection for all wavelengths.
(c) Increases reflection for that wavelength.
(d) Increases reflection for all wavelengths.

- Whew! That's enough. Lets take a break!

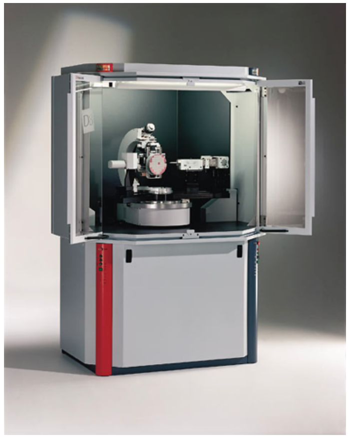


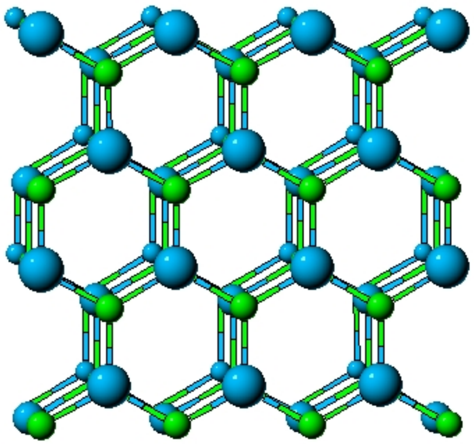
- Bragg reflection (diffraction) of x-rays is used to determine crystallinity (quality) of semiconductors…

why do they use X-rays?



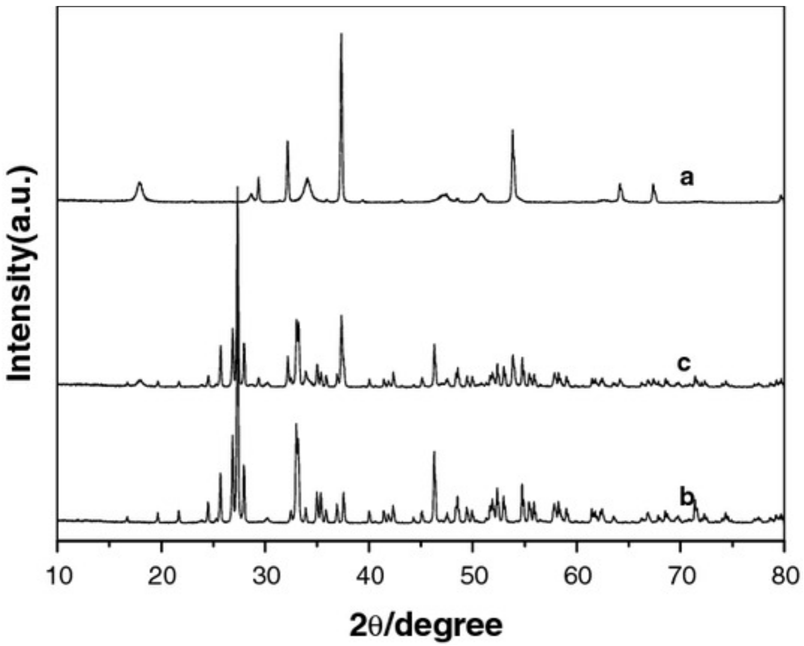
$$m\lambda = 2d\sin\theta \quad m = \text{int}.$$



