Laser Optics-I

ME 677: Laser Material Processing
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Outline

- Electromagnetic Radiation
- Laser-Matter Interaction
- Nonlinear Optics

Nature of Electromagnetic Radiation

- Wave-particle duality
  - de Broglie hypothesis relates wavelength (λ), and momentum (p): $$\lambda = \frac{h}{p}$$
  - h is Planck's constant
  - momentum of a photon is given by p = E/c wavelength by λ = c/ν

    where c is the speed of light in vacuum.

Electromagnetic waves

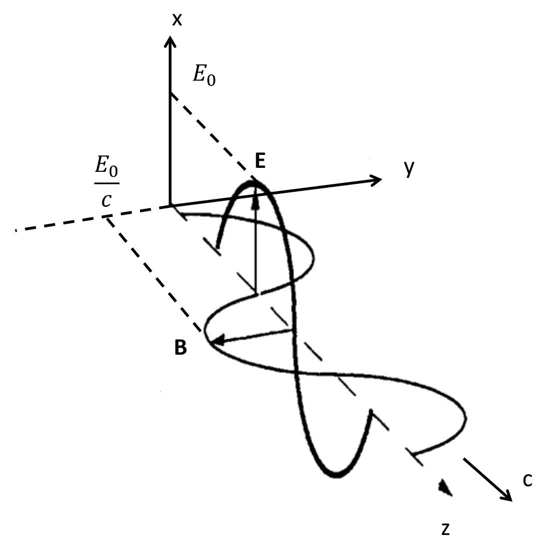
- Maxwell proposed the existence of a transverse wave whose speed, c, in free space was given by,

$$c = \left(\frac{1}{\varepsilon_0 \mu_0}\right)^{\frac{1}{2}}$$

- where μ_0 and ε_0 are the magnetic permeability and electrical permittivity, respectively.

$$\tilde{E}(z,t) = \tilde{E}_0 e^{-i(kz-\omega t)} \hat{x}$$

$$\tilde{B}(z,t) = \tilde{B}_0 e^{-i(kz-\omega t)} \hat{y}$$



Electromagnetic waves

$$B_0 = \frac{k}{\omega} E_0 = \frac{E_0}{c}$$

The real parts are given by,

$$E(z,t) = E_0 \cos(kz - \omega t + \delta)\,\hat{x}$$

$$B(z,t) = \frac{E_0}{c} \cos(kz - \omega t + \delta)\,\hat{y}$$

The energy per unit volume

$$u = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{1}{\mu_0} B^2\right) = \varepsilon_0 E_0^2 \cos^2(kz - \omega t + \delta)$$

Electromagnetic waves

As the wave travels it transports this energy along with it. The energy flux density (energy per unit area, per unit time) transported by the EM wave is given by the Poynting vector, $S = \frac{1}{\mu}(E \times B)$

For monochromatic plane waves propagating in the z direction,

$S = c\varepsilon_0 E_0^2 \cos^2(kz - \omega t + \delta)\,\hat{z} = cu\hat{z}$

It may be noted that the EM waves not only transport energy but also transport momentum. The momentum density (momentum per unit volume) stored in the EM field is given by, $g = \frac{1}{c^2} S$

The average values for a cycle $\left(\frac{1}{2\pi}\int_0^{2\pi} \cos^2\theta\right)$

- $\langle u \rangle = \frac{1}{2}\varepsilon_0 E_0^2$
- $\langle S \rangle = \frac{1}{2} c\varepsilon_0 E_0^2 \hat{z}$ (Intensity is magnitude of energy flux density)
- $\langle g \rangle = \frac{1}{2c}\varepsilon_0 E_0^2 \hat{z}$

