UNIT III

LASER FUNDAMENTALS

LASER = Light Amplification by Stimulated Emission of Radiation.

Fundamental Characteristics of Lasers

Laser technology is one of the most rapidly developing areas in modern technology. When the laser was invented, in 1960, it was classified as a solution in search of a problem , and today laser technology is applied in many different areas such as: medicine, communication, daily use, military, and industry. To explain how the laser can be applied in such diverse areas, we need to understand the basic physical principles of the operation of a laser.

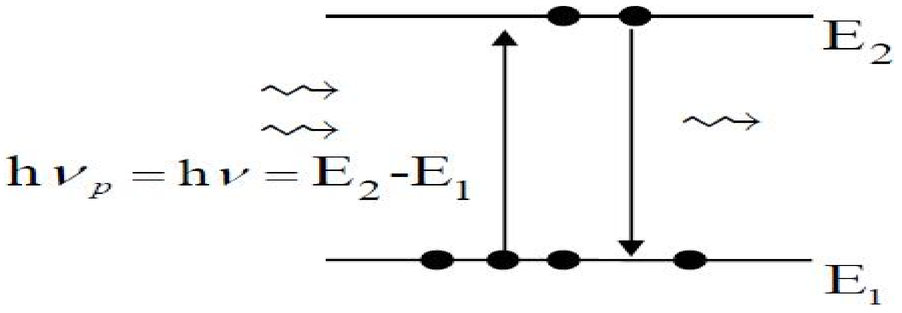
In principle, the laser is a device which transforms s energy from other forms into electromagnetic radiation. This is a very general definition, but it helps to understand the basic physics of the laser. The energy put into the laser can be in any form such as: electromagnetic radiation, electrical energy, chemical energy, etc.Energy is always emitted from the laser as electromagnetic radiation (which includes light beams).

Level Lasers

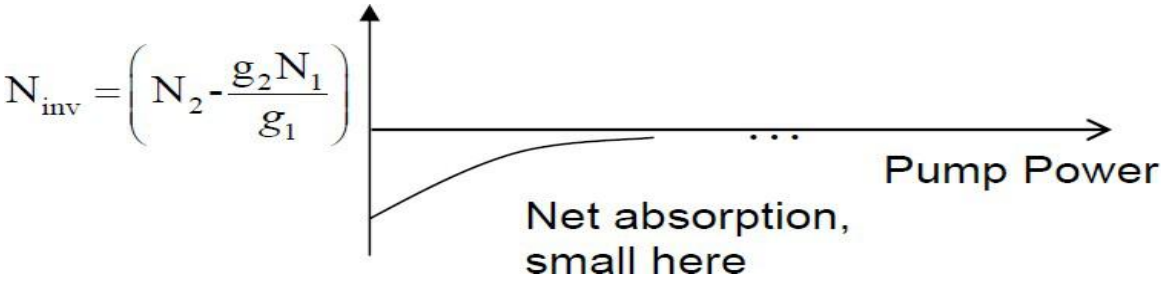
Every atom or molecule in nature has a specific structure for its energy levels. The lowest energy level is called the ground state, which is the naturally preferred energy state. As long as no energy is added to the atom, the electron will remain in the ground state. When the atom receives energy (electrical energy, optical energy, or any form of energy), this energy is transferred to the electron, and raises it to a higher energy level (in our model further away from the nucleus).The atom is then considered to be in an excited state. The electron can stay only at the specific energy states (levels) which are unique for each specific atom. The electron cannot be in between these "allowed energy states", but it can "jump" from one energy level to another, while receiving or emitting specific amounts of energy.

These specific amounts of energy are equal to the difference between energy levels within the atom. Each amount of energy is called a "Quantum" of energy (The name "Quantum Theory" comes from these discrete amounts of energy). Energy transfer to and from the atom Energy transfer to and from the atom can be performed in two different ways:

Two-Level Laser

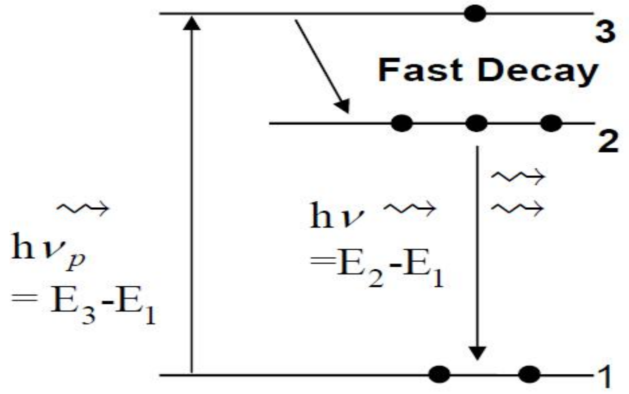


Suppose we try to increase N2 with strong light at hν to create a population inversion



Three Level Laser

(Good → Can Create Population Inversion)



