Chapter 1

# Basic Principles of Laser

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## 1.1 Introduction to Laser Physics

‘LASER’, i.e., Light Amplification by Stimulated Emission of Radiation, is now ubiquitous in its presence in fields as diverse as medical, industrial, defence, nuclear, cosmetics, etc. Implementation of mega projects, viz., ITER, CERN, LIGO, etc. depend heavily on usage of lasers. Lasers have also proven to be remarkable tools for a wide range of applications in the field of nuclear industry [1]. High spatial coherence and spectral purity of lasers make them specially suited for precision spectroscopy experiments, separation of isotopes, remote diagnostics and precision metrology. In 1960, the first laser (ruby laser) was experimentally demonstrated by Theodore Maiman [2], although it was theoretically conceived by Einstein several decades earlier in 1917. Here, the synthetic ruby crystal was optically pumped by using a flash lamp emitting red light at 694 nm of radiation. In the same year, the first gas laser (He-Ne laser) was made by Javan and Bennett emitting red light at 632.8 nm. The first diode laser (GaAs) was made by R. N. Hall in 1962 emitting radiation at 850 nm while Holonyak demonstrated the first semiconductor laser emitting visible light. Scientists have now successfully populated the electromagentic spectrum from deep UV to IR with coherent sources utilising a gamut of lasing media and excitation techniques. People are now talking of X-ray lasers, gamma ray lasers and even lasers without inversion!!

In this chapter, the aim is to provide a glimpse on the basic aspects of laser, viz., working principle, major components, energy levels, properties, and types of lasers.

## 1.2 Principle of Lasing

In 1917, Einstein first theoretically conceived the concept of LASER and MASER (Microwave Amplification by Stimulated Emission of Radiation). Applying the Plank's law of radiation, he proposed the three most fundamental ways [3] in which radiation interacts with matter, viz., (a) absorption, (b) spontaneous emission, and (c) stimulated emission of electromagnetic radiation, as shown in the Fig. 1.1. Let us consider a system of two levels in the presence of electromagnetic radiation. Let there be $N_1$ and $N_2$ number of atoms per unit volume in levels 1 and 2 corresponding to the energies $E_1$ and $E_2$ as depicted in the Fig. 1.1.

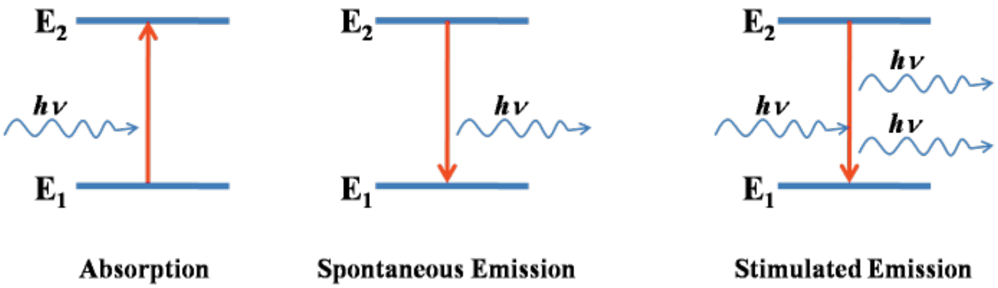

Figure 1.1: Pictorial representation of the three fundamental processes.

### 1.2.1 Process 1 – Absorption

By absorbing the incident photon radiation an atom jumps from the lower ground state energy level ($E_1$) to the higher excited level ($E_2$) when the photon energy equals the energy difference between the two levels, i.e., $E_{photon} = E_2 - E_1$, as shown in Fig. 1.1. This process is called absorption. The process of absorption not only depends on the characteristics of the two states but also the energy-density of the radiation field. The rate of absorption is defined as:

$$\frac{dN_1}{dt} = -B_{12} N_1 \ \rho \tag{1.1}$$

where $\rho$ is the energy-density per unit volume per unit frequency period and $B_{12}$ the Einstein's coefficient of absorption from Level 1 to Level 2.

### 1.2.2 Process 2 – Spontaneous emission

By emitting a photon of energy E spontaneously, the atom in the excited state returns to the ground state as shown in the Fig. 1.1. This process which is found to be random and independent of incident radiation is known as 'spontaneous emission'. It is to be noted that the emitted photon's energy is equal to the difference in energy between the two levels where the transition is taking place, i.e., $E = E_2 - E_1 = h\nu$, where 'h' is the Planck constant and '$\nu$', is the frequency of radiation emitted. The probability of the spontaneous emission depends of the characteristics of the states involved. The rate of spontaneous emission is defined as:

$$\frac{dN_2}{dt} = -A_{21}N_2 \tag{1.2}$$

The negative (-ve) sign is due to the fact that emission causes the population in $N_2$ to reduce. And A the Einstein's coefficient of spontaneous emission.

### 1.2.3 Process 3 – Stimulated emission

The excited atom can be forced to return to its ground state due to interaction with an incident photon whose energy is same as what the atom would emit when it de-excites. In such a case, the emitted photon has the same phase, frequency, polarisation as the incident photon and travels in the same direction (Fig. 1.1). Such a process is known as stimulated emission.

$$\frac{dN_2}{dt} = -B_{21}N_2\ \rho \tag{1.3}$$

As stated, $A_{21}$, $B_{21}$, and $B_{12}$ are called the Einstein coefficients which can be calculated by solving the rate equations as described below.

$$\text{Rate of absorption (upward transition rate)} = B_{12}N_1\rho$$

$$\text{Rate of emission (downward transition rate)} = B_{21}N_2\rho + A_{21}N_2$$

For a system in equilibrium, the upward and downward transition rates must be equal.

$$B_{12}N_1\rho = B_{21}N_2\rho + A_{21}N_2$$

$$\rho = \frac{A_{21}}{B_{12}\frac{N_1}{N_2} - B_{21}}$$

Applying the Boltzmann distribution law and rearranging,

$$\rho = \frac{A_{21}}{B_{21}} \frac{1}{\frac{B_{12}}{B_{21}} e^{\frac{h\nu}{k_B T}} - 1} \tag{1.4}$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \tag{1.5}$$

From Planck's energy distribution radiation law, where the energy density ($\rho$) is defined as:

$$\rho = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1} \tag{1.6}$$

Therefore, by comparing the above two expressions of the energy density ($\rho$), by analogy, the relationship among the Einstein coefficients are as follows.

$$B_{12} = B_{21} = B$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

### 1.2.4 Population inversion

In general, emission occurs through spontaneous process as upper levels are less populated. The stimulated emission has to dominate over spontaneous emission for the enhancement of the number of coherent photons. The above mentioned criteria can only be fulfilled if the number of excited atoms are more than the number of the ground state atoms obeying the criteria $N_2 > N_1$ so that emitted photons are more likely to encounter excited atoms and stimulate further emission than be lost due to absorption by atoms in the lower level. Such a configuration of atoms as shown in Fig. 1.2 is called a 'population inversion' because this condition is contrary to the equilibrium situation where lower energy level is always more populated than the upper level.

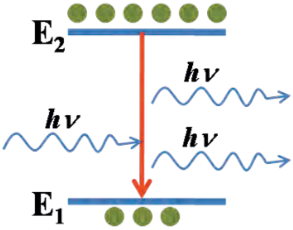

Figure 1.2: Schematic representation of population inversion.

## 1.3 Elements of a Laser

### 1.3.1 Principle of laser action

Let us assume a situation of population inversion. A spontaneously emitted photon, as it encounters an excited atom can stimulate it to produce a photon identical to itself. Thus these photons of same frequency, energy and phase (Fig. 1.1), as they travel through the medium, can cause further stimulation of the excited species generating more number of photons, identical in all respects which continue to cause further stimulation. Therefore, in every step, the photons get multiplied and eventually gives rise to an intense beam that is found to be coherent and is highly directional. Since the light is getting amplified by the process of stimulated emission, thereby, it is popularly named as, LASER [4]. To achieve population inversion followed by the process of stimulated emission of radiation, the three basic components that a laser should comprise of are, viz., (i) active medium, (ii) excitation

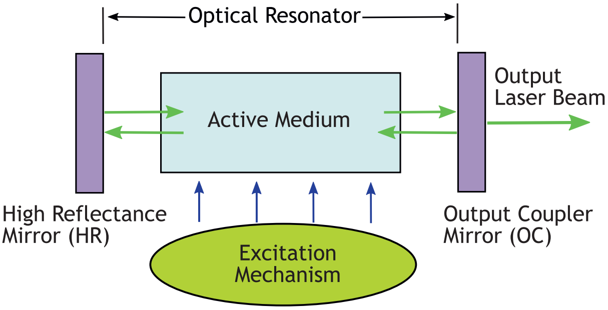

Figure 1.3: Basic components of a laser.

source (pump), and (iii) reflecting mirrors (resonator) as shown in the Fig. 1.3. In this section, a brief description of these components is provided.

### 1.3.2 Active medium

The medium where population inversion can be achieved is known as the 'active medium'. It is a state of inverted population of atoms or molecules satisfying the condition $N_2 > N_1$. The two states should be carefully chosen for the lasing action must possess certain unique characteristics. Firstly, the upper lasing level should have a relatively long life time to sustain population inversion condition and not lose the excitation by spontaneous emission. Secondly, there exists an effective method of 'pumping' atoms or molecules that is required to populate the upper lasing level to create population inversion. Thirdly, a mechanism is needed to depopulate the lower lasing level effectively so that inversion can be maintained. The active medium of a laser is considered to be an 'optical amplifier'. The name signifies that the coherent light is getting amplified with enhanced intensity on passing through the active medium by the process of stimulated emission. In this way, the active medium provides optical gain. It is to be noted that the active medium could be solid, liquid, or gas.

### 1.3.3 Pumping mechanism

In the pumping mechanism, excitation energy pumps the atoms or molecules in the active medium from the ground state to the excited state to create a population inversion. The methods commonly used for pumping are as follows:

#### Optical pumping (Excitation by photons)

When an appropriate light source shines on a medium, the ground state atoms absorb these radiations and jump to the higher energy state. This process of excitation is commonly known as 'Optical pumping'. The optical source could be a broadband source, e.g., a flash lamp is used for pumping ruby/Nd-YAG lasers or a coherent source like laser, e.g., diode laser pumps a solid state laser, $CO_2$ laser pumps an $NH_3$ laser.

#### Electrical discharge (Excitation by electrons)

An electrical discharge tube is used to produce the electrons. The electrons which are accelerated in the electric field transfer part of their energy to the gas atoms or molecules through inelastic collisions thereby exciting them to higher energy states. This results in population inversion. This pumping method is effectively employed in gas lasers, viz., argon ion laser, $CO_2$ laser, excimer laser etc.

#### Direct conversion method

This method is commonly used in the semiconductor like GaAs where the recombination of electrons and holes takes place by applying the electrical energy across direct band gap. In this above mentioned recombination process, the direct conversion of the electrical energy to the light energy has been made possible.

### 1.3.4 Optical resonators (Reflecting mirrors)

Feedback mechanism is essential for further amplification of the light by stimulated emission. Here, a part of the originally produced coherent light is reflected back and forth in the active medium. The degree of population inversion and the strength of the stimulating signal determine the amount of the coherent light produced. In general, the feedback mechanism consists of two mirrors of which one is highly reflecting (HR) mirror while the other is the partially transmitting mirror known as output coupler (OC). The HR and OC are fixed at the opposite ends of the active medium. They are so aligned that they reflect the coherent light back and forth in the active medium (Fig. 1.3). The laser, a part of the oscillating radiation flux emanates in the form of a highly directional beam through the OC. The resonator cavity not only allows efficient utilisation of the population inversion inside the cavity but also renders the output more directional and monochromatic.

## 1.4 Number of Energy Levels

### 1.4.1 Two-level systems

In reality, it has not been possible to make a working laser based on only absorption and emission processes between merely two energy levels as shown in the Fig. 1.1. It is already seen that the Einstein's B coefficients for absorption and emission are equal for a pair of energy levels. Hence once the population of the two levels becomes equal, it is easy to understand that the rate of absorption and emission are equal. Therefore, steady state population inversion cannot be achieved except under special conditions as in excimer lasers where the lower level is unstable.

### 1.4.2 Three-level systems

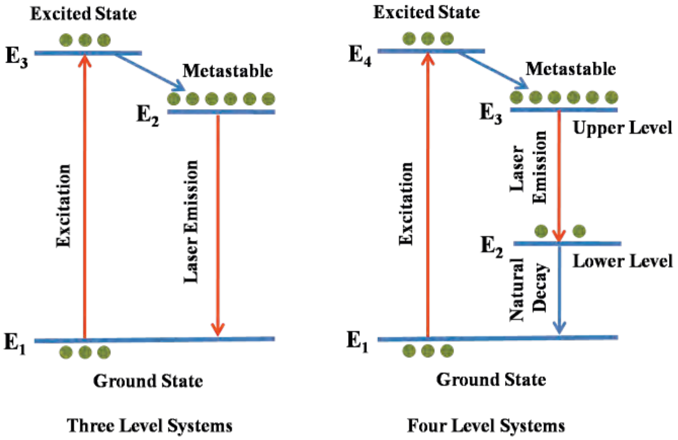

Figure 1.4: Pictorial representation of three-level and four-level laser systems.

Here, the pump excites the atoms from the ground level 1 ($E_1$) to the excited level 3 ($E_3$) from which they undergo fast decay to level 2 ($E_2$) through non-radiative process as shown in the Fig. 1.4. The upper lasing level is higher level 2 ($E_2$) while the lower lasing level is the ground level 1 ($E_1$). Laser emission occurs between the metastable state ($E_2$) and the ground state ($E_1$). Since the ground level $E_1$ is also the lower lasing level, therefore, more than 50% of the ground state atoms must be lifted to the upper lasing level in order to obtain the population inversion. Ruby laser, the first laser to be demonstrated, is a 3-level system.

### 1.4.3 Four-level systems

Most of the lasers utilise the principle of four level system as depicted in Fig. 1.4. Level 1 ($E_1$) is the ground state while the levels 2 ($E_2$), 3 ($E_3$), 4 ($E_4$) are the excited states of the system. The atoms present in $E_1$ are effectively pumped to $E_4$, from which they undergo a rapid non-radiative transition (relaxation) to $E_3$ (upper lasing level). In general, $E_3$ is considered to be a metastable level possessing a long lifetime. Transition from $E_3$ to $E_2$ forms the laser transition. In order to sustain a population inversion between $E_3$ and $E_2$, level 2 ($E_2$) must possess a very short lifetime so that the atoms are quickly removed from $E_2$ to $E_1$ and are available to contribute to the process of lasing once again. If the relaxation rate from $E_2$ to $E_1$ is faster than the rate of arrival of the atoms to $E_2$, then the population inversion between $E_3$ and $E_2$ will be easily achieved even for very small pump powers. Most of the efficient lasers, e.g., $CO_2$ laser, Nd-YAG laser etc are 4-level systems.

## 1.5 Properties of Laser Light

Unlike any other ordinary source of light, since all the excited atoms or molecules are forced to emit identical photons in the same direction making laser a unique source of light. Laser light is distinguished from the conventional light source based on the following unique characteristics [5]:

- Monochromaticity;
- Coherence;
- Directionality;
- High intensity;
- Brightness;
- Tunability;
- Short pulse operation capability.

### 1.5.1 Monochromaticity

Monochromaticity of a light source is a measure of smallness of its spectral width. The spectral width is described as the full width at half maximum (FWHM) and represented by '$\Delta\lambda$'. If $\Delta\lambda$ is very small, the laser is said to be highly monochromatic. Depending on the operating pressure, levels participating in lasing action, their broadening, and the losses in the cavity, some lasers are inherently highly monochromatic while some are not, e.g., $\Delta\lambda$ for He-Ne laser is $\sim$0.02 Å while that for Nd-glass laser is $\sim$100 Å, etc. However, the emission can be made more monochromatic through additional intracavity optics like grating prism, etalon etc. Due to its monochromatic nature, the lasers are extensively used in the laser isotope separation process, scattering experiments, etc.

### 1.5.2 Coherence (Temporal and Spatial)

In case of ordinary source of light, the different waves in a beam do not bear a specific phase relationship with one another. This light is said to be 'incoherent' having no internal order as shown in the Fig. 1.5. In contrast, in the laser light, all the individual waves are 'in-phase' relationship with one another at every instant and every point of space. The in-phase property of light waves within a beam can be best described as 'Coherence' as depicted in the Fig. 1.5. Needless to mention, coherence is the most fundamental and unique property of laser light which make it distinct from any the other sources of light. There exists two types of coherence, viz., temporal and spatial. Temporal coherence is associated with the phase-correlation of waves at a given point in space at two different instants of time. In contrast,

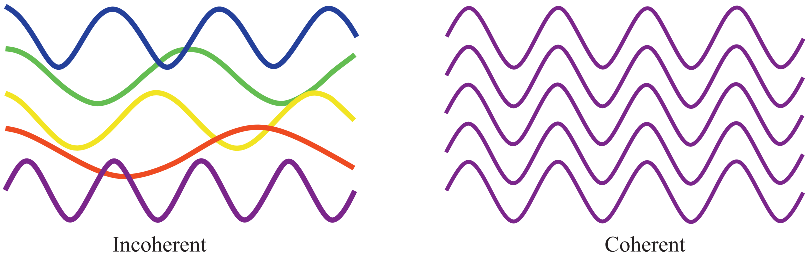

Figure 1.5: Graphical representation of incoherent and coherent light waves.

the spatial coherence is defined as the phase-correlation of two different points across a wave front at a given instant of time. Temporal coherence is related to the frequency, i.e., spectral band width of the source. Light will be temporally coherent if it approximates to a single frequency. On the contrary, spatial coherence is related to the beam-size. If the light approaches to a point source, then it is said to be greater spatial coherence.

### 1.5.3 Directionality (Divergence)

In general, the conventional light sources emit light that spreads out in all the directions in $4\pi$ solid angle while laser emission is highly directional. The inherent nature of stimulated emission coupled with the effect of a cavity causes the emission of a laser to travel in the same direction within a very narrow cone of divergence. A laser beam, therefore, can be focussed to a very small spot thereby greatly increasing its intensity. Although the divergence of a laser beam is extremely small, it is limited by the inherent property of light viz., diffraction, as it traverses through an aperture. The divergence of a Gaussian shaped laser beam (in radians) is given by the following equation:

$$\theta = \ 1.27\,\frac{\lambda}{d} \tag{1.7}$$

Here, $\theta$ is the divergence of the laser beam, '$\lambda$' is the wavelength of the laser, and 'd' is the effective aperture of the output coupler.

### 1.5.4 High intensity

Intensity (I) is defined as the power (P) per unit area (A):

$$I = \frac{P}{A} \quad \left(W\ cm^{-2}\right) \tag{1.8}$$

Small divergence means that the light can be focused to a very small spot. Therefore, the directional property of the laser beam makes it a highly intense source of light.

### 1.5.5 Brightness

Brightness depends on the intensity of the source and the extent to which the light spreads out after it leaves the source. The spreading out of light is measured in terms of solid angle formed by the light leaving the source. In laser technology, brightness (B) of an optical source is defined as power emitted (P) per unit area of the light source ($A_{source}$) per unit solid angle ($\phi$).

$$B = \frac{P}{A_{source} \times \phi} \left(W cm^{-2} sr\right) \tag{1.9}$$

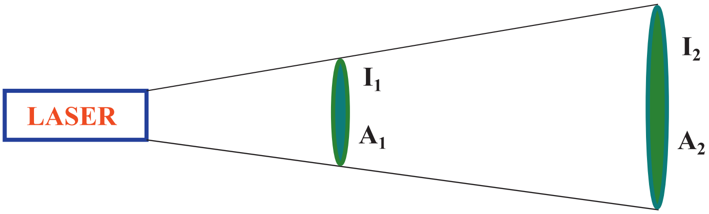

Figure 1.6: Pictorial representation of brightness and intensity.

While brightness and intensity appear synonymous, it has to be understood that brightness is a property of the source itself and does not depend upon the distance from it. In contrast, the intensity of light not only depends on the characteristics of the source but also depends on the distance of the point from the source. From the Fig. 1.6, it is quite evident that the intensity at two different points is different ($I_1 > I_2$) while the brightness is same on those points since brightness is independent of the distance.

### 1.5.6 Tunability

In general, depending on the lasing transitions involved, the laser emits on a predecided wavelength. However, some lasers can be tuned in certain range of wavelengths. There are two types of tuning, viz., line tuning and continuous tuning. Line tuning lasers are those that can be made to emit on discrete frequencies, e.g., Argon ion laser, $CO_2$ laser, etc. On the contrary, few lasers can be tuned over a continuous band of frequencies, e.g., dye lasers, Ti-sapphire solid state laser, etc.

### 1.5.7 Short pulse duration

Laser emission can be in the form of short pulses in the range of nano-, pico-, femto- and even atto- second time scales. There are various methods to obtain the short pulses, e.g., 'Q-switching' is used to produce nano-second pulses, 'Mode Locking' is used for the production of pico- and femto-second pulses. The short pulses provide high peak power which is useful in nonlinear frequency mixing techniques for the generation of various frequencies. These ultra-short pulses can be readily used to study the transient (transition state) species involved in a chemical reaction in real time.

## 1.6 Types of Lasers

There are several ways to classify lasers based on different criteria listed in Table 1.1. Al-

Table 1.1: Classification of lasers based on various parameters.

| **Active Medium** | **Spectral Range of $\lambda$s** | **Pumping** | **Characteristics of Laser** | **Number of Energy Levels** |
|---|---|---|---|---|
| • Gas<br>• Liquid<br>• Solid<br>• Semi-conductor | • Infra-red<br>• Visible<br>• UV | • Optical<br>• Electrical<br>• Chemical | • Continuous<br>• Pulsed | • Two<br>• Three<br>• Four |

though lasers can be categorised in several types, here the different type of lasers are classified based on the nature of active medium, viz., gas, liquid, solid, semiconductor, etc.

## 1.6.1 Gas lasers

Active Laser Medium, Gas or Vapour [6]:

i. Molecular gas Lasers: $CO_2$, $N_2$, CO, etc.

ii. Neutral Atom Lasers: He-Ne, Metal vapour (Cu, Au, etc.) etc.

iii. Excimer Lasers: KrF, XeCl, etc.

iv. Ion Lasers: $Ar^+$, $Kr^+$, etc.

Gas as an active medium has the following characteristic features:

- Low number density that leads to very low population inversion than solids, e.g., $\sim 10^{21}$ atoms/cc in He-Ne whereas $\sim 10^{25}$ $Nd^{3+}$ ions/cc in Nd-YAG
- Much more homogeneous than solids
- Can be readily circulated for cooling and replacement purposes
- Narrow emission line-width

Pumping is generally accomplished by

a) Excitation in an electrical discharge

b) Gas dynamic expansion

c) Chemical pumping

d) Optical pumping by means of another laser

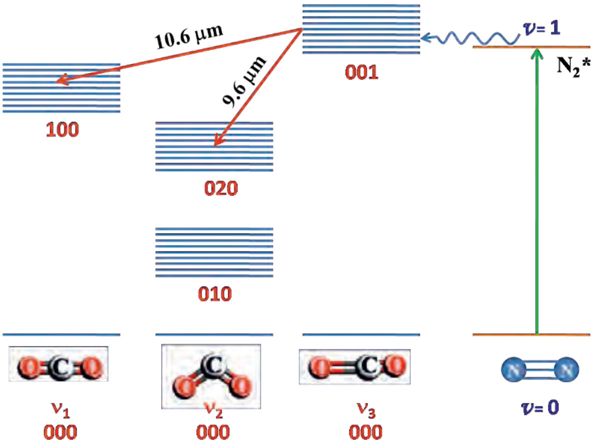

Figure 1.7: Energy level diagram of a $CO_2$ laser.

Figure 1.7 depicts the energy level diagram for the $CO_2$ laser emission. Characteristic features of various gas lasers along with their most important applications are listed in the table 1.2.

Table 1.2: Characteristic features of various gas lasers and their important applications.

| **Gas Lasers** | **No. of Levels** | **Pumping** | **Active Medium** | **Output $\lambda$ ($\mu$m)** | **Output Power** | **Application** |
|---|---|---|---|---|---|---|
| $CO_2$ | Four | Electrical | $CO_2$:$N_2$: He = 1:1:8 | 10.6 & 9.6 | 0.1 – 150 W | Material processing, industrial |
| CO | Four | Electrical | CO & He | 5.2 – 6.0 | > 1 W | Spectroscopy, plasma density measure. |
| $NH_3$ | Three | $CO_2$ Laser | $NH_3$, He & $CO_2$ | 11–13 | 2 W | Medical, expt. |
| p-$H_2$ Raman | Three | $CO_2$ Laser | p-$H_2$, He & $CO_2$ | ∼16 | 30 MW | Spectroscopy, MLIS. |
| $CF_4$ | Three | $CO_2$ Laser | $CF_4$, He & $CO_2$ | ∼16 | ∼1 mW | Spectroscopy, MLIS. |
| He-Ne | Four | Electrical | He:Ne = 5:1 or 9:1 | 0.6328 | 0.5 – 50 mW | Alignments, scanners, pointer. |
| $Ar^+$ | Four | Electrical | Ar | 0.514 & 0.488 | 1 – 20 W | Holography, eye surgery, light shows. |
| Cu vapour | Three | Electrical | Cu:Ne = 1:500 | 0.578 & 0.510 | 10 – 40 W | Machining, industrial, AVLIS. |
| Au vapour | Three | Electrical | Au:Ne = 1:500 | 0.628 & 0.312 | 10 – 40 W | Photodynamic therapy, dermatology. |
| $N_2$ | Four | Electrical | $N_2$ = 20 torr – 1 atm | 0.3371 | 10 kW – 2.5 MW | Pumping dye lasers, fluorescence measurements. |
| $H_2$ | Three | Electrical | $H_2$ | 0.60 & 0.116 | 100 kW | Spectroscopy, expt. |
| ArF | Two | Electrical | Ar & $F_2$ | 0.193 | ∼1 GW | Medical, industry |
| ArCl | - do - | - do - | Ar & $Cl_2$ | 0.175 | - do - | - do - |
| $Ar_2$ | - do - | - do - | Ar > 10 atm | 0.126 | - do - | - do - |
| KrF | - do - | - do - | Kr & $F_2$ | 0.248 | - do - | - do - |
| KrCl | - do - | - do - | Kr & $Cl_2$ | 0.223 | - do - | - do - |
| XeF | - do - | - do - | Xe & $F_2$ | 0.351 | - do - | - do - |
| XeCl | - do - | - do - | Xe & $Cl_2$ | 0.308 | - do - | - do - |
| XeBr | - do - | - do - | Xe & $Br_2$ | 0.282 | - do - | - do - |
| $Xe_2$ | - do - | - do - | Xe > 10 atm | 0.172 | - do - | - do - |

## 1.6.2 Liquid lasers

### Chelate lasers

In 1965, Lempicki et al. [7] reported first successful liquid laser, $EuB_4P$, an europium chelate prepared with benzoylacetonate and dissolved in alcohol to give a europium concentration of 1.2 x$10^{19}$ centres cm$^{-3}$. Pumping energy was supplied by a conventional spiral flash tube surrounding the resonator. This liquid laser emitted a radiation of wavelength 613.0 nm (orange colour) with an output energy of ∼30 mJ $cm^{-3}$

### Dye lasers

Dye lasers [8] basically use a liquid laser medium where a complex organic dye is dissolved or suspended. In this laser, the organic dye dissolved in a suitable liquid such as ethanol, methanol, toluene, benzene, acetone, water, etc. is used as an active medium. The most effective dyes are classified into several groups where the lasing range varies from 0.3 – 1.3 $\mu$m. The most important feature of the dye laser is its 'tunability'. Owing to a wide range of wavelengths in the visible light, the tunable dye lasers are now extensively used in high resolution atomic and molecular spectroscopy. Optical pumping using a flash lamp or another laser is considered to be the most common method for the excitation processes for the dye lasers, e.g., Argon-ion, nitrogen laser, Second harmonic of a YAG laser, etc. A tunability over 100 nm bandwidth in the red region (620 nm) of the spectrum makes versatile application of the Rhodamine 6G dye. The lasing action taken place between $S_1$ and $S_0$ levels in the four level dye lasers whose energy diagram is shown in the Fig. 1.8. It is extensively used in spectroscopy, AVLIS process, etc. ***Dye as an active medium has the following unique features:***

a) Much more homogeneous than solids;
b) Easily circulated for cooling and replacement purposes;
c) Broad absorption band – efficient optical pumping;
d) High quantum yield of fluorescence;
e) No overlap between the absorption and emission band.

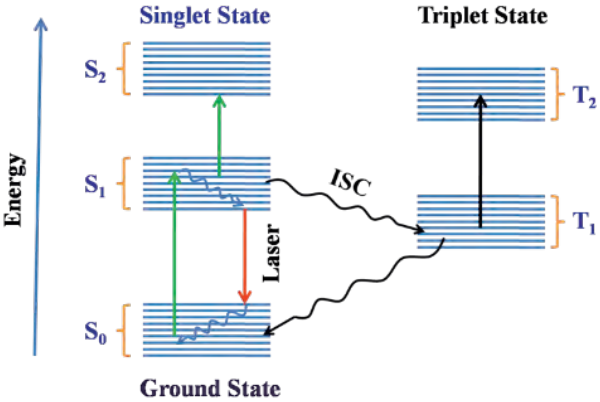

Figure 1.8: Energy profile diagram of dye laser.

### 1.6.3 Solid lasers

In the solid state lasers [9], the active medium is usually a solid. It may be a solid rod or a crystalline insulator slab with a small amount of doped impurity. It is to be noted that the impurity constituent only provides the required energy structure to produce laser action. On the other hand, the overall energy structure is strongly influenced by the crystalline lattice primarily known as a 'host' material. It is sometimes called as 'doped insulator laser' in order to differentiate it from the 'semiconductor laser'.

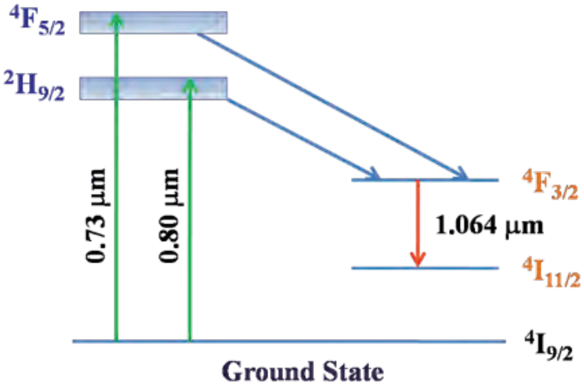

Figure 1.9: Energy level diagram of the Nd:YAG laser.

***Requirements of the host materials*:**

- Absence of refractive index variation to have good beam quality
- Resistance to radiation induced colour centres
- Good mechanical and thermal properties to withstand in thermal operational load
- Hardness and chemical inertness
- Must accept or accommodate dopant ions having local crystal field of symmetry

***Types of the host materials:***

- Glass; Crystals: Sapphire ($Al_2O_3$), Garnets (Yttrium aluminium, $Y_3Al_5O_{12}$, YAG)

***Active dopant ions:***

- The growth of the impurity doped crystal must be possible performing high optical quality and high yield; Two types of dopant ions: (i) Transition Metal Ions: $\mathrm{Cr}^{3+}$, $\mathrm{Ti}^{3+}$, etc. (ii) Rare Earth Ions: $\mathrm{Nd}^{3+}$, $\mathrm{Er}^{3+}$, etc.

In the table 1.3, the unique properties of various solid state lasers with their applications are listed. For an example, the energy level diagrams of the Nd:YAG laser is depicted in Fig. 1.9. In this four level laser system, $\mathrm{Nd}^{3+}$ ion is incorporated in the YAG lattice. Basically, the excitation is possible from the ground level ($^4I_{9/2}$) to the excited level ($^4F_{5/2}$) through the optical pumping either by W or Kr flash lamps. Fluorescence occurs from the metastable upper lasing level ($^4F_{3/2}$) to the lower lasing level ($^4I_{11/2}$) with the emission of 1.064 $\mu$m IR laser beam.

### 1.6.4 Semiconductor lasers

Semiconductor lasers are occasionally referred as diode lasers. Semiconductor devices usually contain two layers of materials sandwiched together. These are basically very small in dimension producing modest power and can be built into larger arrays. Laser diodes are extensively used for optical communications, in compact disc (CD) players, retail scanners, printers, medical, distance detectors, remote sensing system, range finders, etc. Semiconductor laser diodes [10] are pumped by an externally applied current. Various types of diode lasers operate in range of spectrum from IR to visible wavelengths with the power from mW to W. The wavelengths can be tuned by altering the applied current, temperature, or external magnetic field. The most commonly used diodes are given below.

Table 1.3: Unique properties of various solid state lasers and their important applications.

| **No. of Levels** | **Pumping** | **Host Material** | **Dopant Ions** | **Output $\lambda$ ($\mu$m)** | **Application** |
|---|---|---|---|---|---|
| Three | Flash tube | Sapphire ($Al_2O_3$) | Cr$^{3+}$ | 0.6943 | Range finding, industrial |
| Four | Ar-ion or second harmonic of Nd:YAG | Sapphire ($Al_2O_3$) | Ti$^{3+}$ | ∼0.800 | Nuclear fusion, industry |
| Four | W or Kr lamps, diode laser | YAG ($Y_3Al_5O_{12}$) | Nd$^{3+}$ | 1.064 | Spectroscopy, plasma density measure., etc. |
| Four | Flash lamp, diode laser | Silicate ($SiO_2$) | Nd$^{3+}$ | 1.062 | Range finding, nuclear fusion, medical |
| Four | Flash lamp, diode laser | Phosphate ($P_2O_5$) | Nd$^{3+}$ | 1.054 | |
| Four | Diode laser | Calcium fluoride (CaF$_2$ ) | U$^{3+}$ | 2.42 & 2.49 | Defence, industry |
| Three | Diode laser | Calcium fluoride (Ca$F_2$) | Yb$^{3+}$ | 1.015 –1.060 | Defence, industry |

- GaAs laser diode emits 840 nm IR beam
- Alloy of GaAs and GaP provides an emission at ∼650.0 nm in visible red spectrum
- PbSe diode laser emits IR radiation in the range of 8–14 $\mu$m
- Single crystal $Pb_{1-x}Sn_xTe$ diode lasers emit mid-IR radiation in the range of 5-25 $\mu$m

## 1.6.5 Other lasers

In addition of the above mentioned lasers, there are few different classes of lasers. These lasers are found to be more interesting and challenging to construct. A brief overview of chemical lasers, free electron lasers (FELs), and X-ray lasers are discussed here.

### Chemical lasers

It is named as ‘chemical laser’ [11] because the population inversion is achieved by way of chemical reaction. It becomes increasingly important due to its unique properties:

- Operates in both CW and pulsed mode
- Emits shorter IR wavelengths 3–4 $\mu$m
- Higher power density and high operating efficiency

It has following four elements in common:

- System for mixing gases
- Method of instigating chemical reaction
- Initiation and sustain of lasing action in the optical cavity
- Spent reactant gases removal from the resonator through the exhaust and vent system

The chemical reactions that are most promising for laser action are exothermic in nature: $A+BC \rightarrow AB{*}+C$. In the above chemical reaction, the product (AB*) is born excited which is suitable for laser action while the lower state of such a molecule is practically empty. The chemical reaction is intrinsically supplying energy for its own pumping. Hence, a chemical reaction could be extremely efficient for achieving a very high population inversion. Various available chemical lasers are listed in table 1.4.

