Department of ECE

SUBJECT CODE: EC6016

SUBJECT NAME: OPTO ELECTRONIC DEVICES

Regulation: 2013 **Year and Semester: IV / VII**

COURSE SYLLABUS

EC6016	**OPTO ELECTRONIC DEVICES**	**L T P C**
		3 0 0 3

OBJECTIVES:

- To understand the basics of solid state physics.
- To understand the basics of display devices.
- To understand the optical detection devices.
- To understand the design of optoelectronic integrated circuits.

UNIT I ELEMENTS OF LIGHT AND SOLID STATE PHYSICS 9

Wave nature of light, Polarization, Interference, Diffraction, Light Source, review of QuantumMechanical concept, Review of Solid State Physics, Review of Semiconductor Physics and Semiconductor Junction Device.

UNIT II DISPLAY DEVICES AND LASERS 9

Introduction, Photo Luminescence, Cathode Luminescence, Electro Luminescence, Injection Luminescence, Injection Luminescence, LED, Plasma Display, Liquid Crystal Displays, Numeric Displays, Laser Emission, Absorption, Radiation, Population Inversion, Optical Feedback, Threshold condition, Laser Modes, Classes of Lasers, Mode Locking, laser applications.

UNIT III OPTICAL DETECTION DEVICES 9

Photo detector, Thermal detector, Photo Devices, Photo Conductors, Photo diodes ,Detector Performance.

UNIT IV OPTOELECTRONIC MODULATOR 9

Introduction, Analog and Digital Modulation, Electro-optic modulators, Magneto Optic Devices,Acoustoptic devices, Optical, Switching and Logic Devices.

UNIT V OPTOELECTRONIC INTEGRATED CIRCUITS 9

Introduction, hybrid and Monolithic Integration, Application of Opto Electronic Integrated Circuits, Integrated transmitters and Receivers, Guided wave devices.

TOTAL: 45 PERIODS

TEXTBOOKS:

1. Pallab Bhattacharya "Semiconductor Opto Electronic Devices", Prentice Hall of India Pvt., Ltd.New Delhi, 2006.

2. Jasprit Singh, "Opto Electronics – As Introduction to Materials and Devices", Mc Graw-Hill International Edition, 1998

REFERENCES:

1. S C Gupta, Opto Electronic Devices and Systems, Prentice Hal of India, 2005.

2. J. Wilson and J.Haukes, "Opto Electronics – An Introduction", Prentice Hall, 1995

1. EC6016 OPTO ELECTRONIC DEVICES L T P C

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2. Aim and Objective of the Subject

The student should be made

- To understand the basics of solid state physics.
- To understand the basics of display devices.
- To understand the optical detection devices.
- To understand the design of optoelectronic integrated circuits

3. Need and Importance for Study of the Subject

The students will be able to:

- To design display devices.
- To design optoelectronic detection devices and modulators.
- To design optoelectronic integrated circuits

4. Industry Connectivity and Latest Developments

Industry Connectivity:

- The following companies (Industries) are linked to Opto Eletronics Devices:

  .CCL Opto electronics private Limited,Thane

  Spark opto electronics company,Chennai

Latest Developments:

- Fiber Distribution Frames
- Metro Ethernet Network
- LED Products

4. Industrial Visit (Planned if any):

Planned to visit Spark Opto electronics company,Chennai at the end of August 2016.

UNIT I

ELEMENTS OF LIGHT AND SOLID STATE PHYSICS

Schrodinger equation, explain the formation of energy bands in solids.

In general the Schrodinger equation includes both space and time dependencies and is of the form.

$$\frac{h^2}{2\square}\left(\frac{\square^2\square}{\square\square^2}+\frac{\square^2\square}{\square\square^2}+\frac{\square^2\square}{\square\square^2}\right)-\square\square-\square h\frac{\square\square}{\square\square}$$

Where i=$\sqrt{-1}$.

V-Potential energy

□ - Wave function

Both of which depend on position and time, that is we have $\square = \square(\square, \square, \square, \square)$ and V=V(x,y,z,t). The above equation is often referred to as the time-dependent Schrodinger equation, it is sufficient to consider situations in which the potential energy of the particle does not depend on time. The forces that act upon it, and hence Then vary only with the position of the particle. In this case the above equation reduces to the time-independent form,which,in one dimension, may be written as

$$\frac{\square^2\square(\square)}{\square\square^2}+\frac{2\square}{h^2}(\square-\square(\square))\square(\square)=0$$

Where □ is the time-independent wave equation E is the total energy of the particle.

Energy bands in solids:

In a solid many atoms are brought together so that the split energy levels form a set of bands of very closely spaced levels with forbidden energy gaps between them.

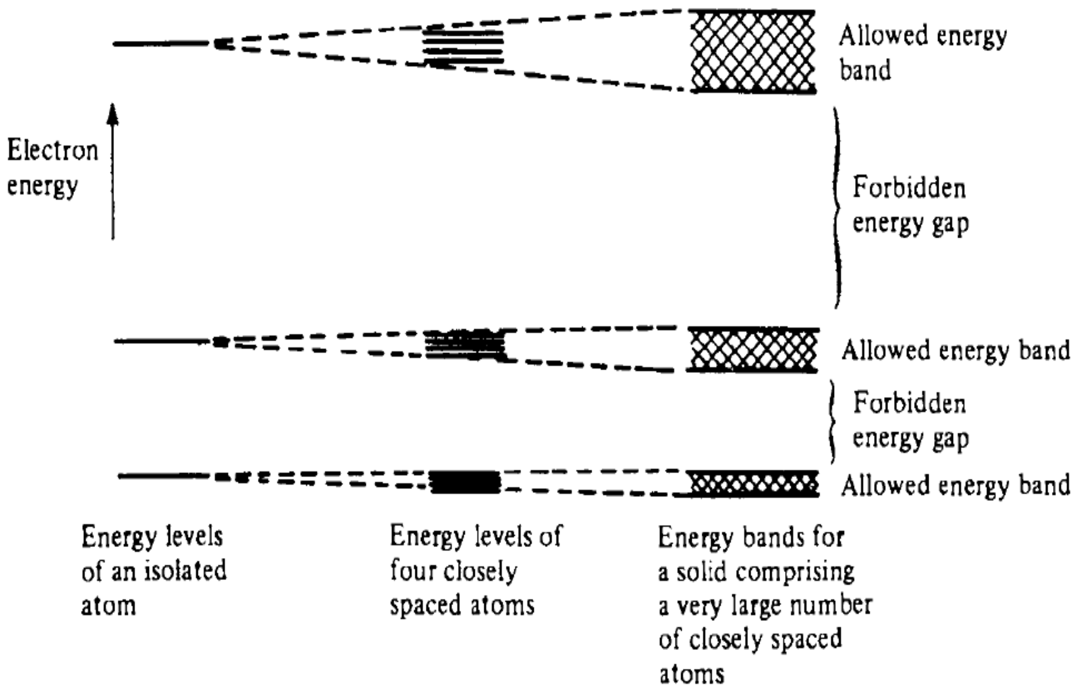


Fig:(i).Schematic representation of how the energy levels of interacting atoms form energy bands in solids

The lower energy bands are occupied by electrons first; those energy bands which are completely occupied are not important, in general, in determining the electrical properties of the solid.

Conductors, Semiconductors and insulators

On the other hand the electrons in higher energy bands of the solid are important in determining many of the physical properties of the solid.In particular the two highest energy bands, called the valence and conduction bands, are of crucial important in this respect, as is the forbidden energy region between them which is referred to as the energy gap E_g.

In a different solids the valence band completely might be filled, nearly filled or only half filled with electrons, while the conduction band is never more than slightly filled.To extent to which these bands are occupied and the size of the energy gap determines the nature of a given solid.

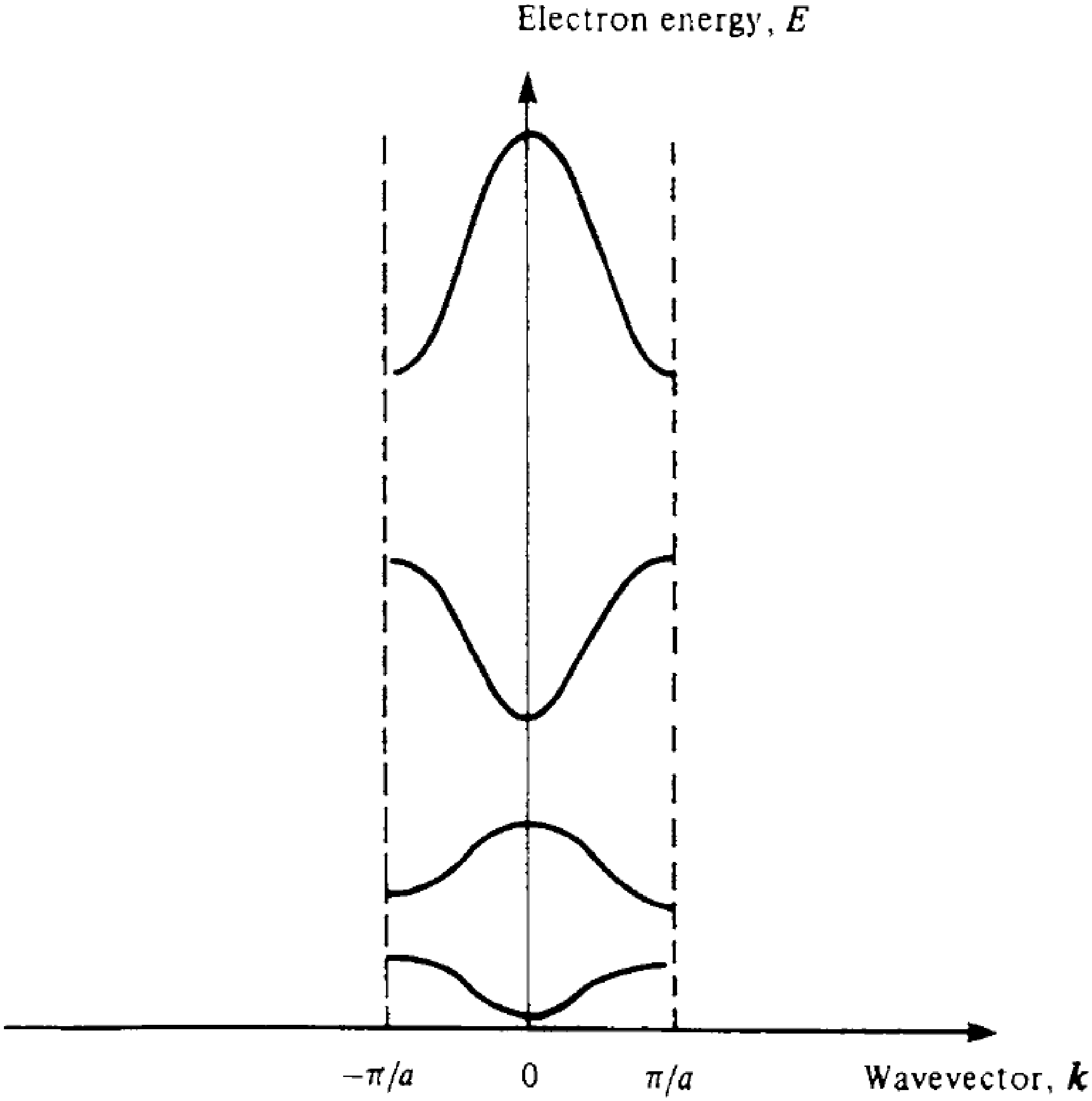


Fig:ii.Reduced zone representation of the E-K Relationship shown in fig (iii),this representation is constructed by translating the segments of the E-K curve so that they all lie between k=-/a and k=+/a which comprises the first brillouin zone.

By considering an ideal crystalline solid the atoms are arranged in a periodic array. The potential experienced by electron in a solid is correspondingly spatially periodic, so that, after a distance in the crystal equal to the lattice spacing, the potential V repeats itself, that is

$$V=V(x+a)=V(x+2a)=\ldots$$

Where ‘a’ is the periodicity of the lattice.

We find that there are ranges of allowed energies separated by ranges of disallowed energies, that is, the electrons in a solid can occupy certain bands of energy levels which are separated by forbidden energy gaps.

The discontinuities between allowed and forbidden energy values occur at values of the wave vector k given by $k=\pm n\pi/a$ where n is an integer.

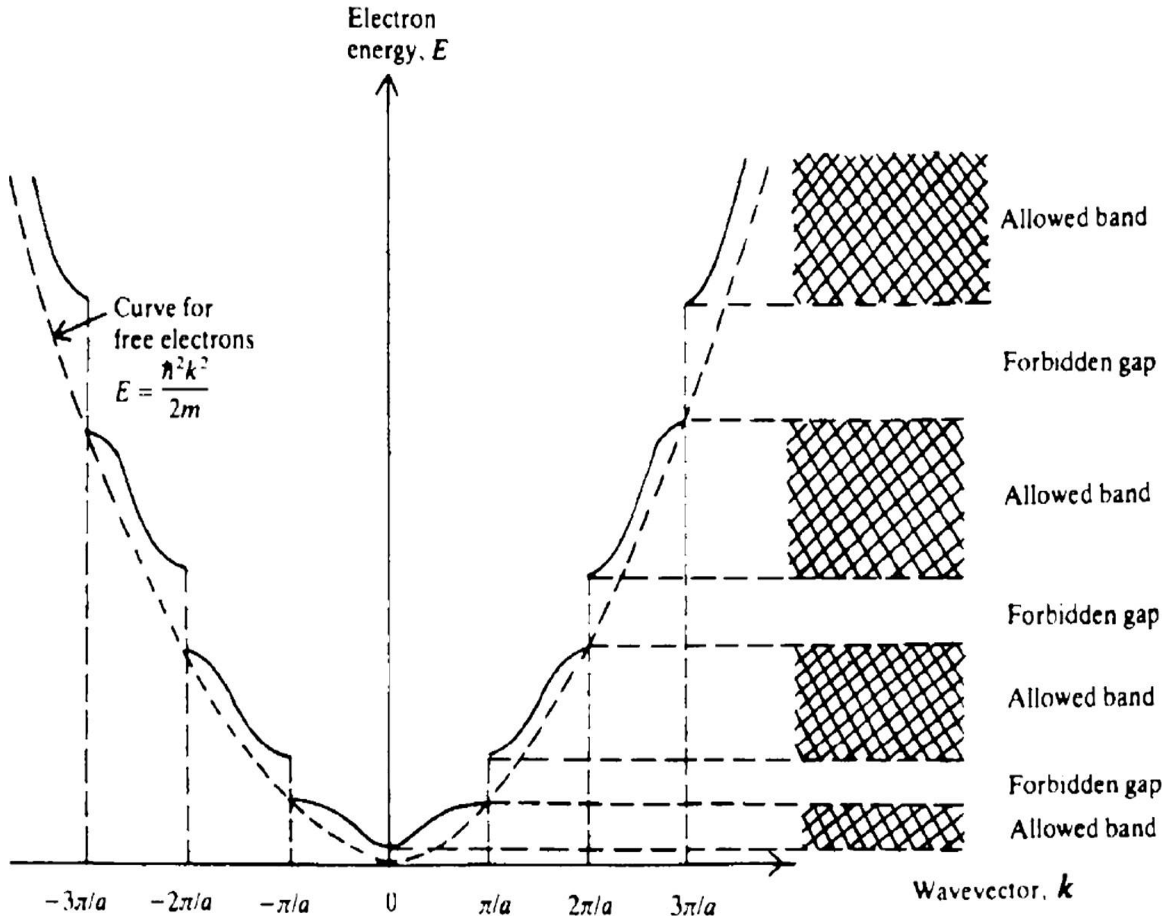


Fig:iii. Relationship of E-K for electrons subjected to the potential distribution of the kronig-penney model and the corresponding energy band structure. The E-K relationship for free electrons is shown for comparison

The region in figure for which $-\pi/a<k<\pi/a$ is called the first brillouin zone.it is often convenient to redraw figure by translating the segments of the E-K Curve so that they all lie within this range.