Example: Ruby Laser

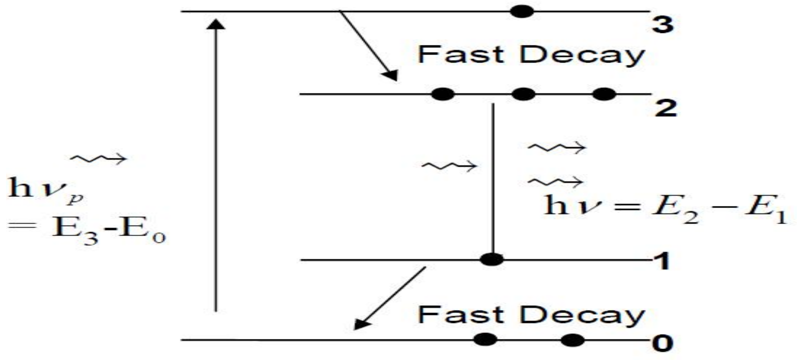
In a three level system, the terminal level for the fluorescence process is the ground level(ie) the level with the lowest energy. Here, The population inversion is produced by raising electrons to the high energy level by the process of pumping with an auxiliary light source. It is observed to excite electrons from level 1 to level 3. Then , a very fast radiation less transition accomplished by thermal vibrations of the atoms will drop the electrons to level 2. The difference in energy between levels 3 and 2 appears as heat. Stimulated emission occurs between levels 2 and 1 at frequency,

It substantial power at frequency $f_3$is supplied, the transition rate from level 1 to 3 will be large.

Quasi Three Level Laser

1. Collisions with other atoms, and the transfer of kinetic energy as a result of the collision. This kinetic energy is transferred into internal energy of the atom.

(Better → Easier to get a large inversion)



Example: Nd:YAG Laser

2. Absorption and emission of electromagnetic radiation. Since we are now interested in the lasing process, we shall concentrate on the second mechanism of energy transfer to and from the atom (The first excitation mechanism is used in certain lasers, like Helium-Neon, as a way to put energy into the laser.

The interactions between electromagnetic radiation and matter cause changes in the energy states of the electrons in matter.

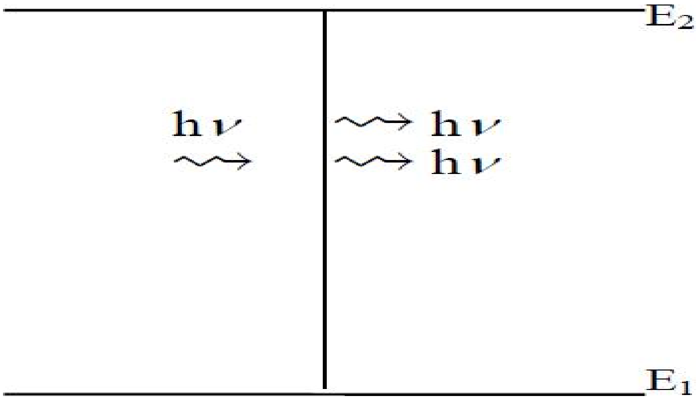
•Electrons can be transferred from one energy level to another, while absorbing or emitting a certain amount of energy. This amount of energy is equal to the energy difference between these two energy levels (E2-E1).
•When this energy is absorbed or emitted in a form of electromagnetic radiation, the energy difference between these two energy levels (E2-E1) determines uniquely the frequency (ν) of theelectromagnetic radiation: (ΔE) = E2-E1= hν= h(bar)ω
Eg: The laser is a system that is similar to an electronic oscillator. An Oscillator is a system that produces oscillation s without an external driving mechanism.

Properties Of Laser

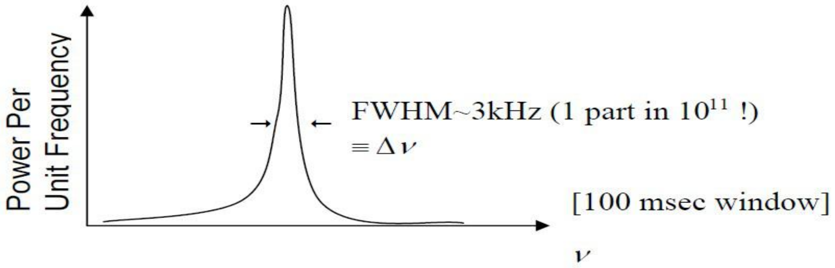
Monochromaticity:

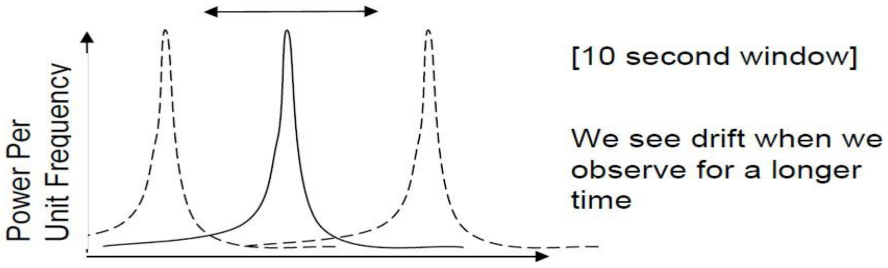
This property is due to the following two factors.

First, only an EM wave of frequency n0= (E2-E1)/h can be amplified, n0has a certain range which is called linewidth, this linewidth is decided by homogeneous broadening factors and inhomogeneous broadening factors, the result linewidth is very small compared with normal lights. Second, the laser cavity forms a resonant system, oscillation can occur only at the resonance frequencies of this cavity. This leads to the further narrowing of the laser linewidth, the narrowing can be as large as 10 orders of magnitude! So laser light is usually very pure in wavelength, we say it has the property of monochromaticity.



