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CHAPTER

Basic Theory

1.1 INTRODUCTION

The word laser is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

Laser is one of the outstanding inventions of the second half of the last century. Laser has become a valuable tool in a variety of fields starting with medicine to communications. Laser is a light source but it is very much different from many of traditional light sources. Laser is not used for illumination purposes as we use the other light sources. Lasers produce a highly directional and high intensity beam with a narrow frequency range than that available from the common types of light sources. They are more widely used as a high power electromagnetic beam rather than a light beam. The laser beams are used as a special type of drill bit to drill holes in hard materials, as a saw to cut thick metal sheets, as a phonograph needle for compact discs, as a knife during surgical operations, as target designators for military weapons and so on. Thus, laser is a high technology device affecting our lives in many ways.

1.2 A BRIEF HISTORY OF THE LASER

Lasers are in fact generators of light. They are based on the amplification of light by means of stimulated radiation of atoms or molecules. In 1917 Einstein predicted the possibility of such stimulated radiation.

In 1952, Ch. Townes, J. Gordon and H. Zeiger in U.S.A. and N. Basov and A. Prokhorov in USSR, independently suggested the principle of generating and amplifying microwave oscillations based on the concept of stimulated radiation. It lead to the invention of MASER (Microwave Amplification by Stimulated Emission of Radiation) in 1954. MASERS used a two-level system. In 1955, Basov and Prokhonov suggested use of three-level system.

In 1958, Townes and Schawlow and Basov and Prokhorov independently expressed their ideas about extending the maser concept to optical frequencies. They developed the concept of an optical amplifier surrounded by an optical mirror resonant cavity to allow for growth of the beam. Townes, Basov and Prokhorov both received Nobel Prizes for their work in this field.

In 1960, Theodore Maiman of Hughes Research Laboratories produced the first laser using a ruby crystal as the amplifier and a flashlamp as the energy source. The helical flashlamp surrounded a rod-shaped ruby crystal, and the optical cavity was formed by coating the flattened ends of the rudy rod with a highly reflecting material. An intense red beam was observed to emerge from the end of the rod when the flashlamp was fired.

The first gas laser was developed in 1961 by A. Javan, W. Bennett, and D. Harriott of Bell Laboratories, using a mixture of helium and neon gases. At the same laboratories, L.F. Johnson and K. Nassau demonstrated the first neodymium laser, which has since become one of the most reliable lasers available. This was followed in 1962 by the first semiconductor laser, demonstrated by R. Hall at the General Electric Research Laboratories. Table 1.1 gives the major landmarks in the development of lasers.

TABLE 1.1

MAJOR LANDMARKS IN THE DEVELOPMENT OF LASERS

Year	*Discoverer*	*Type of Laser/Principle*
1917	Albert Einstein	Stimulated Emission Process
1952	N.G. Basov, A.M. Prokhorov and Townes	Maser Principle
1954	Townes, Gordon, Zeiger	Maser
1958	Townes, Schawlow, Basov, Prokhorov	Laser Principle
1960	Theodore Maiman	Ruby Laser
1961	A. Javan, W. Bennett and D. Harriott	Helium-Neon Laser
1961	L.F. Johnson and K. Nassau	Neodymium Laser
1962	R.Hall	Semiconductor Laser
1963	C.K.N. Patel	Carbon dioxide Laser
1964	W. Bridges	Argon Ion Laser
1966	W. Silfvast, G.R. Fowles, and B.D. Hopkins	He-Cd Laser
1966	P.P. Sorokin and J.R. Lankard	Tunable Dye Laser
1975	J.J. Ewing and C. Brau	Excimer Laser
1976	J.M.J. Madey and coworkers	Free-electron Laser
1979	Walling and coworkers	Alexandrite Laser
1985	D.Mathews and coworkers	X-ray Laser

Difference between laser and ordinary light beam.

Laser light differs from ordinary light is following respects:

(*i*) Laser beam is highly monochromatic.

(*ii*) It travels as a highly concentrated parallel beam along a particular direction.

(*iii*) Laser beam is highly coherent with all the waves exactly in phase with each other and in the same state of polarization. The beam has both spatial and temporal coherence.

On the other hand-

(*i*) Ordinary light is not monochromatic. Light spectrum from a source may extend over a wide range of wavelength.

(*ii*) The light from an ordinary source travels and spreads in all directions.

(*iii*) Ordinary light is incoherent *i.e.*, there is a wide phase difference between the light observed at a point at different times and at different points in space.

Directionality, monochromacity, intensity and coherence are the peculiar properties of laser beam (see details in chapter 3).

1.3 INTERACTION OF LIGHT AND MATTER

Light is a form of radiant energy. Different hypotheses were put forward at different stages regarding the nature of light. Newton considered light as a stream of corpuscles while Huygens regarded light as made up of waves. Maxwell established that light belongs to the group of electromagnetic waves which propagate at a speed '*c*' in a vacuum. The frequency and the wavelength of the light wave are related to *c* through the expression

$$\boxed{c = \nu\lambda} \qquad \text{...(1.1)}$$

It is implicit in this visualization that light waves are continuous; are of infinite extension; and could carry any arbitrary amounts of energy.

When light is incident on a substance, there may occur reflection, transmission, absorption and scattering ~~of light~~ to varying degrees depending on the nature of the substance.

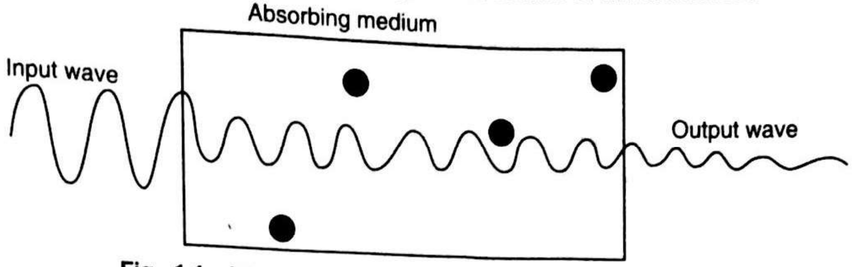

Fig. 1.1. Attenuation of a light wave in an absorbing medium.

A light wave incident on a transparent solid induces periodic oscillations of orbital electrons in step with its own frequency. The oscillating electrons act as point sources and emit waves in all directions. If the medium is homogeneous, the secondary waves destroy one another in all directions except in the direction of propagation of the incident wave. The resultant beam will have maximum intensity in that direction and constitutes the transmitted beam.

Part of the incident light energy gets transformed into the energy of motion of the atoms in the solid. It leads to a loss of energy and as a result, the light intensity decreases with distance in the solid as shown in Fig. 1.1. We say in this case that the medium absorbs light. The reduction in intensity of light with increasing length of propagation in a medium is called *absorption* or *attenuation* of light. We can describe the attenuation of light in an optical medium with the help of absorption coefficient α.

When a beam of light passes through a thin section *dx* of a transparent material (Fig. 1.2), let the decrease in intensity of the light be *dI*. It is found that *dI* is proportional to the initial intensity of light, *I*, and to the thickness of the medium, *dx*. Thus,

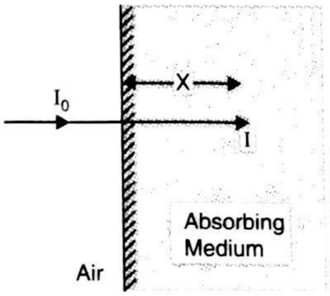

Fig. 1.2. Absorption of light in a medium.

$$dI = -\alpha I \, dx \qquad \text{...(1.2)}$$

where α is the constant of proportionality. It is called the *coefficient of absorption* (the fraction of light absorbed per unit length) of the optical medium. The negative sign indicates that the intensity decreases with distance. We can rearrange Eq. (1.2) as

$$\frac{dI}{I} = -\alpha \, dx \qquad \text{...(1.3)}$$

The total loss in light intensity after passing through a distance x in the medium is obtained by integrating Eq. (1.3). Thus, if I_0 is the value of intensity at $x = 0$, the value of the intensity I at a distance x is

$$\int_{I_0}^{I} \frac{dI}{I} = -\alpha \int_0^x dx$$

$$\ln \frac{I}{I_0} = \alpha x$$

or

$$\boxed{I = I_0 e^{-\alpha x}} \qquad \text{...(1.4)}$$

Eq. (1.4) shows that light intensity decreases exponentially with distance in the medium.

When a light beam encounters obstacles which have sizes smaller than a wavelength ($d << \lambda$), it is redirected into different directions. We say light is *scattered* by the obstacle. Scattering phenomenon also causes attenuation of energy because part of the light energy is lost from the original beam. Scattering effects are described by an exponential law that is much similar in form to Eq.(1.4).

$$I = I_0 e^{-\alpha_s x} \quad ...(1.5)$$

where α_s is the *scattering coefficient.*

By designating attenuation coefficient due to absorption as α_a, we combine equations (1.4) and (1.5) as

$$I = I_0 e^{-(\alpha_a + \alpha_s) x} \quad ...(1.6)$$

Eq. (1.6) describes attenuation of light due to both absorption and scattering effects.

1.4 A BRIEF HISTORY OF QUANTUM THEORY

Phenomena such as motions of mechanical objects involving distances larger than about 10^{-6}m can be explained satisfactorily by applying the laws of classical theoretical physics which is based on the following basic laws:

(*i*) Newton's laws of motion,

(*ii*) Newton'a law of gravitational attraction,

(*iii*) Coulomb's inverse square law of attraction or repulsion between two electrically charged bodies,

(*iv*) Law of force on a moving chanrge in a magnetic field, *i.e.*, the Lorentz force.

However, certain phenomena such as spectral distribution of energy in black body radiation, photo-electric effect etc., and phenomena involving distances of the order of 10^{-10} could not be explained by classical physics. The failure of classical physics to explain above facts. particularly to expalin energy distibution in the spectrum of a block body led Max Planck to propose the *quantum hypothesis* in 1900 and this was the origin of quantum theory.

1.5 PLANCK'S QUANTUM THEORY

In 1900, Max Planck proposed that light consists of discrete bundles or chunks of energy. The amount of energy of each bundle is "$h\nu$". These bundles of radiant energy are called *quanta*. In 1905, Einstein refined the quantum hypothesis of Planck and provided theoretical justification for the features of photoelectric effect. He gave the name *photon* to the quantum of light energy.

A photon represents the minimum energy unit of light. It is localized in a small volume of space and remains localized as it moves away from the light source. Each photon carries an amount of energy proportional to the frequency of the light wave, as given by

$$\boxed{E = h\nu} \quad ...(1.7)$$

where h is Planck's constant. It is obvious that the higher the frequency of a photon, the more energy it possesses. Thus UV light photons are more energetic than visible light photons.

In the quantum theory of radiation Max Planck assumed that the atoms in the walls of a black body behave like simple harmonic oscillators and each has a characteristic frequency of oscillation. In this theory, he made the following two radical assumptions:

(1) A simple harmonic oscillator can not have any arbitrary values of energy but only those vales of the total energy E that are given by the relation:

$$E = nh\nu \qquad \text{...(1.9}a\text{)}$$

Where $n = 0, 1, 2, \ldots\ldots$, n is called the *quantum number*, ν is the frequency of oscillation and h is a universal constant called Planck's constant ($h = 6.626 \times 10^{-34}$ Js). In this relation $h\nu$ is the basic unit of energy and is called a *quantum of energy*. Thus, the relation shows that the total energy of an oscillator is *quantized.*

(2) As long as the oscillator has energy equal to one of the allowed values given by the relation $E = nh\nu$, it can not emit or absorb energy. Therefore, the oscillator is said to be in a stationary state or a quantum state of energy. *The emission or absorption of energy occurs only when the oscillator jumps from one energy state to another.* If the oscillator jumps down from a higher energy state of quantum number n_2 to a lower energy state of quantum number n_1, the energy *emitted* is given by

$$E_2 - E_1 = (n_2 - n_1)h\nu \qquad \text{...(1.9}b\text{)}$$

if $n_2 - n_1$ = one unit, then $E_2 - E_1 = h\nu$

Similarly an oscillator *absorbs* a quantum $h\nu$ of energy when it jumps to its higher energy state.

According to Planck, the quantum theory is applicable only to the process of emission and absorption of radiant energy.

In 1905, Einstein extended Planck's quantum theory by assuming that a monochromatic radiation of frequency ν consists of a stream of photons each of energy $h\nu$ and the photons travel through space with the speed of light.

