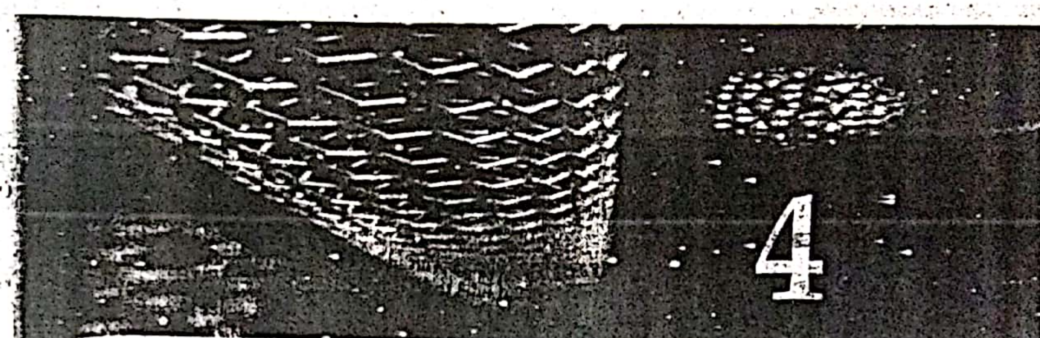


4

Lasers and Holography

4.1 INTRODUCTION

In the previous chapters, interesting phenomena of interference and diffraction of light including its polarisation have been investigated in detail. It was discussed that the interference has scientific as well as engineering applications. The concept of interference is applied to testing the surface quality of optical components and this led to the development of flatness interferometers. An exciting use of the concept of interference is made in the preparation of nonreflecting or antireflecting coatings that are applied to surfaces of lenses (for example, eye glass lenses) and other optical devices for reducing the reflections and hence in improving the efficiency of the system like telescope. However, you would have learnt that in order to realise the above mentioned phenomena in an efficient way there is a need of using the coherent and monochromatic sources as the phase of incoherent source (light) varies randomly with time and position. This need of monochromatic and coherent sources contributed to the birth of a special type of device that amplifies light and produces a high intense and highly directional beam which mostly has a very pure wavelength. This device is called LASER. Lasers are available with power ranging roughly from 1 nW ($= 10^{-9}$ W) to 10^2 PW (1 PW = 10^{15} W) and with frequency ranging from 100 GHz (1 GHz = 10^9 Hz) to 100 PHz. Now a days the lasers with pulse duration as short as ~ 1 fs (~ 10^{-15} s) are available with their pulse energies as high as 10 kJ.

The name LASER is an acronym of Light Amplification by Stimulated Emission of Radiation. The immediate originator to the LASER is the MASER, formerly acronym of Microwave Amplification by Stimulated Emission of Radiation. Since the techniques have been extended to the infrared and optical regions, it has now come to stand for Molecular rather than Microwave amplification. A laser uses some processes that amplify light signals. These processes mainly include stimulated emission and optical feedback provided by mirrors. The stimulated emission takes place in amplifying medium contained by the laser. The application of set of mirrors is to feed the light back to the amplifying medium so that the developed beam is grown continuously. The key concept for realisation of the laser operation is the principle of coherence accompanying stimulated emission.

[illegible] Emission of Radiation

It is well known that an atom can be excited by supplying energy with an amount equal to the difference of its any two energy levels. Then after a very short duration of time the atom shall radiate energy when it comes down to its lower energy state. An electron undergoes a transition between two energy states E_1 and E_2 if the atom emits or absorbs a photon of appropriate energy as per the relation $E_2 - E_1 = h\nu$ where h is planck's constant and ν is the frequency of radiation.

4.2.1. Absorption of Radiation

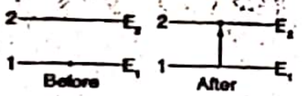


Fig. 4.1

At low temperatures, most of the atoms stay in lower energy states. If an atom is initially in the lower energy state E_1, it can be raised to the higher energy state E_2 by the absorption of a photon of energy $h\nu$, as shown in Fig. 4.1. This is known as absorption of radiation and is represented by

$$E_2 = E_1 + h\nu$$

$$\Rightarrow E_2 - E_1 = \Delta E = h\nu \quad \text{(i)}$$

The probability of occurrence of this absorption from state 1 to state 2 is proportional to the energy density $u(\nu)$ of the radiation

$$P_{12} = B_{12}\, u(\nu) \quad \text{(ii)}$$

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

Take an example of electron transition associated with visible and ultraviolet interactions with matter. Here the absorption of a photon occurs only when the quantum energy of the photon precisely matches the energy gap between the initial and final states. In such interaction of radiation with matter, if there is no pair of energy state such that the photon energy can elevate the system from the lower to upper state, then the matter will be transparent to that radiation.

4.2.2. Spontaneous Emission

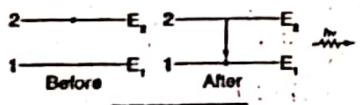


Fig. 4.2

If an atom is initially in the upper state E_2, it can come down to lower state E_1 by emitting a photon of energy $h\nu$ as shown in Fig. 4.2. This is known as *spontaneous emission.* This is the natural radiation decay process that is inherent in all excited states of all materials. However, such emission is not always the dominant decay process.

The probability of occurrence of this spontaneous emission transition from state 2 to state 1 depends only on the properties of states 2 and 1 and is given by

$$P'_{21} = A_{21} \quad \text{(iii)}$$

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

4.2.3. Stimulated (Induced) Emission

Einstein was the first to a point out a third possibility of induced emission, in which an incident photon of energy $h\nu$ causes a transition from upper state E_2 to the lower state E_1, as shown in Fig. 4.3. This occurs when

$$h\nu = \Delta E = E_2 - E_1$$

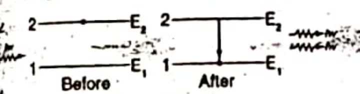


Fig. 4.3

in a system of atoms in thermal equilibrium, the number of atoms in the ground state is generally much greater than in higher energy state. This is known as *normal population* of atoms among the available energy states. A state in which the number of atoms in higher energy state is greater than that of lower energy state is known as *population inversion.*

Therefore, the incoming photon stimulates the transition to the lower state and produces a second photon of the same energy, when a sizable population of electrons resides in upper level (Fig. 4.4). This condition is called a population inversion. This population inversion sets the stage for stimulated emission of multiple photons. This is the precondition for the light amplification in a laser. Since the emitted photons have a definite time and phase relation with each other, the light has a high degree of coherence. If these emitted photons are passed through an assembly of atoms, which fulfil the condition of population inversion, they are amplified. This amplification is very much clear from Fig. 4.4, which shows multiplication of photons emitted during the process of stimulated emission.

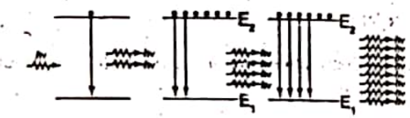


Fig. 4.4

The probability of occurrence of stimulated emission transition from the upper level 2 to the lower level 1 is proportional to the energy density $u(\nu)$ of the radiation and is expressed as

$$P''_{21} = B_{21}\, u(\nu) \quad \text{(iv)}$$

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

Thus, the total probability of emission transition from the upper level 2 to the lower level 1 is given by

$$P_{21} = P'_{21} + P''_{21}$$

$$\text{or } P_{21} = A_{21} + B_{21}\, u(\nu) \quad \text{(v)}$$

4.2.4. Relation between Einstein's Coefficients

Let N_1 and N_2 be the number of atoms at any instant in the state 1 and 2, respectively. The probability of absorption transition for number of atoms from state 1 to 2 per unit time is given by

$$N_1 P_{12} = N_1 B_{12}\, u(\nu) \quad \text{(vi)}$$

The total probability of transition for number of atoms from state 2 to 1, either by spontaneously or by stimulated emission per unit time is given by

$$N_2 P_{21} = N_2[A_{21} + B_{21}\, u(\nu)] \quad \text{(vii)}$$

In thermal equilibrium at temperature T, the absorption and emission probabilities are equal and thus, we can write

$$N_1P_{12} = N_2P_{21}$$

or $$N_1P_{12}u(\nu) = N_2[A_{21} + B_{21}u(\nu)]$$

or $$u(\nu) = \frac{N_2A_{21}}{N_1B_{12} - N_2B_{21}}$$

or $$u(\nu) = \frac{A_{21}}{B_{21}}\frac{1}{(N_1/N_2)(B_{12}/B_{21}) - 1} \quad \text{(viii)}$$