Photon Properties of Different Lasers

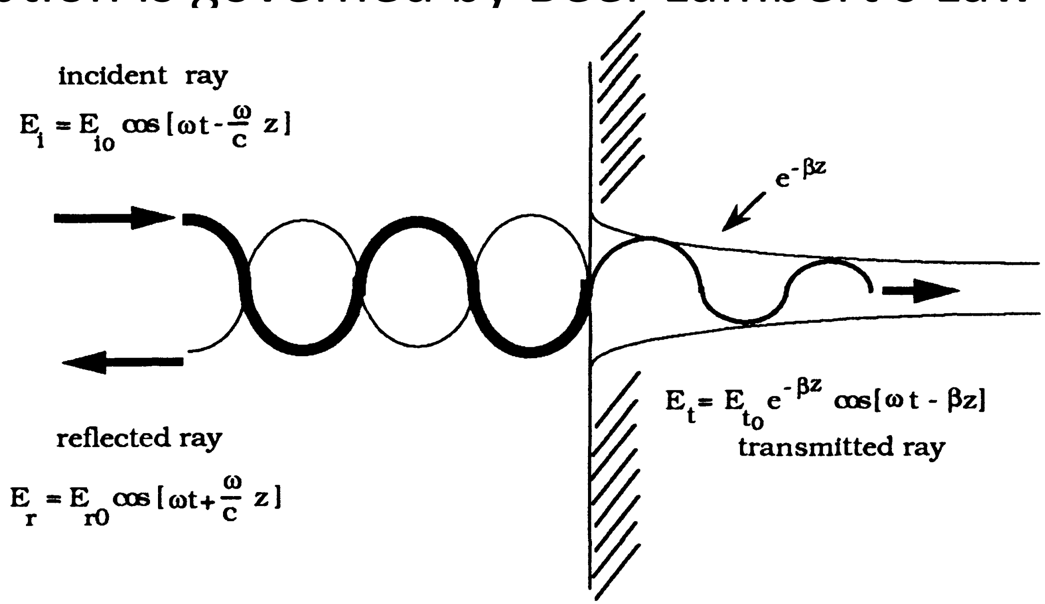
Table 2.1 Photon Properties of Different Lasers

Device	Source of Laser Energy	Wavelength λ (micron)	Frequency ν (Hz)	Energy Ep* (eV)	Energy Ep* (J x 1.0 E20)
Cyclotron	Accelerator	0.1(X-ray)	2.9 E15	12.3	192
Free Electron Laser (FEL)	Magnetic wiggler	1 E3-6	1 E8-11	1 E-6	1 E-2 to -5
Excimer	Atomic electron orbits	0.249 (u/v)	1.2 E15	4.9	79.4
Argon		0.488 (blue)	6.1 E14	2.53	40.4
He/Ne		0.6328 (red)	4.7 E14	1.95	31.1
Nd-YAG	Molecular vibration	1.06 (IR)	2.8 E14	1.16	18.5
CO		5.4	5.5 E13	0.23	3.64
CO2		10.6	2.8 E13	0.12	1.85

* Energy calculated from $E_p = h\nu$; 1eV = 1.6 E-19 J

Interaction of Electromagnetic Radiation with Matter

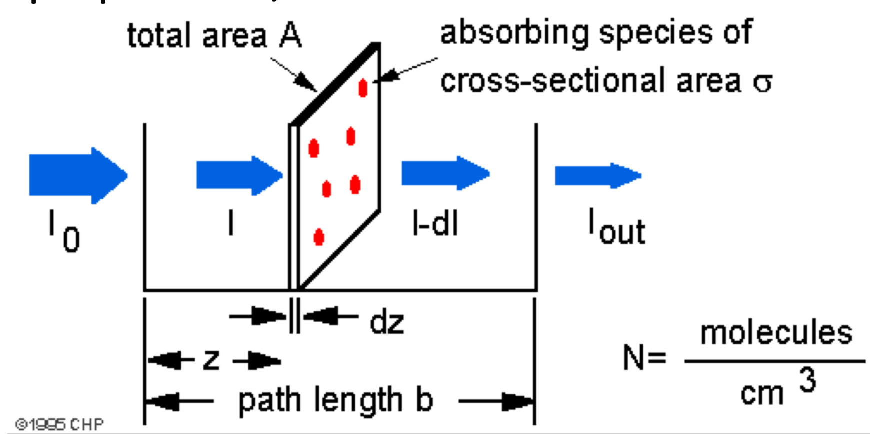
- When electromagnetic radiation strikes a surface
  - Reflection/Absorption/Transmission
  - Absorption is governed by Beer Lambert's Law



Beer Lambert's Law

- z as an axis parallel to the motion; A and dz are the area and thickness, respectively
  - dz is sufficiently small that one particle in the slab cannot obscure another particle
  - N is the concentration of opaque particles in the slab (particles/m^3) which absorb light
  - No. of photons absorbed is equal to the photons in the opaque area,
  - σ is the opaque area in m^2 of each particle
  - Fraction of photons absorbed = Opaque area/Total Area

