Part I
Laser Fundamentals

1

Laser Basics

1.1 Introduction

Although lasers were confined to the premises of prominent research centres such as the Bell laboratories, Hughes research laboratories and major academic institutes such as Columbia University in their early stages of development and evolution, this is no longer the case. Theodore Maiman demonstrated the first laser five decades ago in May 1960 at Hughes research laboratories. The acronym 'laser', Light Amplification by Stimulated Emission of Radiation, first used by Gould in his notebooks is a household name today. It was undoubtedly one of the greatest inventions of the second half of the 20th century along with satellites, computers and integrated circuits; its unlimited application potential ensures that it continues to be so even today. Although lasers and laser technology are generally applied in commercial, industrial, bio-medical, scientific and military applications, the areas of its usage are multiplying as are the range of applications in each of these categories.

This chapter, the first in Laser basics, is aimed at introducing the readers to operational fundamentals of lasers with the necessary dose of quantum mechanics. The topics discussed in this chapter include: the principles of laser operation; concepts of population inversion, absorption, spontaneous emission and stimulated emission; three-level and four-level lasers; basic laser resonator; longitudinal and transverse modes of operation; and pumping mechanisms.

1.2 Laser Operation

The basic principle of operation of a laser device is evident from the definition of the acronym 'laser', which describes the production of light by the stimulated emission of radiation. In the case of ordinary light, such as that from the sun or an electric bulb, different photons are emitted spontaneously due to various atoms or molecules releasing their excess energy unprompted. In the case of stimulated emission, an atom or a molecule holding excess energy is stimulated by a previously emitted photon to release that energy in the form of a photon. As we shall see in the following sections, *population inversion* is an essential condition for the stimulated emission process to take place. To understand how the process of population inversion subsequently leads to stimulated emission and laser action, a brief summary of quantum mechanics and optically allowed transitions is useful as background information.

1.3 Rules of Quantum Mechanics

According to the basic rules of quantum mechanics all particles, big or small, have discrete energy levels or states. Various discrete energy levels correspond to different periodic motions of its constituent nuclei and electrons. While the lowest allowed energy level is also referred to as the *ground state*, all other relatively higher-energy levels are called *excited states*. As a simple illustration, consider a hydrogen

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atom. Its nucleus has a single proton and there is one electron orbiting the nucleus; this single electron can occupy only certain specific orbits. These orbits are assigned a quantum number N with the innermost orbit assigned the number $N = 1$ and the subsequent higher orbits assigned the numbers $N = 2$, 3, 4 . . . outwards. The energy associated with the innermost orbit is the lowest and therefore $N = 1$ also corresponds to the ground state. Figure 1.1 illustrates the case of a hydrogen atom and the corresponding possible energy levels.

The discrete energy levels that exist in any form of matter are not necessarily only those corresponding to the periodic motion of electrons. There are many types of energy levels other than the simple-to-describe electronic levels. The nuclei of different atoms constituting the matter themselves have their own energy levels. Molecules have energy levels depending upon vibrations of different atoms within the molecule, and molecules also have energy levels corresponding to the rotation of the molecules. When we study different types of lasers, we shall see that all kinds of energy levels – electronic, vibrational and rotational – are instrumental in producing laser action in some of the very common types of lasers.

Transitions between electronic energy levels of relevance to laser action correspond to the wavelength range from ultraviolet to near-infrared. Lasing action in neodymium lasers (1064 nm) and argon-ion lasers (488 nm) are some examples. Transitions between vibrational energy levels of atoms correspond to infrared wavelengths. The carbon dioxide laser (10 600 nm) and hydrogen fluoride laser (2700 nm) are some examples. Transitions between rotational energy levels correspond to a wavelength range from 100 microns (μm) to 10 mm.

In a dense medium such as a solid, liquid or high-pressure gas, atoms and molecules are constantly colliding with each other thus causing atoms and molecules to jump from one energy level to another. What is of interest to a laser scientist however is an *optically allowed transition*. An optically allowed transition between two energy levels is one that involves either absorption or emission of a photon which satisfies the resonance condition of $\Delta E = h\nu$, where ΔE is the difference in energy between the two involved energy levels, h is Planck's constant ($= 6.626\,075\,5 \times 10^{-34}$ J s or $4.135\,669\,2 \times 10^{-15}$ eV s) and ν is frequency of the photon emitted or absorbed.

1.4 Absorption, Spontaneous Emission and Stimulated Emission

Absorption and emission processes in an optically allowed transition are briefly mentioned in the previous section. An electron or an atom or a molecule makes a transition from a lower energy level to a higher energy level only if suitable conditions exist. These conditions include:

1. the particle that has to make the transition should be in the lower energy level; and
2. the incident photon should have energy ($= h\nu$) equal to the transition energy, which is the difference in energies between the two involved energy levels, that is, $\Delta E = h\nu$.

If the above conditions are satisfied, the particle may make an absorption transition from the lower level to the higher level (Figure 1.2a). The probability of occurrence of such a transition is proportional to both the population of the lower level and also the related Einstein coefficient.

There are two types of emission processes, namely: *spontaneous emission* and *stimulated emission*. The emission process, as outlined above, involves transition from a higher excited energy level to a lower energy level. Spontaneous emission is the phenomenon in which an atom or molecule undergoes a transition from an excited higher-energy level to a lower level without any outside intervention or stimulation, emitting a resonance photon in the process (Figure 1.2b). The rate of the spontaneous emission process is proportional to the related Einstein coefficient. In the case of stimulated emission (Figure 1.2c), there first exists a photon referred to as the stimulating photon which has energy equal to the resonance energy ($h\nu$). This photon perturbs another excited species (atom or molecule) and causes it to drop to the lower energy level, emitting a photon of the same frequency, phase and polarization as that of the stimulating photon in the process. The rate of the stimulated emission process is proportional to the population of the higher excited energy level and the related Einstein coefficient. Note that, in the case of spontaneous emission, the rate of the emission

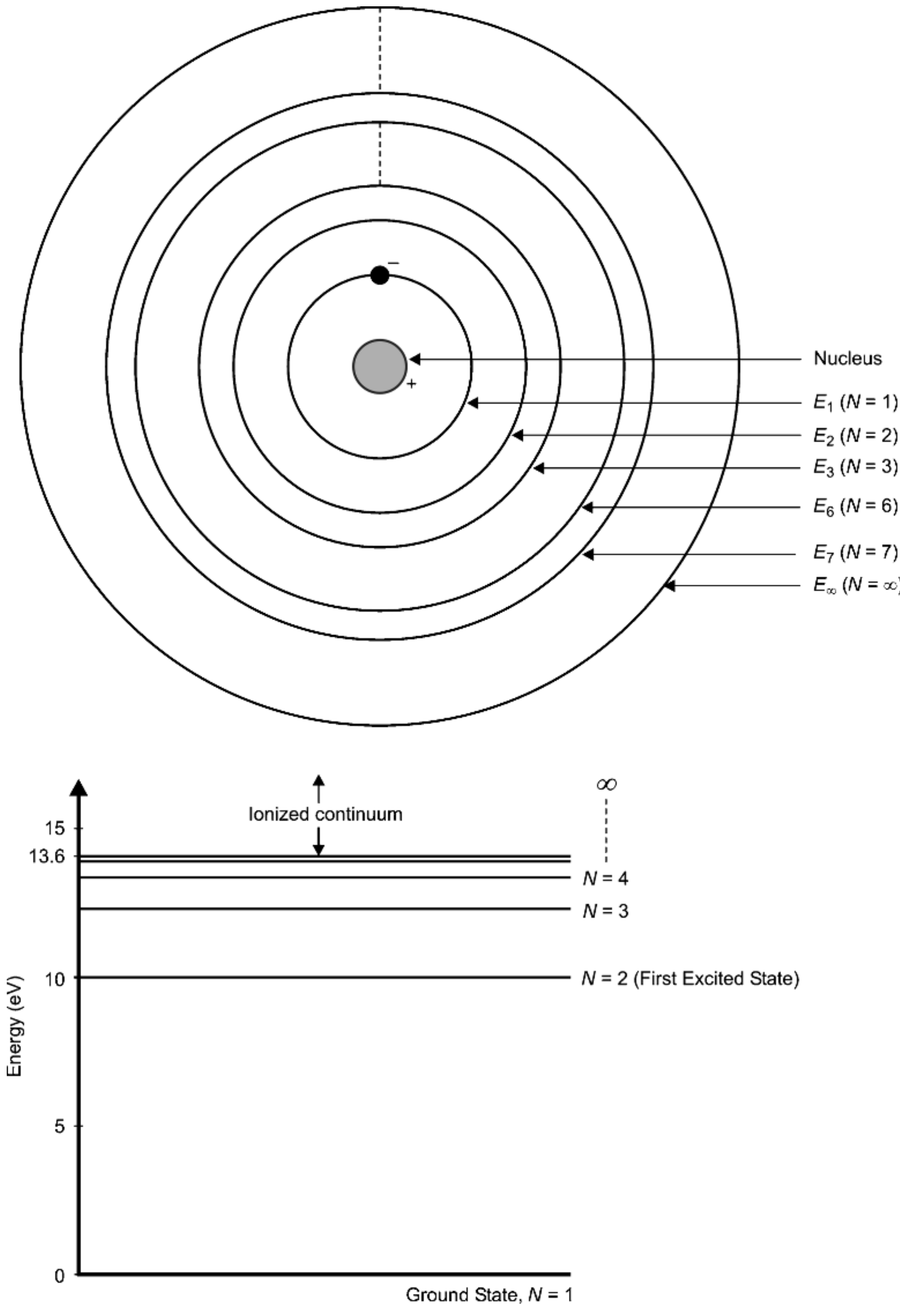

Figure 1.1 Energy levels associated with the hydrogen atom.

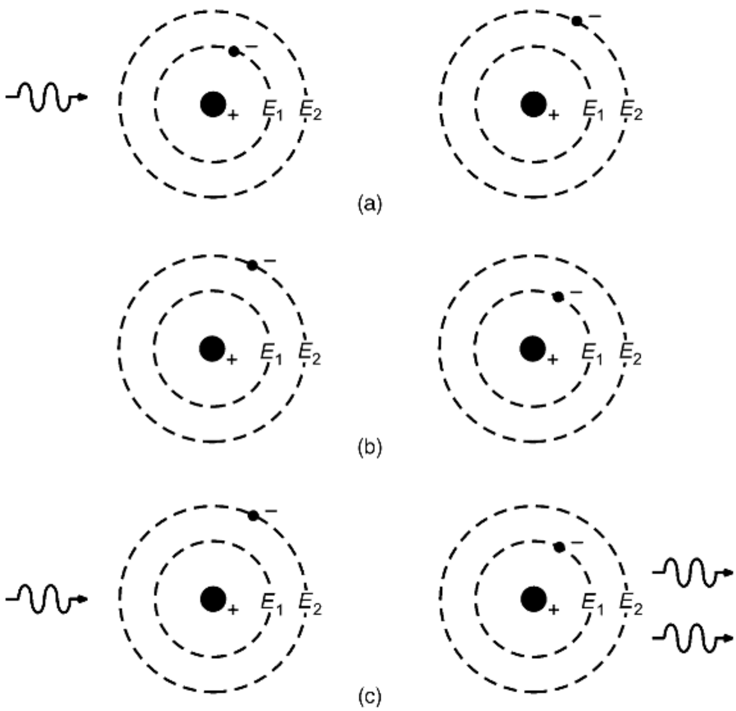

Figure 1.2 Absorption and emission processes: (a) absorption; (b) spontaneous emission; and (c) stimulated emission.

process does not depend upon the population of the energy state from where the transition has to take place, as is the case in absorption and stimulated emission processes. According to the rules of quantum mechanics, absorption and stimulated emission are analogous processes and can be treated similarly.

We have seen that absorption, spontaneous emission and stimulated emission are all optically allowed transitions. Stimulated emission is the basis for photon multiplication and the fundamental mechanism underlying all laser action. In order to arrive at the necessary and favourable conditions for stimulated emission and set the criteria for laser action, it is therefore important to analyze the rates at which these processes are likely to occur. The credit for defining the relative rates of these processes goes to Einstein, who determined the well-known '*A*' and '*B*' constants known as Einstein's coefficients. The '*A*' coefficient relates to the spontaneous emission probability and the '*B*' coefficient relates to the probability of stimulated emission and absorption. Remember that absorption and stimulated emission processes are analogous phenomenon. The rates of absorption and stimulated emission processes also depend upon the populations of the lower and upper energy levels, respectively.

For the purposes of illustration, consider a two-level system with a lower energy level 1 and an upper excited energy level 2 having populations of N_1 and N_2, respectively, as shown in Figure 1.3a. Einstein's coefficients for the three processes are B_{12} (absorption), A_{21} (spontaneous emission) and B_{21} (stimulated emission). The subscripts of the Einstein coefficients here represent the direction of transition. For instance, B_{12} is the Einstein coefficient for transition from level 1 to level 2. Also, since absorption and stimulated emission processes are analogous according to laws of quantum mechanics, $B_{12} = B_{21}$. According to Boltzmann statistical thermodynamics, under normal conditions of thermal equilibrium atoms and molecules tend to be at their lowest possible energy level, with the result that population decreases as the energy level increases. If E_1 and E_2 are the energy levels

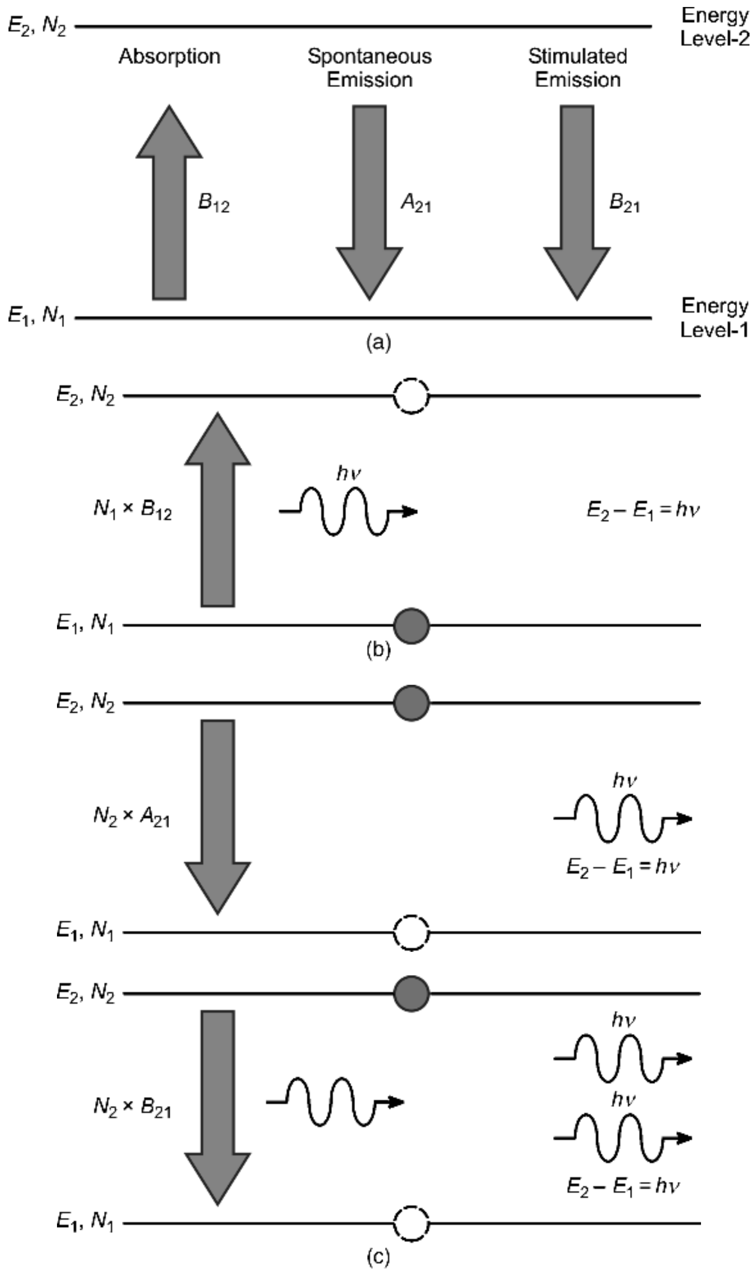

Figure 1.3 Absorption, spontaneous emission and stimulated emission.

associated with level 1 and level 2, respectively, then the populations of these two levels can be expressed by Equation 1.1:

$$\frac{N_2}{N_1} = \exp[-(E_2 - E_1)/kT] \tag{1.1}$$

where

$k =$ Boltzmann constant $= 1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ or $8.6 \times 10^{-23}\,\mathrm{eV\,K^{-1}}$
$T =$ absolute temperature in degrees Kelvin

Under normal conditions, N_1 is greater than N_2. When a resonance photon ($\Delta E = h\nu$) passes through the species of this two-level system, it may interact with a particle in level 1 and become absorbed, in the process raising it to level 2. The probability of occurrence of this is given by $B_{12} \times N_1$ (Figure 1.3b). Alternatively, it may interact with a particle already in level 2, leading to emission of a photon with the same frequency, phase and polarization. The probability of occurrence of this process, known as stimulated emission, is given by $B_{21} \times N_2$ (Figure 1.3d). Yet another possibility is that a particle in the excited level 2 may drop to level 1 without any outside intervention, emitting a photon in the process. The probability of this spontaneous emission is A_{21} (Figure 1.3c). The spontaneously emitted photons have the same frequency but have random phase, propagation direction and polarization.

If we analyze the competition between the three processes, it is clear that if $N_2 > N_1$ (which is not the case under the normal conditions of thermal equilibrium), there is the possibility of an overall photon amplification due to enhanced stimulated emission. This condition of $N_2 > N_1$ is known as *population inversion* since $N_1 > N_2$ under normal conditions. We shall explain in the following sections why population inversion is essential for a sustained stimulated emission and hence laser action.

Example 1.1

Refer to Figure 1.4. It shows the energy level diagram of a typical neodymium laser. If this laser is to be pumped by flash lamp with emission spectral bands of 475–525 nm, 575–625 nm, 750–800 nm and 820–850 nm, determine the range of emission wavelengths that would be absorbed by the active medium of this laser and also the wavelength of the laser emission.

Solution

1. Referring to the energy level diagram of Figure 1.4, two edges of the absorption band correspond to energy levels of 12 500 cm^{-1} and 13 330 cm^{-1}. Corresponding wavelengths (of photons) that would have these energy levels are computed as:

   Wavelength corresponding to 12 500 cm^{-1} = (1/12 500) cm = (10^7/12 500) nm = 800 nm
   Wavelength corresponding to 13 330 cm^{-1} = (1/13 330) cm = (10^7/13 330) nm = 750.19 nm ≅ 750 nm

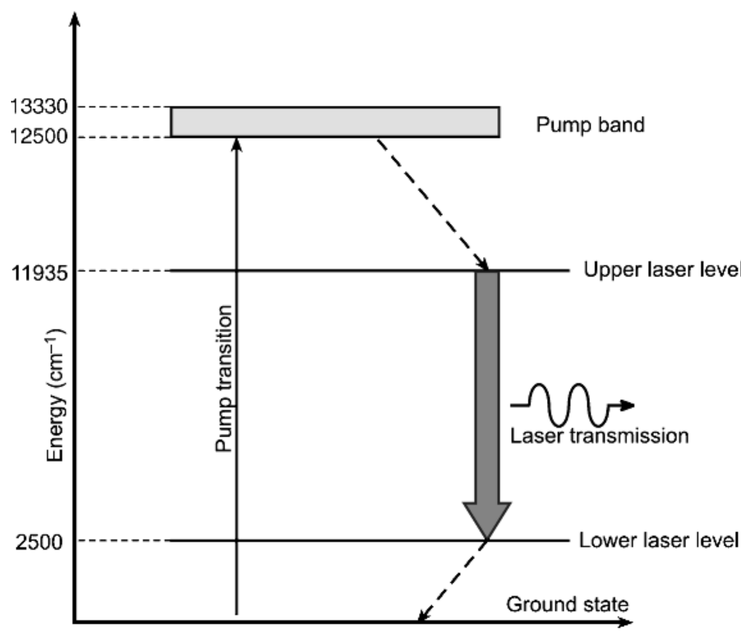

Figure 1.4 Example 1.1: Energy level diagram.

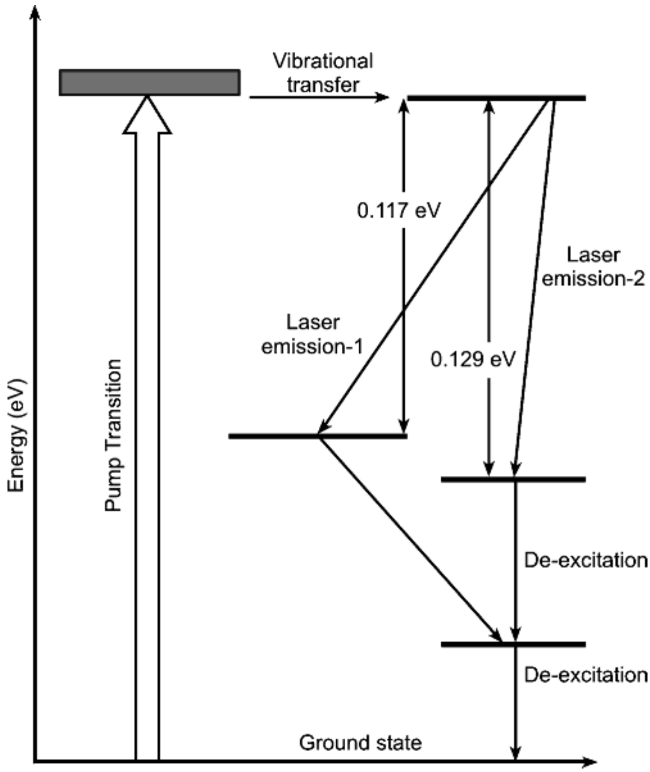

Figure 1.5 Example 1.2: Energy level diagram.

2. The absorption band of the active medium is therefore 750–800 nm. This is the band of wavelengths that would be absorbed by the active medium.
3. Lasing action takes place between metastable energy level 11 935 cm^{-1} and the lower energy level 2500 cm^{-1}. The difference between two energy levels is 11 935−2500 cm^{-1} = 9435 cm^{-1}.
4. This energy corresponds to a wavelength of (1/9435) cm = (10^7/9435) nm = 1059.88 nm ≅ 1060 nm.
5. The emitted laser wavelength is therefore = 1060 nm.

Example 1.2

Figure 1.5 shows the energy level diagram of a popular type of a gas laser. Determine the possible emission wavelengths.

Solution

1. The emission wavelength is such that the corresponding energy value equals the energy difference between the involved lasing levels.
2. **For emission 1**, the energy difference (from Figure 1.5) = 0.117 eV.

If λ_1 is the emission wavelength, then $hc/\lambda_1 = 0.117$ where
h = Planck's constant = $6.626\ 075\ 5 \times 10^{-34}$ J s = $4.135\ 669\ 2 \times 10^{-15}$ eV s
$c = 3 \times 10^{10}$ cm s^{-1}
Substituting these values, $\lambda_1 = (4.135\,669\,2 \times 10^{-15} \times 3 \times 10^{10})/0.117$ cm $= 106.04 \times 10^{-5}$ cm = 10 604 nm.

3. **For emission 2**, the energy difference (from Figure 1.5) = 0.129 eV

   If λ_1 is the emission wavelength, then $hc/\lambda_1 = 0.129$. Substituting these values, $\lambda_1 = (4.1\ 356\ 692 \times 10^{-15} \times 3 \times 10^{10})/0.129\ \text{cm} = 96.178 \times 10^{-5}\ \text{cm} = 9617.8\ \text{nm}$.
4. The energy level diagram shown in Figure 1.5 is that of carbon dioxide laser, which is also evident from the results obtained for the two emission wavelengths.

Example 1.3

We know that absorption and emission between two involved energy levels takes place when the photon energy corresponding to the absorbed or emitted wavelength equals the energy difference between the two energy levels. If ΔE is energy difference in eV, prove that the absorbed or emitted wavelength (in nm) approximately equals ($1240/\Delta E$).

Solution

1. Emitted or absorbed wavelength $\lambda = hc/\Delta E$
2. In the above expression, if we substitute the value of h in eV s, c in nm s^{-1} and ΔE in eV, we obtain λ in nm.
3. Now, $h = 4.135\,669\,2 \times 10^{-15}$ eV s and $c = 3 \times 10^{8}\ \text{m s}^{-1} = 3 \times 10^{17}\ \text{nm s}^{-1}$

   Therefore, λ (in nm) $= 4.135\ 669\ 2 \times 10^{-15} \times 3 \times 10^{17}/\Delta E \cong 1240/\Delta E$.

1.5 Population Inversion

We shall illustrate the concept of population inversion with the help of the same two-level system considered above. If we compute the desired transition energy for an optically allowed transition, let us say at a wavelength of 1064 nm corresponding to the output wavelength of a neodymium-doped yttrium aluminium garnet (Nd:YAG) laser, it turns out to be about 1 eV (transition energy $\Delta E = h\nu$). For a transition energy of 1 eV, we can now determine the population N_2 of level 2, which is the upper excited level here, for a known population N_1 of the lower level at room temperature of 300 K from Equation 1.1. The final relationship is $N_2 = 1.5 \times 10^{-17} N_1$.

This implies that practically all atoms or molecules are in the lower level under thermodynamic equilibrium conditions. Let us not go that far and instead consider a situation where the population of the lower level is only ten times that of the excited upper level. We shall now examine what happens when there is a spontaneously emitted photon. Now there are two possibilities: either this photon stimulates another excited species in the upper level to cause emission of another photon of identical character, or it would hit an atom or molecule in the lower level and be absorbed. Since there are 10 atoms or molecules in the lower level for every excited species in the upper level, we can say that 10 out of every 11 spontaneously emitted photons hit the atoms or molecules in the lower level and become absorbed. Only 9% (1 out of every 11) of the photons can cause stimulated emission. The photons emitted by the stimulated process will also become absorbed successively due to the scarcity of excited species in the upper level. Another way of expressing this is that when the population of the lower level is much larger than the population of the excited upper level, the probability of each spontaneously emitted photon hitting an atom or molecule in the lower level and becoming absorbed is also much higher than the same stimulating another excited atom or molecule in the upper level. The same concept underlies the expressions for the probability of absorption, spontaneous emission and stimulated emission previously outlined in Section 1.4:

Probability of absorption $= B_{12} \times N_1$
Probability of spontaneous emission $= A_{12}$
Probability of stimulated emission $= B_{21} \times N_2$

If we want the stimulated emission to dominate over absorption and spontaneous emission, we must have a greater number of excited species in the upper level than the population of the lower level. Such a situation is known as *population inversion* since under normal circumstances the population of the lower level is much greater than the population of the upper level. Population inversion is therefore an essential condition for laser action. The next obvious question is that of the desired extent of population inversion. Spontaneous emission depletes the excited upper level population (N_2 in the present case) at a rate proportional to A_{21} producing undesired photons with random phase, direction of propagation and polarization. Due to this loss and other losses associated with laser cavity (discussed in Section 1.7), each laser has a certain minimum value of N_2-N_1 for the production of laser output. This condition of population inversion is known as the *inversion threshold* of the laser. *Lasing threshold* is an analogous term.

Next, we shall discuss how we can produce population inversion.

1.5.1 Producing Population Inversion

That population inversion is an essential condition for laser action is demonstrated above. Population inversion ensures that there are more emitters than absorbers with the result that stimulated emission dominates over spontaneous emission and absorption processes. There are two possible ways to produce population inversion. One is to populate the upper level by exciting extra atoms or molecules to the upper level. The other is to depopulate the lower laser level involved in the laser action. In fact, for a sustained laser action, it is important to both populate the upper level and depopulate the lower level.

Two commonly used pumping or excitation mechanisms include optical pumping and electrical pumping. Both electrons and photons have been successfully used to create population inversion in different laser media. While optical pumping is ideally suited to solid-state lasers such as ruby, Nd:YAG and neodymium-doped glass (Nd:Glass) lasers, electrical discharge is the common mode of excitation in gas lasers such as helium-neon and carbon dioxide lasers.

The excitation input, optical or electrical, usually raises the atoms or molecules to a level higher than the upper laser level from where it rapidly drops to the upper laser level. In some cases, the excitation input excites atoms other than the active species. The excited atoms then transfer their energy to the active species to cause population inversion. A helium-neon laser is a typical example of this kind where the excitation input gives its energy to helium atoms, which subsequently transfer the energy to neon atoms to raise them to the upper laser level.

The other important concept essential for laser action is the existence of a *metastable state* as the upper laser level. For stimulated emission, the excited state needs to have a relatively longer lifetime of the order of a few microseconds to a millisecond or so. The excited species need to stay in the excited upper laser level for a longer time in order to allow interaction between photons and excited species, which is necessary for efficient stimulated emission. If the upper laser level had a lifetime of a few nanoseconds, most of the excited species would drop to the lower level as spontaneous emission. The crux is that, for efficient laser action, the population build-up of the upper laser level should be faster than its decay. A longer upper laser level lifetime helps to achieve this situation.

1.6 Two-, Three- and Four-Level Laser Systems

Another important feature that has a bearing on the laser action is the energy level structure of the laser medium. As we shall see in the following sections, energy level structure, particularly the energy levels involved in the population inversion process and the laser action, significantly affect the performance of the laser.

1.6.1 Two-Level Laser System

In a *two-level laser system*, there are only two levels involved in the total process. The atoms or molecules in the lower level, which is also the lower level of the laser transition, are excited to the upper level by the pumping or excitation mechanism. The upper level is also the upper laser level. Once the population inversion is achieved and its extent is above the inversion threshold, the laser action can take place. Figure 1.6 shows the arrangement of energy levels in a two-level system. A two-level system is, however, a theoretical concept only as far as lasers are concerned. No laser has ever been made to work as a two-level system.

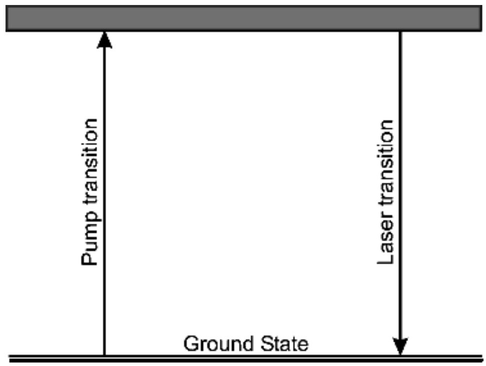

Figure 1.6 Two-level laser system.

1.6.2 Three-Level Laser System

In a *three-level laser system*, the lower level of laser transition is the ground state (the lowermost energy level). The atoms or molecules are excited to an upper level higher than the upper level of the laser transition (Figure 1.7). The upper level to which atoms or molecules are excited from the ground state has a relatively much shorter lifetime than that of the upper laser level, which is a metastable level. As a result, the excited species rapidly drop to the metastable level. A relatively much longer lifetime for the metastable level ensures a population inversion between the metastable level and the ground state provided that more than half of the atoms or molecules in the ground state have been excited to the uppermost short-lived energy level. The laser action occurs between the metastable level and the ground state.

A ruby laser is a classical example of a three-level laser. Figure 1.8 shows the energy level structure for this laser. One of the major shortcomings of this laser and other three-level lasers is due to the lower laser level being the ground state. Under thermodynamic equilibrium conditions, almost all atoms or molecules are in the ground state and so it requires more than half of this number to be excited out of the ground state to achieve laser action. This implies that a much larger pumping input would be required to exceed population inversion threshold. This makes it very difficult to sustain population inversion on a continuous basis in three-level lasers. That is why a ruby laser cannot be operated in continuous-wave (CW) mode.

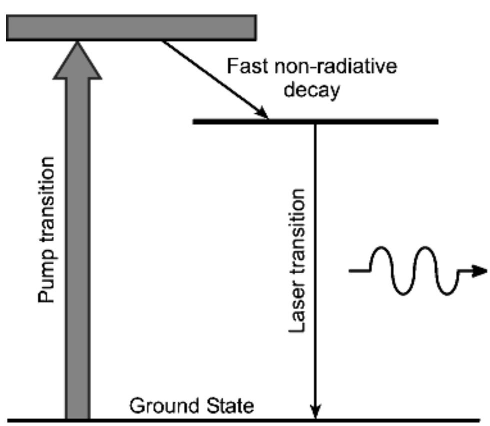

Figure 1.7 Three-level laser system.

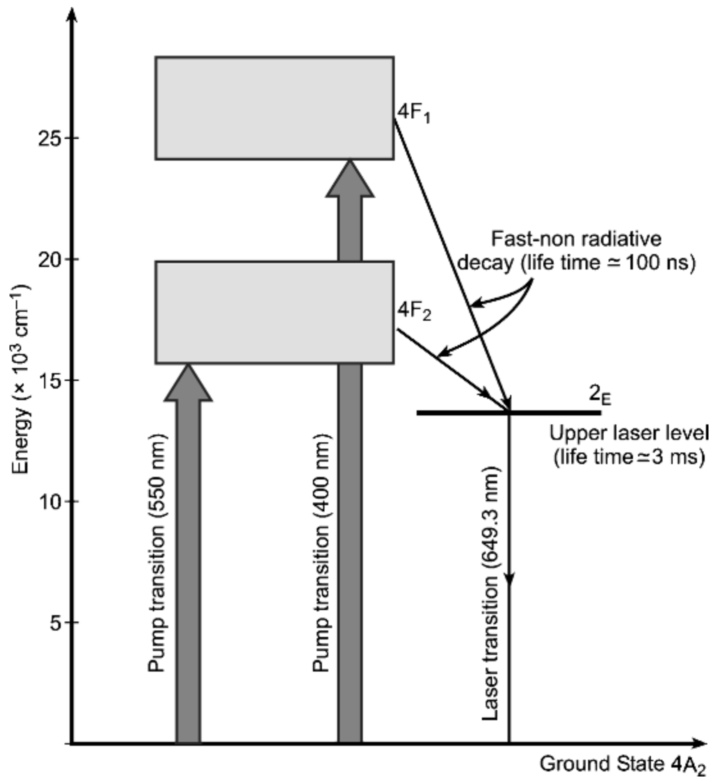

Figure 1.8 Energy level diagram of ruby laser.

An ideal situation would be if the lower laser level were not the ground state so that it had much fewer atoms or molecules in the thermodynamic equilibrium condition, solving the problem encountered in three-level laser systems. Such a desirable situation is possible in four-level laser systems in which the lower laser level is above the ground state, as shown in Figure 1.9.

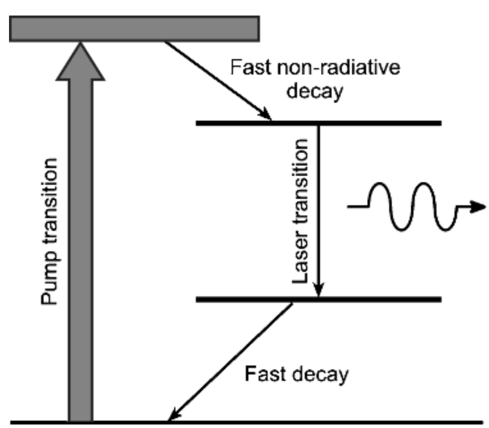

Figure 1.9 Four-level laser system.

1.6.3 Four-Level Laser System

In a *four-level laser system*, the atoms or molecules are excited out of the ground state to an upper highly excited short-lived energy level. Remember that the lower laser level here is not the ground state. In this case, the number of atoms or molecules required to be excited to the upper level would depend upon the population of the lower laser level, which is much smaller than the population of the ground state. Also if the upper level to which the atoms or molecules are initially excited and the lower laser level have a shorter lifetime and the upper laser level (metastable level) a longer lifetime, it would be much easier to achieve and sustain population inversion. This is achievable due to two major features of a four-level laser. One is rapid population of the upper laser level, which is a result of an extremely rapid dropping of the excited species from the upper excited level where they find themselves with excitation input to the upper laser level accompanied by the longer lifetime of the upper laser level. The second occurrence is the depopulation of the lower laser level due to its shorter lifetime. Once it is simpler to sustain population inversion, it becomes easier to operate the laser in the continuous-wave (CW) mode. This is one of the major reasons that a four-level laser such as an Nd:YAG laser or a helium-neon laser can be operated in the continuous mode while a three-level laser such as a ruby laser can only be operated as a pulsed laser.

Nd:YAG, helium-neon and carbon dioxide lasers are some of the very popular lasers with a four-level energy structure. Figure 1.10 shows the energy level structure of a Nd:YAG laser. The pumping or excitation input raises the atoms or molecules to the uppermost energy level, which in fact is not a single level but instead a band of energy levels. This is a highly desirable feature, the reason for which is discussed more fully in Section 1.11 on pumping mechanisms. The excited species rapidly fall to the upper laser level (metastable level). This decay time is about 100 ns. The metastable level has a

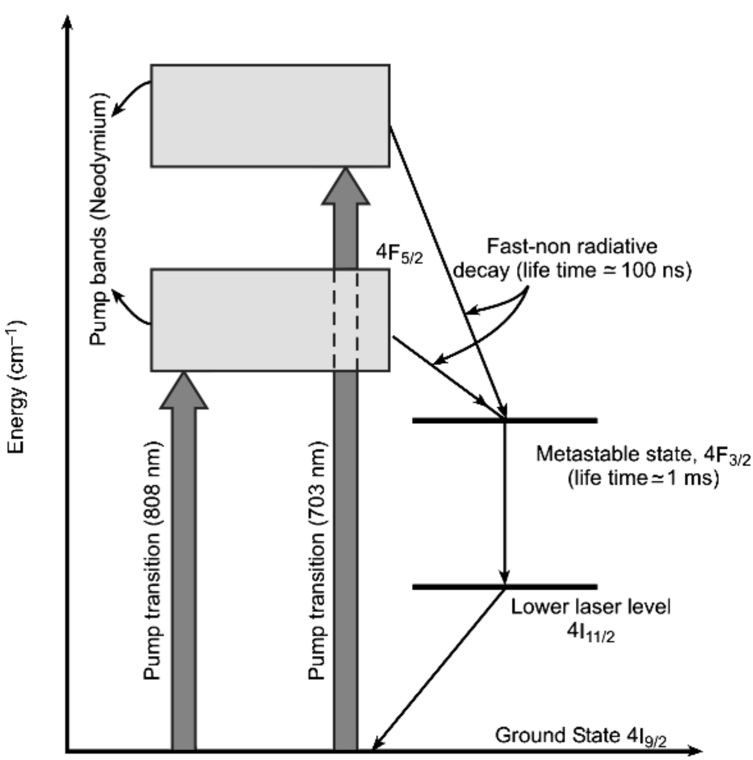

Figure 1.10 Energy level diagram of Nd:YAG laser.

metastable lifetime of about 1 ms and the lower laser level has a decay time of 30 ns. If we compare the four-level energy level structure of a Nd:YAG laser with that of a neodymium-doped yttrium lithium fluoride (Nd:YLF) laser, another solid-state laser with a four-level structure, we find that there is a striking difference in the lifetime of the metastable level. Nd:YLF has a higher metastable lifetime (typically a few milliseconds) as compared to 1 ms of Nd:YAG. This gives the former a higher storage capacity for the excited species in the metastable level. In other words, this means that a Nd:YLF rod could be pumped harder to extract more laser energy than a Nd:YAG rod of the same size.

1.6.4 Energy Level Structures of Practical Lasers

In the case of real lasers, the active media do not have the simple three- or four-level energy level structures as described above, but are far more complex. For instance, the short-lived uppermost energy level, to which the atoms or molecules are excited out of the ground state and from where they drop rapidly to the metastable level, is not a single energy level. It is in fact a band of energy levels, a desirable feature as it makes the pumping more efficient and a larger part of the pumping input is converted into a useful output to produce population inversion. The energy levels involved in producing laser output are not necessarily single levels in all lasers. There could be multiple levels in the metastable state, in the lower energy state of the laser transition or in both states. This means that the laser has the ability to produce stimulated emission at more than one wavelength. Helium-neon and carbon dioxide lasers are typical examples of this phenomenon. Figure 1.11 shows the energy level structure of a helium-neon laser.

Another important point worth mentioning here is that it is not always the active species alone that constitute the laser medium or laser material. Atoms or molecules of other elements are sometimes added with specific objectives. In some cases, such as in a helium-neon laser, the active species producing laser transition is the neon atoms. Free electrons in the discharge plasma produced as a result of electrical pumping input excite the helium atoms first as that can be done very efficiently. When the excited helium atoms collide with neon atoms, they transfer their energy to them. As another example, in a carbon dioxide laser the laser gas mixture mainly consists of carbon dioxide, nitrogen and helium. While

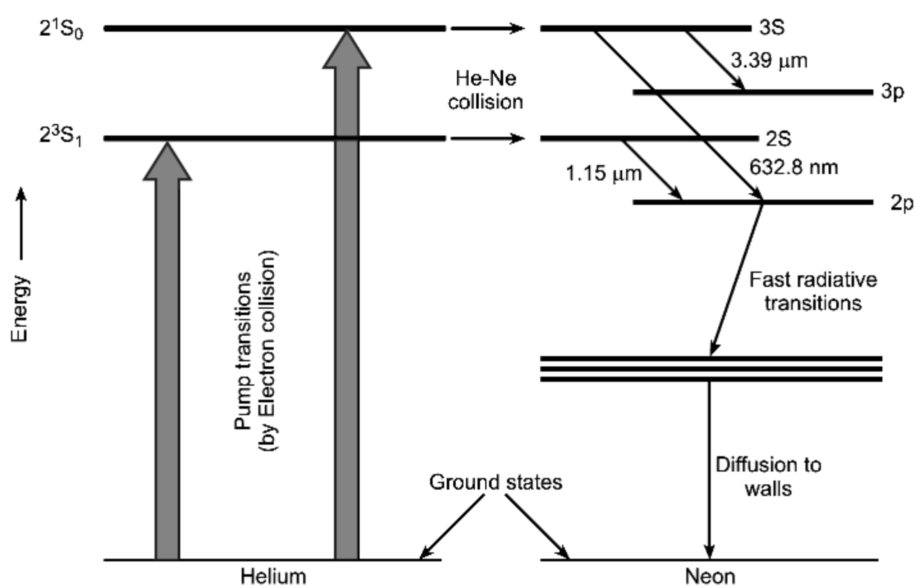

Figure 1.11 Energy level diagram of He-Ne laser.

nitrogen participates in the excitation process and plays the same role as that played by helium in a helium-neon laser, the helium in a carbon dioxide laser helps in depopulating the lower laser level.

1.7 Gain of Laser Medium

When we talk about the *gain* of the laser medium we are basically referring to the extent to which this medium can produce stimulated emission. The gain of the medium is defined more appropriately as a *gain coefficient*, which is the gain expressed as a percentage per unit length of the active medium. When we say that the gain of a certain laser medium is 10% per centimetre, it implies that 100 photons with the same transition energy as that of an excited laser medium become 110 photons after travelling 1 cm of the medium length. The amplification or the photon multiplication offered by the medium is expressed as a function of the gain of the medium and the length of the medium, as described in Equation 1.2:

$$G_{\mathrm{A}} = e^{\alpha x} \tag{1.2}$$

where

G_{A} = amplifier gain or amplification factor
α = gain coefficient
x = gain length

The above expression for gain can be re-written in the form:

$$G_{\mathrm{A}} = (e^{\alpha})^{x} = (1+\alpha)^{x} \qquad \text{for } \alpha \ll 1 \tag{1.3}$$

Therefore, to a reasonably good approximation, we can write

$$\text{Amplification factor} = (1 + \text{gain coefficient})^{\text{length of medium}}$$

This implies that when the medium with a gain coefficient of 100% is excited and population inversion created, a single spontaneously emitted photon will become two photons after this spontaneously emitted photon travels 1 cm of the length of the medium. The two photons cause further stimulated emission as they travel through the medium. This amplification continues and the number of photons emitted by the stimulation process keeps building up just as the principal amount builds up with compound interest. The above relationship can be used to compute the amplification. It would be interesting to note how photons multiply themselves as a function of length. For instance, although 10 photons become 11 photons after travelling 1 cm for a gain coefficient of 10% per centimetre, the number reaches about 26 for 10 cm and 1173 after travelling gain length of 50 cm, as long as there are enough excited species in the metastable state to ensure that stimulated emission dominates over absorption and spontaneous emission. On the other hand it is also true that, for a given pump input, there is a certain quantum of excited species in the upper laser level. As the stimulated emission initially triggered by one spontaneously emitted photon picks up, the upper laser level is successively depleted of the desired excited species and the population inversion is adversely affected. This leads to a reduction in the growth of stimulated emission and eventually saturation sets in; this is referred to as *gain saturation*.

Another aspect that we need to look into is whether the typical gain coefficient values that the majority of the active media used in lasers have are really good enough for building practical systems. Let us do a small calculation. If a 5 mW CW helium-neon laser were to operate for just 1 s, it would mean an equivalent energy of 5 mJ. Each photon of He-Ne laser output at 632.8 nm would have energy of approximately 3×10^{-19} J, which further implies that the above laser output would necessitate generation of about 1.7×10^{16} photons. With the kind of gain coefficient which the helium-neon laser plasma has, the required gain length can be calculated for the purpose. For any useful laser output, the solution therefore lies in having a very large effective gain length, if not a physically large gain length.