Example: **Nd:YAG Laser** $\lambda=1.064\mu\text{m}$, $\nu=2.8\times10^{14}$ Hz





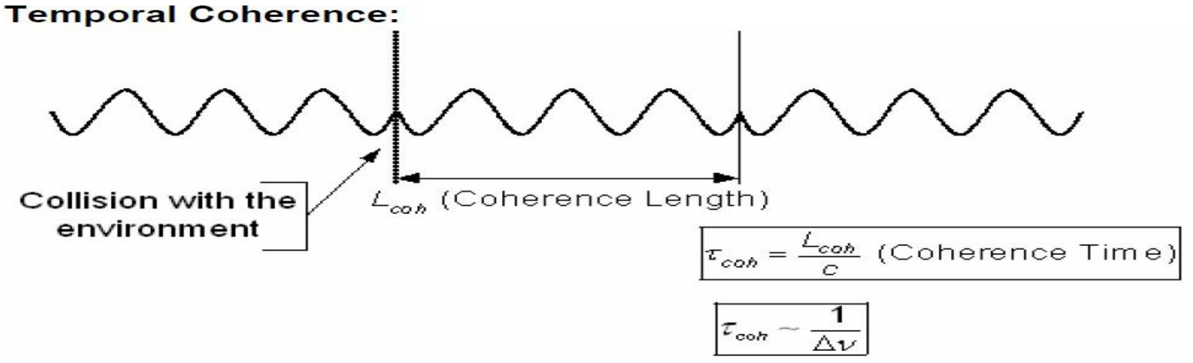
Coherence:

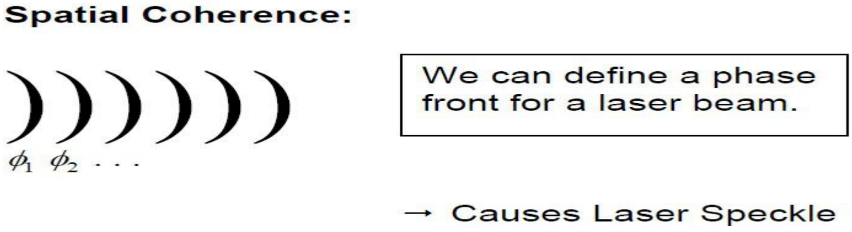
For any EM wave, there are two kinds of coherence, namely spatial and temporal coherence. Let’s consider two points that, at time t=0, lie on the same wave front of some given EM wave, the phase difference of EM wave at the two points at time t=0 is k0. If for any time

t>0 the phase difference of EM wave at the two points remains k0, we say the EM wave has perfect coherence between the two points. If this is true for any two points of the wave front, we say the wave has perfect spatial coherence. In practical the spatial coherence occurs only in a limited area, we say it is partial spatial coherence.

Now consider a fixed point on the EM wave front. If at any time the phase difference between time t and time t+dt remains the same, where "dt" is the time delay period, we say that the EM wave has temporal coherence over a time dt. If dt can be any value, we say the EM wave has perfect temporal coherence. If this happens only in a range 0<dt<t0, we say it

has partial temporal coherence, with a coherence time equal to t0. We emphasize here that spatial and temporal coherence are independent. A partial temporal coherent wave can be perfect spatial coherent. Laser light is highly coherent, and this property has been widely used in measurement, holography, etc.



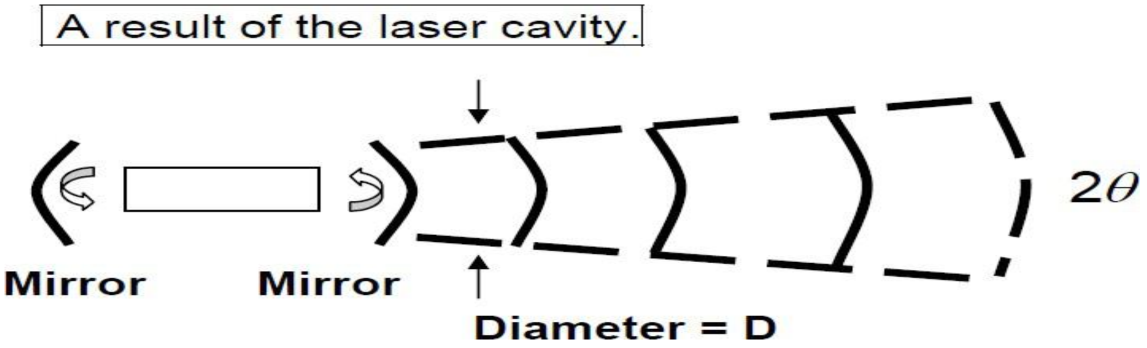


Divergence and Directionality:

Laser beam is highly directional, which implies laser light is of very small divergence. This is a direct consequence of the fact that laser beam comes from the resonant cavity, and only waves propagating along the optical axis can be sustained in the cavity. The directionality is described by the light beam divergence angle. Please try the figure below to see the relationship between divergence and optical systems. For perfect spatial coherent light, a beam of aperture diameter D will have unavoidable divergence because of diffraction. From diffraction theory, the divergence angle qd is: qd= b l /D Where l and D are the wavelength and the diameter of the beam respectively, b is a coefficient whose value is around unity and depends on the type of light amplitude distribution and the definition of beam diameter. qd is called diffraction limited divergence. If the beam is partial spatial coherent , its divergence is bigger than the diffraction limited divergence. In this case the divergence becomes:

$$q = b\, l /(S_c)^{1/2}$$

whereS_c is the coherence area.



Brightness:

The brightness of a light source is defined as the power emitted per unit surface area per unit solid angle. A laser beam of power P, with a circular beam cross section of diameter D and a divergence angle q and the result emission solid angle is p q 2, then the brightness of laser beam is:

$$B=4P/(p\ Dq)^2$$

The max brightness is reached when the beam is perfect spatial coherent.

Bmax=4P/(p l b)2

In case of limited diffraction (q d= l b /D, D=l b /q d, q d=q)

Laser Modes

Surely laser cavity is also very important for a laser in many other aspects, for example, its dimension decides the longitudinal laser modes.Generally speaking light modes means possible standing EM waves in a system. The number of modes in this meaning is huge. Laser mode means the possible standing waves in laser cavity. We see that stimulated lights are transmitted back and forth between the mirrors and interfere with each other, as a result only light whose round trip distance is integer multiples of the wavelength l can become a standing wave. That is:

m = 2L/(c/f) =2L/l , or f = m c/(2L), D f = c/(2L)

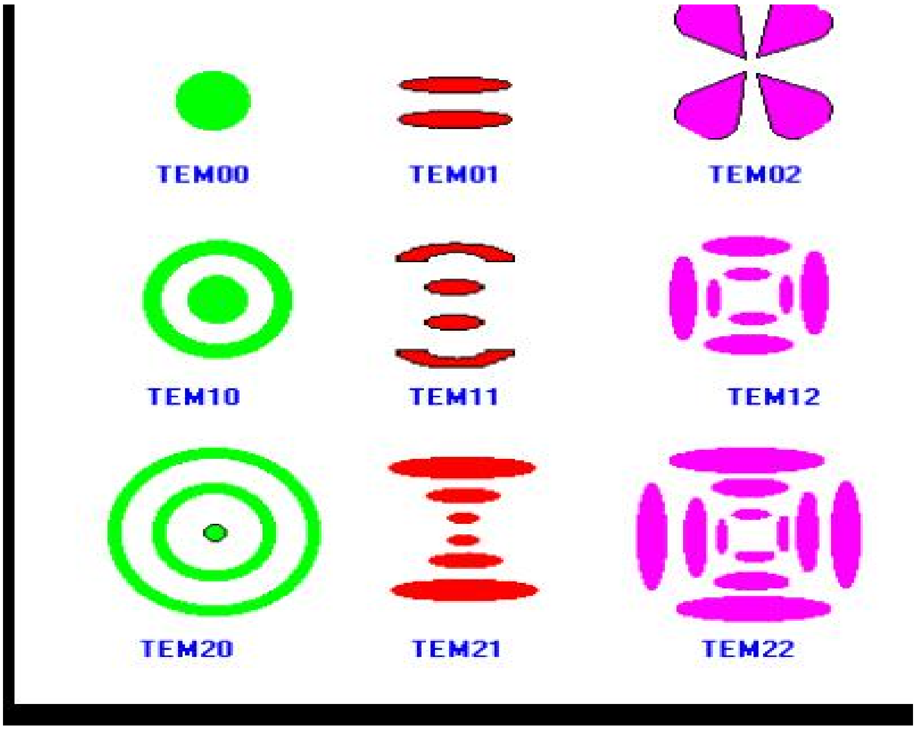
Where L is the length of cavity, c is the light speed in laser cavity, f is the frequency of standing wave, l is the wavelength, m is an integer , D f is the frequency difference between two consecutive modes. The number of longitudinal modes may be very large, it can also be as small as only a few (below 10). If we intersect the output laser beam and study thetransverse beam cross section, we find the light intensity can be of different distributions (patterns). These are called Transverse Electromagnetic Modes (TEM). Three index are used t$_o$ indicate the TEM modes—TEM$_{plq}$, p is the number of radial zero fields, l is the number of angular zero fields, q is the number of longitudinal fields. We usually use the first two index

to specify a TEM mode, like TEM00, TEM10, etc. Clearly, the higher the order of the modes the more difficult it is poor to focus the beam to a fine spot. That is why some times TEM00 mode
or Gaussian beam is preferred

TEM Mode, Beam Diameter, Focal Spot Size and Depth of Focus

Modes are the standing oscillating electromagnetic waves which are defined by the cavity geometry. In the above section, we already computed the Longitudinal Modes frequencies for some simple cases. If the cavity is of closed form, i.e., both the mirrors and side walls are reflective, there will be large amounts of longitudinal modes oscillating inside the cavity, a typical value can be 109 modes for a He-Ne laser.

