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Introductory Concepts

Introductory Concepts

In this introductory chapter, the fundamental processes and the main ideas behind laser operation are introduced in a very simple way. The properties of laser beams are also briefly discussed. The main purpose of this chapter is thus to introduce the reader to many of the concepts that will be discussed later on, in the book, and therefore help the reader to appreciate the logical organization of the book.

1.1. SPONTANEOUS AND STIMULATED EMISSION, ABSORPTION

To describe the phenomenon of spontaneous emission, let us consider two energy levels, 1 and 2, of some atom or molecule of a given material, their energies being $E1$ and $E2$.$E1 < E2$/ (Fig. 1.1a). As far as the following discussion is concerned, the two levels could be any two out of the infinite set of levels possessed by the atom. It is convenient, however, to take level 1 to be the ground level. Let us now assume that the atom is initially in level 2. Since $E2 > E1$, the atom will tend to decay to level 1. The corresponding energy difference, $E2$-$E1$, must therefore be released by the atom. When this energy is delivered in the form of an electromagnetic (e.m. from now on) wave, the process will be called *spontaneous* (or *radiative*) *emission*. The frequency v_0 of the radiated wave is then given by the well known expression

$$v_0 = (E_2 - E_1)/h \qquad (1.1.1)$$

where h is Planck's constant. Spontaneous emission is therefore characterized by the emission of a photon of energy $hv_0 = E2 - E1$, when the atom decays from level 2 to level 1 (Fig. 1.1a). Note that radiative emission is just one of the two possible ways for the atom to decay. The decay can also occur in a nonradiative way. In this case the energy difference $E2 - E1$ is delivered in some form of energy other than e.m. radiation (e.g. it may go into kinetic or internal energy of the surrounding atoms or molecules). This phenomenon is called *non-radiative decay*.

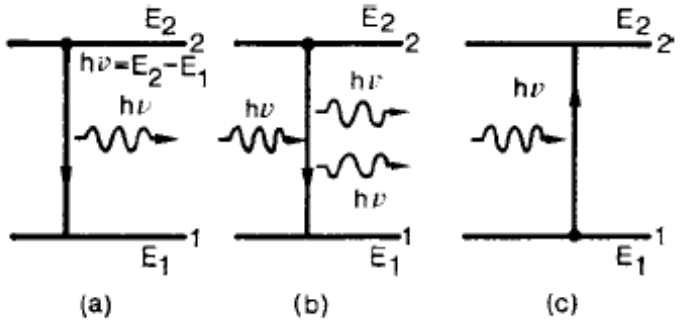

FIG. 1.1. Schematic illustration of the three processes: (a) spontaneous emission; (b) stimulated emission; (c) absorption.

Let us now suppose that the atom is found initially in level 2 and that an e.m. wave of

frequency $\nu = \nu_0$ (i.e., equal to that of the spontaneously emitted wave) is incident on the material (Fig. 1.1b). Since this wave has the same frequency as the atomic frequency, there is a finite probability that this wave will force the atom to undergo the transition 2 ! 1. In this case the energy difference *E*2 - *E*1 is delivered in the form of an e.m. wave that adds to the incident one. This is the phenomenon of *stimulated emission*. There is a fundamental difference between the spontaneous and stimulated emission processes. In the case of spontaneous emission, the atoms emits an e.m. wave that has no definite phase relation with that emitted by another atom. Furthermore, the wave can be emitted in any direction. In the case of stimulated emission, since the process is forced by the incident e.m. wave, the emission of any atom adds in phase to that of the incoming wave and along the same direction.

Let us now assume that the atom is initially lying in level 1 (Fig. 1.1c). If this is the ground level, the atom will remain in this level unless some external stimulus is applied to it. We shall assume, then, that an e.m. wave of frequency $\nu = \nu_0$ is incident on the material.

In this case there is a finite probability that the atom will be raised to level 2. The energy difference *E*2 - *E*1 required by the atom to undergo the transition is obtained from the energy of the incident e.m. wave. This is the *absorption* process.

To introduce the probabilities for these emission and absorption phenomena, let *N* be the number of atoms (or molecules) per unit volume which, at time *t*, are lying in a given energy level. From now on the quantity *N* will be called the *population* of the level.

For the case of spontaneous emission, the probability for the process to occur can be defined by stating that the rate of decay of the upper state population, (*dN*2 / *dt*)*sp*, must be proportional to the population *N*2. We can therefore write

$$\left(\frac{dN_2}{dt}\right)_{sp} = -AN_2 \qquad (1.1.2)$$

where the minus sign accounts for the fact that the time derivative is negative. The coefficient A, introduced in this way, is a positive constant and is called the rate of spontaneous emission or the Einstein A coefficient (an expression for A was in fact first obtained by Einstein from thermodynamic considerations). The quantity $\tau_{sp} = 1/A$ is called the spontaneous emission (or radiative) lifetime. Similarly, for non-radiative decay, we can often write

$$\left(\frac{dN_2}{dt}\right)_{nr} = -\frac{N_2}{\tau_{nr}} \qquad (1.1.3)$$

where τ_{nr} is referred to as the non-radiative decay lifetime. Note that, for spontaneous emission, the numerical value of A (and τ_{sp}) depends only on the particular transition considered.

For non-radiative decay, τ_{nr} depends not only on the transition but also on the char

acteristics of the surrounding medium. We can now proceed, in a similar way, for the stimulated processes (emission or absorption). For stimulated emission we can write

$$\left(\frac{dN_2}{dt}\right)_{st} = -W_{21}N_2 \qquad (1.1.4)$$

where .dN_2=dt/st is the rate at which transitions 2 →1 occur as a result of stimulated emission andW21 is called the rate of stimulated emission. Just as in the case of the A coefficient defined by Eq. (1.1.2) the coefficient W_{21} also has the dimension of .time^{-1}. Unlike A, however,W21 depends not only on the particular transition but also on the intensity of the incident e.m. wave. More precisely, for a plane wave, it will be shown that we can write

$$W_{21} = \sigma_{21}F \qquad (1.1.5)$$

where F is the photon flux of the wave and σ_{21} is a quantity having the dimension of an area (the stimulated emission *cross section*) and depending on the characteristics of the given transition.

In a similar fashion to Eq. (1.1.4), we can define an absorption rate W_{21} by means of the equation

$$\left(\frac{dN_1}{dt}\right)_a = -W_{12}N_1 \qquad (1.1.6)$$

where $(dN_1/dt)_a$ is the rate of the $1 \rightarrow 2$ transitions due to absorption and N_1 is the population of level 1. Furthermore, just as in Eq. (1.1.5), we can write

$$W_{12} = \sigma_{12} F \tag{1.1.7}$$

where σ_{12} is some characteristic area (the *absorption cross section*), which depends only on the particular transition.

In what has just been said, the stimulated processes have been characterized by the stimulated emission and absorption cross-sections, σ_{21} and σ_{12}, respectively. Now, it was shown by Einstein at the beginning of the twentieth century that, if the two levels are non-degenerate, one always has $W_{21} = W_{12}$ and $\sigma_{21} = \sigma_{12}$. If levels 1 and 2 are g_1-fold and g_2-fold degenerate, respectively one has instead

$$g_2 W_{21} = g_1 W_{12} \tag{1.1.8}$$

i.e.

$$g_2 \sigma_{21} = g_1 \sigma_{12} \tag{1.1.9}$$

Note also that the fundamental processes of spontaneous emission, stimulated emission and absorption can readily be described in terms of absorbed or emitted photons as follows

(see Fig. 1.1). (1) In the spontaneous emission process, the atom decays from level 2 to level 1 through the emission of a photon. (2) In the stimulated emission process, the incident photon stimulates the $2 \rightarrow 1$ transition and we then have two photons (the stimulating plus the stimulated one). (3) In the absorption process, the incident photon is simply absorbed to produce the $1 \rightarrow 2$ transition. Thus we can say that each stimulated emission process creates while each absorption process annihilates a photon.

1.2. THE LASER IDEA

Consider two arbitrary energy levels 1 and 2 of a given material and let N_1 and N_2 be their respective populations. If a plane wave with a photon flux F is traveling along the z direction in the material (Fig. 1.2), the elemental change, dF, of this flux along the elemental length, dz, of the material will be due to both the stimulated and emission processes occurring in the shaded region of Fig. 1.2. Let S be the cross sectional area of the beam. The change in number between outgoing and incoming photons, in the shaded volume per unit time, will thus be SdF. Since each stimulated process creates while each absorption removes a photon, SdF must equal the difference between stimulated emission and absorption events occurring in the shaded volume per unit time. From (1.1.4) and (1.1.6) we can thus write $SdF = (W_{21}N_2 - W_{12}N_1)(Sdz)$ where Sdz is, obviously, the volume of the shaded region. With the help of Eqs. (1.1.5), (1.1.7) and (1.1.9) we obtain

$$dF = \sigma_{21} F \left[N_2 - (g_2 N_1 / g_1)\right] dz \tag{1.2.1}$$

Note that, in deriving Eq. (1.2.1), we have not taken into account the radiative and non-radiative decays. In fact, non-radiative decay does not add any new photons while the photons created by the radiative decay are emitted in any direction and do not contribute to the incoming photon flux F.

Equation (1.2.1) shows that the material behaves as an amplifier (i.e., $dF/dz > 0$) if $N_2 > g_2 N_1 / g_1$, while it behaves as an absorber if $N_2 < g_2 N_1 / g_1$. Now, at thermal equilibrium, the populations are described by Boltzmann statistics. So, if N_1^e and N_2^e are the thermal equilibrium

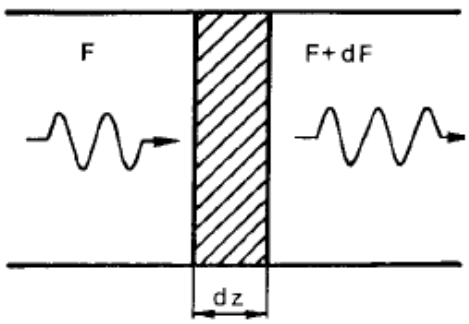

FIG. 1.2. Elemental change dF in the photon flux F fro a plane e.m. wave in traveling a distance dz through the material.

populations of the two levels, we have

$$\frac{N_2^e}{N_1^e} = \frac{g_2}{g_1} \exp -\left[\frac{E_2 - E_1}{kT}\right] \tag{1.2.2}$$

where k is Boltzmann's constant and T the absolute temperature of the material. In thermal equilibrium we thus have $N_2^e < g_2 N_1^e / g_1$. According to Eq. (1.2.1), the material then acts as an absorber at frequency ν. This is what happens under ordinary conditions. If, however, a non-equilibrium condition is achieved for which $N_2 > g_2 N_1 / g_1$ then the material will act as an amplifier. In this case we will say that there exists a *population inversion* in the material, by which we mean that the population difference $N_2 - (g_2 N_1 / g_1)$ is opposite in sign to that which exists under thermodynamic equilibrium $[N_2 - (g_2 N_1 / g_1) < 0]$. A material in which this population inversion is produced will be called an *active material*.

If the transition frequency $\nu_0 = (E_2 - E_1)/kT$ falls in the microwave region, this type of amplifier is called a *maser* amplifier. The word *maser* is an acronym for "*m*icrowave *a*mplification by *s*timulated *e*mission of *r*adiation." If the transition frequency falls in the optical region, the amplifier is called a *laser* amplifier. The word *laser* is again an acronym, with the letter *l* (*l*ight) substituted for the letter *m* (*m*icrowave).

To make an oscillator from an amplifier, it is necessary to introduce a suitable positive feedback. In the microwave region this is done by placing the active material in a resonant cavity having a resonance at frequency ν_0. In the case of a laser, the feedback is often obtained by placing the active material between two highly reflecting mirrors (e.g. plane parallel mirrors, see Fig. 1.3). In this case, a plane e.m. wave traveling in the direction perpendicular to the mirrors will bounce back and forth between the two mirrors and be amplified on each passage through the active material. If one of the two mirrors is made partially transparent, a useful output beam is obtained from this mirror. It is important to realize that, for both masers and lasers, a certain threshold condition must be reached. In the laser case, for instance, the oscillation will start when the gain of the active material compensates the losses in the laser (e.g. the losses due to the output coupling). According to Eq. (1.2.1), the gain per pass in the active material (i.e. the ratio between the output and input photon flux) is $\exp\{\sigma[N_2 - (g_2 N_1 / g_1)]l\}$ where we have denoted, for simplicity, $\sigma = \sigma_{21}$, and where l is the length of the active material. Let R_1 and R_2 be the power reflectivity of the two mirrors (Fig. 1.3) and let L_i be the internal loss per pass in the laser cavity. If, at a given time, F is the photon flux in the cavity, leaving mirror 1 and traveling toward mirror 2, then the photon flux, F', again leaving mirror 1 after one round trip will be $F' = F \exp\{\sigma[N_2 - (g_2 N_1 / g_1)]l\} \times (1 - L_i) R_2 \times \exp\{\sigma[N_2 - (g_2 N / g_1)]l\} \times (1 - L_i) R_1$. At threshold we must have $F' = F$, and therefore $R_1 R_2 (1 - L_i)^2 \exp\{2\sigma[N_2 - (g_2 N_1 / g_1)]l\} = 1$. This equation shows that threshold is reached when the population inversion, $N = N_2 - (g_2 N_1 / g_1)$, reaches a critical value, known as the *critical inversion*, given by

populations of the two levels, we have

$$\frac{N_2^e}{N_1^e} = \frac{g_2}{g_1} \exp - \left[\frac{E_2 - E_1}{kT}\right] \tag{1.2.2}$$

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$$N_c = -[\ln R_1 R_2 + 2 \ln (1 - L_i)] / 2\sigma l \tag{1.2.3}$$

FIG. 1.3. Scheme of a laser.

The previous expression can be put in a somewhat simpler form if we define

$$\gamma_1 = -\ln R_1 = -\ln (1 - T_1) \tag{1.2.4a}$$

$$\gamma_2 = -\ln R_2 = -\ln (1 - T_2) \tag{1.2.4b}$$

$$\gamma_i = -\ln (1 - L_i) \tag{1.2.4c}$$

where T_1 and T_2 are the two mirror transmissions (for simplicity mirror absorption has been neglected). The substitution of Eq. (1.2.4) in Eq. (1.2.3) gives

$$N_c = \gamma / \sigma l \tag{1.2.5}$$

where we have defined

$$\gamma = \gamma_i + (\gamma_1 + \gamma_2)/2 \tag{1.2.6}$$

Note that the quantities γ_i, defined by Eq. (1.2.4c), may be called the logarithmic internal loss of the cavity. In fact, when $L_i \ll 1$ as usually occurs, one has $\gamma_i \simeq L_i$. Similarly, since both T_1 and T_2 represent a loss for the cavity, γ_1 and γ_2, defined by Eq. (1.2.4a and b), may be called the logarithmic losses of the two cavity mirrors. Thus, the quantity γ defined by Eq. (1.2.6) will be called the single pass loss of the cavity.

Once the critical inversion is reached, oscillation will build up from spontaneous emission. The photons that are spontaneously emitted along the cavity axis will, in fact, initiate the amplification process. This is the basis of a laser oscillator, or laser, as it is more simply called. Note that, according to the meaning of the acronym laser as discussed above, the word should be reserved for lasers emitting visible radiation. The same word is, however, now commonly applied to any device emitting stimulated radiation, whether in the far or near infrared, ultraviolet, or even in the X-ray region. To be specific about the kind of radiation emitted one then usually talks about infrared, visible, ultraviolet or X-ray lasers, respectively.

1.3. PUMPING SCHEMES

We will now consider the problem of how a population inversion can be produced in a given material. At first sight, it might seem that it would be possible to achieve this through the interaction of the material with a sufficiently strong e.m. wave, perhaps coming from a sufficiently intense lamp, at the frequency $\nu = \nu_o$. Since, at thermal equilibrium, one has $g_1 N_1 > g_2 N_2 g_1$, absorption will in fact predominate over stimulated emission. The incoming wave would produce more transitions $1 \rightarrow 2$ than transitions $2 \rightarrow 1$ and we would hope in this way to end up with a population inversion. We see immediately, however, that such a system would not work (at least in the steady state). When in fact the condition is reached such that $g_2 N_2 = g_1 N_1$, then the absorption and stimulated emission processes will compensate one another and, according to Eq. (1.2.1), the material will then become transparent. This situation is often referred to as two-level *saturation*.

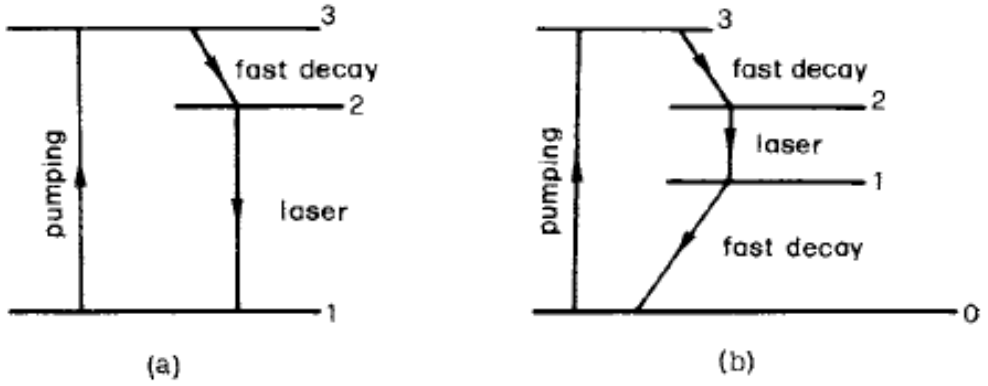


FIG. 1.4. (a) Three-level and (b) four-level laser schemes.

With just two levels, 1 and 2, it is therefore impossible to produce a population inversion. It is then natural to question whether this is possible using more than two levels out of the infinite set of levels of a given atomic system. As we shall see, the answer is in this case positive, and we will accordingly talk of a *three-level laser* or *four-level laser*, depending upon the number of levels used (Fig. 1.4). In a three-level laser (Fig. 1.4a), the atoms are in some way raised from the ground level 1 to level 3. If the material is such that, after an atom has been raised to level 3, it decays rapidly to level 2 (perhaps by a rapid nonradiative decay), then a population inversion can be obtained between levels 2 and 1. In a four-level laser (Fig. 1.4b), atoms are again raised from the ground level (for convenience we now call this level 0) to level 3. If the atom then decays rapidly to level 2 (e.g. again by a fast nonradiative decay), a population inversion can again be obtained between levels 2 and 1. Once oscillation starts in such a four-level laser, however, the atoms will then be transferred to level 1, through stimulated emission. For continuos wave (henceforth abbreviated as cw) operation it is therefore necessary that the transition $1 \rightarrow 0$ should also be very fast (this again usually occurs by a fast nonradiative decay).

We have just seen how to make use of a three or four levels of a given material to produce population inversion. Whether a system will work in a three- or four-level scheme (or whether it will work at all!) depends on whether the various conditions given above are fulfilled. We could of course ask why one should bother with a four level scheme when a three-level scheme already seems to offer a suitable way of producing a population inversion. The answer is that one can, in general, produce a population inversion much more easily in a four-level than in a three-level laser. To see this, we begin by noting that the energy difference among the various levels of Fig. 1.4 are usually much greater than kT. According to Boltzmann statistics [see, e.g., Eq. (1.2.2)] we can then say that essentially all atoms are initially (i.e., at equilibrium) in the ground level. If we now let N_t be the atom density in the material, these will initially all be in level 1 from the three-level case. Let us now begin raising atoms from level 1 to level 3.

They will then decay to level 2 and, if this decay is sufficiently fast, level 3 will remain more or less empty. Let us now assume, for simplicity, that the two levels are either non-degenerate (i.e. $g_1 = g_2 = 1$) or have the same degeneracy. Then, according to Eq. (1.2.1), the absorption losses will be compensated by the gain when $N_2 = N_1$. From this point on, any further atom that is raised will then contribute to population inversion. In a four-level laser, however, since level 1 is also empty, any atom that has been raised to level 2 immediately produces population inversion. The above discussion shows that, whenever possible, we should look for a material that can be operated as a four-level rather than a three-level system. The use of more than four levels is, of course, also possible. It should be noted that the term "four-level laser" has come to be used for any laser in which the lower laser level is essentially empty, by virtue of being above the ground level by many kT. So if level 2 and level 3 are the same level, then one has a level scheme which would be described as "four-level" in the sense above, while only having three levels! Cases based on such a "four-level" scheme do exist. It should also be noted that, more recently, the so-called *quasi-three-level lasers* have also become a very important cathegory of laser. In this case, the ground level consists of many sublevels, the lower laser level being one of these sublevels. Therefore, the scheme of Fig. 1.4b can still be applied to a quasi-three-level laser with the understanding that level 1 is a sublevel of the ground level and level 0 is the lowest sublevel of the ground level. If all ground state sublevels are strongly coupled, perhaps by some fast non-radiative decay process, then the populations of these sublevels will always be in thermal equilibrium. Let us further assume that the energy separation between level 1 and level 0 (see Fig. 1.4b) is comparable to kT. Then, according to Eq. (1.2.2), there will always be some population present in the lower laser level and the laser system will behave in a way which is intermediate between a three- and a four-level laser.

The process by which atoms are raised from level 1 to level 3 (in a three-level scheme), from 0 to 3 (in a four-level scheme), or from the ground level to level 3 (in a quasi-three-level scheme) is known as *pumping*. There are several ways in which this process can be realized in practice, e.g., by some sort of lamp of sufficient intensity or by an electrical discharge in the active medium. We refer to Chap. 6 for a more detailed discussion of the various pumping processes. We note here, however, that, if the upper pump level is empty, the rate at which the upper laser level becomes populated by the pumping, $(dN_2/dt)_p$, can in general be written as $(dN_2/dt)_p = W_p N_g$ where W_p is a suitable rate describing the pumping process and N_g is the population of the ground level for either a three- or four-level laser while, for a quasi-three-level laser, it can be taken to be the total population of all ground state sublevels. In what follows, however, we will concentrate our discussion mostly on four level or quasi-three-level lasers. The most important case of three-level laser, in fact, is the Ruby laser, a historically important laser (it was the first laser ever made to operate) although no longer so widely used. For most four-level and quasi-three-level lasers in commun use, the depletion of the ground level, due to the pumping process, can be neglected.* One can then write $N_g = \text{const}$ and the previous equation can be written, more simply, as

$$(dN_2/dt)_p = R_p \tag{1.3.1}$$

where R_p may be called the pump rate per unit volume or, more briefly, the *pump rate*. To achieve the threshold condition, the pump rate must reach a threshold or critical value, R_{cp}. Specific expressions for R_{cp} will be obtained in Chap. 6 and Chap. 7.

1.4. PROPERTIES OF LASER BEAMS

Laser radiation is characterized by an extremely high degree of (1) monochromaticity, (2) coherence, (3) directionality, and (4) brightness. To these properties a fifth can be added,

* One should note that, as a quasi-3-level laser becomes progressively closer to a pure 3-level laser, the assumption that the ground state population is changed negligibly by the pumping process will eventually not be justified. One should also note that in fiber lasers, where very intense pumping is readily achieved, the ground state can be almost completely emptied.

viz., (5) short time duration. This refers to the capability for producing very short light pulses, a property that, although perhaps less fundamental, is nevertheless very important. We shall now consider these properties in some detail.

1.4.1. Monochromaticity

Briefly, we can say that this property is due to the following two circumstances: (1) Only an e.m. wave of frequency ν_0 given by (1.1.1) can be amplified. (2) Since the two-mirror arrangement forms a resonant cavity, oscillation can occur only at the resonance frequencies of this cavity. The latter circumstance leads to the laser linewidth being often much narrower (by as much as to ten orders of magnitude!) than the usual linewidth of the transition $2 \rightarrow 1$ as observed in spontaneous emission.

1.4.2. Coherence

To first order, for any e.m. wave, one can introduce two concepts of coherence, namely, spatial and temporal coherence.

To define spatial coherence, let us consider two points P_1 and P_2 that, at time $t = 0$, lie on the same wave-front of some given e.m. wave and let $E_1(t)$ and $E_2(t)$ be the corresponding electric fields at these two points. By definition, the difference between the phases of the two field at time $t = 0$ is zero. Now, if this difference remains zero at any time $t > 0$, we will say that there is a perfect coherence between the two points. If this occurs for any two points of the e.m. wave-front, we will say that the wave has *perfect spatial coherence*. In practice, for any point P_1, the point P_2 must lie within some finite area around P_1 if we want to have a good phase correlation. In this case we will say that the wave has a *partial spatial coherence* and, for any point P, we can introduce a suitably defined coherence area $S_c(P)$.

To define temporal coherence, we now consider the electric field of the e.m. wave at a given point P, at times t and $t + \tau$. If, for a given time delay τ, the phase difference between the two field remains the same for any time t, we will say that there is a temporal coherence over a time τ. If this occurs for any value of τ, the e.m. wave will be said to have perfect time coherence. If this occurs for a time delay τ such that $0 < \tau < \tau_0$, the wave will be said to have partial temporal coherence, with a coherence time equal to τ_0. An example of an e.m wave with a coherence time equal to τ_0 is shown in Fig. 1.5. The figure shows a sinusoidal electric field undergoing random phase jumps at time intervals equal to τ_0. We see that the concept of temporal coherence is, at least in this case, directly connected with that of monochromaticity. We will show, in fact, in Chap. 11, that any stationary e.m. wave with coherence time τ_0 has a bandwidth $\Delta\nu \simeq 1/\tau_0$. In the same chapter it will also be shown that, for a non-stationary but repetitively reproducing beam (e.g., a repetitively Q-switched or a mode-locked laser beam) the coherence time is not related to the inverse of the oscillation bandwidth $\Delta\nu$ and may actually be much longer than $1/\Delta\nu$.

It is important to point out that the two concepts of temporal and spatial coherence are indeed independent of each other. In fact, examples can be given of a wave having perfect spatial coherence but only limited temporal coherence (or vice versa). If, for instance, the wave shown in Fig. 1.5 were to represent the electric fields at points P_1 and P_2 considered earlier,

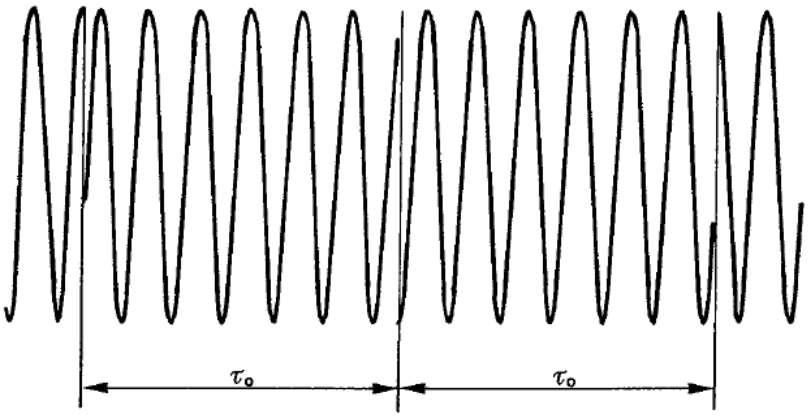


FIG. 1.5. Example of an e.m. wave with a coherence time of approximately τ_0.

the spatial coherence between these two points would be complete still the wave having a limited temporal coherence.

We conclude this section by emphasizing that the concepts of spatial and temporal coherence provide only a first-order description of the laser's coherence. Higher order coherence properties will in fact discussed in Chap. 11. Such a discussion is essential for a full appreciation of the difference between an ordinary light source and a laser. It will be shown in fact that, by virtue of the differences between the corresponding higher-order coherence properties, a laser beam is fundamentally different from an ordinary light source.

