Optical and Photonic Glasses

Lecture 35:

Laser Glasses I

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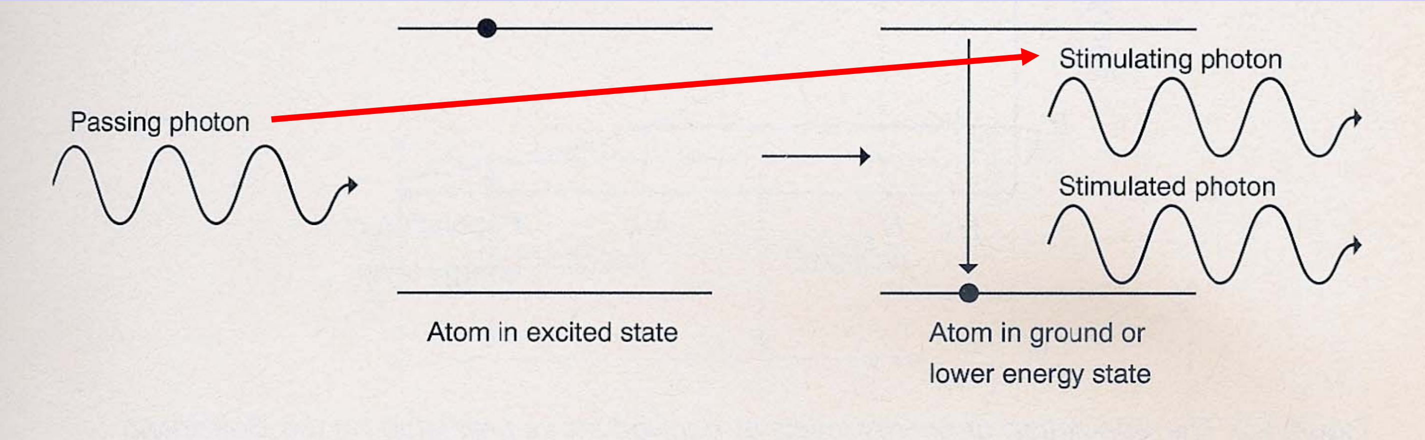
Laser glasses

In the photoluminescence (PL) processes previously discussed, *spontaneous*, rather than *stimulated* emission was considered. Spontaneous light emission is *incoherent*, that is, there is no phase relation between the different photons emitted.

On the contrary, in a LASER (Light Amplification by Stimulated Emission of Radiation), the (stimulated) emitted radiation is *coherent*, that is, all photons are *in phase* with each other and have the same frequency and polarization, in addition to being highly collimated along the direction of propagation.

In the stimulated emission process, an excited atom or ion is *persuaded* to emit a photon by the passage of another photon of the correct energy near the excited atom:

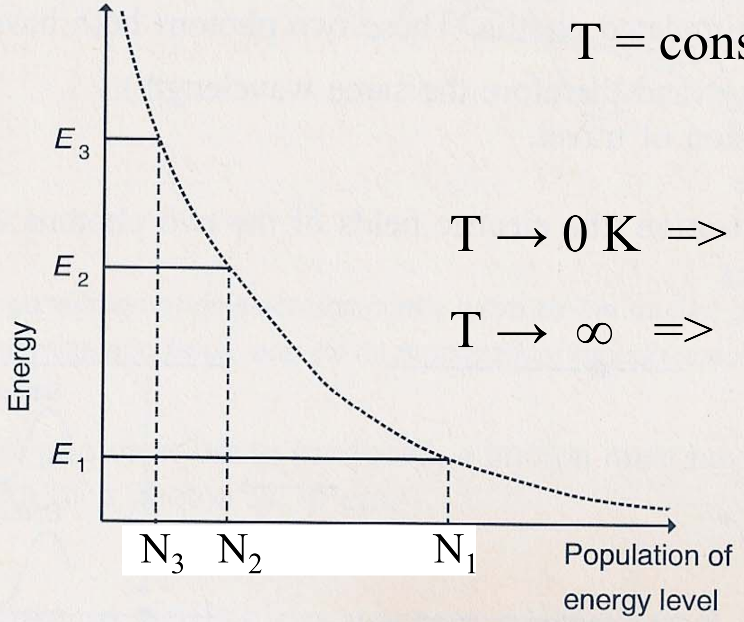


The process of stimulated emission.