The interaction of light with matter is better explained using the concept of the photon rather than by the wave concept. When light interacts with matter, the energy exchange can take place only at certain discrete values for which the photon is the minimum energy unit that light can give or accept.

Photon energy is usually expressed in terms of electron-volts (eV). The photon energy (in eV) corresponding to light of wavelength λ is given by

$$E = \frac{12,400}{\lambda} \qquad \text{...(1.9)}$$

where λ is in Angstrom unit.

The wave picture of light is classical and the photon picture is quantum mechanical.

The laser is inherently a quantum mechanical device because its operation depends on the existence of photons.

Example 1.1. *The He-Ni system is capable of lasing at several different IR wavelengths, the prominent one being 3.3913 μm. Determine the energy difference (in eV) between the upper and lower levels for this wavelength.*

Solution :
$$E = \frac{12400}{\lambda\,(\text{Å})}\,\text{eV} = \frac{12400}{33913\ \text{Å}}\,\text{eV}$$

$$= \mathbf{0.37eV}$$

Example 1.2. *The CO_2 laser is one of the most powerful lasers. The energy difference between the two laser levels is 0.117 eV. Determine the frequency and wavelength of the radiation.*

Solution :
$$\lambda\,(\text{Å}) = \frac{12400}{E(\text{eV})} = \frac{12400}{0.117}$$

or
$$\lambda = 105983\ \text{Å}$$
$$= \mathbf{10.5\ \mu m}$$

$$\therefore \qquad \nu = \frac{c}{\lambda} = \frac{3\times10^{8}\ m/s}{10.5\times10^{-6}\ m} = \mathbf{2.9\times10^{13}\ Hz}$$

Example 1.3. *A pulsed laser is constructed with a ruby crystal as the active element. The ruby rod contains typically a total of 3 × $10^{19}Cr^{3+}$ ions. If the laser emits light at 6943 Å wavelength, find (a) the energy of one emitted photon (in eV) and (b) the total energy available per laser pulse (assuming total population inversion).*

Solution : (*a*) The photon energy in eV is given by

$$E = \frac{12400}{\lambda\ (\text{Å})}\ \text{eV}$$

$$\therefore \qquad E = \frac{12400}{6943\ \text{Å}} = \mathbf{1.79eV}$$

(*b*) Energy per pulse = (Energy of one photon) × (Total number of photons)

= (Energy of one photon) × (Total number of atoms in the excited state)

$$E_T = (1.79\text{eV} \times 1.602 \times 10^{-19}\ \text{J/eV}) \times (3 \times 10^{19})$$
$$= \mathbf{8.6\ J}$$

1.6 PLANCK'S RADIATION LAW

On the basis of quantum theory, Planck obtained the formula for an average energy of an oscillator is

$$E = \frac{h\nu}{e^{h\nu/kT} - 1} \qquad ...(1.10)$$

It can be shown that the number of oscillations or degrees of freedom per unit volume in the frequency range ν and ν + *d*ν and in given by

$$N(\nu)\, d\nu = \frac{8\,\pi\nu^2}{C^3}\, d\nu \qquad ...(1.11)$$

where *c* is the speed of light in vacuum.

Then assuming that the average value of energies of the various modes of oscillations in black body radiation is given by Eq. 1.10, Planck obtained the relation.

$$p_\nu\, d\nu = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{h\nu/kT} - 1}\, d\nu \qquad ...(1.12)$$

Where $p_\nu\, d\nu$ is the energy per unit volume in the frequency range ν and ν + *d*ν and p_ν is the energy per unit volume per unit frequency range at frequency ν.

In terms of wavelength of radiation, the equation is expressed as

$$p_\lambda\, d\lambda = \frac{8\pi hc}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1}\, d\lambda \qquad ...(1.13)$$

Eq. (1.12) and Eq. (1.13) are two forms of Planck's radiation law.

When the values of p_λ as obtained from Eq. (1.13) for different values of λ are plotted against the corresponding values of λ, we get curves as shown in fig. (1.3).