1.4.3. Directionality

This property is a direct consequence of the fact that the active medium is placed in a resonant cavity. In the case of the plane parallel one of Fig. 1.3, for example, only a wave propagating in a direction orthogonal to the mirrors (or in a direction very near to it) can be sustained in the cavity. To gain a deeper understanding of the directional properties of a laser beam (or, in general, of any e.m. wave), it is convenient to consider, separately, the case of a beam with perfect spatial coherence and the case of partial spatial coherence.

Let us first consider the case of perfect spatial coherence. Even for this case, a beam of finite aperture has unavoidable divergence due to diffraction. This can be understood with the help of Fig. 1.6, where a monochromatic beam of uniform intensity and plane wave-front is assumed to be incident on a screen S containing an aperture D. According to Huyghens' principle the wave-front at some plane P behind the screen can be obtained from the superposition of the elementary waves emitted by each point of the aperture. We thus see that, on account of the finite size D of the aperture, the beam has a finite divergence θ_d. Its value can be obtained from diffraction theory. For an arbitrary amplitude distribution we get

$$\theta_d = \beta \lambda / D \qquad (1.4.1)$$

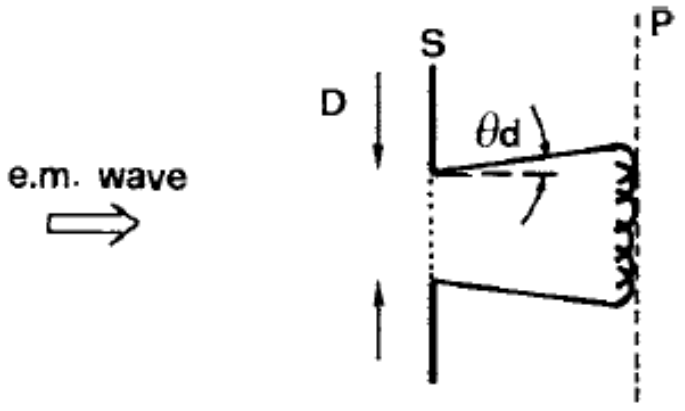


FIG. 1.6. Divergence of a plane e.m. wave due to diffraction.

where λ and D are the wavelength and the diameter of the beam. The factor β is a numerical coefficient of the order of unity whose value depends on the shape of the amplitude distribution and on the way in which both the divergence and the beam diameter are defined. A beam whose divergence can be expressed as in Eq. (1.4.1) is described as being *diffraction limited*.

If the wave has only a partial spatial coherence, its divergence will be larger than the minimum value set by diffraction. Indeed, for any point P' of the wave-front, the Huygens' argument of Fig. 1.6 can only be applied for points lying within the coherence area S_c around point P'. The coherence area thus acts as a limiting aperture for the coherent superposition of the elementary wavelets. The beam divergence will now be given by

$$\theta = \beta\lambda / [S_c]^{1/2} \tag{1.4.2}$$

where. again, β is a numerical coefficient of the order of unity whose exact value depends on the way in which both the divergence θ and the coherence area S_c are defined.

We conclude this general discussion of the directional properties of e.m. waves by pointing out that, given suitable operating conditions, the output beam of a laser can be made diffraction limited.

1.4.4. Brightness

We define the brightness of a given source of e.m. waves as the power emitted per unit surface area per unit solid angle. To be more precise, let dS be the elemental surface area at point O of the source (Fig. 1.7a). The power dP emitted by dS into a solid angle $d\Omega$ around direction OO' can be written as

$$dP = B \cos\theta \, dS \, d\Omega \tag{1.4.3}$$

where θ is the angle between OO' and the normal $\mathbf{n}$ to the surface. Note that the factor $\cos\theta$ arises simply from the fact that the physically important quantity for the emission along the OO' direction is the projection of dS on a plane orthogonal to the OO' direction, i.e. $\cos\theta \, dS$. The quantity B defined through Eq. (1.4.3) is called the source brightness at the point O in the direction OO'. This quantity will generally depend on the polar coordinates θ and ϕ of the direction OO' and on the point O. When B is a constant, the source is said to be isotropic (or a Lambertian source).

Let us now consider a laser beam of power P, with a circular cross section of diameter D and with a divergence θ (Fig. 1.7b). Since θ is usually very small, we have $\cos\theta \cong 1$. Since

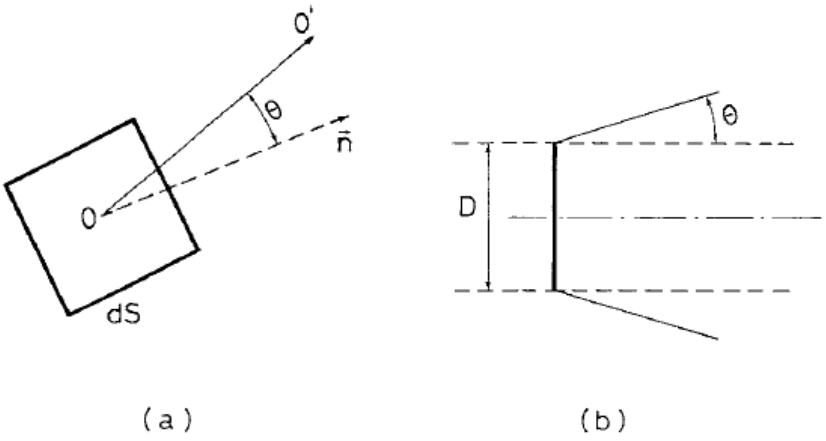


FIG. 1.7. (a) Surface brightness at the point O for a general source of e.m. waves. (b) Brightness of a laser beam of diameter D and divergence θ.

the area of the beam is equal to $\pi D^2/4$ and the emission solid angle is $\pi\theta^2$, then, according to Eq. (1.4.3), we obtain the beam brightness as

$$B = 4P/(\pi D\theta)^2 \tag{1.4.4}$$

Note that, if the beam is diffraction limited, we have $\theta = \theta_d$ and, with the help of Eq. (1.4.1), we obtain from Eq. (1.4.4)

$$B = \left(\frac{2}{\beta\pi\lambda}\right)^2 P \tag{1.4.5}$$

which is the maximum brightness that a beam of power P can have.

Brightness is the most important parameter of a laser beam and, in general, of any light source. To illustrate this point we first recall that, if we form an image of any light source through a given optical system and if we assume that object and image are in the same medium (e.g. air), then the following property holds: The brightness of the image is always less than or equal to that of the source, the equality holding when the optical system provides lossless imaging of the light emitted by the source. To further illustrate the importance of brightness, let us consider the beam of Fig. 1.7b, having a divergence equal to θ, to be focused by a lens of focal length f. We are interested in calculating the peak intensity of the beam in the focal plane of the lens (Fig. 1.8a). To make this calculation we recall that the beam can be decomposed into a continuous set of plane waves with an angular spread of approximately θ around the propagation direction. Two such waves, making an angle θ' are indicated by solid

and dashed lines, respectively, in Fig. 1.8b. The two beams will each be focused to a distinct spot in the focal plane and, for small angle θ', the two spots are transversely separated by a distance $r = f\theta'$. Since the angular spread of the plane waves which make up the beam of Fig. 1.8a is equal to the beam divergence θ, we arrive at the conclusion that the diameter, d, of the focal spot in Fig. 1.8a is approximately equal to $d = 2f\theta$. For an ideal, lossless, lens the overall power in the focal plane equals the power, P, of the incoming wave. The peak intensity in the focal plane is thus found to be $I_p = 4P/\pi d^2 = P/\pi(f\theta)^2$. In terms of beam brightness, according to (1.4.4) we then have $I_p = (\pi/4)B(D/f)^2$. Thus I_p increases with increasing beam

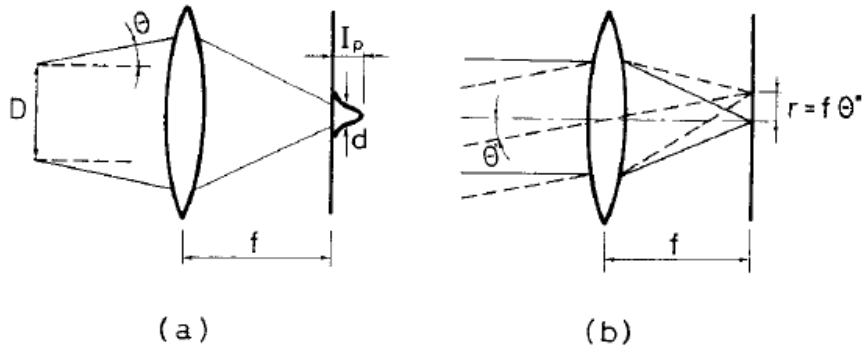


FIG. 1.8. (a) Intensity distribution in the focal plane of a lens for a beam of divergence θ. (b) Plane-wave decomposition of the beam of a.

diameter D. The maximum value of I_p is then attained when D is made equal to the lens diameter D_L. In this case we obtain

$$I_p = (\pi/4)\,(N.A.)^2\,B \tag{1.4.6}$$

where $N.A. = \sin[\tan^{-1}(D_L/f)] \cong (D_L/f)$ is the lens numerical aperture. Equation (1.4.6) then shows that, for a given numerical aperture, the peak intensity in the focal plane of a lens depends only on the beam brightness.

A laser beam of even moderate power (e.g. a few milliwatts) has a brightness that is several orders of magnitude greater than that of the brightest conventional sources (see, e.g., problem 1.7). This is mainly due to the highly directional properties of the laser beam. According to Eq. (1.4.6), this means that the peak intensity produced in the focal plane of a lens can be several order of magnitude larger for a laser beam compared to that of a conventional source. Thus the focused intensity of a laser beam can reach very large values, a feature which is exploited in many applications of lasers.

PROBLEMS

1.1. The part of the e.m. spectrum that is of interest in the laser field starts from the submillimiter wave region and goes down in wavelength to the X-ray region. This covers the following regions in succession: (1) far infrared; (2) near infrared; (3) visible; (4) ultraviolet (uv); (5) vacuum ultraviolet (vuv); (6) soft X-ray; (7) X-ray: From standard textbooks find the wavelength intervals of the above regions. Memorize or record these intervals since they are frequently used in this book.

1.2. As a particular case of Problem 1.1, memorize or record the wavelengths corresponding to blue, green, and red light.

1.3. If levels 1 and 2 of Fig. 1.1 are separated by an energy $E_2 - E_1$ such that the corresponding transition frequency falls in the middle of the visible range, calculate the ratio of the populations of the two levels in thermal equilibrium at room temperature.

1.4. When in thermal equilibrium at $T = 300\,\mathrm{K}$, the ratio of the level populations N_2/N_1 for some particular pair of levels is given by $1/e$. Calculate the frequency ν for this transition. In what region of the e.m. spectrum does this frequency fall?

1.5. A laser cavity consists of two mirrors with reflectivities $R_1 = 1$ and $R_2 = 0.5$ while the internal loss per pass is $\mathrm{L_i} = 1\%$. Calculate the total logarithmic losses per pass. If the length of the active material is $l = 7.5\,\mathrm{cm}$ and the transition cross section is $\sigma = 2.8 \times 10^{-19}\,\mathrm{cm}^2$, calculate then the threshold inversion.

1.6. The beam from a ruby laser ($\lambda \cong 694\,\mathrm{nm}$) is sent to the moon after passing through a telescope of 1 m diameter. Calculate the approximate value of beam diameter on the moon assuming that the beam has perfect spatial coherence (the distance between earth and moon is approximately 384,000 km).

1.7. The brightness of probably the brightest lamp so far available (PEK Labs type 107/109, excited by 100 W of electrical power) is about $95\,\mathrm{W/cm}^2$ sr in its most intense green line ($\lambda = 546\,\mathrm{nm}$). Compare this brightness with that of a 1 W Argon laser ($\lambda = 514.5\,\mathrm{nm}$), which can be assumed to be diffraction limited.

Before studying about lasers, you must be familiar with basic terms used to describe electromagnetic waves:
Wavelength (ʎ) Frequency (v) Period (T) Velocity of light (c) Index of refraction (n). We will briefly review these terms, but it is much better if you are familiar with:
Some terms from geometric optics such as: refraction, reflection, thin lenses etc.
Some terms from "Modern Physics" such as photons, Models of atoms, etc.

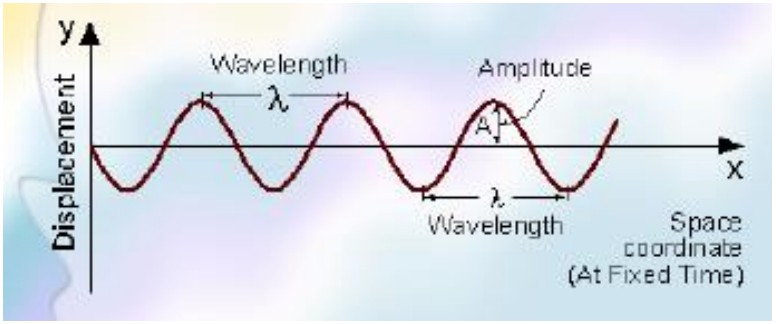
Electromagnetic Radiation

Electromagnetic Radiation is a transverse wave, advancing in vacuum at a constant speed which is called: velocity of light.

All electromagnetic waves have the same velocity invacuum, and its value is approximately:

$$c = 300{,}000 \text{ [km/sec]} = 3*10^8 \text{ [m/sec}$$

One of the most important parameters of a wave is its wavelength. Wavelength (λ) (Lamda) is the distance between two adjacent points on the wave, which have the same phase. As an example (see figure below) the between two adjacent peaks of the wave. distance



Frequency

In a parallel way it is possible to define a wave by its frequency. Frequency (μ) is defined by the number of times that the wave oscillates per second.

Between these two parameters the relation is: $c = \lambda * \mu$

From the physics point of view, all electromagnetic waves are equal (have the same properties) except for their wavelength (or frequency).

As an example: the speed of light is the same for visible light, radio waves, or x-rays.

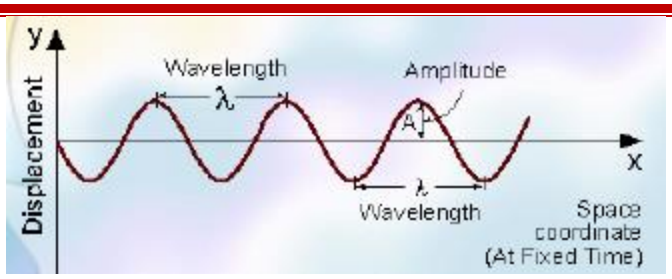
Wave Description

A wave can be described in two standard forms:

1. Displacement as a function of space when time isheld constant.
2. Displacement as a function of time at a specific placein space

Displacement as a function of space

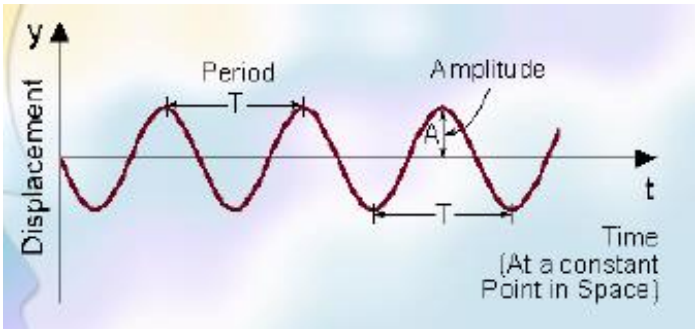
Displacement as a function of space, when time is "frozen" (held constant). In this description, the minimum distance between two adjacent points with the same phase is wavelength (λ). Note that the horizontal (x) axis is space coordinate



A = Amplitude = Maximum displacement from equilibrium

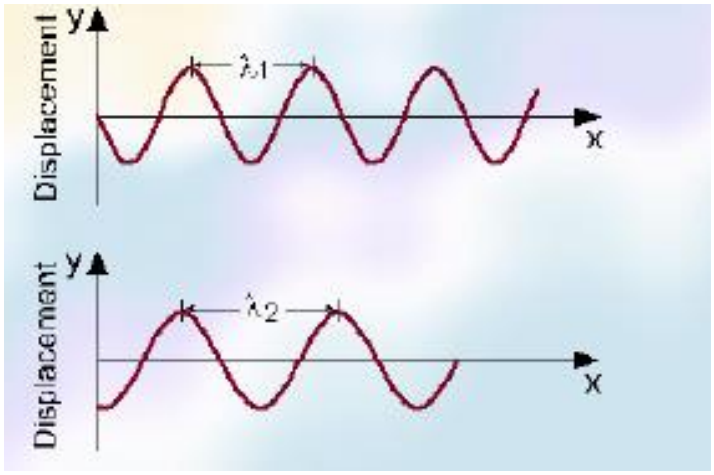
Displacement as a function of time

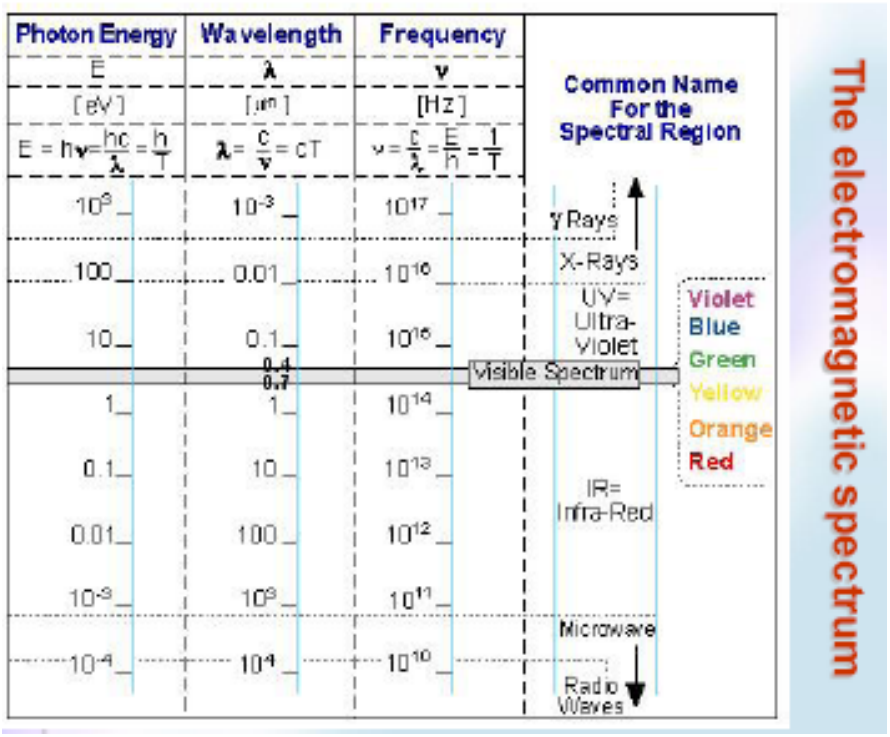
Displacement as a function of time, in a specific place in space, as described in figure. In this description, the minimum distance between two adjacent points with the same phase is period (T). Note that the horizontal (x) axis is time coordinate



Wavelengths Comparison

The Figure describes how two different waves (with different wavelengths) look at a specific moment in time. Each of these waves can be uniquely described by its wavelength.





The most important ideas summarized infigure are:

1. Electromagnetic waves span over many orders of magnitude in wavelength (or frequency).
2. The frequency of the electromagnetic radiation is inversely proportional to the wavelength.
3. The visible spectrum is a very small part of the electromagnetic spectrum.
4. Photon energy increases as the wavelength decreases. The shorter the wavelength, the more energetic are its photons.

Examples for electromagnetic waves are:

- Radio-waves which have wavelength of the order of meters, so they need big antennas.
- Microwaves which have wavelength of the order of centimeters. As an example: in a microwave oven, these wavelengths can not be transmitted through the protecting metal grid in the door, while the visiblespectrum which have much shorter wavelength allow us to see what is cooking inside the microwave oven through the protecting grid.
- x-Rays which are used in medicine for taking pictures ofthe bone structure inside the body.
- Gamma Rays which are so energetic, that they cause ionization, and are classified as ionizing radiation.

Electromagnetic Radiation in Matter

Light Velocity in Matter

When electromagnetic radiation passes through matter with index of refraction n, its velocity (v) is less than the velocity of light in vacuum (c), and given by the equation:

$$v = c / n$$

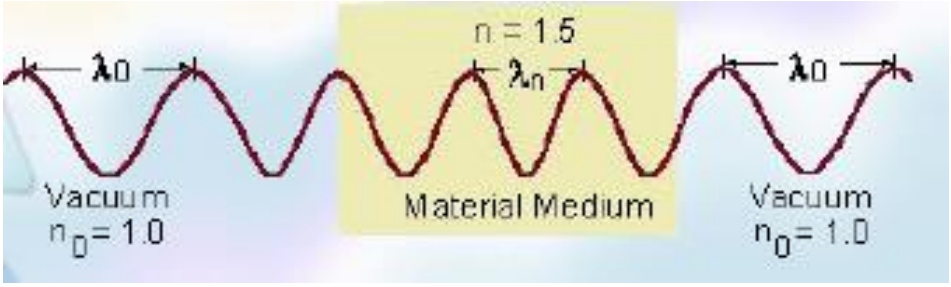
(speed of light This equation is used as a definition of the index of refraction n = in vacuum)/(speed of light in matter) n = c/v

Gases, including air, are usually considered as having index of refraction equal to vacuum n_0=1.

The values of the index of refraction of most materials transparent in the visible spectrum is between 1.4-1.8, while those of materials transparent in the Infra-Red (IR) spectrum are higher, and are 2.0-4.0.

Wavelength in Matter

We saw that the velocity of light in matter is slower than in vacuum. This slower velocity is associated with reduced wavelength: $\lambda = \lambda_0/n$, while the frequency remains the same



Refraction of Light Beam - Snell Law

Reducing the velocity of light in matter, and reducing its wavelength, causes refraction of the beam of light.

While crossing the border between two different materials, the light changes its direction of propagation according to the Snell Equation

$$n_1 \cdot \sin(\Theta_1) = n_2 \cdot \sin(\Theta_2)$$

THE BOHR MODEL

The Essentials: Atoms Bohr model of the atom

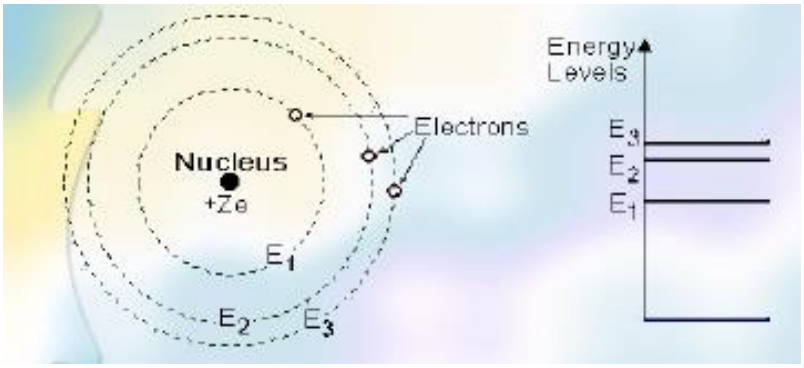
Lasing action is a process that occurs in matter.

Since matter is composed of atoms, we need to understand about the structure of the atom, and its energy states.

We shall start with the semi-classical model, as suggested in 1913 by Niels Bohr

, and called: The Bohr model of the atom. According to this model, every atom is composed of a very massive nucleus with a positive electric charge (Ze), around it electrons are moving in specific paths.

Z = Number of protons in the nucleus, e = Elementary charge of the electrons: e = $1.6*10^{-19}$ [Coulomb]



Every "allowed orbit" of the electron around the nucleus, is connected to a specific energy level.

The energy level is higher as the distance of the "orbit" from the nucleus increases. Since for each atom there are only certain "allowed orbits", only certain discrete energy levels exist, and are named: E1, E2, E3, etc

Energy States (Levels)

Every atom or molecule in nature has a specific structure for its energy levels.

The lowest energy level is called the ground state, which is the naturally preferred energy state. As long as no energy is added to the atom, the electron will remain in the ground state.

When the atom receives energy (electrical energy, optical energy, or any form of energy), this energy is transferred to the electron, and raises it to a higher energy level.

The atom is then considered to be in an excited state.

The electron can stay only at the specific energy states (levels) which are unique for each specific atom. The electron can not be in between these "allowed energy states", but it can "jump" from one energy level to another, while receiving or emitting specific amounts of energy.

These specific amounts of energy are equal to the difference between energy levels within the atom.

Each amount of energy is called a "Quantum" of energy (The name "Quantum The

ory" comes from these discrete amounts of energy).

Photons and the energy diagrams

Electromagnetic radiation has, in addition to its wave nature, some aspects of "particle like behavior".

In certain cases, the electromagnetic radiation behaves as an ensemble of discrete units of energy that have momentum. These discrete units (quanta) of electromagnetic radiation are called "Photons".

The relation between the amount of energy (E) carried by the photon, and its frequency (v), is determined by the formula (first given by Einstein):

$E = hv$

The proportionality constant in this formula is Planck's constant (h):

$h = 6.626*10^{-34}$ [Joule-sec]

This formula shows that the frequency of the radiation (v), uniquely determines the energy of each photon in this radiation.

$$E = h\,v$$

This formula can be expressed in different form, by using the relation between the frequency (v) and the wavelength: $c = \lambda * v$ to get:

$E = h * c/ \lambda$

This formula shows that the energy of each photon is inversely proportional to its wavelength. This means that each photon of shorter wavelength (such as violet light) carries more energy than a photon of longer wavelength (such as red light).

Since h and c are universal constants, so either wavelength or frequency is enough to fully describe the photon.

Chapter 2

Interaction of Radiation with Atoms and Ions

2

Interaction of Radiation with Atoms and Ions

2.1. INTRODUCTION

This chapter deals with the interaction of radiation with atoms and ions which are weakly interacting with any surrounding species, such as atoms or ions in a gas phase or impurity ions in an ionic crystal. The somewhat more complicated case of interaction of radiation with molecules or semiconductors will be considered in the next chapter. Since the subject of radiation interaction with matter is, of course, very wide, we will limit our discussion to those phenomena which are relevant for atoms and ions acting as active media. So, after an introductory section dealing with the theory of blackbody radiation, a milestone for the whole of modern physics, we will consider the elementary processes of absorption, stimulated emission, spontaneous emission, and nonradiative decay. They will first be considered within the simplifying assumptions of a dilute medium and a low intensity. Following this, situations involving a high beam intensity and a medium that is not dilute (leading, in particular, to the phenomena of saturation and amplified spontaneous emission) will be considered. A number of very important, although perhaps less general, topics relating to the photophysics of dye lasers, free-electron lasers, and *X*-ray lasers will be briefly considered in Chaps. 9 and 10 immediately preceding the discussion of the corresponding laser.

2.2. SUMMARY OF BLACKBODY RADIATION THEORY[1]

Let us consider a cavity filled with a homogeneous and isotropic medium. If the walls of the cavity are kept at a constant temperature, T, they will continuously emit and receive power in the form of electromagnetic (e.m.) radiation. When the rates of absorption and emission

where V is the total volume of the cavity. If we now define $p(\nu)$ as the number of modes per unit volume and per unit frequency range, we have

$$p(\nu) = \frac{1}{V}\frac{dN}{d\nu} = \frac{8\pi\nu^2}{c_n^3}. \qquad (2.2.16)$$

2.2.2. The Rayleigh-Jeans and Planck Radiation Formula

Having calculated the quantity $p(\nu)$ we can now proceed to calculate the energy density ρ_ν. We can begin by writing ρ_ν as the product of the number of modes per unit volume per unit frequency range, $p(\nu)$, multiplied by the average energy $<E>$ contained in each mode, i.e.

$$\rho_\nu = p_\nu <E> \tag{2.2.17}$$

To calculate $<E>$ we assume that the cavity walls are kept at a constant temperature T. According to Boltzmann's statistics, the probability dp that the energy of a given cavity mode lies between E and $E + dE$ is expressed by $dp = C\exp[-(E/kT)]dE$, where C is a constant to be established by the condition $\int_0^\infty C\exp[-(E/kT)dE = 1$. The average energy of the mode $<E>$ is therefore given by

$$<E> = \frac{\int_0^\infty E\exp[-(E/kT)]dE}{\int_0^\infty \exp[-(E/kT)]dE} = kT \tag{2.2.18}$$

From Eq. (2.2.16), Eqs. (2.2.17), and (2.2.18) we then get

$$\rho_\nu = \left(\frac{8\pi\nu^2}{c_n^3}\right)kT \tag{2.2.19}$$

This is the well known Rayleigh-Jeans radiation formula. It is, however, in complete disagreement with the experimental results. Indeed, it is immediately obvious that Eq. (2.2.19) must be wrong since it would imply an infinite total energy density ρ [see Eq. (2.2.2)]. Equation (2.2.19) does, however, represent the inevitable conclusion of the previous classical arguments.

The problem remained unsolved until, at the beginning of this century, Planck introduced the hypothesis of light quanta. The fundamental hypothesis of Planck was that the energy in a given mode could not have any arbitrary value between 0 and ∞, as was implicitly assumed in Eq. (2.2.18), but that the allowed values of this energy should be integral multiples of a fundamental quantity, proportional to the frequency of the mode. In other words, Planck assumed that the energy of the mode could be written as

$$E = nh\nu \tag{2.2.20}$$

where n is a positive integer and h a constant (which was later called Planck's constant). Without entering into too many details, here, on this fundamental hypothesis, we merely wish to note that this essentially implies that energy exchange between the inside of the cavity

and its walls must involve a discrete amount of energy $h\nu$. This minimum quantity that can be exchanged is called a light quantum or photon. According to this hypothesis, the average energy of the mode is now given by

$$E = \frac{\sum_0^\infty {}_n nh\nu \exp[-(nh\nu/kT)]}{\sum_0^\infty {}_n \exp[-(nh\nu/kT)]} = \frac{h\nu}{\exp(h\nu/kT) - 1} \tag{2.2.21}$$

This formula is quite different from the classical expression Eq. (2.2.18). Obviously, for $h\nu \ll kT$, Eq. (2.2.21) reduces to Eq. (2.2.18). From Eq. (2.2.16), Eqs. (2.2.17), and (2.2.21) we now obtain the Planck formula,

$$\rho_\nu = \frac{8\pi\nu^2}{c_n^3} \frac{h\nu}{\exp(h\nu/kT) - 1} \tag{2.2.22}$$

which is in perfect agreement with the experimental results, provided that we choose for h the value $h = 6.62 \times 10^{-34}$ J $\times$ s. For example, Fig. 2.3 shows the behavior predicted by Eq. (2.2.22) for ρ_ν vs frequency ν for two values of temperature T.

Lastly, we may notice that the ratio

$$<\phi> = \frac{<E>}{h\nu} = \frac{1}{\exp(h\nu/kT) - 1} \qquad (2.2.23)$$

gives the average number of photons $<\phi>$ for each mode. If we now consider a frequency ν in the optical range ($\nu \approx 4 \times 10^{14}$ Hz), we get $h\nu \approx 1\,eV$. For $T \cong 300$ K we have $kT \cong (1/40)$ eV, so that from Eq. (2.2.23) it is $<\phi> \cong \exp(-40)$. We thus see that the average number of photons per mode, for blackbody radiation at room temperature, is very much smaller than unity. This value should be compared with the number of photons ϕ_0 that can be obtained in a laser cavity for a single mode (see Chap. 7).

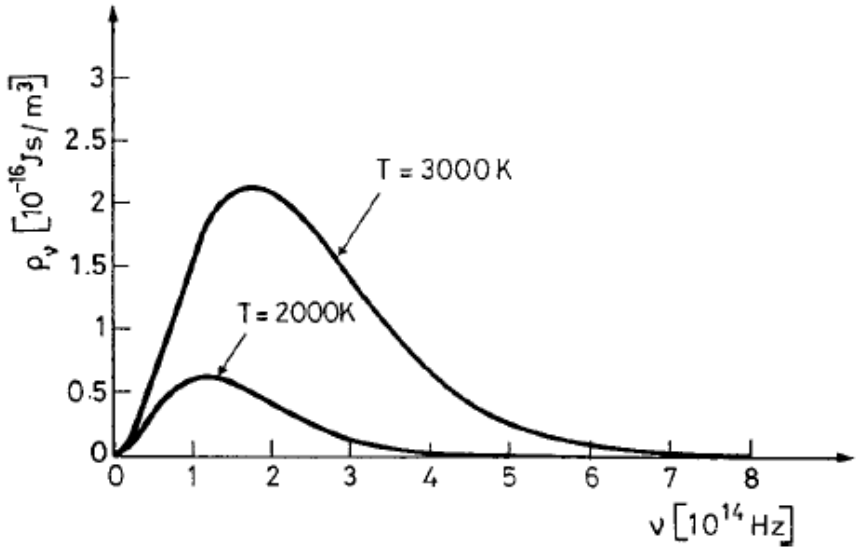


FIG. 2.3. Plot of the function $\rho_\nu(\nu, T)$ as a function of frequency ν at two values of the temperature T.

2.4.4. Einstein Thermodynamic Treatment

In this section we will describe a treatment, given by Einstein,[7] of both spontaneous and stimulated transitions (absorption and emission). In this treatment the concept of stimulated emission was first clearly established and the correct relationship between spontaneous and stimulated transition rates was derived well before the formulation of quantum mechanics and quantum electrodynamics. The calculation makes use of an elegant thermodynamic argument. To this end, let us assume that the material is placed in a blackbody cavity whose walls are kept at a constant temperature T. Once thermodynamic equilibrium is reached, an e.m. energy density with a spectral distribution ρ_ν given by Eq. (2.2.22) will be established and

the material will be immersed in this radiation. In this material, both stimulated-emission and absorption processes will occur, in addition to the spontaneous-emission process. Since the system is in thermodynamic equilibrium, the number of transitions per second from level 1 to level 2 must be equal to the number of transitions from level 2 to level 1. We now set

$$W_{21} = B_{21}\rho_{\nu_0} \tag{2.4.36}$$

$$W_{12} = B_{12}\rho_{\nu_0} \tag{2.4.37}$$

where B_{21} and B_{12} are constant coefficients (the *Einstein B coefficients*), and let N_1^e and N_2^e be the equilibrium populations of levels 1 and 2, respectively. We can then write

$$AN_2^e + B_{21}\rho_{\nu_0}N_2^e = B_{12}\rho_{\nu_0}N_1^e \tag{2.4.38}$$

From Boltzmann statistics we also know that, for non degenerate levels, one has

$$N_2^e/N_1^e = \exp(-h\nu_0/kT) \tag{2.4.39}$$

From Eqs. (2.4.38) and (2.4.39) it then follows that

$$\rho_{\nu_0} = \frac{A}{B_{12}\exp(h\nu_0/kT) - B_{21}} \tag{2.4.40}$$

A comparison of Eq. (2.4.40) with Eq. (2.2.22), when $\nu = \nu_0$, leads to the following relations:

$$B_{12} = B_{21} = B \tag{2.4.41}$$

$$\frac{A}{B} = \frac{8\pi h\nu_0^3 n^3}{c^3} \tag{2.4.42}$$

Equation (2.4.41) shows that the probabilities of absorption and stimulated emission due to blackbody radiation are equal. This relation is therefore analogous to that established, in a completely different way, in the case of monochromatic radiation [see Eq. (2.4.12)]. Equation (2.4.42), on the other hand, allows the calculation of A, once B, i.e., the coefficient for stimulated emission due to blackbody radiation, is known. This coefficient can easily be obtained from Eq. (2.4.30) once we remember that this equation was established for monochromatic radiation. For blackbody radiation, we can write $\rho_\nu d\nu$ for the energy density of radiation whose frequency lies between ν and $\nu + d\nu$ and simulate this elemental radiation by a monochromatic wave. The corresponding elemental transition probability dW is then obtained from Eq. (2.4.30) by substituting $\rho_\nu d\nu$ for ρ. Upon integration of the resulting equation with the assumption that $g_t(\nu - \nu_0)$ can be approximated by a Dirac δ function in comparison with ρ_ν (see Fig. 2.3), we get

$$W = \frac{2\pi^2}{3\,n^2\varepsilon_0\,h^2}|\mu|^2\rho_{\nu_0} \tag{2.4.43}$$

The comparison of Eq. (2.4.43) with Eqs. (2.4.36) or (2.4.37) then gives

$$B = \frac{2\pi^2|\mu|^2}{3\,n^2\varepsilon_0\,h^2} \tag{2.4.44}$$

so that, from Eq. (2.4.42), we obtain

$$A = \frac{16\,\pi^3\nu_0^3\,n|\mu|^2}{3\,h\varepsilon_0\,c^3} \tag{2.4.45}$$

It should be noted that the expression for A that we have just obtained is exactly the same as that obtained by a quantum electrodynamics approach [see Eq. (2.3.19)]. Its calculation is in fact based on thermodynamics and the use of Planck's law (which is quantum electrodynamically correct).

ground state is unlimited. On the other hand, the particle can remain in the excited state for a limited time known as *life time*. The life time of the

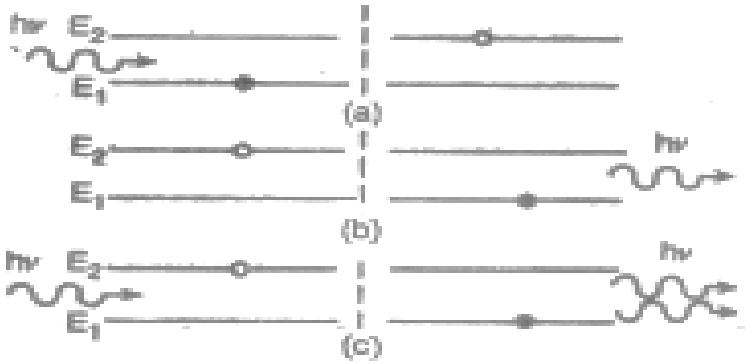


Fig. (1) Excitation and emission of a particle.

excited hydrogen atom is of the order of 10^{-8} sec. However, there exist such excited states in which the life time is greater than 10^{-8} sec. These states are called as *metastable*. Here two points should be remembered. (1) Only certain transitions are possible which are allowed by selection rules. (2) The transition of a particle from one energy state to another can be non-radiative. In such cases the energy is transmitted to other particles which is converted into heat. After being in the excited state, the particle returns to the ground state. The probability of transition to the ground state with emission of radiation is made up of two factors, one constant and the other variable.

Spontaneous emission :

The excited atom does not remain is that state for a long time. After a short interval of time 10^{-8} sec. It falls to its lower energy state by emitting a photon as shown in fig. (1b). Here the excited atom jumps back to its ground state on its own accord and hence the process is known as *spontaneous emission*. ***So the emission which takes place without external incitement is called spontaneous emission.*** The spontaneous emission depends on the type of the particle and type of transition but is independent of outside circumstances. The spontaneous emission (not caused by an extraneous effects) is random in character. The radiation in this case is a random mixture of quanta having various wavelengths. The waves coincide neither in wavelength nor in phase. Thus the radiation is *incoherent* and has a broad spectrum.

Stimulated emission :

Suppose an atom is already in the excited state of energy level E_2 whose ground level energy is E_1. If at this moment, a photon of energy

$h\nu = E_2 - E_1$ is incident on the excited atom, the incident photon stimulates the emission of a similar photon from the excited atom. Now the atom returns to the ground state. The transition takes place much sooner than 10^{-8} sec. ***The process of speeding up the atomic transition from the excited state to lower state is called stimulated emission.*** The stimulated emission is proportional to the intensity of the incident light. This is shown in fig. (1 *c*). The remarkable feature of the stimulated emission is that it is ***coherent*** with the stimulating ineident radiation. It has the same frequency and phase as the incident radiation.

So, the stimulated emission takes place when a photon of right frequency interacts with an excited atom and forces it to emit another photon of the same frequency in same direction and in same phase. As a esult, a large number of photons are emitted. They form the source of *intense, coherent* and *monochromatic* light *i.e.*, laser

In an ordinary source of light, the spontaneous emission dominates.

7·3. DISTINCTION BETWEEN SPONTANEOUS AND STIMULATED EMISSION

The distinction between spontaneous and stimulated emission is as follows :

	Spontaneous emission	Stimulated emission
1.	Transition occurs from a higher energy level to a lower energy level.	Transition also occurs from higher energy level to lower energy level.
2.	No incident photon is required.	Photon whose energy is equal to the difference of two energy levels is required.
3.	Single photon is emitted.	Two photons with same energy are emitted.
4.	The energy of emitted photon is equal to the energy difference of two levels.	The energy of the emitted photons is double the energy of stimulated photons.
5.	This was postulated by Bohr.	This was postulated by Einstein.

7·4. EINSTEIN COEFFICIENTS

In article 7-2 we have studied the processes of absorption, spontaneous emission and stimulated emission.

(1). The probable rate of occurrence of the *absorption transition* from state 1 to state 2 [see. fig. 2*a*] depends on the properties of states 1 and 2 and is proportional to energy density $u(\nu)$ of the radiation of frequency ν incident on the atom. Thus

Fig. (2a)

$$P_{12} \propto u(\nu) \text{ or } P_{12} = B_{12}\, u(\nu) \quad ...(1)$$

The proportionality constant B_{12} is known as *'Einstein's coefficient of absorption of radiation'*.

(2). The probability of spontaneous emission from state 2 to state 1 [see. fig. 2*b*] depends only on the properties of states 1 and 2. This is independent of energy density $u(\nu)$ of incident radiation. Einstein denoted this probability per unit time by A_{21}.

Fig. (2b)

$$\therefore \quad (P_{21})_{spontaneous} = A_{21}$$

A_{21} is known as *'Einstein's coefficient of spontaneous emission of radiation'*.

Here it should be noted that the probability of absorption transition depends upon energy density $u(\nu)$ of incident radiation whereas the probability of spontaneous emission is independent of it. Hence for equilibrium, emission transition depending upon $u(\nu)$ must also exist. Actually these transitions are stimulated emission transitions.

(3). The probability of stimulated emission transition from state 2 to

Fig. (2c)

state 1 [see. fig. 2 *c*] is proportional to the energy density $u(\nu)$ of the stimulating radiation *i.e.*,

$$(P_{21})_{stimulated} = B_{21}\, u(\nu)$$

where B_{21} is *'Einstein's coefficient of stimulated emission of radition'*.

The total probability for an atom in state 2 to drop to the lower state 1 is, therefore

$$P_{21} = A_{21} + B_{21}\, u(\nu) \quad ...(2)$$

7·5. RELATION BETWEEN EINSTEIN'S A AND B COEFFICIENTS.

Consider an assembly of atoms in thermal equilibrium at temperature T with radiation of frequency ν and energy density $u(\nu)$. Let N_1 and N_2 be the number of atoms in energy states 1 and 2 respectively at any instant.

The number of atoms in state 1 that absorb a photon and rise to state 2 per unit time is given by

$$N_1 P_{12} = N_1 B_{12} u(\nu) \qquad ...(3)$$

The number of photons in state 2 that can cause emission process [spontaneous + stimulated] per unit time is given by

$$N_2 P_{21} = N_2 [A_{21} + B_{21} u(\nu)] \qquad ...(4)$$

For equilibrium, the absorption and emission must occur equally, hence

$$N_1 P_{12} = N_2 P_{21}.$$

$$N_1 B_{12} u(\nu) = N_2 [A_{21} + B_{21} u(\nu)]$$

or $$N_1 B_{12} u(\nu) = N_2 A_{21} + N_2 B_{21} u(\nu)$$

or $$u(\nu) [N_1 B_{12} - N_2 B_{21}] = N_2 A_{21}$$

$$\therefore \quad u(\nu) = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}} = \frac{A_{21}}{B_{21}} \frac{1}{\left[\frac{N_1}{N_2}\left(\frac{B_{12}}{B_{21}}\right) - 1\right]} \qquad ...(5)$$

According to Boltzmann distribution law, the number of atoms N_1 and N_2 in energy states E_1 and E_2 in thermal equilibrium at temperature T is given by

$$N_1 = N_0 e^{-E_1/kT} \quad \text{and} \quad N_2 = N_0 e^{-E_2/kT}$$

where N_0 = total number of atoms present and k = Boltzmann's constant

$$\therefore \quad \frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}} = e^{-(E_2 - E_1)/kT} = e^{-h\nu/kT}$$

or $$\frac{N_1}{N_2} = e^{h\nu/kT} \qquad ...(6)$$

Substituting the value of N_1/N_2 from eq. (6) in eq. (5), we get

$$u(\nu) = \frac{A_{21}}{B_{21}} \frac{1}{\left[e^{h\nu/kT}\left(\frac{B_{12}}{B_{21}}\right) - 1\right]} \qquad ...(7)$$

According to Planck's radiation formula

$$u(\nu) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{\left[e^{h\nu/kT} - 1\right]} \quad ...(8)$$

Comparing eqs. (7) and (8), we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{and} \quad \frac{B_{12}}{B_{21}} = 1 \text{ or } B_{12} = B_{21}$$

Hence

(i) As $B_{12} = B_{21}$, the probability of stimulated emission is same as induced absorption.

(ii) $A_{21}/B_{21} \propto \nu^3$ *i.e.*, the ratio of spontaneous emission and stimulated emission is proportional to ν^3. This shows that the probability of spontaneous emission increases rapidly with energy difference between two states.

7·6. LASING ACTION :

In stimulated emission, the emitted photon travels in the same direction as that of incident photon [Fig. (3*a*)]. Now the two photons again stimulate emission of photon from two excited atoms. This results in the emission of four photons from the two excited atoms [Fig. (3*b*)]. In

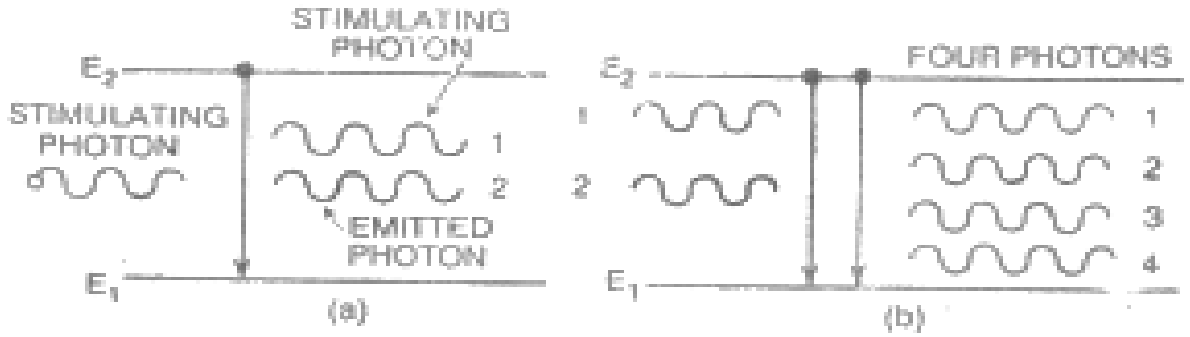
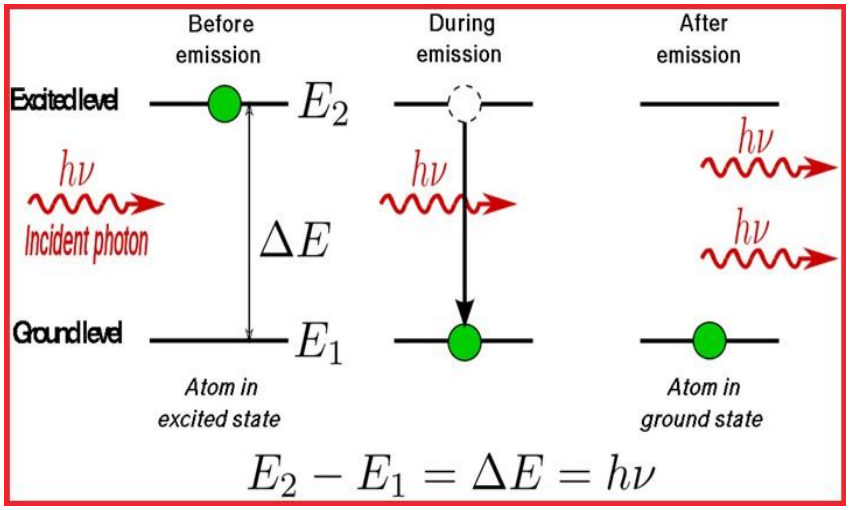
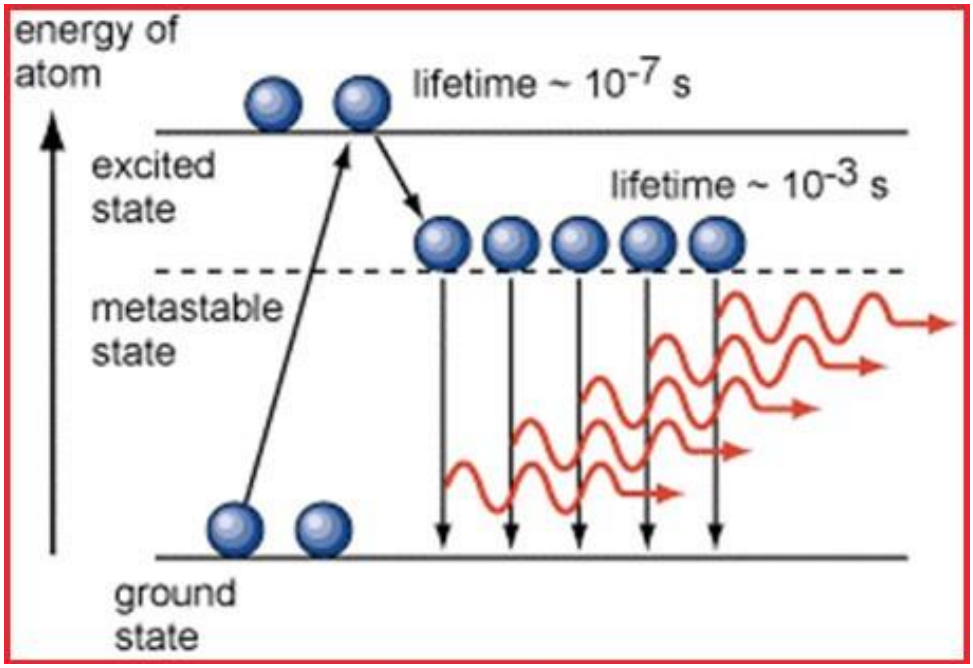


Fig. (3).

a similar way a *chain reaction* or *avalanche effect* is produced. The phenomenon is known as *lasing action*. So a *monochromatic, intense and coherent beam having the same frequency as that of incident beam is obtained*. This is called laser beam. This is the principle of working of a laser.


Before emission
During emission
After emission
Excited level
E_2
$h\nu$
Incident photon
ΔE
$h\nu$
$h\nu$
$h\nu$
Ground level
E_1
Atom in excited state
Atom in ground state
$E_2 - E_1 = \Delta E = h\nu$


energy of atom
lifetime ~ 10^{-7} s
excited state
lifetime ~ 10^{-3} s
metastable state
ground state

2.5. LINE BROADENING MECHANISMS

In this section we will discuss, in some detail, the various line broadening mechanisms mentioned in previous sections. According to the earlier discussion, there is an important distinction to be made from the outset between homogeneous and inhomogeneous line-broadening. A line-broadening mechanism is referred to as *homogeneous* when it broadens the line of each atom in the same way. In this case the line-shape of the single-atom cross section and that of the overall absorption cross section would be identical. Conversely, a line-broadening mechanism is said to be *inhomogeneous* when it distributes the atomic resonance frequencies over some spectral range. Such a mechanism thus broadens the overall line of the system (i.e. that of α) without broadening the lines of individual atoms.

Before proceeding, it is worth recalling that the shape of the function $g_t(\nu - \nu_0)$ can be determined in two ways: (a) By an absorption experiment, with the help of a spectrophotometer. In this case one measures the absorption coefficient as a function of frequency ν, using the spectrophotometer to select the light frequency. From Eq. (2.4.33) one sees that $\alpha \propto \nu g_t(\nu - \nu_0)$. Since the linewidth of the function $g_t(\nu - \nu_0)$ is, typically, much smaller than ν_0, we can approximately write $\alpha \propto \nu_0 g_t(\nu - \nu_0)$. Thus, to a very good approximation, the shape of the α vs ν curve coincides with that of the function $g_t(\nu - \nu_0)$. (b) By an emission experiment, in which one passes the spontaneously emitted light trough a spectrometer of sufficiently high resolution and one determines $g_t(\nu - \nu_0)$ by measuring the shape of the spectral emission. It can be shown that, for any transition, the lineshapes obtained by these two approaches are always the same. So, in the discussion that follows, we will consider the lineshape function either in absorption or in emission, whichever is the more convenient.

2.5.1. Homogeneous Broadening

The first homogeneous line-broadening mechanism we consider is one due to collisions and is known as *collision broadening*. In a gas, it is due to the collision of an atom with other atoms, ions, free electrons, etc. or with the walls of the container. In a solid it is due to the interaction of the atom with the phonons of the lattice. After a collision the two level wavefunctions ψ_1 and ψ_2 of the atom [see Eq. (2.3.1)] will undergo a random phase jump. This means that the phase of the oscillating dipole moment μ_{osc} [see Eq. (2.3.6)] will undergo a random jump compared to that of the incident e.m. wave. These collisions thus interrupt

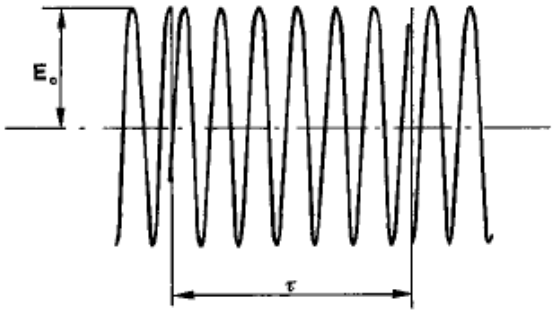


FIG. 2.9. Time behavior of the electric field of an e.m. wave, $E(t)$, as seen from an atom undergoing collisions. Note that, in actual cases, there may 10^7 or more collisions during the collision time τ.

the process of coherent interaction between the atom and the incident e.m. wave. Since it is the relative phase which is important during the interaction process, an equivalent way of treating this problem is to assume that it is the phase of the electric field rather than that of μ_{osc} that undergoes a jump at each collision. The electric field will therefore no longer appear sinusoidal but will instead appear as shown in Fig. 2.9, where each phase jump occurs at the time of a collision. It is therefore clear that, under these conditions, the atom no longer sees a monochromatic wave. In this case, if we write $d\rho = \rho_{\nu'} d\nu'$ for the energy density of the wave in the frequency interval between ν' and $\nu' + d\nu'$, we can use this elemental energy density in the formula valid for monochromatic radiation, i.e., Eq. (2.4.7), which gives

$$dW_{12} = \frac{2\pi^2}{3n^2\varepsilon_0 h^2}|\mu_{21}|^2 \rho_{\nu'} \delta(\nu' - \nu_0) d\nu' \tag{2.5.1}$$

The overall transition probability is then obtained by integrating Eq. (2.5.1) over the entire frequency spectrum of the radiation, thus giving

$$W_{12} = \frac{2\pi^2}{3n^2\varepsilon_0 h^2}|\mu_{21}|^2 \int_{-\infty}^{+\infty} \rho_{\nu'}\,\delta(\nu' - \nu_0)d\nu' \tag{2.5.2}$$

We can now write $\rho_{\nu'}$ as

$$\rho_{\nu'} = \rho\, g(\nu' - \nu) \tag{2.5.3}$$

where ρ is the energy density of the wave [see Eq. (2.4.6)], and $g(\nu' - \nu)$ describes the spectral distribution of $\rho_{\nu'}$. Since one obviously has $\rho = \int \rho_{\nu'} d\nu'$, the integration of both sides of Eq. (2.5.3) then shows that $g(\nu' - \nu)$ must satisfy the normalization condition

$$\int_{-\infty}^{+\infty} g(\nu' - \nu)d\nu' = 1 \tag{2.5.4}$$

Upon substituting Eq. (2.5.3) into Eq. (2.5.2) and using a well known mathematical property of the δ function we get

$$W_{12} = \frac{2\pi^2}{3n^2\varepsilon_0 h^2}|\mu_{21}|^2 \rho\, g(\nu - \nu_0) \tag{2.5.5}$$

As anticipated in Sect. 2.4.1, it is seen that W_{12} is indeed obtained by substituting $g(\nu - \nu_0)$ to $\delta(\nu - \nu_0)$ in Eq. (2.4.7). Note that, according to Eq. (2.5.4), we also have

$$\int_{-\infty}^{+\infty} g(\nu - \nu_0)d\nu = 1 \tag{2.5.6}$$

There now remains the problem of calculating the normalized spectral density of the incident radiation $g(\nu' - \nu)$. This will depend on the time interval, τ, between collisions (Fig. 2.9), which will obviously be different for each collision. We will assume that the distribution of the values of τ can be described by a probability density

$$p_\tau = [\exp(-\tau/\tau_c)]/\tau_c \tag{2.5.7}$$

Here $p_\tau\, d\tau$ is the probability that the time interval between two successive collisions lies between τ and $\tau + d\tau$. Note that τ_c has the physical meaning of the average time $<\tau>$ between collisions. It is easy, in fact, to see that

$$<\tau> = \int_0^\infty \tau\, p_\tau d\tau = \tau_c \tag{2.5.8}$$

At this point the mathematical problem to be solved is well defined. We need to obtain the normalized spectral lineshape of a wave as in Fig. 2.9 for which the time τ between two successive collisions has the statistical distribution p_τ given by Eq. (2.5.7). Referring to the Appendix B for the mathematical details we merely quote the final result here. The required normalized spectral lineshape is given by

$$g(\nu' - \nu) = 2\tau_c \frac{1}{\left[1 + 4\pi^2 \tau_c^2 (\nu' - \nu)^2\right]} \tag{2.5.9}$$

According to Eq. (2.5.5) the line shape of the transition is obtained from Eq. (2.5.9) by substituting ν' by ν_0. We then get

$$g(\nu - \nu_0) = 2\tau_c \frac{1}{\left[1 + 4\pi^2 \tau_c^2 (\nu - \nu_0)^2\right]} \tag{2.5.10}$$

which is our final result. We thus obtain a function with a Lorentzian lineshape, as generally described by Eq. (2.4.8) [see also Fig. 2.6], where the peak value is now $2\tau_c$ and the linewidth $\Delta\nu_0$ is

$$\Delta\nu_0 = 1/\pi\tau_c \tag{2.5.11}$$

Example 2.2. *Collision broadening of a He-Ne laser* As a first example of collision broadening, we consider the case of a transition for an atom, or ion, in a gas at pressure p. An estimate of τ_c is, in this case, given by $\tau_c = l/\upsilon_{th}$ where l is the mean free path of the atom in the gas and υ_{th} is its average thermal velocity. Since $\upsilon_{th} = (3kT/M)^{1/2}$ where M is the atomic mass and taking l to be given by the expression resulting from the hard-sphere model of a gas, we obtain

$$\tau_c = \left(\frac{2}{3}\right)^{1/2} \frac{1}{8\pi} \frac{(MkT)^{1/2}}{pa^2} \tag{2.5.12}$$

where a is the radius of the atom and p is the gas pressure. For a gas of Neon atoms at room temperature and at a pressure $p \cong 0.5$ Torr (typical pressure in a He-Ne gas laser) using Eq. (2.5.12) with $a \cong 0.1$ nm and $\tau_c \cong 0.5\,\mu$s, we find from Eq. (2.5.11) that $\Delta\nu_o = 0.64$ MHz. Note that τ_c is inversely proportional, and hence $\Delta\nu_0$ directly proportional, to p. As a rough "rule of thumb" we can say that, for any atom, collisions in a gas contribute to the line broadening by an amount $(\Delta\nu_0/p) \cong 1$ MHz/Torr, comparable to that shown in the example of Ne atoms. Note also that, during the collision time τ_c the number of cycles of the e.m. wave is equal to $m = \nu\tau_c$ For a wave whose wavelength falls in the middle of the visible range we have $\nu = 5 \times 10^{14}$ Hz and thus the number of cycles is 5×10^8. This emphasizes the fact that Fig. 2.9 is not to scale since the number of cycles in the time τ is much larger than suggested in the figure.

Example 2.3. *Linewidth of Ruby and Nd:YAG* As a third example of collision broadening, we will consider an impurity ion in an ionic crystal. In this case the collisions of the ion occur with the lattice phonons. Since the number of phonons in a given lattice vibration is a strong function of the lattice temperature, we expect the transition linewidth to show a strong dependence on temperature. As a representative example, Fig. 2.10 shows the linewidth versus temperature for both Nd:YAG and ruby, the linewidth being expressed in wavenumbers [cm^{-1}], a quantity widely used by spectroscopists rather than actual frequency.* At 300 K the laser transition linewidths are seen to be $\Delta\nu_0 \cong 4\,cm^{-1} \cong 120$ GHz for Nd:YAG and $\Delta\nu_0 \cong 11\,cm^{-1} = 330$ GHz for ruby.

A second homogeneous line-broadening mechanism has its origin in the phenomenon of spontaneous emission. Since this emission is an inevitable feature of any transition, the corresponding broadening is called *natural* or *intrinsic*. In the case of natural broadening, it is easiest to consider the behavior in terms of the spectrum of the emitted radiation. It should be noted however that, as pointed out in Sect. 2.3.2, spontaneous emission is a purely quantum phenomenon, i.e. it can only be correctly explained by quantizing both matter and radiation. It follows therefore that a correct description of the lineshape of the emitted radiation also needs a quantum electrodynamics treatment. We will therefore limit ourselves to quoting the final result, which happens to be very simple, and to justifying it by some simple arguments. The quantum electrodynamics theory of spontaneous emission[8] shows that the spectrum $g(\nu - \nu_0)$ is again described by a Lorentzian line whose shape can be obtained from Eq. (2.5.10) by replacing τ_c by $2\tau_{sp}$, where τ_{sp} is the decay time of the spontaneous emission. Thus, in particular, the full width of the line (FWHM) is given by

$$\Delta\nu_0 = 1/2\pi\tau_{sp} \tag{2.5.13}$$

* For a given wave of frequency ν, the corresponding frequency in wave numbers (e.g. in cm^{-1}) is given by $w = 1/C$, where c is the velocity of the wave in a vacuum (in cm/s). The true frequency ν is then obtained from the frequency in wave numbers by the simple relation $\nu = cw$ while the corresponding wavelenght is simply given by $\lambda = c/\nu = 1/w$ (in cm). This illustrates the advantages of the wave number notation. The trem wave number arises from the fact that w gives the number of wave periods, n, comprised in a given unitary length l (e.g. in 1 cm). The number n is in fact given by $n = l/\lambda$ so that $n/l = 1\lambda = w$.

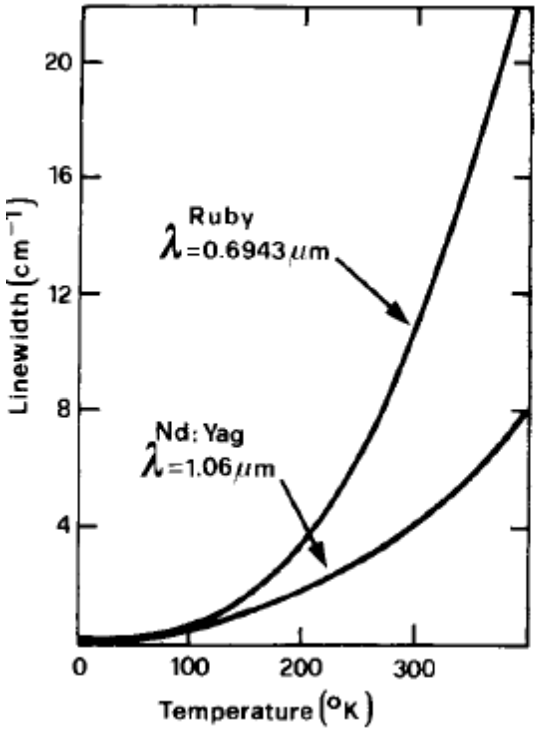


FIG. 2.10. Laser linewidth vs temperature for ruby and Nd:YAG, as determined by phonon broadening.

To justify this result we notice that, since the power emitted by the atom decays in time as $\exp(-t/\tau_{sp})$, the corresponding electric field can be thought as decaying according to the relationship $E(t) = \exp(-t/2\tau_{sp}) \times \cos \omega_0 t$. The decay of emitted intensity [which is proportional to $<E^2(t)>$] would then show the correct temporal behavior, namely, $\exp(-t/\tau_{sp})$. We can now easily calculate the power spectrum corresponding to such a field $E(t)$ and verify that the line shape is Lorentzian and that its width is given by Eq. (2.5.13).

Example 2.4. *Natural linewidth of an allowed transition* As a representative example we can find an order of magnitude estimate for $\Delta\nu_{nat}$ for an electric-dipole allowed transition. Assuming $|\mu| = ea$ with $a \cong 0.1$ nm and $\lambda = 500$ nm (green light) we already obtained in example 2.1 that $\tau_{sp} \cong 10$ ns. From Eq. (2.5.13) we then get $\Delta\nu_{nat} \cong 16$ MHz. Note that $\Delta\nu_{nat}$, just as $A = 1/\tau_{sp}$, is expected to increase with frequency as ν_0^3. Therefore the natural linewidth increases very rapidly for transitions at shorter wavelengths (down to the UV or X-ray region).

2.5.2. Inhomogeneous Broadening

We will now consider some mechanisms where the broadening arises from the distribution of the atomic resonance frequencies (inhomogeneous broadening).

As a first case of inhomogeneous broadening we consider that which occurs for ions in ionic crystals or glasses. Ions will experience a local electric field produced by the surrounding atoms of the material and, due to material inhomogeneities which are particularly significant in glass medium, these fields will be different from ion to ion. These local field variations will then produce, via the Stark effect, local variation of the energy levels and thus of the transition frequencies of the ions (the term inhomogeneous broadening originates from this case). For random local field variations, the corresponding distribution of the transition frequencies $g^*(\nu_0' - \nu_0)$ turns out to be given by a Gaussian function, i.e. by the general expression Eq. (2.4.27) where the linewidth $\Delta\nu_0^*$ (FWHM) will depend upon the extent of variation of transition frequencies in the material and hence upon the amount of field inhomogeneity within the crystal or glass.

Example 2.5. *Linewidth of a Nd:glass laser* As a representative example we consider the case of Nd^{3+} ions doped into a silicate glass. In this case, due to glass inhomogeneities, the linewidth of the laser transition at $\lambda = 1.05\,\mu$m is $\Delta\nu_0^* \cong 5.4$ THz i.e. it is about 40 times broader than that of Nd:YAG at room temperature (see Example 2.3). It should be noted that these inhomogeneities are an unavoidable feature of the glass state.

A second inhomogeneous broadening mechanism, typical of gas, arises from atomic motion and is called Doppler broadening. Assume that an incident e.m. wave of frequency ν is propagating in the positive z direction and let υ_z be the component of atomic velocity along this axis. According to the Doppler effect, the frequency of the wave, as seen from the rest frame of the atom, is $\nu' = \nu[1 - (\upsilon_z/c)]$ where c is the velocity of light in the medium. Notice the well known result that, when $\upsilon_z > 0$, we have $\nu' < \nu$ and vice versa. Of course, absorption by the atom will occur only when the apparent frequency ν' of the e.m. wave, as seen from the atom, is equal to the atomic transition frequency ν_0, i.e., when $\nu[1 - (\upsilon_z/c)] = \nu_0$. If we now express this relation as

$$\nu = \nu_0/[1 - (\upsilon_z/c)] \tag{2.5.14}$$

we can arrive at a different interpretation of the process. As far as the interaction of the e.m. radiation with the atom is concerned, the result would be the same if the atom were not moving but instead had a resonant frequency ν_0' given by

$$\nu_0' = \nu_0/[1 - (\upsilon_z/c)] \tag{2.5.15}$$

where ν_0 is the true transition frequency. Indeed, following this interpretation, absorption is expected to occur when the frequency ν of the e.m. wave is equal to ν_0' i.e. when $\nu = \nu_0'$, in agreement with Eq. (2.5.14) when the expression Eq. (2.5.15) for ν_0' is used. When looked at in this way, one can see that this broadening mechanism does indeed belong to the inhomogeneous category as defined at the beginning of this section.

To calculate the corresponding line shape $g^*(\nu_0' - \nu_0)$ it is now sufficient to remember that, if we let $p_v d\upsilon_z$ be the probability that an atom of mass M in a gas at temperature T has a velocity component between υ_z and $\upsilon_z + d\upsilon_z$, then p_v is given by the Maxwell distribution

$$p_v = \left(\frac{M}{2\pi kT}\right)^{1/2} \exp -(M\upsilon_z^2/2kT) \tag{2.5.16}$$

From Eq. (2.5.15), since $|\upsilon_z| \ll c$, we get $\nu_0' \cong \nu_0[1 + (\upsilon_z/c)]$ and thus $\upsilon_z = c(\nu_0' - \nu_0)/\nu_0$. From Eq. (2.5.16) one then obtains the desired distribution upon recognizing that one must have $g^*(\nu_0' - \nu_0)d\nu_0' = p_\upsilon d\upsilon_z$. One then gets

$$g^*(\nu_0' - \nu_0) = \frac{1}{\nu_0}\left(\frac{Mc^2}{2\pi kT}\right)^{1/2} \exp -\left[\frac{Mc^2}{2kT}\frac{(\nu_0' - \nu_0)^2}{\nu_0^2}\right] \tag{2.5.17}$$

Thus one again obtains a Gaussian function whose FWHM linewidth (Doppler linewidth) is now readily found from a comparison of Eq. (2.5.17) with Eq. (2.4.24), giving

$$\Delta\nu_0^* = 2\nu_0\left[2kT \ln 2/Mc^2\right]^{1/2} \tag{2.5.18}$$

For the purely inhomogeneous case the lineshape will be given by the general expression of Eq. (2.4.27) where $\Delta\nu_0^*$ is given by Eq. (2.5.18).

Example 2.6. *Doppler linewidth of a He-Ne laser* Consider the Ne line at the wavelength $\lambda = 632.8$ nm (the red laser line of a He-Ne laser) and assume T = 300 K. Then from Eq. (2.5.18), using the appropriate mass for Ne, we get $\Delta\nu_0^* \cong 1.7$ GHz. A comparison of this value with those obtained for collision broadening, see example 2.2, and natural broadening, see Example 2.4 (the transition is allowed by electric dipole), shows that Doppler broadening is the predominant line broadening mechanism in this case.

2.5.3. Concluding Remarks

According to the previous discussion, we have seen that the shape of a homogeneous line is always Lorentzian while that of an inhomogeneous line is always Gaussian. When two mechanisms contribute to line broadening, the overall line shape turns out to be always given by the convolution of the corresponding line-shape functions, as indicated in Eq. (2.4.26) for the case of one line being homogeneously and the other inhomogeneously broadened. It can now be shown that the convolution of a Lorentzian line, of width $\Delta\nu_1$, with another Lorentzian line, of width $\Delta\nu_2$, again gives a Lorentzian line whose width is now $\Delta\nu = \Delta\nu_1 + \Delta\nu_2$. The convolution of a Gaussian line, of width $\Delta\nu_1$, with another Gaussian line, of width $\Delta\nu_2$, is again a Gaussian line, this time of width $\Delta\nu = \left(\Delta\nu_1^2 + \Delta\nu_2^2\right)^{1/2}$. For any combination of broadening mechanisms, it is therefore always possible, to reduce the problem to a convolution of a single Lorentzian line with a single Gaussian line and this integral (which is known as the Voigt integral[9]) is tabulated. Sometimes, however, (e.g. as in the previously discussed cases for Ne), one mechanism predominates. In this case, it is then possible to talk of a pure Lorentzian or Gaussian line.

We conclude this section by showing, in Table 2.1, the actual range of linewidths for the various line-broadening mechanisms considered. Note that, in the middle of the visible range, we have $\tau_{sp} \cong 10\,\text{ns}$ and hence $\Delta\nu_{nat} \cong 10\,\text{MHz}$ for an electric dipole allowed transition. For an electric dipole forbidden transition, on the other hand, one has $\tau_{sp} \cong 1\,\text{ms}$ and hence $\Delta\nu_{nat} \cong 1\,\text{kHz}$. Note also that, in the case of a liquid, collision broadening and local field inhomogeneous broadening are the predominant broadening mechanisms. In this case, the average time between two consecutive collisions is indeed much shorter than in the gas phase [$\tau_c \cong 0.1\,\text{ps}$] and hence we have $\Delta\nu_c = 1/\pi\tau_c \cong 100\,\text{cm}^{-1}$. Inhomogeneous broadening arises from the local density variations associated with a given temperature and may produce a value for the linewidth $\Delta\nu_0^*$ comparable to that of collision broadening. In a solid, inhomogeneous broadening due to local field variations may be as high as $300\,\text{cm}^{-1}$ for a glass and as low as $0.5\,\text{cm}^{-1}$, or even lower, for a good quality crystal such as in presently available Nd:YAG crystals.

TABLE 2.1. Typical magnitude of frequency broadening for the various line-broadening mechanisms

	Type	Gas	Liquid	Solid
Homogeneous	Natural	$1\,\text{kHz} \div 10\,\text{MHz}$	Negligible	Negligible
	Collisions	$5 \div 10\,\text{MHz/Torr}$	$\sim 300\,\text{cm}^{-1}$	–
	Phonons	–	–	$\sim 10\,\text{cm}^{-1}$
Inhomogeneous	Doppler	$50\,\text{MHz} \div 1\,\text{GHz}$	Negligible	–
	Local field	–	$\sim 500\,\text{cm}^{-1}$	$1 \div 500\,\text{cm}^{-1}$

2.6. NONRADIATIVE DECAY AND ENERGY TRANSFER

Besides decaying via radiative emission, an excited species can also undergo nonradiative decay. There exists a variety of ways by which this can occur and the detailed description of the various physical phenomena can often be quite complicated. We shall therefore limit ourselves to a qualitative discussion with the main aim being to elucidate the physical phenomena involved. We will then consider the combined effect of radiative and non-radiative decay processes.

2.6.1. Mechanisms of Nonradiative Decay[10]

First we consider a nonradiative decay mechanism which arises from collisions, sometimes called *collisional deactivation*. In this case, for a gas or a liquid, the transition energy is released as excitation and/or as kinetic energy of the colliding species or given to the walls of the container. In the case of a solid, such as an ionic crystal or glass, the energy of the excited ion is taken up by the lattice phonons or by the glass vibrational modes.

The collisional deactivation process, for the case where the energy of an excited species B^* is released as kinetic energy of a colliding species A, can be expressed in the form

$$B^* + A \rightarrow B + A + \Delta E \tag{2.6.1}$$

where ΔE is equal to the excitation energy. Since ΔE ends up as kinetic energy of the colliding partners, the process is also referred to as a *superelastic collision* or a *collision of second kind*. For a process of the form shown in Eq. (2.6.1), the rate of change of B^* population, N_{B^*}, can be written as

$$\frac{dN_{B^*}}{dt} = -k_{B^*A} N_{B^*} N_A \tag{2.6.2}$$

where N_A is the population of species A and k_{B^*A} is a coefficient which depends on the transition of species B and on species A. The process is particularly effective, i.e. k_{B^*A} is particularly large, when A has a very small mass (e.g. the He in the gas of a CO_2 laser) so it can more readily take-up the surplus energy ΔE, from the collision process, as kinetic energy. For the same reason the process can readily occur in a gas discharge when A is a discharge electron (e.g. deactivation of the 2^3S state of He in a He-Ne laser). According to Eq. (2.6.2), we can now define a nonradiative decay rate

$$W_{nr} = k_{B^*A} N_A \tag{2.6.3}$$

From Eqs. (2.6.2) and (2.6.3) we then get

$$\left(\frac{dN_2}{dt}\right) = -\frac{N_2}{\tau_{nr}} \tag{2.6.4}$$

where, to conform with previous notations, we have let N_2 be the population of the species undergoing collisional deactivation and where we have defined a nonradiative decay time as $\tau_{nr} = (1/W_{nr})$.

It should be observed that, in writing Eq. (2.6.2), we have neglected the reverse process of that given by Eq. (2.6.1) i.e.,

$$B + A \rightarrow B^* + A - \Delta E \tag{2.6.5}$$

where species B is excited at the expense of the kinetic energy ΔE of the two colliding partners (*thermal activation* or *collision of first kind*). If this process were taken into account, one should write, instead of Eq. (2.6.2), the following equation

$$(dN_{B^*}/dt) = -k_{B^*A}N_{B^*}N_A + k_{BA}N_BN_A \tag{2.6.6}$$

where k_{BA} is a coefficient describing the process of thermal activation. To find the relationship between k_{BA} and k_{B^*A} we can consider species B in thermal equilibrium with species A and then apply the so-called *principle of detailed balance*. This principle can generally be formulated by requiring that, in thermodynamic equilibrium, the rate of *any* process must be exactly balanced by the rate of the corresponding reverse process*. Thus in this case, according to Eq. (2.6.6), we require

$$k_{B^*A}N_{B^*}N_A = k_{BA}N_BN_A \tag{2.6.7}$$

In thermal equilibrium and for nondegenerate levels we have $N_{B^*} = N_B \exp(-\Delta E/kT)$ where ΔE is the excitation energy of species B and T is the temperature of the ensemble of species B and A. From Eq. (2.6.7) we then get

$$k_{B^*A} = k_{BA} \exp(\Delta E/kT) \tag{2.6.8}$$

which shows that the rate coefficient k for the exothermic reaction Eq. (2.6.1) is always larger than that of the endothermic reaction Eq. (2.6.5). Actually, for electronic and for most vibrational transitions, ΔE is much larger than kT. Thus, according to Eq. (2.6.8), we have $k_{B^*A} \gg k_{BA}$. It is very important also to realize that, although Eq. (2.6.8) has been derived for thermal equilibrium conditions, the same relation still holds if the population of species B is maintained in a non equilibrium state of excitation, e.g. by some pumping process, provided that the translational degrees of freedom of both species B and A are still in thermal equilibrium. In fact, the quantum mechanical calculation of the rate coefficient k does not depend on the population of B but only upon the eigenfunctions of the two species involved, and on their relative velocities. For a steady excitation of species B away from the Boltzmann equilibrium, i.e. when N_{B^*} is of the same order of N_B, we thus have $k_{B^*A}N_{B^*} \gg k_{BA}N_B$ and Eq. (2.6.6) reduces to Eq. (2.6.2). Thus, to conclude, collisional deactivation takes the simple form given by Eq. (2.6.4) only when $\Delta E >> kT$ so that thermal activation may be neglected, which is the case for electronic transitions and for most vibrational transitions. For deactivation of the lowest energy vibrational levels of some molecules [e.g. the (010) state of CO_2] and for rotational transitions, thermal excitation must however be taken into account.

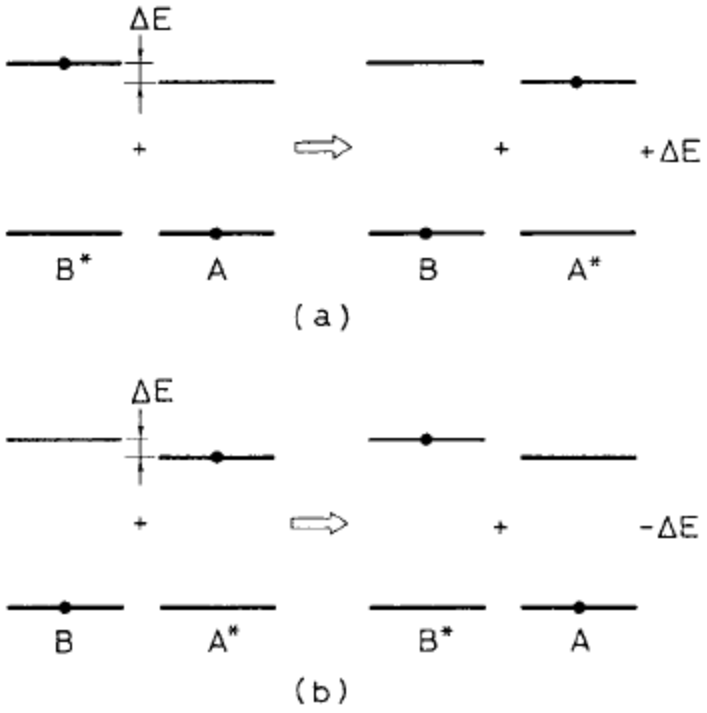


FIG. 2.11. (a) Nonradiative decay of a species B by near resonant energy transfer to a species A. (b) Reverse, back-transfer, process.

When the electronic energy of species B is released in the form of internal energy of some other species A, we can represent this with an equation of the form (collision of the second kind*)

$$B^* + A \rightarrow B + A^* + \Delta E \tag{2.6.9}$$

where $\Delta E = E_B - E_A$ is the difference between the internal energies of the two species (see Fig. 2.11a). The quantum mechanical calculation of the corresponding transition rate is beyond the scope of this book and we refer the reader elsewhere for details.[11] Here we limit ourselves to pointing out that, since ΔE must be added to or removed from the kinetic energy of the two colliding partners, the process turns out to be particularly effective when ΔE is appreciably smaller than kT. Therefore, the process is also called *near-resonant energy transfer* and often plays an important role as a pumping mechanism in gas lasers (e.g. energy transfer between excited He and ground state Ne, in a He-Ne laser, or between excited N_2 and ground state CO_2 in a CO_2 laser). The process also results in an effective deactivation channel for species B. To consider the dynamics of this deactivation process, we must also take into account the reverse process (*back-transfer*, see Fig. 2.11b)

$$B + A^* \rightarrow B^* + A - \Delta E \tag{2.6.10}$$

Actually, again applying the principle of detailed balance one can now show that, e.g., for the case of exact resonance (i.e., $\Delta E = 0$), one has $k_{B^*A} = k_{BA^*}$, where k_{B^*A} and k_{BA^*} are the

* Collisions of the *first kind* involve conversion of the kinetic energy of one species into internal energy of another species [see Eq. (2.6.5)]. In collisions of the *second kind*, internal energy is converted into some other form of energy (other than radiation) such as kinetic energy [see Eq. (2.6.1)], or is transferred into internal energy of another species (same or different species) [see Eq. (2.6.9)]. Collisions of the second kind thus also include, for instance, the conversion of excitation energy into chemical energy.

rate constants of the two processes described by Eqs. (2.6.9) and (2.6.10), respectively. This indicates that the back-transfer reaction often plays a very important role. This process can however be neglected when the decay of species A from its excited state is very fast, as it may occur by the onset of stimulated emission. In this case one has $(N_{A^*}/N_A) \ll (N_{B^*}/N_B)$, the back transfer may be neglected, and the rate of decay of the excited species, B^*, can simply be written as

$$(dN_{B^*}/dt) = -k_{B^*A}N_{B^*}N_A \tag{2.6.11}$$

We again obtain an equation of the general form given by Eq. (2.6.4) where now $(1/\tau_{nr}) = k_{B^*A}N_A$.

Finally we consider the case where collisional deactivation of species B (e.g. an active ion in an ionic crystal) occurs through interaction with lattice phonons or with glass vibrational modes*. In many cases, except for some nonradiative decay processes occurring in tunable solid state lasers (see Chap. 9), we are dealing with electronic transitions and thus with transition energies of species B which are many times (typically at least 3 to 4 times) larger than that of the most energetic phonon. This means that, to conserve energy, the transition energy must be released in the form of many phonons (*multiphonon deactivation*). Thus, in this case, the deactivation process can be represented in the form

$$B^* \rightarrow B + \sum_1^n {}_i(h\nu_i) \tag{2.6.12}$$

where ν_i are the frequencies of the phonons involved and the sum is extended over all phonons created in this resonant or near-resonant process. Again we can define a transition rate W_{nr} according to the relation

$$\frac{dN_{B^*}}{dt} = -W_{nr}B^* \tag{2.6.13}$$

In this case, since many phonons are involved, the quantum mechanical calculation for the process would involve a higher order perturbation theory. It is therefore not considered here in any detail. We simply limit ourselves to pointing out that, if only a phonon of frequency ν is involved, W_{nr} can be written as $W_{nr} = A\exp(-B\Delta E/h\nu)$, where A and B are host-dependent constants and ΔE is the transition energy of species B. We thus see that the transition rate rapidly decreases with the increasing number, $n = \Delta E/h\nu$, of phonons involved i.e. with the increasing order of the multiphonon process. The dominant contribution to the nonradiative process thus comes from the lattice phonon of the highest energy, since this means that the lowest order process is then involved. The large variation in vibrational spectra shown by different material then makes W_{nr} extremely host dependent. By contrast, the rate is found to be relatively independent of the actual electronic state or even the particular active ion involved.

* The absence of translational invariance in glass means that, strictly speaking, one should not talk in terms of phonons, in this case, as one does for a crystal. For now on, however, for brevity we will refer to phonons even in this case.

2.6.2. Combined Effects of Radiative and Nonradiative Processes

Let us first consider the case where the nonradiative decay can be described by an equation of the general form Eq. (2.6.4). The time variation of the upper state population N_2 can then be written as

$$\frac{dN_2}{dt} = -\left(\frac{N_2}{\tau_r} + \frac{N_2}{\tau_{nr}}\right) \tag{2.6.16}$$

Equation (2.6.16) can be put in the simpler form

$$dN_2/dt = -(N_2/\tau) \tag{2.6.17}$$

provided that one defines an overall decay time τ given by

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \tag{2.6.18}$$

The population $N_2(t)$ at time t is then obtained by integrating Eq. (2.6.17). We get

$$N_2(t) = N_2(0)\exp -(t/\tau) \tag{2.6.19}$$

where $N_2(0)$ is the population at $t = 0$. To calculate the time behavior of the spontaneously emitted light, we notice that, according to Eq. (2.6.16), N_2/τ_r gives the number of atoms decaying radiatively per unit volume and unit time. Assuming, for simplicity, that radiative decay occurs to one lower level only, say level 1, and letting ν_0 be the corresponding transition frequency, the spontaneously emitted power at time t will then be

$$P(t) = N_2(t)h\nu_0 V/\tau_r \tag{2.6.20}$$

where V is the volume of the material. With the help of Eq. (2.6.19), Eq. (2.6.20) gives

$$P(t) = [N_2(0)h\nu_0 V/\tau_r]\exp -(t/\tau) \tag{2.6.21}$$

Note that the time decay of the emitted light is exponential with a time constant τ rather than τ_r as one, perhaps, might have expected at a first sight. By monitoring the decay of the spontaneously emitted light from a sample having, at $t = 0$, an initial upper state population $N_2(0)$, one thus measures the overall lifetime τ. To obtain τ_r, let us first define the fluorescence quantum yield ϕ as the ratio of the number of emitted photons to the number of atoms initially raised to level 2. Using Eq. (2.6.21), we have

$$\phi = \frac{\int (P(t)/h\nu_0)dt}{N_2(0)V} = \frac{\tau}{\tau_r} \tag{2.6.22}$$

2.8. SATURATION

The purpose of this section is to examine the absorption and emission behavior of a transition (of frequency ν_0) in the presence of a strong monochromatic e.m. wave of intensity I and frequency $\nu \cong \nu_0$. For simplicity, we will assume the levels to be non degenerate. Consider first the case where I is sufficiently weak that the populations of the two levels, N_1 and N_2, do not differ significantly from their thermal equilibrium values. One then has $N_1 > N_2$ (often $N_1 \gg N_2$) and the absorption processes, of rate WN_1, will dominate the stimulated emission process, of rate WN_2, i.e. more atoms undergo the $1 \rightarrow 2$ transition than the $2 \rightarrow 1$ transition. Consequently, at sufficiently high values of the intensity I, the two populations will tend to equalize. This phenomenon is referred to as *saturation*.

2.8.1. Saturation of Absorption: Homogeneous Line

We will consider first an absorbing transition ($N_1 > N_2$) and assume the line to be homogeneously broadened. The rate of change of the upper state population, N_2, due to the combined effects of absorption, stimulated emission and spontaneous decay (radiative and nonradiative), Fig. 2.17, can be written as

$$\frac{dN_2}{dt} = -W(N_2 - N_1) - \frac{N_2}{\tau} \tag{2.8.1}$$

where N_1 is the population of level 1. We can also write

$$N_1 + N_2 = N_t \tag{2.8.2}$$

where N_t is the total population. Equation (2.8.1) can be put into a simpler form by defining

$$\Delta N = N_1 - N_2 \tag{2.8.3}$$

Equations (2.8.2) and (2.8.3) then give N_1 and N_2 as a function of ΔN and N_t, and Eq. (2.8.1) becomes

$$\frac{d\Delta N}{dt} = -\Delta N\left(\frac{1}{\tau} + 2W\right) + \frac{1}{\tau}N_t \tag{2.8.4}$$

When $(d\Delta N/dt) = 0$, i.e. in the steady state, we get

$$\Delta N = \frac{N_t}{1 + 2W\tau} \tag{2.8.5}$$

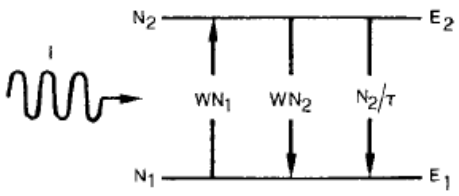


FIG. 2.17. Two-level system interacting with an e.m. wave of high intensity I.

To maintain a given population difference, ΔN, the material needs to absorb from the incident radiation a power per unit volume (dP/dV) given by

$$\frac{dP}{dV} = (h\nu)W\Delta N = (h\nu)\frac{N_t W}{1+2W\tau} \tag{2.8.6}$$

which, at saturation, i.e., for $W\tau \gg 1$, becomes

$$(dP/dV)_s = (h\nu)N_t/2\tau \tag{2.8.7}$$

Equation (2.8.7) shows that the power that must be absorbed by the system to keep it in saturation, $(dP/dV)_s$, is, as expected, equal to the power lost by the material due to the decay of the upper state population ($N_t/2$).

It is sometimes useful to have Eqs. (2.8.5) and (2.8.6) rewritten in a more convenient form. To do this we first notice that, according to Eq. (2.4.17), W can be expressed as

$$W = \sigma I/h\nu \tag{2.8.8}$$

where σ is the absorption cross section of the transition. Equations (2.8.5) and (2.8.6) with the help of Eq. (2.8.8) can be recast in the following forms:

$$\frac{\Delta N}{N_t} = \frac{1}{1+(I/I_s)} \tag{2.8.9}$$

$$\frac{dP/dV}{(dP/dV)_s} = \frac{I/I_s}{1+(I/I_s)} \tag{2.8.10}$$

where

$$I_s = h\nu/2\sigma\tau \tag{2.8.11}$$

is a parameter that depends on the given material and on the frequency of the incident wave. Its physical meaning is obvious from Eq. (2.8.9). In fact, for $I = I_s$, we get $\Delta N = N_t/2$. When $\nu = \nu_0$, the quantity I_s has a value that depends only on the parameters of the transition. This quantity is called the *saturation intensity*.

Let us now see how the shape of an absorption line changes with increasing value of the intensity, I, of the saturating beam. To do this, consider the idealized experimental situation shown in Fig. 2.18 where the absorption measurements are made using a probe beam of variable frequency ν' and whose intensity I' is small enough so as not to perturb the system appreciably. In practice the beams need to be more or less collinear to ensure that the probe beam interacts only with the saturated region. Under these conditions, the absorption coefficient as seen by the probe beam is obtained from Eq. (2.4.33) by substituting the total lineshape $g_t(\nu-\nu_0)$ with the homogeneous lineshape $g(\nu'-\nu_0)$, where ν has been substituted by ν'. Since $N_1 - N_2 = \Delta N$ is now given by Eq. (2.8.9), we can write

$$\alpha = \frac{\alpha_0}{1+(I/I_s)} \tag{2.8.12}$$

PROBLEMS

2.1. For a cavity volume $V = 1\,\text{cm}^3$ calculate the number of modes that fall within a bandwidth $\Delta\lambda = 10\,\text{nm}$ centered at $\lambda = 600\,\text{nm}$.

2.2. Instead of ρ_ν, a spectral energy density ρ_λ can be defined, ρ_λ being such that $\rho_\lambda d\lambda$ gives the energy density for the e.m. waves of wavelength lying between λ and $\lambda + d\lambda$. Find the relationship between ρ_λ and ρ_ν.

2.3. For blackbody radiation find the maximum of ρ_λ vs λ. Show in this way that the wavelength λ_M at which the maximum occurs satisfies the relationship $\lambda_M T = hc/ky$ (Wien's law), where the quantity y satisfies the equation $5\,[1 - \exp(-y)] = y$. From this equation find an approximate value of y.

2.4. The wavelength λ_M at which the maximum occurs for the distribution in Fig. 2.3 satisfies the relation $\lambda_M T = 2.9 \times 10^{-3}\,\text{m} \times \text{K}$ (Wien's law). Calculate λ_M for $T = 6{,}000\,\text{K}$. What is the color corresponding to this wavelength?

2.5. The R_1 laser transition of ruby has, to a good approximation, a Lorentzian shape of width (FWHM) 330 GHz at room temperature (see Fig. 2.10). The measured peak transition cross section in $\sigma = 2.5 \times 10^{-20}\,\text{cm}^2$. Calculate the radiative lifetime (the refractive index is $n = 1.76$). Since the observed room temperature lifetime is 3 ms, what is the fluorescence quantum yield?

2.6. Nd:YAG, a typical active laser material, is a crystal of $Y_3Al_5O_{12}$ (yttrium aluminum garnet, YAG) in which some of the Y^{3+} ions are substituted by Nd^{3+} ions. The typical Nd^{3+} atomic concentration used is 1%, i.e. 1% of Y^{3+} ions are replaced by Nd^{3+}. The YAG density is $4.56\,\text{g/cm}^3$. Calculate the Nd^{3+} concentration in the ground ($^4I_{9/2}$) level. This level is actually made up of five (doubly degenerate) levels (see Fig. 2.16), the four higher levels being spaced from the lowest level by 134, 197, 311,and 848 cm^{-1}, respectively. Calculate the Nd^{3+} concentration in the lowest level of the $^4I_{9/2}$ state.

2.7. The neon laser transition at $\lambda = 1.15\,\mu\text{m}$ is predominantly Doppler broadened to $\Delta\nu_0{}^* = 9 \times 10^8$ Hz. The upper state lifetime is $\approx 10^{-7}$ s. Calculate the peak cross section assuming that the laser transition lifetime is equal to the total upper state lifetime.

2.8. The quantum yield of the $S_1 \rightarrow S_0$ transition (see Chap.9) for Rhodamine 6G is 0.87, and the corresponding lifetime is ≈ 5 ns. Calculate the radiative and nonradiative lifetimes of the S_1 level.

2.9. Calculate the total homogeneous linewidth of the 633 nm laser transition of Ne knowing that $\Delta\nu_{nat} \cong 20\,\text{MHz}$ and $\Delta\nu_c = 0.64\,\text{MHz}$. What is the shape of the overall line?

2.10. Find the relationship between the intensity, I, and the corresponding energy density, ρ, for a plane wave.

5 Passive Optical Resonators

5.1. INTRODUCTION

This chapter deals with the theory of passive optical resonators i.e. where no active medium is present within the cavity. The most widely used laser resonators have either plane or spherical mirrors of rectangular (or, more often, circular) shape, separated by some distance L. Typically, L may range from a few centimeters to a few tens of centimeters, while the mirror dimensions range from a fraction of a centimeter to a few centimeters. Laser resonators thus differ from those used in the microwave field (see e.g. Sect. 2.2.1) in two main respects: (1) The resonator dimensions are much greater than the laser wavelength. (2) Resonators are usually open, i.e. no lateral surfaces are used. The resonator length is usually much greater than the laser wavelength because this wavelength usually ranges from a fraction of a micrometer to a few tens of micrometers. A laser cavity with length comparable to the wavelength would then generally have too low a gain to allow laser oscillation. Laser resonators are usually open because this drastically reduces the number of modes which can oscillate with low loss. In fact, with reference to example 5.1 to be considered below, it is seen that even a narrow linewidth laser such as a He-Ne laser would have a very large number of modes ($\approx 10^9$) if the resonator were closed. By contrast, on removing the lateral surfaces, the number of low-loss modes reduces to just a few ($\approx$6 in the example). In these open resonators, in fact, only the very few modes corresponding to a superposition of waves traveling nearly parallel to the resonator axis will have low enough losses to allow laser oscillation.

According to the previous discussion, it is seen that open resonators have inevitably some losses due to diffraction of the e.m. field, which leads to some fraction of the energy leaving the sides of the cavity (*diffraction losses*). Strictly speaking, therefore, the mode definition given in Sect. 2.2.1 cannot be applied to an open resonator and true modes (i.e. stationary configurations) do not exist for such a resonator. In what follows, however, we shall see that standing-wave configurations having very small losses do exist in open resonators. We will

Here τ_c (the decay time of the square of the electric field amplitude) is called the cavity photon decay time.

Of the various possible resonators we make particular mention of the following types:

a. *Plane – Parallel (or Fabry–Perot) Resonator.* This consists of two plane mirrors set parallel to one another. To a first approximation the modes of this resonator can be thought of as the superposition of two plane e.m. waves propagating in opposite directions along the cavity axis, as shown schematically in Fig. 5.1a. Within this approximation, the resonant frequencies can be readily obtained by imposing the condition that the cavity length L must be an integral number of half-wavelengths, i.e. $L = n\lambda/2$, where n is a positive integer. This is a necessary condition for the electric field of the e.m. standing wave to be zero on the two mirrors. It then follows that the resonant frequencies are given by

$$\nu = n(c/2L) \tag{5.1.2}$$

It is interesting to note that the same expression Eq. (5.1.2) can also be obtained by imposing the condition that the phase shift of a plane wave due to one round-trip through the cavity must equal an integral number times 2π, i.e. $2kL = 2n\pi$. This condition is readily obtained by a self-consistency argument. If the frequency of the plane wave is equal to that of a cavity mode, the phase shift after one round trip must be zero (apart from an integral number of 2π) since only in this case will the amplitudes at any arbitrary point, due to successive reflections, add up in phase so as to give an appreciable total field. Note that, according to Eq. (5.1.2), the frequency difference between two consecutive modes, i.e. modes whose integers differ by one, is given by

$$\Delta\nu = c/2L \tag{5.1.3}$$

This difference is called the frequency difference between two consecutive longitudinal modes with the word longitudinal used because the number n indicates the number of half-wavelengths of the mode along the laser resonator, i.e. longitudinally.

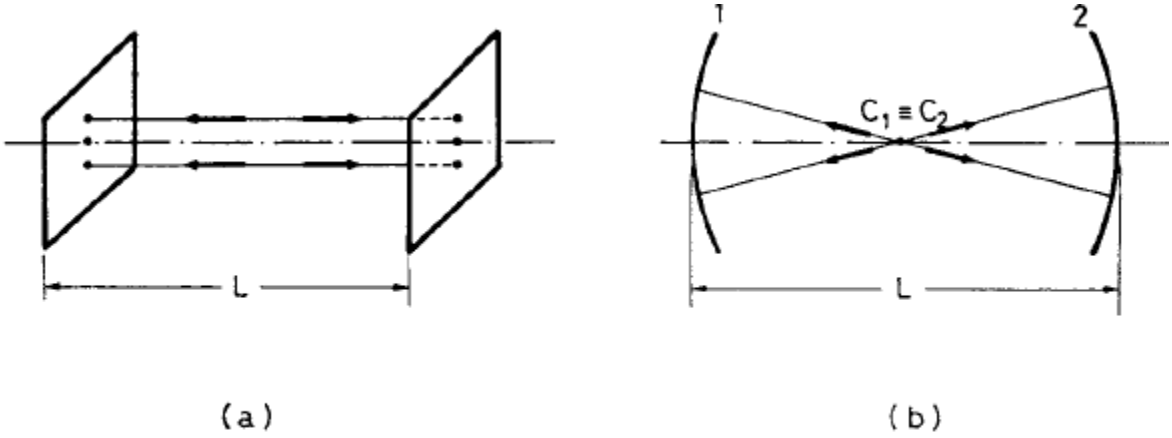


FIG. 5.1. (a) Plane-parallel resonator; (b) concentric resonator.

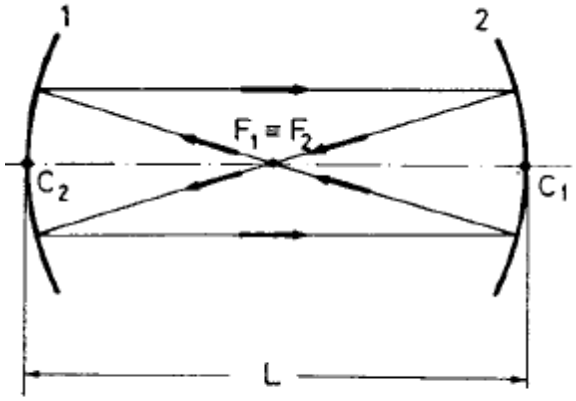


FIG. 5.2. Confocal resonator.

b. *Concentric (or Spherical) Resonator.* This consists of two spherical mirrors having the same radius R and separated by a distance L such that the mirror centers of curvature C_1 and C_2 are coincident (i.e. $L = 2R$) (Fig. 5.1b). The geometrical-optics picture of the modes of this resonator is also shown in the figure. In this case the modes are approximated by a superposition of two oppositly traveling spherical waves originating from the point C. The application of the above self-consistency argument again leads to Eq. (5.1.2) as the expression for the resonant frequencies and to Eq. (5.1.3) for the frequency difference between consecutive longitudinal modes.

c. *Confocal Resonator* (Fig. 5.2). This consists of two spherical mirrors of the same radius of curvature R and separated by a distance L such that the mirror foci F_1 and F_2 are coincident. It then follows that the center of curvature C of one mirror lies on the surface of the second mirror (i.e. $L = R$). From a geometrical-optics point of view, we can draw any number of closed optical paths of the type shown in Fig. 5.2 by changing the distance of the two parallel rays from the resonator axis C_1C_2. Note also that the direction of the rays can be reversed in Fig. 5.2. This geometrical optics description, however, does not give any indication of what the mode configuration will be, and we shall see that in fact this configuration cannot be described either by a purely plane or a purely spherical wave. For the same reason, the resonant frequencies cannot be readily obtained from geometrical-optics considerations.

Resonators formed by two spherical mirrors of the same radius of curvature R and separated by a distance L such that $R < L < 2R$ (i.e. somewhere between the confocal and concentric conditions) are also often used. In addition, we can have $L > R$. For these cases it is not generally possible to use a ray description in which a ray retraces itself after one or a few passes.

All of these resonators can be considered as particular examples of a general resonator consisting of two either concave ($R > 0$) or convex ($R < 0$) spherical mirrors, of different radius of curvature, spaced by some arbitrary distance L. These various resonators can be divided into two categories, namely, *stable* resonators and *unstable* resonators. A resonator will be described as unstable when an arbitrary ray, in bouncing back and forth between the two mirrors, will diverge indefinitely away from the resonator axis. An obvious example of an unstable resonator is shown in Fig. 5.3. Conversely, a resonator for which the ray remains bounded will be described as a stable resonator.

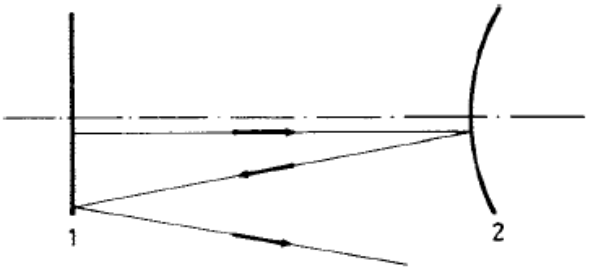


FIG. 5.3. Example of an unstable resonator.

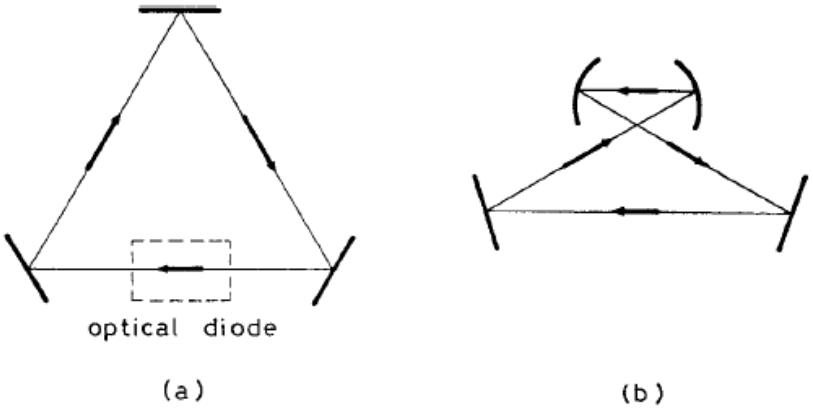


FIG. 5.4. (a) Simplest three-mirror ring resonator. (b) Folded ring resonator.

A particularly important class of laser resonator is the *ring resonator* where the path of the optical rays is arranged in a ring configuration (Fig. 5.4a) or in a more complicated configuration such as the folded configuration of Fig. 5.4b. In both cases the resonance frequencies can be obtained by imposing the condition that the total phase shift along the ring path of Fig. 5.4a or along the closed-loop path of Fig. 5.4b (continuous paths) be equal to an integral number of 2π. We then readily obtain the expression for the resonance frequencies as

$$\nu = nc/L_p \tag{5.1.4}$$

where L_p is the perimeter of the ring or the length of the closed-loop path of Fig. 5.4b, and n is an integer. Note that the arrows of the continuous paths of Fig. 5.4 can in general be reversed which means that e.g. in Fig. 5.4a the beam can propagate either clockwise or anticlockwise. Thus, in general, a standing wave pattern will be formed in a ring resonator. One can see, however, that, if a unidirectional device is used, allowing the passage of e.g. only the right to left beam in Fig. 5.4a (optical diode, see Sect. 7.8.2.2. for more details), then only the clockwise propagating beam can exist in the cavity. So the concepts of a cavity mode and cavity resonance frequency are not confined to standing-wave configurations. Note also that ring resonators can be either of the stable (such as in Fig. 5.4) or unstable configuration.

6 Pumping Processes

6.1. INTRODUCTION

We have seen in Chap. 1 that the process by which atoms are raised from level 1 to level 3 (for a three-level laser, Fig. 1.4a) or from level 0 to level 3 (for a four-level or a quasi-three-level laser, Fig. 1.4b) is called the pumping process. Usually it is performed in one of the following two ways: (i) *Optically*, i.e. by the cw or pulsed light emitted by a powerful lamp or by a laser beam. (ii) *Electrically*, i.e. by a cw, radio-frequency, or pulsed current flowing in a conductive medium such as an ionized gas or a semiconductor.

In *optical pumping* by an incoherent source, the light from a powerful lamp is absorbed by the active medium and the atoms are thereby pumped into the upper laser level. This method is particularly suited to solid-state or liquid lasers (i.e. dye lasers). The line-broadening mechanisms in solids and liquids produce in fact very considerable broadening, so that one is usually dealing with pump bands rather than sharp levels. These bands can, therefore, absorb a sizable fraction of the, usually broad-band, light emitted by the lamp. The availability of efficient and powerful, cw or pulsed, laser sources at many wavelengths has recently made *laser pumping* both attractive and practical. In this case, the narrow line emission from a suitable laser source is absorbed by the active medium. This requires that the laser wavelength fall within one of the absorption bands of the medium. It should be noted, however, that laser's monochromaticity implies that laser pumping needs not to be limited to just solid-state and liquid lasers but can also be applied to gas lasers, provided that one can ensure that the line emitted by the pumping laser coincides with an absorption line of the medium to be pumped. This situation occurs, for instance, in most far-infrared gas lasers (e.g., methyl alcohol or CH_3OH, in the vapor state) which are usually pumped by a suitable rotational-vibrational line of a CO_2 laser. For solid-state or liquid lasers, on the other hand, Argon ion lasers, for cw excitation, Nitrogen or Excimer lasers, for pulsed excitation, and Nd:YAG lasers and their second and third harmonics, either cw or pulsed, are often used. Whenever possible, however, semiconductor-diode lasers, due to the inherently high efficiency of these laser sources (overall optical to electrical efficiencies larger than 60% have been demonstrated), are now commonly used (*diode-laser pumping*). Actually one can foresee that, in a not too far future, diode-laser pumping will become the dominant means of optical pumping, replacing even high power lamps.

Electrical pumping is usually accomplished by means of a sufficiently intense electrical discharge and it is particularly suited to gas and semiconductor lasers. Gas lasers, in particular, do not usually lend themselves so readily to lamp pumping because their absorption lines are typically much narrower than the usual broad-band emission of the pumping lamp. A notable exception that should be mentioned is the case of the optically pumped Cs laser, in which Cs vapor is pumped by a lamp containing low-pressure He. In this case the situation was quite favorable for optical pumping since the strong $\sim$ 390 nm He emission line (which is rather sharp owing to the low pressure used) happens to coincide with an absorption line of Cs. This laser, however, is no longer in use and its importance resides mostly in its historical significance as the most notable lamp-pumped gas laser and, particularly, as it was the earliest proposed laser scheme. Electrical pumping of gas lasers, on the other hand, can be a fairly efficient process (e.g. for pumping the CO_2 laser) because the linewidth of the excitation cross-section of a given transition by electron impact is usually quite large (from a few to a few tens of eV, see Figs. 6.25 and 6.27). This circumstance occurs because electron impact excitation, namely $e + A \rightarrow A^* + e$ where A is the species to be excited, is a non-resonant process. The surplus energy, above that needed to excite species A, is in fact left as kinetic energy of the scattered electron. By contrast, the process of optical excitation by an incoming photon of energy $h\nu$, namely $h\nu + A \rightarrow A^*$, is a resonant process because the photon energy must equal the excitation energy of species A. Actually, as discussed in Chap. 2, some line-broadening processes occur in this case on account of some energy, arising e.g. from thermal movement of species A (as in Doppler broadening), which can be added to the process. The resulting width of the absorption line, however, turns out to be quite small (e.g. $\approx 10^{-5}$ eV for Doppler broadening of Ne atoms) and this is the fundamental reason why optical pumping by a broad-band source would be so inefficient for a gas laser. In the case of semiconductor lasers, on the other hand, optical pumping could be used very effectively, since the semiconductor medium has a strong and broad absorption band. Indeed, a number of optically pumped semiconductor lasers (particularly by laser pumping) have been made to operate. Electrical pumping proves to be more convenient, however, since a sufficiently large current density can be made to flow through a semiconductor, usually in the form of a p-n or p-i-n diode.