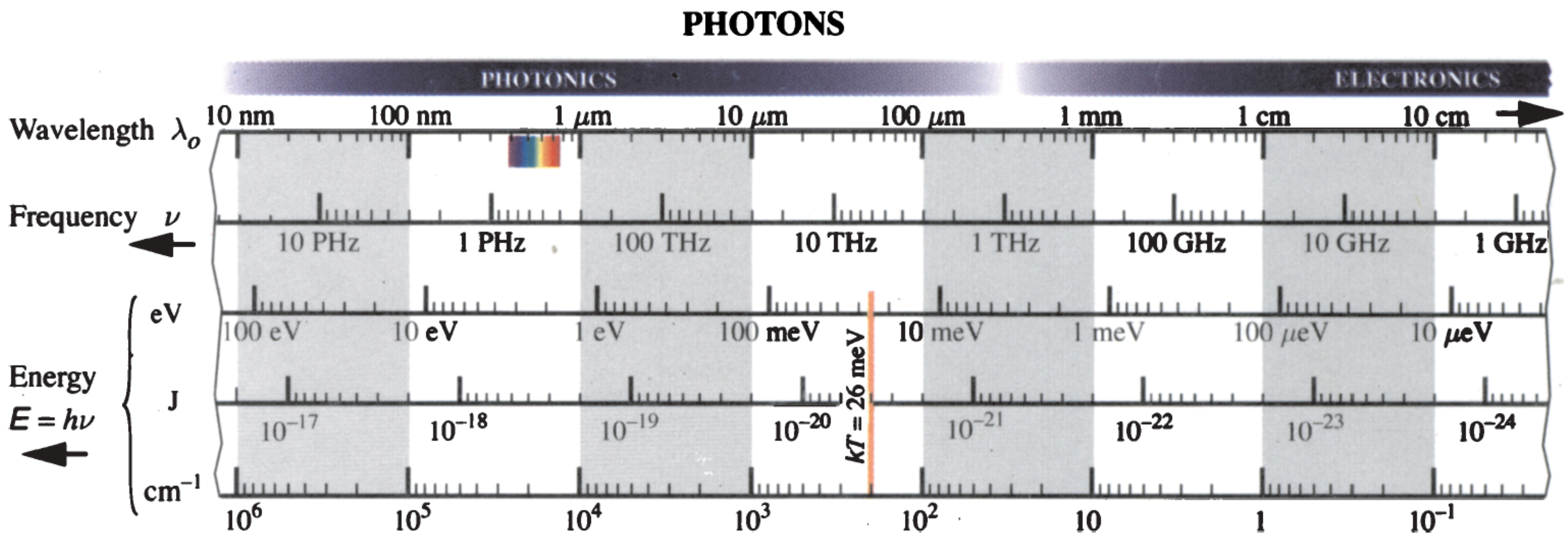


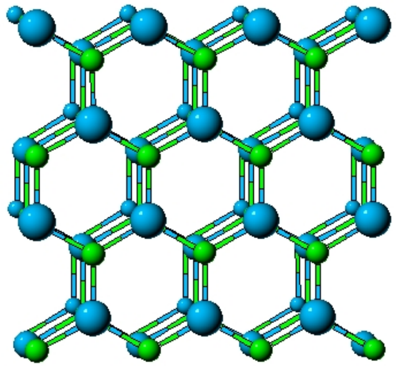
- Reflection spectra for 3 different materials shown at right…

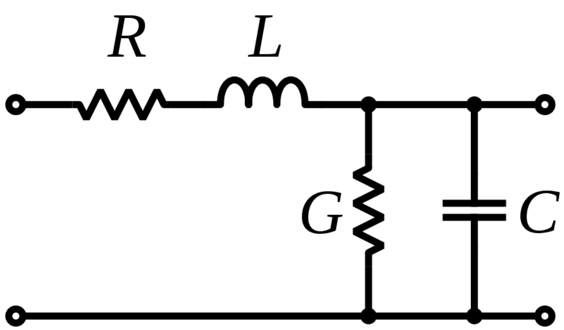
why is it plotted vs. θ (units of degrees)?



- Remember, more broadly, what we are discussing applies for all types of E&M radiation… just remember the materials properties and scales change!



