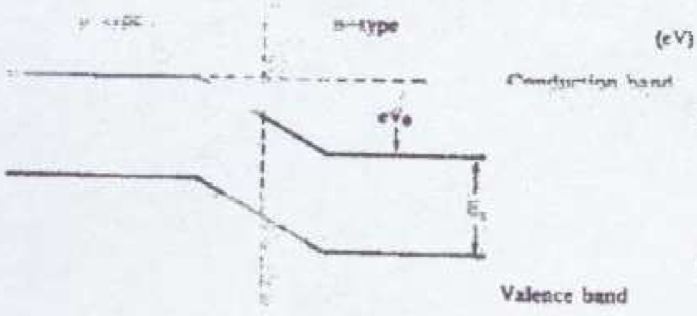
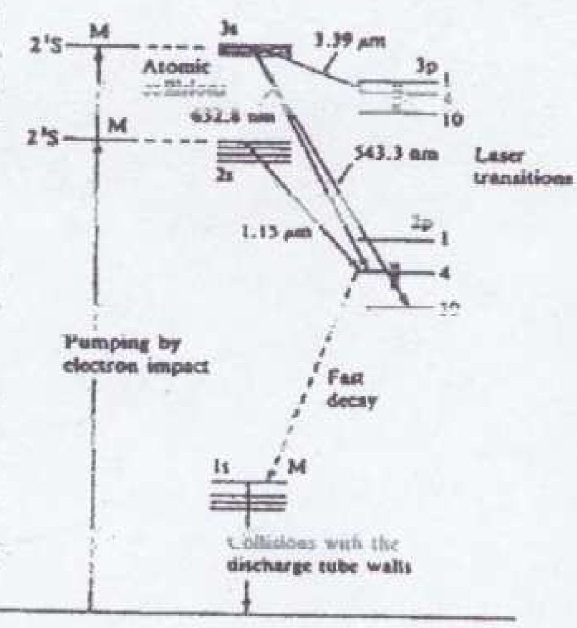
EE 176 **Professor Harold Fetterman**

Midterm **Feb. 13, 2003** **Closed Book**

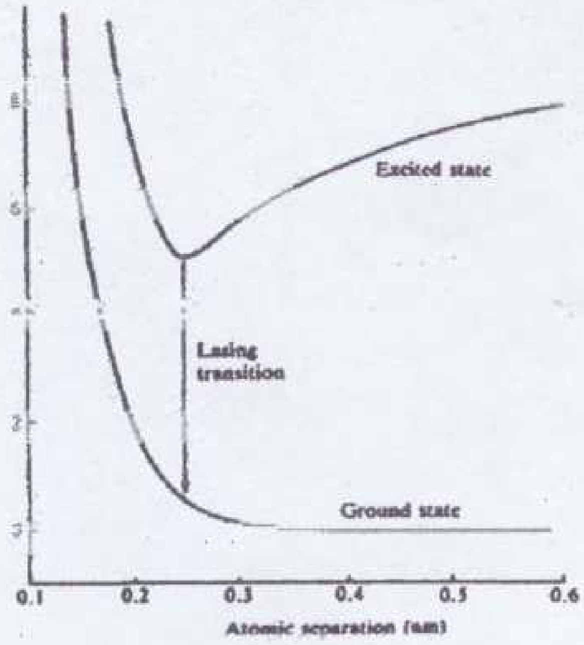
1A. For the following figures identify the system and the basic concept that is shown. In each case use no more than three sentences. Explain the specific lasing material and the mechanism for inversion.



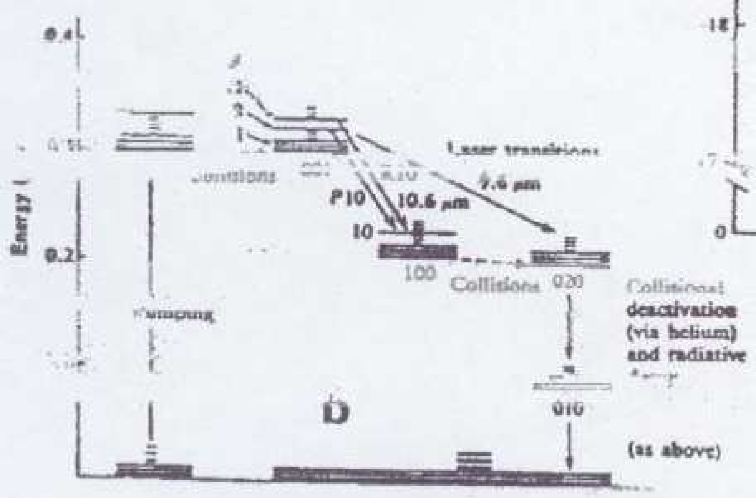
a



c



d



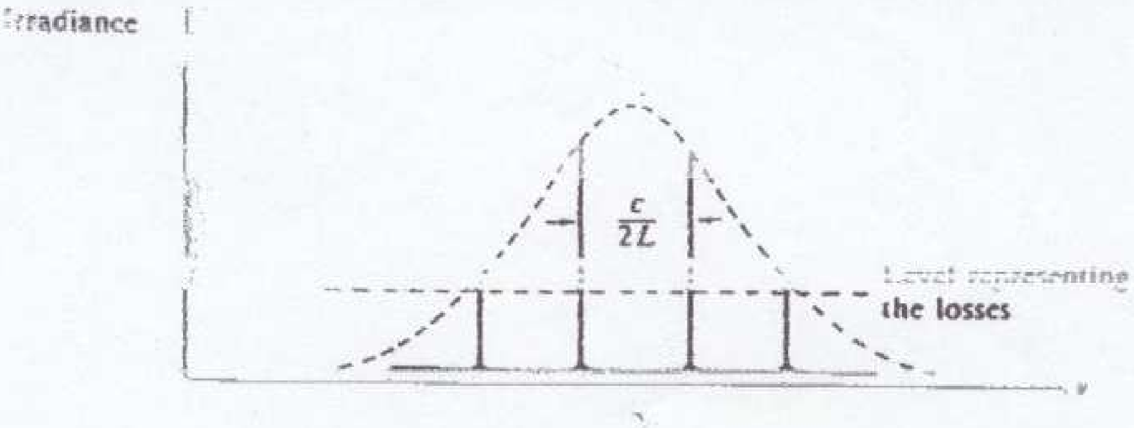
b

1B. In looking at stimulated emission we came up with a formula for the Einstein A and B coefficients.

