DYE LASER,

SEMICONDUCTOR LASER,

PROPERTIES OF LASER LIGHT

AND

APPLICATIONS OF LASERS

By

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Based on the Reference Books

Lasers by Thyagarajan & Ghatak

Electronics: Chapter-23 (Laser): Rakshit & Chattopadhyay

Based on the type of Active Medium, we can classify Lasers as below,

1. Solid State Lasers: **Ruby**, NdYAG, etc.
2. Gas Lasers: **He-Ne**, CO_2, N_2, Ar ion, etc
3. Liquid Laser: Dyes
4. Semiconductor Lasers: p-n junction diode lasers (homojunction and hetero-junction)

Already I taught in class: Ruby Laser, He-Ne Laser.

Home Work given: NdYAG (similar to Ruby) and CO_2 (similar to He-Ne) Lasers

Dye Laser (Liquid Laser)

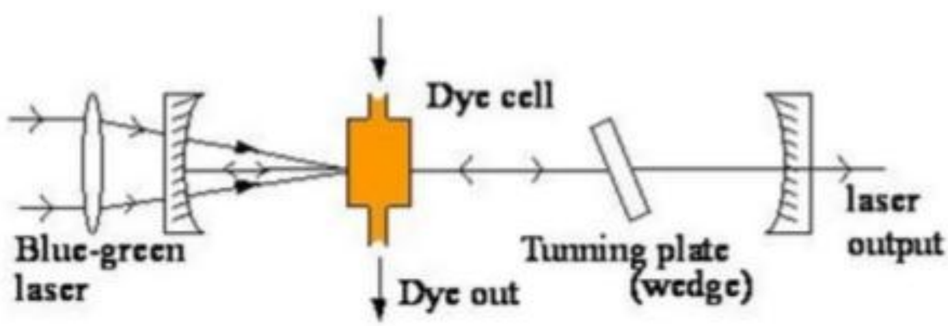
Active medium: Organic dyes, used in the form of liquid. In general dyes are dissolved in chemical solvents such as water, ethyl alcohol, methanol, and ethylene glycol. So the **active medium is a liquid solution** of Organic dye + chemical solvent. Depending on different dyes, the frequency of dye laser most wide range than other lasers (3000 Å to 1.2 μm).

Organic dye: Example: **Rhodamine 6G**, can be used for tuning from 635 nm to 560 nm, and produce laser pulses as short as 16 femtoseconds. Other organic dye will give you other wavelength ranges of the output laser.

Pumping: Strong light source
Example: Flash lamps Or several types of lasers (Diode lasers, Excimer lasers, Nd:YAG lasers, Nitrogen lasers, Ruby lasers)

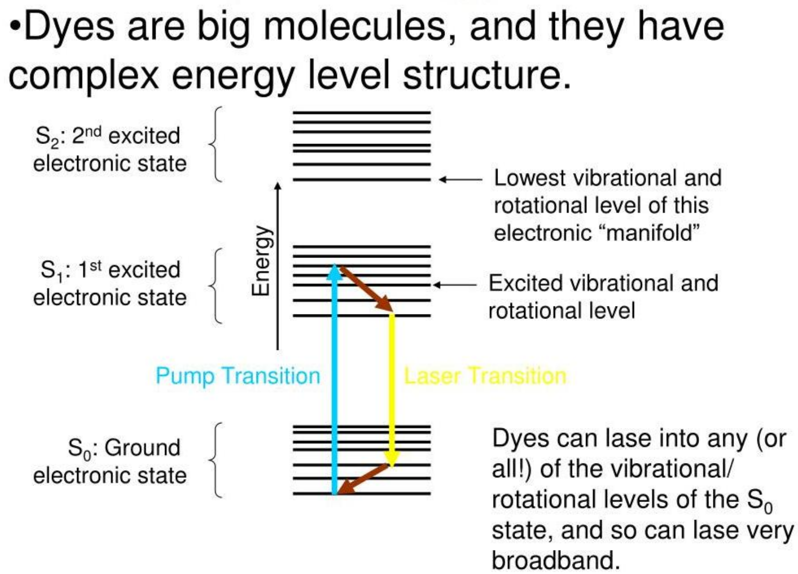
Resonator: Plane parallel mirrors

Construction of Dye Laser System

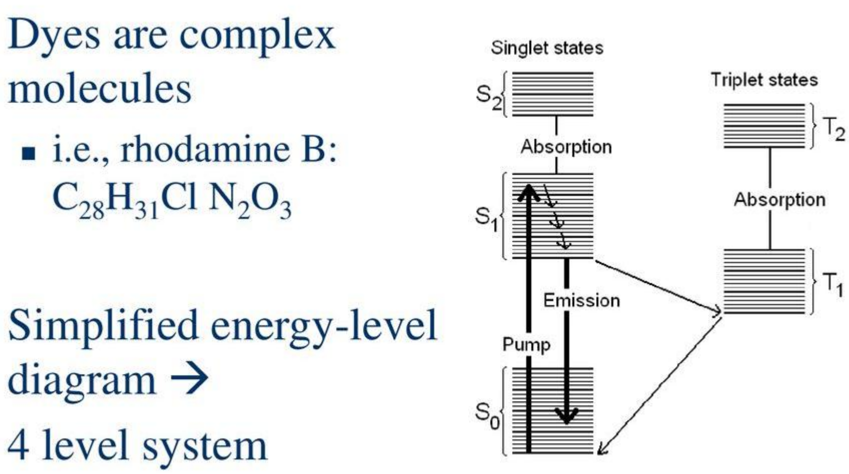


Here, Blue-green laser is used as Optical Pumping Source. You can see two Plano-concave mirrors are placed before and after the Dye cell, these mirrors are acting as a Resonator. Tuning plate is used for frequency tuning of the output laser. When the frequency of a laser light is varying slowly within a certain range (say few nm or micron) and gives you a laser having wavelength/frequency range, then that laser is called Tunable Laser.

Energy Level Diagram of Organic Dyes and Transitions for Laser Action



OR



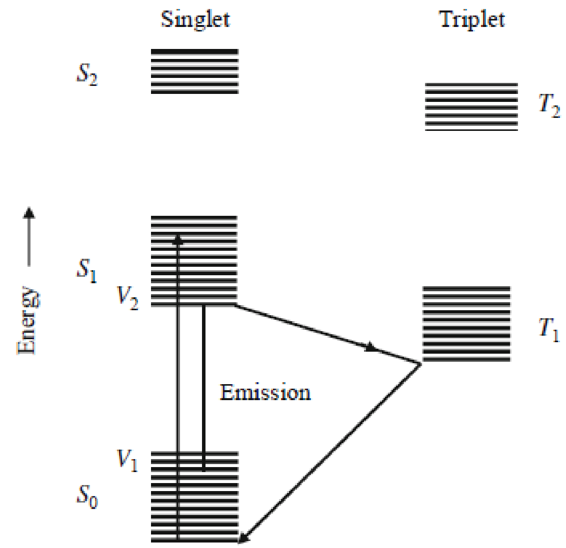
You can see that the optical transitions (pumping and decay transitions) are taking place among the ground (So) and excited (S_1 or S_2) energy levels and these energy levels are manifold levels, means, there are many vibration and rotational energy levels which form a continuum / energy band. As a result, when laser transitions take place from S_1 to S_0 levels (Emission in the above figure), you will get laser light having a range of frequency/wavelength, i.e., the laser is tunable laser.

11.8 Dye Lasers

One of the most widely used tunable lasers in the visible region is the organic dye laser. The dyes used in the lasers are organic substances which are dissolved in solvents such as water, ethyl alcohol, methanol, and ethylene glycol. These dyes exhibit strong and broad absorption and fluorescent spectra and because of this they can be made tunable. By choosing different dyes one can obtain tenability from 3000 Å to 1.2 μm.

The levels taking part in the absorption and lasing correspond to the various vibrational sublevels of different electronic states of the dye molecule. Figure 11.12 shows a typical energy level diagram of a dye in which S_0 is the ground state, S_1 is the first excited singlet state, and T_1, T_2 are the excited triplet states of the dye molecule. Each state consists of a large number of closely spaced vibrational and rotational sublevels. Because of strong interaction with the solvent, the closely spaced sublevels are collision broadened to such an extent that they almost form a continuum.

Fig. 11.12 Typical energy level diagram of a dye molecule



When dye molecules in the solvent are irradiated by visible or ultraviolet radiation then the molecules are excited to the various sublevels of the state S_1. Due to collisions with the solvent molecules, the molecules excited to higher vibrational and rotational states of S_1 relax very quickly (in times $\sim 10^{-11}$–10^{-12} s) to the lowest level V_2 of the state S_1. Molecules from this level emit spontaneously and de-excite to the different sublevels of S_0. Thus the fluorescent spectrum is found to be red shifted against the absorption spectrum.

SEMICONDUCTOR LASER
(DIODE LASER)

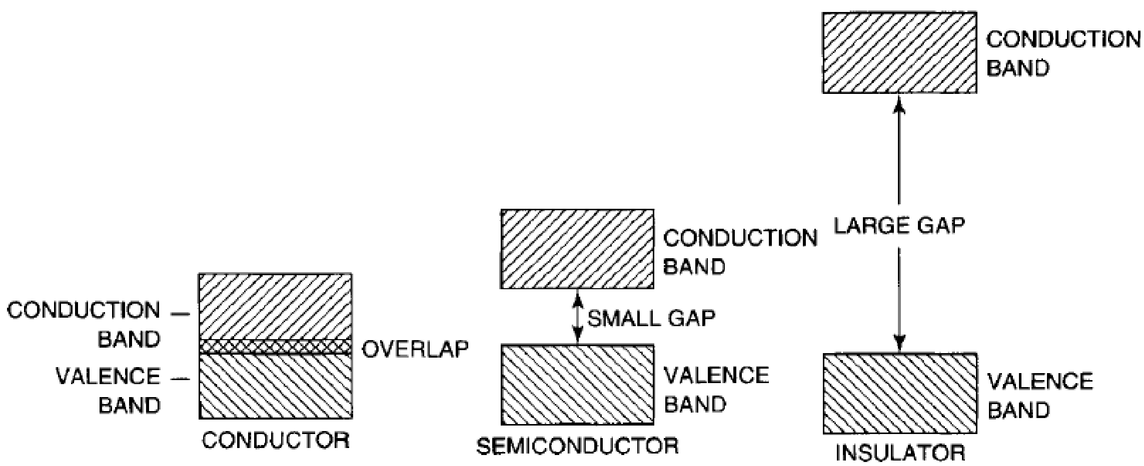
Active Medium: Semiconductor, in general p-n junction diode

Pumping: Electrical power supply

Resonator: Parallel mirrors / basically two opposite polished faces of the diode

Basics of Semiconductor:

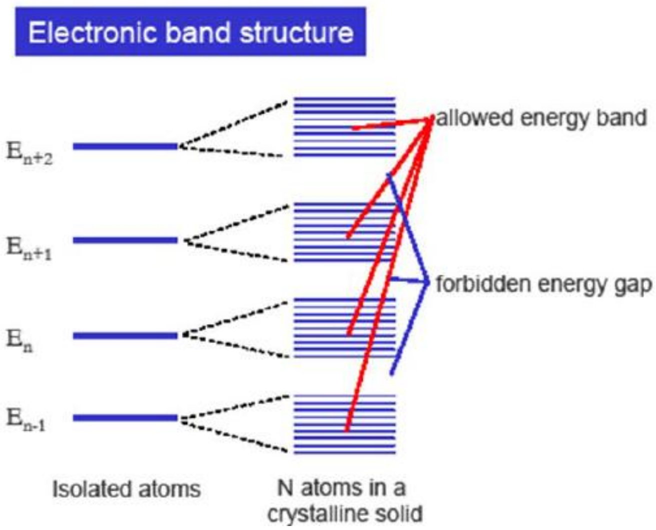
You know very well from your classes on Solid State Physics or Electronics.



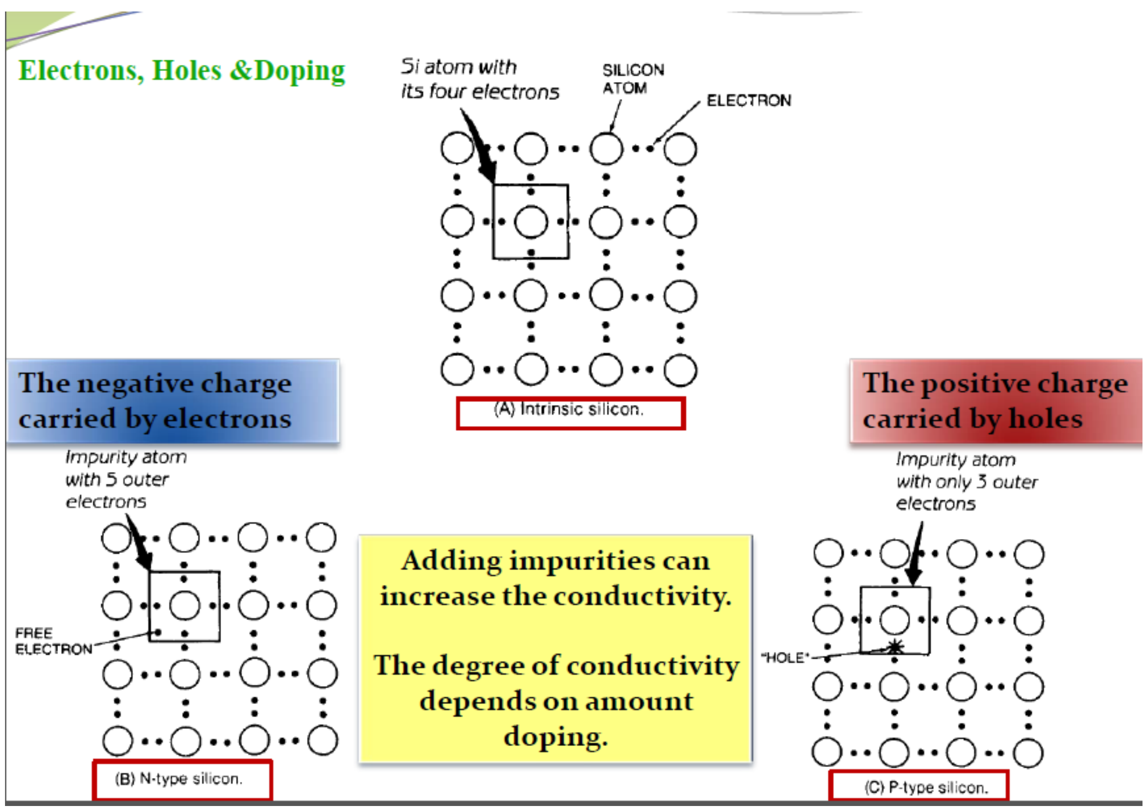
Valence band: in which electrons are bound to atoms.
Conduction band: in which electrons are free to move around in the solid.

The number of electrons N in the valence & conduction bands depends on the band gap energy ΔE & the temperature T as,

$$\frac{N_{conduction}}{N_{valence}} = \exp^{\Delta E / KT}$$



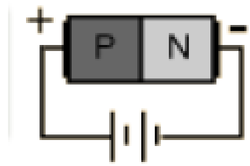
Pauli exclusion principle



Semiconductor diode lasers are called Semiconductor lasers, diode lasers, or laser diodes.

→The first diode lasers were operated at the cryogenic temperature of liquid nitrogen, 77°K. It could only operate in pulsed mode.