When these modes oscillate, they interfere with each other, forming the transversestanding wave pattern on any transverse intersection plane. This mechanism decides the Transverse Electromagnetic Modes (TEM) of the laser beam, which is the wave pattern on the output aperture plane. We use the sign TEMpql to specify a TEM mode, where p is the number of radial zero fields, q is the number of angular zero fields, q is the number of longitudinal fields, and we usually use TEMpq to specify a TEM mode, without the third index. A table of TEM patterns is shown below. Clearly, the mode pattern affects the distribution of the output beam energy, which will thus affect the machining process. Then what is the diameter of a laser beam? Usually this diameter is defined as the distance within which 1/e2 of the total power exists.The higher the order of the mode, the more difficult it is to focus the beam to a fine spot,since the beam of higher order is not from a virtual point, but from patterns as those in the table below.



Focal Spot Size:

Focal spot size determines the maximum energy density that can be achieved when thelaser beam power is set, so the focal spot size is very important for material processing.When a beam of finite diameter D is focussed by a lens onto a plane, the individual parts of the beam striking the lens can be imagined to be point radiators of new wave front.The light rays passing through the lens will converge on the focal plane and interfere with each other, thus constructive and destructive superposition take place.

Resonator Configuration

The most widely used laser resonators or cavities have either plane or spherical mirrors ofrectangular or circular shape, separated by some distance L. There have appeared Plane Parallel Resonators, Concentric (Spherical) Resonators, Confocal Resonators,Generalized Spherical Resonators and Ring Resonators.

Plane Parallel Resonator consists of two plane mirrors set parallel to each other, as shown in the figure below. The one round trip of wave in the cavity should be an integral number times 2ı , the resonant frequencies is ı = kc/(2L), k is an integral number, c is the speed of light in the medium, L is the cavity length. The frequency difference between two consecutive modes (possible standing wave in the cavity) is c/(2L). This difference is referred to as the frequency difference between two consecutive longitudinal modes; the word longitudinal is used because the number k indicates the number of half wavelengths of the mode along the laser resonator, i.e., in the longitudinal direction.

Concentric resonator consists of two spherical mirrors with the same radius R separated by a distance L=2R, so that the centers are coincident. The resonant frequencies use the same equation as above. Confocal resonator consists of two spherical mirrors of the same radius of curvature R separated by a distance of L such that their foci F1 and F2 coincident. In this case, the center of curvature of one mirror lies on the surface of another mirror, L=R. The resonant frequency cannot be readily obtained from geometrical optics consideration.

Resonators formed by two spherical mirrors of the same radius of curvature R and separated by a distance L such that R<L<2R, i.e., in between confocal and concentric, are called Generalized Spherical Resonators, which is also often used.

Ring Resonator is a particularly important class of laser resonators. The path of the optical rays is arranged in a ring configuration or more complicated configurations like folded configurations. We can compute the resonant frequencies by imposing the constraints that the total phase shift along the ring path or the closed loop path must be equal to the integral numbers of 2ı . Then the resonant frequencies are ı = kc/Lp, where k is an integral number, Lp is the loop path length.

Cavities can be identified as stable or unstable according to whether they make the oscillating beam converge into the cavity or spread out of the cavity. The output mirror of the laser resonator is finely coated to reach the required reflection into the cavity, if the beam is too intense, the mirror May suffer breakage. Breakage is serious because it causes shut down of the production. So for powers up to 2kW, lasers mainly use stable cavity designslaser output is from the center of optical axis. Stable cavity design allows the beam to oscillate many times inside the cavity to get high gain, the focal property and directionality are improved. For higher powered lasers, unstable cavities are often used laser output comes from the edge of the output mirror, which is often a totally reflecting metal mirror. The ring shaped beam reduces the intensity of the beam, thus reduces the risk of breakage. In the same time ring shaped beam is poor for focusing. Unstable cavities are suitable for high gain per round trip laser systems, which don’t require large numbers of oscillation between the mirrors.

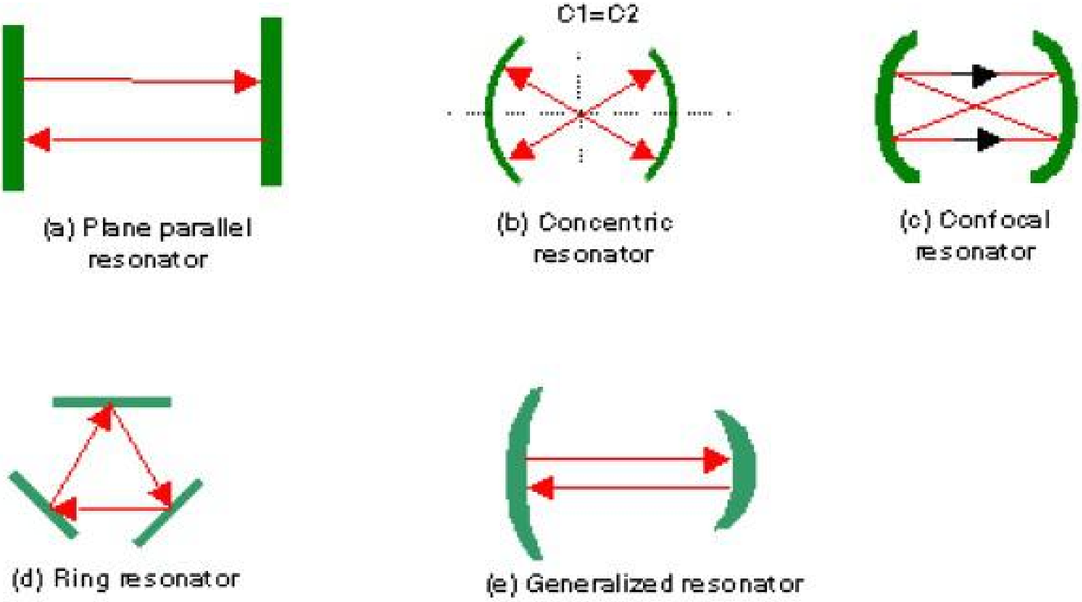
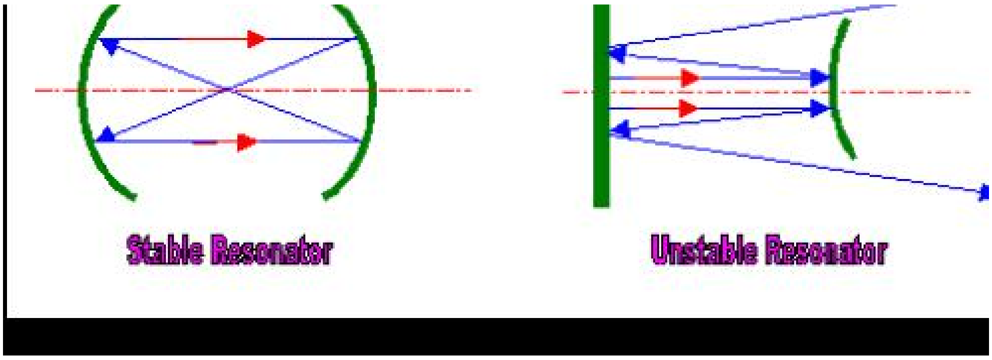


Figure 2.12: Various Resonators

(a) Plane parallel; (b) Concentric; (c) Confocal; (d) Ring; (e) General



Q-Switching and Mode Locking

Q-Switching

Q=————————————————

If the energy stored in the dominant mode is very large, we get high Q. Q – switching means maintaining the population inversion to a very high value above the threshold population inversion and simultaneously bringing down all the atoms to undergo laser transition. This will lead to a gaint pulse with very high power($>10^9$ W)

Energy of the pulse(E)= $\hbar\lambda(N_Q-N_t)V$

Q switching technique:

Pockel cell acts as a quarter wave plate producing a phase difference of $-$. When there is no voltage given to cell, there is no phase shift for linearly polarized light from the polarizer. Let the light photon travel from mirror M1 to M2. Whem=n the voltage is given to the cell, there is a phase shift of $-$. Therefore, the linearly polarized light ius converted into circularly polarized light. Reflection at the mirror M2 changes the direction of rotation of circularly polarized light. So, the polarizer does not allow this light to pass through it. Now, the cavity is switched off. Thus, when the voltage given to the cell is zero, the cavity is Q-switched and if there is voltage, the cavity is inactive to produce laser oscillation. The changes of voltage from zero to a non-zero, the cavity is Q switched and if there is voltage, the cavity is inactive to produce laser oscillations. The change o0f voltage from zero to a non zero value should take place within 1 ns.

Mode Locking:

`Modelocking is a technique in optics by which a laser can be made to produce pulses of light of extremely short duration, on the order of picoseconds (10-12s) or femto seconds (10-15s).The basis of the technique is to induce a fixed phase relationship between the modes of the laser's resonant cavity. The laser is then said to be phase-locked or mode-locked. nterference between these modes causes the laser light to be produced as a train of pulses. Depending on the properties of the laser, these pulses may be of extrem ely brief duration, as short as a few femtoseconds Methods for producing modelocking in a laser may be classified as either active or passive. Active methods typically involve using an external signal to induce a modulation of the intra-cavity light. Passive methods do not use an external signal, but rely on placing some element into the laser cavity which causes self-modulation of the light

Cavity Damping

In addition to Q- switching , cavity dumping is a method for producing short pulses with duration is the nano second to microsecond time. Here the laser is excited simultaneously. The resonance cavity has a high Q so that the laser light simply remains in the cavity. An electro optic and device periodically switches pulses out of cavity

Types Of Lasers

Lasers can be divided into gas lasers, solid state lasers and liquid lasers according to the active medium used.

Gas Lasers:

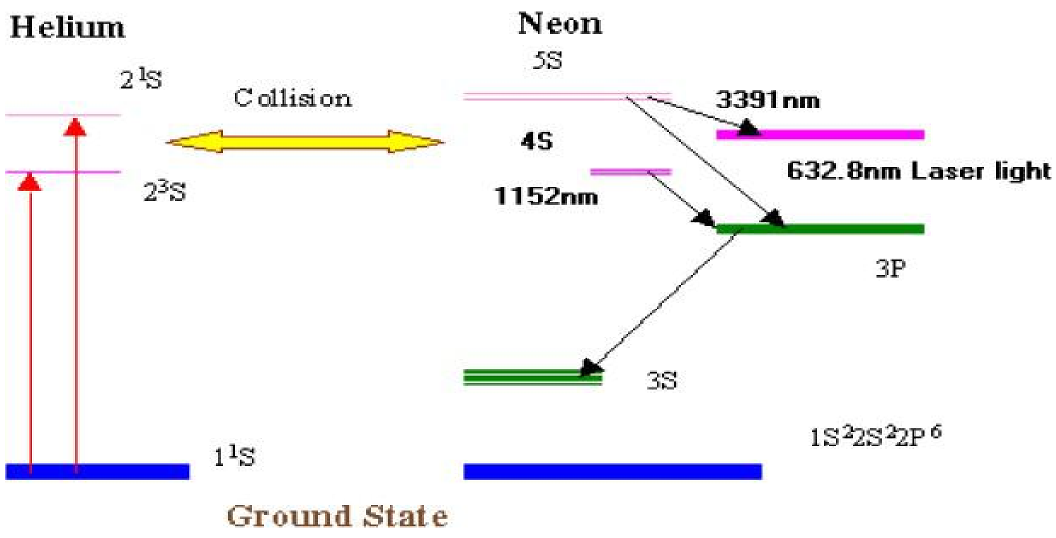
Gas Lasers can be further divided into neutral atom, ion and molecular lasers, whose lasing mediums are neutral atoms, ions or gas molecules respectively.

