MODULE-5

Lasers, Fiber optics & Superconductivity

MODULE 5	**Lasers, Fiber optics & Superconductivity**	
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<u>L1: Principle of Laser and its Properties, Amplification of light by population inversion</u>

Introduction to LASER

The name LASER is an acronym for *Light Amplification by Stimulated Emission of Radiation*. As the name suggests, LASER is an optical device which *produces light through a process of optical amplification based on the principle of stimulated emission of electromagnetic radiation.*

To understand theprinciple of LASER, we should have basic knowledge about two types of emission as follows:-

Spontaneous emission:

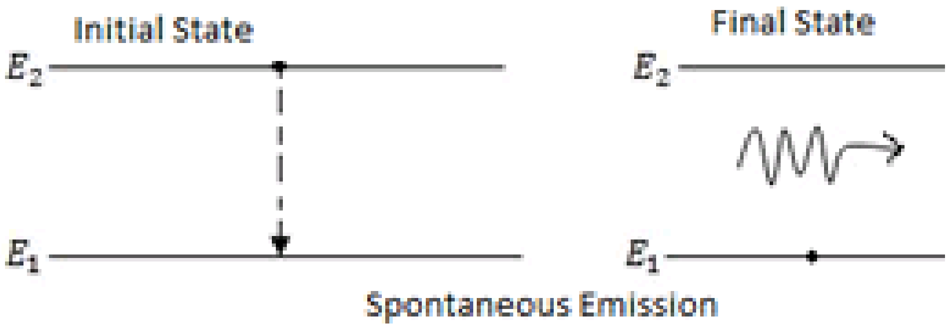

Fig. 5.1. Mechanism of Spontaneous emission

Spontaneous emission is when an atom in a higher energy level drop down to a lower energy level and a photon is emitted with energy equal to the energy difference between the two levels. Suppose the atom is in the higher excited state (Fig. 5.1.) E_2, if we just leave the atom there it will eventually come down to the lower energy state by emitting a photon having energy (E_2-E_1). **This process is called spontaneous emission**. Usually spontaneous emission happens very quickly after an atoms gets into an excited state. In other words, the lifetime of the excited state is very short (the atom only stays in the high energy level for a very short time). However, there are some excited states where an atom can remain in the higher energy level for a longer time than usual before dropping down to a lower level. These excited states are called metastable state

Stimulated emission:

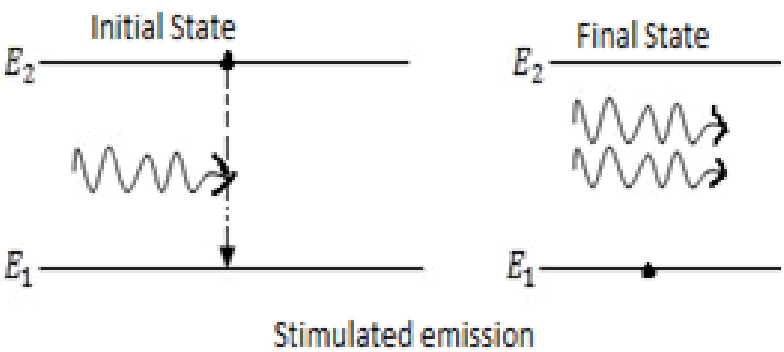

Fig. 5.2. Mechanism of Stimulated emission

As the picture (Fig. 5.2.) above shows, stimulated emission happens when a photon with an energy equal to the energy difference between two levels interacts with an atom in the higher level with stimulated absorption. This stimulates the atom to emit an identical photon and drop down to the lower energy level. This process results in two photons at the end.

Difference between Spontaneous Emission and Stimulated Emission

Spontaneous Emission	Stimulated Emission
(i) The transition of an atom from the excited state to the ground state happens as a result of the natural tendency of the atom without the action of any external agent. The radiation produced as a result of such transitions is called as spontaneous radiation.	(i) Stimulated emission of radiation is the process whereby photons are used to generate other photons that have exact phase and wavelength as that of parent photon.
(ii) This phenomenon is found in LEDs, Fluorescent tubes.	(ii) This is the key process of formation of laser beam.
(iii) There is no population inversion	(iii) Population inversion is achieved by various ‘pumping’ techniques to get amplification
(iv) In spontaneous emission the energy transfer is less.	(iv) In stimulated emission energy transfer is twice that of spontaneous emission.
(v)The light emitted in spontaneous emission is monochromatic and non-polarized.	(v) The light emitted in stimulated emission is monochromatic and polarized.

Principle of LASER beam

A laser works by a process called stimulated emission. In the stimulated emission process, more and more identical photons being emitted in the following way: Imagine we have an atom in an excited metastable state and it drops down to the ground state by emitting a photon. If this photon then travels through the material and meets another atom in the metastable excited state this will cause the atom to drop down to the lower energy level and another photon to be emitted. Now there are two photons of the same energy. If these photons then both move through the material and each interacts with another atom in a metastable state, this will result in them each causing an additional photon to be released, i.e. from 2 photons we then get 4, and so on!

This is how laser light is produced. This can only happen if there are many atoms in a metastable state. If most of the atoms are in the ground state, then they will just absorb the photons and no extra photons will be emitted. However, if more atoms are in the excited metastable state than in the ground state, then the process of stimulated emission will be able to continue. Usually in atoms, most of the atoms are in the lower energy levels and only a few are in excited states. **When most of the atoms are in the excited metastable state and only a few are in the ground state, this is called population inversion and this is when stimulated emission can occur**. To start off the process, the atoms first have to be excited up into the metastable state. This is done using an external energy source and the process is known as population inversion.

Population inversion: Population inversion is when more atoms are in an excited state than in their ground state. It is a necessary condition to sustain a laser beam, so that there are enough excited atoms that can be stimulated to emit more photons.Therefore, materials used to make laser light must have metastable states which can allow population inversion to occur when an external energy source is applied.

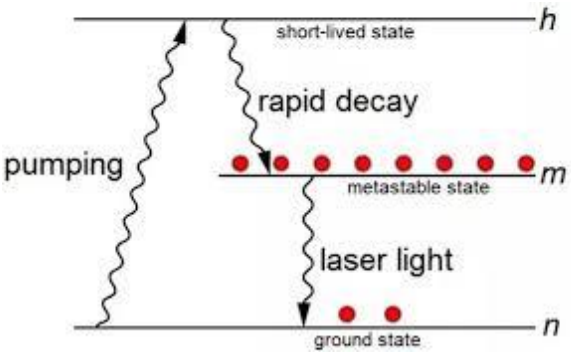

Fig. 5.3. Mechanism of pumping and laser action

Amplification of light by population inversion or LASER action:

For the generation of laser, stimulated emission process is essential. When the population inversion exists between upper and lower levels among atomic systems, it is possible to realize amplified stimulated emission and the stimulated emission has the same frequency and phase as the incident radiation. In atomic, atomic, molecular or ionic systems the upper energy levels are less populated than the lower energy levels under equilibrium conditions. Pumping mechanism excites say, atoms to a higher energy level by absorption. The atom stays at the higher level for certain duration and decays to the lower stable ground level spontaneously, emitting a photon, with a wavelength decided by the difference between the upper and the lower energy levels. **This is referred to as spontaneous emission and the photon is called spontaneous photon**.

The spontaneous emission or fluorescence has no preferred direction and the photons emitted have no phase relations with each other, thus generating an incoherent light output. But it is not necessary that the atom is always de-excited to ground state. It can go to an intermediate state, called metastable state with a radiation less transition, where it stays for a much longer period than the upper level and comes down to lower level or to the ground state. Since period of stay of atoms in the metastable state is large, it is possible to have a much larger number of atoms in metastable level in comparison to the lower level so that the population of metastable state and the lower or ground state is reversed. i.e. there are more atoms in the upper metastable level than the lower level. **This condition is referred to as population inversion**.

Once this is achieved, laser action is initiated in the following fashion. The atom in the metastable state comes down to the ground state emitting a photon. This photon can stimulate an atom in the metastable state to release its photon in phase with it. The photon thus released is called stimulated photon. It moves in the same direction as the initiating photon, has the same wavelength and polarization and is in phase with it, thus producing amplification. Since there are a large number of initiating photons, it forms an initiating electromagnetic radiation field. An avalanche of stimulated photons is generated, as the photons traveling along the length of the active medium stimulates a number of excited atoms in the metastable state to release their photons. This is referred to as the stimulated emission. These photons number and consequently the intensity of stimulated photons increases as they traverse through the active medium, thus increasing the intensity of radiation field of stimulated emission. **This process produces LASER beam.**

Properties/characteristics of LASER

Laser light has three unique properties/characteristics that make it different than "ordinary" light, as follows:

(i) Monochromatic (ii) Directional (iii) Coherent

(i) Monochromatic means that it consists of one single colour or wavelength. Even through some lasers can generate more than one wavelength, the light is extremely pure and consists of a very narrow spectral range.

(ii) Directional means that the beam is well collimated (very parallel) and travels over long distances with very little spread.

(iii) Coherent means that all the individual waves of light are moving precisely together through time and space, i.e. they are in same phase or constant phase.

L2: Types of lasers, lasing action of Ruby laser

Types of lasers: lasers are mainly classified into five types,

1. Solid-State Lasers
2. Gas Lasers
3. Fiber Lasers
4. Liquid Lasers (Dye Lasers)
5. Semiconductor Lasers (Laser Diodes)

Lasing action of Ruby laser:

A ruby laser is a solid-state laser that uses the synthetic ruby crystal as its laser medium. Ruby laser is the first successful laser developed by T. Maiman in 1960. It is one of the few solid-state lasers that produce visible light. It emits deep red light of wavelength 694.3 nm. A ruby laser consists of three important elements: laser medium, the pump source, and the optical resonator. It is shown in the figure 5.4 shown below.

Construction of ruby laser

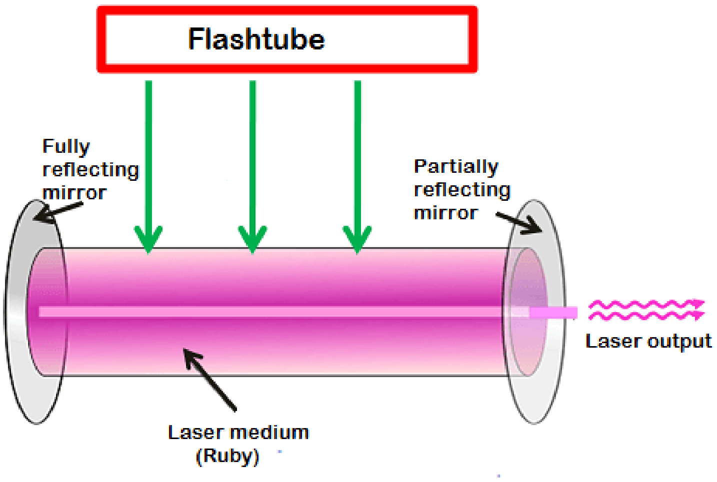

Fig. 5.4. Ruby LASER

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(i) Laser medium or gain medium in ruby laser

In a ruby laser, a single crystal of ruby (Al_2O_3: $Cr3^+$) in the form of cylinder acts as a laser medium or active medium. The laser medium (ruby) in the ruby laser is made of the host of sapphire (Al_2O_3) which is doped with small amounts of chromium ions (Cr^{3+}). The ruby has good thermal properties.

(ii) Pump source or energy source in ruby laser

The pump source is the element of a ruby laser system that provides energy to the laser medium. In a ruby laser, population inversion is required to achieve laser emission. Population inversion is the process of achieving the greater population of higher energy state than the lower energy state. In order to achieve population inversion, we need to supply energy to the laser medium (ruby). In a ruby laser, we use flashtube as the energy source or pump source. The flashtube supplies energy to the laser medium (ruby). When lower energy state atoms in the laser medium gain sufficient energy from the flashtube, they jump into the higher energy state or excited state.

(iii) Optical resonator

The ends of the cylindrical ruby rod are flat and parallel. The cylindrical ruby rod is placed between two mirrors. The optical coating is applied to both the mirrors. The process of depositing thin layers of metals on glass substrates to make mirror surfaces is called silvering. Each mirror is coated or silvered differently. At one end of the rod, the mirror is fully silvered whereas, at another end, the mirror is partially silvered. The fully silvered mirror will completely reflect the light whereas the partially silvered mirror will reflect most part of the light but allows a small portion of light through it to produce output laser light.

Working of ruby laser

The ruby laser is a three level solid-state laser. In a ruby laser, optical pumping technique is used to supply energy to the laser medium. Optical pumping is a technique in which light is used as energy source to raise atoms from lower energy level to the higher energy level. Consider a ruby laser medium consisting of three energy levels E_1, E_2, E_3 with N number of atoms.

We assume that the energy levels will be $E_1 < E_2 < E_3$. The energy level E_1 is known as ground state or lower energy state, the energy level E_2 is known as metastable state, and the energy level E_3 is known as pump state.

Let us assume that initially most of the atoms are in the lower energy state (E_1) and only a tiny number of atoms are in the excited states (E_2 and E_3).

Ruby laser is a three level solid state laser

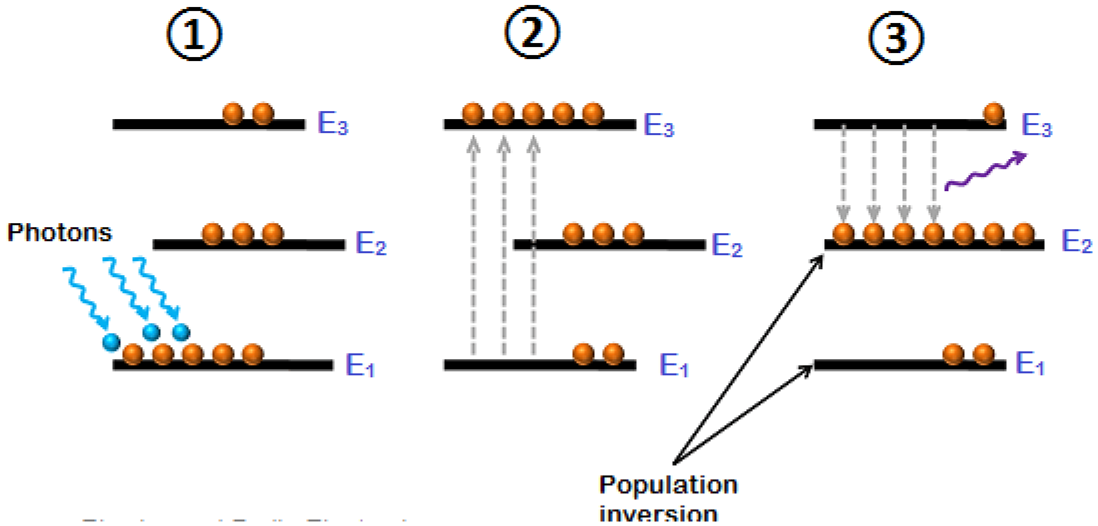

Fig. 5.5. Three level LASER system

When light energy is supplied to the laser medium (ruby), the atoms in the lower energy state or ground state (E_1) gains enough energy and jumps into the pump state (E_3).

The lifetime of pump state E_3 is very small (10^{-8} sec) so the atoms in the pump state do not stay for long period. After a short period, they fall into the metastable state E_2 by releasing radiation less energy. The lifetime of metastable state E_2 is 10^{-3} sec which is much greater than the lifetime of pump state E_3. **Therefore, the atoms reach E_2 much faster than they leave E_2. This results in an increase in the number of atoms in the metastable state E_2 and hence population inversion is achieved.**

After some period, the atoms in the metastable state E_2 falls into the lower energy state E_1 by releasing energy in the form of photons. **This is called spontaneous emission of radiation**.

When the emitted photon interacts with the atom in the metastable state, it forcefully makes that atom fall into the ground state E_1. As a result, two photons are emitted. **This is called stimulated emission of radiation.**

When these emitted photons again interacted with the metastable state atoms, then 4 photons are produced. Because of this continuous interaction with the atoms, millions of photons are produced.

In an active medium (ruby), a process called spontaneous emission produces light. The light produced within the laser medium will bounce back and forth between the two mirrors. This stimulates other atoms to fall into the ground state by releasing light energy. This is called stimulated emission. Likewise, millions of atoms are stimulated to emit light. Thus, the light gain is achieved.

The amplified light escapes through the partially reflecting mirror to produce laser light.

L3: Lasing action of He-Ne laser, Application of LASER

He-Ne laser:

A He-Ne laser is a gas laser consists of three important elements; energy pump, optical gain medium and optical resonator or cavity.

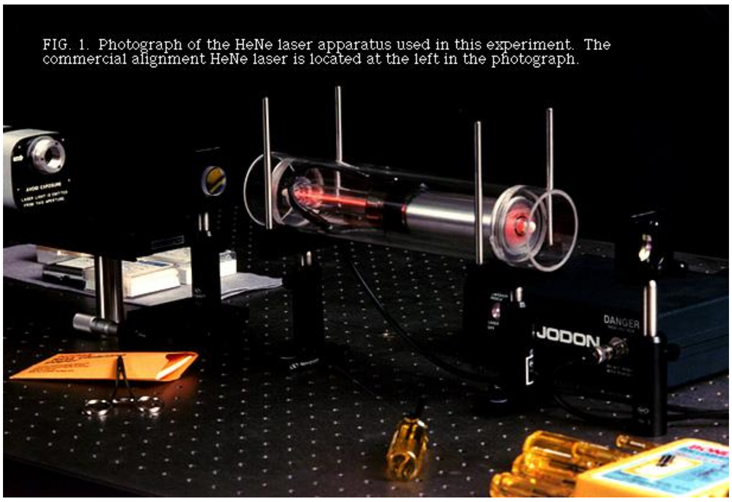

Fig. 5.6. He-Ne LASER

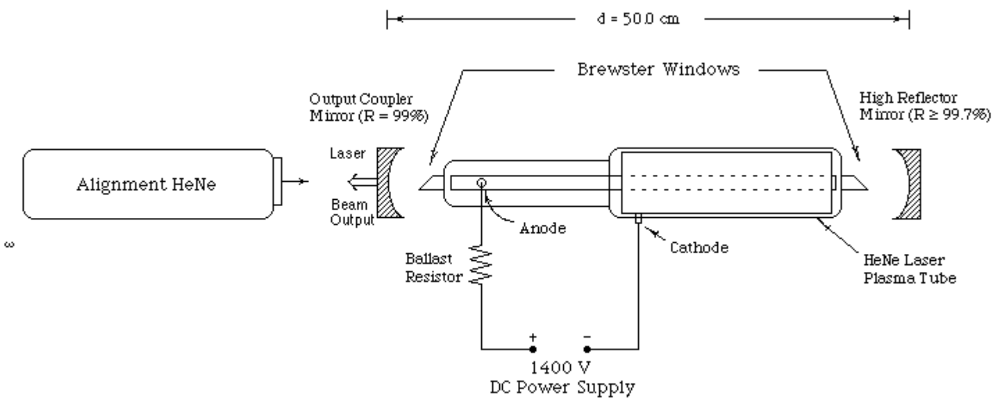

Fig. 5.7. He-Ne LASER construction

(i) Energy pump: A 1400 V high voltage, DC power supply maintains a glow discharge or plasma in a glass tube containing an optimal mixture (typically 5:1 to 7:1) of helium and neon gas, shown in the above diagram. The discharge current is limited to about 5 mA. Energetic atoms accelerating from the cathode to the anode collide with He and Ne atoms in the laser tube, producing a large number of neutral He and Ne atoms in excited states. He and Ne atoms in excited states can deexcite and return to their ground states by spontaneously emitting light. This light makes up the bright pink-red glow of the plasma that is seen even in the absence of laser action. The process of producing He and Ne in specific excited states is known as pumping and in the He-Ne laser this pumping process occurs through atom-atom collisions in a discharge. In other types of lasers, pumping is achieved by light from a bright flash lamp or by chemical reactions. Common to all lasers is the need for some process to prepare an ensemble of atoms, ions or molecules in appropriate excited states so that a desired type of light emission can occur.

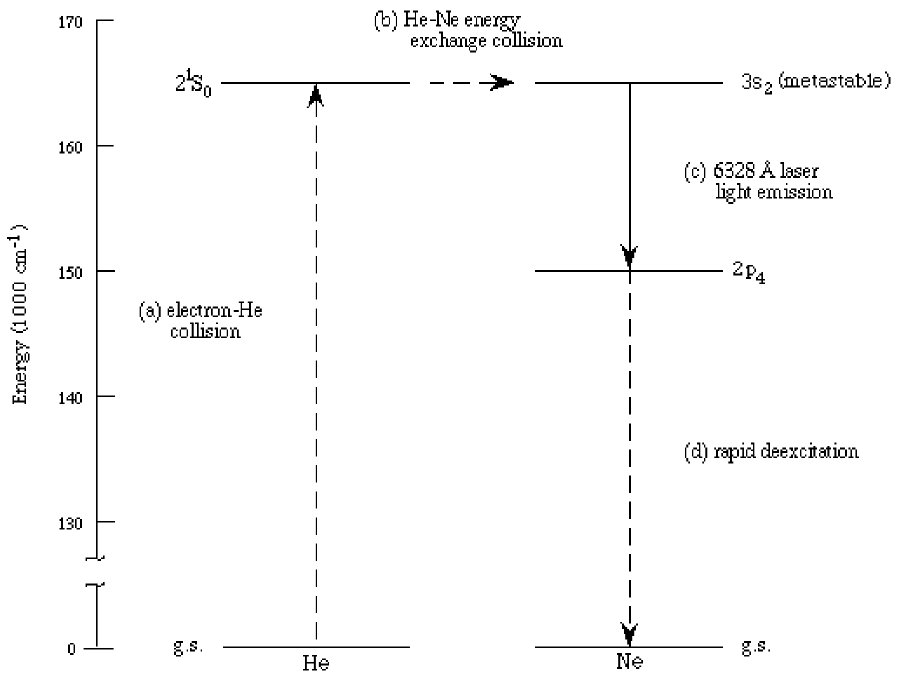

Fig. 5.8. He-Ne LASER action mechanism

(ii) Optical gain medium: To achieve laser action it is necessary to have a large number of atoms in excited states and to establish what is termed a population inversion. To understand the significance of a population inversion to He-Ne laser action, it is useful to consider the processes leading to excitation of He and Ne atoms in the discharge, using the simplified diagram of atomic He and Ne energy levels. A description of the rather complex HeNe excitation process can be given in terms of the following four steps. An energetic atom collisionally excites a He atom to the state labelled 2^1S_0 in Fig. 5.8. A He atom in this excited state is often written He*(2^1S_0), where the asterisk means that the He atom is in an excited state.

(a) The excited He*(2^1S_0) atom collides with an unexcited Ne atom and the atoms exchange internal energy, with an unexcited He atom and excited Ne atom, written Ne*($3S_2$), resulting. This energy exchange process occurs with high probability only because of the accidental near equality of the two excitation energies of the two levels in these atoms.

(b) The $3S_2$ level of Ne is an example of a metastable atomic state, meaning that it is only after a relatively long period of time - on atomic time scales - that the Ne*($3S_2$) atom deexcites to the $2P_4$ level by emitting a photon of wavelength 6328 Å. It is this emission of

6328 Å light by Ne atoms that, in the presence of a suitable optical configuration, leads to lasing action

(c) The excited Ne*($2P_4$) atom rapidly deexcites to its ground state by emitting additional photons or by collisions with the plasma tube walls. Because of the extreme quickness of the deexcitation process, at any moment in the HeNe plasma, there are more Ne atoms in the $3S_2$ state than there are in the $2P_4$ state, and a population inversion is said to be established between these two levels. When a population inversion is established between the $3S_2$ and $2P_4$ levels of the Ne atoms in the discharge, the discharge can act as an optical gain or amplification medium for light of wavelength 6328 Å. This is because a photon incident on the gas discharge will have a greater probability of being replicated in a $3S_2$-->$2P_4$ stimulated emission process (discussed below) than of being destroyed in the complementary $2P_4$-->$3S_2$ absorption process.

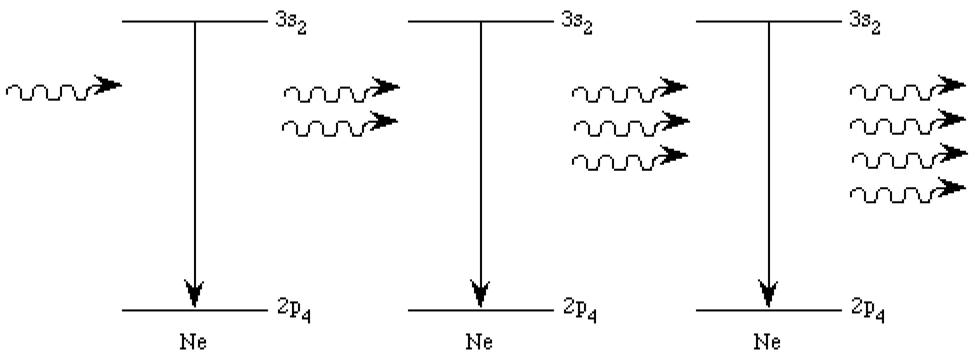

Fig. 5.9. He-Ne LASER action

(iii) Optical resonator or cavity: As mentioned in Fig. 5.8 , Ne atoms in the $3S_2$ metastable state decay spontaneously to the $2P_4$ level after a relatively long period of time under normal circumstances; a He-Ne discharge is placed between two highly reflecting mirrors that form an optical cavity or resonator along the axis of the discharge. When a resonator structure is in place, photons from the Ne* $3S_2$-->$2P_4$transition that are emitted along the axis of the cavity can be reflected hundreds of times between the two highly reflecting end mirrors of the cavity. These reflecting photons can interact with other excited Ne*($3S_2$) atoms and cause them to emit 6328 Å light in a process **known as stimulated emission.**

The new photon produced in stimulated emission has the same wavelength and polarization, and is emitted in the same direction, as the stimulating photon. As stimulated emission processes occur along the axis of the resonator a situation develops in which essentially all $3S_2$-->$2P_4$ Ne* decays contribute de-excitation photons to the photon stream reflecting between the two mirrors. This photon multiplication (light amplification) process produces a very large number of photons of the same wavelength and polarization that travel back and forth between the two cavity mirrors. To extract a light beam from the resonator, it is only necessary to have one of the two resonator mirrors, usually called the output coupler, have a reflectivity of only 99% so that 1% of the photons incident on it travel out of the resonator to produce an external laser beam. The other mirror, called the high reflector, should be as reflective as possible. The small diameter, narrow bandwidth, and strong polarization of the He-Ne laser beam are determined by the properties of the resonator mirrors and other optical components that lie along the axis of the optical resonator.

Uses/Applications of LASER:

Although the first working laser was only produced in 1958, lasers are now found in many household items.

For example, lasers are well-known through their use as

(i) Cheap laser pointers

(ii) Semiconductor lasers which are small, efficient and cheap to make are used in CD players.

(iii) He-Ne Lasers are used in most grocery shops to read in the price of items using their barcodes. This makes the cashiers' job much quicker and easier.

(iv) High energy lasers are used in medicine as a cutting and welding tool. Eye surgery in particular make use of the precision of lasers to reattach the retinas of patients' eyes. The heat from cutting lasers also helps to stop the bleeding of a wound by burning the edges (called cauterising).

(v) laser printers

(vi) laser communication and fiber optics

(vii) optical storage

(viii) lasers as precision measurement tools.

L4: Introduction to optical fiber, types of optical fiber and light guidance principle of optical fiber, Numerical aperture, acceptance angle of optical fiber and application of Fiber optics to communication, medical industry etc.

Introduction:

In the field of optical fiber, the transmission of light along the thin cylindrical glass fiber by total internal reflection was first demonstrated by John Tyndall. Since its invention in the early 1870s, the use of and demand for optical fiber have grown tremendously. This optical fibre deals with the light propagation through thin glass fiber. Optical fibres used in the field of communication as internet, electronic commerce, computer networks, multimedia, voice, data, and video.Today the applications of fiber optics are also extended to medical field in the form of endoscopes and optical sensors.

An optical fiber is a dielectric cylindrical wave guide consisting ofmultiple layers, i.e., core, a surrounding cladding and outer coating (Figure 5.10). The refractive index of the material of the core is higher than that of the cladding. Both are made up of thin,flexible, high quality, transparent fiber of glass or plastic, where light undergoes successive total internal reflections along the length of the fibre and finally comes out at the other end (Figure 5.11). The study of optical fibers are called fiberoptics.