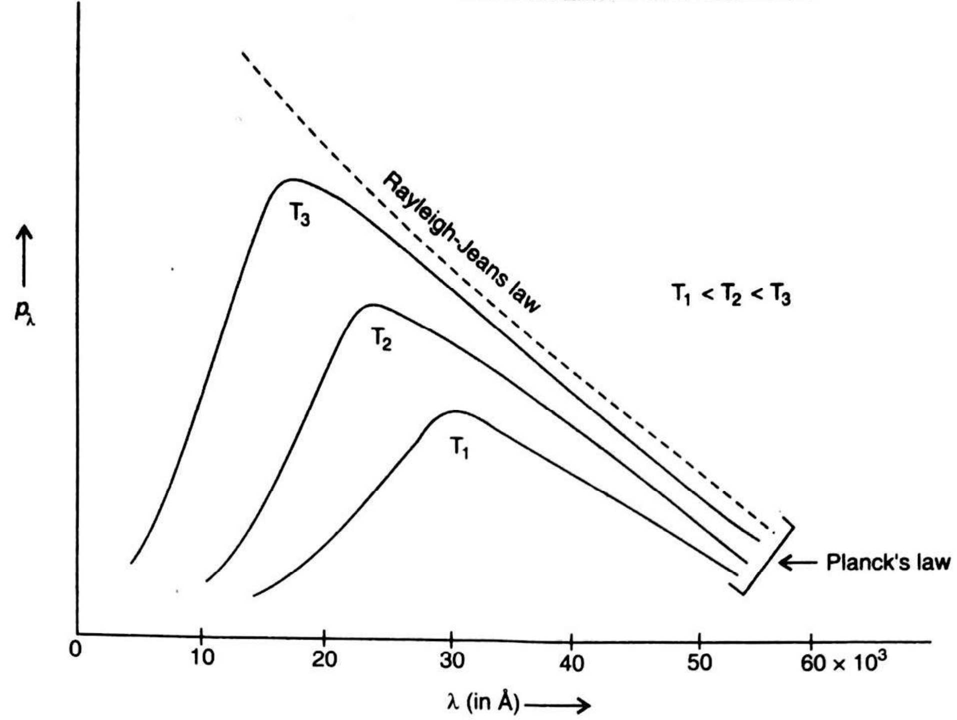

Fig. 1.3

These curves obtained for temperatures T_1, T_2 and T_3 ($T_1 < T_2 < T_3$) agree very well with the experimental results over the whole range of wavelengths.

Further, the Rayleigh-Jeans law, Wien's law and the stefan-Boltzman formula are derived using Planck's law given by Eq. (1.13). Here lies the grand success of quantum theory proposed by Max. Planck.

1.7 PHOTOELECTRIC EFFECT

When an electromagnetic radiation of sufficiently high frequency, as ultraviolet (UV) light and X-rays is incident on a clean metal surface, electrons are emitted out from it. This phenomenon is known as the photoelectric effect and the emitted electron are called as photoelectrons.

The whole range of Electro-magnetic (E-M) spectrum right from Infra-red rays, visible Ultra-violets, *X*-rays, γ-rays produce this effect depending upon the metal. Most metals give this effect when exposed to UV rays or *X*-rays. Sodium is a low *z* material (Here $z = 3$, atomic number) gives this effect when exposed to all radiations of wavelengths smaller than 5455Å. Caesium produces this effect when exposed to all radiations to wavelengths smaller than 6438A°.

Einstein's photoelectric equation. For photoelectric emission of an electron from the metal $h\nu$ must be equal to or greater than W_0 ($h\nu \geq W_0$). Here W_0 is the photoelectric work function of the metal. When an electron at the metal surface absorbs the energy $h\nu$, a certain *mimum* part of this energy is used up by the electron to do work equal to W_0 to overcome the attractive forces of the positive ions of the metal. The remaining *maximum* energy ($h\nu - W_0$) is in the form of maximum kinetic energy $\left(\frac{1}{2}mv_{\max}^2\right)$ of the electron emitted from the metal surface.

$$\therefore \qquad \frac{1}{2}mv_{\max}^2 = h\nu - W_0 \qquad \text{...(1.14)}$$

This is known as Einstein's photoelectric equation.

Putting $W_0 = h\nu_0$ where ν_0 is called the threshold frequency for a given metal surface. Substituting, we get