1. Helium –neon Laser.

2. Carbon dioxide laser

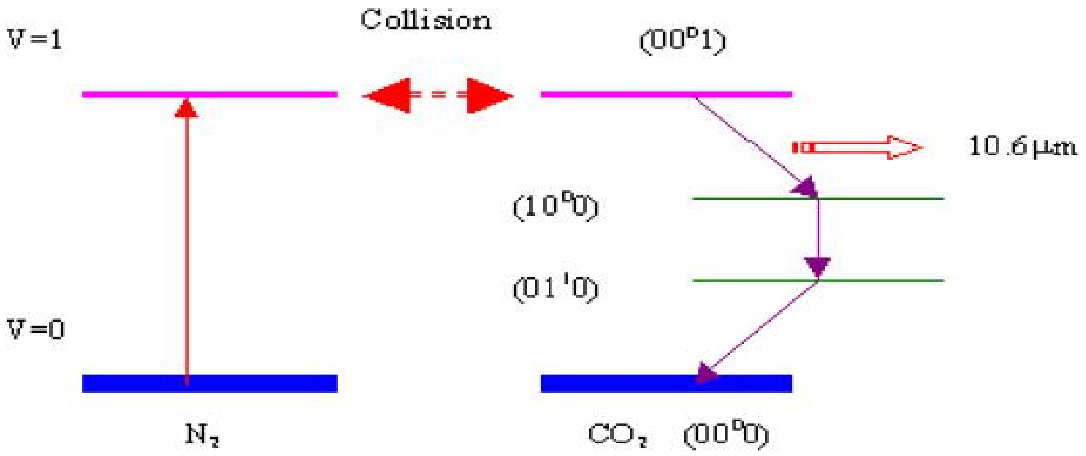
1. Helium –neon Laser.

Helium-neon (He-Ne) laser is a kind of neutral atom gas laser, the common wavelength of a He-Ne laser is 632.8 nm, it is tunable from infrared to various visible light frequencies. He and Ne are mixed according to certain percentage, pumping is by DC electrical discharge in the low pressure discharge tube. First He atom is excited. Because Ne atom has an energy level very near to an energy level of He, through kinetic interaction, energy is readily transferred from He to Ne, and Ne atom emit the desired laser light. The typical power of He-Ne laser is below 50 mW, it is widely used in holography, scanning, measurement, optical fiber communication, etc. It is the mostpopular visible light laser.



2. Carbon dioxide laser

Carbon dioxide laser is a typical molecular gas laser, it emits laser light at a wavelength of 10.6 m m, its beam power ranges from several watts to 25 kW or even to 100 kW, so CO2 laser is widely used in laser machining, welding and surface treating. For this reason, let's investigate it in detail. The active medium of CO2 laser is a mixture of CO2, helium and nitrogen gases, the approximate constitute is CO2:N2:He::0.8:1:7. Pumping is realized by AC or DC electrical discharge. First most of the electrical discharge energy is absorbed by nitrogen gas, only a small part of the energy is Absorbed by CO2 molecules directly which raise them from ground state (000) to upper state (001). Large amounts of CO2 molecules collide with the nitrogen molecules and gain the excitation energy. Once excitation is achieved, the CO2 molecules at (001) state will give out energy and jump to lower energy state (100) or (020), thus giving out laser light at frequency 10.6m m or 9.6 m m respectively. The remaining decay from state (100) to (010), (020) to (010) or (010) to ground state (000) will dissipate energy in the form heat instead of light.



Solid Lasers

In solid state lasers, ions are suspended in crystalline matrix to generate laser light. Theions emit electrons when excited, the crystalline matrix spread the energy among the ions. The first solid state laser is ruby laser, but it is no longer used because of its low efficiency. Two common solid state lasers are Nd:YAG lasers and Nd:glass lasers, there structures are very similar. Both use krypton or xenon flash lamps for optical pumping.

For Nd:glass lasers, the glass rod has the advantage of growing into larger size than YAG crystals, but the low thermal conductivity of glass limits the pulse repetition rate of Nd:glass laser. So Nd:glass lasers are used in applications which require high pulse energies and low pulse repetition rates. It is suitable for hole piercing and deep keyhole welding operations.