If we enclose the laser medium within a closed path bounded by two mirrors, as shown in Figure 1.12, we can effectively increase the interaction length of the active medium by making the

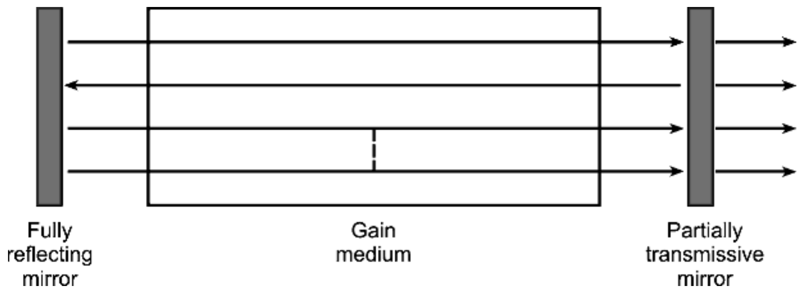

Figure 1.12 Lasing medium bounded by mirrors.

photons emitted by stimulated emission process back and forth. One of the mirrors in the arrangement is fully reflecting and the other has a small amount of transmission. This small transmission, which also constitutes the useful laser output, adds to the loss component. This is true because the fraction of the stimulated emission of photons taken as the useful laser output is no longer available for interaction with the excited species in the upper laser level. The maximum power that can be coupled out of the system obviously must not exceed the total amount of losses within the closed path. For instance, if the gain of the full length of the active medium is 5% and the other losses such as those due to absorption in the active medium, spontaneous emission, losses in the fully reflecting mirror (which will not have an ideal reflectance of 100%) and so on are 3%, the other mirror can have at the most a transmission of 2%.

In a closed system like this, the power inside the system is going to be much larger than the power available as useful output. For instance, for 1% transmission and assuming other losses to be negligible, if the output power is 1 mW the power inside the system would be 100 mW.

Example 1.4

Determine the gain coefficient in case of a helium-neon laser if a 50 cm gain length produces amplification by a factor of 1.1.

Solution

1. We have that $x = 50\,\text{cm}$ and the amplification factor $G_A = 1.1$
2. The gain coefficient α can be computed from $G_A = e^{\alpha x}$

   or $\alpha = (1/x)\ln G_A = (1/50)\ln(1.1) = 0.0019\,\text{cm}^{-1}$

1.8 Laser Resonator

The active laser medium within the closed path bounded by two mirrors as shown in Figure 1.12 constitutes the basic laser resonator provided it meets certain conditions. Resonator structures of most practical laser sources would normally be more complex than the simplistic arrangement of Figure 1.12. As stated in the previous section, with the help of mirrors we can effectively increase the interaction length of the active medium by making the photons emitted by the stimulated emission process travel back and forth within the length of the cavity. One of the mirrors in the arrangement is fully reflecting and the other has a small amount of transmission. It is clear that if we want the photons emitted as a result of the stimulated emission process to continue to add to the strength of those responsible for their emission, it is necessary for the stimulating and stimulated photons to be in phase. The addition of mirrors should not disturb this condition. For example, if the wave associated with a given photon was at its positive peak at the time of reflection from the fully reflecting mirror, it should again be at its positive peak only after it makes a round trip of the cavity and returns to the fully reflecting mirror again. If this happens, then all those photons stimulated by this photon would also satisfy this condition. This is possible if we satisfy the condition given in Equation 1.4:

$$\text{Round trip length} = 2L = n\lambda \tag{1.4}$$

where

$L =$ length of the resonator
$\lambda =$ wavelength
$n =$ an integer

The above expression can be rewritten as

$$f = \frac{nc}{2L} \tag{1.5}$$

where

$c =$ velocity of electromagnetic wave
$f =$ frequency

1.9 Longitudinal and Transverse Modes

The above expression for frequency indicates that there could be a large number of frequencies for different values of the integer n satisfying this resonance condition. Most laser transitions have gain for a wide range of wavelengths. Remember that we are not referring to lasers that can possibly emit at more than one wavelength (such as a helium-neon laser). Here, we are referring to the gain-bandwidth of one particular transition. We shall discuss in detail in Chapter 4 how gas lasers such as He-Ne and CO_2 lasers have Doppler-broadened gain curves. A He-Ne laser has a bandwidth of about 1400 MHz for 632.8 nm transition (Figure 1.13a) and a CO_2 laser has a bandwidth of about 60 MHz at 10 600 nm (Figure 1.13b).

It is therefore possible to have more than one resonant frequency, each of them called a *longitudinal mode*, simultaneously present unless special measures are taken to prevent this from happening. As is clear from Equation 1.5, the inter-mode spacing is given by $c/2L$. For a He-Ne laser with a cavity length of 30 cm for example, inter-mode spacing would be 500 MHz which may allow three longitudinal modes to be simultaneously present as shown in Figure 1.14a. Interestingly, the cavity length could be reduced

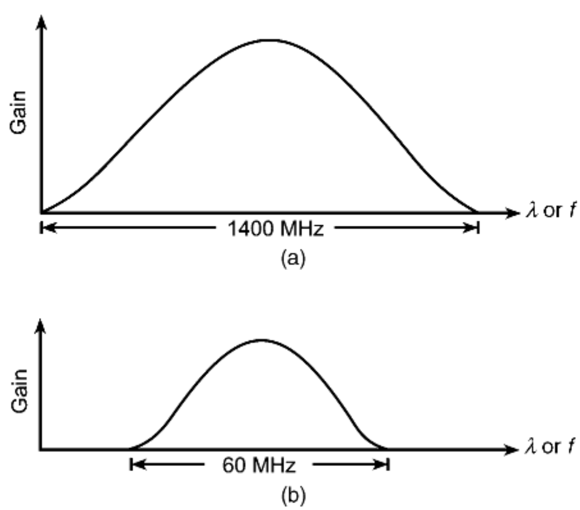

Figure 1.13 Gain-bandwidth curves for He-Ne and CO_2 lasers.

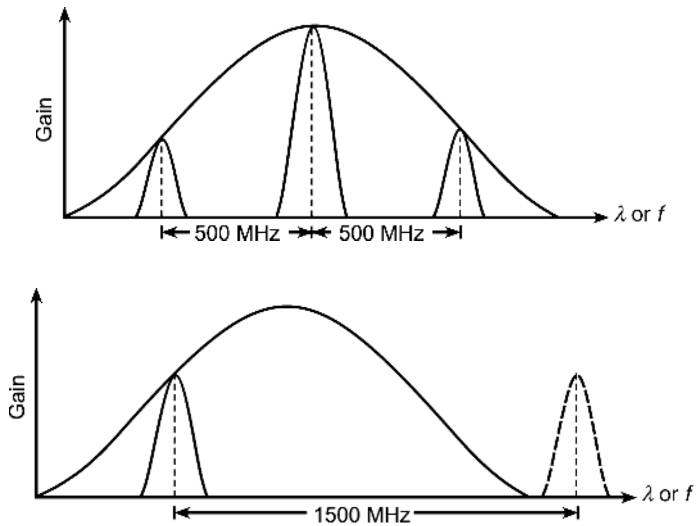

Figure 1.14 Longitudinal modes.

to a point where the inter-mode spacing exceeds the gain-bandwidth of the laser transition to allow only a single longitudinal mode to prevail in the cavity. For instance, a 10 cm cavity length leading to an inter-mode spacing of 1500 MHz would allow only a single longitudinal mode (Figure 1.14b). However, there are other important criteria that also decide the cavity length.

Another laser parameter that we are interested in and that is also largely influenced by the design of the laser resonator is the *transverse mode* structure of the laser output. We have already seen in the previous sections how the resonator length and the laser wavelength together decide the possible resonant frequencies called longitudinal modes, which can simultaneously exist. The transverse modes basically tell us about the irradiance distribution of the laser output in the plane perpendicular to the direction of propagation or, in other words, along the orthogonal axes perpendicular to the laser axis. To illustrate this further, if the z axis is the laser axis, then intensity distribution along the x and y axes would describe the transverse mode structure.

TEM_{mn} describes the transverse mode structure, where m and n are integers indicating the order of the mode. In fact, integers m and n are the number of intensity minima or nodes in the spatial intensity pattern along the two orthogonal axes. Conventionally, m represents the electric field component and n indicates the magnetic field component. Those who are familiar with electromagnetic theory should not find this difficult at all to grasp. Remember that transverse modes must satisfy the boundary conditions such as having zero amplitude on the boundaries. The simplest mode, also known as the fundamental or the lowest order mode, is referred to as TEM_{00} mode. The two subscripts here indicate that there are no minima along the two orthogonal axes between the boundaries. The intensity pattern in both the orthogonal directions has a single maximum with the intensity falling on both sides according to the well-known mathematical distribution referred to as the Gaussian distribution. The Gaussian distribution (Figure 1.15) is given by Equation 1.6:

$$I(r) = I_0 \exp\left(-2r^2/w^2\right) \tag{1.6}$$

where

$I(r)$ = intensity at a distance r from the centre of the beam
w = beam radius at $(1/e^2)$ of peak intensity point, which is about 13.5% of the peak intensity

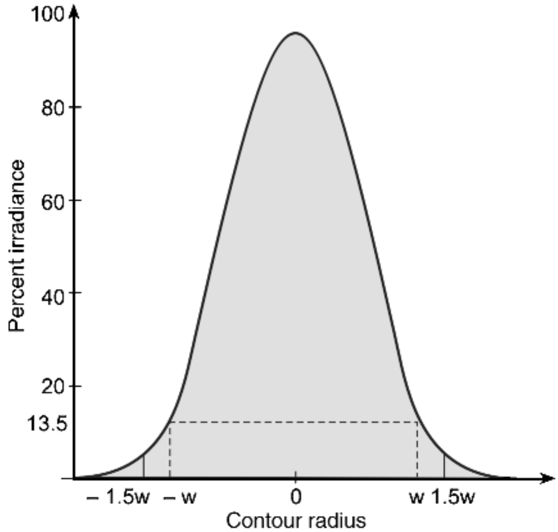

Figure 1.15 Gaussian distribution.

We also have

$$I_0 = \frac{2P}{\pi w^2} \tag{1.7}$$

where

$P =$ total power in the beam

Before we discuss the definite advantages that the operation at lowest order or fundamental modes TEM_{00} offers, we shall have quick look at higher-order modes and also how different transverse mode appear in relation to their intensity distributions. Figure 1.16 shows the spatial intensity distribution of the laser spot for various transverse mode structures of the laser resonator.

Going back to the fundamental mode, we can appreciate that this mode has the least power spreading. To add to this, this mode has the least divergence; it has the minimum diffraction loss and therefore can be focused onto the smallest possible spot. The transverse mode structure is also critically dependent upon parameters such as laser medium gain, type of laser resonator and so on. There are established resonator design techniques to ensure operation at the fundamental mode. Often, lasers optimized to produce maximum power output operate at one or more higher-order modes. Also, lasers with low gain and stable resonator configuration can conveniently be made to operate at fundamental mode. Details are beyond the scope of this book, however.