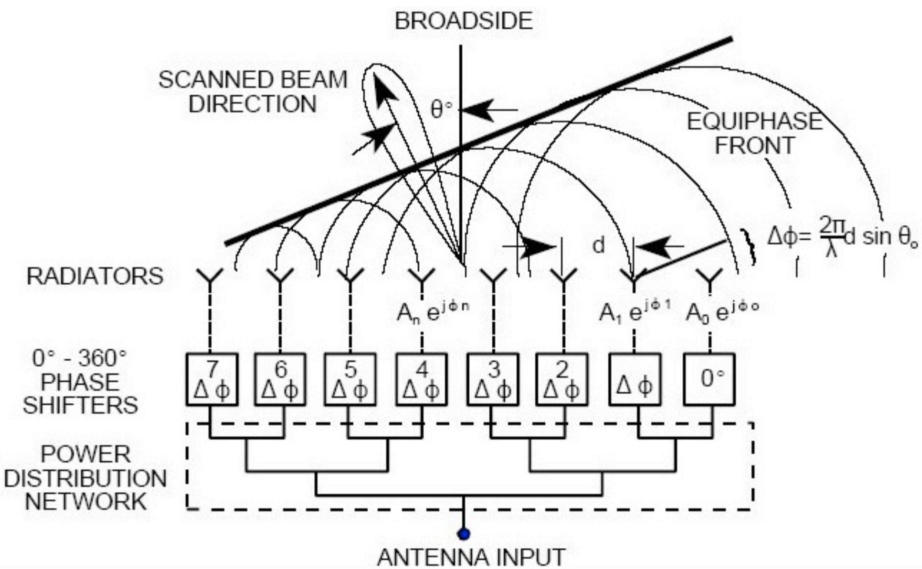




Dept. Electrical Engin.&
Computing Systems
UNIVERSITY OF Cincinnati

- If interference forces E&M radiation to go from destructive interference locations/direction to constructive interference ones… could I emit the radiation from a bunch of point sources of different phases and interfere them to control direction of propagation? Yes or no?

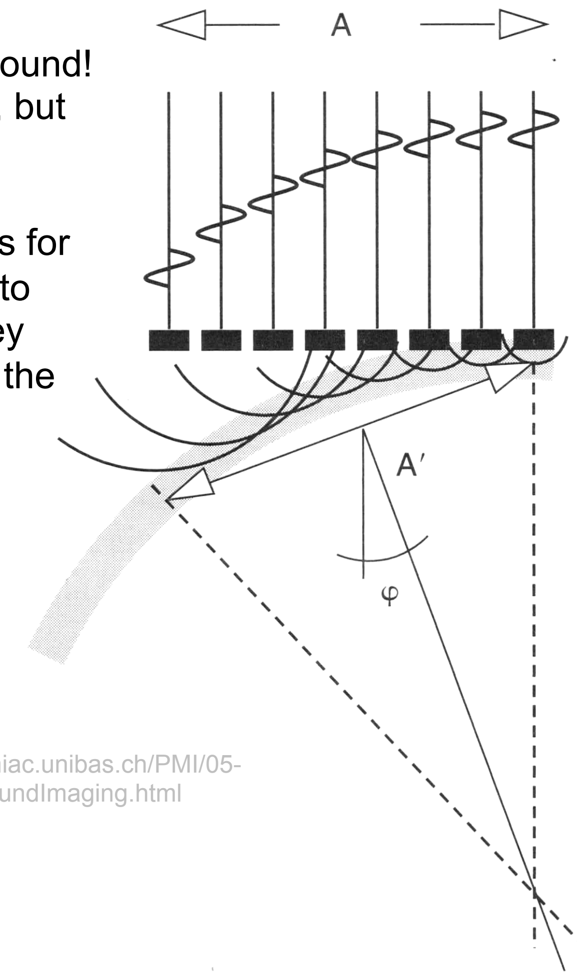
- μ-Wave 'phased array'