(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice hall, 1998)

The distribution of the atoms or ions among the different electronic energy levels has an exponential shape, according to the Maxwell-Boltzmann formula. Thus, the population of the ith energy level, for a system in equilibrium containing N_o atoms in the ground state ($E_o = 0$), is a function of the energy and temperature:

$$N_i = N_o \exp(-E_i / k_B T) \quad \Leftarrow\!\Rightarrow \quad N_i / N_j = \exp[-(E_i - E_j) / k_B T]$$



T = const.

$T \rightarrow 0\text{ K} \Rightarrow N_i \rightarrow 0$

$T \rightarrow \infty \Rightarrow N_i \rightarrow N_o$

The population of energy levels at equilibrium as predicted by the Boltzmann distribution.

(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice hall, 1998)

In the two-energy-level system below, the rate of excitation to level 2 will be:

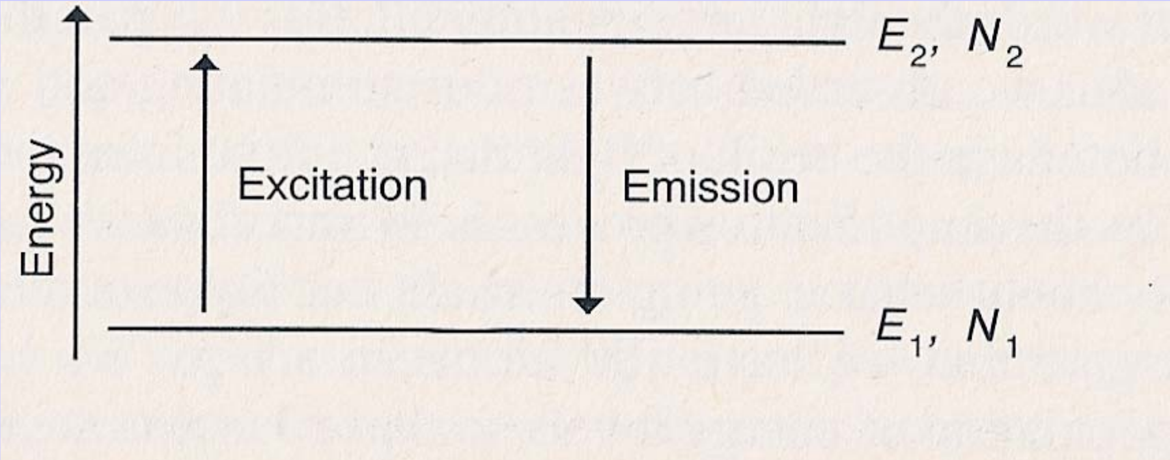
$$W_{1,2} = N_1 B_{1,2} \rho_v$$

where ρ_v is the density of exciting photons and $B_{1,2}$ is the Einstein coefficient for *absorption* (excitation), expressing the absorption probability. The *spontaneous emission* rate is:

$$W_{2,1} = N_2 A_{2,1}$$

and the *stimulated emission* rate is: $W_{2,1} = N_2 B_{2,1} \rho_v$

For a system in equilibrium: $W_{1,2} = \Sigma W_{2,1} \iff N_1 B_{1,2} \rho_v = N_2 B_{2,1} \rho_v + N_2 A_{2,1}$
note that $(B_{1,2} = B_{2,1} = B)$.



Excitation and emission in a two-energy-level system.

(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice Hall, 1998)

The excitation light density may be given by Planck's black-body emission law:

$$\rho_v\,(\lambda) = 8\,\pi\,h\,/\,\{\lambda^3\,[\exp(h\nu/k_BT)-1]\} \qquad (\text{in J s / m}^3)$$

Then:

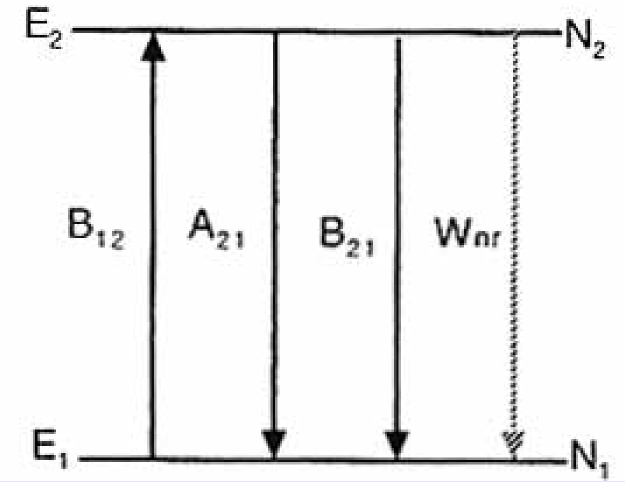
$$N_2\,/\,N_1 = \exp(-\,h\nu/k_BT) = B\,\rho_v\,/\,(B\,\rho_v + A) \Leftrightarrow$$

$$\Leftrightarrow (B\,\rho_v + A)\,/\,(B\,\rho_v) = 1 + A\,/\,B\,\rho_v = \exp(h\nu/kT) \Leftrightarrow$$

$$\Leftrightarrow A\,/\,(B\rho_v) = \exp(h\nu/k_BT)\,-1 \qquad \Leftrightarrow \qquad A\,/\,B = 8\,\pi\,h\,/\,\lambda^3$$

This shows that, at room temperature and for visible or NIR wavelengths ($h\nu >> kT$), spontaneous emission clearly dominates over the stimulated one.

For a system in equilibrium, therefore, spontaneous emission will dominate over the stimulated one, for the temperatures and wavelength ranges of interest . In order to make stimulated emission dominate, the system has to be taken out of equilibrium and the spontaneous emission term has to be made negligible. If one increases ρ_v, this may happen, but, in the limit, one can make $N_2 = N_1$ at most, whereas one actually needs to have $N_2 > N_1$, corresponding to *population inversion*, in order to have light *amplification*.

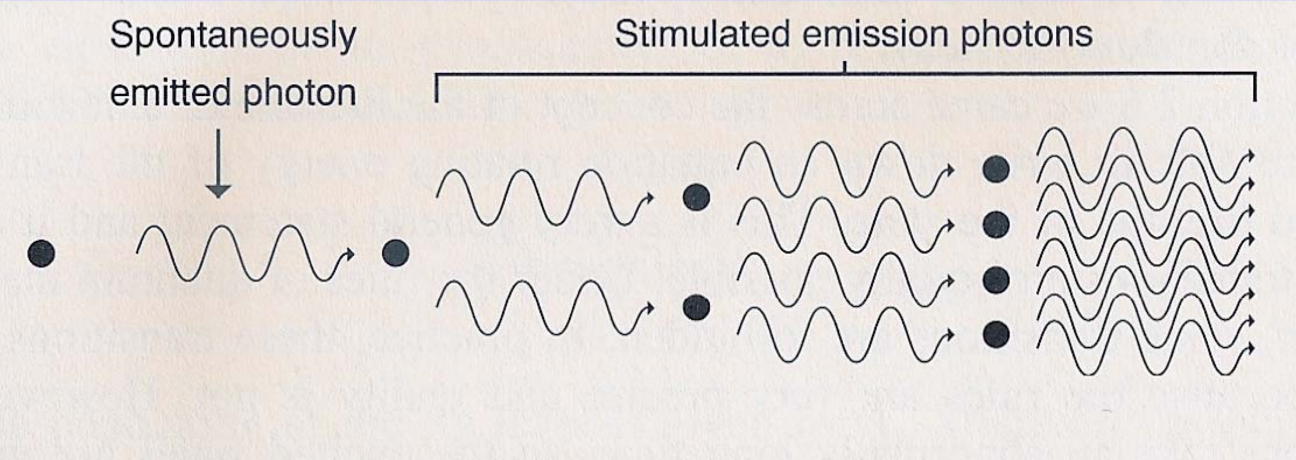


Simple two-level system with population N_1, N_2 and energy E_1 and E_2 respectively.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

The key to *amplification* by stimulated emission is the *cascade* process. If one has 50 atoms in the excited state and 50 in the ground state and one of the excited atoms decays and emits a photon and this photon passes by another excited atom and causes *stimulated emission* of a second photon, these two photons may still stimulate production of a further two photons and so on.

