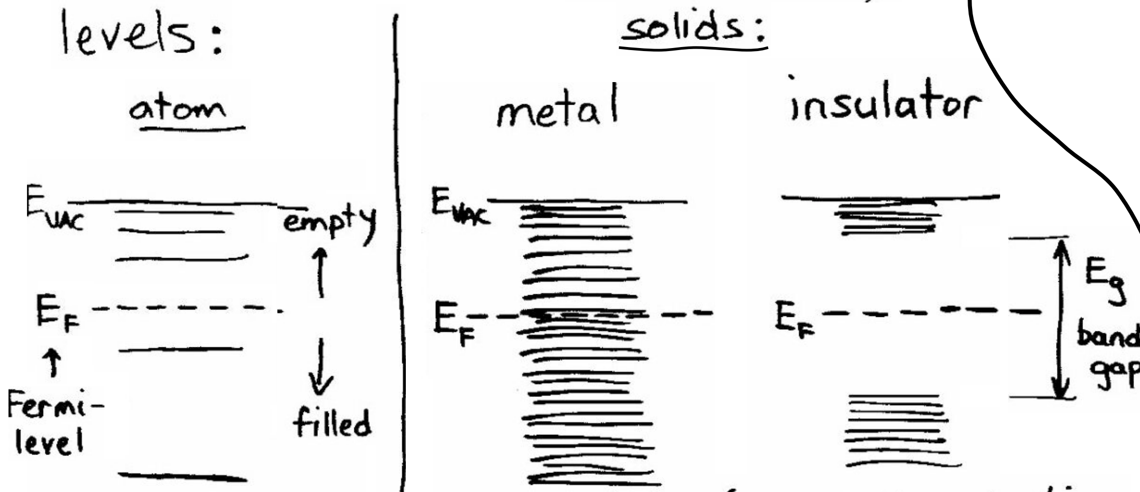
Interaction of Light with Insulators

what is an insulator? Look at energy levels:

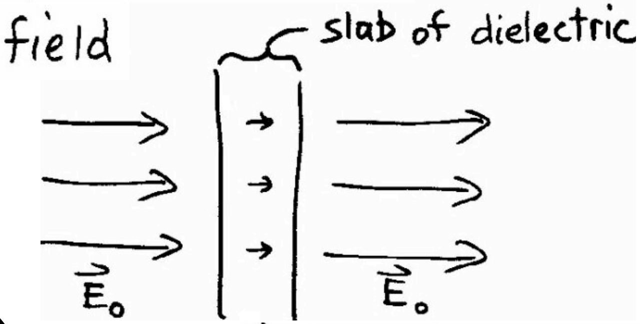


($E_g \lesssim 2$ eV, call this a semiconductor)

- when form solid, get "bands" of densely spaced levels
- for metal, can "excite" electron with arbitrarily small amount of energy (electrons are "free")
- for insulator need large amount of energy ($\geq E_g$) to excite electrons (electrons are "bound").

insulator = dielectric ; screens

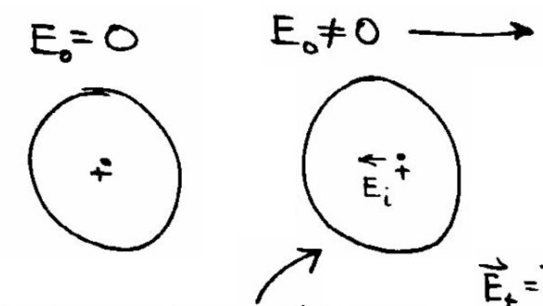
E-field



$E_t = \frac{E_o}{K_E}$; $K_E = 1-10$ dielectric const.