But according to Einstein

$$B_{12} = B_{21} \quad \text{(ix)}$$

Then from Eq. (viii) and (ix), we get

$$u(\nu) = \frac{A_{21}}{B_{21}}\frac{1}{(N_1/N_2) - 1} \quad \text{(x)}$$

According to Boltzmann's law, the distribution of atoms among the energy states E_1 and E_2 at the thermal equilibrium at temperature T is given by

$$\frac{N_1}{N_2} = \frac{e^{-E_1/kT}}{e^{-E_2/kT}} = e^{(E_2-E_1)/kT} \quad \text{(xi)}$$

or $$\frac{N_1}{N_2} = e^{h\nu/kT} \quad \text{(xii)}$$

Here k is the Boltzmann constant.

The from Eq. (x), we can write

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

Planck's radiation formula yields the energy density of radiation $u(\nu)$ as

$$u(\nu) = \frac{8\pi h\nu^3}{c^3}\frac{1}{e^{h\nu/kT} - 1} \quad \text{(xiv)}$$

Comparing Eq. (xiii) and (xiv), we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} \quad \text{(xv)}$$

Equation (xv) gives the relation between the probabilities of spontaneous and stimulated emissions. This is also known as the relation between the Einstein's coefficients A and B.

4.3 CHARACTERISTIC OF LASER LIGHT

As discussed, laser radiation is achieved by the process of stimulated emission and the laser beam is highly intense and directional. This radiation of a very pure frequency has the following main characteristics.

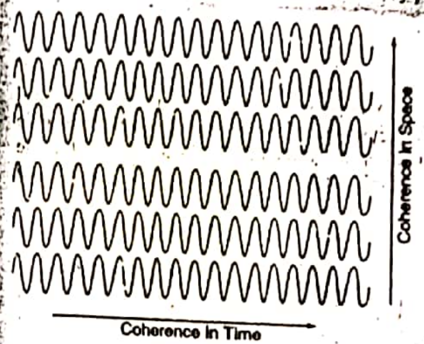


Fig. 4.5

(i) Coherent: In simple words, the meaning of coherent is highly ordered. The word coherent comes from another word *Cohero* which has the meaning *to stick together*. In fact, different parts of the laser beam have a definite relationship with each other. This coherence is described in terms of temporal coherence (coherence in time) and spatial coherence (coherence in space) (Fig. 4.5) which are required to produce high quality interference.

Ordinary light is not coherent because it comes from independent atoms which emit on the time scale of 10^{-8} seconds. A train of incoherent photons is shown in (Fig. 4.6) from which it is clear that these photons are not in order, i.e. they do not have a definite relationship with each other. However, a degree of coherence can be found in sources like the mercury green line, but their coherence does not approach that of a laser.

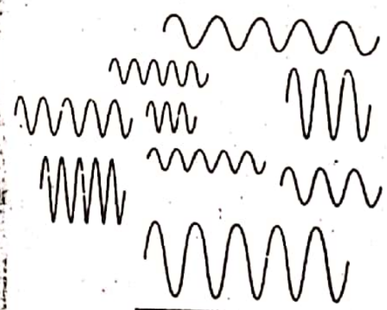


Fig. 4.6

(ii) Monochromatic: The simple meaning of this word is that it is pure in colour or wavelength. The light from a laser typically comes from one atomic transition with a single precise wavelength. So the laser light has a single spectral colour and is almost the purest monochromatic light available. It means the laser light is not exactly monochromatic, but it has high degree of monochromaticity. The deviation from monochromaticity is due to the Doppler effect of the moving atoms or molecules from which the radiation originate.

(iii) Collimated: Collimated means it does not spread out much. The light from a typical laser emerges in an extremely thin beam with very little divergence, i.e. the beam is highly collimated. The high degree of collimation arises from the fact that the cavity of the laser has very nearly parallel front and back mirrors as shown in Fig. 4.7. Because of this the light attains a parallel path after reflections from these mirrors. As it is clear from the figure, the back mirror is made almost perfectly reflecting while the front mirror is about 99% reflecting. Thus about 1% beam comes out of it, which we see as the output beam. Under this process, however, the light passes back and forth between the mirrors many a times in order to gain intensity by the stimulated emission of more photons at the same wavelength. If the light is a bit off axis, it will be lost from the beam.

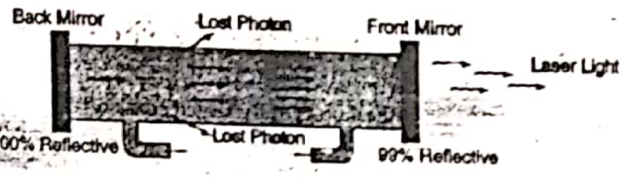


Fig. 4.7

The high degree of collimation or the directionality of a laser beam (single mode) is due to the geometrical design of the laser cavity and to the fact that stimulated emission process produces twin photons. A specific cavity design is shown in Fig. 4.8, where the angular spread of a beam is signified by the angle θ. In fact the cavity mirrors are shaped with concave surfaces towards the cavity. This way the reflecting light is focused back into the cavity, which finally forms a beam waist of radius r_s at one position in the cavity.

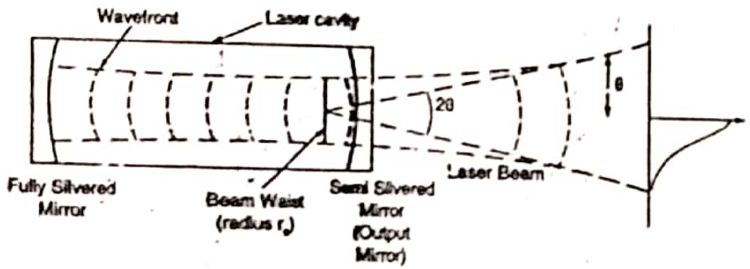


Fig. 4.8

Considering the laser beam as the fundamental TEM_{00} mode (modes will be discussed in chapter 10), the half angle beam spread can be, written as

$$\theta = \frac{\lambda}{\pi r_s}$$

From this we obtain the angular spread as

$$2\theta = \frac{0.637\lambda}{r_s}$$

In addition to this, we can calculate the intensity, i.e. the power per unit area of a typical laser which is much greater than other sources of electromagnetic radiation. This is due to the directionality and compactness of the laser beam. In view of this, the intensity or irradiance of a laser beam in terms of its waist radius is given by the following relation

$$I = \frac{P}{A} = \frac{P}{\pi r_s^2}, \text{ where P is the power.}$$

4.4 MAIN COMPONENTS OF LASER

In order to understand the working principle of a laser, we should first know about the essential components of the laser. These are given below.

(i) **Pumping:** The method of raising the molecules or atoms from their lower energy state to h... energy state is known as *optical pumping*. The optical pumping is needed for achieving popul... inversion which is precondition for stimulated emission. In this case, the rate of stimulated em... will exceed the rate of stimulated absorption. Hence, the intensity of light will increase during... pass through the medium.

(ii) **Active System:** A system in which the population inversion is to be achieved is called an a... system or the gain medium for a laser. Laser systems are named based on the makeup of the... medium, which may be a gas, liquid or solid. The energy levels in the gain medium, those partic... in the radiation, determine the wavelength of laser radiation. Laser action has been observ... over half of the known elements. Two of the most popular transitions in gases are 532.8 nm v... radiation from neon and the 10.6 μm infrared radiation from the CO_2 molecule.