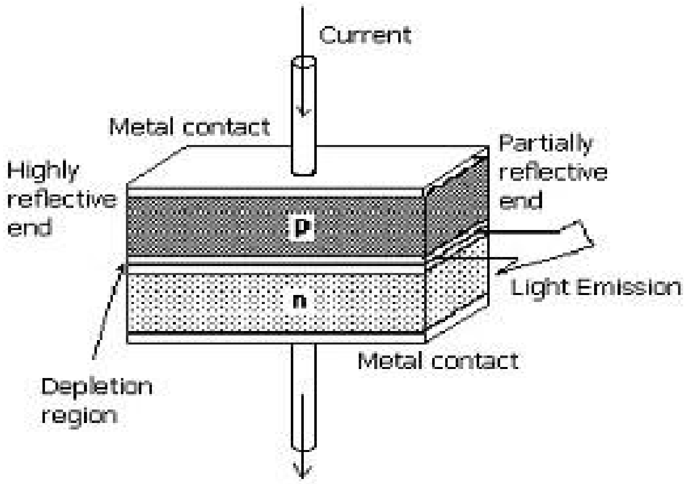
YAG crystal has a higher thermal conductivity than glass, so the thermal dissipation inNd:YAG laser cavity can be improved, operation power can be up to several hundred watts in continuous mode, and high pulse rates (50kHz) can be reached. YAG is a complex crystal of Yttrium-Aluminium-Garnet with chemical composition of Y3Al5O12, it is transparent and colorless. About 1% Nd3+ ions are doped into the YAG crystal, the crystal color then changed to a light blue color. The wavelength of Nd:YAG laser is 1.06m m.Solid state lasers are widely used in laser machining.

Liquid Lasers

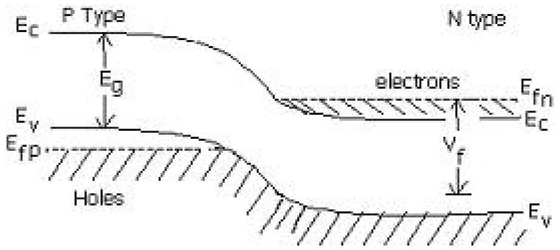
Liquid Lasers use large organic dye molecules as the active lasing medium. These laserscan lase in a wide frequency range, i.e. they are frequency tunable. The spectral range of dyes covers infrared, visible and ultraviolet light. Pumping is by another pulsed/continuous laser, or by pulsed lamp. These lasers are used in spectroscopic investigation and photochemical experiments.

Semiconductor Lasers.

PN-junction Laser: A semiconductor laser is a specially fabricated pn junction device (both the p and n regions are highly doped) which emits coherent light when it is forward biased. It is made from Gallium Arsenide (GaAs) which operated at low temperature and emits light in near IR region. Now the semiconductor lasers are also made to emit light almost in the spectrum from UV to IR using different semiconductor materials. They are of very small size (0.1 mm long), efficient, portable and operate at low power. These are widely used in Optical fibre communications, in CD players, CD-ROM Drives, optical reading, laser printing etc. p and n regions are made from same semiconductor material (GaAs). A p type region is formed on the n type by doping zinc atoms. The diode chip is about 500 micrometer long and 100 micrometer wide and thick. the top and bottom faces has metal contacts to pass the current. the front and rare faces are polished to constitute the resonator

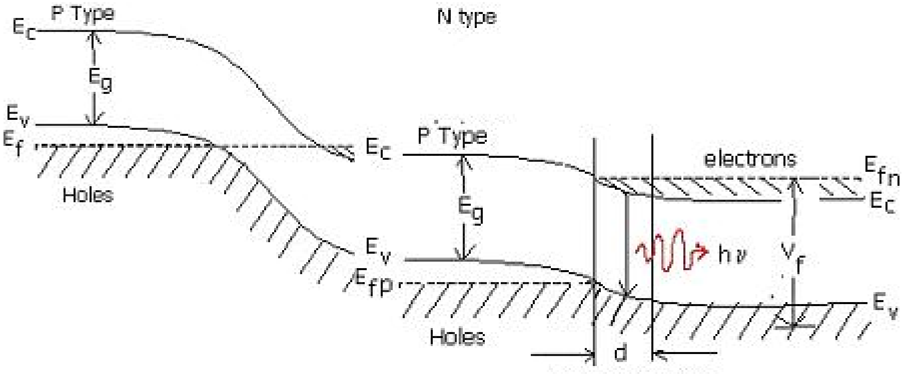


When high doped p and n regions are joined at the atomic level to form pn-junction, the equilibrium is attained only when the equalization of fermi level takes place in this case the fermi level is pushed inside the conduction band in n type and the level pushed inside the valence band in the p type When the junction is forward biased, at low voltage the electron and hole recombine and cause spontaneous emission. But when the forward voltage reaches a threshold value the carrier concentration rises to very high value. As a result the region "d" contains large number of electrons in the conduction band and at the same time large number of holes in the valence band. Thus the upper energy level has large number of electrons and the lower energy level has large number of vacancy, thus population inversion is achieved. The recombination of electron and hole leads to spontaneous emission and it stimulate the others to emit radiation. Ga As produces laser light of 9000 Å in IR region.



Energy Level Diagram of Semiconductor

laser



Energy Level Diagram of Semiconductor laser