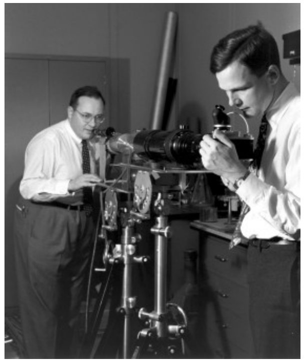
Stimulated Emission Devices
Optical Amplifiers and LASERS

Zhores Alferov (on the right) with Valery Kuzmin (technician) in 1971 at the Ioffe Physical Technical Institute, discussing their experiments on heterostructures. Zhores Alferov carried out some of the early pioneering work on heterostructure semiconductor devices that lead to the development of a number of important optoelectronic devices, including the heterostructure laser. Zhores Alferov and Herbert Kroemer shared the Nobel Prize in Physics (2000) with Jack Kilby. Their Nobel citation is "*for developing semiconductor heterostructures used in high-speed- and opto-electronics*" (Courtesy of Zhores Alferov, Ioffe Physical Technical Institute)

The Laser Patent Wars



Arthur L. Schawlow is adjusting a ruby optical maser during an experiment at Bell Labs, while C.G.B. Garrett prepares to photograph the maser flash. In 1981, Arthur Schawlow shared the Nobel Prize in Physics for his "contribution to the development of laser spectroscopy"
(Courtesy of Bell Labs, Alcatel-Lucent)

Gordon Gould (1920–2005) obtained his BSc in Physics (1941) from Union College in Schenectady, and MSc from Yale University. Gould came up with the idea of an optically pumped laser during his PhD work at Columbia University around 1957. He is now recognized for the invention of optical pumping as a means of exciting masers and lasers. He has been also credited for collisional pumping as in gas lasers, and a variety of application-related laser patents. After nearly three decades of legal disputes, in 1987, he eventually won rights to the invention of the laser. Gould's laboratory logbook even had an entry with at he heading "Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation,", which is the first time that this acronym appears. Union College awarded Gould an honorary Doctor of Sciences in 1978 and the Eliphalet Nott Medal in 1995.

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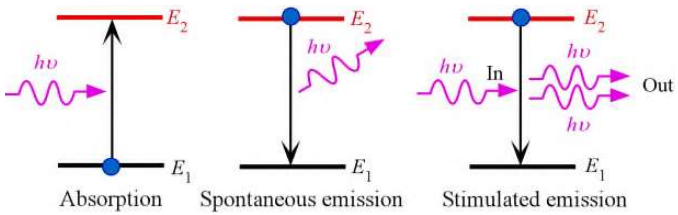
Stimulated Emission Devices
Optical Amplifiers and LASERS



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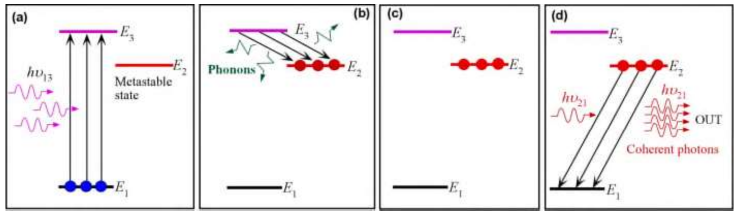
The LASER Principle



The principle of the LASER, using a ruby laser as an example. (a) The ions (Cr^{3+} ions) in the ground state are pumped up to the energy level E_3 by photons from an optical excitation source. (b) Ions at E_3 rapidly decay to the long-lived state at the energy level E_2 by emitting lattice vibrations (phonons). (c) As the states at E_2 are long-lived, they quickly become populated and there is a population inversion between E_2 and E_1. (d) A random photon (from spontaneous decay) of energy $h\upsilon_{21} = E_2 - E_1$ can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.

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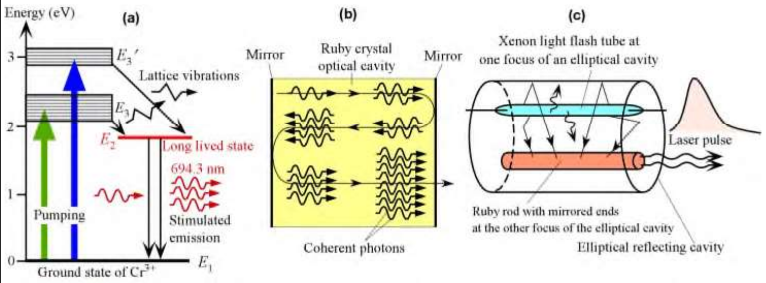
3-Level Lasers: The Ruby Laser



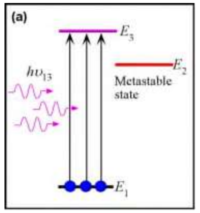
(a) A more realistic energy diagram for the Cr^{3+} ion in the ruby crystal (Al_2O_3), showing the optical pumping levels and the stimulated emission. (b) The laser action needs an optical cavity to reflect the stimulated radiation back and forth to build-up the total radiation within the cavity, which encourages further stimulated emissions. (c) A typical construction for a ruby laser, which uses an elliptical reflector, and has the ruby crystal at one focus and the pump light at the other focus.

EXAMPLE: Minimum pumping power for three level laser systems

Consider the 3-level system Figure 4.2(a). Assuming that the transitions from E_3 to E_2 are fast, and the spontaneous decay time from E_2 to E_1 is τ_{sp}, show that the *minimum* pumping power P_{pmin} that must be absorbed by the laser medium per unit volume for population inversion ($N_2 > N_1$) is

$P_{pmin}/V = (N_0/2)h\upsilon_{13}/\tau_{sp}$ *Minimum pumping for population inversion for 3-level laser* (4.2.12)

where V is the volume, N_0 is the concentration of ions in the medium and hence at E_0 before pumping. Consider a ruby laser in which the concentration of Cr^{3+} ions is 10^{19} cm^{-3}, the ruby crystal rod is 10 cm long and 1 cm in diameter. The lifetime of Cr^{3+} at E_2 is 3 ms. Assume the pump takes the Cr^{3+} ions to the E_3-band in Figure 4.3 (a), which is about 2.2 eV above E_0. Estimate the minimum power that must be provided to this ruby laser to achieve population inversion.



Solution

Consider the 3-level system in Figure 4.2 (a). To achieve population inversion we need to get half the ions at E_1 to level E_2 so that $N_2 = N_1 = N_0/2$ *since* N_0 is the total concentration of Cr^{3+} ions all initially at E_1. We will need $[(N_0/2)h\upsilon_{13} \times$ volume$]$ amount of energy to pump to the E_3-band.

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EXAMPLE: Minimum pumping power for three level laser systems

Solution (continued)

The ions decay quickly from E_3 to E_2. We must provide this pump energy before the ions decay from E_2 to E_1, that is, before τ_{sp} Thus, the *minimum* power the ruby needs to absorb is

$$P_{pmin} = V(N_0/2)h\upsilon_{13}/\tau_{sp}$$

which is Eq. (4.2.12). For the ruby laser

P_{pmin} = $[\pi(0.5\text{ cm})^2(10\text{ cm})][(10^{19}\text{ cm}^{-3})/2](2.2\text{ eV})(1.6\times10^{-19}\text{ J/eV})]/(0.003\text{ s})$
= 4.6 kW

The total pump energy that must be provided in less than 3 ms is **13.8 J**.

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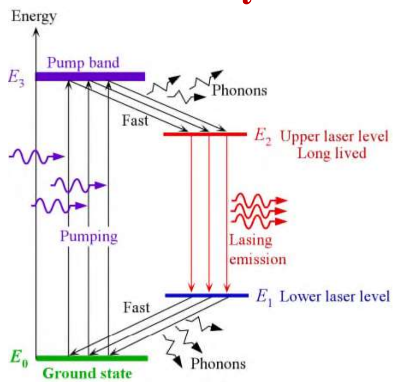
4 Level Laser System



A four energy level laser system
Highly simplified representation of Nd^{3+}:YAG laser

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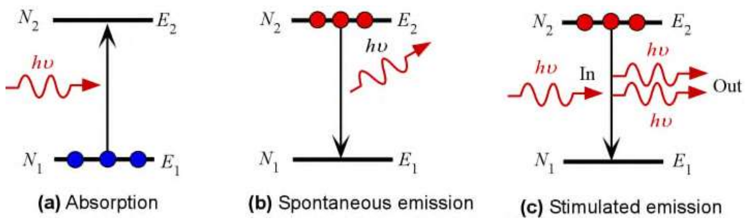
Einstein Coefficients



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

$$\boldsymbol{R_{12} = \underbrace{B_{12}N_1\rho(\upsilon)}_{\text{Absorption}}}$$

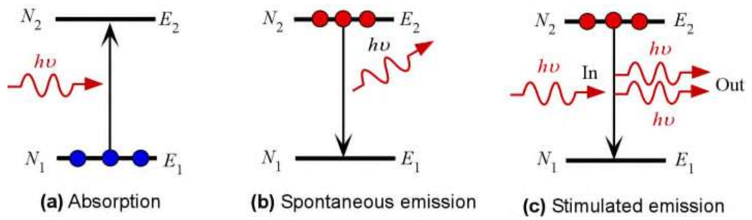
$R_{12} = -dN_1/dt$

$$R_{21} = \underbrace{A_{21}N_2}_{\text{Spontaneous emission}} + \underbrace{B_{21}N_2\rho(\upsilon)}_{\text{Stimulated emission}}$$

$R_{21} = -dN_2/dt$

We need A_{21}, B_{12} and B_{21}

Einstein Coefficients



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

Consider equilibrium $R_{12} = R_{21}$

Boltzmann statistics $N_2 / N_1 = \exp[-(E_2 - E_1)/k_BT]$

E_1 and E_2 have the same degeneracy

Planck's black body radiation law

$$\rho_{eq}(\upsilon) = \frac{8\pi h\upsilon^3}{c^3\left[\exp\left(\frac{h\upsilon}{k_BT}\right)-1\right]}$$

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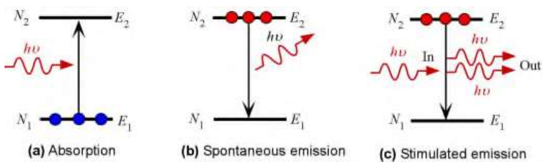
Einstein Coefficients



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

$$\boldsymbol{B_{12} = B_{21}}$$

$$\boldsymbol{A_{21}/B_{21} = 8\pi h\upsilon^3/c^3}$$

$$\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} = \frac{B_{21}N_2\rho(\upsilon)}{A_{21}N_2} = \frac{B_{21}\rho(\upsilon)}{A_{21}} = \frac{c^3}{8\pi h\upsilon^3}\rho(\upsilon)$$

$$\frac{R_{21}(\text{stim})}{R_{12}(\text{absorp})} = \frac{N_2}{N_1}$$

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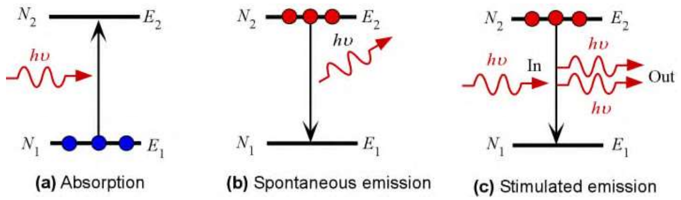
LASER Requirements



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

$$\frac{R_{21}(\text{stim})}{R_{12}(\text{absorp})} = \frac{N_2}{N_1}$$ **Population inversion**

$$\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} \propto \rho(\upsilon)$$ **Optical cavity**

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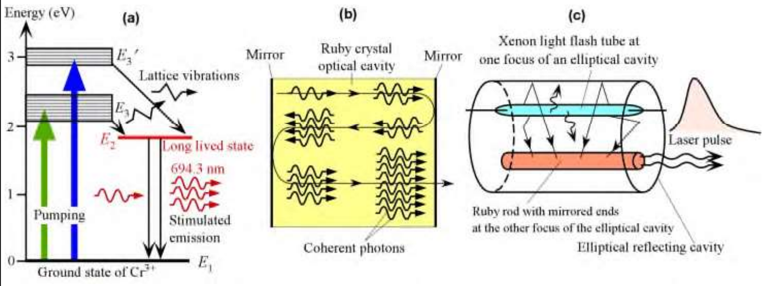
3-Level Lasers: The Ruby Laser

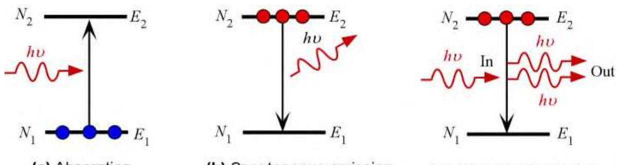


(a) A more realistic energy diagram for the Cr^{3+} ion in the ruby crystal (Al_2O_3), showing the optical pumping levels and the stimulated emission. (b) The laser action needs an optical cavity to reflect the stimulated radiation back and forth to build-up the total radiation within the cavity, which encourages further stimulated emissions. (c) A typical construction for a ruby laser, which uses an elliptical reflector, and has the ruby crystal at one focus and the pump light at the other focus.

3-Level Lasers: The Ruby Laser

Theodore Harold Maiman was born in 1927 in Los Angeles, son of an electrical engineer. He studied engineering physics at Colorado University, while repairing electrical appliances to pay for college, and then obtained a Ph.D. from Stanford. Theodore Maiman constructed this first laser in 1960 while working at Hughes Research Laboratories (T.H. Maiman, "Stimulated optical radiation in ruby lasers", *Nature*, **187**, 493, 1960). There is a vertical chromium ion doped ruby rod in the center of a helical xenon flash tube. The ruby rod has mirrored ends. The xenon flash provides optical pumping of the chromium ions in the ruby rod. The output is a pulse of red laser light. (Courtesy of HRL Laboratories, LLC, Malibu, California.)

Spontaneous Decay Time



$R_{12} = -dN_1/dt$ and $R_{21} = -dN_2/dt$

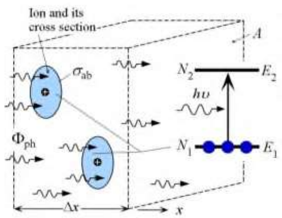
R_{21} = rate at which N_2 is decreasing by spontaneous and stimulated emission

Consider N_2 changes by spontaneous emission

$dN_2/dt = -A_{21}N_2 = -N_2/\tau_{sp}$,

$\tau_{sp} = 1/A_{21}$ = **spontaneous decay time**; or the **lifetime** of level E_2.

Absorption Cross Section



Absorption

Optical power absorbed by an ion

= Light intensity × Absorption cross section of ion

= $I\sigma_{ab}$

$$\boxed{-\frac{\Delta I}{I\Delta x} = \sigma_{ab}N_1 = \alpha}$$