Component of optical fiber:

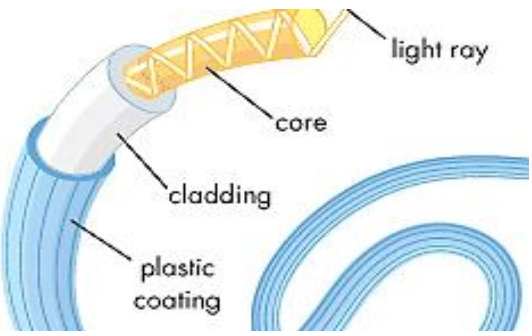

Fig. 5.10. Optical Fiber

The core, cladding, are all components of an optical fibre.

Core: The section of the fiber that transmits light is called the core. Generally core diameter is 50 µm.

Cladding: The material coated over core is known as cladding which often has a lower refractive index than the core. This preventing light from escaping through the sidewalls. The overall diameter of cladding is 125 µm to 200 µm.

Outer Coating:

Buffer: It is made of plastic and the main function of the buffer is to protect the fiber from moisture. The overall diameter of buffer is 250 µm.

Outer Jacket: It is made of polyurethane, which will prevent the cable from damage during pulling, bending, stretching and rolling.

Types of optical fiber:

Types of optical fiber depends on modes of propagation of wave, material used and refractive index of the materials.

<u>Classification based on the refractive index is as follows:</u>

I. Step Index Fibers
II. Graded Index Fibers

<u>Classification based on the materials used is as follows:</u>

I. Plastic Optical Fibers
II. Glass Fibers

<u>Classification based on the mode of propagation of light is as follows:</u>

I. Single-Mode Fibers
II. Multimode Fibers

<u>The mode of propagation and refractive index of the core is used to form four combination types of optic fibres as follows:</u>

I. Step index-single mode fibers
II. Graded index-Single mode fibers
III. Step index-Multimode fibers
IV. Graded index-Multimode fibers

Light Guidance principle of optical fibre

The optical fiber works on the principle of Total Internal Reflection (TIR). Light rays can be used to transmit a huge amount of data, but there is a problem here – the light rays travel in straight lines. So, unless we have a long straight wire without any bends at all, harnessing this advantage will be very tedious. Instead, the optical cables are designed such that they bend all the light rays inwards (using TIR). Light rays travel continuously, bouncing off the optical fibre walls and transmitting end to end data. Although light signals do degrade over progressing distances, depending on the purity of the material used, the loss is much less compared to using metal cables.

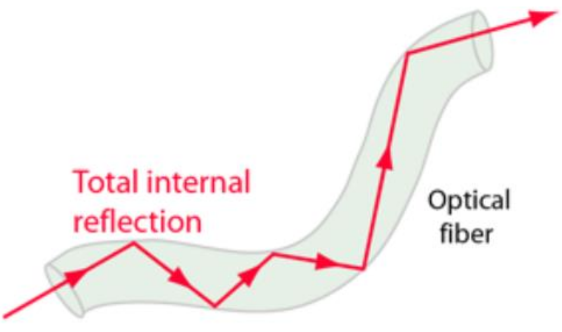

Fig. 5.11. Total internal reflection at optical fiber

Since light undergoes total internal reflection at each stage, there is no appreciable loss in the intensity of the light signal. Optical fibers are fabricated such that light reflected at one side of inner surface strikes the other at an angle larger than the critical angle. Even if the fibre is bent, light can easily travel along its length. Thus, an optical fibre can be used to act as an optical pipe.

Numerical aperture, acceptance angle of optical fiber

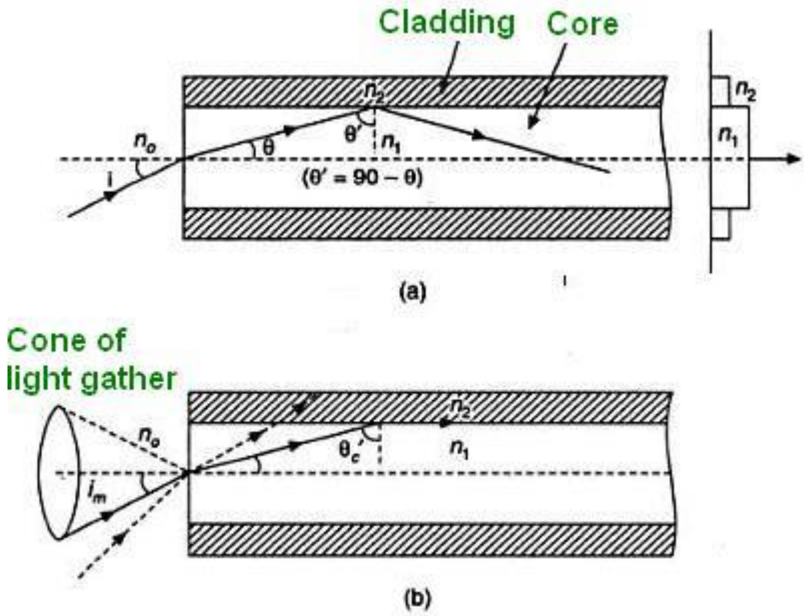

Fig. 5.12. Numerical Aperture in optical fiber

Consider an optical fiber having a core of refractive index n_1 and cladding of refractive index n_2. Let the incident light makes an angle ***i*** with the core axis as shown in Figure 5.12. Then the light gets refracted at an angle **θ** and fall on the core-cladding interface at an angle where,

$$\theta' = (90^0 - \theta)$$

By Snell's law at the point of entrance of light in to the optical fiber we get,

$$n_0 \, Sin \, i = n_1 Sin\theta \tag{1}$$

where n_0 is refractive index of medium outside the fiber. For air n_0 =1.
When light travels from core to cladding it moves from denser to rarer medium and so it may be totally reflected back to the core medium if θ' exceeds the critical angle θ'_c. The critical angle is that angle of incidence in denser medium (n_1) for which angle of refraction become 90°. Using Snell's laws at core cladding interface,

$$n_1 Sin \, \theta_c' = n_2 Sin \, 90^0 \tag{2}$$
$$Sin \, \theta_c' = n_2 / \, n_1 \tag{3}$$

Therefore, for light to be propagated within the core of optical fiber as guided wave, the angle of incidence at core-cladding interface should be greater than θ_c'. As i increases, θ increases and so θ' decreases. Therefore, there is maximum value of angle of incidence beyond which, it does not propagate rather it is refracted in to cladding medium (Figure 5.12). This maximum value of i say i_m is called maximum angle of acceptance and n_0 sin i_m is termed as the numerical aperture (NA). From eq^n 2,

$$NA = n_0\, Sin\, i_m = n_1 Sin\theta = n_1 Sin\,(90^0 - \theta c') = n_1 Cos\,\theta_c{}' = n_1\sqrt{1 - Sin^2\theta_c{}'}$$

From equation 3, $Sin\,\theta_c' = n_2 / n_1$

Therefore, $$\text{NA} = n_1\sqrt{1 - \frac{n_2^2}{n_1^2}}$$

$$\text{NA} = \sqrt{n_1^2 - n_2^2}$$

The significance of NA is that light entering in the cone of semi vertical angle i_m only propagate through the fibre. The higher the value of i_m or NA more is the light collected for propagation in the fibre. Numerical aperture is thus considered as a light gathering capacity of an optical fibre.

Applications

Some of the major application areas of optical fibers are:

• **Communications**- for transmitting audio and video signals through long distances. Voice, data, and video transmission are the most common uses of fiber optics, and these include, telecommunications, local area networks (LANs), industrial control system.

• **Sensing** — Fiber optics can be used to deliver light from a remote source to a detector to obtain pressure, temperature, or spectral information. The fiber also can be used directly as a transducer to measure a number of environmental effects, such as strain, pressure, electrical resistance etc. Environmental changes affect the light intensity, phase and/or polarization in ways that can be detected at the other end of the fiber.

• **Power Delivery** — Optical fibers can deliver remarkably high levels of power for tasks such as lasercutting, welding, marking, and drilling.

• **Illumination** — A bundle of fibers gathered together with a light source at one end can illuminate areas that are difficult to reach, for example in medical field, inside the human body, in conjunction with an endoscope.

• **Optical fibers** are used instead of metal wires because signals travel along them with less loss.

• Optical fibers are extensively used **in medical applications**. For example, these are used as a ―light pipe‖ to facilitate visual examination of internal organs like oesophagus, stomach, and intestines

• Available **decorative lamps** having fine plastic fibres with their free ends forming a fountain like structure,have the end of the fibers is fixed over an electric lamp. When the lamp is switched on, the light travels from the bottom of each fiber and appears at the tip of its free end as a dot of light. The fibers in such decorative lamps are optical fibres.

L5: Introduction of superconductivity

Resistivity of certain metals and alloys when cooled below a certain temperature known as critical temperature (Tc), drops close to zero. They offer negligible resistance and hence exhibit very high conductivity below Tc. Persistent electrical current has been observed to flow without attenuation in superconducting ring for more than a year. These substances are called superconductors. This phenomenon was first discovered by Kamerlingh Onnes in 1911while measuring the electrical conductivity of a few metals at low temperatures.

In a conducting cylinder current decay in about 1/1000 second. However, in a superconducting cylinder current does not decay (≅ less than 0.1% in a year). So, resistance is smaller than Copper by: $\frac{1000 \text{ years}}{\frac{1}{1000}\text{second}}$, i.e., at least 1 trillion times.

Critical or transition temperature

Thetemperatureatwhichthetransitionfromnormalstatetosuperconductingstate occurs upon cooling in the absence of any external magnetic field is calledthe critical temperature or superconducting transition temperature (T_c).

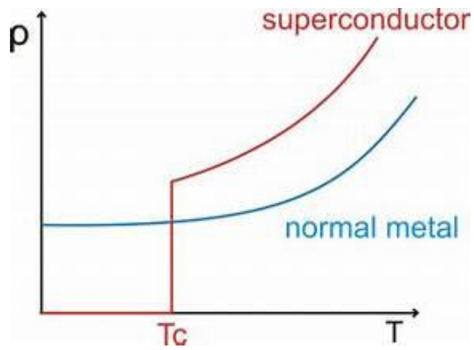

Fig. 1 Resistivity of superconducting material and a normal metal as a function of temperature.

L6: Properties of superconductors:

1. Superconductivity occurs in many metallic elements, some alloys, intermetallic compounds, and doped semiconductors. Several materials become superconducting only under high pressure. Ex: Si becomes superconducting at 165 kbar pressure with Tc=8.3 K
2. Persistent current: When the current flows through a superconducting ring below critical temperature then the loss of energy in the form of heat is negligible. Due to the negligible resistance, there will be no decay in current for very long time and a

constant flow of current will be maintained. This steady current flow without any applied electric potential is known as persistent current.

3. Isotope effects: $Hg^{80}_{199.5}$, $Hg^{80}_{203.4}$ Superconducting critical temperature (T_C) varies inversely with isotopic mass.

$$T_C = \frac{1}{M^{\alpha}}$$

For Hg value of isotopic coefficient, α=0.5

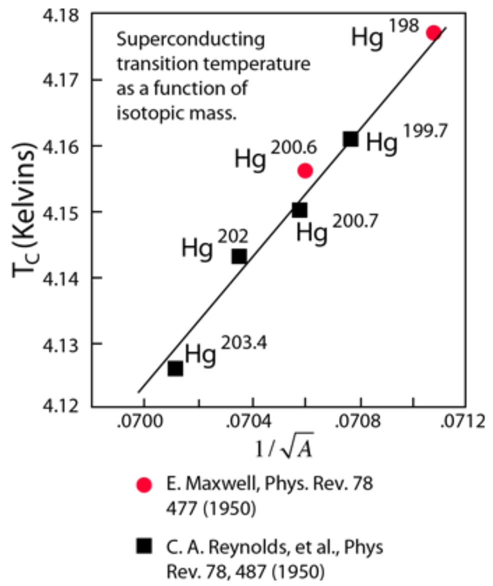

Fig. 2 Variation of critical transition temperature with mass number

Meissner effect:

Magnetic properties of superconductors are also fascinating similar to electrical properties. Bulk superconductors in a weak magnetic field act as perfect diamagnet i.e. zero magnetic induction ($\vec{B}$) in the interior. When a specimen is placed in a moderate external magnetic field and cooled through transition temperature the magnetic flux originally passing through is expelled outside. This effect is known as the Meissner effect as shown in Fig. 2. These exclusive magnetic properties of superconductor are central to the characterization of the superconducting state.

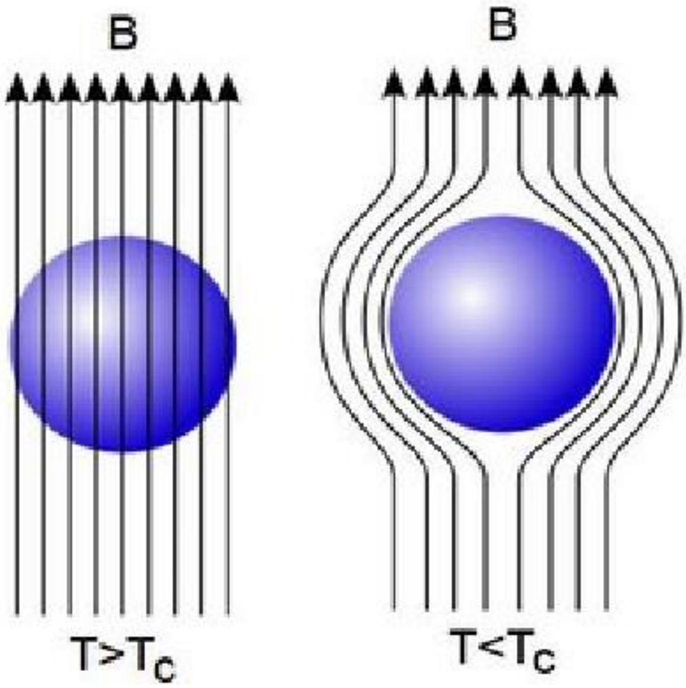

Fig. 3 Meissner effect in a superconducting sphere cooled in a constant applied magnetic field.

If $B_a = \mu_0 H$ is the applied external magnetic field the magnetic induction (B) developed within the superconducting material is given by: $B = B_a + \mu_0 M$. μ_0 is permeability of free spaceand M is intensity of magnetization. Zero magnetic induction inside a superconductor implies magnetic susceptibility:

$$\chi = \frac{M}{H} = -1 \text{ in S.I units}$$

Negative susceptibility implies perfect diamagnetism and a superconductor in it's superconducting state behaves as a perfect diamagnet.

Critical magnetic field (H_c):Destruction of superconductivity by magnetic field

At T < T_c sufficiently high magnetic field will destroy superconductivity. The threshold value or critical value to destroy superconductivity, H_C(t)and is function of temperature. At critical temp T_C,, $H_C(T_C)$ is zero. Variation of $H_C$with temperature is shown in Fig. 3 The threshold curve separates superconducting state (lower left) from normal state (upper right). Critical applied field is denoted as B_{ac}. $H_C=B_{ac}/\mu$ in SI and $H_C=B_{ac}$ in CGS. Critical magnetic field H_C is strongly related to critical temperature T_C of superconductor. It is the nature of superconductor to exclude magnetic field so long as the applied magnetic field does not exceed the critical magnetic field. The $H_C$at 0 K decreases from that magnitude with increasing temperature reaching to zero at critical temperature T_C. $H_C$at any temperature below T_C is related by the following relationship

$$H_c = H_C(0)\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

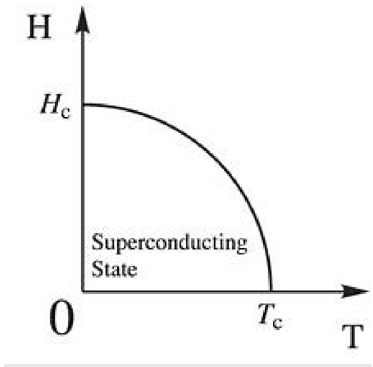

Fig. 4 Variation of critical magnetic field (H_C) as a function of temperature.

Types of superconductors:

Generally, superconductors are classified into two categories based on their behaviour under the influence of external magnetic field when transition is made from superconducting state to normal state. Type -I superconductor and type-II superconductor.

In type-I superconductors: As the applied magnetic field reaches to critical field (H_C) the whole specimen enters into the normal state. Simultaneously, the resistivity returns, magnetic field lines penetrate into the entire specimen. They exhibit complete Meissner effect.They are also known as soft superconductors as the loose superconductivity very easily at low critical magnetic field. Normally exhibited by pure metals: aluminium, lead, mercury.

Type-II super superconductor: The transition to normal state from superconducting state is gradual. For such superconductors two critical fields, namely lower critical field (H_{C1}) and higher critical field (H_{C2}) exist. Below $H_{C1}$the specimen is in superconducting state i.e. the magnetic field lines are completely excluded. As applied magnetic field is increased gradually above H_{C1} the field lines start to penetrate the specimen and the specimen enters into mixed state till H_{C2}.Above H_{C2} magnetic penetration completes and the specimen turns to completely normal state. As type-II semiconductors retains the superconducting state to much higher magnetic fields (H_{C2}) compared to type-I they are also known as hard superconductors. Mixed states are also known as vortex states. Generally, alloys and transition metals with high electrical resistivity exhibits Type-II superconductivity.

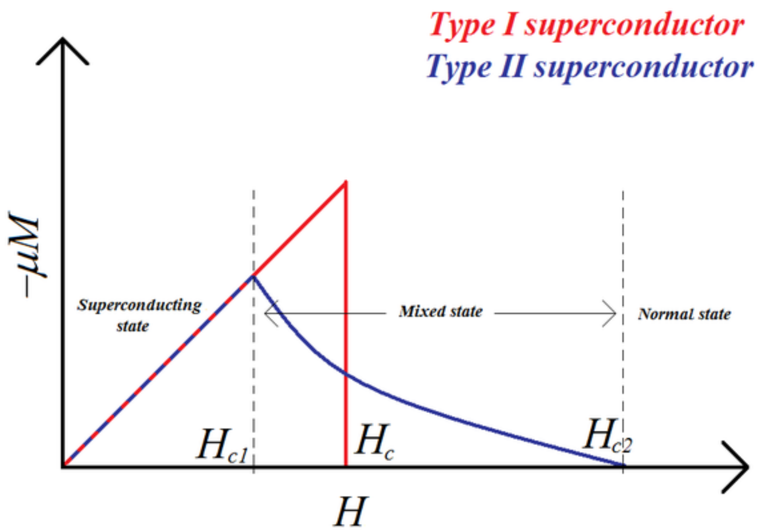

Fig. 5 Variation of magnetization with applied magnetic field in type-I and type-II superconductors

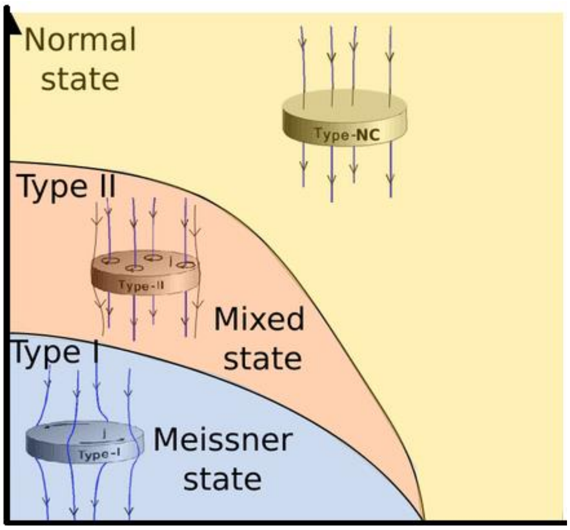

Fig. 6: Phase diagram of type-I and type-II superconductors

Difference between Type-I and Type-II superconductors

Type-I	Type-II
Loose magnetization easily	Loose magnetization gradually
Only one critical field (Hc). Hc is much lower compared with Hc_2 of type-II superconductor.	There are two critical fields. Namely, lower critical field (Hc_1), and higher critical field (Hc_2)

Exhibits complete Meissner effect	Exhibits incomplete Meissner effect
No mixed or vortex state exists	Exhibit mixed or vortex state in between Hc_1 and Hc_2
Also known as soft super conductor	Known as hard superconductor
Examples: Pb, Sn, Hg etc.	Examples: Nb-Sn, Nb-Zr, Nb-Ti etc.

London penetration depth:

According to London's theory when a superconductor in placed in an external magnetic field, B_0 the magnetic field does not drop zero suddenly at the surface inside the superconductor. Instead, it decreases exponentially as we move far inside from the surface and gradually becomes zero at the core. This spatial exponential decay of magnetic field inside the superconductor from the surface is described by London's equations.

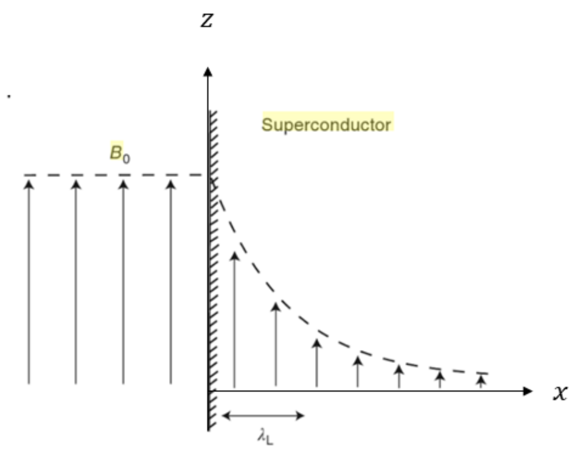

Fig. 7: Spatial distribution of applied magnetic field (within critical field limit) inside bulk of a superconductor

If B_0 is a weak magnetic field applied along z-direction at the surface of specimen then the distribution of magnetic field inside as a function of position x (x>0) can be represented by

$$B(x) = B_0 \exp(-\frac{x}{\lambda_L})$$

λ_L is the London penetration depth which is defined as the distance inside at which the B_0 falls $\frac{1}{e}$ times of its surface value i.e 37% decrement.

Temperature variation of London penetration depth:

Temperature variation of penetration depth for $T < T_c$ is represented by the relation:

$$\lambda_L(T) = \frac{\lambda_L(0)}{\sqrt{1 - (\frac{T}{T_c})^4}}$$

Numerical#1 A superconducting sample has a critical temperature of 4.1K in zero magnetic field and critical field of 0.0505Tat0K.Findthecriticalfield at 2K.

Solution:

Given $H_0 = 0.0505\,T, T_c = 4.1K\ and\ T = 2K$

$$\text{Critical field: } H_c = H_C(0)\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

$$= 0.0505\left[1 - \left(\frac{2}{4.1}\right)^2\right] \text{T}$$

$$= 0.0348\,T$$

Numerical#2 If a sample of indium with a value of Hc(0)=0.0282T is cooled below its superconducting transition temperature of 3.41K, what is the approximate value of itscriticalfieldwhen it isat 2K?

Solution:

Given, $H_C(0) = 0.0282T, T_C = 3.41\text{K}$ and $T = 2K$

$$\text{Critical field: } H_c = H_C(0)\left[1 - \left(\frac{T}{T_C}\right)^2\right]$$

$$= 0.028\left[1 - \left(\frac{2}{3.41}\right)^2\right] T$$

$$= 0.0185\,T$$

Numerical# 3: The penetration depth of Mercury (Hg) at 3.5 K is about 75 nm. Estimate the penetration depth at 0 K. Superconducting transition temperature for Mercury is 4.2 K

Solution: Given, $\lambda_L(T = 3.5\,K) = 75\,nm$;

T_c=4.2 K;

$$T = 3.5K$$

Penetration depth at 0 K, $\lambda_L(0) = \lambda_L(T)\sqrt{1 - (\frac{T}{T_c})^4}$

$$= 75\sqrt{1 - \left(\frac{3.5}{4.2}\right)^4}\ nm$$

$$= 75 \times 0.692\text{nm}$$

$$= 51.96\ nm$$

L8: BCS theory of superconductivity, Applications of superconductor

BCS theory

In 1957 Bardeen, Cooper, and Schrieffer proposed a macroscopic theory to explain mechanism of type-I superconductors and is known as BCS theory. They received Noble prize in Physics for this theory in 1972.

BCS theory relies on the assumption that superconductivity arises when the attractive Cooper pair interaction dominates over repulsive Coulomb force. A Cooper pair is a weak electron-electron bound pair mediated by a phonon interaction or lattice distortion at very low temperature.

When a free electron passes through lattice the positively charged ion cores get attracted to it. With the passage of the electron the lattice becomes locally distorted. This positively charged local lattice distortion, termed as phonon attracts a second electron. In this way two electrons close to the Fermi surface with opposite momentum and spin interact indirectly with an attractive potential and form Cooper pair. In BCS framework superconductivity is a macroscopic effect and which results from condensation of Cooper pairs.

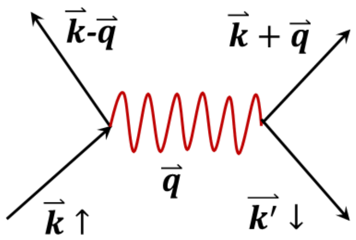

Fig. 8: Interaction between electrons with momenta, $\vec{k}$ and $\vec{k'}$ via a phonon, $\vec{q}$ to form a Cooper pair.

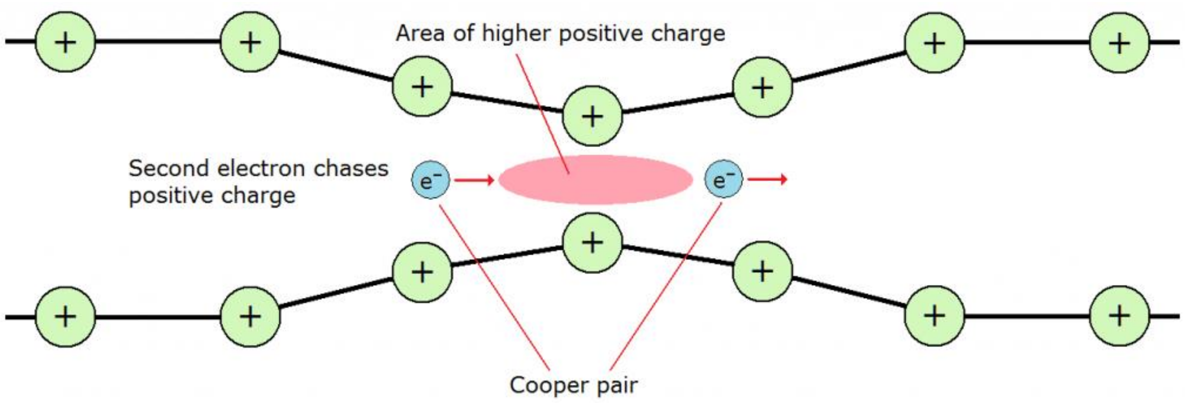

Fig. 9 Formation of Cooper pair through lattice distortion or phonon

Applications of superconductors:

Superconductors have wide range of applications in various fields. Some of the applications include:

- For creating powerful magnets for medical MRI/NMR devices
- Used in particle accelerators, generators, transformers, power transmission lines
- Superconducting quantum interface device (SQUID) based sensitive devices are used for detecting change in smallest fraction of magnetic field and therefore used in different fields of science and technology.
- Superconducting cables are used to transmit power for long distances
- Used in Maglev i.e. Magnetic levitation trains

Question Bank

1. Distinguish between absorption, spontaneous emission and stimulated emission. Give two important uses of Laser.
2. How LASER light is different from ordinary light.
3. Why population inversion is an essential for stimulated emission? Calculate the energy and momentum of a photon of a laser beam of wavelength 6328Å. Discuss how laser can be a useful tool especially for medical field.
4. Under what condition population inversion taking place in a LASER?
5. .Mention different parts of a LASER.
6.. Name some semiconducting materials used in production of LASER
7. A silica glass optical fiber has a core refractive index of 1.5 and cladding refractive index of 1.45. Calculate the numerical aperture of fiber.
8. Calculate the numerical aperture and hence the acceptance angle for an optical fiber, the values of refractive index of core and cladding are 1.45 & 1.40 respectively are given here.
9. What is optical fiber? With a suitable ray diagram, derive an expression for the NA of an optical fiber
10. Write about different types of optical fibers and their applications.
11. What is superconductor? What do you mean by Meissner effect?
12. Explain zero resistivity and critical temperature of superconductor.
13. Write the difference between top-down and bottom-up method for fabrication of nano-materials
14. Explain BCS theory of superconductivity. Write at least two applications of superconductors.
15. Discuss Meissner's effect for a superconductor. Calculate the depth inside a superconducting material where magnetic field becomes 90% less of its initial value.

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