- how does this happen?

eg. H gas polarization



electron cloud shifts relative to nucleus

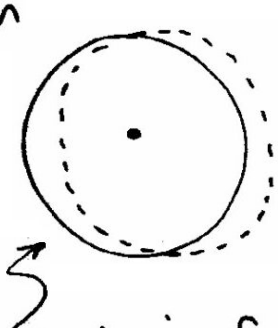
$\vec{E}_t = \vec{E}_i + \vec{E}_o$

$E_t < E_o$

- in solid, atom cores (ions) shift, and electrons shift

• prior description is for zero freq. (static) case. How about for nonzero freq. (dynamic) case?

eg. H atom



have restoring force (like a spring) between nucleus and electron cloud.

$\Rightarrow$ like a <u>driven</u> <u>oscillator</u>

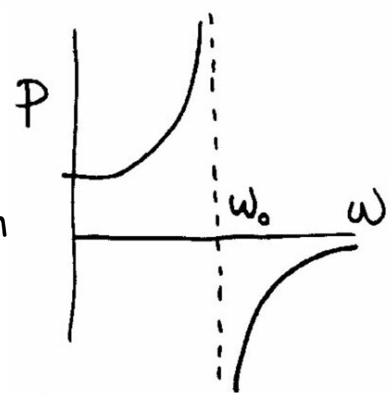
$$x(t) = \frac{e/m_e}{(\omega_0^2 - \omega^2)} E_0(t)$$

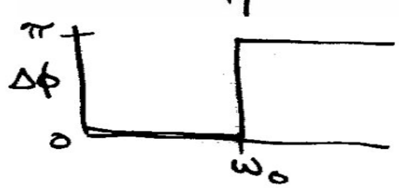
$p = ex$, induced dipole:

(continuum approx)

$$P = \frac{e^2 N E_0 / m_e}{(\omega_0^2 - \omega^2)}$$

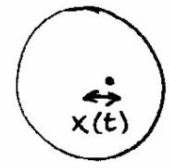
N = density of dipoles

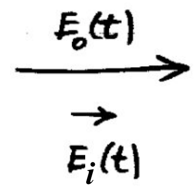




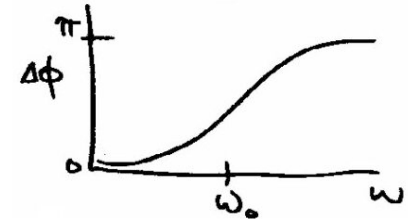
Now, what happens to the light in the material?

1) light causes atoms & electrons to oscillate at freq. ω:

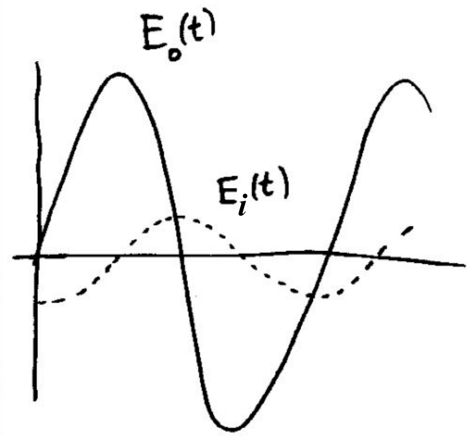


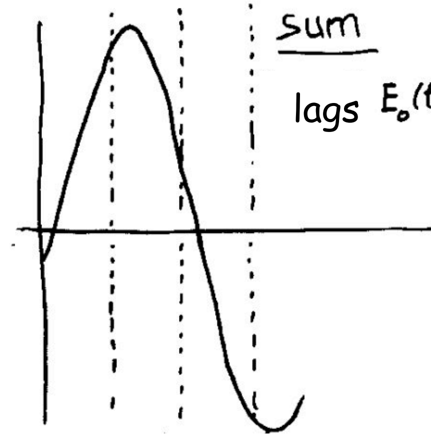


2) moving charges produce EM waves at same freq, but with phase shift:



(includes damping)