http://www.microwaves101.com/encyclopedia/phasedarrays.cfm

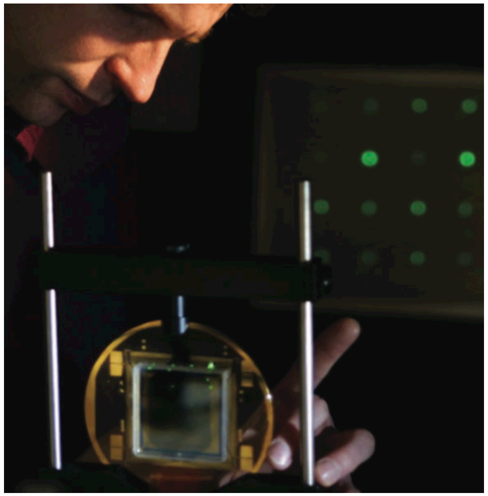
- Even ultrasound! (not radiation, but still waves!)

- The use this for imaging, and to explode kidney stones inside the body!

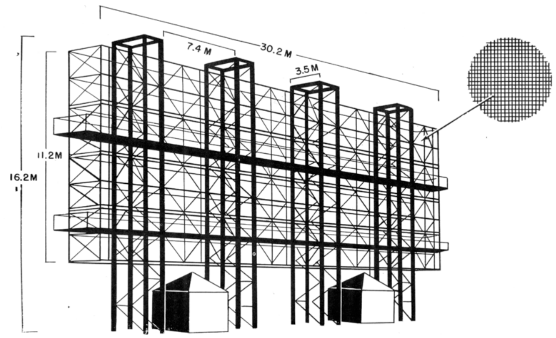


http://miac.unibas.ch/PMI/05-UltrasoundImaging.html

- Optical phased arrays (use liquid crystal plate to create phase-delays, will cover later this semester).



- This is one of the first phased arrays (Germany, WWII) … why so huge? Hint, think of electronics available…

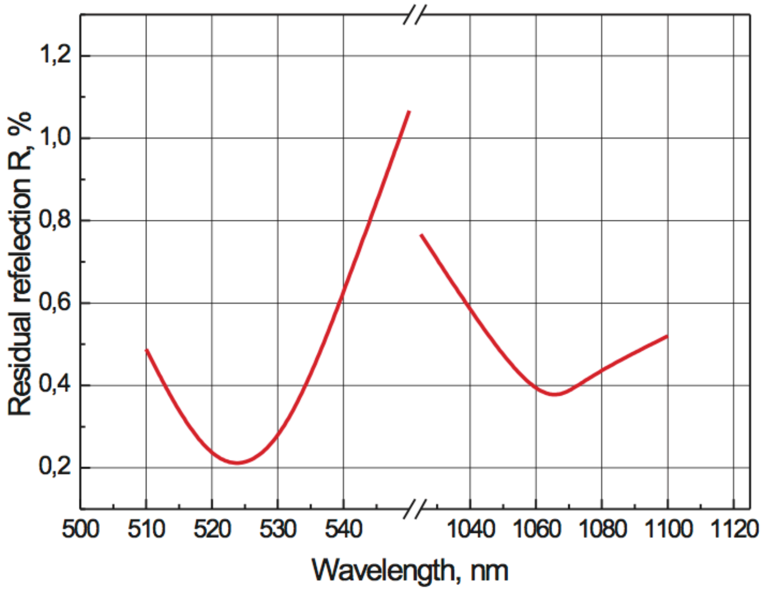


- Modern US Air Force Space Command radar system… think about how quickly can scan, and how precisely can control! Much better than mechanical.

- Each array is very wide, why? Think about last weeks lab…

- Tydex Optics sells the thin film anti-reflection coating shown at right… Was designed for 525 nm light (center of visible spectrum), but they decided to sell it for IR too… how?

(a) It has two coatings on it, one for visible, one for IR.
(b) IR light and visible light do not obey the same laws of optics or physics.
(c) The IR wavelength for anti-reflection is exactly double the visible anti-reflection, same interference principle has been met.
(d) All of the above are possible answers.



- Inteference and phased arrays can be used for:

(a) Steering visible light waves.
(b) Steering radar waves.
(c) Steering sound waves.
(d) All of the above.