(iii) **Resonant Cavity:** In a laser the active system or the gain medium is enclosed in an optical... (or resonant cavity) usually made up of two parallel surfaces, one of which is perfectly refle... and the other surface is partially reflecting. In this resonant cavity, the intensity of photons is ra... tremendously through stimulated emission process.

4.5 TYPES OF LASER

Now a days different kinds of lasers are available, the most common being in a digital communic... Virtually every house now has at least one – in their CD/DVD players and recorders. Some lasers can ch... colour – they are called tunable lasers. The lasers now operate from the infrared to the ultraviolet ra... Moreover, X-ray lasers are being developed using electron accelerators. The lasers now are available i... wide range viz, solid lasers, liquid lasers, gas lasers, semiconductor lasers, etc.

4.5.1. Ruby Laser: Solid State Laser

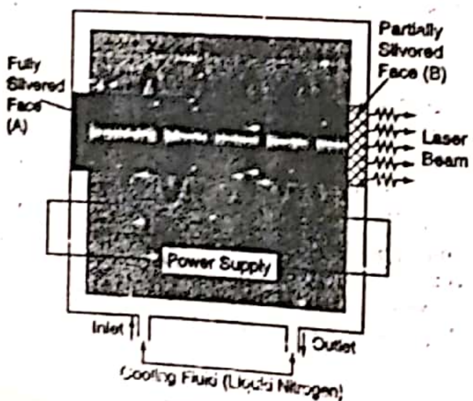


Fig. 4.9

Ruby laser is a solid state laser, which consi... three main parts (i) working material (ii) op... resonant cavity and (iii) excitation source.

Working Material Ruby laser is made up... crystal of ruby in the form of cylindrical rod h... size 2 to 30cm in length and 0.5 to 2cm in dia... whose both ends are optically flat. One of the e... fully silvered and other is partially silvered, s... they can act as fully and partially reflecting surfa... respectively, as shown in Fig. 4.9. Ruby rod i... crystal of Al_2O_3 in which chromium oxide is m... as impurity so that some of the Al^{3+} ions are repl... by Cr^{3+} ions. These 'impurity' chromium ions g... rise to the laser action.

The space between the two faces A and B is kn... as the resonant cavity in which the light (pho... intensity can be built up by multiple reflections and through stimulated emission. The ruby rod is wound... a helical xenon flash light tube with an excitation source in the form of a power supply.

orking Principle of Ruby Laser In this laser, chromium ions are active centres which are responsible the laser transition. A simplified energy level diagram of chromium ions in ruby crystal is shown in Fig. 0. In the normal state, most of the chromium ions are in the ground state E_1. When light from the flash tube wavelength 5500Å is made to fall upon the ruby rod, these incident photons are absorbed by the chromium s that rise to the excited state E_3. Then they give a part of their energy to the crystal structure and reach metastable state, i.e. the E_2 state. These ions in metastable state can remain for a longer duration 10^{-3} sec. erefore, the number of ions in this state goes on increasing while at the same time number of ions in ground te goes on decreasing due to the optical pumping. Thus, the population inversion is established between metastable state and the ground state.

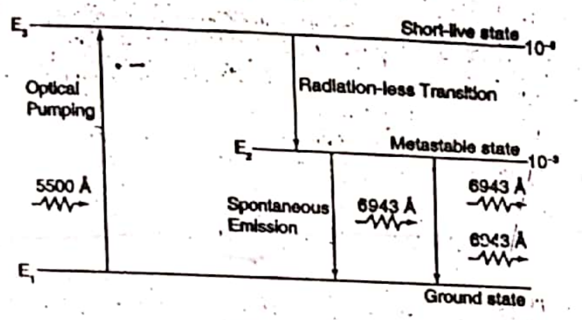


Fig. 4.10

When an excited ion passes spontaneously from the metastable state to the ground state, it emits a photon of wavelength 6943Å. This photon travels parallel to the axis of ruby rod and stimulates the surrounding ions present in the metastable state. Then by stimulated emission other photons are emitted, which are in the phase with the stimulating photons. By successive reflections of these photons at the ends of the rod, every time the stimulated emission is achieved and we obtain an intense, coherent and unidirectional laser beam from the partially silvered face B.

The ruby laser operates at about 1% efficiency. It may produce a laser beam of 1 mm to 25 mm in diameter. The beam obtained is in the form of pulses. However, on the advantage side, very strong beam as strong as 10,000 W in power is produced. Furthermore, the construction of this laser is simple and the operation is very easy. For this reason, this laser is also known as practical laser. Other examples of solid state lasers are Neodymium-YAG (Nd-YAG), Neodymium-Glass (Nd-Glass) and semiconductor lasers.

As we know that the output beam of the ruby laser is not continuous. To overcome this drawback, the gas filled laser was made by A. Javan, W. Bennett and D. Herriott in 1961. It consists of a quartz tube having the size about 1.5 cm in diameter and about 1 meter in length. The both ends of the tube are sealed by optically plane and parallel mirrors, one of them being partially silvered (90% reflective) and the other one is fully silvered (100% reflective).

4.5.2 Nd-YAG Laser: Solid State Laser

This laser is capable of producing very high power emissions, as a result of its lasing medium that operates as four level systems. The schematic of Nd-YAG laser is shown in Fig. 4.11. The lasing medium in the Nd-YAG laser is colourless, isotropic crystal called Yttrium aluminaum garnet (YAG-$Y_3Al_5O_2$). The main dopant in

the lasing medium is Neodinium (Nd^{3+}). When it is used in laser, Neodinium replaces 1% of Yttrium and the crystal takes a light blue colour. The YAG has a relatively high thermal conductivity, which improves thermal dissipation in thermal cavity. So continuous wave operation up to a few hundred Watts is possible. Average power of up to 1kW is available when it is operated in pulse mode.

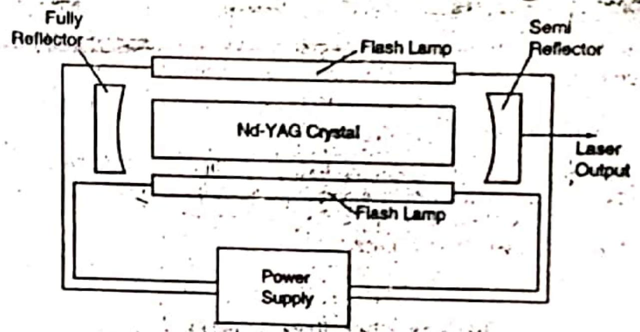


Fig. 4.11

The energy level diagram for Nd-YAG is shown in Fig. 4.12. These levels arise from three inner shell 4f electrons of the Nd^{3+} ion, which are effectively screened by eight outer electrons ($5S^2$ and $5P^6$). For the operation of Nd-YAG lasers a cooling system is required. A Nd-YAG laser produces 30 times as much waste heat as laser output with an efficiency of about 3%. The waste heat must be removed in order to ensure proper laser operation by flooding the optical compartment with water. However optical distortion and image problem is created due to absorption of significant amount of flash lamp energy by water. This problem can be overcome by flowing water over the outside of the optical cavity and by encasing the lasing rod and flash lamp with transparent cooling jacket.

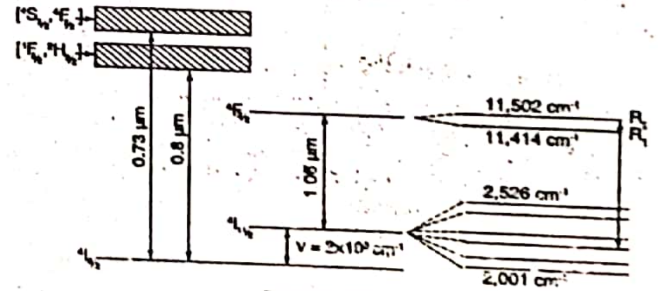


Fig. 4.12

An advantage of Nd-YAG laser is that by using Q-switching, laser beam pulse frequency and shape can be tailored where a shutter moves rapidly in and out of the path of the beam. In this manner beam output is interrupted until a high level of population inversion and energy storage is achieved in the resonator. If the optical cavity is switched from no reflection (low Q) to near total reflection (high Q), the cycle can be optimised to build up the maximum population inversion before the pulse is generated. This way, we get a beam pulse with high energy up to 1 J and a short pulse period down to 10ns is obtained.

Applications

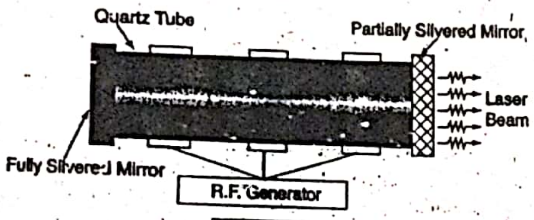
(i) Nd-YAG is used in material processing such as welding and drilling.

(ii) It is also used in photo disruption of transparent membrane of pathological origin, which can appear in the interior chamber of eye or for iridectomy and in endoscopic applications.

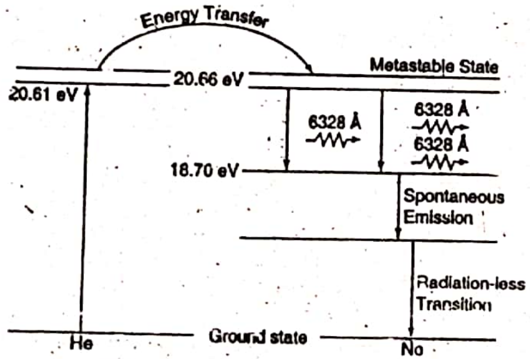
(iii) It is used in range finders and target designators used in military context, which use Q- switched lasers.

(iv) In scientific applications the Q-switched lasers with their second harmonic (λ = 532 nm), third harmonic (λ = 355 nm) and fourth harmonic (λ = 266 nm) are used.

4.5.3 Helium-Neon Laser: Gas Laser



In this laser system, a quartz tube is filled with a mixture of helium and neon gases in the ratio 10:1 respectively, at a pressure of about 0.1 mm of mercury (Fig. 4.13). This mixture acts as the active medium. Helium is pumped upto the excited state of 20.61 eV by the electric discharge. The energy level diagram of He-Ne laser is shown in Fig. 4.14.

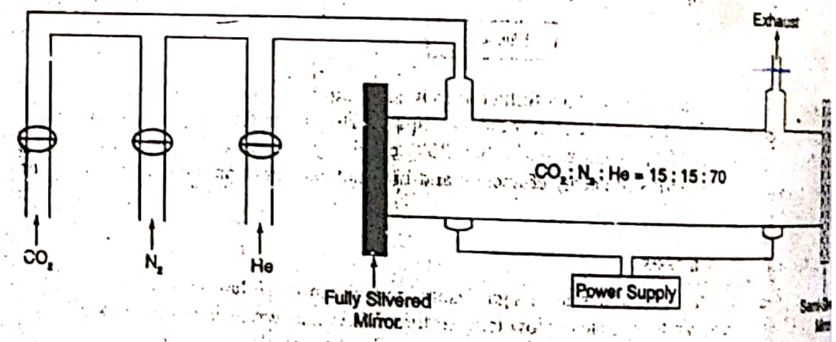


Here, it can be seen that the excited level of He at 20.61 eV is very close to a level in Ne at 20.66 eV close that upon collision of a He and a Ne atom, the energy can be transferred from the He to the Thus, the excited He atoms do not return to their ground state by spontaneously emitting photons transfer their energy to the Ne atoms through collisions. As mentioned, such an energy transfer place when the two colliding atoms have identical states. Thus, the He atoms help achieving inversion in the Ne atoms. An excited Ne atom passes spontaneously from the metastable state to the excited state at 18.70 eV by emitting a photon of wavelength 6328 Å. This photon travels gas mixture parallel to the axis of the tube and stimulates the surrounding Ne atoms present in the state. This way we get other photons that are in the phase with the stimulating photons. These reflected forth and back by the silvered ends and the number of photons gets amplified through emission every time. Finally, a portion of these intensified photons passes through the partially silvered

The He-Ne laser is the most common and inexpensive gas laser. Usually it is constructed to operate red light at 6328 Å. However, it can be constructed to produce laser action in the green light in the infrared at 15,230 Å. According to Garmire, an unfocused 1mW He-Ne laser has a brightness sunshine on a clear day (~ 0.1 W/cm²) and is just as dangerous to stare at directly.

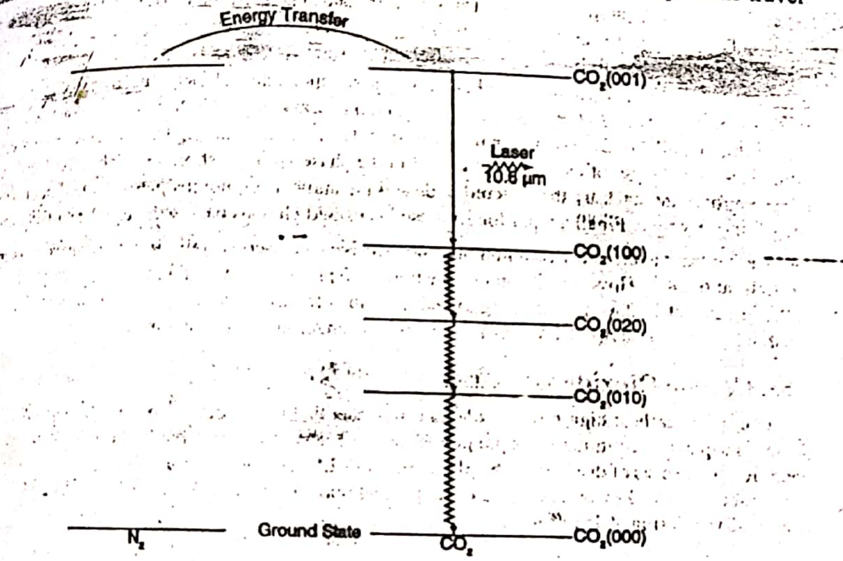
4.5.4 Carbon Dioxide Gas Laser

It is one of the earliest high power molecular gas laser that uses carbon dioxide gas molecule. The device is capable of continuous out put powers above 10 kW. It is also capable of extremely high power operation. It consists of discharge tube of size of about 2.5 cm is diameter and 5.0 cm is length. The of the tube are sealed by optically plane and parallel mirrors, one of them being semi-silvered and is fully silvered. (Fig. 4.15).



The carbon dioxide gas laser mixture contain 15% CO_2, 15% N_2 and 70% He at a pressure of few This mixture is fed into the discharge tube through flow loop which is connected at one end of the tube. The dc excitations source is used that produces electric discharge. In starting nitrogen allowed to enter in the discharge tube. They get excited by collision with electrons. Then excited molecules flow into the whole volume of resonant cavity and collide with the unexcited CO_2 and transfer their energy to the desired laser level (Fig. 4.16). Nitrogen (N_2) and helium (He) improve efficiency of the laser action, while oscillations take place between two vibrational levels of CO_2

helps producing a large populations in upper level and helium helps removing population from lower energy level. Related energy levels of N_2 and CO_2 molecules are shown in Fig. 4.16. The radiated photons travel



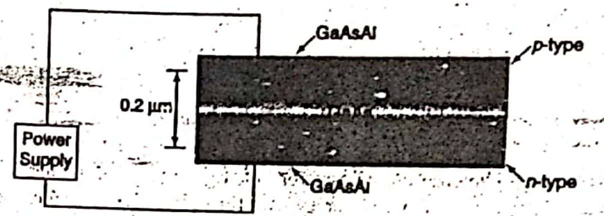
back and forth between the end mirrors and get further amplified. It exhibits laser action at several infrared frequencies but none in the visible. For example, it radiates light at 10.6 μm in far infrared. It is one of the most efficient lasers, capable of operating at more than 30% efficiency. Hence, this laser is suitable for industrial applications both in terms of energy efficiency and high out put beam; particularly it is used for welding and cutting.