$$N_1\rho_\nu B_{12} = N_2\rho_\nu B_{21} + N_2 A_{21}.$$

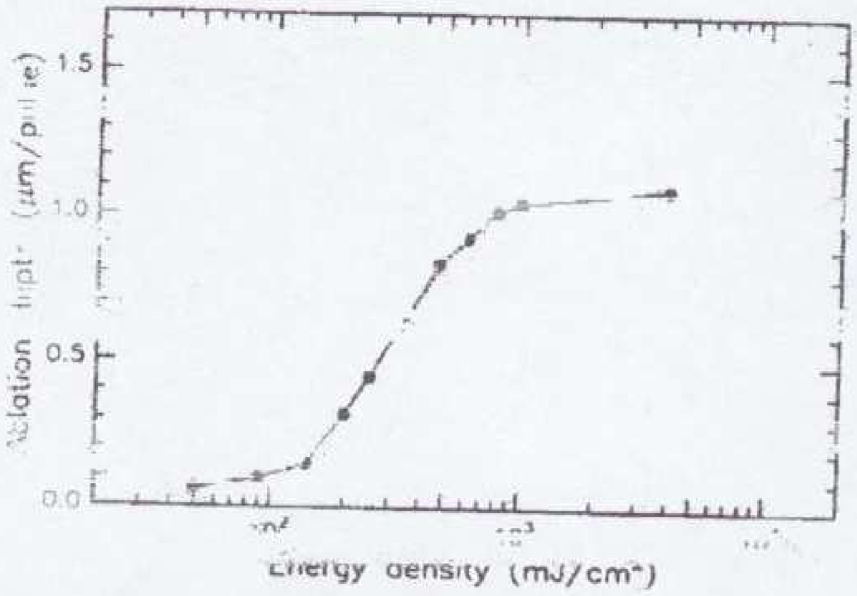
Write an expression for ρ_v and compare it with the equation that Planck derived for a Black body. Using this write an expression for the relationship between A_{21} and B_{21}. Then write the ratio between the rates of spontaneous and stimulated emission. Using this explain why lasers may operate best at low temperatures.

1C. Explain the concepts (using just a few sentences) of Q switched and mode locked lasers. Given the following spectra, how would I estimate the pulse length of this mode locked laser?



2A. We also talked about fibers and their NA. Define both this term and total internal reflection. Write an expression for the critical angle in the fiber θ_c taking the core n_1 and cladding n_2. Explain the difference between a step index fiber and a graded index fiber.

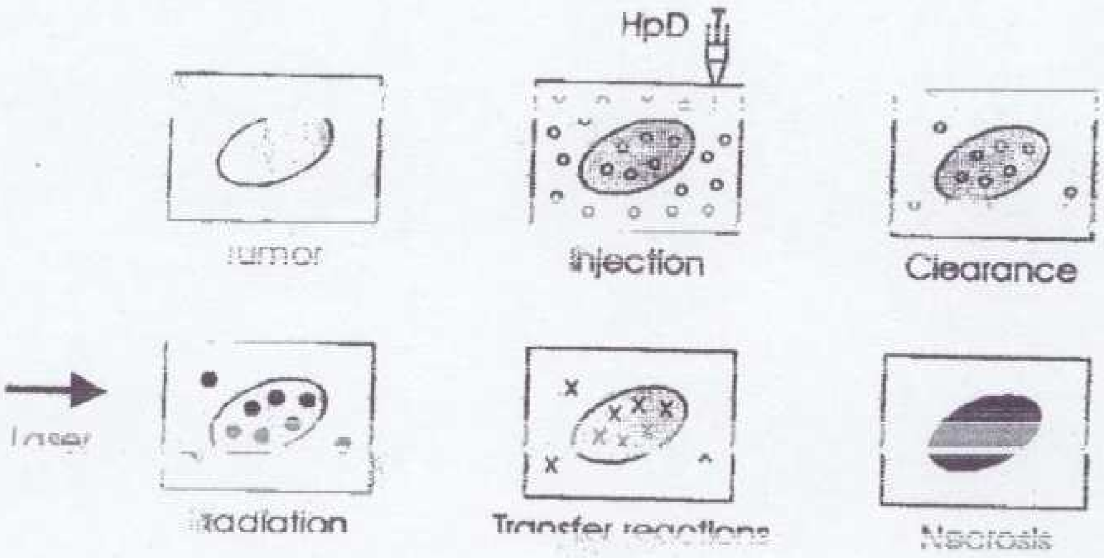
2B. In looking at ablation we derived an expression for depth d in the case of single pulses. Do we want high absorption to obtain deep ablation? Explain the following figure in terms of the threshold I_{ph} and the incident laser intensity.