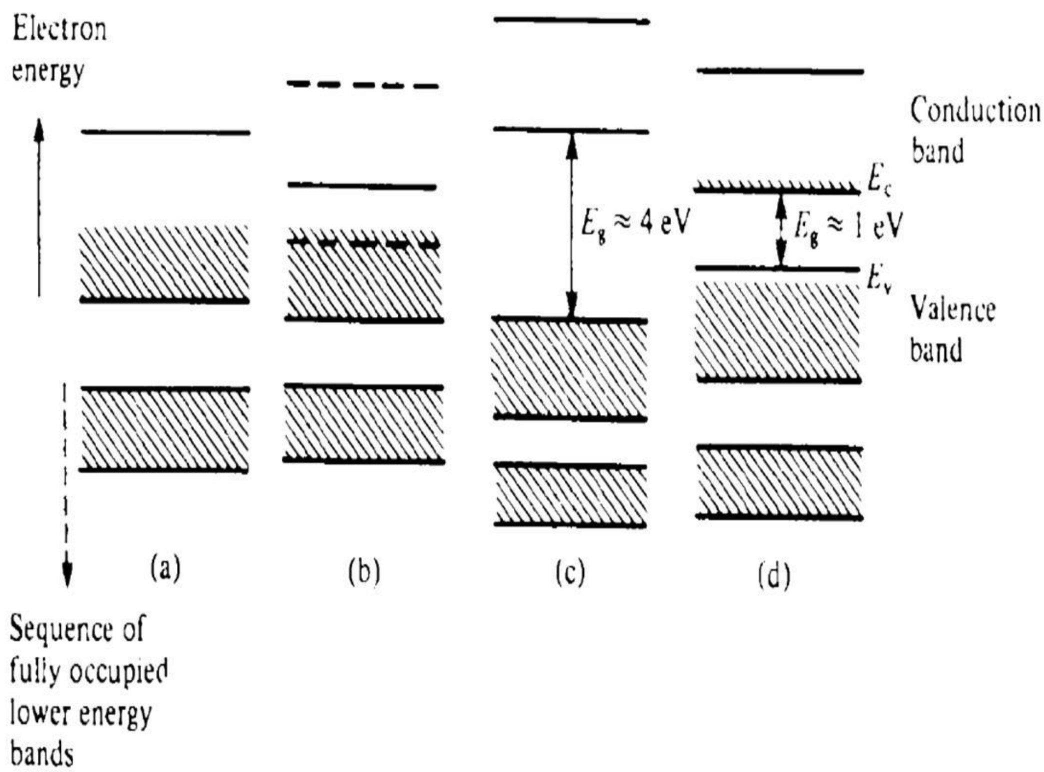


Fig:iv-Schematic representation of energy bands in various materials :(a). a metal with partially filled valence band e.g:Mono valent metals (b).A metal with two overlapping partially filled bands e.g:Di-Valent metals (c).An Insulator (d).An intrinsic semi conductor.

Expression for concentration of electrons and holes in an intrinsic semiconductor, with relevant diagrams.

A perfect semiconductors crystal containing no impurities or lattice defects is called an intrinsic semiconductor. In such a material, there are no charge carriers at absolute zero but as the temperature rises electron-hole pairs are generated. As the carriers are generated in pairs the concentration n of electron in the conduction band equals the concentration p of holes in the valence band, Thus we have

$$n=p=n_i$$

Where n_i is the intrinsic carrier concentration

The value of n_i varies exponentially with temperature, but at room temperature it is usually not very large. For example in silicon n_i=1.61*$10^{16}m^{-3}$ at room temperature, whereas there are about 10^{29} free electrons per cubic metre in a typical metal. Consequently the conductivity of the metals is very much greater than that of intrinsic semiconductors.

As at a given temperature there is a steady state carrier concentration. There must be a recombination of electron-hole pairs as the same rate as that at which the thermal generation occurs.

Recombination takes place when an electron in the conduction band makes a transition into a vacant state in the valence band.

The energy released in the recombination which is equal to E_g , ma be emitted as a photon or give up as heat to the crystal lattice in the form of quantised lattice vibrations, which are called phonons, depending on the nature of the recombination mechanism. When a photon is released, the process is called radiative recombination.

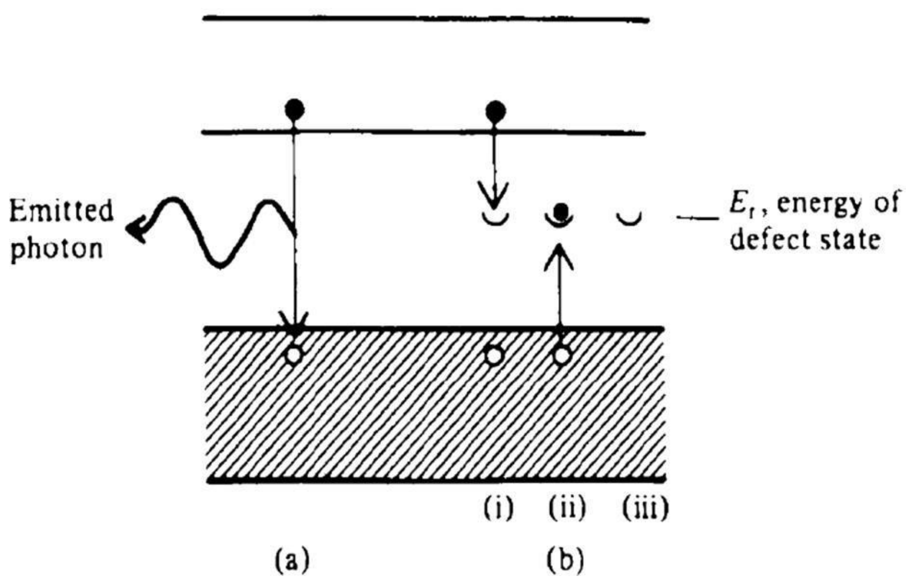


Fig: a).Illustration of band-band recombination

b).Recombination via a detect centre

b)i).Trapping of electron

b)ii).Hole capture

b)iii).If the thermal generation rate is g_1 and the recombination rate is r_1 then in equilibrium

$$g_1 = r_1$$

Both rates are temperature dependent so that if the temperature is raised, g_1 increases and the n_i is established.

At any temperature the probability of an electron recombining is proportional to the number of holes present: thus electrons will disappear at a rate proportional to the product of the electron and hole concentrations. Therefore

$r_i = Bnp = g_i$

B – Constant of proportionality

For intrinsic material $n=p=n_i$

$r_i = Bn_1^2$

Wave nature of light and the principle of superposition

Wave nature of light

The term ‘light’ is taken to include the ultraviolet and near-infrared regions as well as the visible region of the spectrum. Light as an electromagnetic wave is characterised by a combination of time-varying electric (E) and magnetic (H) fields propagating through space. Maxwell showed that both these fields satisfy the same partial differential equation.

$$\nabla^2 (\square, \square) = \frac{1}{\square^2} \frac{\square^2}{\square \square^2} (\square, \square)$$

This is called wave equation.

$$C = V \square_0$$

In any other medium the speed of propagation is given by

$$V = \frac{\square}{\square} = V \square = V \frac{\square_0}{\square}$$

Where n is the refractive index of the medium and $\square$ is the wavelength in the medium, ‘n’ is given by

$$\square = \sqrt{\square_{\square} \square_{\square}}$$

Where μ_r , ϵ_r are the relative permeability and relative permittivity of the medium.

The electric and magnetic fields vibrate perpendicular to one another and perpendicular to the direction of propagation as shown in figure.

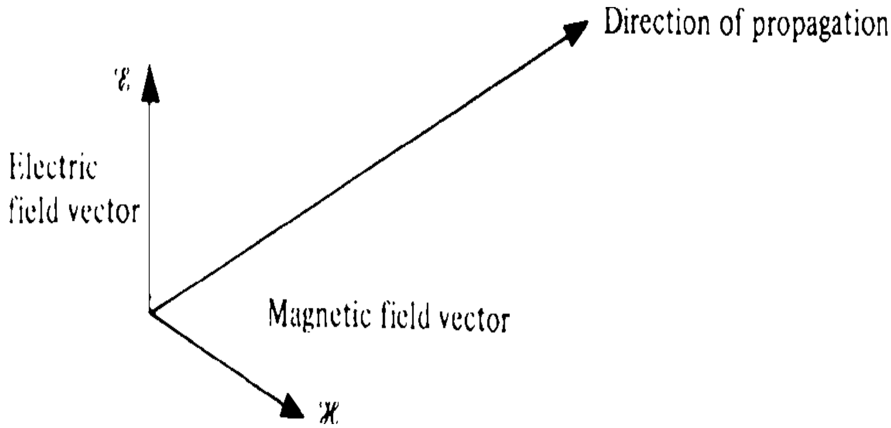


Fig: The Electro Magnetic Wave : The electric vector (E) and magnetic vector (H) vibrate in orthogonal planes and perpendicularly to the direction of propagation.

Light waves are transverse waves. In describing optical phenomena we often omit the magnetic field vector. This simplifies diagrams and mathematical descriptions but we should always remember that there is also a magnetic field component which behaves in a similar way to the electric field component.

The simplest waves are sinusoidal waves , which can be expressed mathematically by the equation

$$E(x, t) = E_0 \cos(\omega t - kx + \phi)$$

Where E is the value of the electric field at the point x at time t, E_0 is the amplitude of the wave , ω is the angular frequency ($\omega = 2\pi\nu$) , k is the wave number ($k=2\pi/\lambda$) and ϕ is the phase constant. The term $\cos(\omega t - kx + \phi)$ is the phase of the wave.

If as a representative time , we take t equal to zero , then the spatial variation of the electric field is given by,

$$E = E_0 \cos kx$$

If we take x equal to zero then the temporal variation of electric field is given by

$$E = E_0 \cos \omega t$$

We also note that the time for one cycle is the period T (T =1/v) as shown below.

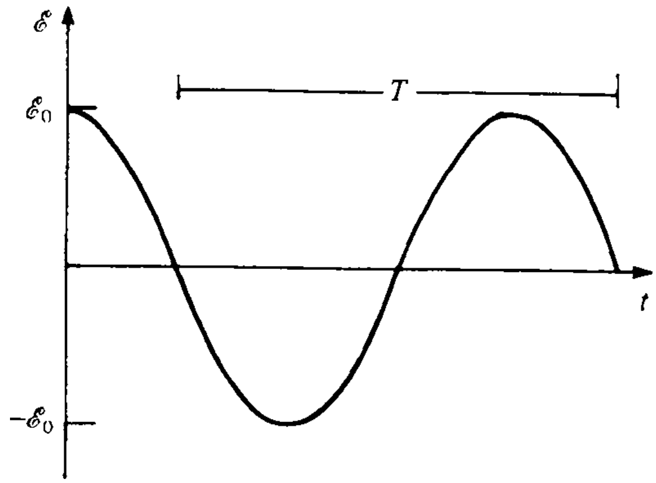


Fig: Electric field (E) of an EM wave plotted as a function of the time t.

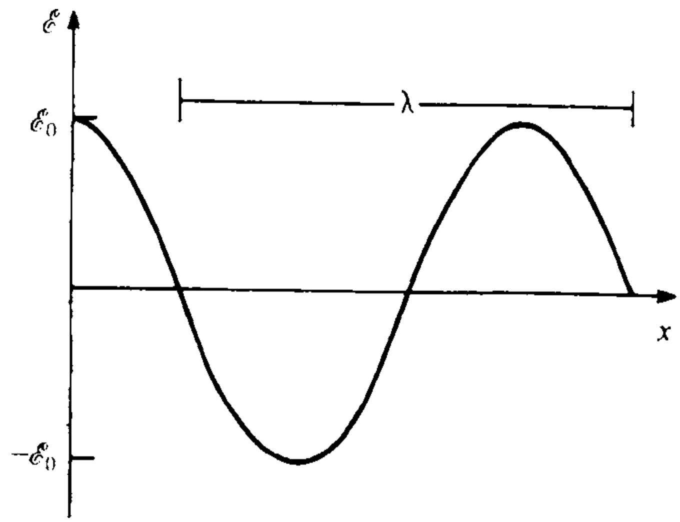


Fig:Electric field (E) of an EM wave plotted as a function of the spatial coordinate x

The group velocity is given by

$$v_g = \frac{d\omega}{dk}$$

The wave can be characterized by a vector k where $|k| = 2\pi/\lambda$ therefore

$$E(x, y, z, t) = E_0 \cos(\omega t - kx + \phi)$$

<u>Principle of superposition:</u>

It states that ‘ The resultant electric field at a given place and time due to the simultaneous action of two or more sinusoidal waves is the algebraic sum of the electric fields of the individual waves’. That is ,

$$E = E_1 + E_2 + E_3 + \ldots$$

Where E_1, E_2, E_3 are the electric fields of the individual waves at the specified time and place. Let us consider the simple case of the superposition of two waves of the same frequency propagating in the same direction given by

$$\square_1 = \square_{01}\sin(\square\square - \square\square + \square_1$$

$$\square_2 = \square_{02}\sin(\square\square - \square\square + \square_2$$

The resultant is $\square = \square_1 + \square_2$

$$\square = \square_{01}\sin(\square\square - \square\square + \square_1) + \square_{02}\sin(\square\square - \square\square + \square_2)$$

Which may be written as

$$\square = \square_{01}\cos\square_1 + \square_{02}\cos\square_2)\sin(\square\square - \square\square) + \square_{01}\sin\square_1 + \square_{02}\sin\square_2)\cos(\square\square - \square\square)$$

This is identical with

$$\square = \square_0\sin(\square\square - \square\square + \square)$$

Provided that

$$\square_0^2 = (\square_{01}\cos\square_1 + \square_{02}\cos\square_2)^2 + (\square_{01}\sin\square_1 + \square_{02}\sin\square_2)^2$$

ii). **Interference:**

The basic mathematical description of ‘two-beam’ interference is given by,

$\square = \square_0^2 = \square_{01}^2 + \square_{02}^2 + 2\square_{01}\square_{02}\cos(\square_{2-}\square_1)$ If

$\square_{01} = \square_{02}$ then

$$\square = 2\square_{01}^2[1 + \cos(\square_{2-}\square_1)]$$

This shows the irradiance distribution of the fringes is given by cosine function.

If the contributions from the coherent sources are equal the irradiance of the fringes varies from $4\square_0^2$ to zero as $(\square_{2-}\square_1)$ varies between 0 and $\square$.

If If $\square_{01} \neq \square_{02}$, the resultant irradiance between $(\square_{01}+\square_{02})^2$ and $(\square_{01}-\square_{02})^2$

To obtain the coherent wave trains required for the observation of interference before the advent of lasers one had to ensure that:

1. The sets of wave trains were derived from the same small source of light and then brought together by different paths.
2. The differences in path were short enough to ensure at least partial coherence of the wave trains.

The basic ways of satisfying these requirements and demonstrating interference can be classified into two groups, namely ‘division of wavefront’ and ‘division of amplitude’.

Interference effects involving amplitude division can be observed in thin films or plates as illustrated in figure below.here the interference occurs between the light reflected at A on the front surface of the plate and at B on the rear surface. If the plate has parallel faces then the two sets of waves from A and C are parallel and a lens must be used to bring them together to interfere.

Using elementary geometry and snell’s law the reader may show that the optical path difference (AB+BC)n-AD is equal to 2nl cos$\square_2$ where $\square_2$is the angle of refraction and L is the plate thickness.The phase difference is then $(\frac{2\square}{\square_0})$(2nl cos$\square_2$) and therefore bright fringes occur when

$$\frac{4\square\square\square\cos\square_2}{} = 2p\square_0$$

That is

$$p\square_0 = 2nl\cos\square_2$$

Where again $\square_0$is the wavelength of the radiation in vaccum, likewise dark fringes occur when $(2p+1)\square_0/2 = 2nl\cos\square_2$

If the plate is optically denser than the surrounding medium,there is a phase change of □ on reflection at the upper surface , thereby causing the above conditions to be interchanged.

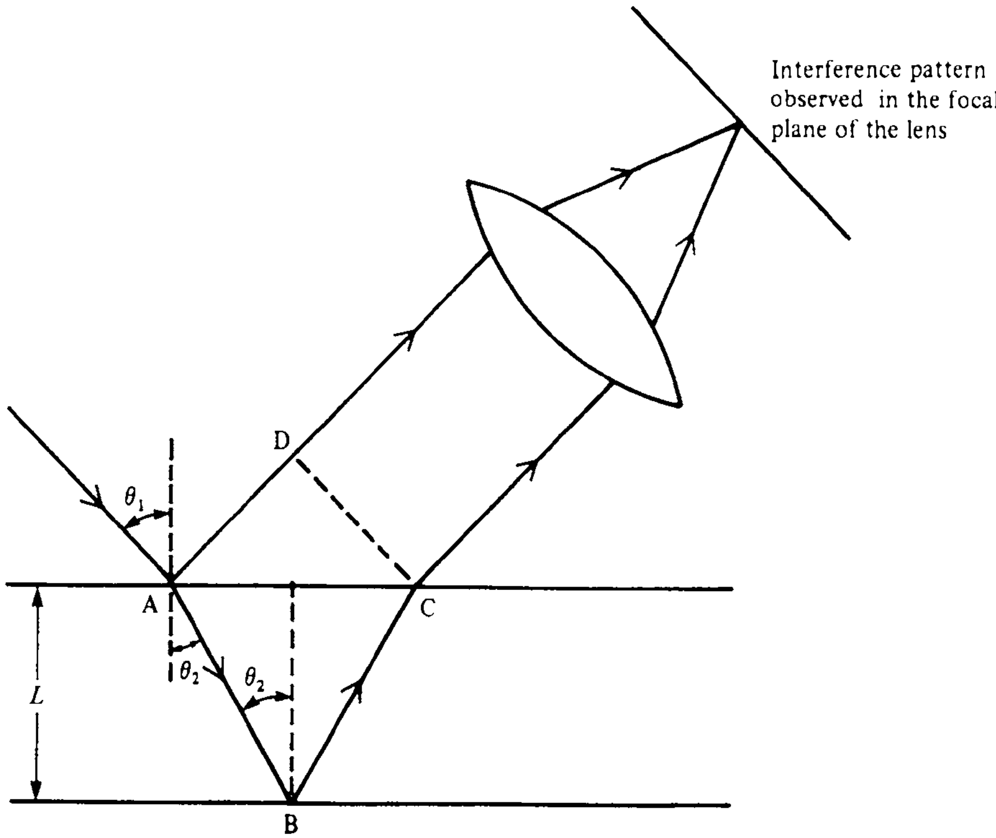


Fig:Schematic diagram of interference effects in a thin film or plate of refractive index n.

For a given fringe p,$□_0$,L and n are constant and therefore $□_2$ must be constant: the fringes are known as 'fringes of equal inclination'.if the angle of incidence is not too large and an extended monochromatic source is used then the fringes are seen as a set of concentric circular rings in the focal plane of the observing lens.

When the optical thickness of the plate is not constant and the optical system is such that $□_2$ is almost constant, the fringes are contours of equal optics thickness nL, The situation ma be illustrated by considering a small angled wedge.If the wedge is uniform the fringes are approximately straight lines parallel to the apex of the wedge. Again it is left to the reader to show that the apex angle □ is given by

$$□ = \tan □ = \frac{□_0}{2□}$$

Young's double slit interference experiment:

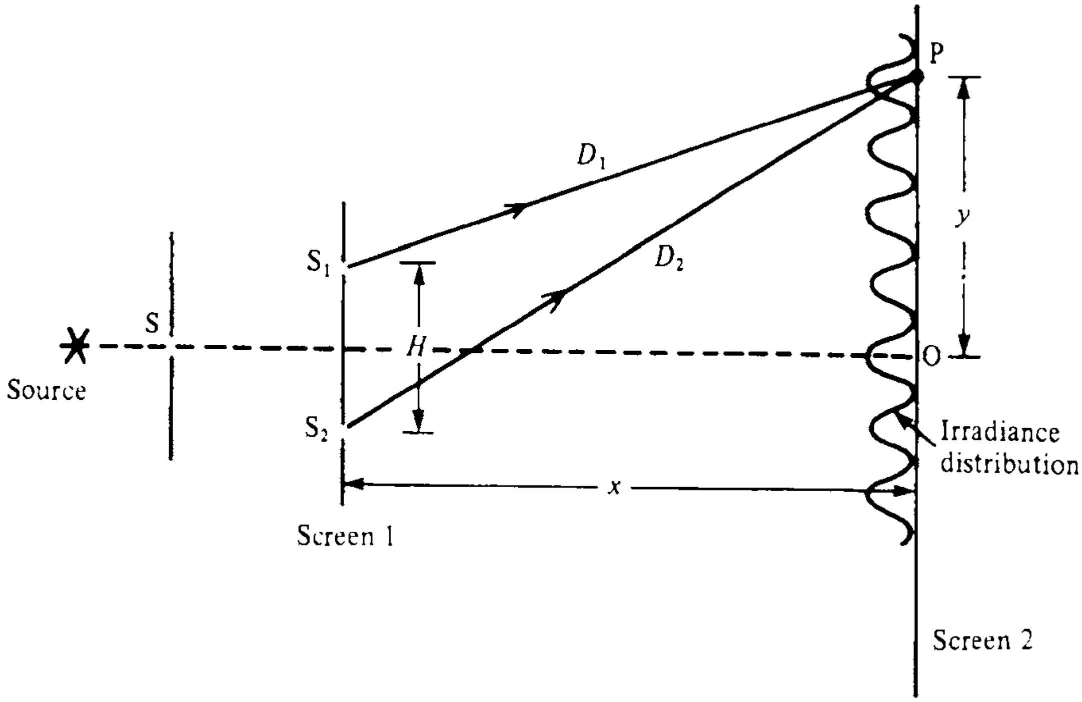


Fig:Schematic laout and geometr for a Youngs double slit interference experiment

In this experiment, a monochromatic light is passed through a pinhole S so as to illuminate a screen containing two further identical pinholes or narrow slits placed close together.

The presence of the single pinhole S provides the necessar mutual coherence between the light beams emerging from the slits S_1 and S_2 .

The wavefronts from S intersect S_1 and S_2 simultaneously so that the light contributions emerging from S_1 and S_2 are derived from the same original wavefront and are therefore coherent.

These contributions spread out from S_1 and S_2 as 'cylindrical' wavefronts and interfere in the region beyond the screen.

If a second screen is placed as shown then an interference pattern consisting of straight line fringes parallel to the slits is observed on it.

To find the irradiance at a given point P it is necessary to find the phase difference δ - between the two sets of waves arriving at P from S_1 and S_2. This in turn depends on the path difference (D_2-D_1) as in general,Phase difference = $\frac{2\pi}{\lambda_0}$ (Optical path difference)

Excess carriers in semiconductors and hence derive an expression for the variation of excess carriers concentration with distance and time.

In calculating semiconductor properties and in analysing device behaviour it is often necessary to know the carrier concentrations.

In metals we can make a fairly good estimate of the free electron concentration by number of atoms per unit volume and multiplying b the valency.

To calculate the carrier concentration in each energy band we need to know the following parameters:

1. The distribution of energy states or levels as a function of energy with in the energy band.
2. The probability of each of these states being occupied by an electron.

The first of these parameters is given by the density of states function Z(E) which may be defined as the number of energy states per unit energy per unit volume. The form of Z(E) which gives the energy levels in a potential well. It is given by,

$$Z(E) = \frac{4\pi}{h^3}(2m^*)^{\frac{3}{2}} E^{1/2}$$

Where E is the measured relative to the bottom of the band.

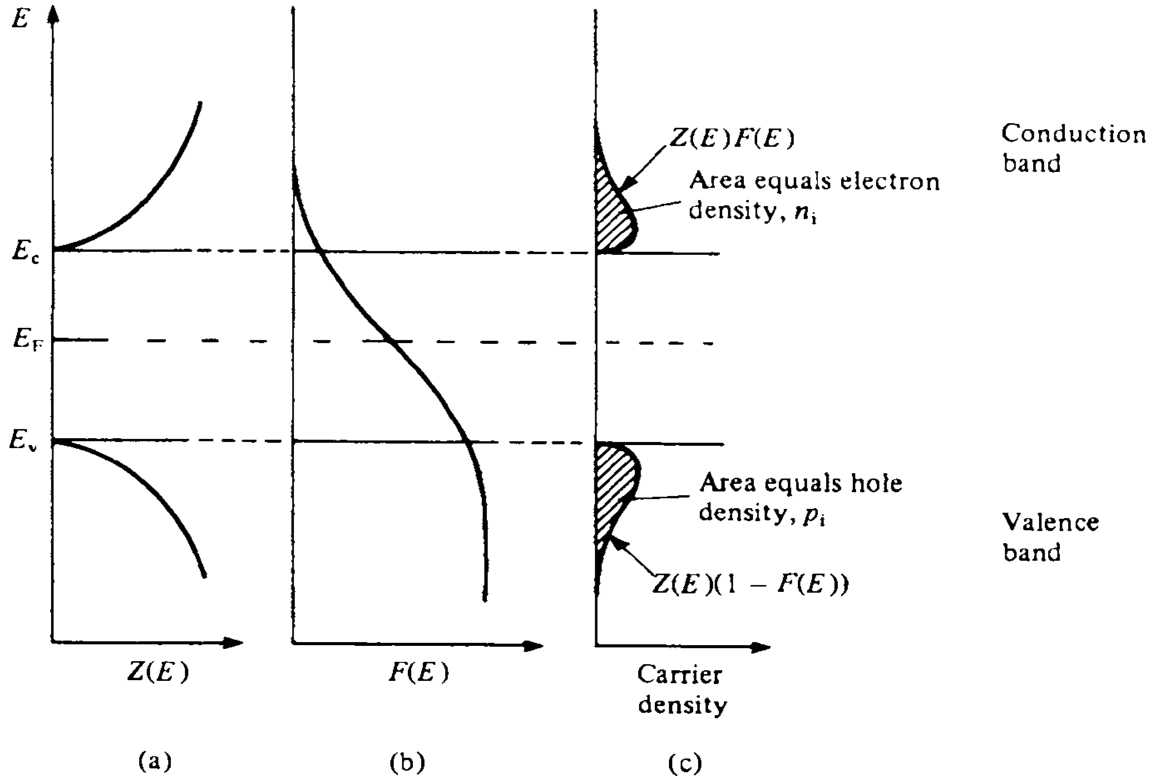


Fig: Graphical representation of a).the density of states, b).the fermi-Dirac distribution and c).Carrier densities for an intrinsic semiconductor.

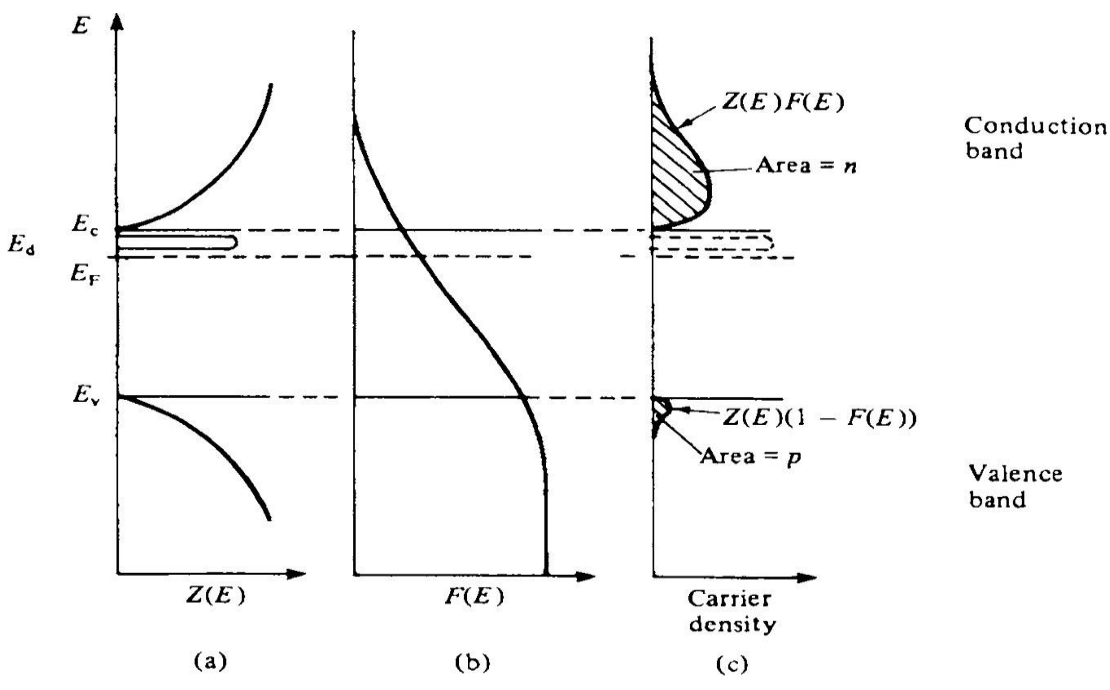


Fig: Graphical representation of (a).the density of states b).the fermi-Dirac distribution and c).Carrier densities for an n-type semiconductor.

Drift and diffusion of carriers with relevant mathematical expressions. Diffusion of carriers

Let us suppose that a concentration gradient of excess minority carriers is created in a rod of n-type semiconductor by injecting holes into one end of the rod via a suitable contact as shown in figure.

Owing to the random thermal motion of the holes at an given location it is probable that more holes will move to the right than to the left in a given time interval, and there will be a net movement or diffusion of holes along the rod down the concentration gradient. The net rate of flow of holes across unit area due to diffusion is found to be proportional to the concentration gradient, that is

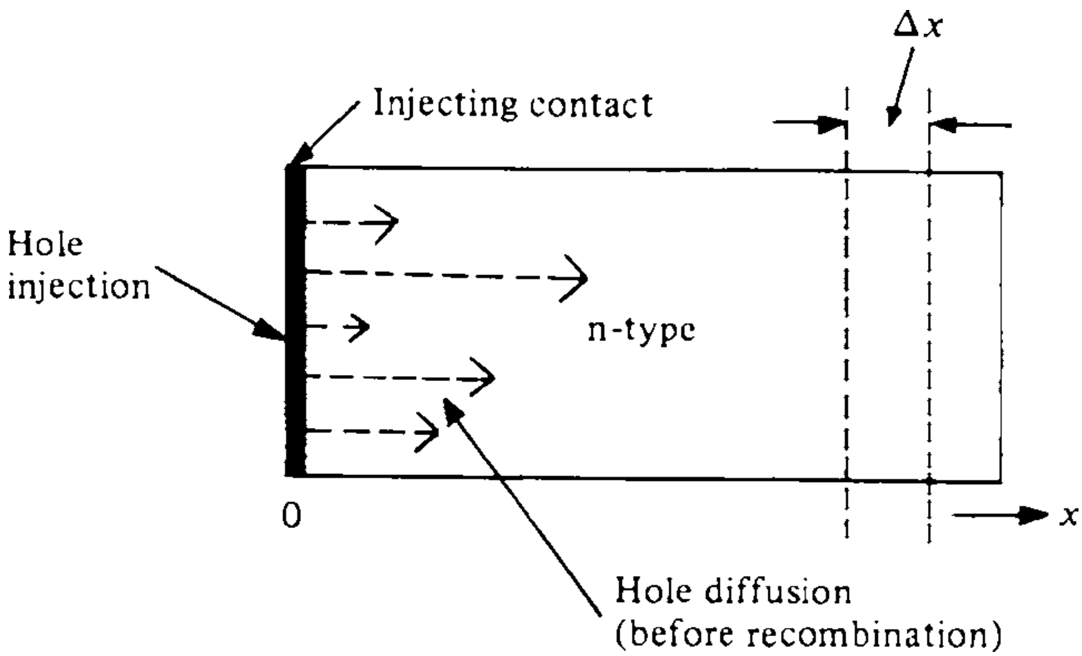


Fig 1:Minority carrier injection and diffusion

UNIT II

DISPLAY DEVICES AND LASERS

The construction and operation of CRT screen. Also explain the principal of obtaining colour display in CRT with relevant diagram

- The cathode ray tube (CRT) is a display device that uses electrons fired at phosphors to create images. The CRT takes input from an external source and displays it, making other devices, such as computers useful.

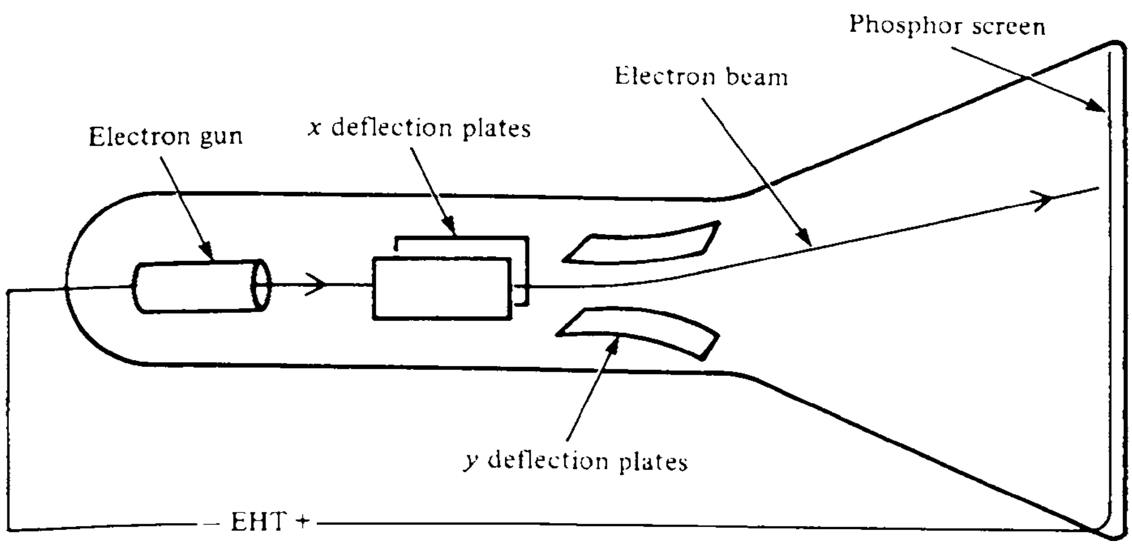


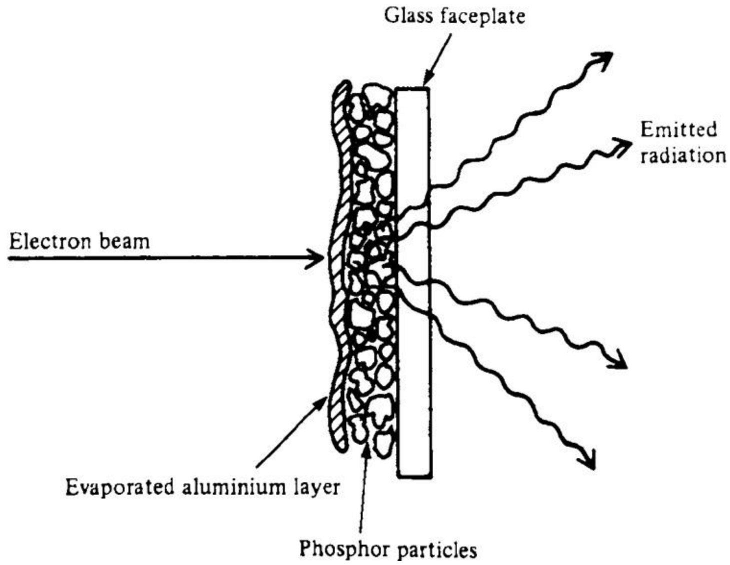
Fig.1 Schematic diagram of a CRT

- Figure 1 shows the basic construction of CRT. Electrons arc generated by thermionic emission by heating a specially Impregnated cathode surface (usually bused on oxides of barium and strontium) and then focused onto the viewing screen by a series of metal electrodes held at various potentials. The whole assembly is known as an 'electron gun'.
- The electron beam is scanned across the viewing screen in it series of lines; when one line scan is completed the beam is rapidly switched to the star! of the line below. Beam deflection is controlled by electrostatic or electromagnetic fields acting at right angles to the beam direction.
- Electrostatic deflection enables the highest beam deflection rates to he achieved, while electromagnetic deflection enables higher beam accelerating potentials to be

employed, which results in a smaller spot size and higher screen brightness, When the beam strikes the viewing screen, radiation is generated by cathode luminescence.

- The screen consists of a thin layer of small (dimensions ≈ 5 µm) phosphor granules. with a layer of aluminium(≈0.1 µm thick) evaporated onto the gun side. This layer serves two purposes:

  1. It prevents charge build-up on the phosphor granules (which generally have low conductivities)
  2. It helps to reflect light emitted in a direction away from the observer back towards him



- A layer of phosphor is sandwiched between a glass faceplate and an evaporated aluminum layer. High energy electrons penetrate the aluminum and excite cathode luminescence in the phosphor particles. The aluminum layer reduces charge build-up and helps to reflect light back out through the faceplate.
- The thicknesses of both the aluminum and phosphor layers are fairly critical. Ifthe aluminum is too thick, an appreciable fraction of the electron beam energy will he absorbed within it. while if it is too thin its reflectivity will be poor.
- If the phosphor layer is too thick, scattering and absorption reduce the light output and it is too thin a layer incomplete coverage of the screen are will occur

- For normal display operations (e.g. television) the beam is scanned line by line over the viewing area. In video applications the display consists of some 625 lines in Europe and525 in North America.
- To avoid an image that 'flickers' the picture must be renewed at a rate greater than about 45 Hz. However, it is possible to avoid having to renew the entire picture at this rate by using a raster scan that splits the picture up into two interlaced halves.
- Thus if a complete picture scan takes t_s, seconds then we may arrange that during the first $t_s/2$ seconds lines 1, 3, 5, 7, etc., are scanned, while during the second ,)2 seconds lines 2,4,6, 8, etc., are scanned.
- Because the two images are effectively superimposed, the eye treats the picture repetition rate as if it were 2/ t_s, Hz rather than 1/ t_s Hz. This reduction in the rate at which picture information is required before flicker becomes very useful because it halves the transmission frequency bandwidth that would otherwise be required.
- Varying light irradiances are obtained by varying the beam current. Ideally. the phosphor used should have a luminescent decay time shorter than the picture cycle time.
- CRT displays can be made sufficiently bright for them to be visible under nearly all ambient lighting conditions. The brightness limits are usually reached when the phosphor screen rapidly deteriorates under high beam currents.
- Colour displays for home video viewing are obtained using the 'shadow mask' principle, in which three electron guns are used that are slightly inclined to each other so that their beams coincide at the plane of the shadow mask.
- The latter is a metal screen, with holes in it, placed just in front of the phosphor screen. Having passed through one of the holes in the shadow mask the three beams diverge and on striking the phosphor screen are again physically distinct. The phosphor screen consists of groups of three phosphor dots placed so that when the three beams pass through a hole in the shadow mask they each hit a different dot.
- Figure 3 illustrates the basic geometry.

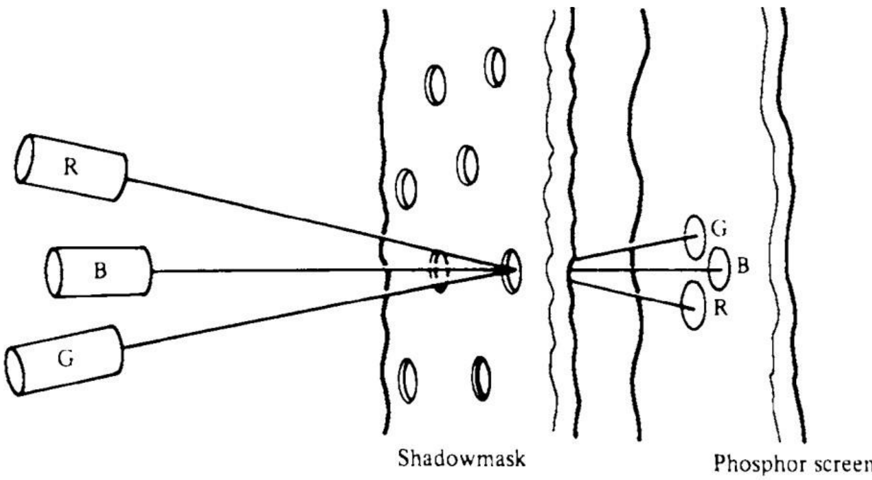


Fig 3 .Use of the shadow mask for obtaining color displays

- Three separate guns are used these are inclined slightly to each other so that their beams will pass through a single hole in the shadow mask. After passing through the hole, the beams diverge so that each falls on one of the three circular areas composed of phosphors, each of which emits one of the three primary colors.

- Some of the more commonly used phosphors are zinc sulfide doped with silver: ZnS:Ag (blue); zinc cadmium sulfide doped with copper:$Zn_xCd_{1-x}S$:Cu (green); and yttrium oxysulfide doped with europium and terbium:Y_2O_2S:Eu,Tb (red).The first two materials are non characteristics materials and latter is characteristic materials
- The alignment of the shadow mask with the guns and the phosphor screen is critical, and can be failed by fairly harsh environmental conditions such as stray magnetic fields. Several modifications have been made to the basic shadow mask principle to try and rectify some of these disadvantages.
- To overcome these disadvantages, different method can be developed and named it as "penetration Phosphor".
- For example a two colour display may obtained by using a mixture of 2 different kind of phosphor particles. One is red (ordinary phosphor particles)other is green non-luminescent particle.

- At low beam voltage the display shows only the red,since the electrons not have sufficient energy to penetrate non luminescence coat. At high beam voltage the display shows both the red, and green emission.
- Further necessary changes in beam potential cannot be achieved for video applications. For a static display it requires fixed colours ,however this technique offers good resolution and freedom from magnetic interference.

Mechanism of electro luminescence with neat diagram and also explain about operation of ac electroluminescence device.

- The other name of electroluminescence is named as 'classical electroluminescence' as opposed to 'injection electroluminescence, which uses fabricated p- n junctions
- Four main types of device may be distinguished. depending on the type of drive (a.c. or d.c.) and the character of the active layer (powder or thin film).
- In this a phosphor powder (usually ZnS:Cu) is suspended in a transparent insulating binding medium of high dielectric constant and is sandwiched between two electrodes(one of which is transparent) as shown in Fig. 4.

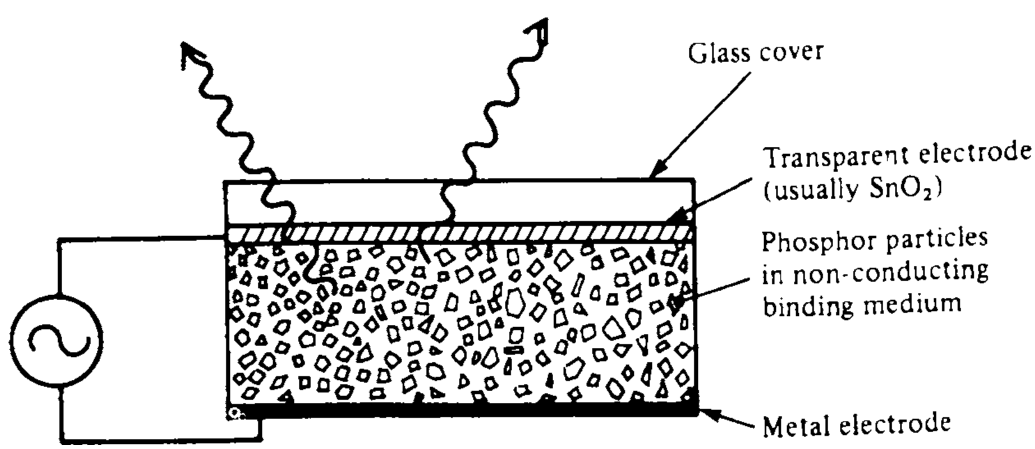


Fig 4 Construction of a a.c electro luminescence device

- The construction of a d.c. electroluminescent device. The phosphor particles have a coating of Cu_xS This coating it removed from the anode side of the particles in contact with the anode by the application of an initial high current pulse. Under normal conditions, light is emitted only from the Cu_xS depleted partcicles.

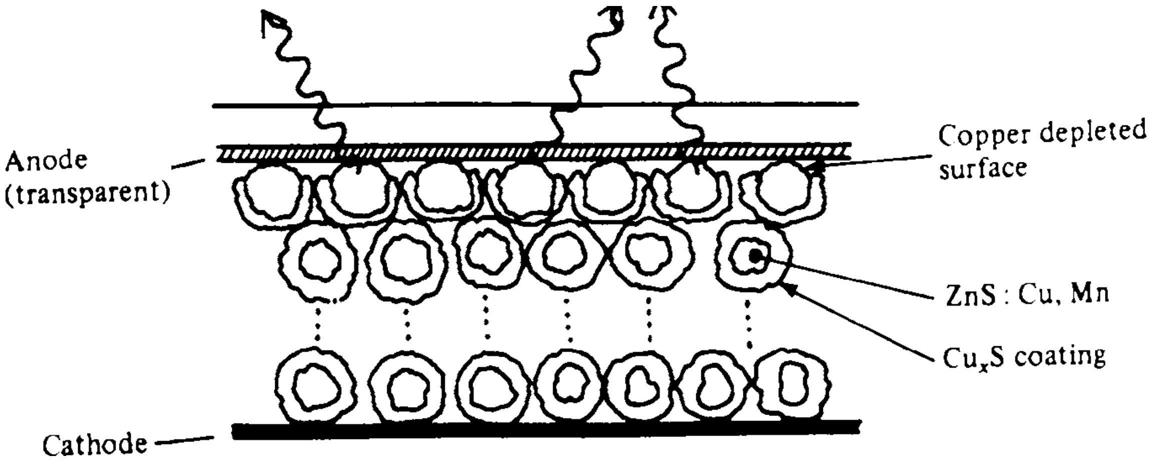
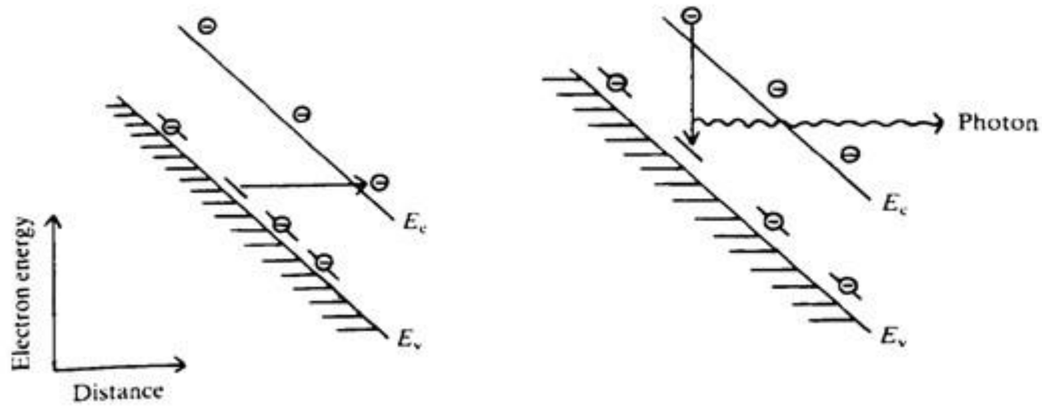


Fig 5 Construction of a d.c electro luminescence device

- Usually there is no complete conducting path between the electrodes, so that d.c. excitation is not possible.
- When an alternating voltage, $V_o \cos(2\pi ft)$, is applied across the cell, however. light is emitted in the form of short bursts which last about 10^{-3} s and occur once every half cycle. It is found that the integrated light output power *P* can be written in the form $P = P_0 \exp\left(\sqrt{\frac{V_1}{V}}\right)$
- where V_1 is a constant and Po(f) is a function of frequency.
- The strongest emission from within the phosphor grain is found to take place from the side temporarily facing the cathode.
- Several possible emission mechanisms have been proposed however. that there will be a high electric field within the phosphor particle. It is then possible that this field is sufficiently strong to enable electrons from occupied acceptor levels to 'tunnel' to states of the same energy in the conduction band, as illustrated in Fig. 6a and other electrons in conduction band are fall into vacant levels and emit radiations. This shows in fig 6 b.



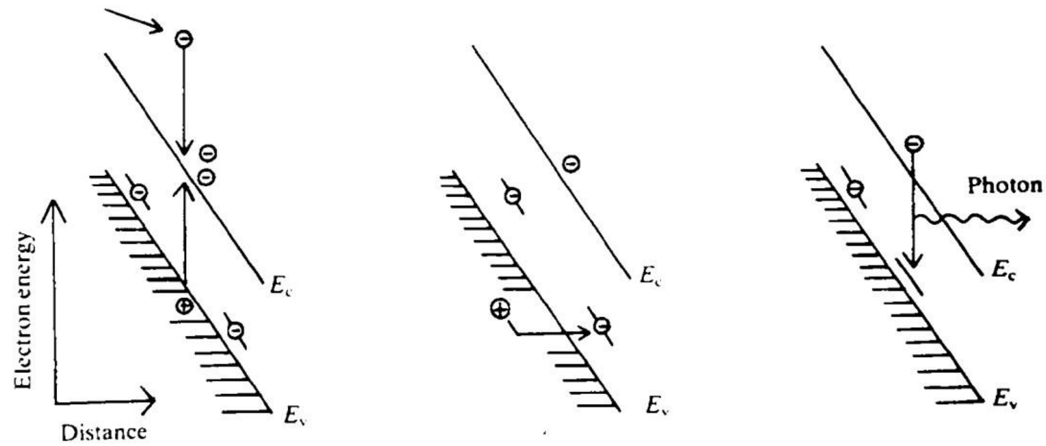
(a) (b)

Fig 6. Possible mechanism for electroluminescence emission involving quantum mechanical tunneling.

In (a) an electron in an acceptor state 'tunnels' through the forbidden gap region into states of the same energy. It is only able to do this if there is a considerable electric field present, thus causing the energy bands to be tilted. An electron in the conduction band may now fall into the vacated level resulting in radiative emission (b).

- Another possibility is that an electron moving in the electric field may acquire sufficient energy to enable it to excite an electron from the valence band to the conduction band. The resulting hole quickly becomes trapped at an impurity acceptor site, thereby effectively emptying it of an electron. An electron in the conduction band can then make a radiative transition by falling into the empty acceptor level. The sequence of events is illustrated in Fig.7.

- Figure 7 explains the Possible mechanism for electroluminescence emission involving an avalanche process. In (a) an electron moving in the high electric fields present may acquire sufficient energy to excite an electron from the valence band into the conduction band. The hole left behind then moves up into an acceptor state effectively emptying it of an electron (b). Finally, an electron in the conduction band ,may then make a radiative transfer into the empty acceptor level (c)



(a) (b) (c)

Fig 7 Possible mechanism for electroluminescence emission involving ,an avalanche process

- In phosphors containing manganese, there is evidence that the Mn^{2+} ions themselves may be directly excited by the high energy electrons radiation being emitted when the ion subsequently undergoes de-excitation.
- A.C. powder devices usually require several hundred volts (r.m.s.) to drive them. They exhibit luminance's of about 40 units have power efficiences (i.e. the ratio of optical power out to electrical power in) of about 1% and life times of about 1000 hours. By using different phosphor powders, red, green, yellow and blue displays are possible.
- The D.C power display basically similar to that of the a.c, device. However. the phosphor particles (ZnS:Cu.Mn) are coated with a conducting layer of Cu_xS. Provided the phosphor particles are not too widely dispersed within the binder there will be a conducting path from the anode to the cathode.
- Before normal operation. the cell must be 'formed' by applying a high voltage across it fora short time. This causes copper ions to migrate away from the phosphor surfaces next to the anode.
- A thin high resistance layer of ZnS is then created next to the anode across which most of the applied voltage appears, and from which light emission takes place liming subsequent operation at lower voltages.

- Luminance of about 300 nits are possible at voltages of around 100 V d.c., although the power conversion efficiencies are low at approximately 0.1 %. The luminance versus drive voltage characteristics for both a.c, and d.c. powder electroluminescent devices are shown in Fig. 8

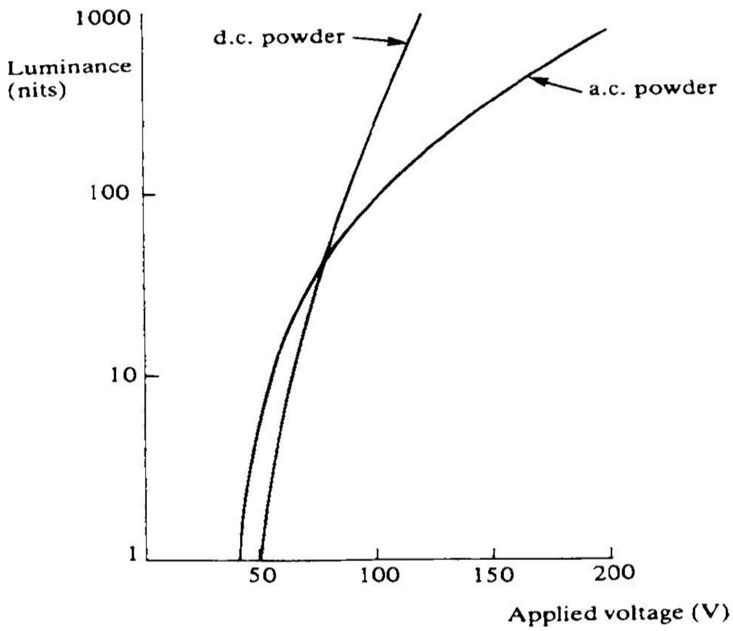


Fig 8:Typical luminance obtained for a.c and d.c. electroluminescent powder device as a function of the applied voltage (r.m.s. volts in the case of the a.c. device).

- Inaddition, a.c. and d.c. devices have been made where the active layer is a vacuum deposited thin film of phosphor material (usually based on ZnS). but both types tend to have rather poor lifetimes. Although a considerable amount of research effort has been put into the development of electroluminescent displays. they have yet to make any significant commercial impact.

Operation of LED and also derive an expression for the frequency response and modulation bandwidth of an LED

LED construction

- A typical LED construction is shown in Fig. 9 6. We assume that, as in Fig. 9, the surface layer is p-type. It is obviously advantageous if most of the radiative recombination take place from the side of the junction nearest the surface. We may ensure this by arranging

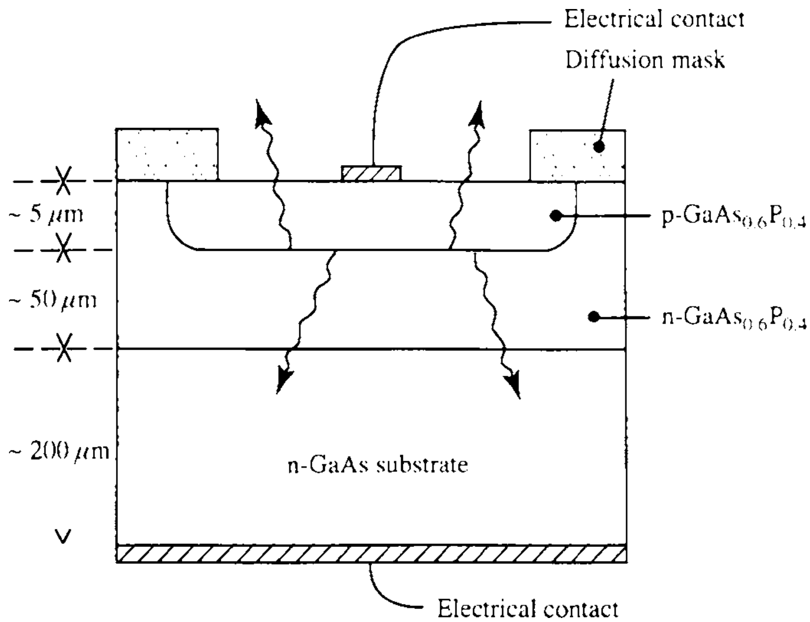


Fig 9: Construction of LED

that most of the current flowing across the diode is carried by those carriers that are injected into the surface layer.

- The fraction of the total diode current that is carried by electrons being injected into the p side of the junction (η_e) is then given by

$$\eta_e = \frac{\frac{eD_e n_p}{L_e}}{\frac{eD_e n_p}{L_e} + \frac{eD_h p_n}{L_h}} \qquad (1)$$

By using the Einstein relation $D_{e,h} = (kT/e)\mu_{e,h}$ and the relation $n_p p_p = n_n p_n = n_i^2$

equation 1 becomes $\eta_e = \left(1 + \frac{N_a L_e \mu_h}{N_d L_h \mu_e}\right)^{-1}$ (2)

- InIII- V compounds $\mu_{e} \gg \mu_{h}$ and so, assuming that $\tau_{e} \approx \tau_{h}$ so η_{i} is closed to unity.Although the internal quantum efficiencies of some LED materials can approach 100%.the external efficiencies are much lower.
- The main reason for this is that most of the emitted radiation strikes the material interface at an angle greater than the critical angle and so remains trapped. Unfortunately, the high refractive indices of the 1Il- V materials discussed here give rise to small critical angles.
- Consider, for example. radiation from a point source within a medium of refractive index III impinging on a plane interface with another medium of refractive index n_2, where $n_2 < n_1$ as shown in Fig. 10. Only those rays (e.g. beam I) that have an angle to the normal less than the critical angle (θ_c) enter the second medium. Those with angles greater than θ_c (e.g. beam 3) are reflected back into the first medium.

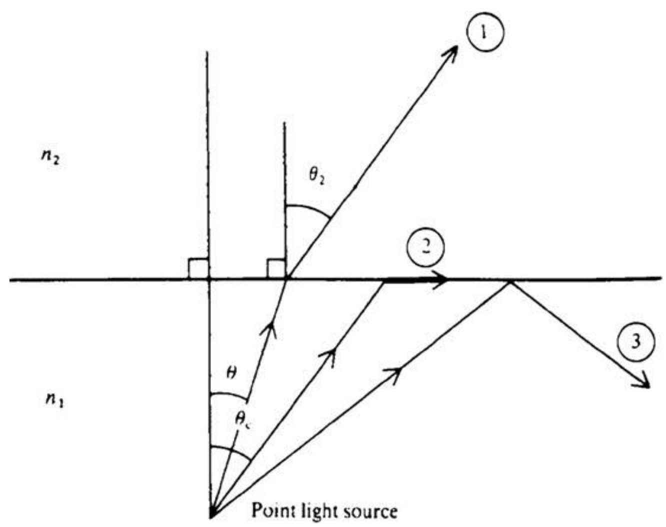


Fig 10: Phenomenon of total internal reflection

From eq. (2). we have that the critical angle θ_c, is given by

$$\theta_c = \sin^{-1}\frac{n_2}{n_1} \qquad (3)$$

- Light originating at recombination centres near the p-n junction will he radiated isotropically, whereas only that within a cone of semi angle θ_c will escape.

The fraction *F* of the total generated radiation that is actually transmitted into the second medium is

$$F \approx \frac{1}{4}\left(\frac{n_2}{n_1}\right)^{-1}\left[1+\left(\frac{n_1-n_2}{n_1+n_2}\right)^{2}\right] \qquad (4)$$

- There are two ways to increase *F*, the first is to ensure that most rays strike the surface at less than the critical angle. This may be achieved by shaping the semiconductor/air interface into a hemisphere, as shown in Fig. 11 (a). This technique isused occasionally in high power diodes, it is too difficult and expensive for most situations.

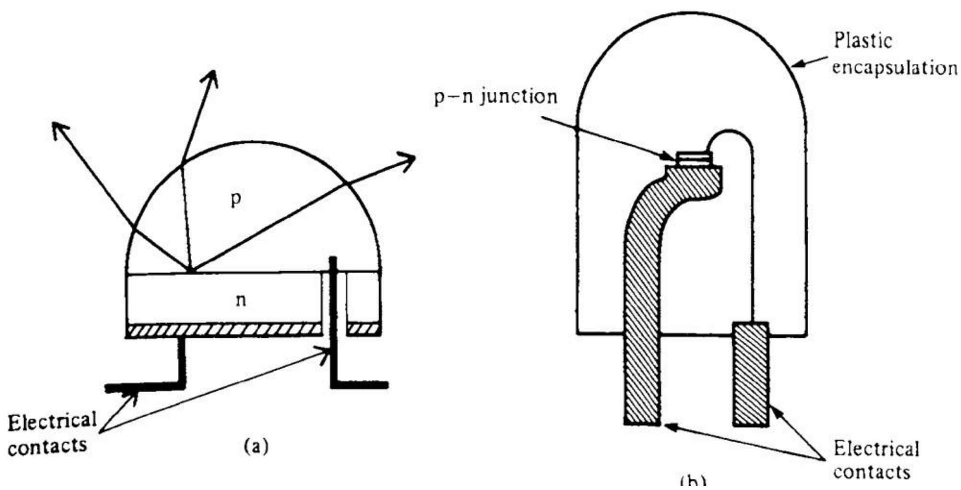


Fig 11: Two methods used to reduce reflection losses in LEDs

- The second, (Fig 11.b) technique is to encapsulate the junction in a transparent medium of high refractive index. This is usually a plastic material with a refractive index of about 1.5. Using eq. (4) with n_1 = 3.6 and n_2 = 1.5 we obtain *F* = 0.036, giving a nearly threefold increase in light output over the simple semiconductor/air

  easily minimized by molding the plastic into an approximately hemispherical shape

- **Frequency Response of LEDs**

$$P(f) = \frac{P(0)}{1+4\pi^2 f^2 \tau^2} \qquad (5)$$

Here,□(□) is frequency response of LED f and τ_e is the minority carrier life time provided for low level injection.

Modulation circuits

- These two circuits provide for continuous 'on' operation. If it is desired to switch the diodeon or off, or to modulate the output, then the circuits shown in Figs 12(a) and (b) respectively may be used.
- In Fig. 12 (a) the transistor is used as a simple switch. With no voltage applied to the base, the transistor has a very high impedance between the collector and emitter and hence no current flows through the LED. If a large enough base voltage is then applied so that the emitter-base junction becomes heavily forward biased. the transistor has a relatively low impedance between emitter and collector and a substantial current can flow, resulting in the LED being turned on

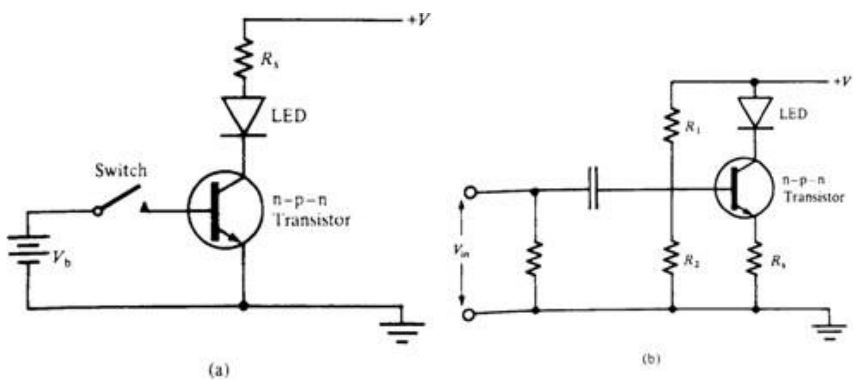


Fig 12: LED modulation circuits

- In Fig. 12(b) the transistor is biased so that the quiescent diode current is about half its peak value and both the transistor and the LED are biased well into their linear regions. Changes in the current flowing through the LED are then directly proportional to changes in the input voltage. Explain the construction and operation of LCD [MAY/JUNE 2013]
- Liquid crystal displays (LCDs) are the 'passive' types of display . There are two basic types of LCD available
- LCD devices is a cell formed between two glass plates each with a conductive coating. The cell has a thickness of about 10 µm (some time less) and is filled with a

liquid crystal material.

- The liquid crystal state is a phase of matter which is exhibited by a large number of organicmaterials over a restricted temperature range. At the lower end of the temperature range. the material becomes a crystalline solid. whilst at the upper end it changes into a clear liquid.
- Within this range it has a milky yellowish appearance and combines some of the optical properties of solids with the fluidity of liquids. A major characteristic of all liquid crystal compounds is the rod-like shape of their molecules.
- When they are in the liquid crystal phase, these molecules can take lip certain orientations relative both to each other and to the liquid crystal surface.
- It is usual to describe this orientation in terms of a *director* that is a unit vector pointing along the time-averaged preferred orientation of the molecules in any small volume.
- There are three basic types of ordering in liquid crystals. which are termed *nematic, cholesteric* and *smtectic.* Only the first two of these are of importance in display devices at presentand are illustrated in Fig.13

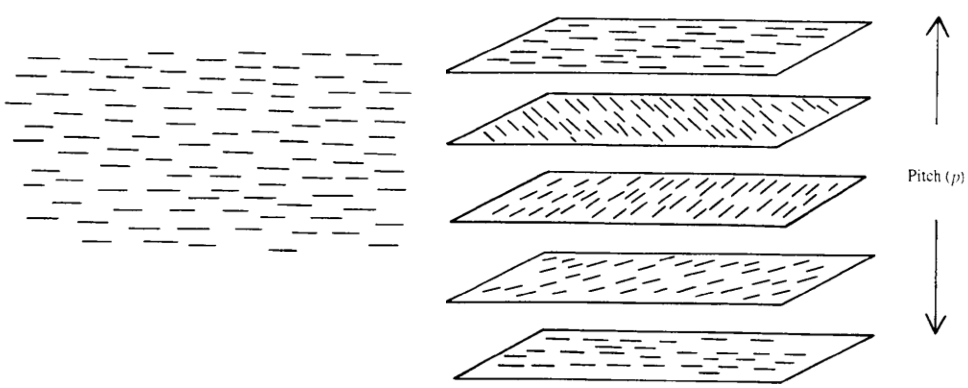


Fig.13 a)Nematic display b)cholesteric display

- **In nematic ordering**. the molecules (or. rather. the directors)are aligned parallel to each other. but apart from remaining parallel the molecules are free to move relative to each other so that the phase has liquid properties. A nematic liquid crystal molecule usually consists of two benzene rings linked with a central group.
- A typical example is 4-rnethoxybenzylidene-4-butylanaline (MBBA), shows liquid crystal behaviour over the temperature range 20°C to 47°C.
- In the **cholesteric phase** the material as being made up from a large number of planes each having a nematic-like structure, but with each plane showing a progressive change in the director direction from the one below. The director directions thus display a helical twist through the material. The distance between planes having the same director direction is called the *pitch ,p,* Cholesteric liquid crystals exhibit some interesting colour effects.

- For example, light of wavelength λ is incident normally on the director planes. then strong Bragg reflection will occur when p = n λ (ns i an integer) but not otherwise. Thus if white light is shone onto a cholesteric liquid crystal it can appear strongly coloured.
- Furthermore, the pitch is usually temperature dependent. So that the colour of the reflected light will also be temperature dependent. Obviously this can form the basis of a thermometer. Most liquid displays, are twisted nematic type.
- When a nematic liquid crystal material comes into contact with a solid surface, the directors often become aligned either perpendicular to the surface (*hemotropic ordering*) or parallel to the surface *(homogeneous* ordering). These two forms can be produced by suitable treatment of the surface.
- In the case of homogeneous ordering, this can often be achieved by rubbing the surface once or twice along a particular direction with a soft fabric (e.g. cotton) before it comes into contact with the liquid crystal material. The liquid crystal directors then take up an orientation parallel to the direction of rubbing.
- One of the most important electrical characteristics of liquid crystal materials is that they show different dielectric constants $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ depending on whether the external

field is parallel to, or perpendicular to, the molecular axis. If $\varepsilon_{\parallel} > \varepsilon_{\perp}$ it is a *positive* material. The application of an external electric field to a positive material will tend to make the molecules lie along the electric field, since this will tend to minimize their energy.

- To change the homogeneous type into a homeotropic type by apply the field perpendicular to the surface (assuming a positive material). This transition is found to take place above a critical field and is illustrated in Fig. 13

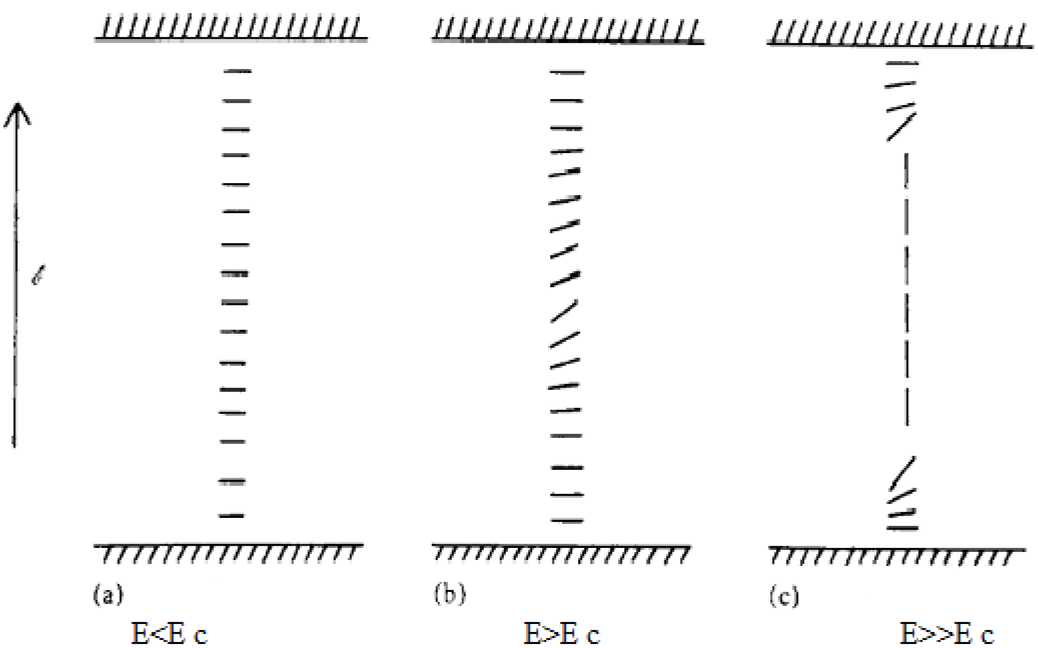


Fig: 14 Behavior of molecules in an initially homogeneous ordered liquid crystal material as an increasing electric field

- The most common liquid crystal display uses a 'twisted nematic' cell. In this, the opposite walls of the cell are treated to produce a homogeneous arrangement in which the molecular alignment directions at the walls are at right angles to each other. Thus the molecules undergo a 90° rotation across the cell as shown in Fig. 15(a).
- When a beam of polarized light is incident on the cell the strong optical anisotropy of the liquid causes the polarization to undergo a 90° rotation. With a strong enough electric field across the cell, however (i.e. $E >> E_c$)the molecular alignments will

become as shown in Fig. 15(b) and in this state the molecular alignments will have no effect on an incident polarized light beam.

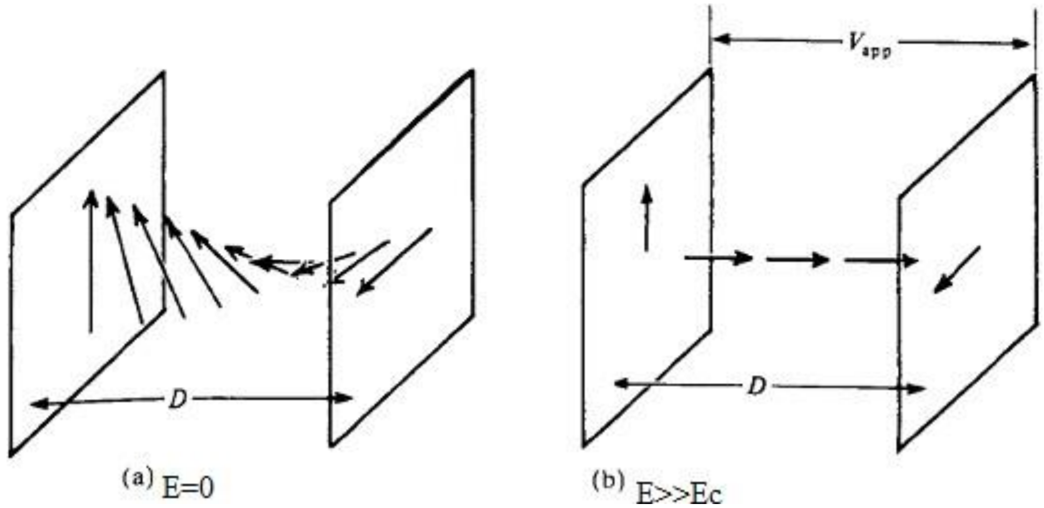


Fig Behavior of molecules in a liquid with thickness D

- In operation, the cell is sandwiched between two pieces of polaroid whose polarizing directions correspond to the director ordering direction of the particular cell surfaces they are next In the reflective mode a reflector is placed behind the back sheet of polaroid. Figure 16 shows the arrangement and traces the behaviour of a polarized beam as it traverses the system.

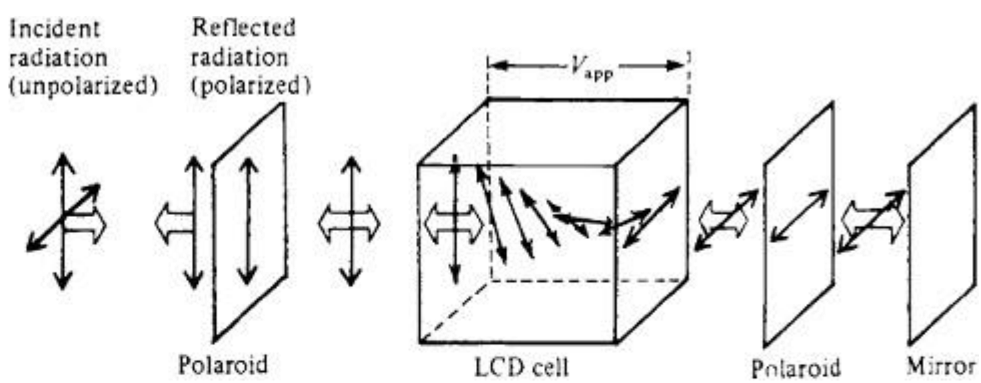


Fig 16the arrangement and traces the behaviour of a polarized beam

- With no applied voltage, the incident light is first polarized then has its polarization direction rotated by 90° as it traverses the cell, then passes through the second polarizer and is then reflected back along its path where the same process is repeated.

- With no field applied therefore, the device reflects incident radiation and appears bright. When a field is applied the direction of polarization of light traversing the ceIl is not rotated and hence cannot pass through the second polarizer. Little light will then be reflected from the device and it will appear dark.
- The amount of light reflected from an LCD as a function of applied voltage is shown schematically in Fig. 14. The reflectance. initially constant. falls rapidly beyond a critical voltage) and again becomes constant beyond a voltage V_{sat}A typical value for V_{sat} is :1 3. V.D.c. operation tends to shorten the operating lifetime of the device owing to electromechanical reactions taking place. and hence a.c. waveforms areinvariably used. The cell responds to the r.m.s. value of the voltage waveform.
- A square waveform which has a frequency of between 25 Hz and I kHz is often used. Transmission LCD displays do not have the reflector and must he provided with rear illumination, but otherwise they operate in a very similar fashion to the reflective displays. Colour displays are possible by incorporating a colour filter. The use of polarizer's in the twisted nematic cell substantially reduces the maximum amount of light that can he reflected from it.

Theory of population inversion and threshold condition in two layer laser system and also explain the various transition involved in a four level system Population inversion

The population inversion condition required for light amplification is a non-equilibrium distribution of atoms among the various energy levels of the atomic system

- The Boltzmann distribution which applies to a system in thermal equilibrium is given by eq (1) and is illustrated in Fig.15(a).

$$N_j = \frac{g_j N_0 \exp(-E_j/kT)}{\sum g_j \exp(-E_j/kT)} \qquad (1)$$

- Where N_j, is the population density of the j[th] energy level and clearly as E_j increases N_j, decreases for a constant temperature. We note that if the energy difference between $E_1$and E_2 were nearly equal to kT (≈0.025 eV at room temperature) then the population of the upper level would be 0.37 of that of the lower level. For an energy difference large enough to give visible radiation (≈2.0 e V), however. the population of the upper level is almost negligible .

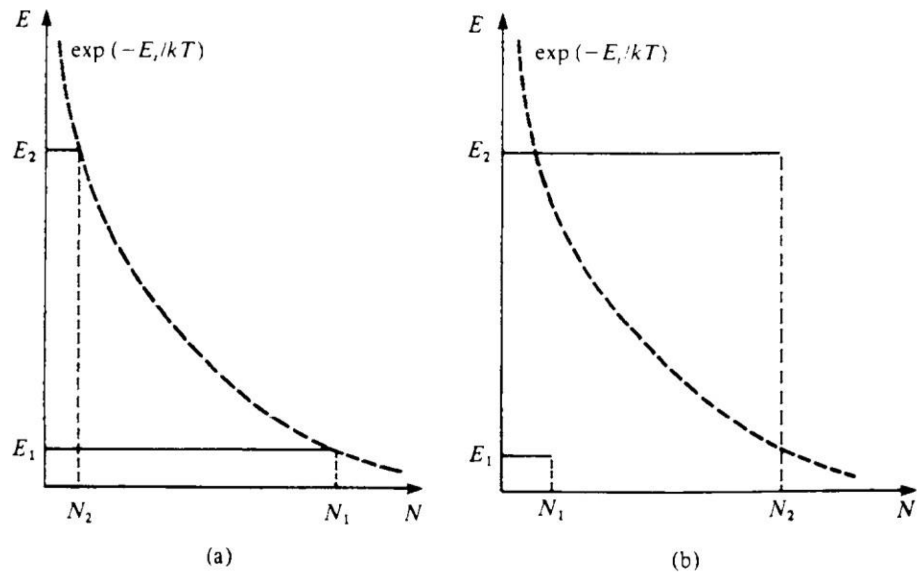


Fig 17 Populations of a two-level energy system: a) in thermal equilibrium; b)in after a population inversion has been produced

- If we are to create a population inversion, illustrated in Fig. 17 (b), we must supply a large amount of energy to excite atoms into the upper level E_2 This excitation process is called *pumping* and much of the technology of lasers is concerned with how the pumping energy can be supplied to a given laser system. Pumping produces it non-thermal equilibrium situation.

Attainment of a population inversion

- One of the methods used for pumping is stimulated absorption that is the energy?y levels which one hopes to use for laser action are pumped by intense irradiation of the system. Now as B_{12} and $B_{21}$are equal (assuming $g_1 = g_2$) once atoms are excited into the upper level the probabilities of further stimulated absorption or emission are equal so that even with very intense pumping the best that can be achieved with the two-level system. considered hither to, is equality of the populations of the two levels.
- As a consequence we must look for materials with either three or four energy level

systems this is not really a disadvantage as atomic systems generally have a large number of energy levels.The three-level system first proposed by Bloembergen is illustrated in Fig18.

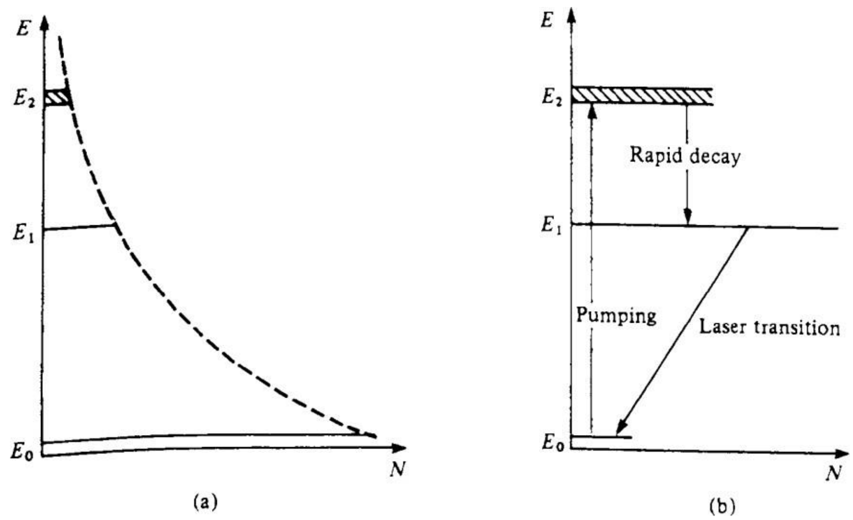


Fig.18 population of the energy levels by pumping in a three-level system: (a) Boltzmann distribution before pumping and (b) distribution after pumping and the transitions Involved

- Initially the distribution obeys Boltzmann's law. If the collection of atoms is intensely illuminated the electrons can be excited (i.e. pumped) into the level $E_2$from the ground state E_o. From $E_2$the electrons decay by non-radiative processes to the level E_1 and a population inversion may be created between E_1 and E_o·
- Ideally, the transition from level $E_2$to E_1should be very rapid, thereby ensuring that there are always vacant states at E_2, while that from E_1 to $E_o$should be very slow, that is E_1 should be a *metastable* state.
- This allows a large build up in the number of atoms in level E_1 as the probability of spontaneous emission is relatively small. Eventually N_1 may become greater than $N_o$and then population inversion will have been achieved.
- The level E_2should preferably consist of a large number of closely spaced levels so that pumping uses as wide a part of the spectral range of the pumping radiation as possible. thereby increasing the pumping efficiency.

- Even so, three-level lasers, for example ruby, require very high pump powers because the terminal level of the laser transition is the ground state. This means that rather more than half of the ground state atoms (this number is usually very nearly equal to the total number of atoms in the collection) have to be pumped to the upper state to achieve a population inversion.

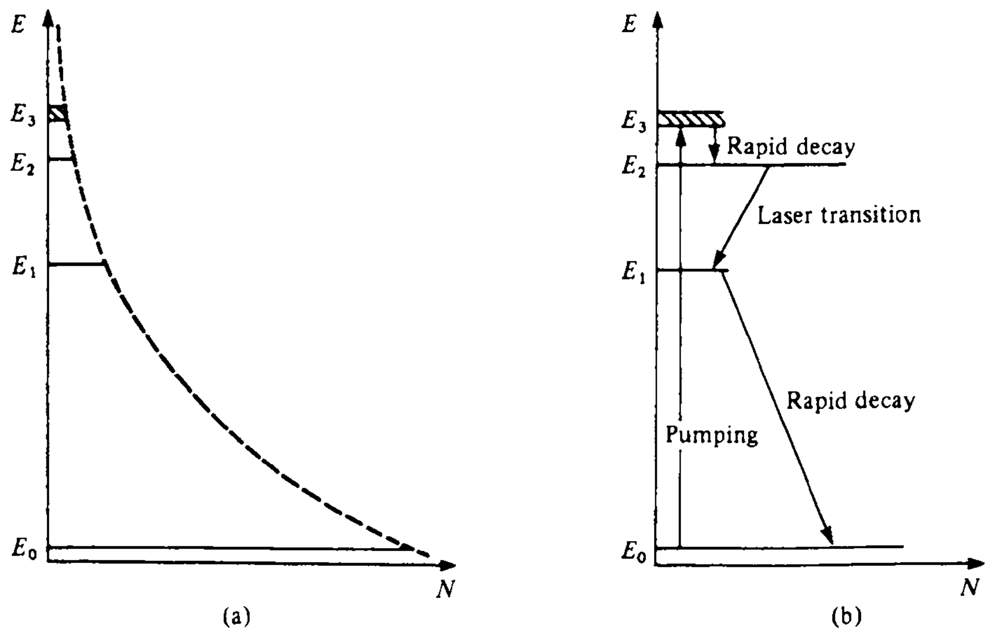


Fig. 19 The four-level system

- The four-level system shown in Fig. 19 has much lower pumping requirements.
- If $(E_1 - Eo)$ is rather large compared with kT (the thermal energy at the temperature of operation). then the populations of the levels E_1, E_2 and $E_3$are all very small in conditions of thermal equilibrium.
- Thus, if atoms are pumped from the ground state to the level $E_1$from which they decay very rapidly to the metastable level E_2 a population inversion is quickly created between levels E_2 and E_1.Again the upper level E_3should preferably consist of a large number of levels for greatest pumping efficiency.

- If the lifetimes of the transitions E_1 *to* E_2 and E_1 *to* E_0 are short the population inversion between E_2 and E_1 can be maintained with moderate pumping and continuous laser action can be achieved more readily.
- In the Nd:Y AG laser. for example, $\tau_{21}\approx 0.5$ ms while $\tau_{10}\approx 0.530$ ns and, although there are many upper levels used for pumping, each has a lifetime of about 10^{-8} s (i.e $\tau_{32}\approx 10^{-8}$ s).
- The details of the mechanisms used for pumping lasers can be quite complicated and, in addition to optical pumping, pumping can occur in an electrical discharge or by electron bombardment, the release of chemical energy, the passage of a current. etc. The energy level schemes of the media used in lasers are often complex, but they can usually be approximated by either three- or four-level schemes.

3. Describe the concept of producing high power short duration pulses from laser.What are the various methods to accomplish this? Explain them [NOV/DEC 2013]

Explain Mode locking of laser

Mode locking is a technique for producing periodic high power short duration laser pulses .The output of such a laser as a function of time depends on the relative phases, frequencies and amplitudes of modes. the total electric fields function of time can be written as,

$$E(t) = \sum_{n=0}^{N-1} (E_0)_n \exp\{i(\omega_n t + \delta_n)\} \qquad (1)$$

Where $(E_0)_n$ is amplitude of nth mode

δ_n is Phase of nth mode

ω_n is angular frequency of nth mode .Usually 3 parameters are time varying, so the modes are in coherent and the total irradiations is simply the sum of the irradiations of the individual modes .

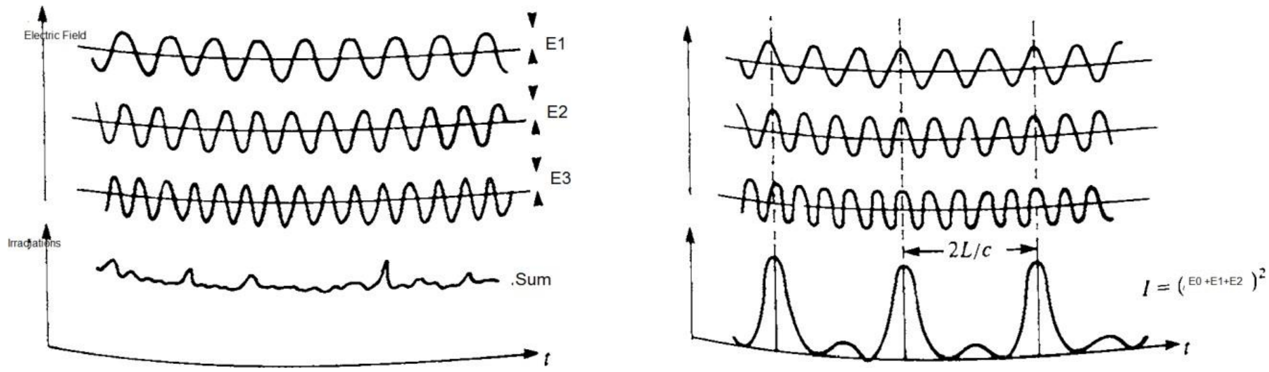


Fig :20 Comparison a) Non mode locked b)Mode locked laser output

$\square = \square\square_0^2$ (2)

We assume that all N modes have the same amplitude E_0.The irradiation may exhibit small fluctuations if 2 or 3 of modes happen to be in phase at any time. Suppose that we mow force the various modes maintain the same relative phase δ to one another i.e mode lock laser such that $\delta_n=\delta$. The total irradiation must now by found adding the individual electric fields rather than the irradiations. using eq(1) the resultant electric field can be now written as

$E(t) = E_0 \exp(i\delta) \sum (i\omega_n t)$ (3)

For simplicity write $\omega_n = \omega - n\delta\omega$

where δω is the angular frequency separation between nodes $\delta\omega = \pi \frac{c}{L}$

eq (3)becomes $E(t) = E_0 \exp(i\delta) \sum_{n=0}^{N-1} i(\omega - n\delta\omega)t$

$$= E_0 \exp i(\omega t + \delta) \sum_{n=0}^{N-1} \exp - \frac{i\pi nct}{L}$$

$E(t) = E_0 \exp i(\omega t + \delta)(1 + \exp(i\phi) + \exp(2i\phi) + \cdots + \exp(-(\square - 1)i\phi))$ (4)

where $\phi = \frac{\square\square\square}{\square}$

$$E(t) = E_0 \exp i(\omega t + \delta) \frac{\sin \frac{N\phi}{2}}{\sin \frac{\phi}{2}}$$

The Irradiation I is then I=E(t).E*(t)

$$I(t) = \square_0^2 \frac{\square\square\square^2 \frac{N\phi}{2}}{\square\square\square^2 \frac{\phi}{2}}$$

Here I(t) is periodic in the time interval t= 2L/c,Which is equals to the round trip transit time with in cavity.The maximum value of the irradiation is $N^2 E_0^2$.This occurs for values of $\phi = 0$ or pπ.

Active Mode Locking

Mode locking is achieved by forcing the longitudinal modes to maintained fixed phase relationships. This can be accomplished by modulating the loss(gain) of the laser cavity at a frequency equal to the internodes frequency separation δv=c/2L(or δω=πc/L).

Let us imagine that the loss modulation is provided by a shutter placed near one of the mirrors. The shutter is closed most of the time and its is only opened every 2L/c sec. Now if the wave packet is exactly as long in time as shutter opens it will be un affected by the presence of the shutter Any parts of the packets that arrive before the shutter opens or after it closes will be eliminated. Thus the phase relationship of the oscillating modes are continuously restores by the periodic operation of the shutter,.

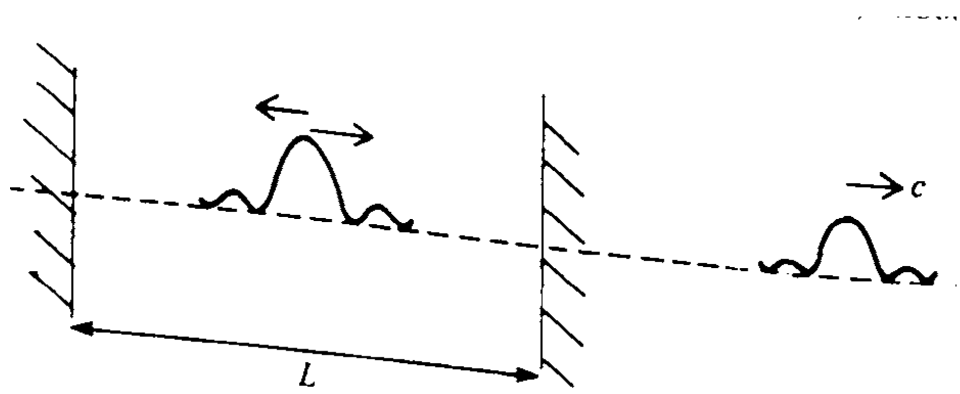


Fig :21 Packet of energy resulting from mode locking of N modes bouncing in between the laser mirrors

Passive mode locking

Mode locking can also accomblished by using certain dyes whose absorption decreases with increasing in irradiation. Materials exhibiting this behaviour is called saturable absorber.

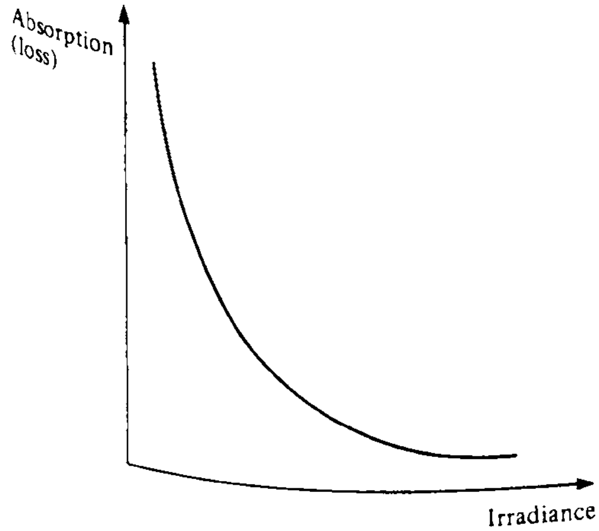


Fig:22 Absorption as a function of incident light irradiance for a saturable absorber

- A dye is chosen which has an absorption band at the lasing transition frequency. Initially at low light levels the dye is opaque owing to the large number of unexcited molecules which can absorb the light.
- As the irradiation increases more of the excited states are populated until eventually all of them are filled so that the dye becomes transparent. The dye is now said to be bleached.
- The growth of the mode locked pulses can be envisaged as follows.
- initially, the laser medium emits spontaneous radiation which gives rise to incoherent fluctuations in the energy density within the cavity.
- Some of these fluctuations, which can be of short duration may be amplified by the laser medium and grow in irradiance to such an extent that the peak part of the fluctuation is transmitted by the saturable absorber with little attenuation.
- The low power parts of the fluctuations are much strongly attenuated and thus a high power pulses can grow within the cavity providing the dye can recover in a time short compared with the duration of the pulses.
- Because of the non-linear behaviour of the dye the shortest and most intense fluctuations grow at the expense of the weaker ones. With careful adjustment of the concentration of the dye within the cavity an initial fluctuation may grow into a

narrow pulse 'bouncing' to and fro within the cavity producing a periodic train of mode-locked pulses.

- Saturable absorbers provide a simple, inexpensive and rugged method of mode locking high power lasers such as Nd:glass and ruby; the so-called 9740 or 9R60 dye solutions and cryptocyanine may be used as the saturable absorber for Nd:glass and ruby respectively.

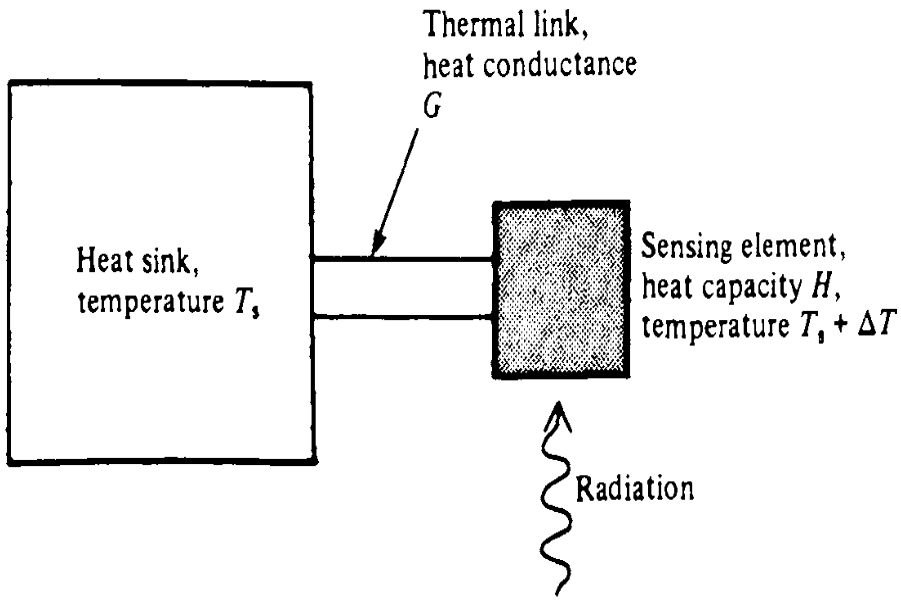
- When saturable absorber is used to mode-lock a laser the laser is simultaneously Q-switched The result is the production of a series of narrow (≈10ps) mode-locked pulses contained within an envelope which may be several hundred nanoseconds long. The peak power within the individual pulses may be enormous because of their very short duration.

UNIT – III

OPTICAL DETECTION DEVICES

Thermal detector

To gain and insight into the performance characteristics of thermal detectors, we consider the behaviour of the simple model shown below.



The incoming radiation is absorbed within the sensing element of heat capacity H, this is connected to a heat sink, at constant temperature T_S , via a heat conducting link which has a thermal conductance G.

If the instantaneous rate of heat absorption is given by W, then during a small time interval □□ , the heat absorbed is W□□ .If we let the temperature of the element be T_S + Δ□

, then during the same time interval the amount of heat lost through the thermal link is GΔ□ □□.

The difference between these two represents the amount of heat available to raise the temperature of the element. Hence we may write:

$$\square \square\square - G\Delta\square \ \square\square = H$$

$\square(\Delta\square)$ If we take the limit $\square\square \rightarrow 0$ we obtain

$$W = H\,\frac{\square(\Delta\square)}{\square\square} + G\Delta\square$$

Now suppose that W has a time dependence given by $W = W_0 + W_f\cos(2\square\square\square)$ where $W_0 \nless W_f$ and also that $\Delta\square$ can similarly be written $\Delta\square = \Delta\square_0 + \Delta\square_f\cos(2\square\square\square + \square_f)$. By substituting these relations into W, it ma be verified by the reader that $\Delta\square_f$ is given by

$$\Delta\square_f = \frac{\square_{\square}}{(\square^2 + 4\square\square^2 h^2)^{\frac{1}{2}}}$$

Looking at the frequency characteristics we ma rewrite the above equation

$$\Delta\square_f = \frac{\square_{\square}}{\square(1 + 4\square\square^2\square_{\square}^2)^{\frac{1}{2}}}$$

Where $\square_{\square}$, the thermal time constant , is given by:

$$\square_{\square} = \frac{\square}{\square}$$

For good response at a frequency f we require :

be made too small, otherwise the response time may become long. Typical values for $\square_{\square}$ found in practice usually range from 10^{-3} upwards, although smaller values can be achieved.

The limiting sensitivity of thermal detectors is governed by temperature fluctuations with in the detector, which arise from random fluctuations in the energy flow rate out of the element. It may be shown that the root mean square (r.m.s) fluctuations in the power (ΔW_f) flowing through a thermal link, which have frequencies between f and f + Δ_f can be written

$$\Delta W_f = (4kT^2G)^{\frac{1}{2}}\Delta\square$$

The smallest value of G obtainable is when energy exchange takes place by means of radiative exchange only, When very large amount of radiation are encountered , more massive detector elements are used; these are often in the form of stainless steel disks or cones.

Photo conductive detector

An electron may be raised from the valence band to the conduction band in a semiconductor where the energy gap is E_g b the absorption of a photon of frequency v provided that

$$hv \geq E_g$$

or in terms of wavelength

$$\lambda \leq \frac{hc}{E_g}$$

We define the bandgap wavelength λ_g, to be the largest value of wavelength that can cause this transition, so that

$$\lambda_g = \frac{hc}{E_g}$$

As long as the electron remains in the conduction band, the conductivity of the semiconductor will be increased. This is the phenomenon of photoconductivity, which is the basic mechanism operative in photoconductive detectors. For convenience we suppose the semi-conductor material to be in the form of a slab of width W, length L, and thickness D with electrodes on opposite ends, as shown in figure below

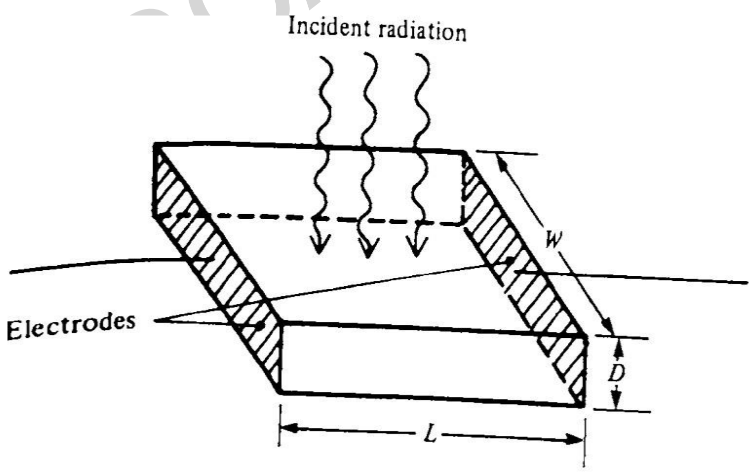


Fig:Geometry of slab of photoconductive material , the slab of length L, width W , and thickness D has electrodes on opposite faces, radiation falls onto the upper surface.

An external potential across the electrodes is usually provided by the simple circuit.