This corresponds to a cascade of stimulated photons and to *amplification* of light, although some of the produced photons may actually be absorbed by atoms in the ground state (GSA). The fewer the atoms in the ground state (due to population inversion), the lower the GSA probability. The stimulated photons of the amplified light all have the same energy, phase, direction and polarization of the stimulating photon (the same direction being ensured by two parallel mirrors at the ends of the laser cavity).



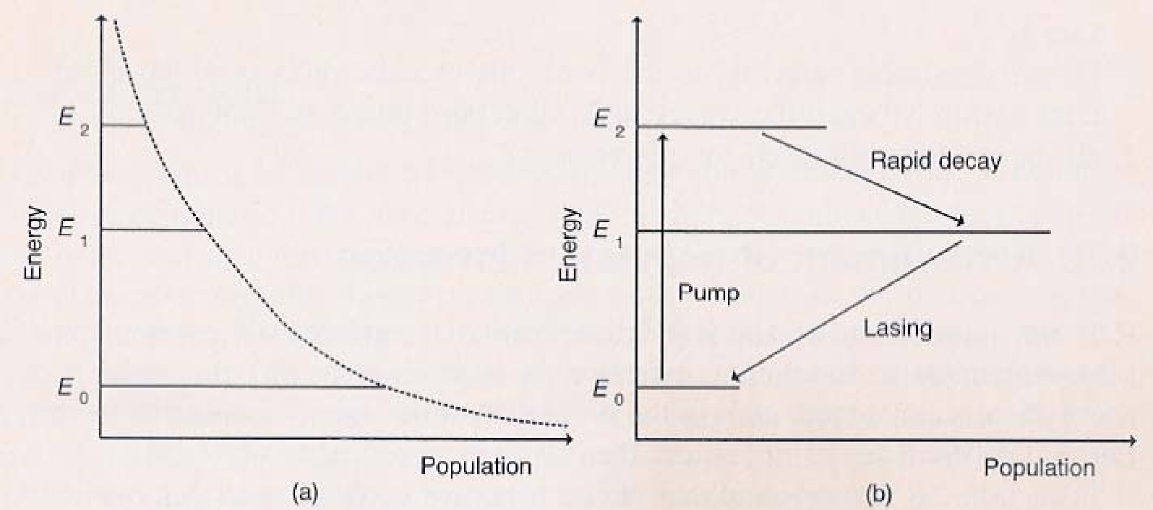
The cascade process.

(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice Hall, 1998)

Achievement of population inversion

With a simple two-level system, it is impossible to achieve population inversion and thus light amplification, even in the presence of stimulated emission. For that, at least 3 levels are needed. Most lasers are 3- or 4-level systems. To achieve a significant population inversion, it is desirable that the excited level be a long-lived, or metastable level, so that atoms can be excited to this state faster than they leave it.

In the example below (3-level), after pumping, the equilibrium population, in (a), changes to a non-equilibrium one, in (b). Ideally, the transition from E_2 to E_1 (the metastable level) should be as rapid as possible and E_2 should consist of a band of energy levels, to use the most pump power, which usually contains a range of energies.



Population of energy levels (a) at equilibrium and (b) far from equilibrium after pumping.

(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice Hall, 1998)