$$I_0 \exp(-\alpha z) \geq I_{ph}$$

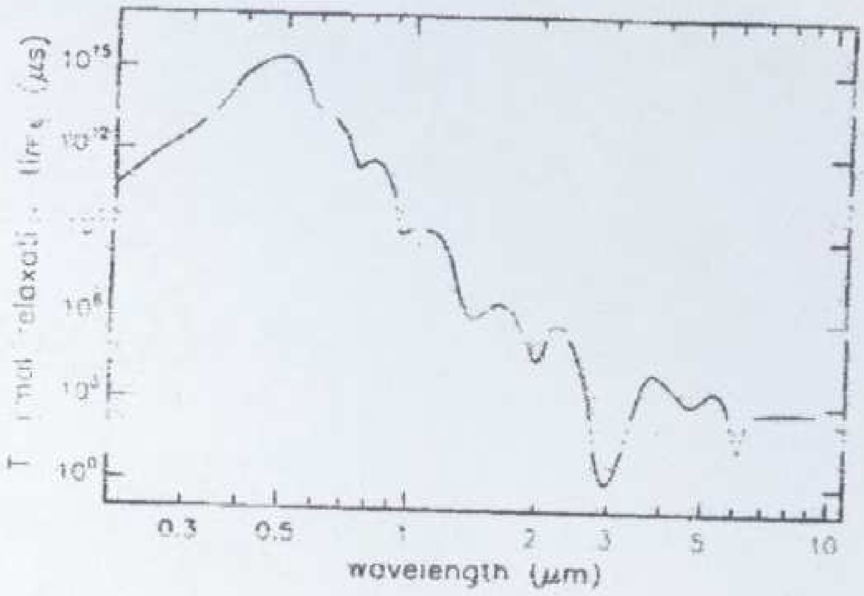
$$d = \frac{1}{\alpha} \ln \frac{I_0}{I_{ph}} \simeq \frac{2.3}{\alpha} \log_{10} \frac{I_0}{I_{ph}}$$

2C. We looked at the concept of PDT and examined the process of using it for cancer treatment. Explain the following diagrams in terms of locating and treating the tumors. Also indicate the mechanism of killing tumors with this technique.



3A. In terms of heat diffusion in tissue we derived an equation for the homogeneous case: On axis (r=0), what happens to the temperature at a given time t, in going from $z = z_o$ to $z = 3z_o$?

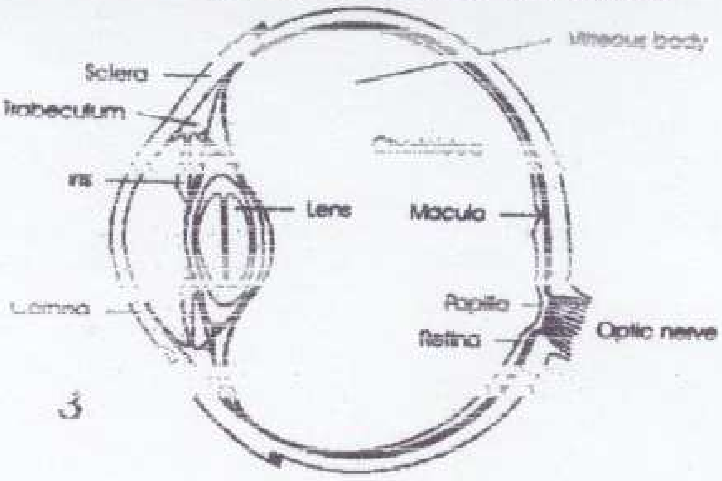
Define a penetration depth z_{therm} where the temperature has decreased to 1/e of its peak value at a given time. Now set this equal to the optical penetration depth $L = 1/\alpha$. This defines a parameter τ_{therm} (the thermal relaxation time). What is the significance of this term? Explain the following figure in terms of the spectral properties of water.

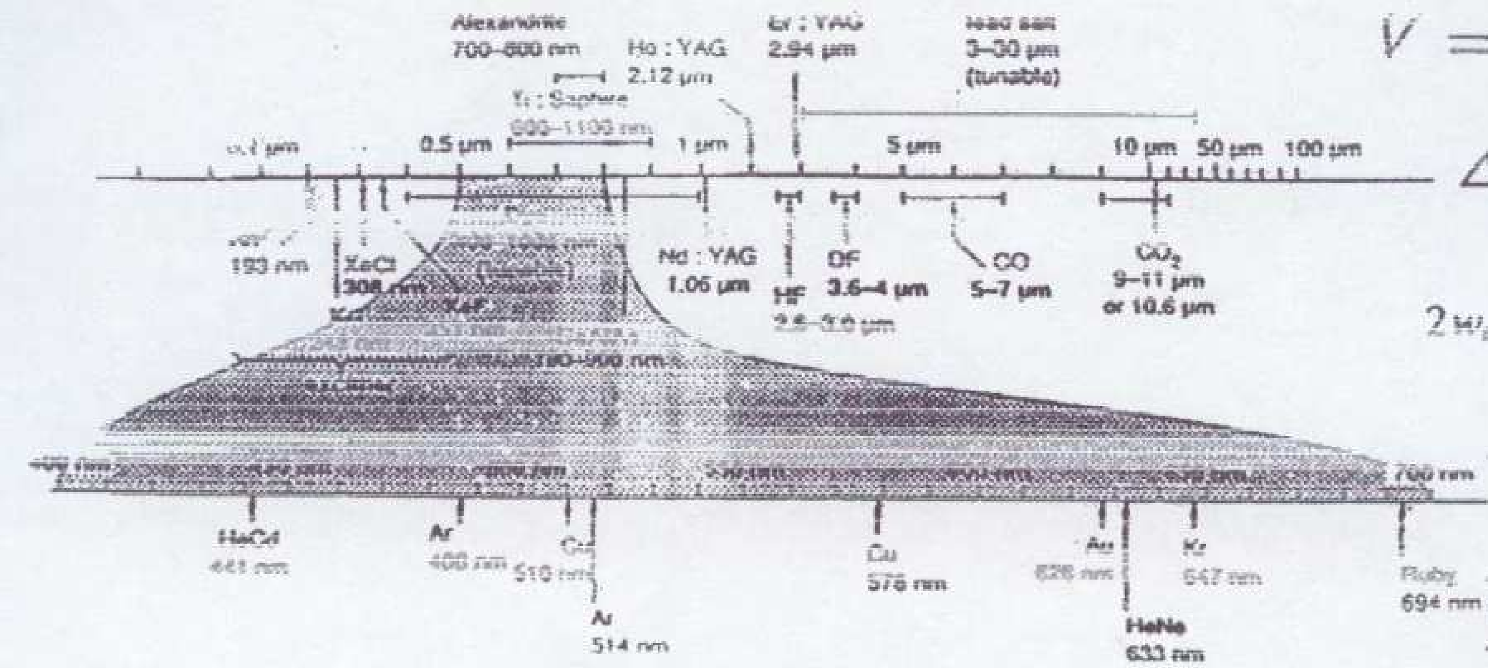


3B. We derived the following formula for the material to be removed to correct for myopia. Write an expression for how we would correct a given degree of myopia expressed in diopters ΔD. How would one correct for hyperopia using lasers in a similar way? Also which laser do we use for this procedure and why?

$$d(y) = \sqrt{R_i^2 - y^2} - \sqrt{R_f^2 - y^2} + \frac{R_i R_f}{y_{max}} \sin\left(\arcsin\frac{y_{max}}{R_i} - \arcsin\frac{y_{max}}{R_f}\right)$$

3C. In using Lasers for Ophtalmology there are problems ranging from Retinal detachment and macular degeneration, to cataract surgery and capsulotomy, and finally to corneal surgery. The lasers used for treatment include ArF excimer, Argon Ion, and Nd:YAG. Using the diagram below explain which laser is used in each procedure and why.