    or, $\sigma N A\, dz/A = dI(z)/I(z)$
  - $I(z)$ @$z=0$ = I_0



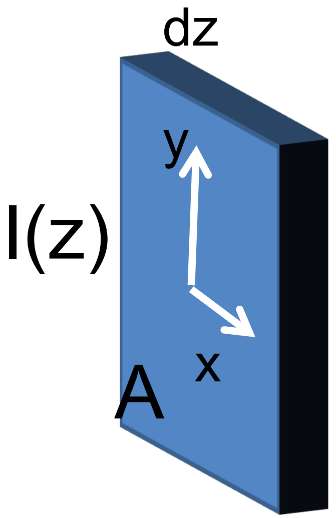
Derivation of Beer Lambert's Law

$$\int_0^z \frac{dI(z)}{I_z} = \int_0^z -\sigma N dz$$

$$\ln(I(z)/I_0) = -\sigma N z$$

$$I(z) = I_0 e^{-\sigma N z}$$

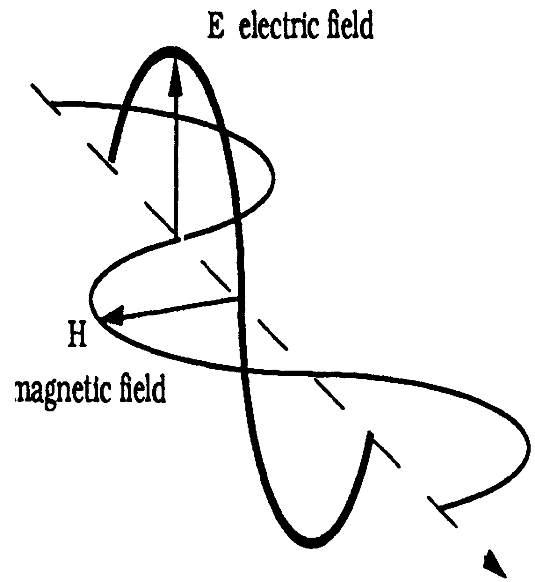
$$I(z) = I_0 e^{-\beta z}$$



β is a function of medium wavelength and intensity

Laser-Matter Interaction

- If the frequency does not correspond to natural frequency absorption does not occur
- Forced vibration induced by electric field, E is small and incapable of vibrating an atomic nucleus
- The energy transmission occurs due to photons interacting with free or bound electrons in metals
- The process of photons being absorbed by electrons is called inverse Bremsstrahlung effect
- This could result in either re-radiation in all directions or the electron is bound by lattice phonons (bonding energy in solid or liquid structure)



Laser-Matter Interaction

- The phonons will cause the structure to vibrate
- The vibration is transmitted by diffusion type process

  $q=-kAdT/dx$
- If sufficient energy is absorbed the vibration intensifies and molecular bonds could be broken which can lead to melting
- Vapor has little capability of photon absorption but plasma again has the capability due to presence of free electrons

Effect of Substrate Material

- In insulators and semiconductors
  - absorption occurs through resonant excitations such as transitions of valence band electrons to the conduction band
  - These excited electronic states can then transfer energy to lattice phonons
  - Photons with energy below the material's band gap will not be absorbed

Absorption in Metals

- Optical absorption is dominated by the free electrons through inverse bremsstrahlung
- Energy is subsequently transferred to lattice phonons by collisions
- The electron density of the material, N_e is related to plasma frequency (e is electron charge; m_e is electron mass and ϵ_0 is the permittivity)

$$\omega_p = \sqrt{\frac{N_e e^2}{m_e \varepsilon_0}}$$

- The absorptivity is high if the frequency of incident light is lower than plasma frequency because the electrons in the metal can screen the light

Absorption

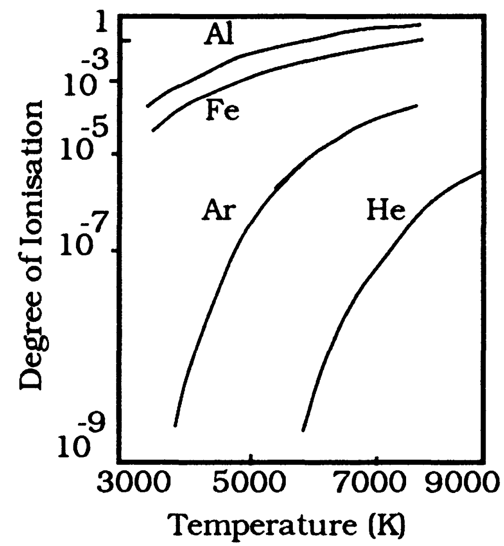
- The electron density in plasma is given by Saha Eqn.

$$\ln\left(\frac{N_i}{N_o}\right)^2 = -5040\left[\frac{V_i}{T}\right] + 1.5\ln(T + 15.385)$$

where Ni = ionisation density; N_o = density of atoms;

V_t = ionization potential, eV; T = absolute temperature, K.