The two pumping processes considered above, optical pumping and electrical pumping, are not the only ones available for pumping lasers. A form of pumping which is somewhat similar to optical pumping is involved when the medium is excited by a beam from an X-ray source (*X-ray pumping*). Likewise, a pumping process somewhat similar to electrical pumping is involved when the medium is excited by a beam of electrons from an electron-beam machine (*e-beam pumping*). Although both X-ray and e-beam pumping are able to deliver high pump powers or energies in a large volume of active medium (generally in gaseous form), these pumping mechanisms are not widely used, in practice, due to the complexity of the X-ray or e-beam apparatus. It should also be noted, in this contest, that possibly the shortest wavelength so far achieved in a laser ($\lambda \cong 1.4$ nm i.e. around the boundary between soft and hard X-ray region) has been achieved using the intense X-rays produced by a small nuclear detonation. The details of this laser are still classified but one can readily appreciate that this pumping configuration is not easily duplicated in the typical laboratory!

A conceptually different and rather interesting type of pumping is involved when the required inversion is produced as a direct result of an exothermic chemical reaction (*chemical pumping*). There are two general kinds of these reactions which can be used, namely: (i) Associative reactions, i.e. $A+B \rightarrow (AB)^*$, resulting in the molecule AB being left in an excited vibrational state. (ii) Dissociative reactions, e.g. where the dissociation is induced by a photon i.e. $AB + h\nu \rightarrow A + B^*$, resulting in species B (atom or molecule) being left in an excited state. Chemical pumping usually applies to materials in the gas phase and generally requires highly reactive and often explosive gas mixtures. On the other hand, the energy available in an exothermic reaction is often quite large and high powers, for cw operation, or energies, for pulsed operation, can be available for laser action if a good fraction of the available energy is converted into laser energy. These features have enabled chemical lasers to produce the largest cw laser powers so far available (2.2 MW for the so-called MIRACL laser, an acronym for Mid Infrared Advanced Chemical Laser). In view of the handling problems associated with reactive and hazardous materials, the use of these lasers has been confined to the military field, for use as directed energy weapons.

Another conceptually different type of pumping mechanism for gas molecules is by supersonic expansion of a gas mixture containing the particular molecule (*gas-dynamic pumping*). In this case, a suitable mixture, usually involving the CO_2 molecule as the active species (e.g. CO_2:N_2:H_2O in the 6:76:1 ratio), is used. The mixture is raised, in a suitable container, to a high pressure (e.g. $\approx$ 17 atm) and temperature (e.g. $\approx$ 1,400 K) by combustion of appropriate fuels (e.g. combustion of benzene, C_6H_6, and nitrous oxide, N_2O, thus automatically supplying hot CO_2 with a CO_2/H_2O ratio of 2:1). The CO_2 molecule in this mixture is, of course, not inverted but, due to the high temperature, a substantial fraction of molecules is found in the lower laser level ($\approx$ 25%) while a lower but still substantial fraction is found in the upper laser level ($\approx$ 10%). It should be noted, in fact, that the CO_2 laser is a roto-vibrational laser and the lower and upper laser levels of the ground electronic state can be significantly excited thermally, i.e., by having the mixture at a high temperature. The gas mixture is then made to expand, adiabatically, to a very low pressure (e.g. $\approx$ 0.09 atm) trough a row of expansion nozzles (an example of this expansion system can be found in the chemical laser section of Chap. 10). Due to expansion, the translational temperature of the mixture will be reduced to a much lower value (e.g. $\approx$ 300 K). Consequently, during the expansion process, upper and lower state populations will tend to relax to the, much lower, equilibrium values appropriate to this lower temperature. For a CO_2 laser, however, the lifetime of the upper state is appreciably longer than that of the lower state. This means that relaxation of the

lower level will occur at an earlier stage, downstream in the expanding beam. Thus there will be a fairly extensive region, downstream from the expansion nozzle, where the population of the lower laser level has decayed, while that of the upper level has persisted at its initial value in the container. Thus a population inversion is created in this region via the expansion process. Gas-dynamic pumping has been mainly applied to CO_2 lasers and has yielded high cw powers ($\approx$ 100 kW). The complications of the system have been an obstacle to its use for civilian applications while its lower power, compared to chemical lasers, has put it at disadvantage for military applications.

As for the case of radiation-matter interaction, considered in Chaps. 2 and 3, where the ultimate goal was the calculation of both stimulated and spontaneous transition rates, so the ultimate goal here would be to calculate the pump rate per unit volume, R_p, as defined by Eq. (1.3.1). When pumping with a broad-band light source, i.e. a lamp, the calculation of R_p becomes rather involved.(1) This is also the case when pumping via electrons in a gas discharge, where a distribution of electron-velocities is involved.(2) So, we will limit ourselves here to a description of various pumping schemes with some discussion of the underlying physical mechanisms involved in the processes.

6.3. LASER PUMPING

Laser beams have often been used to pump other lasers since the early days of lasers, being used for example in the first demonstration of laser action in a dye medium.(5,6) In particular, Ar ion lasers are widely used to pump cw dye and Ti^{3+}:Al_2O_3 lasers, Excimer, Nitrogen and Copper Vapor lasers are used for pulsed pumping of dye lasers, Nd:YAG and its second harmonic beam are used as pumps for cw and pulsed dye and solid-state lasers (including color-center lasers). Laser pumping has become a very much more important pumping technique, however, since efficient and high power diode lasers have been developed and become widely available. A particularly interesting case is the use of diode lasers to pump other solid-state laser materials thus providing an all-solid-state laser. The most relevant examples include: (i) Nd:YAG, Nd:YLF, Nd:YVO_4 or Nd:glass pumped by GaAs/AlGaAs* Quantum Well(QW) lasers at $\sim$ 800 nm (typical oscillation wavelengths are around 1 μm, 1.3 μm and 0.95 μm). (ii) Yb:YAG, Er:glass or Yb:Er:glass pumped by InGaAs/GaAs strained QW lasers in the 950 ÷ 980 nm range (oscillation wavelength is around 1 μm for Yb and 1.54 μm for Er lasers). Note that, in the case of Er:Yb codoping, the pump light is absorbed by Yb^{3+} ions and then transferred to Er^{3+} lasing ions. (iii) Alexandrite, Cr:LISAF or Cr:LICAF pumped by GaInP/AlGaInP QW lasers in the 640 ÷ 680 nm range and oscillating in a $\sim$ 130 nm range at $\sim$ 840 nm. (iv) The Tm:Ho:YAG laser pumped by AlGaAs QW lasers at 785 nm and oscillating around 2.08 μm. Note that, in this case, the pump light is absorbed by Tm^{3+} ions and transferred to the Ho^{3+} lasing ions.

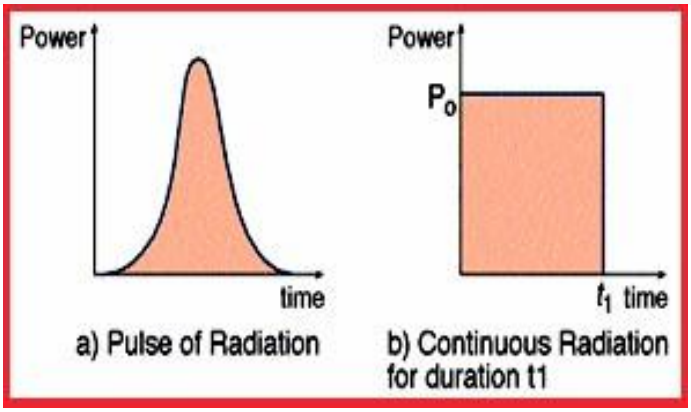
TABLE 6.2. Comparison between pumping parameters and laser wavelengths for different laser materials

	Nd:YAG	Yb:YAG	Yb:Er:glass	Cr:LISAF	Tm:Ho:YAG
Concentr.	1 at. %	6.5 at.%	1 mol.%	6.5 at.% Tm	0.36 at. %Ho
Pumping Diode	AlGaAs	InGaAs	InGaAs	GaInP	AlGaAs
Wav. (nm)	808	950	980	670	785
Active-ion conc. $[10^{20}\ cm^{-3}]$	1.38	9	10 [Yb]	0.9	8 [Tm]
			1 [Er]		0.5 [Ho]
Pump abs. coeff. (cm^{-1})	4	5	16	4.5	6
Oscillation Wav. (μm)	1.06	1.03	1.53	0.72 ÷ 0.84	2.08
	1.32, 1.34				
	0.947				

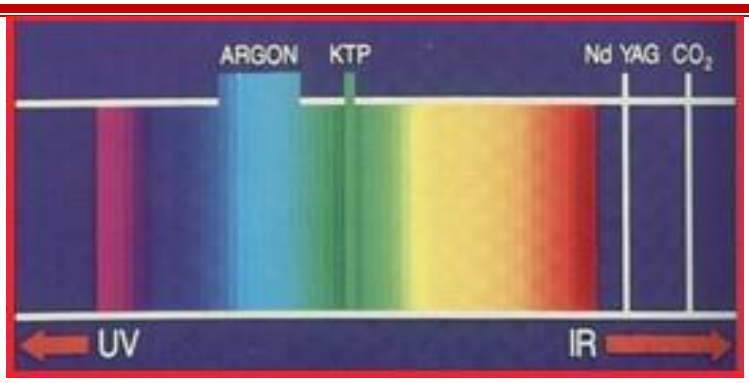
laser classification:

A - Continuity of radiation: continuous or pulsed.

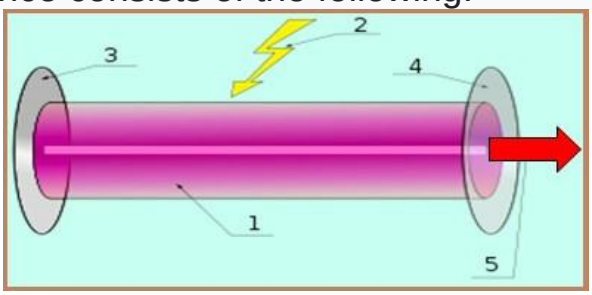
The pulsed laser emits its beam in the form of a series of very short light pulses. These pulses are issued only when the active medium is in its highest excited state. Some types of lasers emit their beams at a rate of one pulse every few minutes. There are types of lasers, such as the carbon dioxide laser, whose waves can be pulsed or continuous.



b - Radiation frequency: visible light, ultraviolet rays, infrared rays, X-ray lasers.



Any laser beam generator device consists of the following:



Three Level Laser

A schematic energy level diagram of a laser with three energy levels is shown in figure .
The two energy levels between which lasing occur are: the lower laser energy level (E_1), and the upper laser energy level (E_2).

To simplify the explanation, we neglect spontaneous emission.
To achieve lasing, energy must be pumped into the system to create population inversion. So that more atoms will be in energy level E_2 than in the ground level (E_1).

Atoms are pumped from the ground state (E_1) to energy level E_3. They stay there for an average time of 10^{-8} [sec], and decay (usually with a non-radiative transition) to the meta-stable energy level E_2.
Since the lifetime of the meta-stable energy level (E_2) is relatively long (of the order of 10^{-3} [sec], many atoms remain in this level.
If the pumping is strong enough, then after pumping more than 50% of the atoms will be in energy level E_2, a population inversion exists, and lasing can occur.

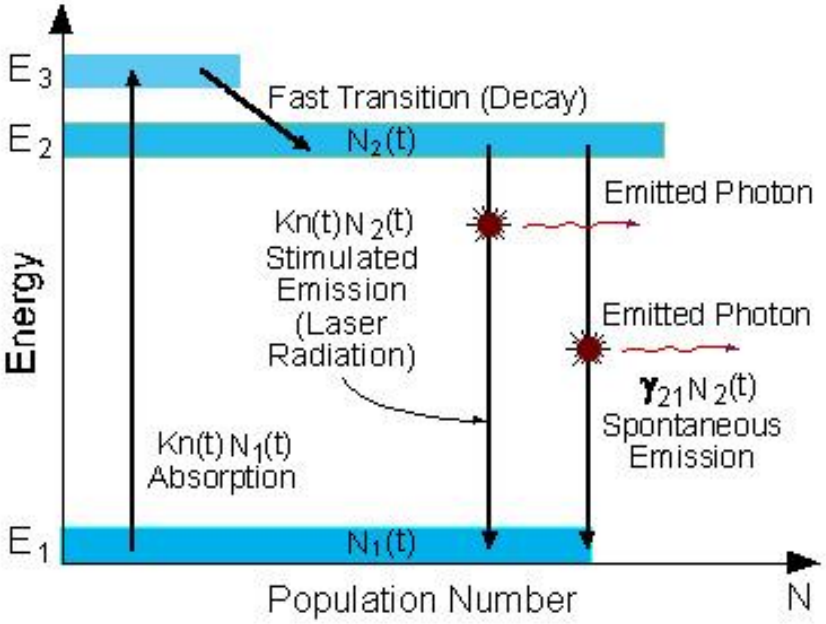


Figure: Energy level diagram in a three level laser

Four Level Laser

The schematic energy level diagram of a four level laser is shown in figure . Compared to the equivalent diagram of a three level laser, there is an extra energy level above the ground state. This extra energy level has a very short lifetime.

The pumping operation of a four level laser is similar to the pumping of a three level laser. This is done by a rapid population of the upper laser level (E_3), through the higher energy level (E_4).

The advantage of the four level laser is the low population of the lower laser energy level (E_2).

To create population inversion, there is no need to pump more than 50% of the atoms to the upper laser level.

The population of the lower laser level ($N_2(t)$) is decaying rapidly to the ground state, so practically it is empty. Thus, a continuous operation of the four level laser is possible even if 99% of the atoms remain in the ground state ( )

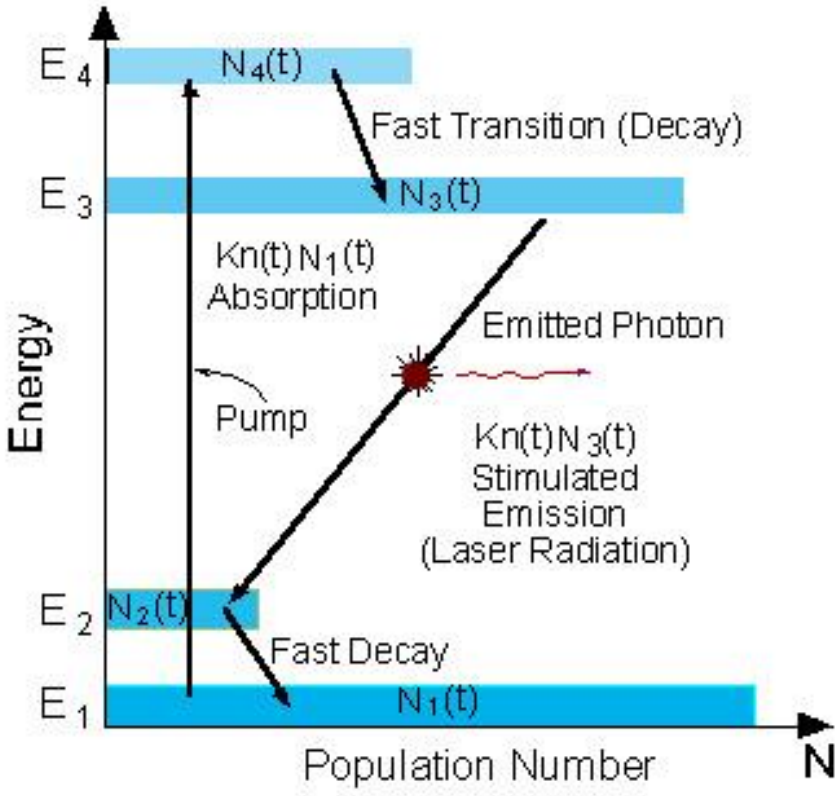
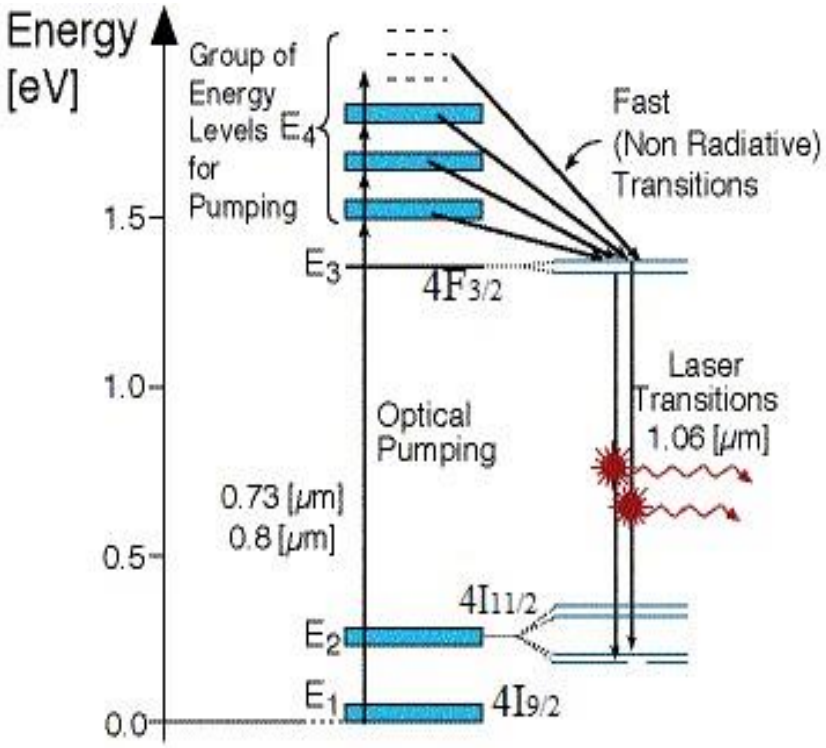
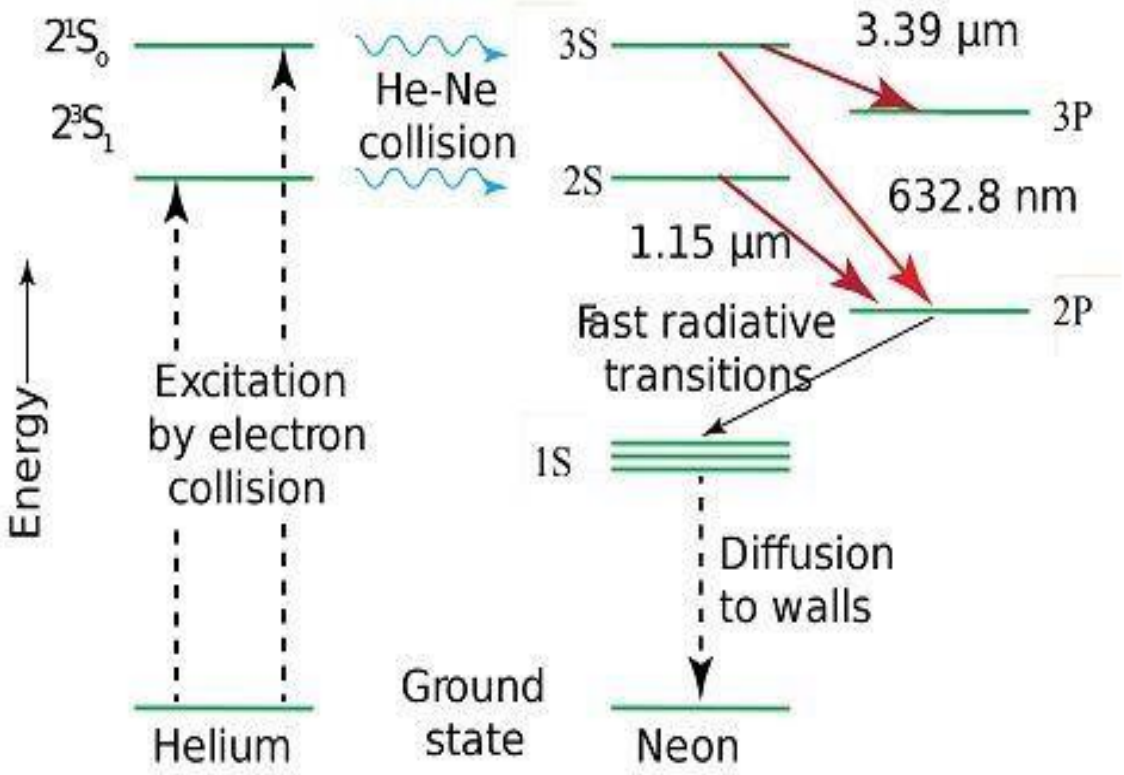
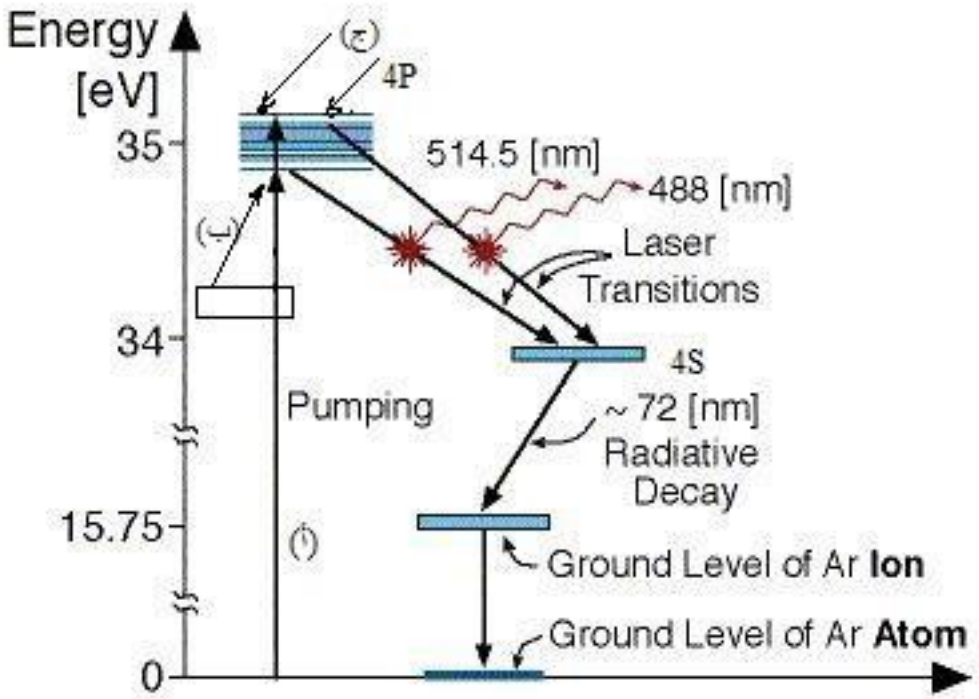


Figure: Energy level diagram in a four level laser




2^1S_0
2^3S_1
He-Ne collision
3S
2S
3.39 µm
3P
632.8 nm
1.15 µm
2P
Fast radiative transitions
1S
Energy
Excitation by electron collision
Diffusion to walls
Ground state
Helium
Neon


Energy [eV]
35
34
15.75
0
4P
514.5 [nm]
488 [nm]
Laser Transitions
4S
Pumping
~ 72 [nm] Radiative Decay
Ground Level of Ar Ion
Ground Level of Ar Atom

الطول الموجي لليزر (nm)	نوع الليزر
193	Argon fluoride (UV)
248	Krypton fluoride (UV)
308	Xenon chloride (UV)
337	Nitrogen (UV)
488 514	Argon (blue) Argon (green)
543	Helium neon (green)
633	Helium neon (red)
570-650	Rhodamine 6G dye (tunable)
694	Ruby ($CrAlO_3$) (red)
1064	Nd:Yag (NIR)
10600	Carbon dioxide (FIR)

Laser classifications risk

إشارة تحذير بوجود ليزر

Are classified as types of lasers in accordance with the laws of toxic in international standards based on the degree of harm to the human body and must be recalled that the more the resulting damage from the use of the laser is not because of the rays, but because of the misuse of sources of energy crisis for some special devices laser large that generating devices power high-voltage or materials harmful chemicals to humans. As for the damage resulting from its rays,

it is mostly on the user's eye, and this does not mean that it is not dangerous to other organs. The damage that the laser may cause to the human eye depends on the following:

1 - The duration of exposure to radiation.

2 - Intensity of radiation.

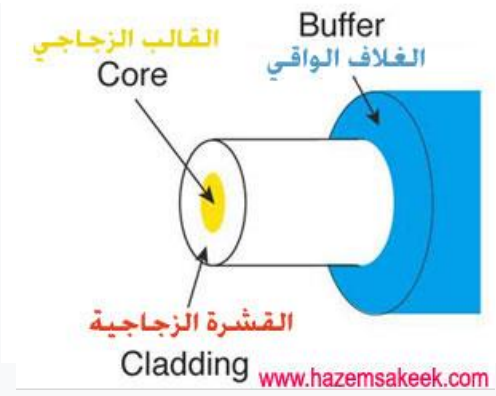
3 - The color of the laser (or what is known as the wavelength).

Fiber Optics

Whenever people talk about telephone or television systems that operate with terrestrial cables or Internet networks, the conversation is always associated with mentioning fiber optics, so what are optical fibers.

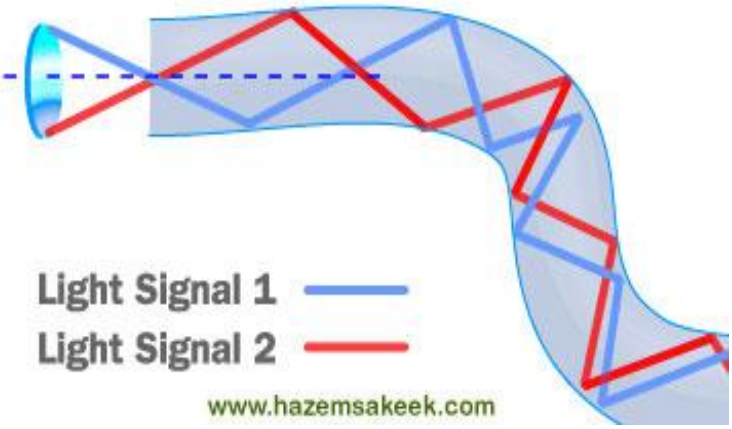
Optical fibers are long filaments of high-purity glass that are as thin as a human hair. These hairs are lined up together in a bundle called an optical cable. If you look closely at one of these optical fibers, you will find that it consists of:

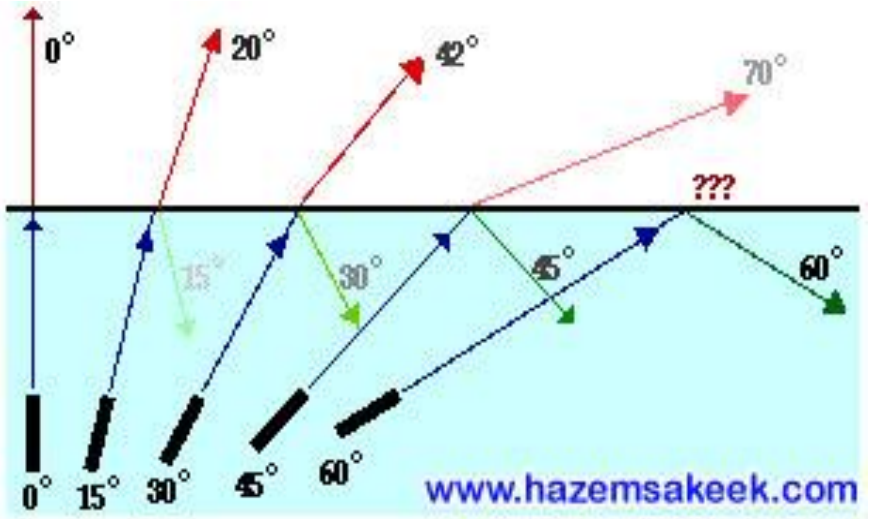
The Core molding is an ultra-clear glass core that represents the path through which light travels.