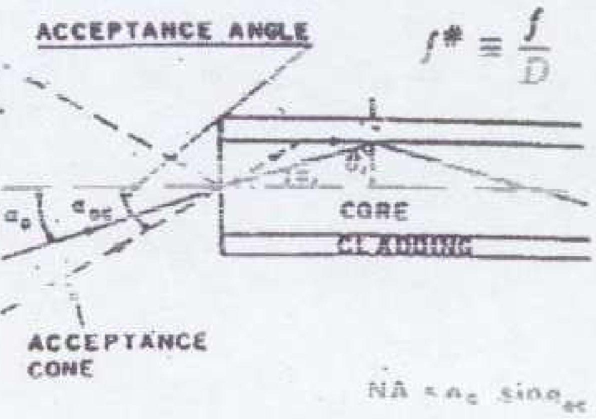


$$V = k_0 a(n_1^2 - n_2^2)^{1/2}$$

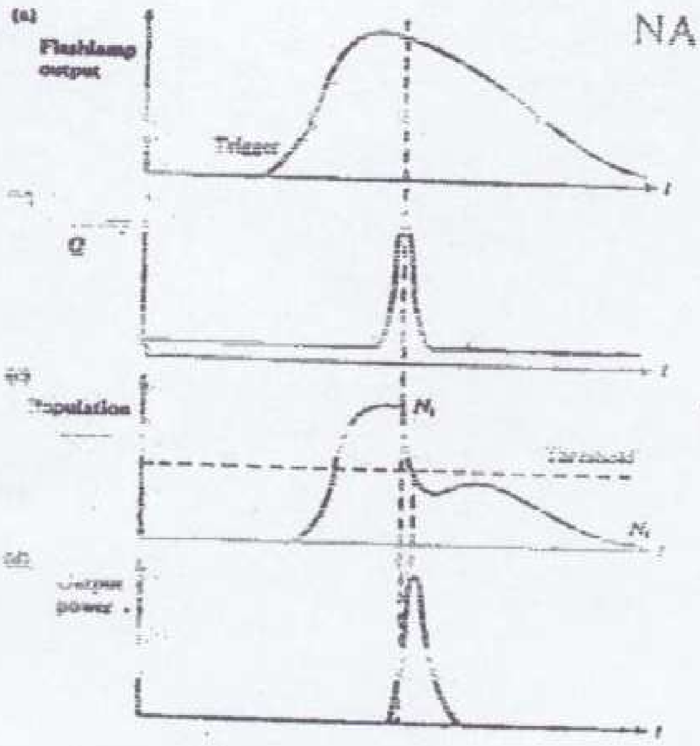
$$\Delta D = (n_c - 1)\left(\frac{1}{R_1} - \frac{1}{R_f}\right)$$

$$2w_0 = (4/\pi)(\lambda f/D) \approx d_0 \approx 2f^{\#}\lambda$$

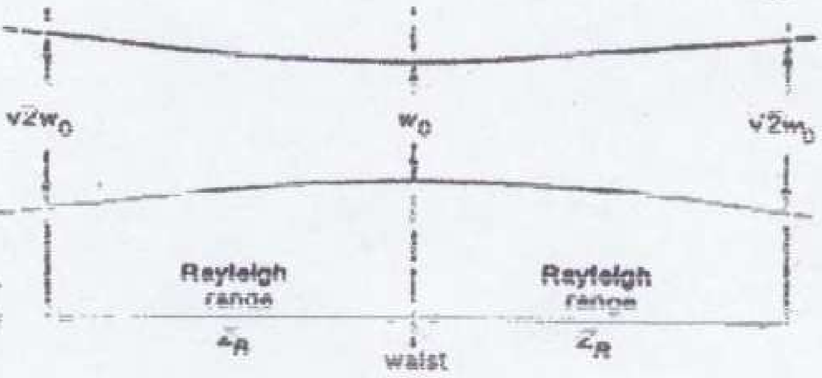
$$f^{\#} \equiv \frac{f}{D}$$



$$\mathrm{NA} = n_0 \sin \alpha_{0\max}$$



$$N \sim \Delta\nu/(c/2d)$$



$$\tau_p \sim \frac{2d}{c} \div \frac{\Delta\nu}{c/2d} \sim \frac{1}{\Delta\nu}$$

$$T(r,z,t) = T_0 + \frac{X_0}{(4\pi\kappa t)^{-3/2}} \exp\left(-\frac{r^2 + z^2}{4\kappa t}\right)$$

collimated range = $2z_R$

$$\rho_\nu = \frac{8\pi h\nu^3}{c^3}\left(\frac{1}{\exp(h\nu/kT) - 1}\right)$$

$\rho_\nu = \mathcal{A}h\nu$,

$$z_R \equiv \frac{\pi w_0^2}{\lambda} = \text{“Rayleigh range.}$$

spontaneous emission rate = $N_2 A_{21}$.

$$I(x) = I(0)\exp(-\alpha x)$$

$$\frac{N_1}{N_2} = \exp((E_2 - E_1)/kT)$$

stimulated emission rate = $N_2 \rho_\nu B_{21}$.

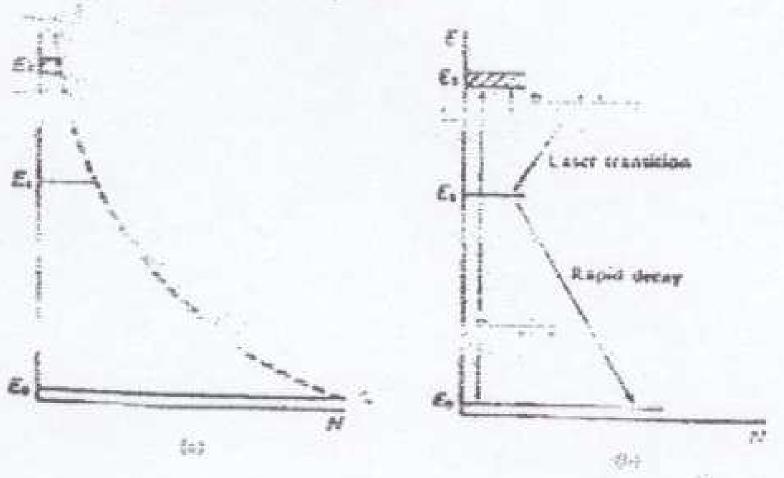
Snell's law:

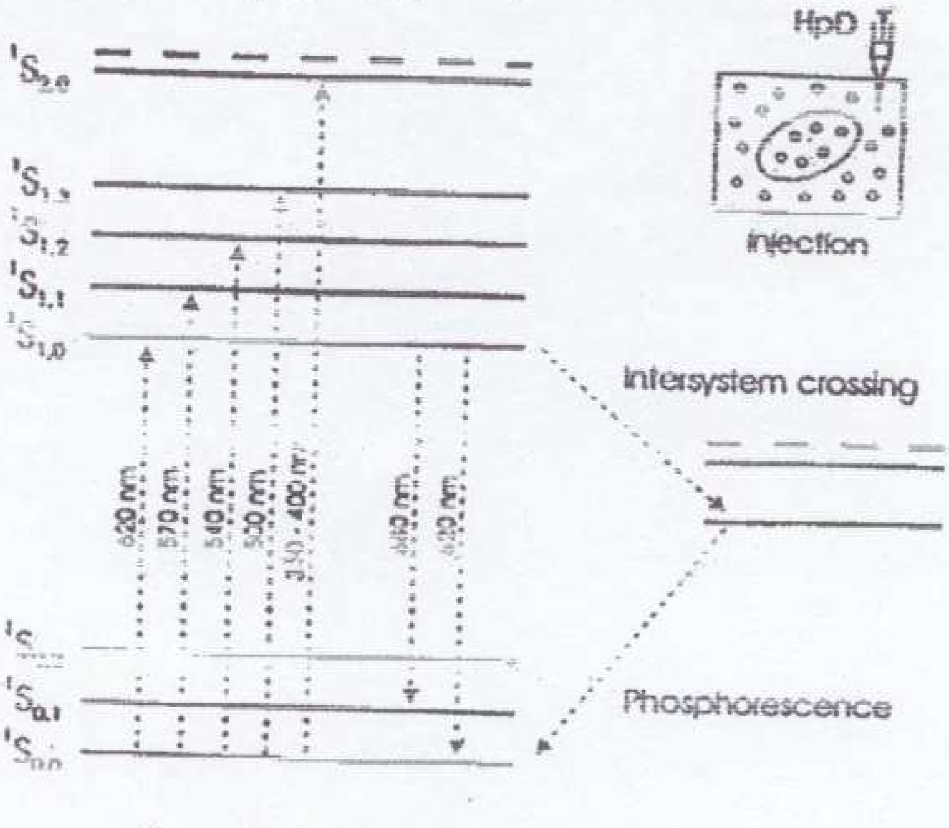
stimulated absorption rate = $N_1 \rho_\nu B_{12}$,

$$n_1 \sin \Theta_1 = n_2 \sin \Theta_2, \quad \theta_B + \theta_r = 90^\circ$$

$$I(t) = \frac{e(t)e^*(t)}{2\eta_0} = \frac{E_0^2}{2\eta_0}\left[\frac{\sin(N\omega_c t/2)}{\sin(\omega_c t/2)}\right]^2$$