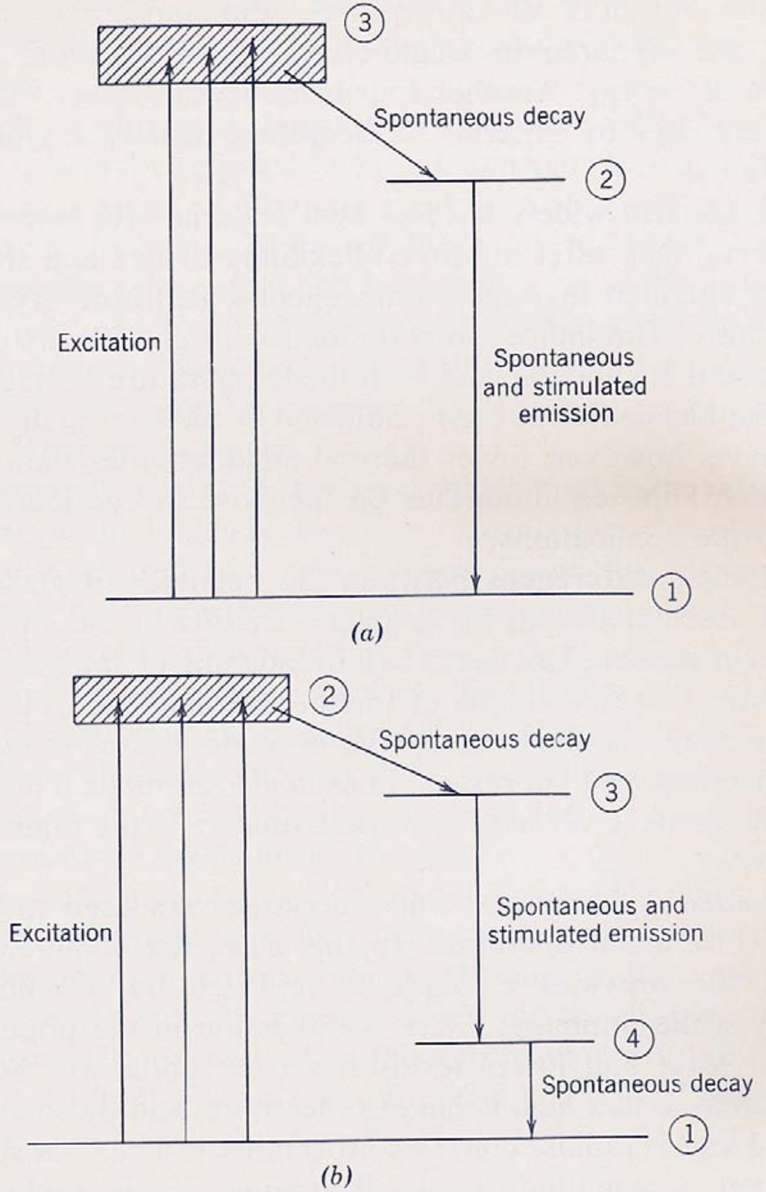
Since the spacing between the energy levels usually decreases as the energy increases, from the Boltzmann distribution, one can see that:

$$N_i / N_{i+1} > N_{i+1} / N_{i+2}$$

so the ratio of populations at equilibrium is largest between E_o and E_1.

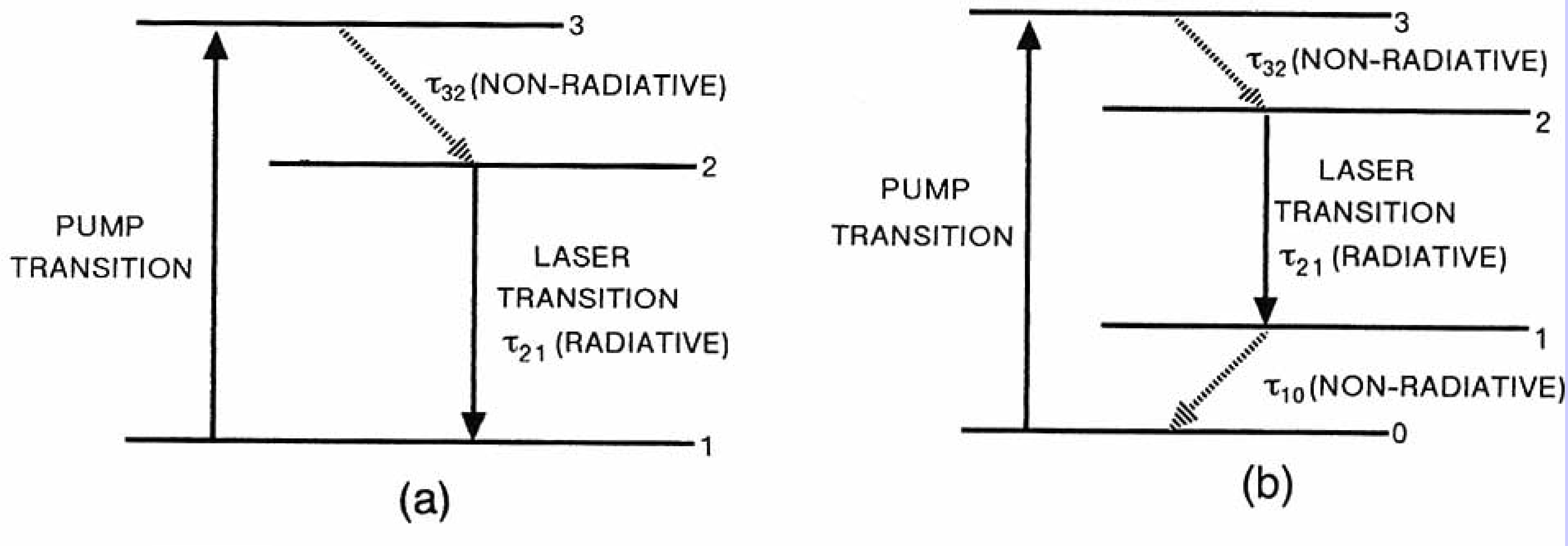
Therefore, fewer atoms have to be pumped to the (i+2)th energy level to achieve inversion over the (i+1)th level than would have to be pumped to the (i+1)th level to achieve inversion over the ith level.