This indicates that temperatures of the order of 10,000-30,000°C are required for significant absorption



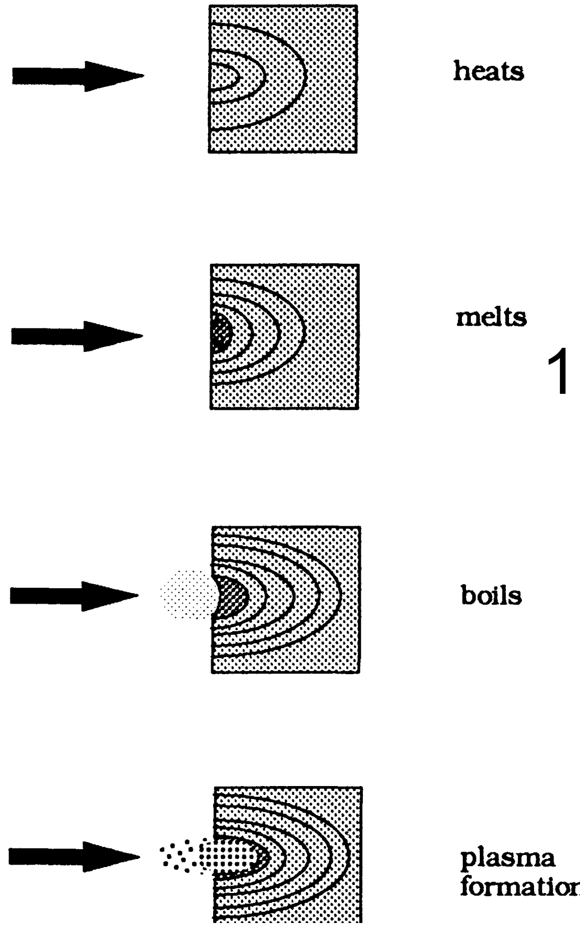
Time for Thermalization

- For most metals, thermalization time is on the order of 10^{-10} to 10^{-12} s

- For non-metals, absorption mechanisms and the thermalization time can be as long as 10^{-6}s

Sequence of Absorption

- Energy Intensity



10^3 W/mm^2

10^4 W/mm^2

10^5 W/mm^2

Nonlinear Optics

- First observed in 1961 Peter Franken at the University of Michigan
  - Ruby laser passing through a quartz crystal gave rise to UV radiation
  - Some of the key effects are presented in the next slides

Flouorescence

- Certain materials will absorb specifically at the frequency of the incident beam.
- The structure thus becomes excited.
- To lose this energy some materials may reradiate at a different frequency.
- This effect is known as fluorescence.

Stimulated Raman Scattering

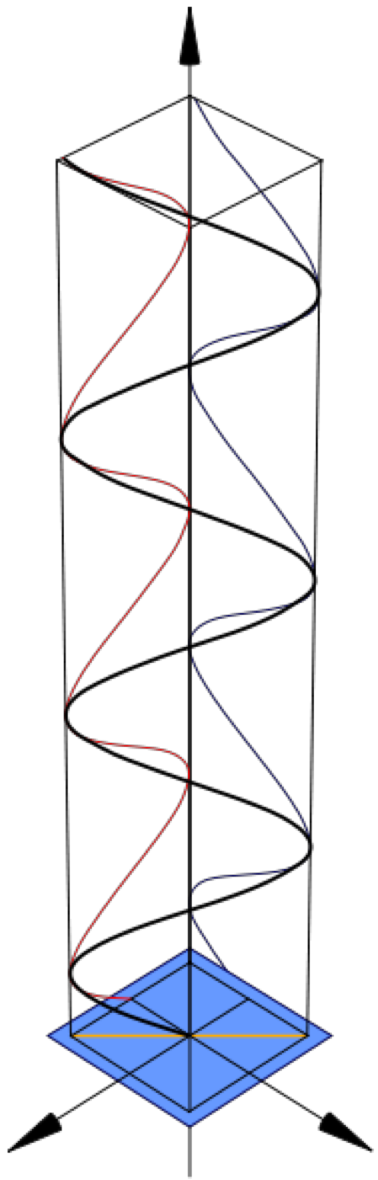
- If low intensity light is transmitted through a transparent material, a small fraction is converted into light at longer wavelengths with the frequency shifted (Stokes shift)
- This corresponds to the optical phonon frequency in the material.
- This process is called Raman scattering.
- At higher intensities, Raman scattering becomes stimulated, and from the spontaneous scattering a new light beam can be built up.