$$\alpha_R = C/\lambda^4$$

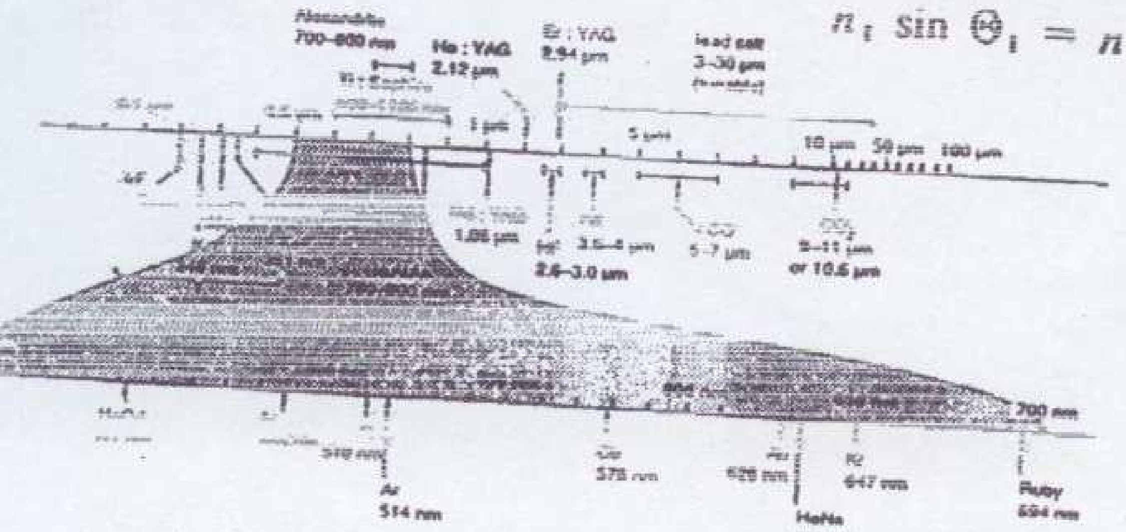




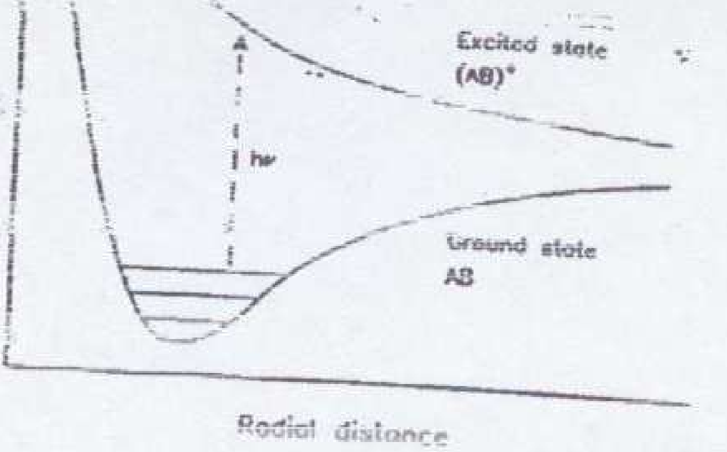
Energy level diagram of HpD

Shell's law:

$$n_1 \sin \Theta_1 = n_2 \sin \Theta_2.$$

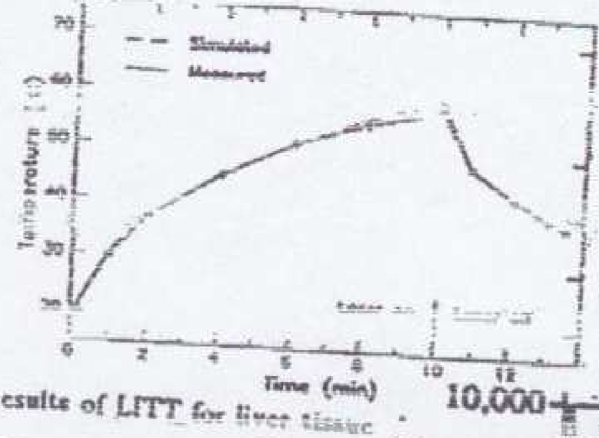


$$N \sim \Delta\nu/(c/2d)$$

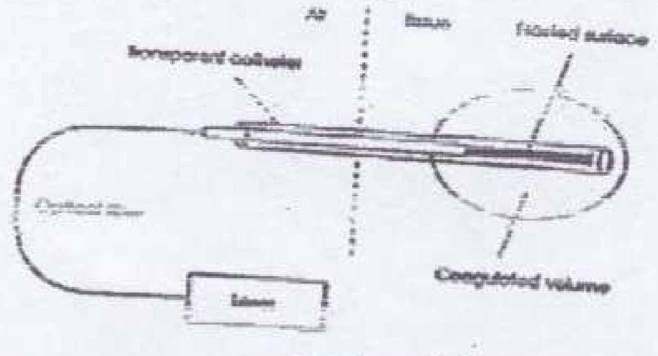


Thermal effects of laser radiation

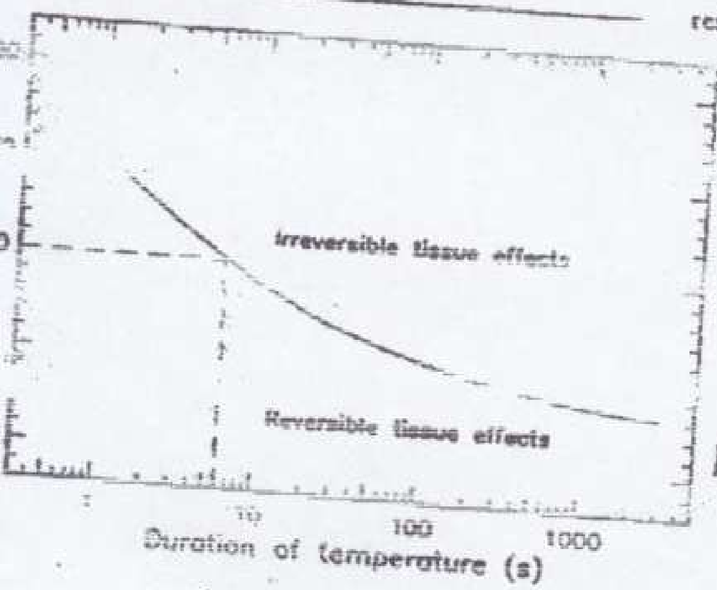
Temperature	Biological effect
37°C	Normal
45°C	Hyperthermia
50°C	Reduction in enzyme activity, Cell immobility
60°C	Denaturation of proteins and collagen, Coagulation
80°C	Permeabilization of membranes
100°C	Vaporization, Thermal decomposition (ablation)
> 150°C	Carbonization
> 300°C	Melting

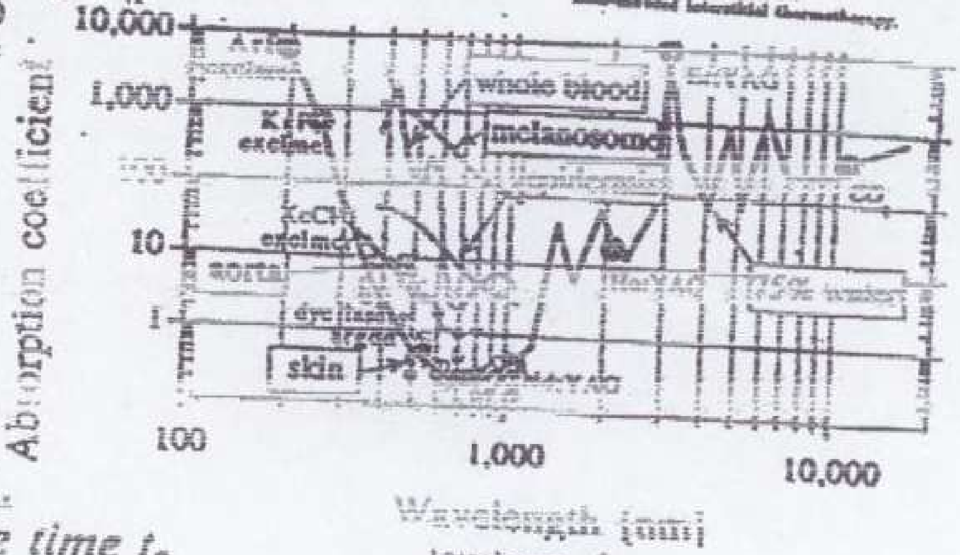


results of LITT for liver tissue



Laser-induced interstitial thermotherapy.