4.5.5 Semiconductor Laser

Semiconductor laser differs from the solid state and gas lasers in many aspects. It has remarkably small size, exhibits high efficiency and can be operated at low temperature. When the current is passed through a *p-n* junction diode in forward bias, holes move from *p*-region to *n*-region and the electrons move from *n*-region to *p*-region. These electrons and holes are recombined in the junction region and emit photons due to the transition of electrons from the conduction band to the valence band. This results in stimulated radiation coming from a very narrow region near the junction. The action is intensified by increasing the current and decreasing the junction thickness.

Semiconductor laser is made up of an active layer of gallium arsenide (GaAs) of thickness 0.2 microns. This is sandwiched in between a *n*-type GaAsAl and *p*-type GaAsAl layer as shown in Fig. 4.17. The resonant cavity is provided by polishing opposite faces of the GaAs crystal and the pumping occurs by passing electrical current from an ordinary source (Power Supply). From this system GaAs semiconductor, laser beams of wavelength ranging from 7000 Å to 30,000 Å can be produced.

Pumping → Forward biasing
Active medium: depletion region



4.5.6 Advantages and Disadvantages of Ruby laser, He-Ne laser and Semiconductor laser

The merits and demerits of solid laser (Ruby), gas laser (He-Ne) and semiconductor laser.

	[illegible]	He–Ne Laser	[illegible]
Advantages	[illegible]		[illegible]
1	[illegible]	Easy to construct and operate	[illegible]
2	[illegible]	Continuous beam	[illegible]
3	[illegible]	Exceptionally monochromatic beam with high operation duration (10,000 hrs.)	[illegible]
Disadvantage	[illegible]		[illegible]
	[illegible]	It has got very low power about 0.5 – 5mW	[illegible]

4.6 APPLICATIONS OF LASERS

Lasers have many applications in science, industry and medicine; some of which are listed below

(i) Lasers have been used to measure long distances, so they are very useful in surveying and ranging. For this purpose, a fast laser pulse is sent to a corner reflector at the point to be measured and the time of reflection is measured to get the distance.

(ii) Lasers are electromagnetic waves of very high intensity and can be used to study the laws of interaction of atoms and molecules.

(iii) Lasers are suitable for communication and they have significant advantages because they are more nearly monochromatic. This allows the pulse shape to be maintained better over long distances. So communication can be sent at higher rates without overlap of the pulses.

(iv) Laser beams are highly intense and are used for welding, cutting of materials, machining an drilling holes, etc. Generally, carbon dioxide laser are used for such purposes, as it carries large power.

(v) Lasers are used most successfully in eye surgery, treatment of dental decay and skin diseases

(vi) The laser beam is used in recording of intensity as well as in holography.

(vii) Laser is used in heat treatments for hardening.

(viii) Lasers are used as barcode scanners in library and in supermarket.

(ix) Laser is used in printers (Laser printers).

(x) Lasers are used in photodiode detection.

[illegible]

So far you have learnt that the laser radiation is highly intense, highly coherent and highly monochromatic light. It is amazing that the field of laser radiation can be used to cool down atoms to very low temperature, for example up to 10^{-9} K. This can be understood based on an atom which is traveling toward a laser beam and absorbs a photon from the laser. In this situation, the atom will be slowed by the fact that the photon has momentum $p = E/c = h/\lambda$, where E is the energy, c is the speed of light, h is the Planck's constant and λ is the wavelength associated with the photon. If we assume that a number of sodium atoms are freely moving in a vacuum chamber at 300K (room temperature), i.e. the rms velocity of the sodium atom is about 570 m/s. Then the momentum of the sodium atom can be reduced by the amount of the momentum of the photon, if a laser is tuned just below one of the sodium d-lines (5890 A° and 5896 A°, about 2.1 eV) and the sodium atom absorbs a laser photon when traveling toward the laser. It would take a large number of such absorptions to cool the sodium atoms to nearly 0 K. The change in speed from the absorption of one photon can be calculated from

$$\frac{\Delta p}{p} = \frac{p_{photon}}{mv} = \frac{\Delta v}{v} \Rightarrow \Delta v = \frac{p_{photon}}{m}$$

The above expression shows a lot of photons, but according to *Chu* a laser can induce on the order of 10^7 absorptions per second so that an atom could be stopped in a matter of milliseconds.

There is a conceptual problem that an absorption can also speed up an atom if it catches it from behind. So more absorptions from head-on photons are necessary to have. This is accomplished in practice by tuning the laser slightly below the resonance absorption of a stationary sodium atom. More precisely, with the opposing laser beams with perpendicular linear polarisations, atoms can be selectively driven or "optically pumped" into the lower energy levels. This method of cooling sodium atoms was proposed by *Theodore Hansch* and *Arthur Schawlow* at Stanford University in 1975 and was achieved by *Chu* at AT & T Bell Labs in 1985. Here sodium atoms were cooled from a thermal beam at 500K to about 240 μK.

4.8 HOLOGRAPHY

Holography is one of the remarkable achievements of modern science and technology, which possible only because of the lasers. The word "holography" was originated from the Greek and "*grapho*". The meaning of "holos" is "*whole*" and of "grapho" is "*write*". So holography record of the image. Holography is a three-dimensional (3D) laser photography. It is lensless which an image is captured as an interference pattern. The image thus obtained is called a hologram true 3D record of the object. Holography not only records the amplitude but also the phase of the with the help of interferometric techniques. This recorded reference pattern contains more a focused image and enables the viewer to view a true 3D image which exhibits parallax. The holography was invented by *Gabor* in 1947.

4.8.1 Principle of Holography

In holography, there are two basic waves that come together to create the interference pattern called *object wave* and another wave is called *reference wave*. When an object wave meets a it creates a standing wave pattern of interference. This is then photographed, which we call a holo

4.8.2 Requirements of Holography

Following are some requirements for the absolute holography.

(i) Since holography is an interference phenomenon, there should not be a path difference object wave and the reference wave more than the coherence length. This is necessary stable interference fringes.

(ii) Spatial coherence is important so that the reference wave and the scattered object different regions can interfere properly.

(iii) Since reconstructed image coordinates depend on wavelength as well as position of the source, it is necessary that the source emits a narrow band of wavelength and it is not interest of obtaining good resolution in the reconstructed image.

(iv) In order to obtain aberrations free reconstructed image, it is necessary that the reconstructing is of the same wavelength and is situated at the same position with respect to the hologram reference source.

(v) All recording arrangement like film, object, mirrors etc. must be motionless during the

4.9 HOLOGRAPHY VERSUS CONVENTIONAL PHOTOGRAPHY

Holography represents a photographic process in a broad sense, but essentially it differs from a as the phase of light waves scattered by the object carries the complete information about 3D the object. A conventional photography is a 2D image of a 3D scene, which brings into focus the scene that falls within the depth of the field of the lens. Due to this, a conventional photograph perception of the depth or the parallax with which we view a real life scene. Since a conventional only records the intensity pattern, 3D character of the object scene is lost. Contrary to this, the contains depth and parallax, which provides the ability to see around the object to objects placed behind. It gives information about amplitude as well as the phase of an object. So hologram preserves information about the object for later observation.

In conventional photography, there is one to one relationship between object and image point as the light originating from a particular point of scene is collected by a lens focused on that particular point. However, in holography lens is not used and this is a complex interference pattern of microscopically spaced fringes. Hologram receives light from every point of a scene and hence there is no one to one relationship. This is a record of entire signal wave.