The glass shell is cladding, which is the outer material that surrounds the glass

heart, and it is made of glass whose refractive index differs from the refractive index of the glass from which the heart is made and constantly reflects light to remain inside the glass mold Buffer coating is a plastic covering that protects the heart from damage Hundreds or perhaps thousands of these optical fibers are lined up together in a bundle to form an optical cord that is protected by an outer covering called





Solid-State, Dye, and Semiconductor Lasers

. INTRODUCTION

In this chapter, the most important types of lasers involving high density active media are considered, namely solid-state, dye and semiconductor lasers. The chapter concentrates on those examples that are in widest use and whose characteristics are representative of a whole class of lasers. The main emphasis here is on stressing the physical behavior of the laser and relating this behavior to the general concepts developed in the previous chapters. Some engineering details are also provided with the main aim again of helping to provide for a better physical insight into the behavior of the particular laser. To complete the picture, some data relating to laser performances (e.g., oscillating wavelength(s), output power or energy, wavelength tunability, etc.) are also included to help providing some indication of the laser's applicability. For each laser, after some introductory comments, the following items are generally covered: (1) Relevant energy levels; (2) excitation mechanisms; (3) characteristics of the laser transition(s); (4) engineering details of the laser structure(s); (5) characteristics of the output beam; (6) applications.

SOLID-STATE LASERS

The use of the term solid-state laser is generally reserved for those lasers having as their active species ions introduced as an impurity in an otherwise transparent host material (in crystalline or glass form). Thus, semiconductor lasers are not usually included in this category, the mechanisms for pumping and for laser action being in fact quite different. These will be considered in a separate section.

TYPES OF LASERS

Gas Lasers

Gas lasers use a low-pressure gas mixture as an active medium. Most gas lasers are excited by passing an electric current through the gas, delivered by electrodes placed at opposite ends of the tube. The helium-neon laser (or HeNe laser) is a common gas laser that produces light in the visible spectrum at a wavelength of 632.8 nm. HeNe laser cavities contain a mixture of helium and neon gas. The helium atoms are excited by an applied current and then collide with neon atoms to excite them to the state that causes the 632.8 nm radiation. The bright red output and relatively low cost of HeNe lasers make them well suited for many low-power applications in educational and research laboratories (FIGURE).

Other

examples of gas lasers include the carbon dioxide (CO_2) laser, which is a high-efficiency laser that operates in the infrared band. Carbon dioxide lasers are commonly used for high-power industrial applications such as welding and cutting.

Excimer lasers are a type of gas laser that rely on the excitation of "dimer" molecules, such as argon fluoride, that are stable only in the excited state. Excimer lasers were first demonstrated in the mid-1970s and are capable of removing extremely fine layers of surface material by breaking molecular bonds without burning or heating the surrounding area. For this reason, excimer lasers are well- suited for precision etching of plastics or semiconductor circuits, as well as delicate eye surgery such as LASIK.

An advantage of gas lasers over other laser types is that the gas medium tends to be both relatively inexpensive and largely resistant to damage. However, gas lasers are also typically larger than other types due to the low density of the medium. In recent years, gas lasers have seen a decline in sales as they have gradually been replaced by solid-state and semiconductor lasers for many commercial applications. For example, HeNe lasers were originally used in grocery store checkout scanners, but have largely been replaced by laser diodes for this purpose.

Solid-State Lasers

Solid-state lasers use an active medium consisting of a solid crystalline or glass rod (known as the host) containing light-emitting atoms (the active species). The first laser ever built was a solid-state laser using synthetic ruby, which is corundum (aluminum oxide crystal) with chromium as an active species. In most solid-state laser materials, the active species is identified first (typically by its chemical symbol), followed by the host material. For example, the Ti:sapphire laser consists of titanium atoms in sapphire crystal. Both the

active species and the host are important in solid-state lasers. The active species determines the laser transition, but its interactions with the host may shift the wavelength slightly.Neodymium (Nd) is commonly used as an active species in solid-state laser crystals. For example, the Nd:YAG (neodymium-yttrium aluminum garnet) is one of the most common types of laser, with applications in research, medicine, manufacturing, and other fields ( ).

Nd:YAG lasers typically emit infrared light with a wavelength of 1064 nm although other wavelengths are possible. Other host materials for neodymium include YLF (yttrium lithium fluoride) and glass. The host material is selected based on its optical, thermal, and mechanical properties.

Semiconductor Diode Lasers

Semiconductor diode lasers, commonly known as laser diodes, operate using the same basic princip

les as light- emitting diodes, but with some important differences. Like an LED, a laser diode consists of two semiconductor layers, an n-type with an excess of electrons and a p-type with electron “holes” to be filled. The semiconductor layers are separated by a microscopic region called the active layer that serves as the optical resonator. Laser diodes operate at much higher currents than LEDs, typically around ten times greater. Whereas an LED emits photons in all directions from its junction layer, a laser diode is configured with reflective ends to form an optical resonator in the region between the semiconductor layers. In a laser diode, stimulated emission occurs when a photon emitted by one electron transition triggers another electron to fill a hole, and so on, resulting in a coherent beam of light that emerges from one side of the diode.

Laser diodes are compact and easy to mass-produce. In terms of sheer numbers, they are the most common type of laser. Their small size makes them well suited for use in low-power applications such as laser pointers, laser printers, and CD/DVD players (FIGURE 64). Laser diodes can also be operated at lower voltages than other types of lasers. While gas and solid-state lasers require input voltages on the order of kilovolts, laser diodes can be operated at only a few volts.

Laser diodes are typically not as collimated as beams from other types of lasers. In many cases, an external lens is used to correct the shape of the beam, which contributes to the overall fragility of the laser since damage to the lens could render it non-functional. Furthermore, the delicate nature of the semiconductors makes laser diodes more sensitive to static discharges and currents. Excess electrical current can cause the diode to become inoperable. Laser diodes can also degrade in power efficiency over time, gradually requiring more power to output the same beam intensity.

1.5. TYPES OF LASERS

The various types of laser that have been developed so far, display a very wide range of physical and operating parameters. Indeed, if lasers are characterized according to the physical state of the active material, one uses the description of *solid state*, *liquid* or *gas lasers*. A rather special case is where the active material consists of free electrons, at relativistic velocities, passing through a spatially periodic magnetic field (*free-electron lasers*). If lasers are characterized by the wavelength of the emitted radiation, one refers to *infrared lasers*, *visible lasers*, *UV* and *X-ray lasers*. The corresponding wavelength may range from $\approx$ 1 mm (i.e. millimeter waves) down to $\approx$ 1 nm (i.e. to the upper limit of hard X-rays). The span in wavelength can thus be a factor of $\approx 10^6$ (we recall that the visible range spans less than a factor 2, roughly from 700 to 400 nm). Output powers cover an even larger range of values. For cw lasers, typical powers go from a few mW, in lasers used for signal sources (e.g. for optical communications or for bar-code scanners), to tens of kW in lasers used for material working, to a few MW ($\approx$ 5 MW so far) in lasers required for some military applications (e.g. for directed energy weapons). For pulsed lasers the peak power can be much higher than for cw lasers and can reach values as high as 1 PW (10^{15} W)! Again for pulsed lasers, the pulse duration can vary widely from the ms level typical of lasers operating in the so-called *free-running* regime (i.e. without any *Q-switching* or *mode-locking* element in the cavity) down to about 10 fs (1 fs = 10^{-15} s) for some mode locked lasers. The physical dimensions can also vary widely. In terms of cavity length, for instance, the length can be as small as $\sim$ 1 μm for the shortest lasers up to some km for the longest (e.g. a laser 6.5 km long, which was set up in a cave for geodetic studies).

This wide range of physical or operating parameters represent both a strength and a weakness. As far as applications are concerned, this wide range of parameters offers enormous potential in several fields of fundamental and applied sciences. On the other hand, in terms of markets, a very wide spread of different devices and systems can be an obstacle to mass production and its associated price reduction.

Chapter 3

Laser Applications

3 Laser Applications.

The number of applications of lasers is enormous, and it is not possible to explain **all** of them here. In this chapter, the **applications are divided into groups**, and our hope is that **with time we will fill the missing information on most of the well known applications of lasers**. Some applications are already described in details, such as:

3.1 Industrial Applications

Industry accepted the laser as a tool soon after the laser was invented in 1960. At first the laser was used for **alignment and measurements**, but with time applications using high power laser beams became more common.
The main industrial applications are:

3.1.1 Accurate measurements (Distance, Movement, Interferometry).

Since laser radiation is **electromagnetic radiation**, traveling at the speed of light, very accurate measurements can be performed with lasers.
Because of its high speed (the speed of light (c) is the ultimate speed …), measurements of high speed moving objects is not a problem, and the information is available in (almost) real time.

- **Measurement of the distance from Earth to the moon:**
  One of the known precise measurements with a laser was measuring the distance from Earth to the moon. The astronauts who landed on the surface of the Moon left there a **corner cube** (a system of three perpendicular mirrors that reflect light in the same direction where it came from).
  A pulsed laser beam was sent from Earth to the moon and was reflected from this corner cube back to Earth.
  The travel time of the pulse was recorded.
  From the known speed of light (c) the distance was calculated, with accuracy of tens of centimeters (!).

3.1.2 Straight line marking, or plan of reference.

Many daily applications require a **precise reference line for alignment**.
Examples are:

- Laying pipes of gas, water, electricity, etc.
- Digging tunnels under-ground (such as the one under the **English Channel** between England and France).
- Alignment of mechanical systems.
- Marking spots for pointing invisible radiation from another laser (such as Nd-YAG

or CO_2 lasers). The visible laser radiation is aligned parralel to the invisible radiation, such that it mark the place where the invisible beam is pointing.

- **Marking a reference plane for construction**:

  By using a **vibrating (or rotating) mirror** to reflect a visible laser light, a perfect plane is defined in space. The mirror is vibrating around one axis, so the light is reflected into consecutive angles continuously, thus defining a perfect plane. Since the vibration of the mirror is at a frequency greater than the persistence of vision in the brain, the viewer see a plane of light. This plane helps aligning walls, sealing, etc. in industrial construction.

3.1.3 Material working

The main advantages of lasers for material processing are:

- **Very high accuracy** in the final processed products that can be obtained without the need for polishing.
- **No wearing of mechanical tools**. Mechanical tools change their dimensions during the working process, and require constant measurements and feedback to adapt their position to original plan in computerized instrumentation.

Material processing include many kinds of processes. A partial list include:

- **Cutting -** The laser can be a very precise cutting tool. High power lasers are used for cutting steel, while other lasers are used to cut fabrics, rubber, plastic, or any other material.
- **Welding -** Combining (fusing) two materials together. By heating the materials near the connecting region, the materials melt locally, and fuse together.
- **Hardening -** By heating specific areas of the material, most metals can be hardened most of the metals. Even **local hardening** of specific part of a tool can be done by local irradiation.
- **Melting -** Absorption of laser beams caused a rise in temperature. Since very high power can be transferred to materials in a very short time, melting can be easily done.
- **Evaporating -** Used to ablate material (transfer it into the gas phase).
- **Photolithography -** specially in the semiconductor industry. Very delicate shapes can be created in materials which are used for masks in photolithography. Special materials respond to light at specific wavelength by changing their properties. Thus it is possible to remove parts of the m

aterial with very high precision (in micrometer range).

- **3-D Laser measurements** - With the help of a scanning laser, it is possible to obtain the information about a shape of a three-dimensional object and put it in the computer.
- **3-D Stereo lithography -** Similar to photolithography, but the laser is used to create three dimensional sculpture of the information stored within a computer.
  A combination of the last two applications enable **creating 3-D models**. Even statue of people were build with high accuracy using these techniques.

3.1.4 Spectral analysis.

We saw in **chapter 2**, and **chapter 5**, that the entire lasing process is based on **absorption** and **emission** of photons at certain specific wavelengths.
The wavelength emitted from the laser is **monochromatic**, and its linewidth is very narrow. Thus, the laser can be used for **controlled excitation of molecules**.
Especially useful for this are the **tunable lasers**, whose wavelength can be precisely tune to excite specific molecule.

3.2 Medical Applications

There are many medical applications of lasers, and there are different ways to classify them into **groups**:
According to the **organ to be treated by the laser**, such as: **Eye**, **General Surgery**, **Dentistry**, **Dermatology**, Blood vessels, Cardiac, etc.
According to the **type of laser used for treatment**, such as: **CO_2**, **YAG**, and **Argon**.
According to the **type of treatment**, such as diagnostic, surgery, connecting blood vessels.
The classification used here is basically according to the **type of treatment**, with comments on suitable lasers used for each application:

3.2.1 Lasers in medical surgery.
3.2.2 Lasers in diagnostic medicine, and in combination with drugs.
3.2.3 Lasers for specific applications: Soft lasers.

When using lasers for medical treatments, a good understanding of the **interaction between specific laser radiation with specific biological tissue** is required.

3.2.1 Lasers in Medical Surgery

Almost every medical surgery in which a **removal of tissue** is required or a **cut**

needs to be made, can be done with a laser.
In general, the results of surgery using lasers are better than the results using a surgical knife.

The Advantages of Laser Surgery:

- **Dry field of surgery**, because laser energy seals small blood vessels.
- **Less postoperative pain**, because of the sealing of nerve ends.
- No contact with mechanical instruments, so **sterilization** is built in.
- **Clear field of view**, because no mechanical instrument blocks it.
- Possible **wavelength specific reaction** of specific colors of biological tissue.
- Possibility to perform **microsurgery under a microscope**. The laser beam passes through the same microscope.
- Possibility to **perform surgical procedures inside the body without opening it**, using optical fibers to transmit the laser beam.
- The laser can be used as a **precise cutting tool**.
- It can be **controlled by a computer**, and operate with a very small area of effect **under a microscope**.

3.2.2 Lasers in Diagnostic Medicine, and in combination with Drugs:
Diagnostics of cancer cells using Fluorescence, and Photo Dynamic Therapy (PDT)
One of the biggest problems in medicine today is to find a cure for cancer.
There are many treatments for cancer to destroy the cancer cells, such as:
Disectomy of the infected organ.
Radioactive irradiation.
Heat treatment.
All these treatments improve the chance of cure in some cases, but the "magic" medicine has not yet been found. Since there is no solution yet, the medical professionals are looking for new ways to solve the big problem of cancer.

3.2.3 Soft lasers

Most of the medical laser applications were until recently based on the thermal effects caused by the electromagnetic radiation which was absorbed in the biological tissue.
In the last few years, some new applications are using low power lasers with output power less than 1 Watt.
Some of the effects of these low power levels on the biological tissue is not thermal, and in effect the mechanism of interaction is not yet clear.
It is sometimes referred to as Biostimulation, which does not explain a lot.

3.3 Military Applications

Since the invention of the laser, its potential military uses were exploited.
Large number of projects on lasers were done in secret laboratories, and many years passed until the public was notified about these projects.
In the last few years, with the fall of the "Iron Curtain", and the creation of collaboration between the super-powers, the public found about some of these big projects that cost so much money.
We shall concentrate on some of the simplest and most known applications, such as:

3.1 Laser Range-finder

Measuring distances with high speed and high accuracy was the immediate military application after the laser was invented. Since the laser beam is electromagnetic light, it is traveling in space with known velocity (the velocity of light c).
By sending a short laser pulse to the target and measuring the time it take the beam to arrive at the target and reflect back to the sender, it is easy to calculate the distance. Measuring distances with high accuracy is important for military applications such as:
Measuring the distance to a shooting target for artillery and missiles. Navigation.
Numerical Example:
How much time will the laser pulse travel, when it hit a target at a distance of 1.5 kilometer?
$t = s/c = 3{,}000\ [m]/3*10^{8}\ [m/s] = 10^{-5}\ [sec] = 10\ [micro\text{-}sec]$
This time is well within the response time of standard electronic equipment.

3.3.2 Laser Target Designator

The laser is used to mark targets for attack by "smart" artillery and guided missiles.
The properties that make the laser so attractive as laser designator are:
The laser beam advance great distances in a straight line.
The laser beam propagate at very high speed (speed of light).
It is possible to modulate the laser beam to include information for identification.
A soldier in the field, or a flying vehicle can be used to send a laser beam on the target.
The laser is designed to send a series of pulses in a specific pattern (code) of pulses of invisible light.
Special detecting systems are locked on these specific pattern of laser pulses, and

guide the "Smart Bombs" to hit the marked target.
An example showing several laser designator system are shown in figure 9.1.

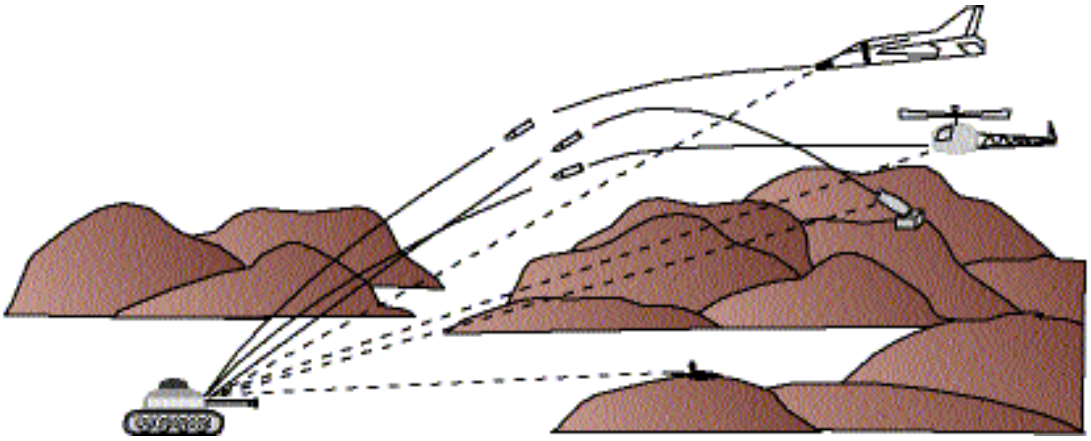


Figure 9.1: Laser Designator systems in the Battlefield.

3.3.3 Laser weapons ("Star War").

A lot was written on the **Strategic Defense Initiative (SDI)** of the US government.
This futuristic project was named by the public **"Star Wars"**.
The idea behind this initiative was to **build high power devices** that can send beams over very big distances in a very high accuracy and very high speed.
These high power devices were supposed to destroy the USSR missiles above their lounching sites right after this launch. Since these missiles were supposed to carry nuclear weapons, it was not possible to let them arrive above Europe or the US. By destroying the missiles at the launch zone a great damage would be caused to the attacker, so such defense system was a threat to the other side.

3.3.4 Laser blinding for man and sensitive equipment.

A simple and very promising project, which is being developed at many sites all over the world, is **laser system for blinding enemy soldiers and their optical equipment**.
The **power required is not specially high**, because of the high sensitivity of our sight system, and the high sensitivity of the optical detection systems in use at the battlefield.
The operation of blinding laser system is simple:

The laser beam is used to scan the space in front of the military troops, blinding enemy soldiers and their equipment.

As can be seen in the **Appendix**, optical power density higher than the safe level can cause blindness (temporary or permanent) to humans, and saturation or damage to sensitive optical equipment.

3.4 Daily applications

Since the daily applications of the laser are the most familiar to us, they are described in more details. They are classified as: **Laser at home**, which include:

3.4.1 Compact Disc and CD-ROM

Optical storage of digital information.

Preface

Since the beginning of history, man searched for means of storing information, in order to inherit knowledge to following generations.

At first the cave-man marked the hunting drawings on the cave walls.

Then came shard boards, parchment scrolls, paper, printing, and now the magnetic recordings.

Magnetic recordings is used on many devices such as: Tape recorders, computer tapes for storing information in big computers, computer diskettes, and hard drives for storing information in personal computers (pcs).

As society developed more, the amount of information is growing at an exponential rate. People are trying to find better ways to store information, and the current trend is toward:

3.4.2 Laser Printer

Everyone heard about laser printers, and most offices are using laser printers for printing their documents. We are all aware of the quality of the printing out of a laser printer, but few knows to answers questions about the operation principles of the laser printer:

What is the role of the laser in a laser printer?

What is the difference between a laser printer and a photocopy machine?

Can the same system be used for printing documents from a computer and photocopying documents?

What are the advantages of the laser printer compared to the dot printers?

The following pages will try to answer such and similar questions by explaining about the laser printer, and the physical principles underlying its operation.

3.4.3 Optical Storage of Information

We already saw the **Compact-Disc, or CD-ROM in section 9.4.1** as a way to store information and read it optically. There are storage devices which act like magnetic hard disc drives of a computer, but store the information optically. Both writing the information on the optical disc and reading it are done using lasers.
These devices allow rewriting information on the optical disk thousands of times, unlike CD, which is write-once device.

New devices, which are now at a research stage, are based **on holographic writing and reading** of information (see chapter 10). These devices **store a complete page as an image**, unlike the storage of bits in standard storage devices.

3.4.4 optical computer - processing information at the speed of light!

Electronic computers are limited by the speed of current flow through the wires inside the computer. By using **pulses of light instead of electrical currents** it is possible to **increase by orders of magnitude the speed of the computers**.In electronics, it is possible today to put millions of transistors into one **integrated circuit (IC)**.
For optical computers, similar circuits are needed to be developed, and they are called **integrated optics (IO)**. This is a new research subject and there are not yet commercial products of optical computers. In the laboratory, scientists have demonstrated simple operations of edition and multiplication, but it will probably take more than 10-20 years until such products will be available.

3.4.5 Bar code scanner.

With increased automation in every-day life, there was a need for a standard automatic identification system for consumer products. Many automatic systems for identifying products are based on **optical systems**. Such systems are based on a beam of light, which scan a bar code on the product. The reflected light is read by an optical system.

Bar code is a code based on a series of dark and bright bands with specific distances between them. It is made by **writing dark bands on white background**. Usually the bar code appears on a paper label. **In a common bar code the information is coded in one dimension**: the width of the dark and brig

ht bands. The length of the bands is just for easy reading and does not contain any meaningful information.

3.4.6 Holograms on credit cards and other valuable products to avoid forgery.

Holography is described in chapter 2.
Here we shall just mention one of the expanding application of laser in everyday life.
Since we now know how to **mass-produce holograms** that can be seen without using a laser, people are using these holograms in many applications.
The production of the master hologram requires sophisticated equipment and special knowledge. This makes them ideal in **preventing forgery**.
The laser is used only in the first production stage of the master hologram

Examples for this use of holograms are on:

- Every "Visa" credit card.
- "Microsoft" software.
- Special bank notes.

Applications in the future will proobably include all kinds of identification cards.

3.4.7 Optical Fiber Communications

Each channel in communications needs a **bandwidth** (range of frequencies around the central transmission frequency).
Optical frequencies (in the visible or Near-Infra-Red spectrum region) are very high frequencies (10^{14}-10^{15} [Hz]).
The **bandwidth of voice communication** over phone lines is about 10 [kHz].
Thus, the number of phone conversations that can be send over optical communications system is measured in enormous numbers.
Diode lasers can be modulated at speeds of tens of Giga-Hertz (10^{10} [Hz]). and their light can be transmitted over tens of kilometers of optical fibers without the need for amplification.
Thus, Optical fiber communications provide the perfect solution for reliable high volume communication. This subject need its own Web site, so we shall just mention here a few facts.

Advantages of Optical Fibers:

- Wide bandwidth.
- Immunity from electrical interference.
- Low weight.
- Low cost.
- More secure transmission.

Using optical fibers instead of the metal wires that transmit electrical signal have so many advantages, that all the new communication lines are made of optical fibers.

In one optical fiber to the home, all the communications need can be fulfilled:

Phone, television, radio, cable TV, computer communication, etc.

3.4.8 Free Space Optical Communications

The very high modulation speed of **Diode Lasers** enables **direct line of sight optical communication at very high speed**. **The main applications of free space optical communications are:**

- **Communication between satellites in space** which can transfer information at a bit rates of 10^{10} bits per second. Thus tens of thousands of phone conversations can be transmitted simultaneously.
- **Military use** of free space optical communication channels are used especially in the battle field, when it is not practical to have fiber optics links. The communication is based on direct line of sight, and provides a **secure link** because of the very narrow divergence of the laser beam. The advantages of optical communications were described in **section 3.4.7**.

3.4.9.0 Lasers in Art and entertainment

Using **lasers that emit in the visible spectrum range**, it is possible to create impressive visual effects. When a laser beam pass through a region of humidity, smoke, or any other small particles in the air, the **scattered light** can be seen by observers from all sides.

In big outdoor shows, when the effect need to be seen from a distance, it is possible by moving a small optical element (such as mirror) to move laser beams over large area.

For entertainment it is common to use lasers which emit few laser wavelengths. First

each color is separated, using prisms, to create many laser beams of different colors. Using small **vibrating mirrors**, controlled by a computer, it is possible to move each laser beam very rapidly, and create moving colored images. Since our vision is based on seeing the image a little time after it has disappeared, we see a full picture created by laser beam, although the laser beam illuminates each point for a brief period of time.

The first devices were used to create **two dimentional moving pictures on screens**, but the new devices are used to create **three dimentional moving sculptures in space** (with small particles in it). Using emitted laser powers of few watts, it is possible to create **big moving images**, in free space, an impossible task to create by other means.

3.4.10 Holograms for exibitions and museums

(Details about holography and its applications are described in chapter 10).
Holograms allows us to see three dimensional images. Thus there are special holography museums which show holograms as an art by itself.
A more advanced use is to **show holograms of rare exibits**, which can be damaged by exposing to the public. Such exibits include:
Archeological exibits which need to be kept at special light, temperature and humidity conditions.
Very expensive items, which can be stolen or damage by the public.
Rare items which can not be exibited in every museum, but their holograms can.
Good hologram contains all the information included in the original object. Once **color holography** will be developed, many special exibits will be available to be seen at many museums.

3.4.11 Kinetic sculptures.

Visible light is used to create visual effects.

Using lasers in the visible spectrum, with the help of optical elements which cause reflection **refraction,** and dispersion, it is possible to **create three dimensional sculptures which are moving in space.** In order to **see the laser beams in space** we need a **medium which scatter light in all directions**. The standard medium is **smoke** which contains very small particles suspended in the air. When using higher power visible lasers, it is possible to see the reflections from the particles in "standard" air, without the use of smoke.

The best lasers for these application are the **Argon Ion** and the **Krypton Ion lasers**.

A "wall" (plane) of light can be easily created by a rotating or vibrating mirror. By using multiple rotating and/or vibrating mirrors, controlled by computers, it is possible to design complicated shapes which appear in space.

3.5 Scientific/Research Applications

3.5.1 Spectroscopy.

Every material has its own characteristic absorption and emission spectrum. By selective excitation using specific wavelengths, it is possible to identify materials with high certainty, even if only small traces exist.

Spectroscopy is used in the research of molecules by optically exciting the molecules. It is one of the most important tools in the research of the structure of matter.

The laser allows the use of **definite controlled wavelengths**, which results in a **very high resolution measurements**. Increasing the accuracy of the determination of the wavelength allows a distinction between smaller details in the material structure.

Photo-chemistry is the science of chemical changes which are the result of light.

Examples are:

- "Tanning" of the skin in the sun light.
- **Photosynthesis in plants**.
- The process of **vision** within the retina cells of the eye.
- **Induced fluorescence** is a very sensitive process, which allows selective excitation of specific energy levels in a specific molecule. This process is used in **forensic science** to identify trace residuals of molecules.

3.5.2 Inertial Fusion by laser

Equivalence between mass (m) and energy (E):

Mass and energy are related by the mathematical formula: $E = mc^2$

This well-known formula was discovered by **Albert Einstein** in 1905, and he explained the equivalence between mass and energy using this relation.