Example 1.5

Given that the Doppler-broadened gain curve of a helium-neon laser with a 50-cm-long resonator emitting at 1.15 μm is 770 MHz, determine (a) inter-longitudinal mode spacing and (b) the number of maximum possible sustainable longitudinal modes.

Solution: Resonator length $L = 50$ cm. Therefore, inter-longitudinal mode spacing $= c/2L = 3 \times 10^{10}/100 = 300$ MHz.

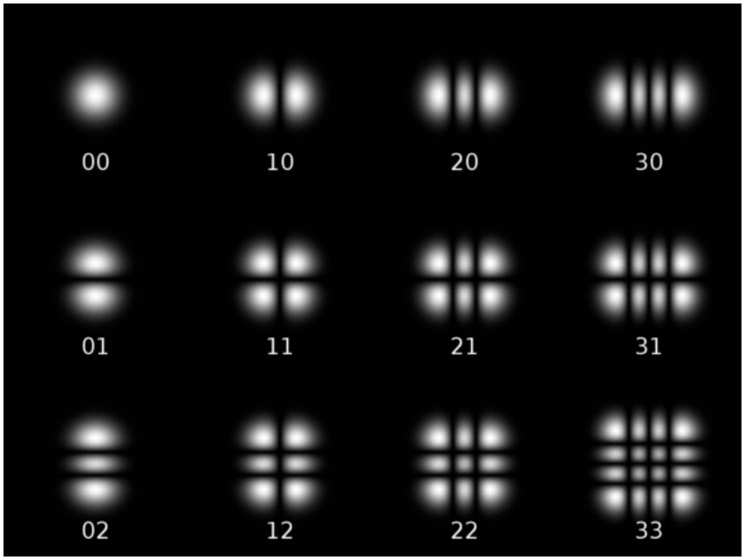

Figure 1.16 Spatial intensity distribution for various transverse modes.

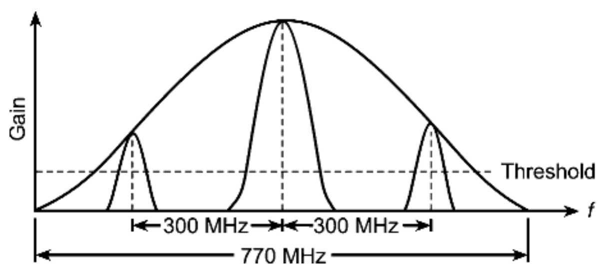

Figure 1.17 Diagram for Example 1.5.

Width of Doppler-broadened gain curve = 770 MHz. The number of longitudinal modes possible within this width = 3 (Figure 1.17).

1.10 Types of Laser Resonators

According to the type of end mirrors used and the inter-element separation, which largely dictates the extent of interaction between the emitted photons and the laser medium and also the immunity of the laser resonator to misalignment of end components, the resonators can be broadly classified as *stable* and *unstable* resonators. A *stable resonator* is one in which the photons can bounce back and forth between the end components indefinitely without being lost out the sides of the components. Due to the focusing nature of one or both components, the light flux remains within the cavity in such a resonator. A *plane-parallel resonator* (Figure 1.18) in which both end components are plane mirrors and are placed precisely at right angles to the laser axis is a stable resonator. In practice, however, this is not true. A slight misalignment of even one of the mirrors would ultimately lead to light flux escaping the laser cavity after several reflections from the two mirrors. Nevertheless, such a resonator encompasses a large volume of the active medium. It is not used in practice, as it is highly prone to misalignment.

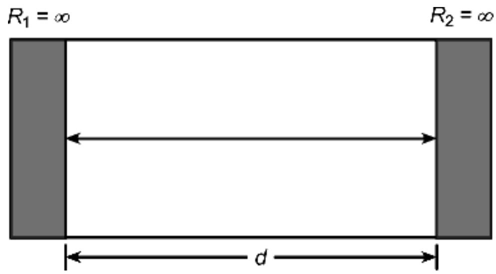

Figure 1.18 Plane-parallel resonator.

This problem can be overcome by using one plane and one curved mirror, as is the case for *hemispherical* and *hemifocal* resonators shown in Figure 1.19a and b, respectively, or two curved mirrors, as is the case for *concentric* and *confocal* resonators shown in Figure 1.20a and b, respectively.

Although the problem of sensitivity of the plane-parallel resonator to misalignment of cavity mirrors is largely overcome by the use of different stable resonator configurations discussed above (Figures 1.19 and 1.20), not all of them have emitted photons interacting with a large volume of the excited species, which is also equally desirable. It is also true that in the case of low-gain media with consequent very low transmission output mirrors, the photons travel back and forth a large number of times within the cavity before their energy appears at the output. This makes the resonator alignment more critical. That is why a plane-parallel resonator will never be the choice for a low-gain laser medium.

On the other hand, in a high-gain medium a certain amount of light flux leakage can be tolerated. This fact is made use of in an *unstable resonator* configuration, which otherwise achieves interaction of the emitted photons with a very large volume of the excited species. Figure 1.21 shows one possible type of unstable resonator. Note that photons escape from the sides of the mirror after one or two passes within the cavity. This light leakage, which also constitutes the useful laser output, is more than compensated for by a high-gain medium and large interaction volume. Further, since the photons have to make

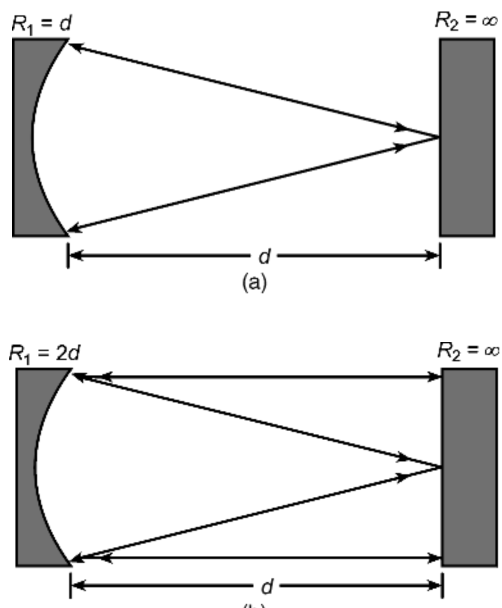

Figure 1.19 (a) Hemispherical resonator and (b) hemifocal resonator.

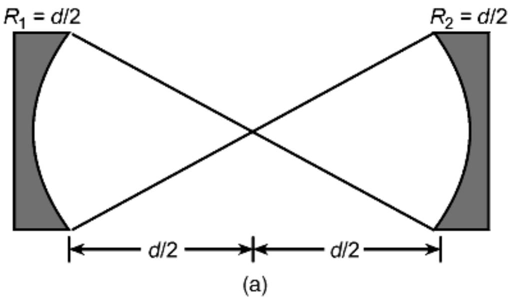

Figure 1.20 (a) Concentric resonator and (b) confocal resonator.

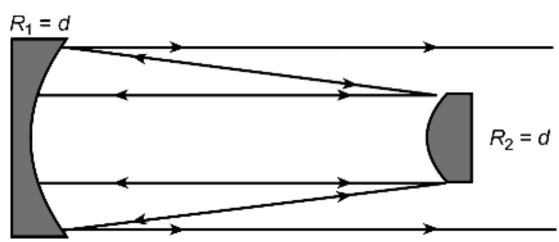

Figure 1.21 Unstable resonator.

relatively fewer passes within the cavity as compared to a low-gain stable resonator configuration before drifting out, the alignment becomes much less critical.

1.11 Pumping Mechanisms

By pumping mechanism, we mean the mechanism employed to create population inversion of the lasing species. Commonly employed pumping mechanisms include:

1. optical pumping;
2. electrical pumping; and
3. other mechanisms such as pumping by chemical reactions, electron beams and so on.

One aspect that is common to all pumping mechanisms is that the pumping energy/power must be greater than the laser output energy/power. When applied to optical pumping, it is obvious that the optical pump wavelength must be smaller than the laser output wavelength. This has to be true as the

Figure 1.22 Linear flash lamps.

lasing species are first excited to the topmost level from where they drop to the upper laser level. Since the energy difference between the ground state and the topmost pump level is always greater than the energy difference between the two laser levels, the wavelength of the pump photon must be less than the wavelength of the laser output. Another aspect that is common to all schemes is that pumping efficiency largely affects the overall laser efficiency. For instance, if the energy difference for the pump transition is much greater than that of the laser transition, the laser efficiency is bound to be relatively poorer. An argon-ion laser is a typical example. Yet another aspect that is common to all pumping mechanisms is that the topmost pump level is not a single energy level but rather a band of closely spaced energy levels with allowed transitions to a single and, in some cases, more than one metastable level. When applied to optical pumping, this allows the use of optical sources such as flash lamps with broadband outputs.

1.11.1 Optical Pumping

Optical pumping is employed for those lasers that have a transparent active medium. Solid-state and liquid-dye lasers are typical examples. The most commonly used pump sources are the flash lamp in the case of pulsed and the arc lamp in the case of continuous-wave solid-state lasers.

Flash lamps are pulsed sources of light and are widely used for the pumping of pulsed solid-state lasers. These are available in a wide range of arc lengths (from a few centimetres to as large as more than a metre, although arc length of 5–10 cm is common), bore diameter (typically in the range of 3–20 mm), wall thickness (typically 1–2 mm) and shape (linear, helical). Figures 1.22 and 1.23 depict the constructional features of typical linear (Figure 1.22) and helical (Figure 1.23) flash lamps.

Flash lamps for pumping solid-state lasers are usually filled with a noble gas such as xenon or krypton at a pressure of 300–400 torr. Two electrodes are sealed in the envelope that is usually made of quartz. An electrical discharge created between the electrodes leads to a very high value of pulsed current, which further produces an intense flash. The electrical energy to be discharged through the lamp is stored in an energy storage capacitor/capacitor bank.

Xenon-filled lamps produce higher radiative output for a given electrical input as compared to krypton-filled lamps. Krypton however offers a better spectral match, more so with Nd:YAG. That is, the emission spectrum of a krypton flash lamp is better matched to the absorption spectrum of Nd:YAG. Emission spectra in the case of xenon- and krypton-filled lamps are depicted by Figures 1.24 and 1.25, respectively. The absorption spectrum of a Nd:YAG laser is given in Figure 1.26.

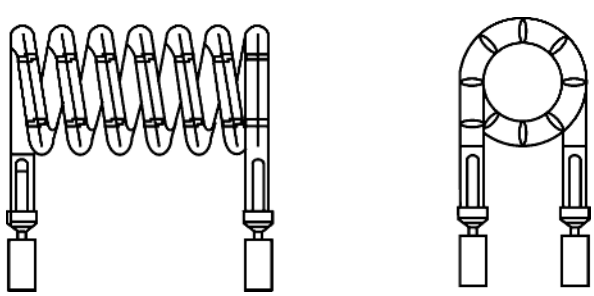

Figure 1.23 Helical flash lamp.