In conventional photography, radiated energy is recorded and phase relationship of wave arriving from different distances and directions is lost. However, in holography phase relationship is recorded by using the technique of interference of light waves.

4.10 RECORDING AND RECONSTRUCTION OF IMAGE ON HOLOGRAPH

Recording of a hologram is a result of superpositions of the object wave and the reference wave, which is usually a plane wave. This interference pattern is recorded by a photographic plate that contains information about amplitude as well as phase of the object wave. In order to see the image, hologram is illuminated with another wave called the reconstruction wave which is identical to the reference wave in most of the cases. This is called reconstruction of image on the hologram.

Theory

If the object is a point scatterer and it is made of large number of such points, then the composite wave reflected by the object will be the vectorial sum of all object waves scattered from are these points. As mentioned earlier, holography records the object wave, particularly the phase (say φ) associated with it. So we can represent the object wave, which is due to the superposition of waves from point scatterers on the object, as

$$Y_1(x, z) = A_1(x, z)\cos(\phi - \omega t) \qquad \text{(i)}$$

where w is the frequency. The object wave represented by Eq. (i) lies in the plane of photographic plate at $y = 0$

Now we consider a reference wave propagating in the xy plane and inclined at an angle α from the y axis. In view of this, the field associated with the reference wave can be written as

$$Y_2(x, y, z) = A_2 \cos(\vec{k}\cdot\vec{r} - \omega t)$$

$$= A_2 \cos(kx \sin\alpha + ky \cos\alpha - \omega t) \qquad \text{(ii)}$$

At the photographic plate, i.e., at $y = 0$, this field becomes

$Y_2(x,z) = A_2 \cos(kx \sin\alpha - \omega t)$.

Since the propagation constant $k = 2\pi/\lambda$, $kx \sin\alpha = \dfrac{\sin\alpha}{\lambda} 2\pi x$

Here $\sin\alpha/\lambda$ is defined as the spatial frequency (say ξ). So the field associated with the reference wave becomes,

$$Y_2(x, z) = A_2 \cos(2\pi\xi x - \omega t) \qquad \text{(iii)}$$

A comparison of equation (iii) with equation (i) yields that the phase linearly varies with x.

Simple method of superposition enables us to calculate the total field at the photographic plate (at $y = 0$) as

$$Y = Y_1 + Y_2$$

$$Y(x,z,t) = A_1(x,z)\cos(\phi - \omega t) + A_2 \cos(2\pi\xi x - \omega t) \qquad \text{(iv)}$$

In view of the response of photographic plate to the intensity we find below the measure of intensity pattern recorded by the photographic plate as

$I(x, z)$ = Average value of $Y^2(x,z,t)$

$$= \langle Y^2(x,z,t)\rangle$$

or

$$I(x, z) = A_1^2(x, z)\langle\cos^2(\phi - \omega t)\rangle + A_2^2\langle\cos^2(2\pi\xi x - \omega t)\rangle$$

$$+ 2A_1(x, z)A_2\langle\cos(\phi - \omega t)\cos(2\pi\xi x - \omega t)\rangle \qquad \text{(v)}$$

As we know that $\langle\cos^2(\phi - \omega t)\rangle = \tfrac{1}{2}$,

$$\langle\cos^2(2\pi\xi x - \omega t)\rangle = \tfrac{1}{2},$$

$$\langle 2\cos(\phi - \omega t)\cos(2\pi\xi x - \omega t)\rangle$$

$$= \tfrac{1}{2}\langle\cos(\phi + 2\pi\xi x - 2\omega t) + \cos(\phi - 2\pi\xi x)\rangle$$

[Using $2\cos\theta_1\cos\theta_2 = \cos(\theta_1 + \theta_2 + \cos(\theta_1 + \theta_2))$]

The average value of $\cos(\phi + 2\pi\xi x - 2\omega t)$ can be obtained by using simple integration

$$\frac{1}{2\pi}\int_0^{2\pi/\omega}\cos(\phi + 2\pi\xi x - 2\omega t)\,dt,$$

as the average value of $\cos\omega t$ over the period $T = 2\pi/\omega$

$$= \frac{1}{2\pi}\int_0^{2\pi/\omega}\cos\omega t\,dt.$$

So it comes out to be zero. With this, the intensity $I(x,z)$ is written as

$$I(x,y) = A_1^2(x,z)/2 + A_2^2/2 + A_1(x,z)A_2\cos(\phi - 2\pi\xi x) \qquad \text{(vi)}$$

The above equation shows that the intensity I is the function of phase $\phi(x, z)$. It means the phase information of the object wave is recorded in the intensity pattern.

In order to obtain a hologram, we develop the photographic plate containing above intensity pattern. In this context, the ratio of the transmitted field to the incident field is defined as the transmittance of the hologram that depends on $I(x, z)$. Using a suitable developing process, the condition under which the transmittance is linearly related to $I(x, z)$ can be obtained. Under this condition, if $R_e(x, z)$ denotes the field of the reconstruction wave, at the hologram plane, then the transmitted field can be taken as

$$T_e(x, z) \propto R_e(x, z)\, I(x, z).$$

Taking K_p as the proportionality coefficient and putting the value of $I(x, z)$ from equation (vi), we obtain

$$T_t(x,z) = K_p R_t(x,z)\left[\frac{A_1^2(x,z)}{2} + \frac{A_2^2}{2} + A_1(x,z)\,A_2\cos(\phi - 2\pi\xi x)\right] \quad \text{(vii)}$$

In the case when the reconstruction wave is identical to the reference wave $Y_2(x, z)$, the above equation becomes

$$T_t(x,z) = K_p A_2\left[\frac{A_1^2(x,z)}{2} + \frac{A_2^2}{2}\right]\cos(2\pi\xi x - \omega t)$$
$$+ K_p A_2^2 A_1(x,z)\cos(2\pi\xi x - \omega t)\cos(\phi - 2\pi\xi x)$$

Again using $2\cos\theta_1\cos\theta_2 = \cos(\theta_1 + \theta_2) + \cos(\theta_1 - \theta_2)$, we get the following expression for $T_t(x, z)$

$$T_t(x,z) = K_p A_2\left[\frac{A_1^2(x,z)}{2} + \frac{A_2^2}{2}\right]\cos(2\pi\xi x - \omega t)$$
$$+ \frac{K_p A_2^2 A_1(x,z)}{2}\cos(\phi - \omega t)$$
$$+ \frac{K_p A_2^2 A_1(x,z)}{2}\cos(4\pi\xi x - \phi - \omega t) \quad \text{(viii)}$$

The above equation contains three terms, which may be analysed as follows.

(i) First term being proportional to A_2^2 represents the reconstruction wave whose amplitude is modulated by the term $A_1^2(x, z)$, i.e. by the amplitude of object wave. The factor $\cos(2\pi\xi x - \omega t)$ shows that this part of the total field is traveling in the direction of the reference wave.

(ii) The second term is identical to equation (i) within a constant term. Hence, this represents the original object wave. Having appeared in transmitted field, it gives rise to a virtual image.

(iii) The third term carries the phase $\phi(x, z)$ in addition to the term $4\pi\xi x$, but with negative sign. It means this wave has a curvature opposite to the object wave, i.e. if the object wave is diverging spherical wave, then the last term (third term) shows a converging spherical wave. Hence, this wave forms a real image of the object contrary to the second term. This image can be photographed with the help of a film.

4.11 TYPES OF HOLOGRAMS

In order to construct a hologram, we need two coherent light waves, one is the object wave carrying information about the object and the other is a plane wave that is called reference wave. There are various types of holograms, but the most common ones are the transmission hologram and the reflection holograms.