➔ The simplest diode lasers generate light from recombination of electron-hole pairs at a **forward-biased p-n** junction.



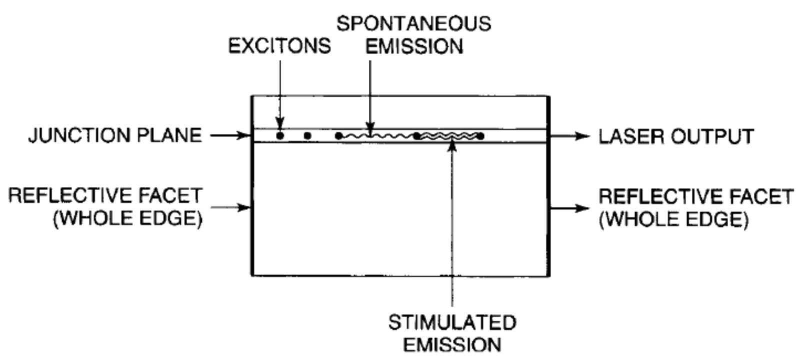
- ➔ Below the laser threshold current, diode laser produces spontaneous emission with an intensity that depends on the drive current
- ➔ To make a good diode laser, a material should be a semiconductor with a **direct band gap,** such that Gallium arsenide (GaAs)

  So, GaAs is a semiconductor used in laser diode. Also AlGaAs is another semiconductor used in laser diode.

  H.W.: what is **direct band gap?** Read from book.

- ➔ The semiconductor material of the diode cuts in such a way that the diode has two reflective surfaces which form resonator.

- ➔ The excitons (electron-hole pairs) are in the thin layer of the p-n junction plane, so stimulated emission increases along the junction.

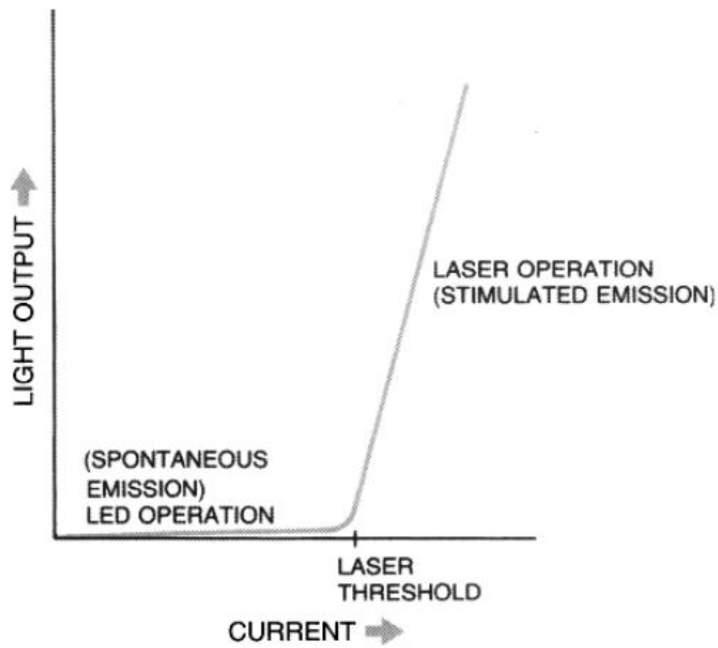


The large population inversion at **high drive current** makes gain high in semiconductor lasers.

About threshold current:

- ➔ All Semiconductor laser diodes have a light current characteristic, with a defined threshold current.

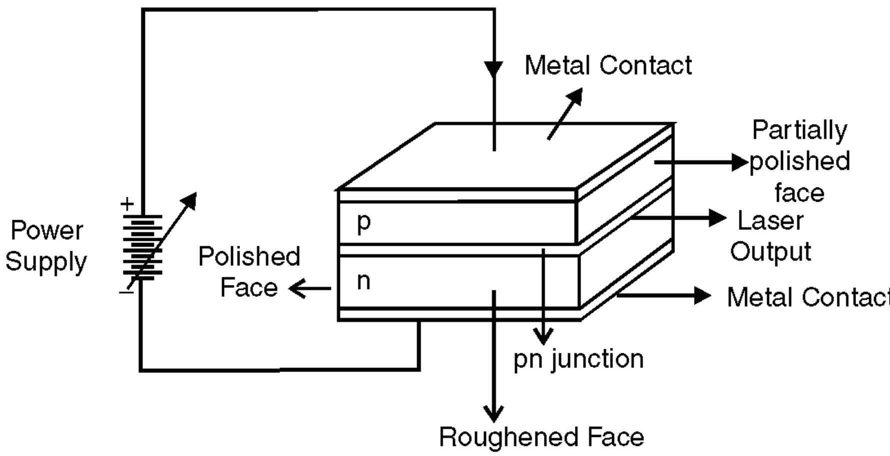
- ➔ **Below** the threshold, the diode operates as a light Emitting Diode (LED).
- ➔ **Above** the threshold, the diode operates as a laser.



Here current means the forward bias current of a p-n junction laser diode.

The key difference between these two diodes is that while an ordinary LED uses spontaneous emission to generate light, the laser diode uses stimulated emission to generate coherent light. For the LED it is beneficial to couple as much light out as possible, while in a laser diode it is necessary to build up a high number of photons in order to get stimulated emission.

Structure / Construction of Semiconductor Diode Laser



See the above figure,

1. **Left face is polished, means one mirror of the resonator; Right face is partially polished, means it is another partial mirror of the resonator.**
2. **As I taught in class, laser comes out from the partial mirror and it is shown right side.**
3. **Above and below surfaces are metal contacts used for forward biased current supply by the power supply.**
4. **Toward and backward faces are roughened faces, has no work at all, but prohibit any emission from these surfaces.**
5. **P-N junction is a thin layer, which is sometimes called the active medium of laser diode. And it is shown in figure that laser output is coming from that thin junction layer of the diode.**

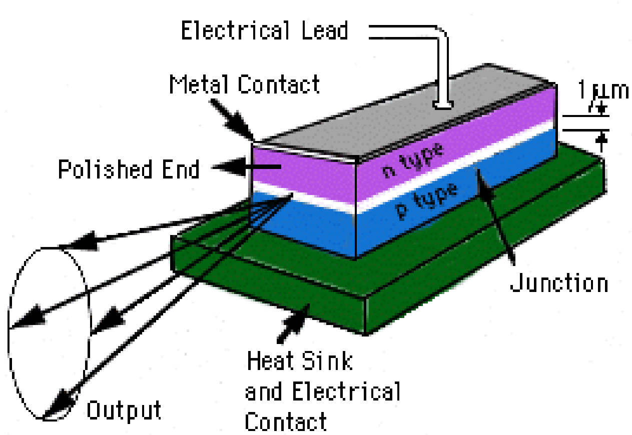


Diagram of Semiconductor Laser

- A diode laser must contain at least three layers: p-type layer, n-type layer, & an intermediate active or junction layer where recombination of holes and electron takes place and causes light emission.
- Lasers are grown by depositing a series of thin layers on a substrate, which is a semiconductor or an insulator.
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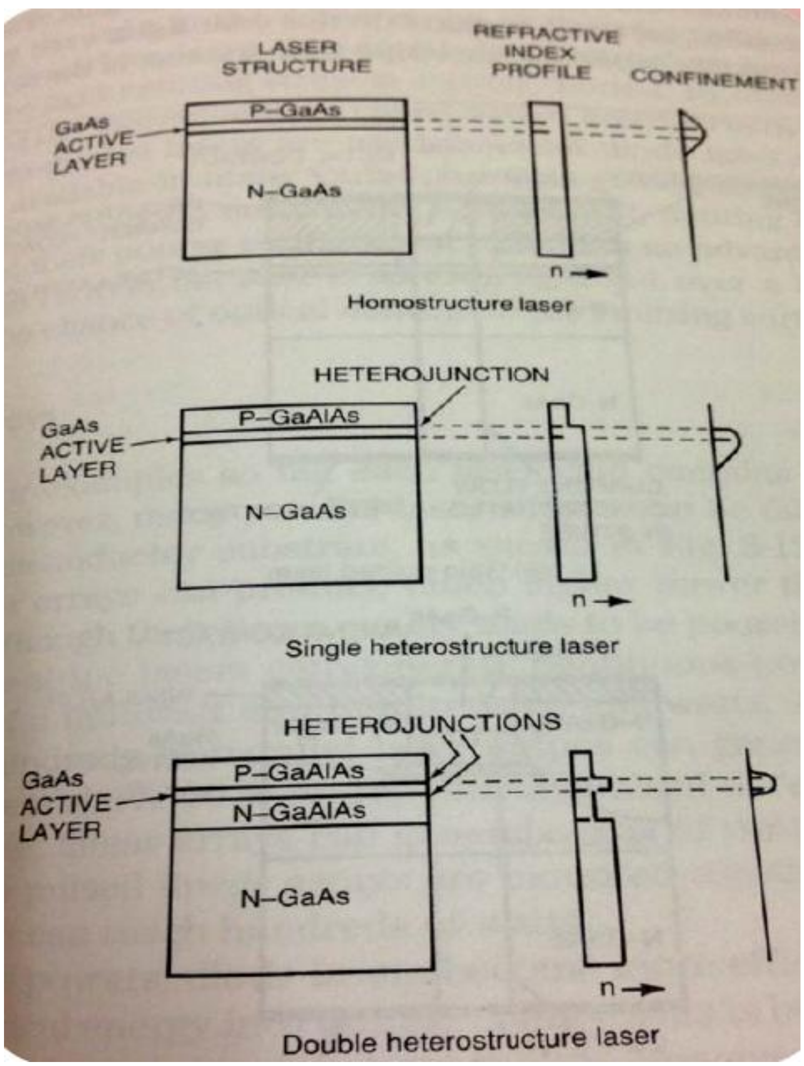
  - The boundaries between active layer & surrounding layers are very important in determining the efficiency of a diode laser.
  - Homo-structure
    Hetero-structure



Additional Reading: Semiconductor Diode Laser

(Book: Lasers by Ghatak and Thyagarajan)

13.1 Introduction

Semiconductor-based light sources such as light-emitting diodes (LED) and laser diodes have revolutionized the application of photonic components in science, engineering, and technology. They have become ubiquitous components and are found in most places, be it markets where they are used as scanners for products, at home where they are found in CD and DVD readers or laser printers, in communication systems as sources, etc. Unlike the lasers discussed earlier, laser diodes are based on semiconductors such as gallium arsenide (GaAs), gallium indium arsenide (GaInAs), gallium nitride (GaN), etc. They cover the range of wavelengths from the blue region to the infrared.

As compared to other laser systems, semiconductor lasers have some very attractive characteristics: they are very small in size, can be directly modulated by varying the drive current, are very efficient converters of electrical energy to light, can be designed to emit a broad range of wavelengths, etc.

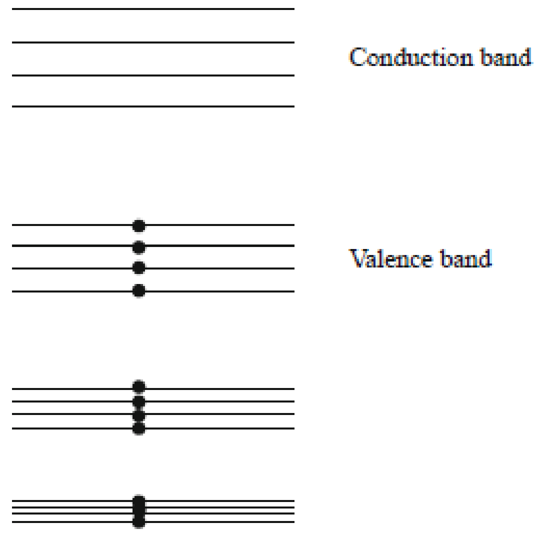
In this chapter, we will discuss the basic principle of operation of semiconductor laser diodes and some of their important properties that lead to their widespread applications.

13.2 Some Basics of Semiconductors

The primary difference between electrons in semiconductors and other laser media is that in semiconductors, all the electrons occupy and share the entire volume of the crystal, while in the case of other laser systems such as neodymium:YAG laser and ruby laser, the lasing atoms are spaced far apart and the electrons are localized to their respective ions with very little interaction with other ions. Thus in a semiconductor, the quantum mechanical wave functions of all electrons overlap with each other and according to Pauli exclusion principle cannot occupy the same quantum state. Thus each electron in the crystal must be associated with a unique quantum state.

The atoms comprising the semiconductor when isolated have the same electron configuration. Thus electrons belonging to different atoms may be in the same

Fig. 13.1 Schematic diagram showing energy band diagram in a solid; each *horizontal line* corresponds to an energy level and *filled circles* represent electrons occupying the levels



energy state. However, when the atoms are brought close together to form the solid, interactions among the atoms lead to a splitting of the energy levels and this leads to the formation of energy bands which are separated by forbidden regions of energy. Figure 13.1 shows a schematic diagram in which each energy level is represented by a horizontal line; in each band formed by a group of energy levels, there are as many sublevels as there are atoms in the crystal. Since the number of atoms is very large, within each band, the allowed energy values are almost continuous. The highest energy band in a solid that is completely filled or occupied by electrons at 0 K is known as the valence band and the next higher band that is either vacant or partially occupied is known as the conduction band.

If the energy gap between the valence band and the conduction band is large, say > 3 eV, then thermal excitation from the valence band to the conduction band is very rare (thermal energy at room temperature of 300 K is about 25 meV). In such a case the medium behaves like an insulator. If the gap is smaller (< 2 eV), then electrons can get thermally excited from the valence band to the conduction band and they exhibit a finite electrical conductivity at temperatures higher than 0 K, which increases with temperature. Such media are referred to as semiconductors.

13.3.3 Interaction with Light

Like in the case of atoms and molecules, electrons in the conduction band and holes in the valence band can interact with incident photons via three different mechanisms:

Absorption: An electron in the valence band can absorb a photon and get excited to the conduction band. Since there are no energy levels within the energy gap, the incident photon has to have a minimum amount of energy for this process to take place. If E_g ($=E_c - E_v$) represents the energy gap, then the photon frequency must be greater than E_g/h. This process of absorption leads to the generation of electron–hole pairs (see Fig. 13.4a).

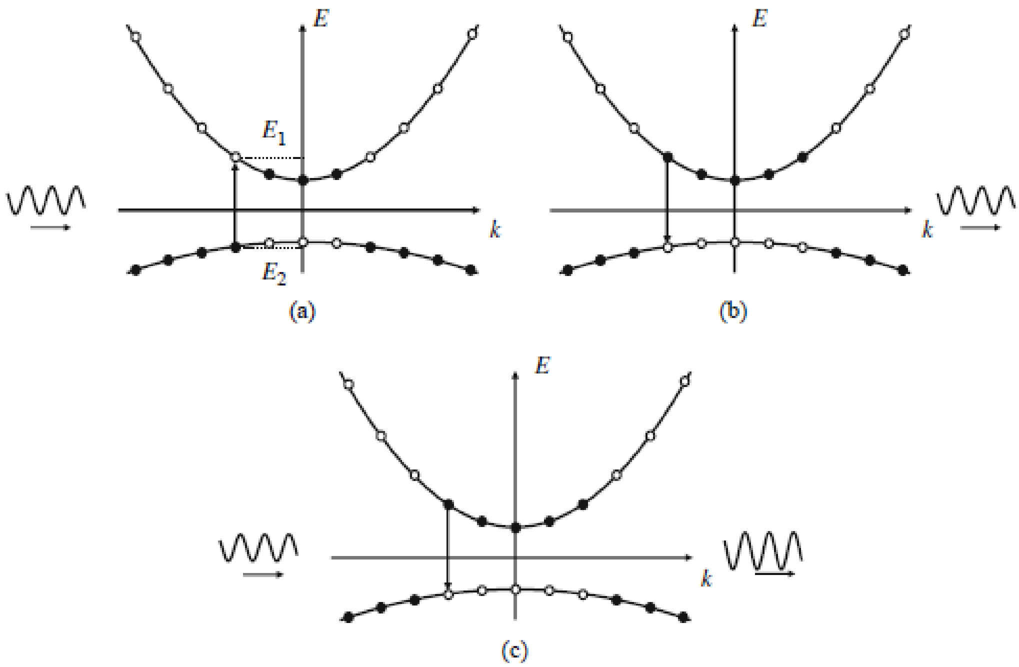


Fig. 13.4 (a) In the absorption process, an electron occupying a state in the valence band can absorb a photon of appropriate energy and get excited to a vacant state in the conduction band. (b) In the spontaneous emission process, an electron occupying a state in the conduction band can emit a photon of appropriate energy and get de-excited to a vacant state in the valence band. (c) In the case of stimulated emission, an incident photon of appropriate energy can stimulate an electron to make a transition from the conduction band to the valence band

Spontaneous emission: An electron in the conduction band can combine with a hole in the valence band (i.e., an electron can jump from the conduction band to a vacant state in the valence band) and release a photon of energy equal to the difference in the energies of the electron before and after the emission process. The photon frequency would be larger than E_g/h. This process takes place even in the absence of any photons and is termed spontaneous emission. The process of spontaneous emission is random and the emitted photon can appear in any direction. Light-emitting diodes are based on spontaneous emission arising out of electron–hole recombination (see Fig. 13.4b).

Stimulated emission: Just like in atomic systems, an incident photon having a frequency greater than E_g/h can induce a de-excitation of electron from the conduction band to the valence band (electron–hole recombination) and the emitted radiation is coherent with respect to the incident radiation. It is this process which is used in semiconductor lasers (see Fig. 13.4c).

Certain conditions are required for the above processes to take place. For absorption of an incident photon, it is essential that there be an electron available in the valence band *and a* vacant state be available in the conduction band at an energy difference corresponding to the energy of the photon (see Fig. 13.4a). Thus if ν is the frequency of the incident photon, then an electron having an energy E_1 lying in the valence band can absorb this photon and get excited to a vacant energy state with energy E_2 lying in the conduction band such that

$$E_2 - E_1 = h\nu \tag{13.15}$$

Similarly for the spontaneous emission of a photon of energy $h\nu$, an electron occupying an energy level with energy E_2 can jump down to a vacant state (hole) with energy E_1 lying in the valence band and lead to a photon of energy $(E_2 - E_1)$. This is also termed electron–hole recombination. For stimulated emission the condition is the same as spontaneous emission with the emitted light being completely coherent with the incident light.

13.4.2 Gain in a Forward-Biased p–n Junction

Consider a p–n junction formed between a p-doped and an n-doped semiconductor as shown in Fig. 13.10a. Because of different carrier concentrations of electrons and holes in the p and n regions, electrons from the n region diffuse into the p region and holes from the p region diffuse into the n region. The diffusion of these carriers across the junction leads to a built-in potential difference between the positively charged immobile ions in the n side and the negatively charge immobile ions in

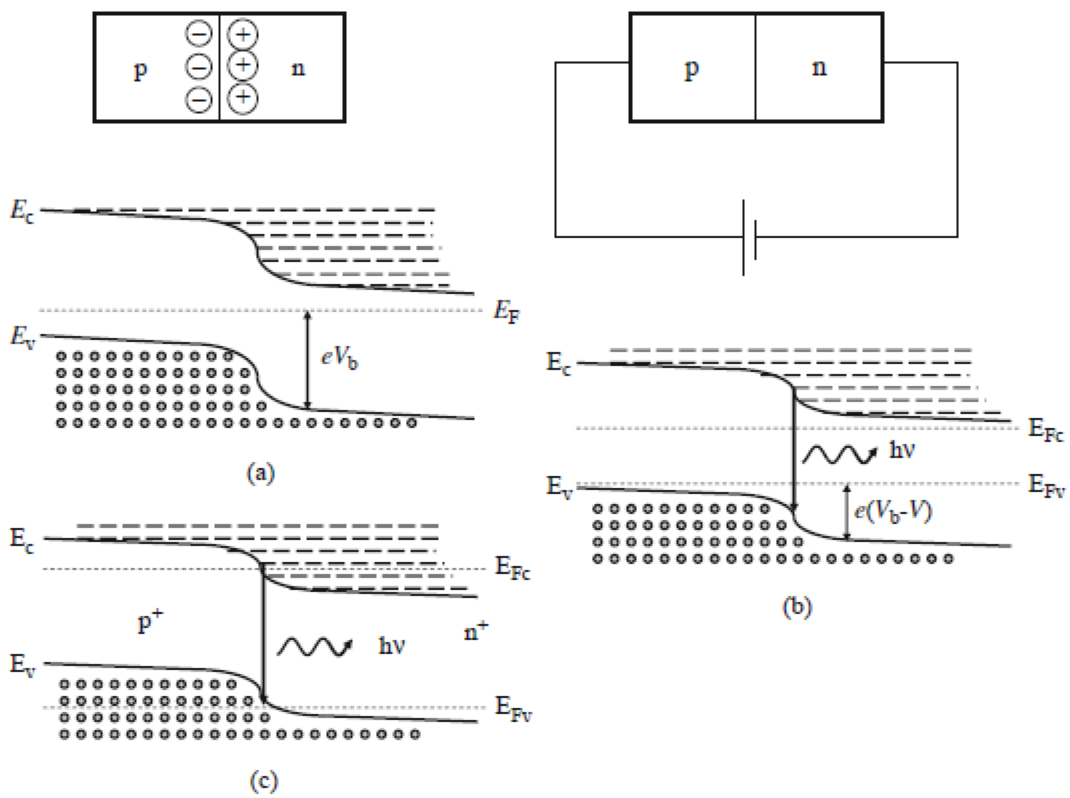


Fig. 13.10 (**a**) Unbiased p–n junction and (**b**) forward-biased p–n junction. When the p–n junction is forward biased, we can create a situation satisfying Eq. (13.35) in the depletion region and thus achieve optical amplification over a certain range of photon energies. (**c**) Forward-biased, heavily doped p–n junction

the p side of the junction. This built-in potential V_b lowers the potential energy of the electrons in the n side with respect to the potential energy of electrons in the p side, which is represented by "bending of energy bands" near the p–n junction as shown in Fig. 13.10a. Note that the Fermi levels on both sides of the p–n junction are aligned at the same energy value. This is necessary because, in the absence of any applied external energy source, the charge neutrality in the material requires that the probability of finding an electron should be the same everywhere and therefore only one Fermi function should be described the carrier distribution. In this case, there will be no net current in the medium.

If we forward bias the p–n junction by means of an external supply voltage V, then the potential energy of electrons in the n side increases and the band moves up. The band offset decreases and the Fermi levels separate out as shown in Fig. 13.10b. The increased potential energy of the carriers brings them into the depletion region, where they recombine constituting a forward current through the junction. The forward biasing leads to injection of electrons and holes into the junction region, where they recombine generating photons via spontaneous emission process. This phenomenon is also referred to as injection luminescence. Note that even though the separation between the quasi-Fermi levels is less than the bandgap energy E_g, there would be light emission because of a forward current through the device. This is the basis of operation of light-emitting diodes (LEDs) and the device therefore does not have any threshold value for the forward current to start emitting light. However, for amplification by stimulated emission, as we saw earlier, the quasi-Fermi levels have to satisfy Eq. (13.35).

It is usually not possible to satisfy Eq. (13.35) in p–n junctions formed between moderately doped p- and n-type semiconductors. However, if one starts with a p–n junction formed by highly doped p- and n-type semiconductors, in which the Fermi levels are located inside the respective bands, application of a strong bias can lead to the gain condition (see Fig. 13.10c). Indeed this is the basis of operation of injection laser diode.

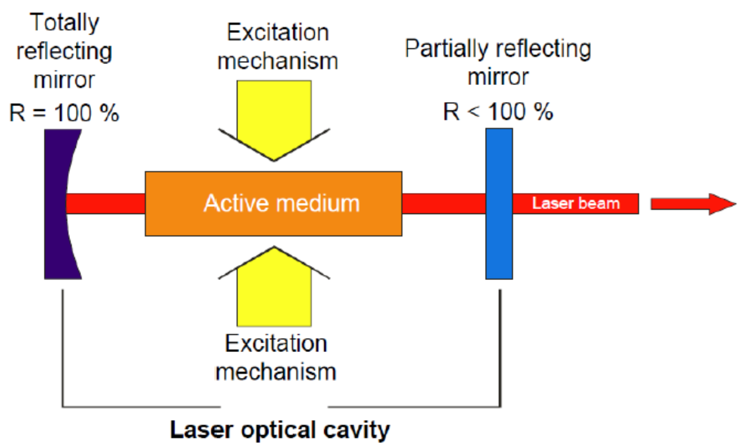
As mentioned earlier, a laser diode consists basically of a forward biased p–n junction of a suitably doped direct bandgap semiconductor material. Two ends of the substrate chip are cleaved to form mirror-like end faces, while the other two ends are saw cut so that the optical resonator is formed in the direction of the cleaved ends only. The large refractive index difference at the semiconductor–air interface provides a reflectance of about 30%, which is good enough to sustain laser oscillations in most semiconductor diodes. This is primarily due to the large gain coefficients that are available in semiconductors (see Fig. 13.7).

Characteristics / Properties of Laser Light:

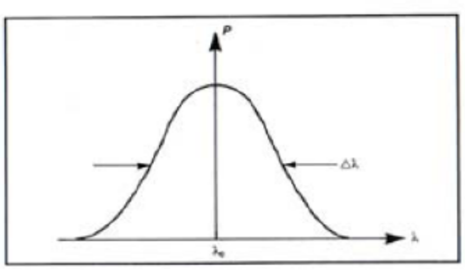
Basically the light from both a laser and any ordinary source of light is electromagnetic in nature, but laser light can be extremely monochromatic, highly directional, and very intense.

Light from the laser arises primarily from stimulated emission and the resonator cavity within which the amplifying medium is kept leads to the following special properties:

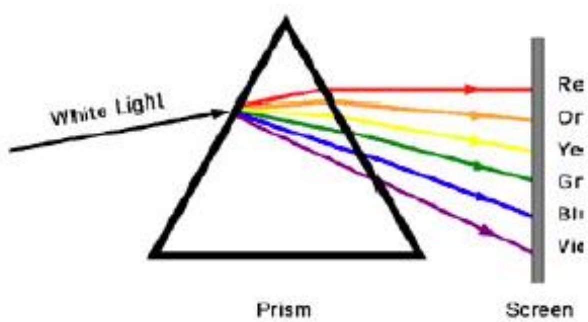
- ➔ **Directionality**
- ➔ **Spectral purity**
- ➔ **High power**
- ➔ **Extremely short pulse durations**



Monochromaticity:



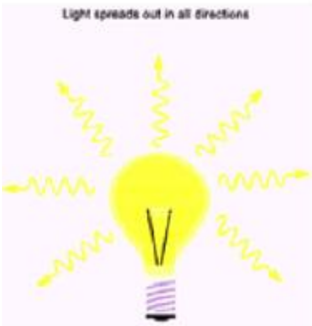
Nearly monochromatic light

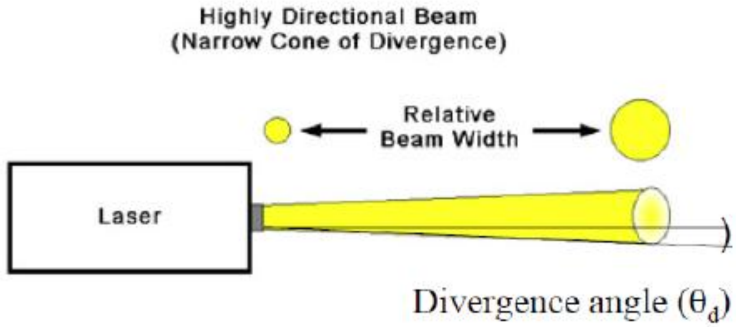


Example:

He-Ne Laser	Diode Laser
$\lambda_0 = 632.5$ nm	$\lambda_0 = 900$ nm
$\Delta\lambda = 0.2$ nm	$\Delta\lambda = 10$ nm

Directionality:



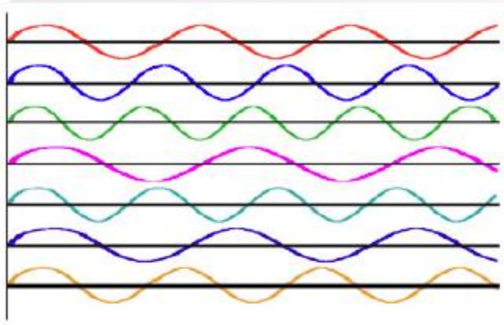


Conventional light source

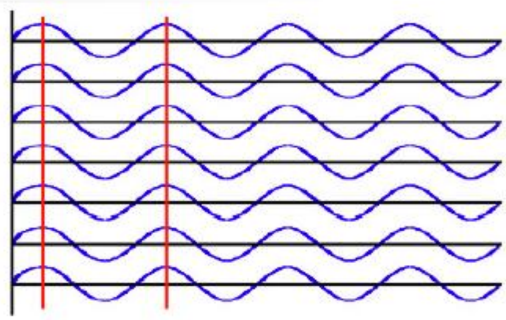
Beam divergence: $\theta_d = \beta\,\lambda / D$

$\beta \sim 1$ = f(type of light amplitude distribution, definition of beam diameter)
λ = wavelenght
D = beam diameter

Coherence:



Incoherent light waves



Coherent light waves

Laser light Cannot: be perfectly monochromatic
be perfectly directional
perfect coherent

For details: Read from the Book: Electronics by Rakshit & Chattopadhyay

The useful features of a laser beam are (*i*) directionality, (*ii*) intensity, (*iii*) monochromaticity, and (*iv*) coherence. We discuss these features below:

(*i*) **Directionality:** Laser beams are highly directional, i.e., they proceed along one direction. The directionality of the beam is measured by the *full angle beam divergence* which is two times the angle subtended by the outer edge of the beam with the beam axis. The outer edge of the beam is taken to be the line where the beam intensity decreases to 1/exp(1) times its value at the axis. Let an aperture of diameter d radiate a beam having a plane wavefront. If λ is the radiated wavelength, the beam travels as a parallel beam through distance of about d^2/λ, termed the *Rayleigh range*. Thereafter, the beam begins to spread with distance owing to diffraction (Fig. 23.1). The aperture diameter d controls the angular spread $\Delta\theta$ of the far-field beam, the relationship between $\Delta\theta$ and d being

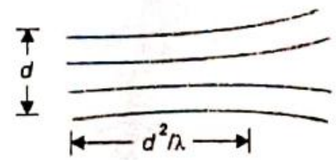


Fig. 23.1 Beam spread beyond Rayleigh range

$$\Delta\theta = \frac{\lambda}{d}.$$

For a typical laser, the beam divergence is less than 10^{-5} radian, showing that the beam spreading is less than 10^{-5} m for every meter.

(*ii*) **Intensity:** Lasers emit narrow beams of light, so that the energy is concentrated in a small region. The spatial and spectral confinement of energy accounts for the high intensity of the laser beam. In fact, a 1 W laser gives out a beam which is more intense than a 100 W ordinary lamp. Laser beams can generate power densities millions of times greater than those on the surface of the sun. When a laser beam is focussed by a lens, the tremendous intensity at the focal point can produce a radiation pressure of about 10^6 kg/cm^2.

(*iii*) **Monochromaticity:** Several physical mechanisms account for the departure from perfect monochromaticity of the light emitted from the source:

(*a*) The discrete energy levels of atoms between which transitions occur are not infinitely narrow. If τ is the lifetime of the state in question, the quantum mechanical uncertainty requires an energy spread $\Delta E = \frac{\hbar}{\tau}$. The corresponding frequency spread is $\Delta\nu = \frac{\Delta E}{2\pi\hbar} = \frac{1}{2\pi\tau}$. This *intrinsic* or *natural broadening* is relatively small and often masked by other mechanisms.

(*b*) In a gas, an atom emitting a photon can collide with other atoms, ions, or walls of the container, particularly at high temperatures. During the short collision time, the phase of the radiated wavetrain is changed. This random dephasing collisions of the atoms produce a broadening, called the *collision broadening*, of the emitted line.

(*c*) The atoms or molecules emitting the photons move in a gas with high thermal velocities. Due to the *Doppler effect*, there is an apparent shift of the frequency of the emitted light. The atoms travelling towards the observer appear to emit light of a higher frequency than the stationary atoms, whereas the receding atoms emit light of a lower frequency. The line broadening caused by the Doppler effect is known as *Doppler broadening*.

The Doppler broadening is usually larger than the natural broadening. At high pressures, the collision broadening often predominates. The departure from monochromaticity of a wave is expressed in terms of the relative bandwidth $\xi = \frac{\Delta\nu}{\nu_o}$, where $\Delta\nu$ is the linewidth giving the frequency spread and ν_o is the central frequency of the light beam. The quantity $\Delta\nu$ is the width of the intensity versus frequency plot where the intensity drops to 1/2 the peak intensity I_m (Fig. 23.2*a*). Figure 23.2(*b*) shows that the light given out by a laser is much more monochromatic than that emitted by a conventional source. For a laser, the wavelength spread is about 10^{-9} nm at $\lambda = 600$ nm.

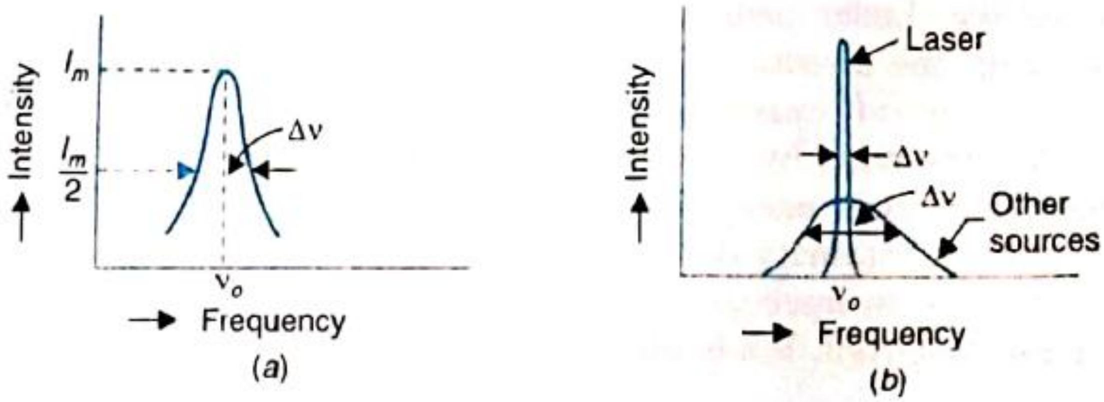


Fig. 23.2 (a) Nonmonochromaticity of a line: (b) Strong monochromaticity of a laser beam.

(*iv*) **Coherence:** Laser radiation is characterised by a high degree of coherence, *i.e.*, a high degree of ordering of the light field compared to other sources.

Temporal Coherence: Let E_1 be the electric field of the light wave at the point (x, y, z) at time t_1, and E_2 be the same at the same point (x, y, z) at a later time t_2. If the phase difference between the two fields is a constant during the measurement of time, the wave is said to have *temporal coherence*. If the phase difference changes irregularly during the time of measurement, the temporal coherence is lost.

The average time in which the wave can be represented as a pure sine wave is termed the *coherence time* τ_c (Fig. 23.3). The coherence time τ_c and the frequency spread $\Delta\nu$ of the wave are related by $\tau_c = \frac{1}{\Delta\nu}$.

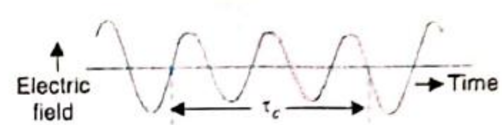


Fig. 23.3 Coherence time τ_c

The frequency spread $\Delta\nu$ measuring the deviation from perfect monochromaticity and therefore the coherence time, arises from factors such as natural, collisional and Doppler broadening, as discussed above. If ν_o is the central frequency, the major part of the radiant energy is confined to frequencies ranging from $\nu_o - \frac{\Delta\nu}{2}$ to $\nu_o + \frac{\Delta\nu}{2}$.

The coherence time gives an idea of the time interval in which the phase in a quasimonochromatic light remains correlated. For a perfectly collimated beam, the phase is correlated over the distance $L_c = c\tau_c = \frac{c}{\Delta\nu}$, where c is the velocity of light in free space. The distance L_c is termed the *longitudinal coherence length* or simply the *coherence length*.

The degree of nonmonochromaticity ξ can be expressed in terms of τ_c and L_c:

$$\xi = \frac{\Delta\nu}{\nu_o} = \frac{1/\tau_c}{\nu_o} = \frac{c}{L_c \nu_o} .$$

So, when the coherence time is large, ξ is small and hence the monochromaticity is high. Therefore, *the concept of temporal coherence is intimately linked with monochromaticity.*

Spatial Coherence: For a perfectly collimated beam, the phase is the same at all points on any surface normal to the direction of propagation. Thus there is a perfect transverse coherence or spatial coherence in the beam. If the beam is imperfectly collimated, the transverse coherence is not perfect. Spatial coherence is determined here in terms of a *lateral* or a *transverse coherence length* L_t which is the distance in a plane transverse to the main propagation direction over which the phases at two points are correlated. The individual phases change, but they change together, maintaining the correlation. Interference is obtained if the light from the two points separated by a distance less than L_t is brought together. It follows that *a spatially coherent beam is markedly directional*.

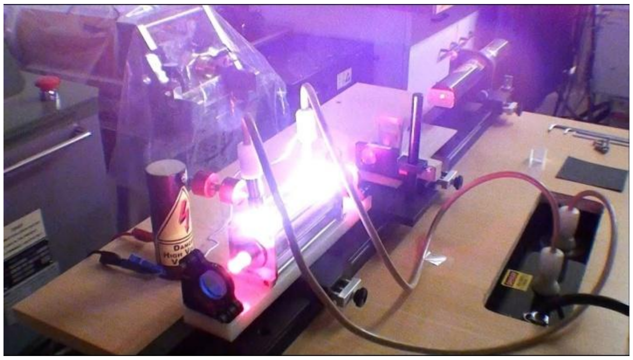
In terms of the photon picture, a light beam is perfectly coherent when all the constituent photons have the same energy, the same direction of momentum, and identical polarization. The primary characteristics of laser light, namely, intensity, directionality, and monochromaticity are linked with the high degree of coherence possessed by it. Therefore, *the most important feature of a laser radiation is its coherence.*