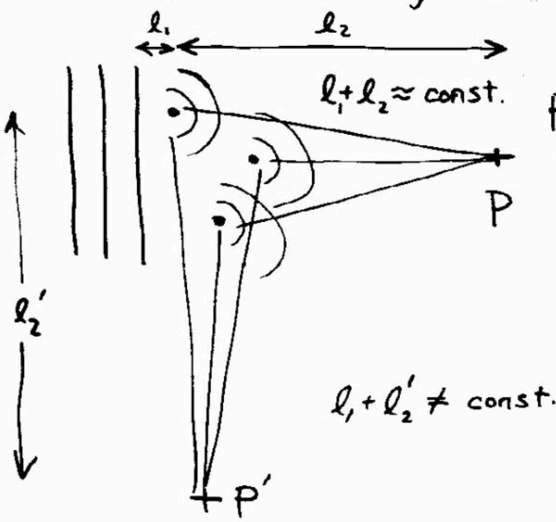
<u>sum</u>

lags $E_0(t)$

(sum may lead or lag $E_0(t)$)

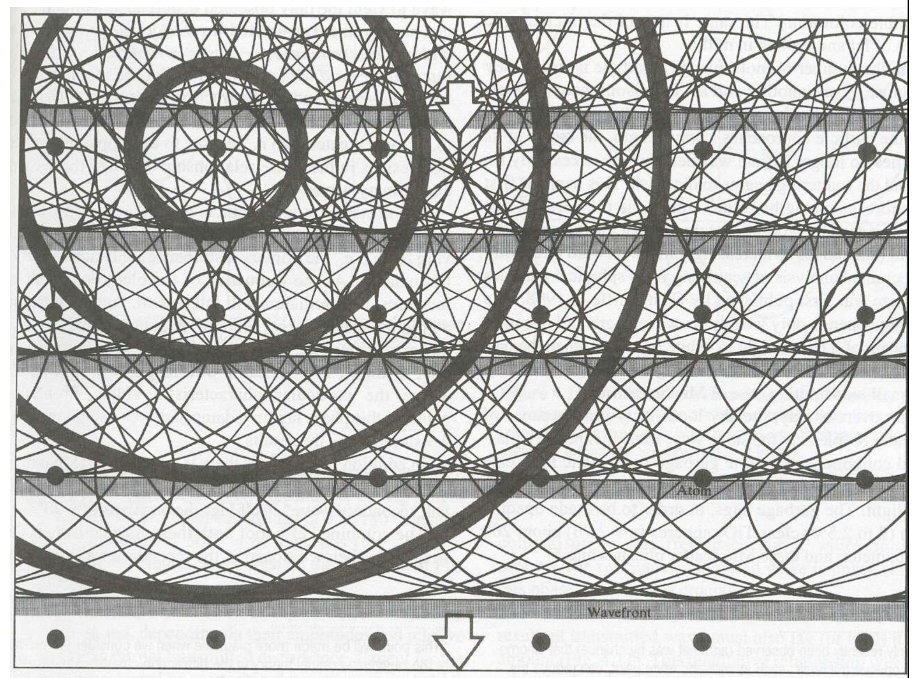
3) that new EM radiation interacts with successive atoms and is further phase shifted.

4) as light progresses thru dense solid, it is mainly <u>forward</u> <u>scattered</u>



phase of scattered wave at P is similar for forward scattering <u>only</u>.

Similarly for a plane wave incident on a broad array of scatterers:



(Fig. 4.8, Hecht)

[when sum all the phases of interfering waves get nontrivial result - will discuss later]

5) result is that the velocity of the EM wave in the material changes!

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}, \quad v = \frac{1}{\sqrt{\mu \varepsilon}} = \frac{1}{\sqrt{K_M \mu_0 K_E \varepsilon_0}} \Rightarrow n = \sqrt{K_E K_M}$$

$$v = \frac{c}{n} \quad ; \quad n^2 = K_E$$

n = index of refraction (neglect magnetic K_M term).

expression for n:

$E_{tot} = E_0 + E_i = K_E E_0 \qquad E_i = \frac{P}{\varepsilon_0}$ (!)