Because of this, the input pump power threshold of a 4-level laser, where the lower lasing level is not the ground state, is lower than that of a 3-level laser.



[redacted]. Simplified energy-level diagrams for (*a*) a three-level and (*b*) a four-level lasing system.

(Adapted from: *Introduction to ceramics*, W.D. Kingery et al., John Wiley, 1976)

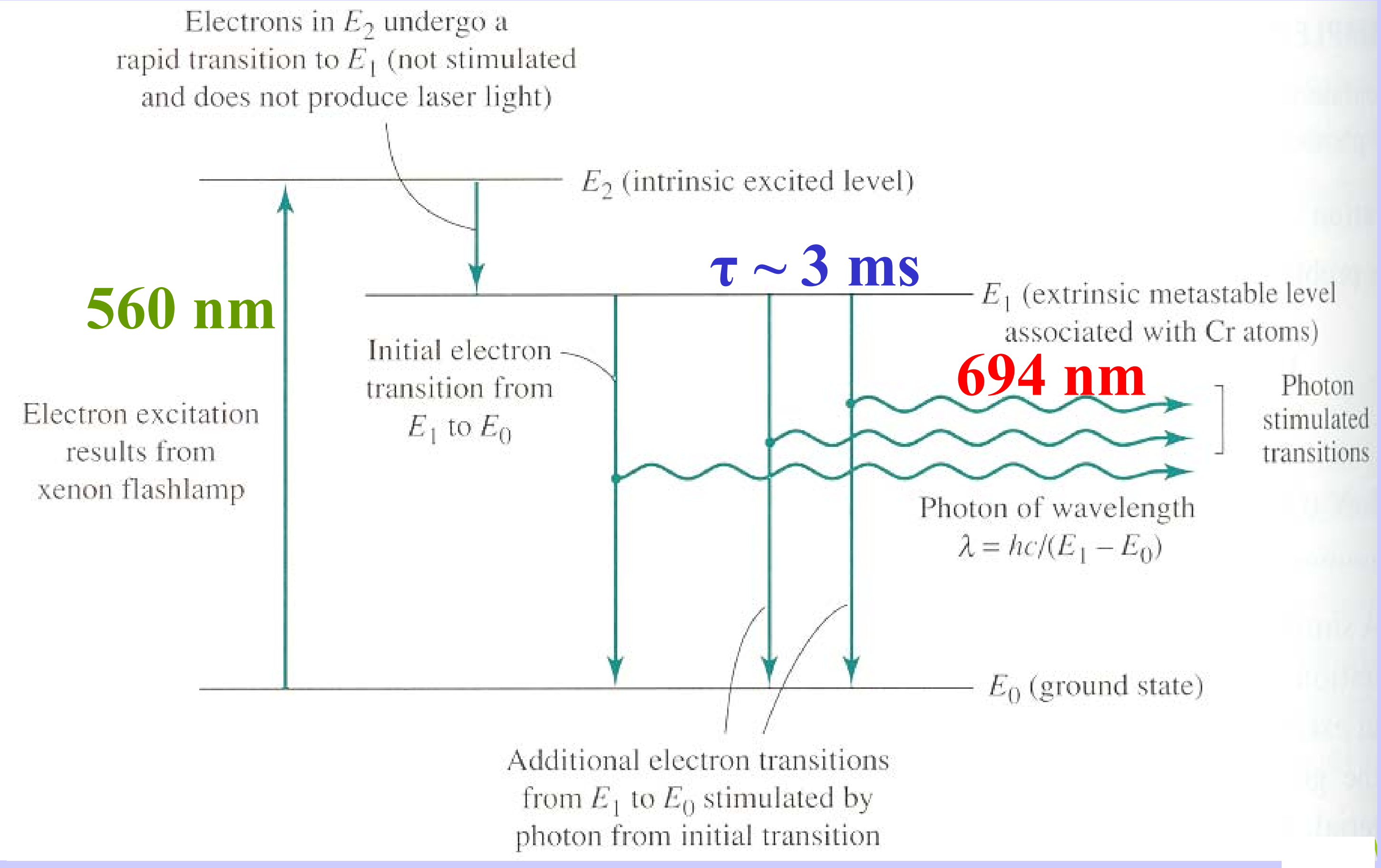


Simplified energy diagrams used to explain the operation of optically pumped (a) three-level and (b) four-level laser systems.

(Adapted from: *Glasses for photonics*, M. Yamane and Y. Asahara, Cambridge Univ. Press, 2000)

At least 3 energy levels are needed to achieve population inversion in a laser.

Example of the ruby laser

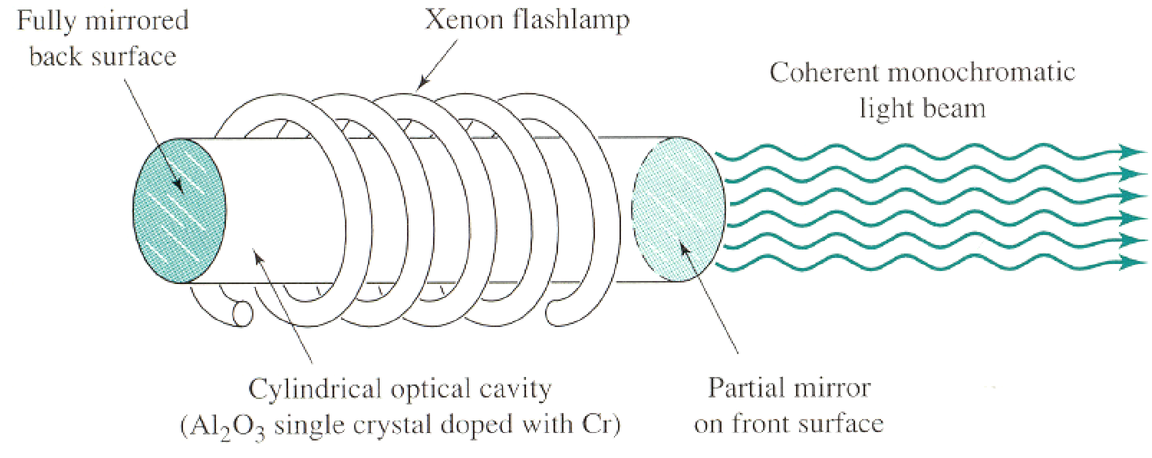


(Adapted from: *The science and design of engineering materials*, J.P. Schaffer, McGraw-Hill, 1999)

Example: the **ruby laser**

The ruby is a corundum (Al_2O_3) crystal doped with ~ 0.05% Cr^{3+} (a substitutional transitional metal ion impurity which gives it its characteristic red color), corresponding to a 3-level laser system which can be pumped @ 560 nm (by a Xe flash lamp) to an excited level, from which it decays non-radiatively to a metastable level ($\tau \sim 3$ ms), followed by fluorescent emission @ 694.3 nm to the ground state.

The crystal is polished with two highly parallel faces, one of them being 100% mirrored, whereas the other is only partly (~ 50%) mirrored. After pumping, only those 694.3 nm *stimulating* photons (spontaneously emitted) and the *stimulated* photons (of the same energy, phase and polarization as the former) which travel perpendicularly (in a highly collimated fashion) to the crystal faces will participate in the *cascade* process. This will end in a final light pulse (with a 0.6 ms duration) which leaves the partially mirrored face of the crystal.



(Adapted from: SSASW)