Applications of Lasers: Read from any standard book

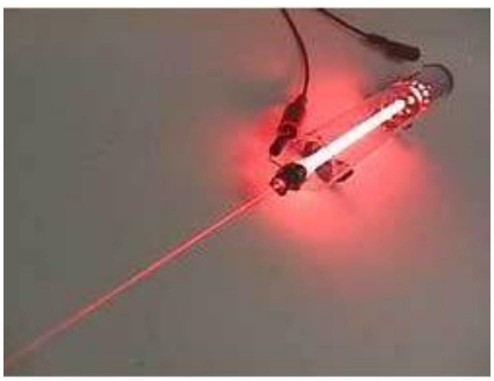
1. **Medical science:** Write a short note by yourself
2. **Industry:** Write a short note by yourself
3. **Defense/ Military:** Write a short note by yourself
4. **Research in physics, chemistry, biology:** Write a short note by yourself
5. **Teaching and learning /general laboratory:** Write a short note by yourself
6. **Daily life (laser pointer, laser printer, CD/DVD writing/reading, barcode scanner, etc.):** Write a short note by yourself
7. **Fiber optic communication:** Write a short note by yourself
8. **Holography**

Extra Flavour

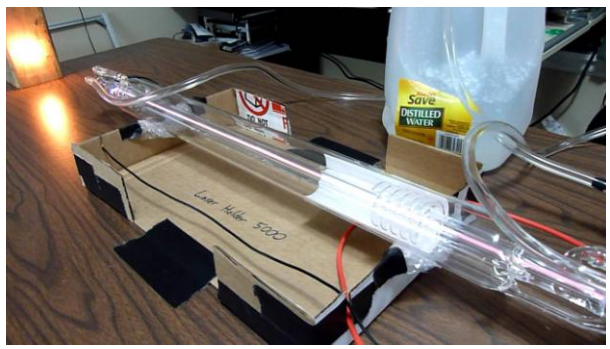
Ruby Laser



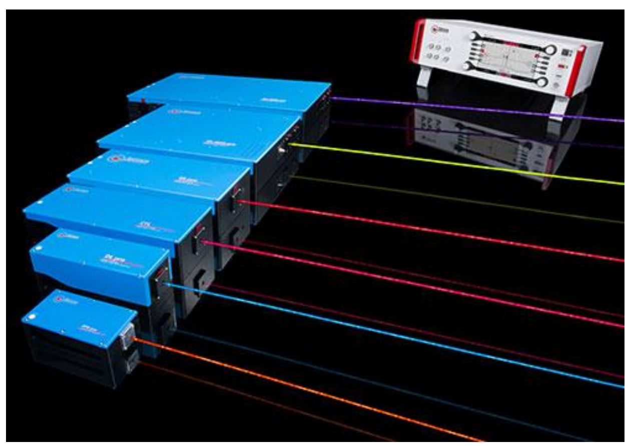
He-Ne Laser



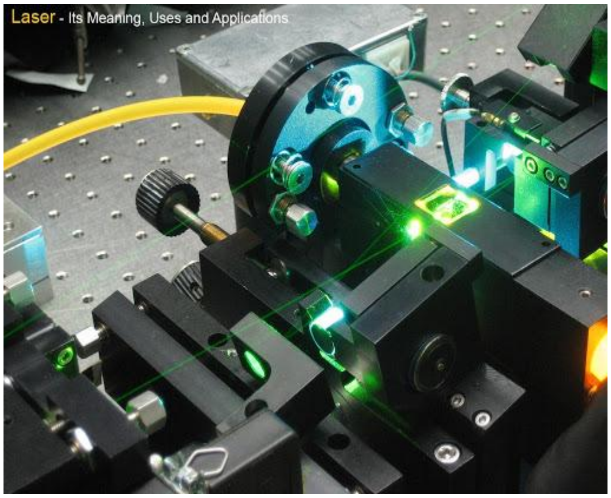
CO_2 Laser

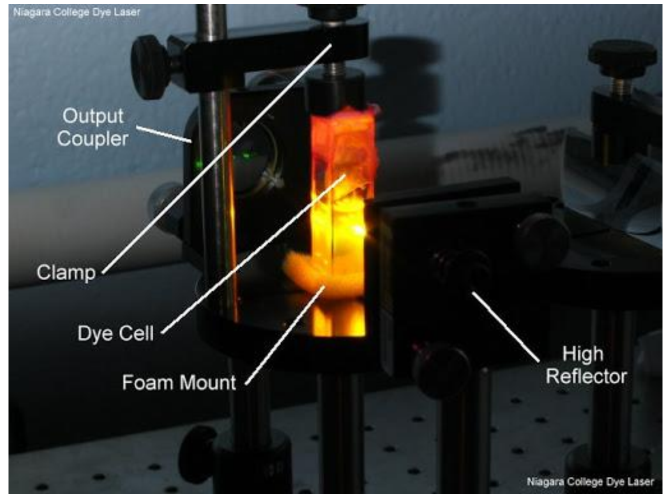


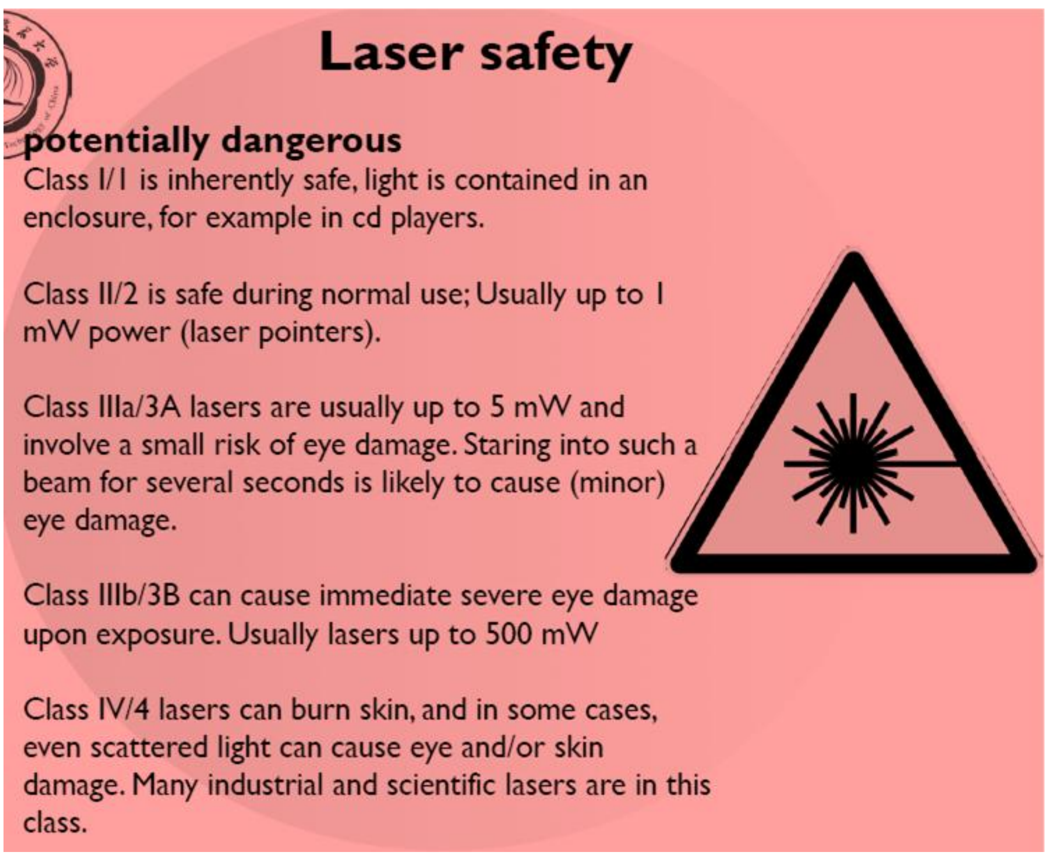
Diode Laser



Dye Laser







Solve Numerical Problems from Any Standard Undergraduate Book on Optics