Table 1.4: Important parameters of various chemical lasers.

| **Chemical Lasers** | **Pumping** | **Gas Mixtures** | **Output $\lambda$s ($\mu$m)** | **Chemical Reactions** |
|---|---|---|---|---|
| HF Laser | Electrical | $H_2$, $F_2$ & $SF_6$ | 2.6 to 3.6 | $SF_6 + e \rightarrow SF_5 + F + e$<br>$F + H_2 \rightarrow H + HF^*$<br>$H + F_2 \rightarrow F + HF^*$ |
| HCl Laser | Electrical | $H_2$, & $Cl_2$ | 3.77 | $H_2 + e \rightarrow 2H + e$<br>$H + Cl_2 \rightarrow Cl + HCl^*$<br>$Cl + H_2 \rightarrow H + HCl^*$ |
| DF-$CO_2$ Laser | Electrical | $D_2$, $F_2$, $CO_2$& NO | 9.6 – 10.6<br>($CO_2$ Laser Emission) | $NO + F_2 \rightarrow NOF + F$<br>$F + D_2 \rightarrow D + DF^*$<br>$D + F_2 \rightarrow F + DF^*$<br>$DF^* + CO_2 \rightarrow CO_2^* + DF$ |
| CO Chemical Laser | Electrical | O & $CS_2$ | 1.8 & 2.6 (CO Emission) | $O + CS_2 \rightarrow CO^*$ |
| Bromine Laser | Electrical | $I_2$ & $Br_2$ | 2.713 | $I_2 + e \rightarrow 2I^* + e$<br>$I^* + Br_2 \rightarrow Br^* + IBr$<br>$I^* + IBr \rightarrow Br^* + I_2$ |

### Free electron lasers

A fourth generation laser is the FEL which is a synchrotron light source. It emits very short and bright pulses of synchrotron radiation. Instead of atomic and molecular systems, the relativistic electrons are used as a gain medium in the free electron laser [12]. In general, a synchrotron radiation is produced when a bunch of electrons pass through a periodic arrangement of magnets popularly known as ‘undulator’ or ‘wiggler’ as shown in the Fig. 1.10. In FEL, the coherent source of laser beam is generated when this synchrotron radiation re-interacts with the relativistic electron resulting in an exponential rise in the overall intensity. Since the kinetic energy of the relativistic electrons can be changed by varying the undulator parameters, the FEL lasers could be tuned for a wide range of frequencies from microwave to X-rays with variable energies. In this context, it is to be noted that the first FEL was developed by Madey in 1971 at Stanford University using an undulator which was built by Motz in 1953.

### X-ray lasers

An X-ray laser [3] generates an electromagnetic radiation ($\lambda \sim$few 10s of nm) in the range of near X-ray to far UV region of spectrum by using the principle of stimulated emission. Here, the active medium is highly ionised plasma which has a very short existence. The plasma is produced by depositing enough energy into a solid to vaporize and subsequently ionize it. It emits X-rays, amplifies them by stimulated emission and quickly dissipates. Because of the very high gain, this operates without mirrors producing X-rays by a single pass. The emitted X-rays possess relatively low spatial coherence since it is amplified by spontaneous emission. In 1980s, a nuclear explosion-pumped X-ray laser for ballistic missile defence was attempted to develop by the US military forces. It is also used in various fields including the coherent diffraction imaging, microscopy, plasma physics, medical imaging, etc.

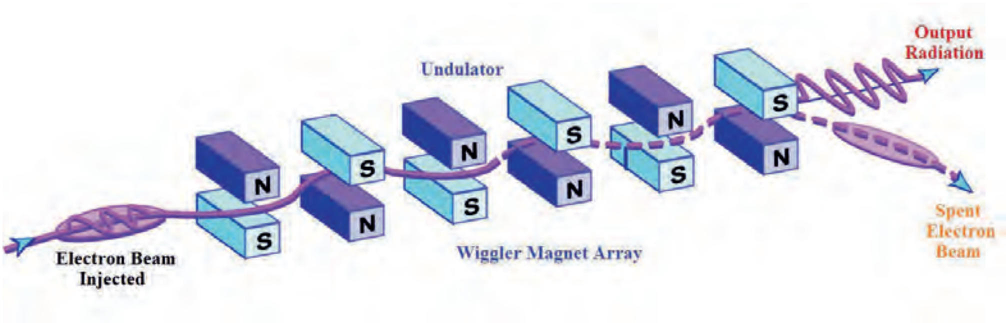

Figure 1.10: Schematic representation of an undulator (the core of FEL).

## 1.7 Summary

Of late, lasers have become an indispensable tool in everyday life. A wide range of applications in diverse fields entices researchers to engage and explore its further development. Although there are numerous lasers covering from X-ray to IR regions of the electromagnetic spectrum, operating in continuous to ultra short pulse regime, the quest for newer lasers and their newer applications still goes on.

### Frequently Asked Questions

Q1. Is it possible to have a two level system of laser?

Q2. What are the basic differences between a laser light and an ordinary light?

Q3. Why stimulated emission should overcome than spontaneous emission in order to obtain a LASER?

Q4. Which gas lasers emit UV radiation and which emits IR light?

Q5. Which lasers are used in decontamination and decommissioning of nuclear reactor?

Q6. What are the advantages of laser compared to the other conventional methods in nuclear industry?

Q7. Is it possible to obtain all range of light spectrum by using a single laser?

Q8. In which lasers the wavelength tuning is feasible?

Q9. What basic properties are important in case of selecting a laser for isotope separation?

Q10. Name some lasers which is used in day-to-day life?