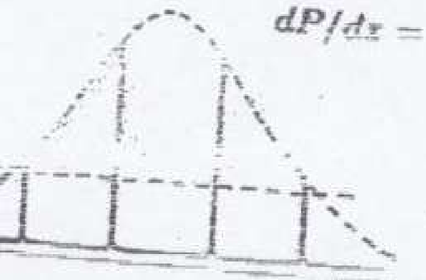
$$NA = n_0 \sin \alpha_{0max}$$

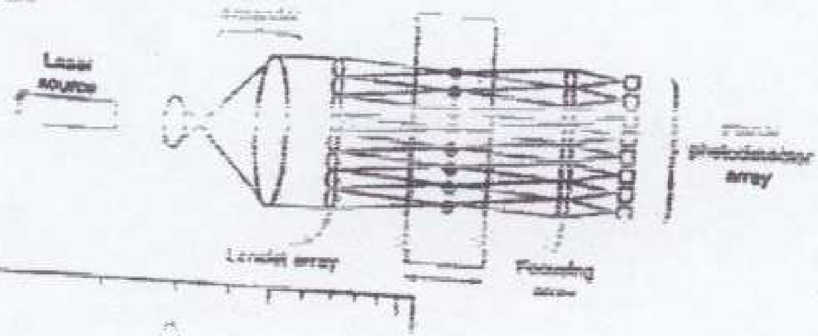
The coherence time t_c

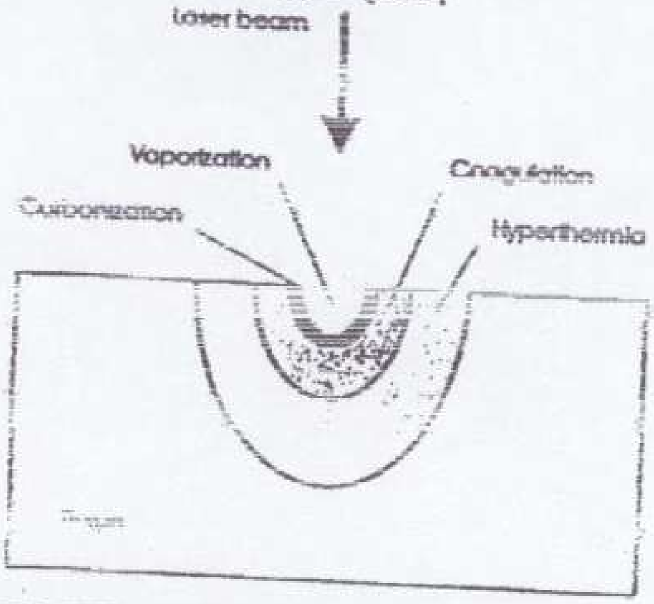
$$t_c = \frac{1}{\Delta\nu}.$$

Attenuation Coefficient

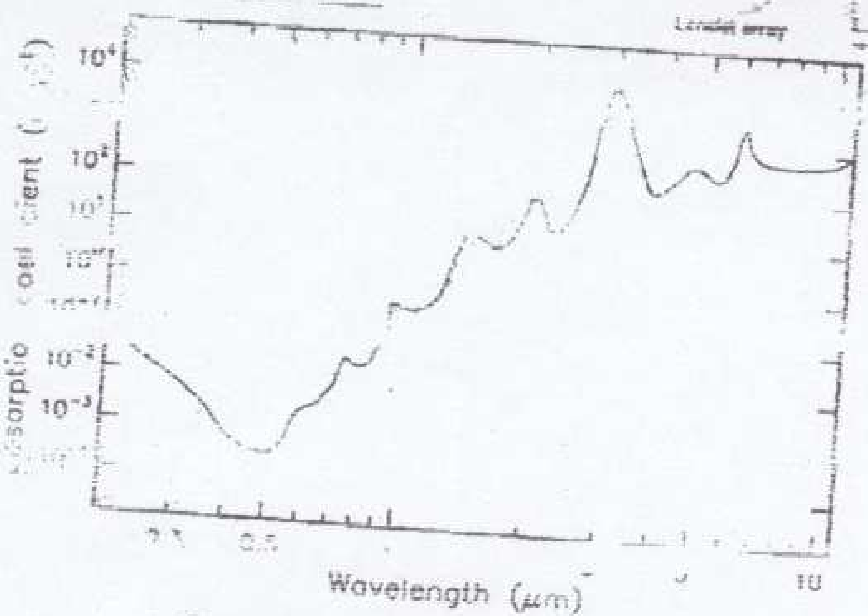
$$dP/dz = -\alpha P$$







Wavelength (nm)	Laser type	α (cm⁻¹)	L (cm)
193	ArF	0.1	10
248	KrF	0.018	55
308	XeCl	0.0058	170
[illegible]	XeF	0.0023	430
514	Argon ion	0.00029	3400
633	He-Ne	0.0029	340
694	Ruby	0.0068	150
800	Diode	0.020	50
1053	Nd:YLF	0.57	1.7
1064	Nd:YAG	0.61	1.6
2120	Ho:YAG	36	0.028
2940	Er:YAG	12000	0.00008
10600	CO₂	860	0.001



Doppler

$$\delta\nu/\nu = 2v/c$$

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1A a) semiconductor pn junction laser
Inversion from injection of carriers
in forward bias. Visible – near-IR.

b) CO_2 molecular gas laser. It lases in the infrared at 10.6 and 9.6 microns on vibrational-rotation levels. CO_2 is excited by collisions with N_2.

c) He Ne laser at 632 nm in the visible
He excited by current collides with Ne atoms. Also has a strong Near IR line at 1.15 μm.

d) excimer laser in the UV. Excimer is bound in excited state and not in the ground state. This is one of the few 2 level systems.