4.11.1 Transmission Hologram

This type of hologram is commonly used. If the object wave and the reference wave emerge from the same side of the holographic film, then the hologram is called transmission hologram (Fig. 4.18). Another characteristic of transmission hologram is the low diffraction efficiency and weak image reconstruction.

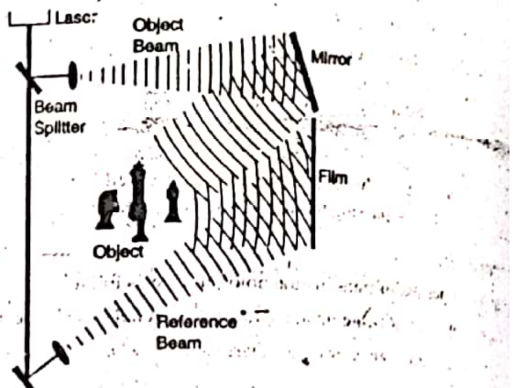


Fig. 4.18

4.11.1.1 Recording Process

As mentioned, in order to make a hologram, two coherent light waves (laser light) are required. The first one is called the object wave, which is reflected from the object and carries information of the object. The second one is called reference wave and is a plane wave without information. These generate an interference pattern, which is recorded in the form of a hologram on film emulsion. For the stable interference patterns, absolutely stable conditions are required during the exposure of the recorded hologram is called transmission hologram because the light passes through the hologram

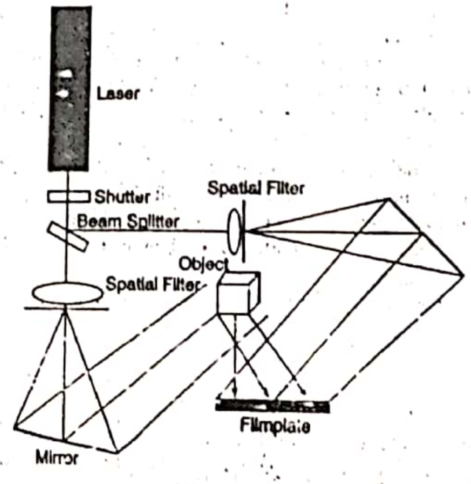


Fig. 4.19

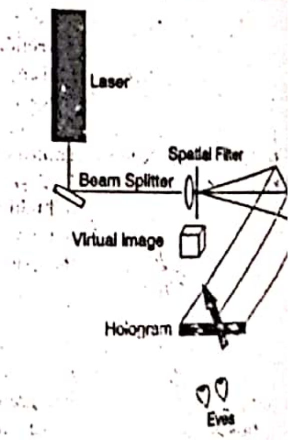


Fig. 4.20

4.11.1.2 Reconstruction Process

We can reconstruct the holographic image by developing the hologram and then placing it in its original position in the reference beam as during its recording. If we look along the reconstructed object wave, we see a replica of the object and as we shift viewpoints we see object from different perspectives. Thus the object appears to be three-dimensional. During the reconstruction of the transmission hologram, the light does not pass through the image, but it creates a wavefront that makes it appear as though the light had been generated at the position of the object. This image thus formed is called virtual image (Fig. 4.20). Contrary to this, an image having light actually passing through it is called a real image.

4.11.1.3 Properties

Some important properties of transmission hologram are as follows.

(i) When viewed with white light, the transmission holograms look like a blurry rainbow image.

(ii) These holograms are viewed as sharp images when we use the shining laser light through the hologram.

(iii) Less resolving power is needed in materials.

(iv) Transmission hologram can be formed in a simple setup.

(v) Greater depth of the scene is possible in transmission holograms.

4.11.2 Reflection Hologram

The holograms that are viewed with white light source on the same side as the viewer are known as reflection holograms. In such a hologram, a truly three-dimensional image is seen near its surface. This hologram is the most common type shown in galleries. The light is located on the viewer's side of the hologram at a specific angle and distance. The image thus formed consists of light reflected by the hologram. There are two types of reflection holograms.

4.11.2.1 One Step Hologram

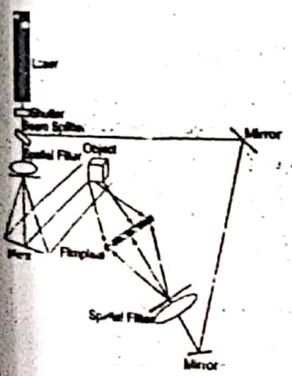


Fig. 4.21

Here, the resolution of film emulsion is high, as the recording of reflection hologram needs 10 to 100 times much power than a transmission hologram. Thus exposure time is long. During the process of recording the hologram, the two waves namely the reference wave and the object wave illuminate the film plate on opposite sides (Fig. 4. 21). In this case, the fringes are formed in layers and are more or less parallel to the surface of the emulsion. If a highly directed beam of white light illuminates a reflection hologram, it selects the appropriate band of wavelengths to reconstruct the image and the remainder of the light passes straight through.

4.11.2.2 Two Step Hologram

This hologram involves two steps. First we make a transmission hologram called H1 (Fig. 4. 22). This is called a master or first hologram. We make multiple copies from the master hologram. We make transfer copies of master hologram. Transfer copy means making another hologram using the image on the master as the subject. These transfer holograms are either laser-visible transmission holograms or reflection holograms H2. Suppose we want any object in the final hologram just to appear half in front and half behind the recording plate. In such circumstances, the two step hologram is of great use.

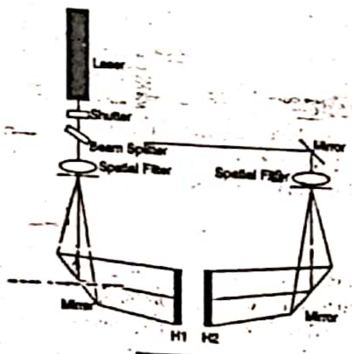


Fig. 4.22

4.11.2.3 Properties

Some important properties of reflection hologram are as follows.

(i) These holograms can be viewed in regular light.

(ii) The finished reflection hologram is monochromatic.

4.11.3 White Light Hologram: Rainbow Hologram

Rainbow holograms that can be viewed in white light and produce 3D images are very popular holograms. A double holographic process makes them, in which an ordinary hologram is used as the object and a second hologram is made through a slit. A horizontal slit limits the vertical perspective of the first image so that there is no vertical parallax. The coherence requirement can be removed by using slit process. So the image brightness is obtained from ordinary room light while maintaining the 3D character of the image as the viewer eye is moved horizontally. If viewer eye is moved vertically, no parallax is seen and the image colour sweeps through the rainbow spectrum from blue to red.

4.11.3.1 Embossed Hologram

Many variations of hologram can be made between the reflection and transmission types of holograms. Embossed hologram is one of such types of holograms, which is used widely in most security applications. These holograms offer an effective method of protection against any forms of manipulation, as they are too difficult to copy due to their complex structure. All credit cards and passports have embossed hologram. In this hologram, the original hologram is recorded in a photosensitive material called *photoresist*. These holograms are easily produced at large scale and also at a very low cost.

4.11.3.2 Volume Hologram

Volume holograms are produced when the thickness of the recording material is much larger than the light wavelength used for recording. These are transmission holograms and are also known as *thick holograms*, which are mainly considered as a high-density data storage technology. These are 3D holograms created by recording the interference pattern of two mutually coherent light waves. The angle of difference between the object wave and the reference wave is 90° to 180°. Due to certain unique properties, volume holograms are used widely in various spectroscopic and imaging applications.

4.12 APPLICATIONS OF HOLOGRAPHY

Holography represents examples of recombining of scattered radiation. It is a product of interference of light, which is used to measure very small optical path lengths with precision by using wavelength of light and interference. Now holography is being used in industry, communication and other engineering problems also. You would have seen hologram on tickets, original covers of software programs, credit cards etc. This is used to prevent *falsification*. Another important application is through bar code readers used in shops, warehouses, libraries and so on. In aircraft industry, holography technology is used through head up displays (HUD) which help the pilot to see instrument panel on to the windscreen.

Some other important applications of holography are given below.

4.12.1 Time Average Holographic Interferometry

This interferometry is very useful for determining or studying the modes of vibration of complex structures. Hologram is prepared using a long exposure time than the periods of vibrations being studied. This hologram freezes many images, mapping the motion of vibrating surface. Interference fringes pattern provides information about the relative vibrational amplitudes as a function of position on the surface.

4.12.2 Microscopy

A hologram contains many separate observations of microscopic particles. Image provided by hologram may be viewed by focusing on any depth of unchanging field. Microscopic hologram is made by illuminating the specimen by laser light, a part of which is split off outside the microscope and is routed to the photographic plate to rejoin the subject beam processed by the microscope. It can be shown that if $\lambda r > \lambda s$, where λr is the wavelength of reconstructing light and λs is the wavelength used in holography, then the magnification is

$$M = \left(\frac{v}{u}\right)\left(\frac{\lambda r}{\lambda s}\right)$$

Here u is the object distance from the film and v is the corresponding image distance from the hologram. However, these distances are equal, i.e., $u = v$, if the reference and reconstructed wavefronts are both plane wave.

4.12.3 Ultrasonic Hologram

As the words "ultrasonic holograms" suggest, the waves producing a hologram may not necessarily be electromagnetic in nature. Also, the holographic principles do not depend on the transverse nature of the radiation. Holograms generated with the help of ultrasonic waves are very useful because of the ability of such waves to penetrate the objects that are opague to visible light. Holograms formed by ultrasonic waves are very useful to get 3D images inside the opaque bodies.

4.12.4 Holocameras

Hologram can be developed and viewed with the help of holocameras, which do not use photographic film. Thermoplastic recording material is used in holocameras and image development is done by electrical and thermal means. The image development does not need wet chemical processing. Also, it can be completed in a few seconds without repositioning the recording.

4.12.5 Holographic Data Storage

Data can be stored by holographic technique. It is very interesting that the data can be reduced to dimensions of the order of wavelength of light. Therefore, volume holograms can be useful to record vast quantities of information. Photosensitive crystal like potassium bromide with colour centres or lithium niobate are used in place of thick layered photoemulsion. Small rotation of crystal takes place of turning pages.

4.13 SUMMARY

The main topics discussed in this chapter are summarized below.

(1) Laser was introduced as a special type of device that amplifies light and produces a high and highly directional beam which mostly has a very pure frequency.

(2) It was made clear the population inversion is the basic requirement for the operation of

(3) For achieving the laser radiation, the concept of stimulated emission was discussed in de with the inclusion of Einstein's coefficients.

(4) The main components of laser were discussed and based on the gain medium the la classified as solid state laser, gas laser or semiconductor laser.

(5) Ruby laser, Nd-YAG laser, He-Ne laser, CO_2 laser and semiconductor laser were discuss and the energy diagrams provided.

(6) It was mentioned that the lasers have diverse applications in different fields of sci technology. These applications were talked about in brief.

(7) A new concept of laser cooling was discussed in detail. It was shown how a highly in coherent light of laser can cool the sodium atoms to 10^{-6} K.

(8) Another exciting filed of holography was introduced and it was mentioned that with th lasers the holograms can be developed that give 3D picture of the objects.

(9) Principle and the requirements of the holography were discussed.

(10) The advance/additional features of holography from those of conventional photogr talked about.

(11) Detailed description of recording and reconstruction of image on holograph were discuss

(12) Two types of holograms, namely transmission holograms and reflection holograms, were in detail along with their recording and reconstruction processes and the properties.

(13) White light hologram was introduced, which is also known as rainbow hologram. I embossed and volume holograms were talked about.

(14) Various applications of holography were discussed including time average hol interferometry, microscopy, ultrasonic holograms, holocameras and the holographic data s

SOLVED EXAMPLES

Example 1 A three-level laser emits a light of wavelength of 5500 Å.

What will be the ratio of population of upper level (E_2) to the lower energy level optical pumping mechanism is shut off (Assume T = 300 K).

At what temperature for the conditions of (a) would the ratio of populations be

Solution Given λ = 5500 Å

Example: For an ordinary source, the coherence time $\tau_c = 10^{-10}$ sec. Obtain the degree of non-monochromaticity for $\lambda_o = 5400$ Å.

Solution: Given $\tau_c = 10^{-10}$ sec

$$\Delta\nu = \frac{1}{\tau_c} = \frac{1}{10^{-10}} = 10^{10}\,\text{Hz}$$

For $\lambda_o = 5400$ Å, $\nu_o = \frac{c}{\lambda_o} = \frac{3.0\times10^{8}}{5400\times10^{-10}} = \frac{1}{18}\times10^{16}$

Degree of non-monochromaticity

$$\frac{\Delta\nu}{\nu_o} = \frac{18\times10^{10}}{10^{16}} = 18\times10^{-6} = 0.000018.$$

OBJECTIVE TYPE QUESTIONS

Q.1 LASER is a short form of
(a) Light Amplification Stimulated Emission Radiation
(b) Light Amplification by Stimulated Emission of Radiation
(c) Light Absorption by Stimulated Emission of Radiation
(d) Light Absorption by Spontaneous Emission of Radiation.

Q.2 What is the life-time of electron in metastable state?
(a) 10^{-3} sec.
(b) 10^{-5} sec
(c) 10^{-8} sec
(d) 10^{-7} sec.

Q.3 In the population inversion
(a) the number of electrons in higher energy state is more than the ground state,
(b) the number of electrons in lower energy state is more than higher energy state.
(c) the number of electrons in higher and lower energy state are same.
(d) none of them.

Q.4 The relations between Einstein's coefficient A and B is
(a) $\frac{8\pi h\nu^3}{c^3}$
(b) $\frac{8\pi^2h^3\nu^3}{c^2}$
(c) $\left(\frac{2\pi h\nu}{c}\right)^3$
(d) $\frac{8\pi hc}{\lambda}$

Q.5 Laser beam is made of
(a) electrons
(b) highly coherent photons
(c) very light and elastic particles
(d) none of them.

Q.6 In ruby laser which ions give rise to the laser action?
(a) Al_2O_3
(b) Al^{3+}
(c) Cr^{3+}
(d) none of them.

Q.7 Which one of the following laser have highest efficiency, ruby, He-Ne and semiconductor and carbon dioxide
(a) ruby
(b) semiconductor
(c) He – Ne
(d) carbon-dioxide.

Q.8 The method of population inversion to the laser action in He – Ne laser is:
(a) molecular collision
(b) direction conversion
(c) electric discharge
(d) electron impact.

Q.9 Ruby laser produces the laser beam of wavelength
(a) 6943 Å
(b) 6328 Å
(c) 6320 Å
(d) 6940 Å.

Q.10 Characteristics of laser beam are
(a) highly directional
(b) highly intense
(c) highly monochromatic
(d) all of them.

PRACTICE PROBLEMS

Q.1 What do you mean by laser and its working principle, important requirements and applications?

Q.2 (a) Explain the term 'absorption', 'spontaneous' and 'stimulated' emission of radiation. Obtain a relation between transition probabilities of spontaneous and stimulated emission.
(b) What are Einstein's coefficient? Derive Einstein relation.

Q.3 Explain the construction and working principle of Ruby laser.

Q.4 What is the principle of laser?

Q.5 Discuss salient characteristics of laser beam

Q.6 Describe various applications of laser?

Q.7 Explain the characteristics of laser beam. What are the necessary conditions for Lasing action?

Q.8 Explain the concept of directionality and monochromaticity as applied to lasers.

Q.9 Discuss Einstein's coefficients. Derive relation between them.

Q.10 Explain the terms: spontaneous and stimulated emission, population inversion, optical pumping.

Q.11 What is meant by population inversion and how is it achieved in practice.