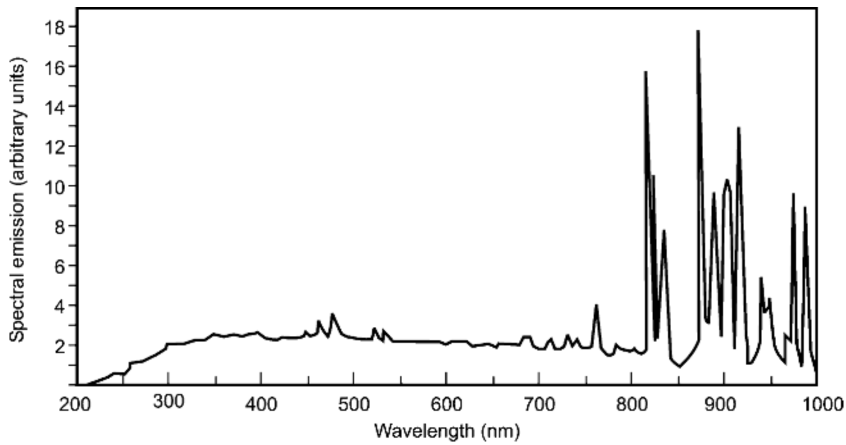

Figure 1.24 Emission spectrum of xenon-filled flash lamp.

Major electrical parameters include the flash lamp impedance parameter, maximum average power, maximum peak current, minimum trigger voltage and explosion energy. Impedance characteristics of a flash lamp are extremely important as they determine the energy transfer efficiency from energy storage capacitor, where it is stored, to the flash lamp.

Table 1.1 gives typical values of various characteristic parameters of xenon-filled and krypton-filled pulsed flash lamps from Heraeus Noblelight Ltd. The type numbers chosen for the purpose include both air-cooled as well as liquid-cooled flash lamps of different bore diameter and arc length. This assortment of flash lamps highlights the variation of the electrical parameters with bore diameter and arc length for a

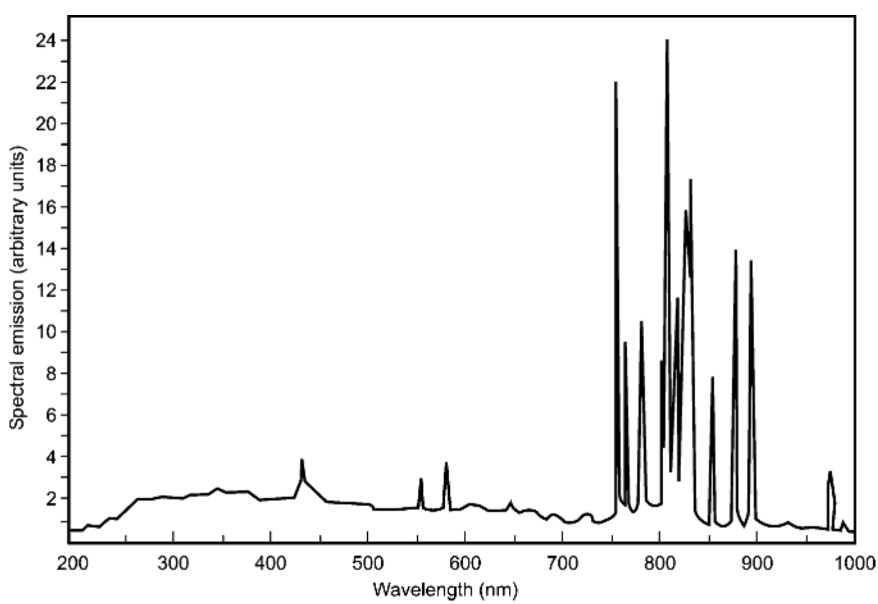

Figure 1.25 Emission spectrum of Krypton-filled flash lamp.

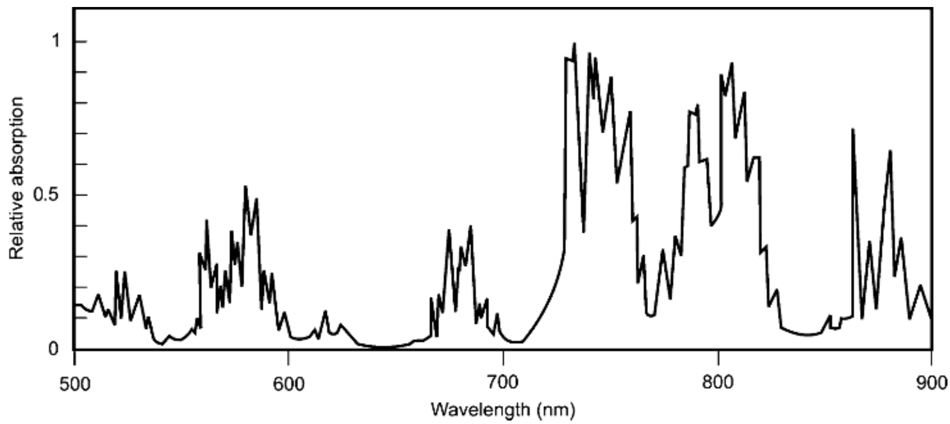

Figure 1.26 Absorption spectrum of Nd:YAG.

Table 1.1 Characteristic parameters of linear flash lamps. (In the case of maximum average power specification of air-cooled lamps, the listed value is for forced-air cooling. In the case of convection air-cooled, it is half of the value given for forced-air cooling.)

Flash lamp number	Bore diameter (mm)	Arc length (mm)	Impedance constant (K_0) ($\Omega A^{1/2}$)	Explosion energy constant ($Ws^{1/2}$)	Maximum average power (W)	Minimum trigger voltage (kV)	Minimum trigger pulse width (μs)
3 × 25XAP[1]	3	25.4	10.8	1.87×10^4	72	16	0.2
3 × 76XAP	3	76.2	32.3	5.62×10^4	214	16	0.6
3 × 25XFP[2]	3	25.4	11.2	1.87×10^4	479	16	0.2
3 × 76XFP	3	76.2	33.7	5.62×10^4	1436	16	0.6
3 × 25KAP[3]	3	25.4	8.9	1.87×10^4	72	18	0.2
3 × 76KAP	3	76.2	26.7	1.87×10^4	214	18	0.6
3 × 25KFP[4]	3	25.4	9.0	1.87×10^4	479	18	0.2
3 × 25KFP	3	76.2	29.2	1.87×10^4	1436	18	0.6
5 × 51XAP	5	50.8	12.9	6.25×10^4	238	16	0.4
5 × 102XAP	5	101.6	25.8	1.25×10^5	478	16	0.8
5 × 51XFP	5	50.8	13.5	6.25×10^4	1595	16	0.4
5 × 102XFP	5	101.6	27.0	1.25×10^5	3190	16	0.8
5 × 51KAP	5	50.8	10.6	6.25×10^4	238	18	0.4
5 × 102KAP	5	101.6	24.4	1.25×10^5	478	18	0.8
5 × 51KFP	5	50.8	10.9	6.25×10^4	1595	18	0.4
5 × 102KFP	5	101.6	21.7	1.25×10^5	3190	18	0.8
8 × 76XAP	8	76.2	12.1	1.50×10^5	574	18	0.6
8 × 102XAP	8	101.6	16.1	2.00×10^5	764	18	0.8
8 × 76XFP	3	76.2	12.7	1.50×10^5	3830	18	0.6
8 × 102XFP	3	101.6	16.9	2.00×10^5	5106	18	0.8
8 × 76KFP	8	76.2	10.2	1.50×10^5	3830	20	0.6
8 × 102KFP	8	101.6	9.9	2.00×10^5	5106	20	0.8
13 × 102XAP	13	101.6	14.9	3.25×10^5	1244	20	0.8
13 × 152XAP	13	152.4	16.1	4.87×10^5	1866	22	1.2
13 × 102XFP	13	101.6	10.4	3.25×10^5	8299	20	0.8
13 × 152XFP	13	152.4	15.6	4.87×10^5	12 448	25	1.2
13 × 102KFP	13	101.6	8.3	3.25×10^5	8299	25	0.8
13 × 152KFP	13	152.4	12.5	4.87×10^5	12 448	25	1.2

[1]Xenon-filled air-cooled; [2]Xenon-filled liquid cooled; [3]Krypton-filled air-cooled; [4]Krypton-filled liquid-cooled.

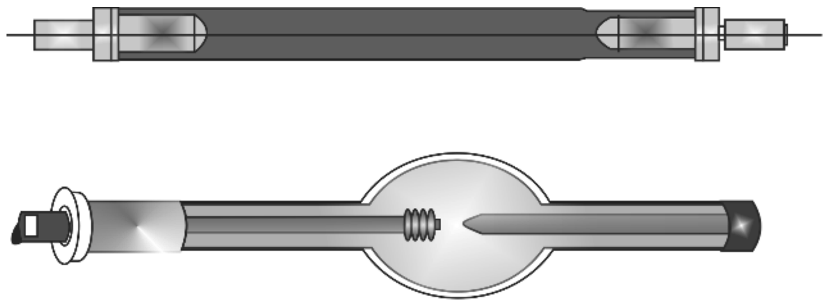

Figure 1.27 Construction of linear arc lamp.

given category of flash lamps, and also the range of values for bore diameter and arc length with the different categories of flash lamps.

Arc lamps are used for CW pumping of solid-state lasers. Like flash lamps, arc lamps are also gas-discharge devices. Arc lamps suitable for solid-state laser pumping are linear lamps (Figure 1.27), which are very much like linear flash lamps except for electrode design. As evident from Figure 1.27, arc lamps use pointed cathodes rather than the rounded cathodes used in flash lamps. Arc lamps are filled with xenon or krypton at a pressure of 1–3 atmospheres. Krypton-filled linear arc lamps are more common because of their relatively better spectral match to the Nd:YAG absorption band. Bore diameters of 4–7 mm and arc lengths in the range of 50–150 mm are common.

Table 1.2 provides typical values for various characteristic parameters in the case of linear krypton-filled arc lamps for different values of bore diameter and arc length. The information given in the table is based on the technical data of linear krypton-filled arc lamps from EG&G Electro-optics.

However, the efficiency with which pump output is usefully transferred to excite the lasing species is definitely lower in the case of the broadband optical pumping provided by flash lamps and arc lamps. Optical pumping at a single wavelength in a laser with an absorption level corresponding to that wavelength in the pump band achieves a relatively higher pumping efficiency, which leads to higher overall laser efficiency. Optical pumping of solid-state lasers by semiconductor lasers in what are better known as diode-pumped solid-state lasers achieves an efficiency that is 25–30 times that currently achievable in the case of flash lamp pumped solid-state lasers.

Laser diode arrays for solid-state laser pumping are available in various package configurations. The basic element in these arrays, also called stacks, is the laser diode bar (Figure 1.28). Each bar has multiple emitters. Laser bars are available in both conduction-cooled as well as liquid-cooled varieties. State-of-the-art bars offer up to 100 W of CW power. Stacks of these bars are also available for higher

Table 1.2 Characteristic parameters of linear krypton-filled arc lamps

Bore diameter (mm)	Arc length (mm)	Maximum average input power (W)	Maximum steady-state voltage (V)	Maximum steady-state current (A)	Maximum starting anode voltage (V)	Maximum trigger voltage (kV)
4	48	2200	104	20	1800	25
4	51	2100	95	20	2000	25
4	76	3200	160	20	2500	25
6	76	3000	120	40	2500	30
6	102	5500	140	38	3000	30

Figure 1.28 Laser diode bar.

pump power requirement (Figure 1.29). However, the maximum pump power available from diode laser arrays is still much lower than that possible from flash lamps.

1.11.2 Electrical Pumping

Pumping by electrical discharge is common in gas lasers. The excited electrons in the gas-discharge plasma transfer their energy to the lasing species either directly or indirectly through the atoms

Figure 1.29 Laser diode stack.

or molecules of another element. A helium-neon laser is a typical example of an indirect transfer of pump energy. The electrons first transfer the energy to helium atoms and then the excited helium atoms transfer the energy to neon atoms. A high voltage initially ionizes the gas and, once the discharge is struck, it can be sustained by a relatively much lower voltage and current. In a typical He-Ne laser, initiating voltage is of the order 8–10 kV while the sustaining voltage is around 1.5–2 kV.

Diode lasers are also electrically pumped, but not in the same way as gas lasers. In the case of diode lasers, the electrical current in the forward-biased diode frees electrons to create electron-hole pairs. The electrons and holes recombine to emit photons. In doing so, electrons drop back to the lower state.

1.11.3 Other Methods of Pumping

Some of the other methods of pumping or creating population inversion, which are specific to certain types of lasers, include excitation by *combustion reaction* as in gas dynamic CO_2 lasers, c*hemical reaction* as in chemical lasers such as hydrogen fluoride (HF) laser, deuterium fluoride (DF) laser and chemical oxygen iodine laser (COIL) and electron acceleration as in free electron lasers. In the case of a gas dynamic laser for example, a combustion reaction produces a high-temperature high-pressure mixture of CO_2 and other gases required in a CO_2 laser. This gas mixture is then rapidly expanded through a set of nozzles to a very low-pressure low-temperature condition. Although the temperature and pressure drop rapidly a large number of molecules still remain in the excited state, thus creating population inversion.

1.12 Summary

- Lasers were undoubtedly one of the greatest inventions of the second half of 20th century – along with satellites, computers and integrated circuits – and continue to be so today due to their unlimited application potential.
- The basic principle of operation of a laser device is based on stimulated emission of radiation. In the case of ordinary light, such as that from the sun or an electric bulb, different photons are emitted spontaneously due to various atoms or molecules releasing their excess energy. In the case of stimulated emission, an atom or a molecule holding excess energy is stimulated by another previously emitted photon to release that energy in the form of a photon.
- A laser scientist is interested in an *optically allowed transition* between two energy levels, which involves either absorption or emission of a photon satisfying the resonance condition of $\Delta E = h\nu$ where ΔE is the difference in energy between the two involved energy levels, h is Planck's constant ($= 6.626\,075\,5 \times 10^{-34}$ J s or $4.135\,669\,2 \times 10^{-15}$ eV s) and ν is the frequency of the photon emitted or absorbed.
- There are two types of emission processes: spontaneous emission and stimulated emission. The emission process involves transition from a higher excited energy level to a lower energy level. Spontaneous emission is the phenomenon in which an atom or molecule undergoes a transition from an excited higher energy level to a lower level without any outside intervention or stimulation, emitting a resonance photon in the process.
- Under thermodynamic equilibrium conditions, practically all atoms or molecules are in the lower level. A condition of population inversion is said to be achieved when the population N_2 of a higher energy level is greater than the population N_1 of a lower energy level. Population inversion is an essential condition for the laser action.
- There are two possible ways to produce population inversion. One is to populate the upper level by exciting extra atoms or molecules to the upper level. The other is to depopulate the lower laser level involved in the laser action. In fact, for a sustained laser action, it is important to both populate the upper level and depopulate the lower level.

- Energy level structure of the laser medium has an important bearing on the laser action and associated characteristics. All lasers operate as either three-level (e.g. ruby laser) or four-level lasers (e.g. Nd: YAG, He-Ne, CO_2).
- The gain of the medium is defined as gain coefficient, which is the gain expressed as a percentage per unit length of the active medium. The gain of the laser medium refers to the extent to which this medium can produce stimulated emission. The amplification or the photon multiplication offered by the medium is expressed as a function of the gain of the medium and the length of the medium by: Amplification $= (1 + \text{gain})^{\text{Length of medium}}$.
- A resonator is the active laser medium within the closed path bounded by two mirrors, providing it meets certain conditions. One of the mirrors in the arrangement is fully reflecting and the other has a small amount of transmission. A laser resonator satisfies: Round trip length $= 2L = n\lambda$ where L, n and λ denote length of the resonator, an integer and wavelength, respectively.
- The resonators can be broadly classified as stable and unstable resonators. A stable resonator is one in which the photons can bounce back and forth between the end components indefinitely without being lost out the sides of the components. In an unstable resonator photons escape from the sides of the mirror after one or two passes within the cavity. An unstable resonator is usually chosen with laser media that have a very high gain, as alignment in this resonator type is much less critical.
- It is possible to have more than one resonant frequency (each referred to as a longitudinal mode) to be simultaneously present unless special measures are taken to prevent this from happening. The inter-mode spacing is given by $c/2L$.
- The transverse modes basically tell us about the irradiance distribution of the laser output in the plane perpendicular to the direction of propagation or, in other words, along the orthogonal axes perpendicular to the laser axis.
- Commonly employed pumping mechanisms include optical pumping and electrical pumping. Other pumping mechanisms include by chemical reactions and electron beams.

Review Questions

1.1. Differentiate between the processes of absorption, spontaneous emission and stimulated emission with particular reference to lasers.

1.2. In light of the fact that laser emission is nothing but stimulated emission of radiation, briefly explain why population inversion is an essential condition for the laser action to take place.

1.3. Compare and contrast three-level and four-level laser systems with reference to lasing threshold, conversion efficiency and ability to operate as a CW laser.

1.4. Differentiate between a stable resonator and an unstable resonator and explain why an unstable resonator is better when the laser medium has high gain.

1.5. What are longitudinal and transverse modes? What is their bearing on the laser characteristics such as beam divergence, coherence and directionality?

1.6. Briefly describe gain of laser medium. What do you understand by gain coefficient and what is its significance in laser resonator design?

Problems

1.1. Figure 1.30 depicts the energy level diagram of a popular four-level laser. Determine the emission wavelength.
[1064 nm]

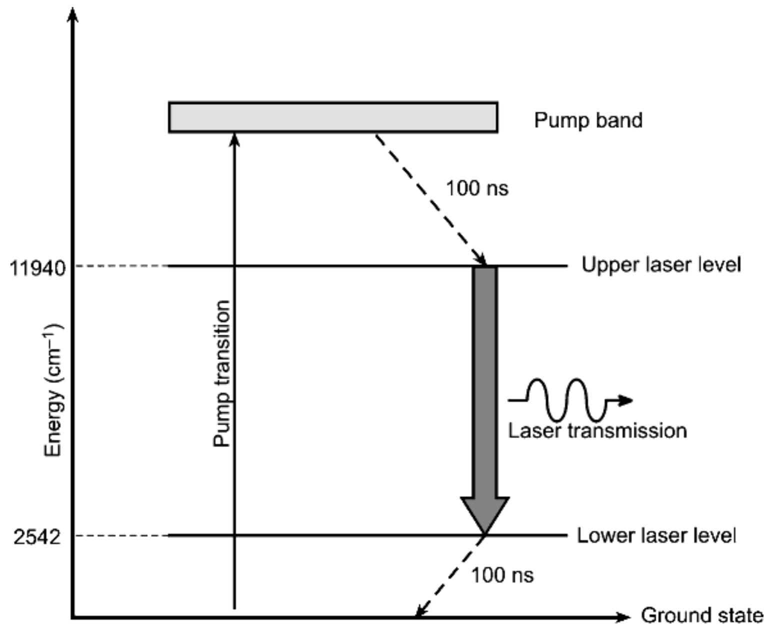

Figure 1.30 Problem 1.1.

1.2. After travelling 10 cm through the laser medium, 1000 photons become 2718 photons. Determine the gain coefficient of the medium.
[0.1 cm^{-1} or 10% cm^{-1}]

1.3. Given that the Doppler-broadened gain curve of a helium-neon laser with a 30-cm-long resonator emitting at 632.8 nm is 1400 MHz, determine the number of maximum possible sustainable longitudinal modes.
[3]

Self-evaluation Exercise

Multiple-choice Questions

1.1. Laser power input to a 10 cm long gain medium is 2 W. If the gain coefficient is 10% per centimetre, output power will be
a. 5.436 W
b. 2.718 W
c. 3 W
d. none of these

1.2. Which of the following is a stable resonator configuration?
a. plane-parallel resonator
b. confocal resonator
c. hemispherical resonator
d. concentric resonator
e. all of the above

1.3. When we say that gain coefficient of a laser medium is 10% per centimetre, it implies that 100 photons having the same transition energy as that of excited laser medium after travelling 1 cm will increase to
a. 101 photons
b. 110 photons
c. 1000 photons
d. none of these

1.4. What attributes does the fundamental transverse mode have?
a. least power spreading
b. minimum diffraction loss
c. can be focused to smallest possible spot
d. all of the above

1.5. A helium-neon laser having a resonator length of 10 cm and a Doppler-broadened gain curve of 1400 MHz and emitting at 633 nm can have
a. only one longitudinal mode
b. two longitudinal modes
c. any number of longitudinal modes
d. only one transverse mode

1.6. The transverse mode that is associated with the least beam divergence is
a. TEM_{00} mode
b. TEM_{01} mode
c. TEM_{10} mode
d. TEM_{03} mode

1.7. Flash lamps suitable for solid-state laser pumping are usually filled with
a. xenon
b. krypton
c. xenon or krypton
d. a mixture of xenon and krypton

1.8. Lasers used for optical pumping of laser media by another laser
a. are laser diode arrays
b. are pulsed solid-state lasers
c. include diode lasers, pulsed and CW solid-state lasers, excimer lasers, metal vapour lasers and so on.
d. none of these

1.9. A dye laser emitting in the visible wavelength band could possibly be pumped by
a. a diode laser emitting in near-infrared
b. an excimer laser emitting in ultraviolet
c. a frequency doubled Nd:YAG laser
d. any of the above lasers

1.10. An unstable resonator is associated with
a. high-gain laser medium
b. large interaction volume
c. less critical alignment
d. all of the above

Answers

1. (a) 2. (e) 3. (b) 4. (d) 5. (a) 6. (a) 7. (c) 8. (c) 9. (b) 10. (d)

Bibliography

1. *Laser Fundamentals*, 2008 by William Thomas Silfvast, Cambridge University Press.
2. *Fundamentals of Light Sources and Lasers*, 2004 by Mark Csele, Wiley-Interscience.
3. *Lasers: Fundamentals and Applications*, 2010 by K. Thyagarajan and Ajoy Ghatak, Springer.
4. *The Laser Guidebook*, 1999 by Jeff Hecht, McGraw Hill.
5. *Principles of Lasers*, 2009 by Orazio Svelto, Plenum Press.
6. *Understanding Lasers: An Entry Level Guide*, 2008 by Jeff Hecht, IEEE Press.
7. *Introduction to Laser Physics*, 1986 by Koichi Shimoda, Springer-Verlag.
8. *Introduction to Lasers and their Applications*, 1977 by Donald C. O'Shea, W. Russell Callen and William T. Rhodes, Addison-Wesley Publishing Co.
9. *Laser Handbook*, 1972 by F.T. Arechhi and E. O. Schulz-Dubois, Amsterdam North-Holland Publishing Co.
10. *Lasers and Light: Readings from Scientific American*, 1969 by A.L. Schawlaw, San Francisco, W. H. Freeman.
11. *Lasers and Optical Engineering*, 1990 by P. Das, Springer-Verlag.
12. *Lasers Theory and Applications*, 1981 by K. Thyagarajan and A.K. Ghatak, Plenum Press.
13. *Lasers*, 1986 by A.E. Siegman, University Science Books.
14. *Handbook of Laser Technology and Applications*, 2003 Volume I by Collin E. Webb and Julian D. C. Jones, Institute of Physics Publishing.