Every reaction, which results in products with total mass less than the original mass, releases energy. The amount of energy released is equal to the mass difference times the square of the velocity of light.

The amount of energy per unit mass, which is released by the nuclear fusion reaction, is millions times higher than the chemical energy released by burning coal or oil.

The first artificial use of fusion energy was in the **Hydrogen bomb** (October 1952). Since then, scientists are trying to control the nuclear fusion reaction; in order to make controlled use of the energy released.

3.5.3 Lasers which emit very short pulses (10^{-15}-10^{-18} [sec]).

Very short pulses are a new tool for research.

Applications of very short pulses:

- They can be used to study rapid processes. Illuminating the process at short intervals, and taking a picture.
- **Optical communications**. The shorter the pulse, the greater the number of pulses that can be send in a second. This number determine the amount of information that can be transmitted in a given time.

3.5.4 Laser cooling of atoms.

All atoms in nature are moving because they are at a temperature higher than 0 [^{0}K], thus they have **thermal energy**. **At low temperatures, it is possible to almost stop atoms by using the momentum of the photons of the laser radiation.**

Explanation:

A beam of laser light moving in the opposite direction of a beam of atoms can be made to interact with each other in such a way that the atoms absorb photons from the laser beam. The process occurs when the photons energy (which is determined by the photon frequency) is exactly equal to the energy difference betw
een

energy levels of these atoms.

When the atom is in motion, then by the **Doppler effect** this atom "sees" a slightly different frequency of the incoming photons. By using a few beams from opposite directions, it is possible to stop the movement of atoms. The **frequency of the laser beam** is chosen such that it is very close to the absorption frequency of the atom, but not identical to it. Each time the atom starts to move toward one of the laser beams, the Doppler effect causes the radiation from that beam to be absorbed by the atom, so it returns to its place.

3.5.5 Study of the interaction of electromagnetic radiation with matter.

Electromagnetic radiation can react with matter by many different mechanisms. The research of the mechanisms of interaction between electromagnetic radiation and matter is a very productive research field, which produce many new applications.

- For all the **medical applications** of the laser this research is of valuable importance.
- For all the **industrial material processing** applications by lasers this research is of valuable importance.
- We shall mention the advance in recent years of the interaction of electromagnetic radiation with different **biological molecules**, and the potential of **genetic engineering** (changing the gene properties by manipulations on the DNA molecules within the nucleus of the biological cell).

3.6 Special applications.

The applications of lasers are expanding, and many new special applications have been discovered. In the next few sections we shall mentioned briefly just a few of the more common special applications.

3.6.1 Energy transport in space.

Space stations are planned for the near future. And space opens new possibilities for the human race. The energy for the space station will be collected by big collections of solar cells.

There is an idea to **build such big solar collectors in space**. These solar cells will convert the solar energy into electricity. The electrical energy will be send to Eart
h in

Electromagnetic radiation form as a beam of laser energy.

3.6.2 Laser gyroscope.

Gyroscope is an instrument that helps maintain orientation in space.

In the past the gyroscopes were **mechanical spinning systems**, in which the principle of conservation of angular momentum help keep the device pointing in one direction. These devices were very massive and required motors and maintenance. **Optical gyroscopes** are based on a principle called **Sagniac effect**.

This effect which was discovered at the beginning of the 20th century, states that: " An electromagnetic wave which moves in a closed path, which surrounds a finite area, is influenced from the angular velocity of the system which is included in this area".

Principle of Operation of Optical Gyroscope:

Two laser beams are moving in opposite directions in the same ring path. Any change in the direction of the system will cause a difference in the path of these two beams. By using **inteferometric measurements** (), it is possible to detect very small changes, so the laser gyroscope is a very sensitive device. There are two kinds of optical gyroscopes, both based on the same principle:

1. **Laser Gyroscope** is a **laser with ring cavity**. The laser cavity is made of three or four mirrors which form of a closed loop.
2. **Fiber Gyroscope** is a similar device, but the beams of the laser light are traveling along a fiber optic, which is in a form of a coil.

3.6.3 Fiber laser.

It is possible to **create a laser action within an optical fiber**. The active medium is an optical fiber made of impurity atoms embedded in the glass of the fiber core. **The advantages of the fiber-laser are:**

- The optical fiber confine the laser beam within the fiber (the active medium).
- The optical pumping is done by light which is confined within the fiber.

Fiber-laser can directly amplify an incoming signal of laser light, without having to transform it to an electrical signal which is then amplified electronically, and transformed back into light.

The main use of fiber-laser is in optical communication, where the signal transmitted over long distances (such as over the ocean) need to be amplified along the way.The most known family of fiber laser is the **Erbium (Er) Doped Fiber Amplifier (EDFA)**, which is used in optical communications.

Holography

In everyday life we see everything in 3-D, and we accept it as obvious. However, when we look at a hologram which show a 3-D image of something, we are impressed.

Holographyenables looking at a 3 dimensional scene, where the perspective and **parallax** are kept as in real life. (**Parallax** is the relative position of the bodies in the picture, as seen from different points of view Click here to read more about parallax).

The medium on which the 3-D image is recorded is called "**Hologram**"

The name **Hologram** comes from the Greek language, and means "**whole message (picture)**".

Looking at a hologram from different angles, show different perspectives of the scene.

All the information on the 3 dimensional scene is retained in the hologram.

Since hologram is based on **interferometry**, it will be explained first:

What is recorded on the hologram is not the image (as in standard film photography), but the interference pattern created by the waves from all parts of the bodies in the scene.

Interference pattern is created between two beams of light (waves) occupying the same place in space at the same time.

, there are links to holographic Web sites, where nice **At the end of Chapter** pictures of holograms can be seen, and more information can be read, especially on commercial products.

Classifications of lasers into groups, according to safety precautions needed:

The **American National Standards Institute (ANSI) divides all lasers into four groups according to the risk involved in using them** . These **laser hazard classifications** are used to signify the level of hazard inherent in a laser system, and the extent of safety controls required. These range from class I lasers (which are inherently safe for direct beam viewing under most conditions) to class IV lasers (which require the most strict controls).

This division is based on the maximum radiation emitted from the laser which can cause damage. For this, they defined two parameters:

- The **aperture** **through which the radiation is received.**
- **The distance from the laser** , in which the measurement is done.

Laser Applications

Medical applications	Welding and Cutting	Surveying
Garment industry	Laser nuclear fusion	Communication
Laser printing	CDs and optical discs	Spectroscopy
Heat treatment	Barcode scanners	Laser cooling

Medical Uses of Lasers

The highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density. This makes it useful as a cutting and cauterizing instrument. Lasers are used for photocoagulation of the retina to halt retinal hemorrhaging and for the tacking of retinal tears. Higher power lasers are used after cataract surgery if the supportive membrane surrounding the implanted lens becomes milky. Photodisruption of the membrane often can cause it to draw back like a shade, almost instantly restoring vision. A focused laser can act as an extremely sharp scalpel for delicate surgery, cauterizing as it cuts. ("Cauterizing" refers to long-standing medical practices of using a hot instrument or a high frequency electrical probe to singe the tissue around an incision, sealing off tiny blood vessels to stop bleeding.) The cauterizing action is particularly important for surgical procedures in blood-rich tissue such as the liver.
Lasers have been used to make incisions half a micron wide, compared to about 80 microns for

Welding and Cutting

The highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density for welding and cutting.
The automobile industry makes extensive use of carbon dioxide lasers with powers up to several kilowatts for computer controlled welding on auto assembly lines.
Garmire points out an interesting application of CO_2 lasers to the welding of stainless steel handles on copper cooking pots. A nearly impossible task for conventional welding because of the great difference in thermal conductivities between stainless steel and copper, it is done so quickly by the laser that the ther

mal conductivities are irrelevant.

Surveying and Ranging

Helium-neon and semiconductor lasers have become standard parts of the field surveyor's equipment. A fast laser pulse is sent to a corner reflector at the point to be measured and the time of reflection is measured to get the distance.
Some such surveying is long distance! The Apollo 11 and Apollo 14 astronauts put corner reflectors on the surface of the Moon for determination of the Earth-Moon distance. A powerful laser pulse from the MacDonald Observatory in Texas had spread to about a 3 km radius by the time it got to the Moon, but the reflection was strong enough to be detected. We now know the range from the Moon to Texas within about 15 cm, a nine significant digit measurement. A pulsed ruby laser was used for this measurement.

Lasers in the Garment Industry

Laser cutters are credited with keeping the U.S. garment industry competitive in the world market. Computer controlled laser garment cutters can be programmed to cut out 400 size 6 and then 700 size 9 garments - and that might involve just a few cuts. The programmed cutter can cut dozens to hundreds of thicknesses of cloth, and can cut out every piece of the garment in a single run.
The usefulness of the laser for such cutting operations comes from the fact that the beam is highly collimated and can be further focused to a microscopic dot of extremely high energy density for cutting.

Lasers in Communication

Fiber optic cables are a major mode of communication partly because multiple signals can be sent with high quality and low loss by light propagating along the fibers. The light signals can be modulated with the information to be sent by either light emitting diodes or lasers. The lasers have significant advantages because they are more nearly monochromatic and this allows the pulse shape to be maintained better over long distances. If a better pulse shape can be maintained, then the communication can be sent at higher rates without overlap of the pulses. Ohanian quotes a factor of 10 advantage for the laser modulators.
Telephone fiber drivers may be solid state lasers the size of a grain of sand and consume a power of only half a milliwatt. Yet they can sent 50 million pulses per second into an attached telephone fiber and encode over 600 simultaneous telephone conversations (Ohanian).

Heat Treatment

Heat treatments for hardening or annealing have been long practiced in metallurgy. But lasers offer some new possibilities for selective heat treatments of met

al parts. For example, lasers can provide localized heat treatments such as the hardening of the surfaces of automobile camshafts. These shafts are manufactured to high precision, and if the entire camshaft is heat treated, some warping will inevitably occur. But the working surfaces of the cams can be heated quickly with a carbon dioxide laser and hardened without appreciably affecting the remainder of the shaft, preserving the precision of manufacture.

Barcode Scanners

Supermarket scanners typically use helium-neon lasers to scan the universal barcodes to identify products. The laser beam bounces off a rotating mirror and scans the code, sending a modulated beam to a light detector and then to a computer which has the product information stored. Semiconductor lasers can also be used for this purpose.

Laser Fusion

Laser fusion attempts to force nuclear fusion in tiny pellets or microballoons of a deuterium-tritium mixture by zapping them with such a high energy density that they will fuse before they have time to move away from each other. This is an example of inertial confinement.

Two experimental laser fusion devices have been developed at Lawrence Livermore Laboratory, called Shiva and Nova. They deliver high power bursts of laser light from multiple lasers onto a small deuterium-tritium target. These lasers are neodymium glass lasers which are capable of extremely high power pulses.

Nova Laser System

Nova is the name given to the second generation laser fusion device at Lawrence Livermore Laboratories. It employs lasers ten times more powerful than the Shiva laser fusion device and will attempt to reach the breakeven point for fusion. Nova makes use of ten lasers which are focused on a 1 mm diameter target area, dumping 100,000 joules of energy into the target in a nanosecond.

As of 1994, Nova has reached the Lawson criterion, but at a temperature too low for fusion ignition.

Particle Beam Fusion

If a high energy beam of electrons or other particles can be directed onto a tiny pellet or microballoon of deuterium-tritium mixture, it could cause it to explode like a miniature hydrogen bomb, fusing the deuterium and tritium nuclei in a time frame too short for them to move apart.

Compact Disc Audio

Analog sound data is digitized by sampling at 44.1 kHz and coding as binary nu

mbers in the pits on the compact disc. As the focused laser beam sweeps over the pits, it reproduces the binary numbers in the detection circuitry. The same function as the "pits" can be accomplished by magnetooptical recording. The digital signal is then reconverted to analog form by a D/A converter.
The tracks on a compact disc are nominally spaced by 1.6 micrometers, close enough that they are able to separate reflected light into it's component colors like a diffraction grating.
This is an active graphic. Click on any bold text for further details.

Laser for Compact Discs
The detection of the binary data stored in the form of pits on the compact disc is done with the use of a semiconductor laser. The laser is focused to a diameter of about 0.8 mm at the bottom of the disc, but is further focused to about 1.7 micrometers as it passes through the clear plastic substrate to strike the reflective layer.
The Philips CQL10 laser has a wavelength of 790 nm in air. The depth of the pits is about a quarter of the wavelength of this laser in the substrate material.
This is an active graphic. Click on any bold text for further details.

Laser Cooling
Starting in about 1985 with the work of Steven Chu and others, the use of lasers to achieve extremely low temperatures has advanced to the point that temperatures of 10-9 K have been reached. If an atom is traveling toward a laser beam and absorbs a photon from the laser, it will be slowed by the fact that the photon has momentum $p = E/c = h/\lambda$. If we take a sodium atom as an example, and assume that a number of sodium atoms are freely moving in a vacuum chamber at 300K, the rms velocity of a sodium atom from the Maxwell speed distribution would be about 570 m/s. Then if a laser is tuned just below one of the sodium d-lines (589.0 and 589.6 nm, about 2.1 eV), a sodium atom traveling toward the laser and absorbing a laser photon would have its momentum reduced by the amount of the momentum of the photon. It would take a large number of such absorptions to cool the sodium atoms to near 0K since one absorption would slow a sodium atom by only about 3 cm/s out of a speed of 570 m/s. A straight projection requires almost 20,000 photons to reduce the sodium atom momentum to zero.
A conceptual problem is that an absorption can also speed up an atom if it catches it from behind, so it is necessary to have more absorptions from head-on photons if your goal is to slow down the atoms. This is accomplished in practice by tuning the laser slightly below the resonance absorption of a stationary sodium atom. From the atom's perspective, the headon photon is seen as Doppler shifted upward toward its resonant frequency and it therefore more strongly absorbed than a photon traveling in the opposite direction which is Doppler shift

ed away from the resonance. In the case of our room temperature sodium atom above, the incoming photon would be Doppler shifted up 0.97 GHz, so to get the head on photon to match the resonant frequency would require that the laser be tuned below the resonant peak by that amount. This method of cooling sodium atoms was proposed by Theodore Hansch and Arthur Schawlow at Stanford University in 1975 and achieved by Chu at AT&T Bell Labs in 1985. Sodium atoms were cooled from a thermal beam at 500K to about 240 □K. The experimental technique involved directing laser beams from opposite directions upon the sample, linearly polarized at 90° with respect to each other. Six lasers could then provide a pair of beams along each coordinate axis. The effectively "viscous" effect of the laser beams in slowing down the atoms was dubbed "optical molasses" by Chu.

Exercises

1- Find the wavelength at which the rate of spontaneous emission is equal to the stimulated emission at a temperature under the condition of thermal equilibrium.

2 - Explain mathematically that there is no laser beam generation when the thermal energy is equal the photon energy .

Planck's constant $6.63\times10^{-34}\,\mathrm{J.s}$ and Boltzmann's constant $1.38\times10^{-23}\,\frac{\mathrm{J}}{\mathrm{K}}$

3 - What is the temperature for the occurrence of the laser action and laser generation?

4- Calculate the ratio between the spontaneous emission and stimulated emission of a tungsten lamp due to a heat T = 1727 C , the light is visible.

Glossary of laser definitions

Absorption of radiation

- Receiving electromagnetic radiation by interaction with the material, and transforming it to different form, which is usually heat (rise in temperature). The absorption process is dependent on the **wavelength** of the **electromagnetic radiation** and on the absorbing material.

Active Medium

- Collection of atoms or molecules which can be **stimulated** to a **population inversion**, and emit **electromagnetic radiation** in a **stimulated emission**.

Amplification

- The process in which the **electromagnetic radiation** inside the active medium within the **laser optical cavity** increase by the process of **stimulated emission**.

Amplitude

- The maximum value of a wave, measured from its equilibrium.

Anode

- The positive electrode of a **gas laser**, used for **electrical excitation** of the gas in the tube.

Aperture

- A small opening through which the **electromagnetic radiation** pass.

Argon Laser

- A **gas laser** in which argon ions are the **active medium**. This laser emits in the blue - green **visible spectrum**, primarily at 488 and 515 [nm].

Attenuation

- The decrease in radiation energy (power) as a beam passes through an absorbing or scattering medium.

Beam Diameter

- Defined as the diameter of a circular beam at a certain point where the intensity drop to a fraction of its maximum value. The common definitions are 1/e (0.368) and $1/e^2$ (0.135) of the maximum value.

Beam Divergence

- Angle of beam spread, measured in **(milli)radians**. Can be approximated for small angle by the ratio of the beam diameter to the distance from the laser aperture.

Brewster Windows

- Windows at the ends of a gas laser, used to produce **polarized electromagnetic radiation**. The window is at Brewster angle to the optical axis of the laser, so only one type of **polarization** can pass through.

Brightness

- The visual sensation of the luminous intensity of a light source.

Carbon Dioxide (CO_2) Laser

- A **gas laser** in which CO_2 molecules are the **active medium**. This laser emits in the **infrared spectrum**, primarily at 9-11 [μm], with the strongest emission line at 10.6 [μm].

Cathode

- The negative electrode of a **gas laser**, used for **electrical excitation** of the gas in the tube.

Coherence

- A property of electromagnetic waves which are in phase in both time and space. Coherent light has **Monochromaticity** and low **beam divergence**, and can be concentrated to high power densities. Coherence is needed for interference processes like **holography**.

Diffraction

- A wave property which create deviation from a straight line when the beam pass near an edge of an opaque object.

Divergence

- Increase in beam diameter with distance from the aperture (see **beam divergence**).

Diode Laser

Semiconductor Laser

Electromagnetic Radiation (Spectrum)

- A wave which propagate in vacuum with the speed of light, and composed of simultaneous oscillations of electric field and magnetic field perpendicular to each other, and perpendicular to the direction of propagation of the beam. Created by accelerating electric charge, and include X-rays, **visible spectrum**, **infrared spectrum**, microwave etc.

Electron Volt [eV]

- Unit of energy: The amount of energy that the electron accuire while accelerating through a potential difference of 1 [Volt].

$$1\ [eV] = 1.6*10^{-19}\ [Joule]$$

Excimer Laser

- A **gas laser** which emits in the **UV spectrum**. The **active medium** is an "Excited Dimer" which does not have a stable **ground state**.

Excitation

- Energizing the **active medium** to a state of **population inversion**.

Fluorescence

- Emission of light of particular **wavelength**, as a result of **absorption of light** at shorter **wavelength**. It is a property of some materials, each material has a specific **wavelength** of **absorption** and emission.

Frequency (ν) (nu)

- The ***number of times that the wave oscillates per second*** (The number of periods of oscillations per second). For more information click Here.

Gain

- see **Amplification**.

Gas Laser

- A laser in which the **active medium** is a gas. The gas can be composed of molecules (like CO_2), Atoms (like He-Ne), or ions (like Ar+).

Ground State

- Lowest energy level of an atom or molecule.

Helium-Neon (He-Ne) Laser

- A **gas laser** in which Helium (He) and Neon (Ne) atoms are the **active medium**. This laser emits primarily in the **Visible spectrum**, primarily at 632.8 [nm], but also have some lines in the near Infrared.

Hologram

- An interference phenomena captured on a plate (or film). It can contain enormous amount of information and a 3 dimensional image can be constructed from it.

Injection Laser

A type of laser which produces its output from semiconductor materials such as GaAs.

Infrared Spectrum (IR)

- Invisible electromagnetic radiation between 0.7-1,000 [μm].

Injection Laser

- See **Diode Laser.**

Ion Laser

- A laser in which the **active medium** is composed of ions of a Nobel gas (like Ar+ or Kr+). The gas is usually **excited** by high discharge voltage at the ends of a small bore tube.

Irradiance (E)

- Radiant flux (radiant power) per unit area incident upon a given surface. Units: Watts per square centimeter. (Sometimes referred to as **power** density, although not exactly correct).

Laser

- An acronym for **Light Amplification by Stimulated Emission of Radiation**. A laser device is an **optical cavity**, with mirrors at the ends, filled with material such as crystal, glass, liquid, gas or dye. A device which produces an intense beam of light with the unique properties of **coherence**, collimation and **monochromaticity**.

Laser Accessories

- The hardware and options available for lasers, such as **Brewster windows**, **Q-switches** and optical components used to control laser radiation.

Laser Medium

- (See **Active Medium**)

Laser Rod

- A solid-state, rod-shaped **active medium** in which ion excitation is caused by a source of intense light (**optical pumping**), such as a flash lamp. Various materials are used for the rod, the earliest of which was synthetic **ruby** crystal (see **Solid State Laser**).

Laser Pulse

- A discontinuous burst of laser radiation, as opposed to a continuous beam. A true laser pulse achieves higher peak powers than that attainable in a CW output.

Lens

-A curved piece of optically transparent material which depending on its shape, is used to either converge or diverge light.

Light

- Usually referred to the **visible spectrum**. The range of **electromagnetic radiation** frequencies detected by the eye, or the **wavelength** range from about 400 to 700 **nanometers**. The term is sometimes used loosely to include radiation beyond visible spectrum limits.

Limit Accessible Emission Level (AEL)

- permitted within a particularly class. In ANSI Z-136.1, AEL is determined as the product of Accessible Emission **Maximum Permissible Exposure limit (MPE)** and the area of the limiting aperture (7mm for visible and near infrared lasers).

Limiting Aperture

- The maximum circular area over which radiance and radiant exposure can be averaged when determining safety hazards.

Longitudinal (Axial) Modes

- Specific wavelengths in the laser output, determined by standing waves within the **laser cavity**. Only longitudinal modes under the laser gain curve, above the laser threshold are found in the laser output.

Maximum Permissible Exposure (MPE)

- The level of laser radiation to which person may be exposed without hazardous effect or adverse biological changes in the eye or skin.

Metastable State

- The upper laser level. An **excited state** of the atom or molecule, which have a long **lifetime**.

Micron

- Micro-meter, one millionth of a meter (10^{-6} [m]).

Milliradian

- A unit to measure angles, one thousandth of a radian. 1 milliradian [mrad] = 0.057°.

Mode locked

- A method of controlling the length of the output **laser pulse** . Produce very short (10^{-12} [sec]) burst of pulses.

Monochromatic Light

- Theoretically, light at one specific **wavelength**. Practically, light with very narrow bandwidth. The light out of a laser is the most monochromatic source known to man.

Nanometer [nm]

- one billionth of a meter (10^{-9} [m]).

Nd:Glass Laser

- A solid-state laser in which a Nd doped glass rod is used as a laser **active medium**, to produce 1064 [nm] **wavelength**.

Nd:YAG Laser

- A **solid-state laser** in which Neodymium doped **Y**ttrium **A**luminum **G**arnet is used as a laser **active medium**, to produce 1064 [nm] wavelength.. **YAG** is a synthetic crystal.

Neodymium (Nd)

- The rare earth element that is the active element in **Nd:YAG laser** and **Nd:Glass lasers**.

Optical Cavity (Resonator)

- Space between the laser mirrors where lasing action occurs.

Optical Density

- A logarithmic expression for the **attenuation** produced by an attenuating medium, such as an eye protection filter.

Optical Fiber

- A filament of quartz or other optical material, capable of transmitting light along its length by **multiple internal reflection** and emitting it at the end.

Optical Pumping

- The excitation of the **active medium** in a laser by the application of light, rather than electrical discharge. Light can be from a conventional source like Xenon or Krypton lamp, or from another laser.

Optical Radiation

- **Ultraviolet**, **visible** and **infrared spectrum** (0.35-1.4 μm) that falls in the region of transmittance of the human eye.

Optical Resonator

- The mirrors (or reflectors) making up the **laser cavity** including the laser rod or tube. The mirrors reflect light back and forth to build up **amplification**.

Output Coupler

- The part of the laser which enable light to come out of the laser. Usually it is a partially reflecting mirror at the end of the laser **optical cavity**.

Output Power

- The energy per second (measured in Watts) emitted from the laser in the form of **coherent light**.

Photon

- The elemental unit of light. Quantum of light with energy (E) proportional to the wavelength (λ) (lambda) (or frequency f).

$E = hf = hc / \lambda$ (lambda). (λ (lambda) = **wavelength**, c = speed of light, h = Planks constant).

Polarization

- Vibration of the electric field vector in specific direction perpendicular to the direction of propagation of the wave.

Population Inversion

- An excited state of matter, in which more atoms (or molecules) are in upper state than in a lower one. This is a required situation for a laser action.

Power

- The rate of energy delivery in a unit of time, expressed in Watts (Joules per second). Thus: 1 [Watt] = 1 [Joule]/1 [sec].

Pulse Duration

- The "On" time of a **pulsed laser**.

Pulsed Laser

- Laser which delivers energy in the form of a single or train of **laser pulses**.

Pumping

- (See **Optical Pumping**). Addition of energy (thermal, electrical, or optical) into active laser medium. Used to produce a state of **population inversion**.

Radian

- A unit of measurement of angles. 2π [rad] = 360°, 1 [rad] = 57.3°.

Radiant Energy (Q)

- Energy in the form of **electromagnetic waves** usually expressed in units of **Joules** (watt-seconds).

Radiant Exposure (H)

- The total energy per unit area incident upon a given surface. It is used to express exposure to **pulsed laser** radiation in units of J/cm^2.

Reflection

- The return of **radiant energy** (incident light) by a surface, with no change in **wavelength**.

Refraction

- The change of direction of propagation of any wave, such as an electromagnetic wave, when it passes from one medium to another in which the wave velocity is different. The bending of incident rays as they pass from one medium to another (e.g.: air to glass).

Ruby Laser

- The first laser type. A **solid state laser** which use a crystal of sapphire (aluminum oxide) containing trace amounts of chromium oxide as an **active medium**.

Scanning Laser

- A laser having a time-varying direction, origin or pattern of propagation with respect to a stationary frame of reference.

Semiconductor Laser

- (see **diode laser**) A type of laser which produces its output from semiconductor materials such as GaAs.

Solid Angle

- The ratio of the area on the surface of a sphere to the square of the radius of that sphere. It is expressed in steradians (sr).

Solid State Laser

- A laser in which the **active medium** is in solid state (usually not including semiconductor lasers).

Spontaneous Emission

- Random emission of a **photon** by decay of an **excited state** to a lower level. Determined by the lifetime of the excited state.

Spot Size

- A measure of the diameter of the beam of laser radiation.

Stimulated Emission

- **Coherent** emission of radiation, stimulated by a **photon** absorbed by an atom (or molecule) in its excited state.

Transverse Mode

- The geometry of the power distribution in a cross section of a laser beam.

Tunable Laser

- A laser system that can be "tuned" to emit laser light over a continuous range of **wavelengths** or frequencies.

Tunable Dye Laser

- A laser whose **active medium** is a liquid dye, pumped by another laser or flash lamps, to produce various colors of light. The color of light may be tuned by adjusting optical tuning elements and/or changing the dye used.

Ultraviolet (UV) Radiation

- **Electromagnetic radiation** with **wavelengths** between soft X-rays and visible violet light, often broken down into UV-A (315-400 [nm]), UV-B (280-315 [nm]), and UV-C (100-280 [nm]).

Visible Spectrum (light)

- **Electromagnetic radiation** which can be detected by the human eye. It is commonly used to describe **wavelengths** which lie in the range between 400 nm and 700-780 nm.

Wavelength (λ) (Lamda)

- The length of the light wave. The shortest distance at which the wave pattern fully repeats itself, usually measured from crest to crest. The wavelength of light in the visible spectrum determines its color. Common units of measurement are the **micrometer (micron)**, the **nanometer**, and (old unit) the Angstrom unit. [For more information click here]

YAG = Yttrium Aluminum Garnet

- a widely used solid-state crystal which is composed of yttrium and aluminum oxides which is doped with a small amount of the rare-earth neodymium.

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