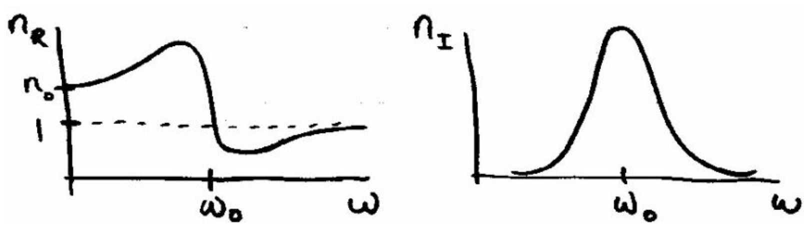
have $K_E = 1 + \frac{P(t)}{\varepsilon_0 E_0(t)}$

$$\Rightarrow n^2(\omega) = 1 + \frac{Ne^2}{\varepsilon_0 m_e}\left(\frac{1}{\omega_0^2 - \omega^2 + i\gamma\omega}\right)$$

damping term

need complex $\tilde{n} = n_R - i n_I$

result for one oscillator:



- n_R gives result for change in velocity
- n_I indicates absorption (attenuation) of wave

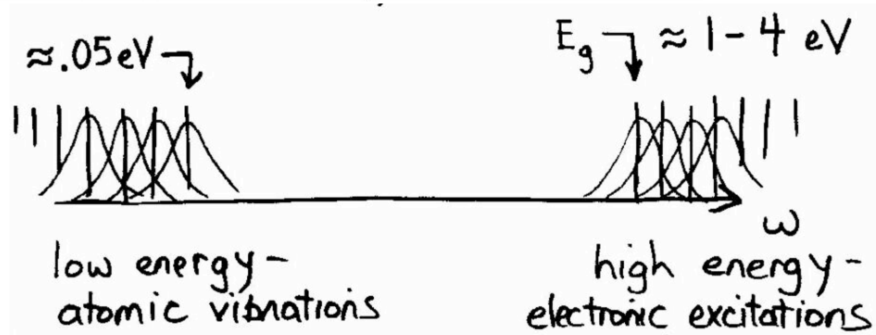
show this: consider $e^{i(\omega t - kx)} = e^{i\omega(t - x/v)}$

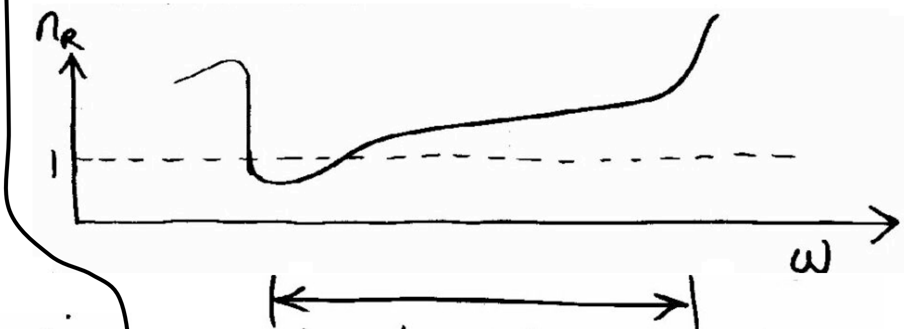
$v = \frac{c}{\tilde{n}} \Rightarrow$ have $e^{i\omega(t - \tilde{n}x/c)}$

$= e^{i\omega(t - \frac{n_R}{c}x + \frac{i n_I}{c}x)}$

$= \underbrace{e^{i(\omega t - \frac{n_R}{c}\omega x)}}_{\text{travelling wave}} \; \underbrace{e^{-\frac{n_I}{c}\omega x}}_{\text{absorption}}$

insulator - many "oscillators"





low absorption region; here, n_R increases slowly with ω (decreases with λ).

→ "Dispersion" of material.

eg. various glasses: