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## Laser

Syllabus: Spontaneous & Stimulated emission of radiation, Population inversion, Einstein's A & B coefficients, (derivations included), Optical resonator and conditions necessary for active Laser action, Ruby Laser, He-Ne Laser, Applications.

1. Overview: A laser is a device that amplifies light and produces a highly directional, high-intensity beam that most often has a very pure frequency or wavelength. It comes in sizes ranging from approximately one tenth the diameter of a human hair to the size of a very large building, in powers ranging from  $10^{-9}$  to  $10^{20}$  W, and in wavelengths ranging from the microwave to the soft-x-ray spectral regions (frequency range:  $10^{11}$  to  $10^{17}$  Hz). Lasers have pulse energies as high as  $10^4$  J and pulse durations as short as  $5 \times 10^{-15}$ . They can easily drill holes in the most durable of materials and can weld detached retinas within the human eye.

Other uses: CD players, Special surgical knife for many types of medical procedures, Rapid checkout at supermarkets, Target designators for military weapons (checkout scanners).

The laser makes use of processes that increase or amplify light signals after these signals have been generated by other means. These processes include (1) stimulated emission, and (2) optical feedback (present in most lasers) that is usually provided by mirrors. Thus, in its simplest form, a laser consists of a gain or amplifying medium (where stimulated emission occurs), and a set of mirrors to feed the light back into the amplifier for continued growth of the developing beam.

- He-Ne Laser -  $\lambda: 6328\text{Å}$  (& 11523 Å and 33912 Å in the infrared)
- Ruby Laser -  $\lambda: 6943\text{Å}$

Absorption: Suppose an atom is in its lowest energy or ground-state configuration. A photon having an adequate amount of energy interacts with the atom, imparting that energy to the atom, thereby causing the electron cloud to take on a new configuration. That is, the atom jumps into a higher-energy excited state. This is the basic mechanism of ~~absorption~~ (stimulated) absorption.



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## 2. Spontaneous Emission

Atoms radiate electromagnetic energy when an excited electron jumps from an upper energy state ( $j$ ) to a lower energy state ( $i$ ), thereby emitting a photon of frequency  $\nu_{ji}$  and wavelength  $\lambda_{ji}$  corresponding to the exact energy difference  $\Delta E_{ji}$  between the two levels such that  $\Delta E_{ji} = h\nu_{ji} = hc/\lambda_{ji}$ .

Such an excited state / excess-energy configuration (of the atom) is usually (though not always) exceedingly short-lived, and in 10ns or so, without the intervention of any external influence, the atom will emit its overload of energy as a photon. As it does, it reverts to a stable state in a process called spontaneous emission. Every atom transferred to an excited energy level will eventually decay by spontaneous emission if left isolated for a sufficient time.

## 3. Stimulated Emission

For a medium inundated with electromagnetic radiation, it is possible for a photon to interact with an excited atom while that atom is still in its higher energy configuration. The atom can then dump its excess energy in steps with the incoming photon, in a process now called stimulated emission.

This process was first <sup>predicted</sup> by Einstein and <sup>is</sup> crucial to the operation of a laser.

The laser accomplishes "light amplification" by making use of energetic atoms in a medium to reinforce the light field. Let's therefore examine the manner in which the energy states of a system of atoms at some arbitrary temperature is normally distributed. We will use the Maxwell-Boltzmann distribution.

### Population of Energy Levels

~~Consider a collection of atoms at temperature T. The following is the probability of finding an atom in an excited state of energy Ei.~~ Imagine a chamber filled with a gas in equilibrium at some temperature  $T$ . The classical Maxwell-Boltzmann distribution maintains that, on average, a number of atoms per unit volume,  $N_i$ , will be in any excited state of energy  $E_i$  such that

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$$N_i = N_0 e^{-E_i/kT} \quad (1)$$

where  $N_0$  is a constant for a given temperature. So, the higher the value of the energy, the fewer the atoms that will have that energy.

Since we will be interested in atomic transitions between arbitrary states, consider the  $j$ th energy level where  $E_j > E_i$ . Then  $N_j (= N_0 e^{-E_j/kT}) < N_i$ , and their ratio is

$$\frac{N_j}{N_i} = e^{-(E_j - E_i)/kT}, \text{ i.e., } N_j = N_i e^{-(E_j - E_i)/kT}$$

$$\Rightarrow N_j = N_i e^{-(E_j - E_i)/kT} = N_i e^{-h\nu_{ji}/kT} \quad (2)$$

where  $E_j - E_i = h\nu_{ji}$  as mentioned earlier.

### The Einstein A and B Coefficients

Silfvest p. 216-219; Hecht p. 554-556  
Reinhold & Eisberg p. 392-393 (new)

In 1916 Einstein developed a simple theoretical treatment of the dynamic equilibrium existing for a material medium bathed in electromagnetic radiation, absorbing and re-emitting. His analysis basically created the theoretical foundation of the laser.

To recapitulate, there are three radiative processes involving two discrete boundary levels (corresponding to energies  $E_i$  and  $E_j$  - ray) in a material: spontaneous emission, absorption (stimulated absorption), and stimulated emission. It is important to note in this context that just like in the case of stimulated absorption, the energy (related to the frequency) of the light must correspond exactly to that of the energy difference between the two energy states (i.e.,  $E_j - E_i = h\nu_{ji}$ ) - this same is also true for stimulated emission to take place. In other words if a photon in an incident beam is to trigger an excited atom (at energy  $E_j$ ) into stimulated emission (thereby causing the atom to jump back to its lower energy state  $E_i$ ), it must have the frequency  $\nu_{ji}$ . A remarkable feature of this process is that the emitted photon is in phase with, has the polarization of, and propagates



See side-note.

frequency, direction, and speed (temporal coherence)

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in the same direction as, the stimulating radiation. (These characteristics basically follow from the laws of conservation of energy and momentum.)

We will now derive the absorption and stimulated emission coefficients associated with these processes by considering radiation in thermal equilibrium. We will consider a group of atoms having electrons occupying either energy levels 1 or 2 with population densities  $N_1$  and  $N_2$  (number of atoms per unit volume) and with  $E_2 > E_1$ . We assume the atoms are in thermal equilibrium with each other and must therefore be related by the Boltzmann distribution function given in Eq.(2),

$$\frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}} = e^{-(E_2-E_1)/kT} = e^{-\Delta E_{21}/kT} \quad (2)$$

where  $\Delta E_{21} = E_2 - E_1$ .

We will consider photons interacting with such a collection of atoms. The photons will be assumed to have energies  $\Delta E_{21}$  such that  $\Delta E_{21} = h\nu_{21}$ , corresponding to the exact difference in energy between the levels 2 and 1.

We now define  $A_{21}$  as the spontaneous transition probability, which is basically the rate at which spontaneous transitions occur from level 2 to level 1 (number per unit time). Thus, the number of spontaneous transitions from 2 to 1 per unit time per unit volume is simply  $N_2 A_{21}$ .

In other words, the transition rate from level 2 is  $\left(\frac{dN_2}{dt}\right)_{SP}$  which is simply the number of atoms per unit volume per unit time taking part in spontaneous emission process. This rate is clearly dependent only on the total population of level 2 at any instant of time and independent of the photon field environment; i.e.,

$$\left(\frac{dN_2}{dt}\right)_{SP} \propto N_2$$

i.e.,

$$\left(\frac{dN_2}{dt}\right)_{SP} = -A_{21} N_2 \quad (4)$$

SP - Spontaneous emission

J&W p 633 "Amazingly enough this stimulated photon has exactly the same frequency, direction, and exactly the same phase and speed (spatial coherence)"

"The Cherenkov Report to Lorentz"

Also see Ant. 6.6 p III, Longhurst -



→ to the population at that level. Why? Because the higher the population at a level, the greater the number of atoms that can leave that level per second.

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where  $A_{21}$  is the constant of proportionality and the minus sign arises because  $N_2$  is decreasing. [Keep in mind that the transition rate, the number of atoms making transitions per second, divided by the number of atoms, is the probability of a transition occurring per second,  $P$ . Consequently, the probability per second of spontaneous emission is  $P_{SP} = A_{21}$ .]

We have also suggested that stimulated processes (both absorption and emission) should occur. These processes would be proportional to the photon energy density  $u(v)$  at frequency  $v_{21}$ , as well as to the population at the appropriate level. Then the upward flux - the number of stimulated upward transitions per unit volume per unit time would be

$$\left( \frac{dN_1}{dt} \right)_{AB} = -B_{12} N_1 u(v) \quad (5)$$

where  $B_{12}$  is the constant of proportionality for stimulated absorption.

Similarly, the downward flux would be (due to stimulated emission)

$$\left( \frac{dN_2}{dt} \right)_{ST} = -B_{21} N_2 u(v) \quad (6)$$

ST - Stimulated emission.

where  $B_{21}$  - constant of proportionality for stimulated emission.

The constants  $A_{21}$ ,  $B_{12}$ , and  $B_{21}$  are referred to as the Einstein A and B coefficients.

Now following Einstein's lead, we have already assumed (a) that thermodynamic equilibrium exists between the radiation field (i.e., the photon field) and the atoms in it at any  $T$ , and (b) that the number densities of the two states are in accord with the Maxwell-Boltzmann distribution - both these assumptions are essentially incorporated in Eq. (3).

So given that the system is in thermodynamic equilibrium, the rate of upward transitions ( $1 \rightarrow 2$ ) must equal the rate of downward transitions ( $2 \rightarrow 1$ ); i.e.,

$$\left( \frac{dN_1}{dt} \right)_{AB} = \left( \frac{dN_2}{dt} \right)_{SP} + \left( \frac{dN_2}{dt} \right)_{ST} \quad (7)$$

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Substituting from (4), (5), and (6),

$$\text{i.e., } -B_{12} N_1 u(v) = -A_{21} N_2 - B_{21} N_2 u(v)$$

$$B_{12} N_1 u(v) = B_{21} N_2 u(v) + A_{21} N_2 \quad (8)$$

From this equation we can solve for  $u(v)$  as follows: From (8),

$$(B_{12} N_1 - B_{21} N_2) u(v) = A_{21} N_2$$

$$\therefore u(v) = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2} \quad (9)$$

Dividing the numerator and denominator of the right hand side of (9) by  $N_2$  we get,

$$u(v) = \frac{A_{21}}{B_{12} \left( \frac{N_1}{N_2} \right) - B_{21}} \quad (10)$$

Substituting for  $\frac{N_1}{N_2}$  from Eq. (3),

$$u(v) = \frac{A_{21}}{B_{12} e^{\Delta E_{21}/kT} - B_{21}} \quad (11)$$

Using the relationship  $\Delta E_{21} = h\nu_{21}$ , we get

$$\begin{aligned} u(v) &= \frac{A_{21}}{B_{12} e^{h\nu_{21}/kT} - B_{21}} \\ &= \frac{A_{21}}{B_{21}} \cdot \frac{1}{\left( \frac{B_{12}}{B_{21}} e^{h\nu/kT} - 1 \right)} \end{aligned} \quad (12)$$

$$= \frac{A_{21} / B_{21}}{\frac{B_{12}}{B_{21}} e^{h\nu/kT} - 1}$$



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Once again following Einstein's lead we assume that the energy density  $\nu(v)$  has the characteristics of a black body at temperature  $T$ , i.e.,

$$\nu(v) = \frac{8\pi h v^3}{c^3 (e^{hv/kT} - 1)} \quad (13)$$

Equations (12) and (13) must be equivalent as per Einstein's assumption. This required equivalence follows if

$$(i) \quad \frac{B_{12}}{B_{21}} = 1 \Rightarrow \text{i.e., } B_{12} = B_{21} \quad (14)$$

and

$$(ii) \quad \frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{c^3} \quad (15)$$

$\therefore$  From (14) and (15),

$$B_{12} = B_{21} = \frac{c^3}{8\pi h v^3} A_{21} \quad (16)$$

Equation (14) shows that the probability of stimulated emission is identical to the probability of stimulated absorption: an atom in the lower state is just as likely to make a stimulated transition up, as an excited atom is to make a stimulated transition down.

Next, Eq.(15) shows that the probability of spontaneous emission (i.e.,  $A_{21}$ ) is proportional to the probability of stimulated emission ( $\sim B_{21}$ ) - this implies that an atom susceptible to one mechanism is proportionately susceptible to the other; in short if  $B_{21}$  is high, so is  $A_{21}$ . Now as mentioned earlier, lasers work by stimulated emission, and anything that enhances spontaneous emission (i.e.  $A_{21}$ ) at the price of stimulated emission (i.e.  $B_{21}$ ) can be expected to work to the detriment of the process.



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Because the ratio of  $\frac{A_{21}}{B_{21}}$  varies as  $v^3$ , it would seem that X lasers ought to be very difficult to build - they actually are. \*

IGNORE → [Now imagine a system of atoms in thermodynamic equilibrium having only two possible states 1 and 2, with  $E_2 > E_1$  ( $E_2 \& E_1 \rightarrow$  energy corresponding to states 2 and 1 respectively). Furthermore, require that atoms have a long mean life so that we can ignore spontaneous emission. When the system is inundated by photons of the proper energy ( $\equiv h\nu_{21} = E_2 - E_1$ ), stimulated absorption depopulates the lower level 1, while stimulated emission depopulates the upper level 2.]

\* The dependence of  $\frac{A_{21}}{B_{21}}$  on  $v^3$  basically implies that the bigger the energy difference between the two states, the larger the value of  $\nu_{21}$  ( $\because E_2 - E_1 = h\nu$ ) and consequently spontaneous emission (proportional to  $A_{21}$ ) is the more likely compared to stimulated emission (proportional to  $B_{21}$ ).]

Next recall:  $A_{21} \rightarrow$  probability of spontaneous emission per unit volume per unit time  
 $B_{21}u(v) \rightarrow$  " " stimulated " " " " "  
&  $B_{21}s(v) \rightarrow$  " " " absorption " " "

In short:  $A_{21} \rightarrow$  spontaneous emission probability  
 $B_{21}u(v) \rightarrow$  stimulated " " "  
 $B_{21}s(v) \rightarrow$  " " absorption " ]

Student - remember this.

From (13) & (15),  $u(v) = \frac{8\pi h v^3}{c^3 (e^{hv/kT} - 1)}$  (13)

&  $\frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{c^3},$  (15)

i.e., the ratio of the probabilities of spontaneous and stimulated emissions is

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From (16), if the spontaneous and stimulated emission probabilities are the same (i.e.,  $A_{21} = B_{21}(\nu)$ ), then  $\frac{dN_2}{dt} = 2 \Rightarrow \frac{dN_2}{dt} = \ln 2 \cdot \frac{N_2}{kT}$ . For visible transitions in the green portion of the spectrum (photon energies of 2-5 eV),  $kT \approx 0.033,500\text{K}$ . Thus in the visible spectrum, the dominance of stimulated emission over spontaneous emission normally happens only in lasers, in certain laboratory plasmas, or in lasers.

$$\frac{A_{21}}{B_{21}u(\nu)} = \frac{e^{h\nu/kT} - 1}{e^{h\nu/kT} + 1} \quad (16)$$

This shows that, for atoms in thermal equilibrium with the radiation, spontaneous emission is far more probable than stimulated emission if  $h\nu \gg kT$ . Since this condition applies to electronic transitions in both atoms and molecules, stimulated emission can be ignored in such transitions. Stimulated emission can become significant, however, if  $h\nu \approx kT$ , and it may be dominant if  $h\nu \ll kT$ , a condition that applies at room temperature to atomic transitions in the microwave region of the spectrum where  $\nu$  is relatively small. [Also see side-note]

We are now in a position to understand the concept behind lasers. Recall that the ~~emission~~ rates for spontaneous and stimulated processes are

$$\left( \frac{dN_2}{dt} \right)_{SP} = -A_{21} N_2 \quad \text{and} \quad \left( \frac{dN_2}{dt} \right)_{ST} = -B_{21} N_2 u(\nu)$$

respectively from Eqs. (4) and (6). Also, from Eq. (5), the stimulated absorption rate is

$$\left( \frac{dN_1}{dt} \right)_{AB} = -B_{12} N_1 u(\nu)$$

Therefore the ratio of the emission rate to the absorption rate can be written as

$$\begin{aligned} R &= \frac{\text{Rate of Emission}}{\text{Rate of Absorption}} = \frac{\left( \frac{dN_2}{dt} \right)_{SP} + \left( \frac{dN_2}{dt} \right)_{ST}}{\left( \frac{dN_1}{dt} \right)_{AB}} \\ &= \frac{A_{21} N_2 + B_{21} u(\nu) N_2}{B_{12} u(\nu) N_1} \end{aligned} \quad (17)$$

In thermodynamic equilibrium, this ratio will be of course equal to 1 - see Eq. (8).

### Population Inversion & Optical Pumping

From Eq.(14),  $B_{21} = B_{12}$  so Eq. (17) reduces to

$$R = \frac{N_2}{N_1} \left[ \frac{A_{21}}{B_{21}u(\nu)} + 1 \right] = \left[ 1 + \frac{A_{21}}{B_{21}u(\nu)} \right] \frac{N_2}{N_1} \quad (18)$$

$$\frac{A_{21}}{B_{21}e(v)} = e^{hv/kT} - 1 \quad (16)$$

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$$R = \frac{\text{Rate of Emission}}{\text{Rate of Absorption}} = \left[ 1 + \frac{A_{21}}{B_{21}e(v)} \right] \frac{N_2}{N_1} \quad (18)$$

If we have energy states such that  $E_2 - E_1 \ll kT$ , or  $hv \ll kT$ , then  $e^{hv/kT} - 1$  is very small compared to unity, and the term  $\frac{A_{21}}{B_{21}e(v)}$  in Eq. (18) can be ignored. One then obtains,

$$R \approx \frac{N_2}{N_1} \quad (19)$$

Note that Eq. (19) is general in the sense that we have not assumed equilibrium situation. In situations of thermal equilibrium, where the Boltzmann factor applies (i.e.,  $\frac{N_2}{N_1} = e^{-hv/kT}$ ), we expect  $N_2 < N_1$ . But in nongraphical equilibrium situations any ratio is possible in principle. If we have a means of inverting the normal population of states so that  $N_2 > N_1$ , then  $R = \frac{\text{Emission Rate}}{\text{Absorption Rate}} \approx \frac{N_2}{N_1} > 1$ , i.e., the emission rate would exceed the absorption rate. This means that the applied radiation (i.e. the incident radiation causing the stimulated emission) of frequency  $v = v_{21} = \frac{E_2 - E_1}{h}$  will be amplified in intensity by the interaction process more such radiation emerging than entering. Of course, such a process will reduce the population of the upper state until equilibrium is reestablished. In order to sustain the process, therefore, we must use some method to maintain the population inversion of the states. Devices that do this are called lasers or masers depending upon the portion of the electromagnetic spectrum in which they operate. Energy must be injected into the system, most commonly by a method called optical pumping, and the output is an intense, coherent, monochromatic beam of radiation. Let us explain this point a bit - see p. 15.

\*1 The ruby is primarily a single crystal of synthetic pink ruby which consists of a transparent crystal of corundum ( $\text{Al}_2\text{O}_3$ ) doped with approximately 0.05% of trivalent chromium ions in the form of  $\text{Cr}_2\text{O}_3$ , the latter providing its pink  $^{13}\text{C}$  color. The aluminum and oxygen atoms of the corundum are inert; the chromium ions are the active ingredients.



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### The Ruby Laser

In the solid state laser that operates with a ruby crystal, some Al atoms in the  $\text{Al}_2\text{O}_3$  molecules are replaced by Cr atoms. These "impurity" chromium atoms account for the laser action.

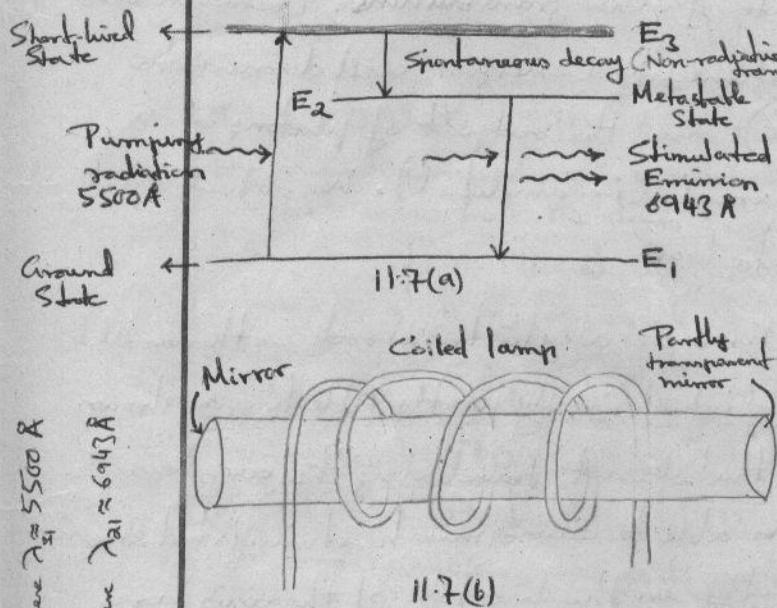


Fig. 11.7 (Remnick & Fisberg, p. 397) (a) The relevant energy levels of chromium atoms in a ruby laser. State 3 is broad (large  $\Delta E$ ) because it is short lived (small  $\Delta t$ ). State 2 is very sharp (small  $\Delta E$ ) because it is long lived ( $\Delta t$  large). Optical pumping raises the atom from ground state 1 to excited state 3, the latter's breadth facilitating the process. Then spontaneous decay occurs to state 2, the energy released usually going into mechanical energy in the ruby crystal rather than photon radiation. Finally, state 2 decays to the ground state through spontaneous emission or through stimulated emission due to photons from other such transitions.

(b) A schematic of the ruby laser, showing the optical pumping lamp, the escape of photons not moving axially, suggesting the buildup of repeatedly reflected axially moving photons which stimulate further emission, and indicating the escape of a fraction of the axial photons through the partially reflecting mirror at one end.

In Fig. 11.7 above we show a simplified version of the appropriate energy-level scheme of chromium.  $E_1 \rightarrow$  ground state energy level and  $E_3 \rightarrow$  an unstable higher energy state with a short lifetime ( $\approx 10^{-8} \text{ sec}$ );  $E_3 - E_1 \approx 3.61 \text{ eV}$

$E_2$  - An intermediate excited state energy level which is metastable with the lifetime of an atom in this state being about  $3 \times 10^{-3} \text{ sec}$ ;  $E_2 - E_1 \approx 2.86 \text{ eV}$ . If the chromium atoms are in thermal equilibrium, the population numbers  $N_1, N_2, N_3$  in the levels  $E_1, E_2, E_3$  respectively are such that  $N_3 < N_2 < N_1$ . By pumping in radiation of wavelength  $5500 \text{ Å}$ , however, we stimulate absorption of incoming photons by Cr atoms in the ground state, thereby raising the population number of energy state  $E_3$  and depleting energy state  $E_1$  of occupants. Spontaneous decay\*, bringing atoms from state 3 to state 2,

J2N p.625  
Spontaneous decay here occurs, not by the emission of photons, but by the conversion of the atoms from the vibrational energy of the crystal lattice.



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then enhances the occupancy of state 2, which is relatively long-lived. The result of this optical pumping is to decrease  $N_1$  and increase  $N_2$ , so that  $N_2 > N_1$ , and population inversion exists. Now when an atom does make a transition from state 2 to state 1, the emitted photon of wavelength  $6943\text{\AA}$  will stimulate further transitions (between level  $E_2$  and  $E_1$ ). Because  $N_2 > N_1$ , stimulated emission will dominate stimulated absorption (see Eq. 19) and the output of photons of wavelength  $6943\text{\AA}$  is much enhanced (i.e. amplified). We obtain an intensified coherent monochromatic beam.

In practice, the ruby laser is a cylindrical rod with parallel optically flat reflecting ends, one of which is only partly reflecting as shown in Fig. 11.7. The emitted photons that do not travel along the axis escape through the sides before they are able to cause much stimulated emission. But those photons that move exactly in the direction of the axis are reflected several times, and they are capable of stimulating emission repeatedly. Thus the number of photons is built up rapidly, those escaping from the partially reflecting end giving a unidirectional beam of great intensity and sharply defined wavelength.

The ruby laser was the first operative laser produced in 1960 by Maiman and this was followed by the helium-neon gas laser in 1961 (<sup>by</sup> Savan et al.). The ruby laser is a pulsed laser which is pumped by the coiled lamp in Fig. 11.7(b) which is essentially an electronic flashtube. It produces a high-power pulse of short duration<sup>1</sup>. The helium-neon gas laser on the other hand is capable of operating continuously, but at very much lower power.

JEW p.635 The ruby laser uses a single crystal of synthetic pink ruby as its resonating cavity (see p. 16). As grown in the laboratory, a ruby crystal is cylindrical in shape. It is cut some 10 cm or so long and the ends polished flat and parallel<sup>\*1</sup>. In a typical ruby laser, one end is highly reflective (about 96%), and the other end is close to half-silvered (about 50%).



## CONTENTS OF THIS PAGE FOR INTERESTED STUDENTS ONLY

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Continued from p. 12. (Longhurst p. 496) : The following is basically a brief review of laser action, parts of which has been discussed before.

In the ordinary absorption process a photon raises an atom from a lower to a higher state, and in spontaneous emission the photon is emitted as the atom falls from the higher state to the lower state. If, however, an identical photon strikes the atom while it is in the higher state, it can trigger the transition so that a second photon is emitted. It will be seen that as a result of this stimulated emission process the total light intensity will increase if there is what is known as a population inversion where there are more atoms in the higher state than there are in the lower - there can be said to be negative absorption. This is the principle of the laser. The population inversion can be achieved as in the ruby laser by "optical pumping", where light from a separate source raises the atoms concerned to the higher energy state to await the arrival of a stimulating photon. Alternatively, the inversion can be achieved as a result of inelastic collisions between the atoms in, for example, a mixture of gases : in the helium-neon gas laser helium atoms (which are excited to a metastable state in an ordinary gas discharge tube arrangement) collide with, and excite, neon atoms. In practice the medium in which the stimulated emission occurs is contained in a Fabry-Perot etalon so that light of the appropriate wavelength is reflected to and fro. If the amplification due to stimulated emission is sufficient to balance the loss of light from the system, one has the positive feed-back characteristic of the oscillator - a laser source is, in fact, an optical oscillator. If the gain is sufficient, the emission can be maintained while some of the light emerges through one of the etalon mirrors. The crucial factor is that in stimulated emission the light emitted is coherent and in phase with the incident light, and since the losses from the etalon are smallest for light travelling parallel to the axis, the light emerging from a laser is predominantly in the form of a highly coherent, highly collimated, beam. Since the amplification is larger if the light path is longer, lasers tend to use long etalons ; plane mirrors would then be difficult to adjust for parallelism. In consequence, lasers often use confocal spherical etalons or etalons consisting of one spherical and one plane mirror ; each of these is easier to align. It is usual for the gas tube to have end windows inclined at the polarizing (or Brewster) angle ; in consequence, the ultimate output is plane polarized.

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## The Optical Resonator (Miscellaneous notes)

or The Resonant Cavity

Resnick & Eisberg p. 396: In the ordinary atomic light sources there is a random relationship between the phases of the photons emitted by different atoms so the resulting radiation is incoherent. The reason is that there is no correlation in times that the atoms make their transitions. In laser light sources, on the other hand, atoms radiate in phase with the inducing radiation because their oscillations are in phase with that radiation. Since in a laser the inducing radiation is a coherent parallel beam formed by reflection between the ends of a resonator, the emitted photons are all in phase and act coherently. The resulting intensity is the square of the constructively combined amplitudes, as correspondingly high states between which transitions are made are an upper metastable state, relatively long lifetime allows it to be highly populated, and the lower ground state of infinitely long lifetime. From the uncertainty relation  $\Delta E \cdot \Delta t \approx h$ , with  $\Delta t$  = the long lifetime of the upper state, we conclude that the energy uncertainty in energy difference of the states is small and the emitted transition frequency is giving a highly monochromatic beam. In practical devices the beam is also unidirectional, the coherence property making it possible to obtain essentially collimation, or focusing. This further enhances the concentration of energy density. Some indication of the concentration of energy in a laser beam is given by the fact that a laser with less power than a typical light bulb can burn a hole in a metal plate.

Jenkins & White p. 634 & p 636 + Hecht Ch. 13

In order to produce a laser, one must collimate the stimulated emission, and this is done by properly designing a cavity in which the waves can be used over and over again. [Here in optics the principles of the Fabry-Pérot interferometer are applied. Suppose we retain the high reflecting power of the two end mirrors (p. 14), for example; the system of mirrors is called the etalon) and increase the distance between them.] - IGNORE THIS PORTION The two ends of the cavity are capped by mirrors with high reflecting powers. Into this cavity we then introduce an appropriate solid, liquid or gas having metastable states in the atoms or molecules of its structure (see Fig. 301). (Note: In the case of the ruby laser, the crystal itself is the cavity.)

By one means or another we now excite electrons in these atoms

\*2 Note:  $\nu_m = \frac{v}{\lambda}$  where  $v = c/\mu$  &  $\lambda = \lambda_0/\mu$  where  $\lambda_0$  = wavelength of this light in free space.  $\therefore \nu_m = \frac{c/\mu}{\lambda_0/\mu} = \frac{c}{\lambda_0}$  which is consistent with our understanding that the frequency does not change.



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molecules and produce a population inversion. If one or more atoms in a metastable state spontaneously radiate, these photons moving at an appreciable angle to the walls of the cavity, or tube, will escape and be lost. Those emitted parallel to the axis will reflect back and forth from end to end. Their chance of stimulated emission will now depend upon a high reflectance at the end mirrors and a high population density of metastable atoms within the cavity. If both these conditions are satisfied, the buildup of photons surging back and forth through the cavity can be self-sustaining and the system will oscillate, or lase, spontaneously.

A laser cavity can be operated in a variety of oscillation modes (similar to that of a waveguide). As waves travel back and forth between the end mirrors, a distance  $d$  apart, standing waves are set up when there is an integer number ( $m$ ) of half wavelengths across the length  $d$ :

$$m = \frac{d}{(\lambda/2)} = \frac{2d}{\lambda} \quad *1 \quad (20)$$

where  $m$  is a large integer. The frequency of the oscillation  $\nu_m$  is given by

$$\nu_m = \frac{v}{\lambda} = \frac{1}{d} \cdot v = \frac{m}{2d} \cdot v \quad (21) *2$$

where  $v$  is the speed of the waves in the cavity medium ( $v = \frac{c}{\mu}$ ;  $\mu$  refractive index of the medium)

The frequency difference between successive modes is given by

$$\Delta\nu = \nu_{m+1} - \nu_m = \frac{m+1}{2d} \cdot v - \frac{m}{2d} \cdot v = \frac{v}{2d},$$

$$\text{i.e., } \Delta\nu = \frac{v}{2d}, \quad (22)$$

which is actually the reciprocal of the round-trip time. For a gas laser 1 m long,

$$\Delta\nu = \frac{3 \times 10^8}{2 \times 1} = 1.5 \times 10^8 \text{ Hz} = 150 \times 10^6 \text{ Hz} = 150 \text{ MHz. } (v=c \text{ in a gas})$$

In a spectrum-rich source single wavelengths can be selected for oscillation using the above principle (For more information, interested students <sup>can</sup> look up Jenkins & White, p. 647) as now explained. The resonant modes of the cavity are considerably narrower in frequency than the 'bandwidth' of the normal spontaneous atomic transition. These modes, whether the device is constructed so that there is one or more, will be the ones that are sustained in the cavity, and hence the emerging beam is restricted to a region close to those frequencies. In other words, the radiative transition makes available a relatively broad range of frequencies out of which the cavity will select and amplify only certain narrow bands and, if desired, even only one such band. This is the origin of the laser's extremely high degree of monochromaticity.

\*1 In other words, the cavity resonates, i.e., standing waves exist within it when there is an integer number ( $m$ ) of half wavelengths spanning the region between the mirrors. The idea is simply that there must be a node of each mirror, and this can only happen when  $d$  equals a whole number multiple of  $\lambda/2$ .

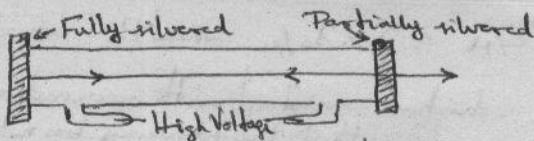


Fig. 304. Simple components of alk-Ne laser. 18

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### The Helium-Neon Gas Laser (J&W p. 636)

He 2  
Ne 10

This was the first successful gas laser put into operation by Townes et al. in 1961. Since that time many different gas lasers, using gases of many kinds and mixtures have been put into operation. Because it is inexpensive, unusually stable, and emits continuously, the He-Ne laser is widely used in optics and physics laboratories over the world.

An early form of He-Ne laser is shown in Fig. 304. It is composed of a glass tube nearly 1 m long and contains He at a pressure of approximately 1 torr and Ne at a pressure of approximately  $\frac{1}{10}$  torr (1 torr = 1 mm Hg pressure). Highly reflecting mirrors at the ends are precision-adjusted and made parallel to a high degree of accuracy.

A high voltage, such as that obtained from a step-up transformer, supplied by means of sealed-in electrodes or by metal bands around the end and middle. For convenience we now write down the ground and excited states of He and Ne below:

[Although there are 10 times as many He atoms (whose visible spectrum contains high intensity lines in the red, yellow, green, and blue, so the discharge appears as white light) present in the mixture as there are neon atoms, the overall color of the gaseous discharge is characteristic of neon atoms (whose visible spectrum has many strong or high intensity lines in the orange and red and very few in the green, blue, and violet - so its gaseous discharge appears to be orange-red. The neon spectrum also contains a large number of lines in the near infrared.)]

Helium ground state (Atomic # 2) : 1s<sub>2</sub>

Helium excited state : 2 states  $\rightarrow$  2'S & 2'S

Neon ground state (Atomic # 10) : 1s<sub>2</sub> 2s<sub>2</sub> 2p<sup>6</sup>  $\rightarrow$  2p<sup>6</sup>

Neon excited states : 2p<sup>5</sup> 3s  $\rightarrow$  4 levels      Neon ground state

2p<sup>5</sup> 3p  $\rightarrow$  9 levels \*

2p<sup>5</sup> 4s  $\rightarrow$  4 levels

2p<sup>5</sup> 5s  $\rightarrow$  4 levels

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Corresponding to the electronic configurations of the excited states, there are a significant number of energy levels corresponding to each electronic configuration. This follows from quantum mechanics which is not in your syllabus. However you do need to be aware of the existence of these levels in order to understand the lasing action in this system. The crucial point here is that the excited states of He are close to some of the excited states of Ne. This will be discussed below.

Pumping in this system is usually accomplished by electrical discharge. Free electrons (and ions) are accelerated by an applied field and, as a result of collisions, cause further ionization and excitation of the gaseous medium. As a result of collision with the electrons, many He atoms accumulate in the two excited states  $2^1S$  &  $2^3S$  as shown in Fig 13.17. There are metastable states ~~in the excited state~~. The excited He atoms inelastically collide with and transfer energy to ground-state Ne atoms, raising them in turn to the  $5s$  and  $4s$  states (of Ne). This energy transfer between the He and Ne atoms is 'efficient' because the Ne  $5s$  and  $4s$  states are very close in energy to the two He excited states.

The Ne  $5s$  and  $4s$  states are the upper laser levels, and inelastic collisions with the excited state He atoms ensure a sustained population inversion in these levels with respect to the lower  $4p$ - and  $3p$  states\*. There is no transition between the  $5s$  and  $4s$  states. Spontaneous photons initiate stimulated emission, and the chain reaction begins.

Dominant laser transitions:

- i).  $4s \rightarrow 3p$  -  $\lambda = 11523\text{\AA}$
- ii).  $5s \rightarrow 4p$  -  $\lambda = 33912\text{\AA}$
- iii).  $5s \rightarrow 3p$  -  $\lambda = 6328\text{\AA}$       Visible (bright red)

The p-states drain off into the 3s-state, thus themselves remaining uncrowded and thereby continuously sustaining the inversion. In contrast to the ruby, where the laser transition is down to the ground state, stimulated emission



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in the He-Ne laser occurs between two upper levels. The significance of this, for example, is that since the 3p-state is ordinarily only sparsely occupied population inversion is very easily obtained, and this without having to half empty the ground state.