1B)
$$\rho_\nu = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}}$$

comparing $B_{12} = B_{21}$

$$A_{21} = B_{21} \frac{8\pi h \nu^3}{c^3}$$

now
$$R = \frac{N_2 A_{21}}{N_2 B_{21} \rho_\nu} = \frac{8\pi h \nu^3}{\rho_\nu c^3}$$

sub.
$$R = e^{\frac{h\nu}{kT}} - 1$$
This actually gets larger as $T \to 0$

However in an actual laser the lower level is depopulated and thus works better!

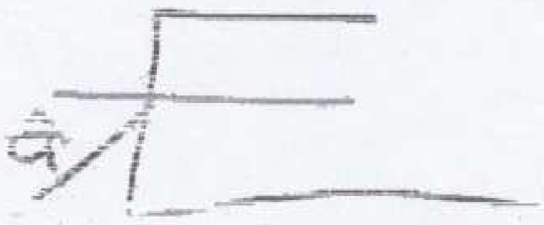
1C Q switching permits the inversion to build up to higher levels before lasing. This permits high power pulsed operation.

In a mode locked system the modes are oscillating with the same phase relationship. This permits them to add and produce high power pulsed output.

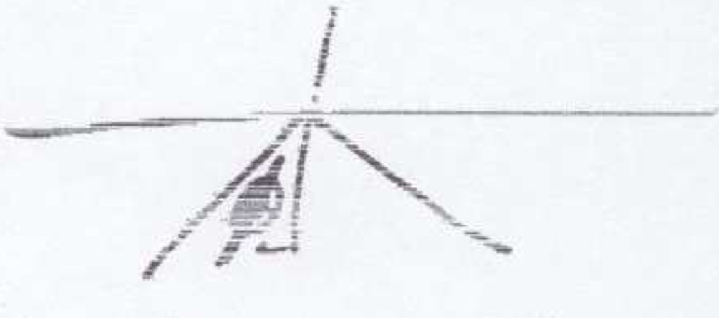
$$\text{now } \Delta t = \frac{1}{\Delta\nu} = \frac{1}{3\left(\frac{c}{2L}\right)} = \frac{2}{3}\frac{L}{c}$$

$\Delta\nu$ → total for all modes.

2A. NA - numerical aperture
$= n_0 \sin\theta_i$



now for total internal reflection



$\sin\phi_c = \frac{n_2}{n_1}$ this occurs when
$\phi > \phi_c$ and
$n_1 > n_2$

Since the sine of the refracted signal cannot be greater than 1.

a graded system has the light travel different amounts and thereby reduces multipath dispersion.

2B. In the single pulsed model,
the smaller $\alpha \Longrightarrow$ gives the deepest
pit

$\frac{1}{\alpha} \ln \frac{I}{I_{th}}$ There is a threshold
region – a linear region
for the log of I_0
Finally a saturation region.

2C.

1. a tumor is located
2. HpD is injected
3. It is taken up selectively by the cell and clears
4. light is shown [illegible] intensity creating $^1O^*$
5. This kills cancer cells

parts of the cell
are damaged by
the singlet $^1O_2^*$

Equations show role of 620 nm light

3A. $\frac{T_{z_0}}{T_{3z_0}} = \frac{e^{-\frac{z_0^2}{4\kappa\tau}}}{e^{-\frac{9z_0^2}{4\kappa\tau}}}$

$= e^{\frac{8z_0^2}{4\kappa\tau}} = e^{\frac{2z_0^2}{\kappa T}}$.

$z_{therm} = \sqrt{4\kappa t}$ ← when T is reduced to $\frac{1}{e}$ levels.

$L = \sqrt{4\kappa t} = \sqrt{4\kappa t_{therm}}$.

$\tau_{therm} = \frac{L^2}{4\kappa} = \frac{1}{4\alpha^2\kappa}$ If the light pulse is
longer than this it will damage tissue from thermal

2B. In the single pulsed model, the smaller $\alpha \Longrightarrow$ gives the deepest pit.

$d = \frac{1}{\alpha} \ln \frac{I_0}{I_{th}}$ There is a threshold region – a linear region for the log of I_0 – finally a saturation region.

2C.

1. a tumor is located
2. HpP is injected
3. It is taken up selectively by the cell and clear
4. light is shown on it to activate creating $'O^*$
5. This kills cancer cells

parts of the cell are damaged by the singlet $'O^*$ Equations show role of 620 nm light

3A. $$\frac{T_{z_0}}{T_{3z_0}} = \frac{e^{-\frac{z_0^2}{4K\tau}}}{e^{-\frac{9z_0^2}{4K\tau}}} = e^{\frac{8z_0^2}{4K\tau}} = e^{\frac{2z_0^2}{K\tau}}.$$

$z_{therm} = \sqrt{4Kt}$ ← when T is reduced to $\frac{1}{e}$ leve

$\frac{1}{\alpha} = \sqrt{4Kt} = \sqrt{4K\tau_{therm}}$.

$\tau_{therm} = \frac{L^2}{4K} = \frac{1}{4\alpha^2 K}$ If the light pulse is longer than this it will damage tissue from therm diffusion processes. Note the figure is the inverse of the absorption curve in the equations section.

3B. Solve for R_f in terms of ΔD.

Then we substitute in the equation using the initial R_i, the R_f in terms of ΔD and y. This gives us $d(y)$ for each y.

3C. Argon laser for the Retinal detachment and macular since it penetrates to the back of the eye.
excimer ArF is totally absorbed in the cornea ← surgery and corneal correction.
The Nd : YAG is used for cataract surgery and capsulotomy since it is high power and penetrates soft tissue.