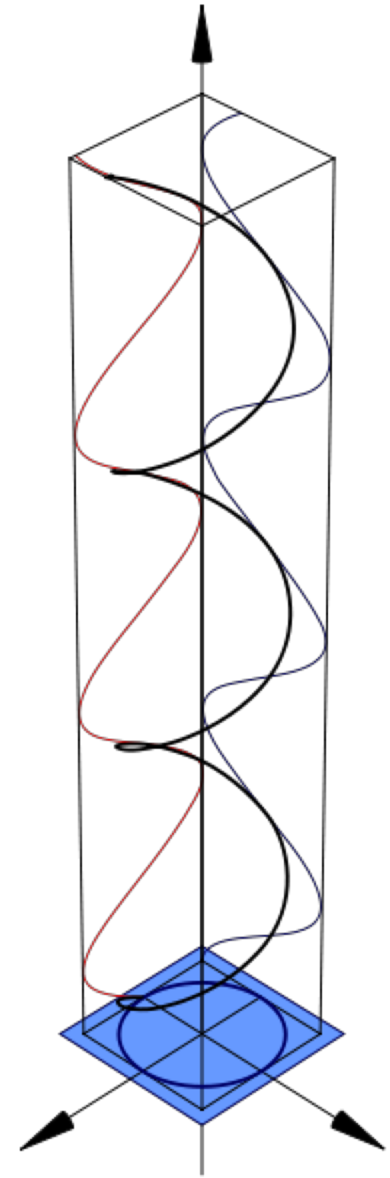
Stimulated Brillouin Scattering

- Acoustical phonons: Sound waves instead of light
- The corresponding frequency shift is much smaller. Acoustical phonons are sound waves
- The frequency shift exists only for the wave in the backward direction
- Again at high intensities the Brillouin effect becomes a stimulated process

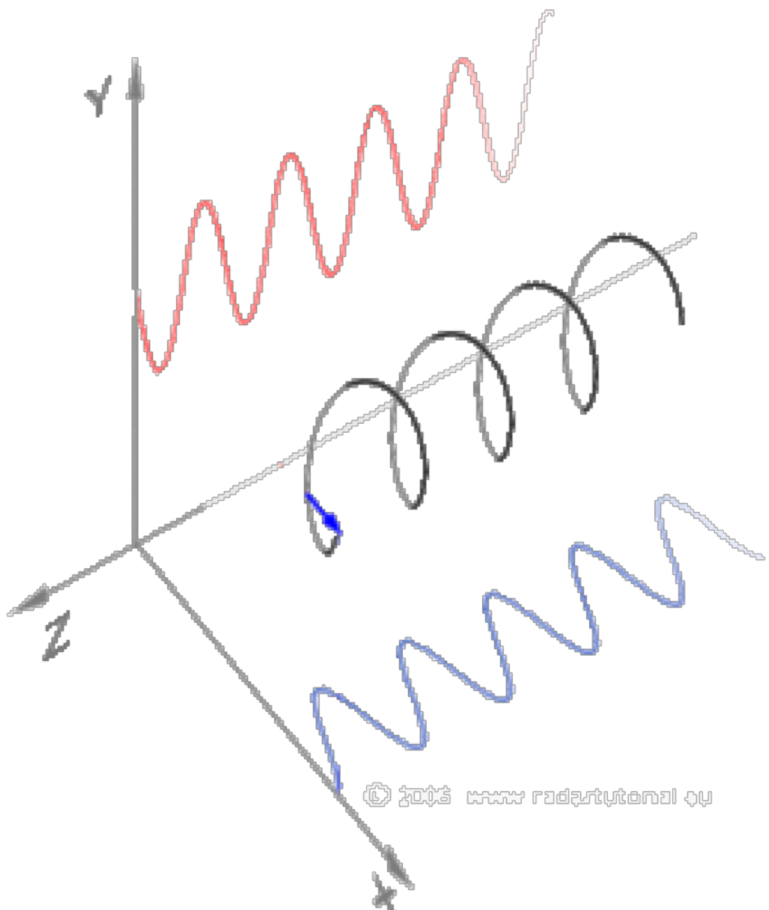
Second Harmonic Generation

- Second harmonic generation (SHG; also called frequency doubling) is a nonlinear optical process,
- Photons interacting with a nonlinear material are effectively "combined" to form new photons with twice the energy
- Yields twice the frequency and half the wavelength of the initial photons
- Uses birefringement crystal Lithium Niobate, Lithium Borate





Circular polarization



Optical Kerr Effect

- Variation in index of refraction which is proportional to the local irradiance of the light
- Refractive index variation is responsible for the nonlinear optical effects of self-focusing, self-phase modulation and modulational instability

Laser-Summary

- Electromagnetic radiation
- Absorption
- Nonlinear Optics
- Next will be optics
- Mode, focusing, propogation