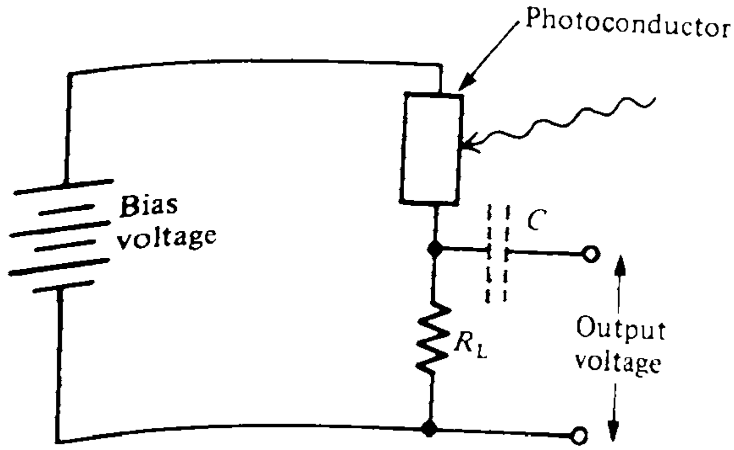


Fig: Photoconductor bias circuit, the photoconductor is placed in series circuit comprising a voltage source, a load resistor R_L and the photoconductor itself. Changes in the resistance of the photoconductor cause changes in the voltage appearing R_L. If only the a.c component of this voltage is required , then a blocking capacitor C may be placed.

Any change in the conductivity of the detector results in an increased flow of current round the circuit which will increase the potential across the load resistor R_L . this may then be detected using a high impedance volt meter. If we are only interested in the time-varying part of the incident radiation, then a blocking capacitor C may be inserted in the output line to remove any d.c. component. The optimum size for R_L in a particular situation is determined by the fractional change in the resistance of the photodetector when under maximum illumination.

The reflection coefficient (assuming no antireflection layer is present) is given by 'r' where r is given by

$$r = \frac{(n-1)^2}{(n+1)^2}$$

The irradiance just inside the surface of the slab is thus

$$I(O)=I_O(1-r)$$

Now the irradiance at a point a distance x into the semiconductor, I(x), can be written as

$$I(x)=I(0)\ \exp(-\alpha x)$$

The fraction of the incident irradiance which is actually absorbed in the semiconductor can thus be written (1-r) * $\square_{abs}$

Where $\square_{abs}$ = 1-exp ($\square\square$)

If we write $\square$= (1-r) * $\square_{abs}$ the total number of electron-hole pairs generated within the slab per second is $\square\square_0$WL / hv. The average generation rate r_g of carriers per unit volume is then given by

$$r_g = \square\square_0 WL / hvWLD$$

1.Explain the principle, construction and working of pyro-electric detector. NOV/DEC2016

Pyroelectric detectors are a more recent development, and while the do not have the same sensitivity as the golay cell they can be made with very rapid responses time and are very robust. The incident radiation is absorbed in a ferroelectric material which has molecules.

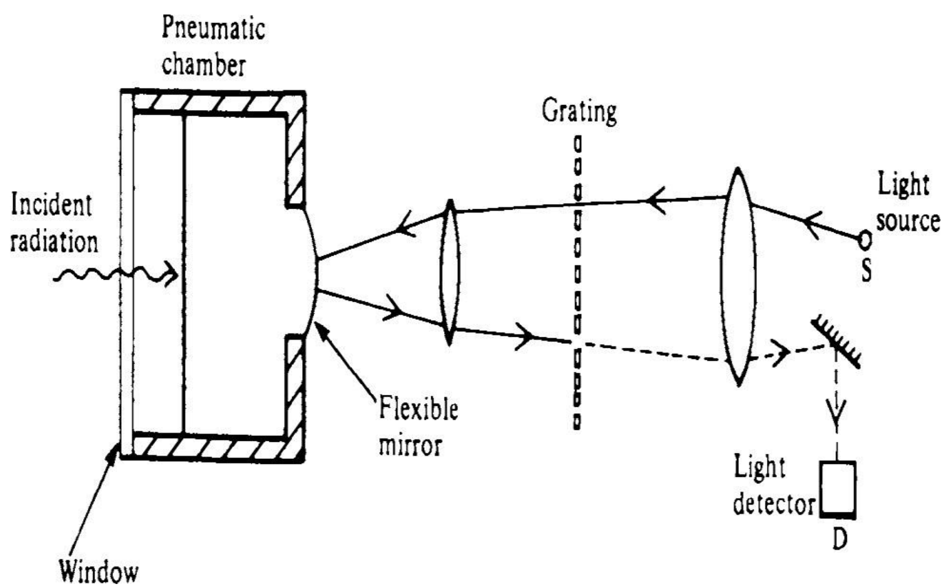


Fig: Schematic diagram of a Golay cell detector. A beam of light originating from a source S passes through a grating. It is then reflected from a flexible mirror which forms part of the wall of a pneumatic chamber. The beam subsequently repasses through the grating and is directed onto a light detector D. Radiation absorbed with in the chamber causes pressure fluctuations which in turn cause the curvature of the flexible mirror to change.

With a permanent electrical dipole moment. Below a critical temperature, the curie temperature T_c, the dipoles are partially aligned along a particular crystallographic axis giving rise to a net electrical polarization of the crystal as a whole. When the material is heated, the increased thermal agitation of the dipoles decreases the net polarization, which eventually becomes zero above T_c as shown in figure.

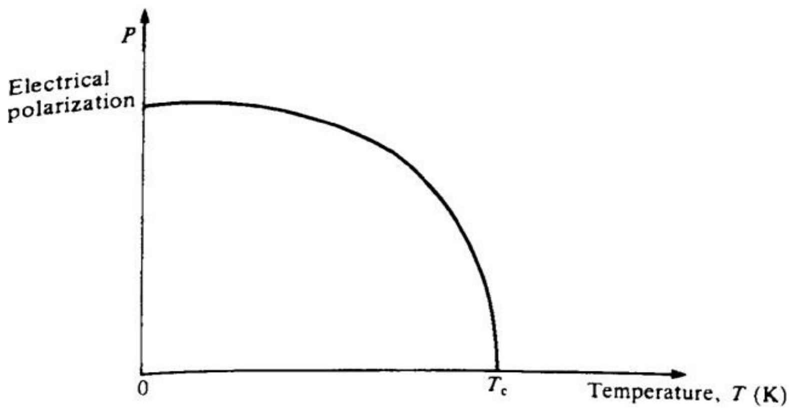


Fig: Spontaneous electrical polarization versus temperature for a ferroelectric material (Schematic diagram). The polarization falls to zero at the curie temperature T_c

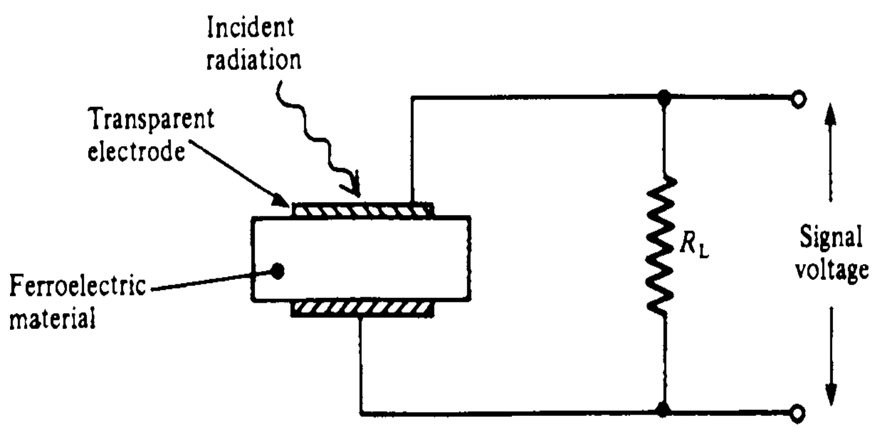


Fig 1 :A Pyro electric detector

A slab of ferroelectric material is sandwiched between two electrodes (one being transparent). The electrodes are connected by a load resistor R_L. Radiation absorbed with in the ferroelectric material causes it to change its polarization. The induced charge on the electrodes changes and current flows through R_L causing a voltage signal to appear across R_L.

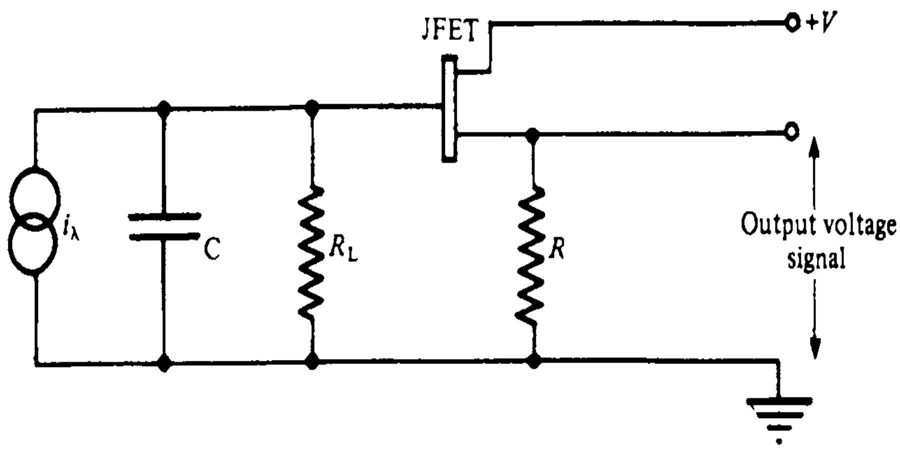


Fig ii: Equivalent circuit and typical impedance matching circuitry for a pyroelectric detector. The varying amounts of charge stored on the electrodes are equivalent to a current generator feeding into the electrode capacitance C. The resistor R_L is in parallel with C. since R_L is usually very high (about $10^9\Omega$ or more), an impedance matching circuit is often employed to reduce signal sourceimpedance. A typical circuit using a JFET is shown here; the output impedance in this case is then R (≈ □□Ω).

As the voltage output is proportional to R_L,there is a trade-off between sensitivity and frequency response. Typically, a detector with a frequency bandwidth of 1 Hz at an operating frequency of 100 Hz can detect radiation powers of about10^{-8}W.

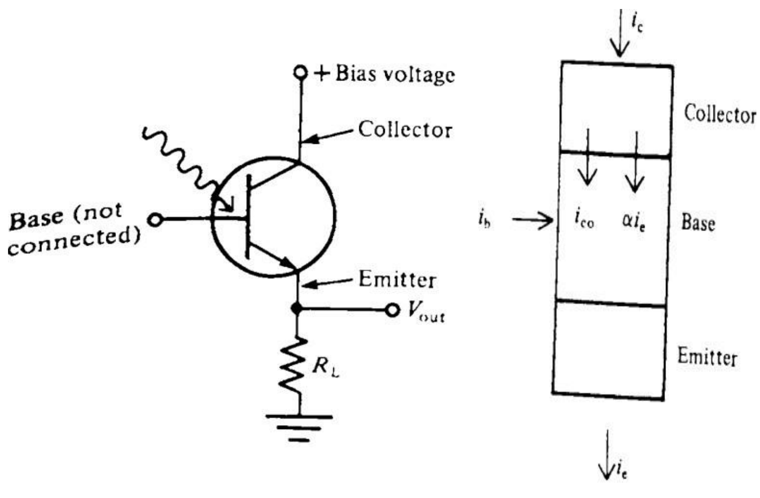
Because of the comparatively large values of the load resistor encountered in pyroelectric detectors, an impedance matching circuit is usually built into the detector. A source follower circuit using a JFET is commonly used as shown in figure ii.

Pyroelectric detectors can be made with response times in the nano second region and with a wavelength response extending out to 100□□. They have proved very useful as low cost, robust IR detectors in such uses as fire detection and intruder alarms.

Photo transistors

The photo transistor is another device, like the avalanche photodiode, where the current flow from a p-n junction detector is internally amplified. The construction is basically that of a junction transistor, with the base region exposed to the incident radiation.

Normally no external connection is made to the base (see fig:a) . To understand the operation of the



(a) (b)

device, we consider the external currents to be as shown in (see fig:b). The base current i_b will be supplied by the photo generated current.

Fig: External connetions made to an n-p-n photo transistor (a).Light absorbed with in the base region causes an emitter current to flow through the load resistor R_L and thus a signal voltage will appear across it . (b).The currents assumed to be flowing in the photo transistor.

t hW h e e

r e i c a n d i e a r e

c o l l e c t o r a n d +1)

emitter currents respectively. The collector currents has two components: (a) The normal diode reverse saturation current i_{co} and (b) the part of the emitter current that manages to cross to the collector .(The current is carried by minority carrier diffusion across the base, and not all the minority carriers leaving the emitter will reach the collector.) We write this latter current as ∝ $□_e$, where ∝ is slightly less than unity.

$$i_{co} + \propto □_e = i_e - i_b$$

□+ □0 $\overline{1-□}$

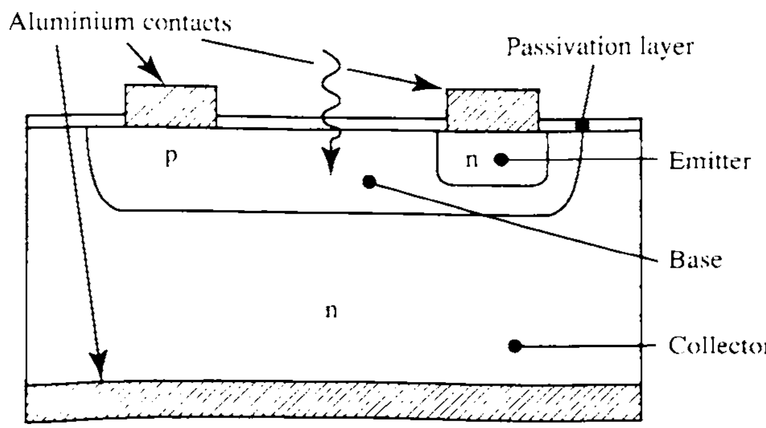
= (□□+□□0) (h_{fe} + 1)

Where h_{fe} = □/1 − □ is known as the common emitter current gain of the transistor.typical dark values for h_{fe} in phototransistors are about 100. With no incident radiation □□=0 and the current flowing , □□0(h_{fe} + 1), is the dark current of the device. This is obviously larger than for comparable p-n junction devices when the dark current in this notation is just i_{co}.

When illuminated there will be a base current of magnitude □□,where □□=□(□0 Ae □0 /hc).The external current flowing is now (□□+□□0) (h_{fe} + 1) which , if □□ ≫□□0, is equal to □□(h_{fe} + 1). Thus the device gives us internal gain, and has a responsivity lying between that of a p-i-n photodiode and an avalanche photodiode.

Silicon based photo-transistors are readily available at low cost; a typical device structure is shown below.

Such detectors usually suffer from a poor frequency bandwidth, often being limited to a few hundred kilohertz. This arises both from the high capacitance of the base-collector junction and the long carrier transit times across the base region. However the presence of internal gain can greatly simplify detection circuitry where the small



bandwidth is not a problem (e.g. in remote control devices for TVs and videos).

Fig: Structure of a silicon phototransistor.

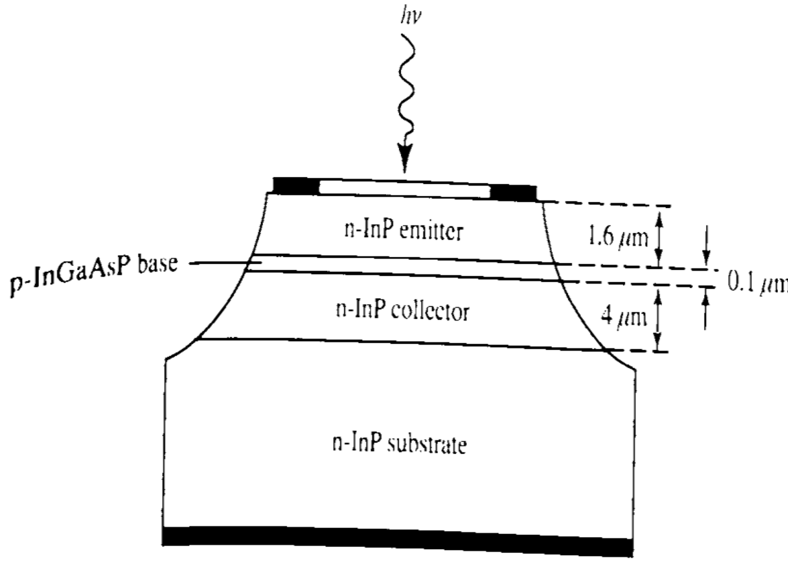


Fig: Structure of an n-p-n photo transistor based on an InGaAsP/InP heterojunction

Working of a vidicon type imaging tube.

The vidicon is a generic name for a family of devices that relies on the phenomenon of photoconductivity to convert an optical image into an electrical signal.The below figure shows the typical structure.

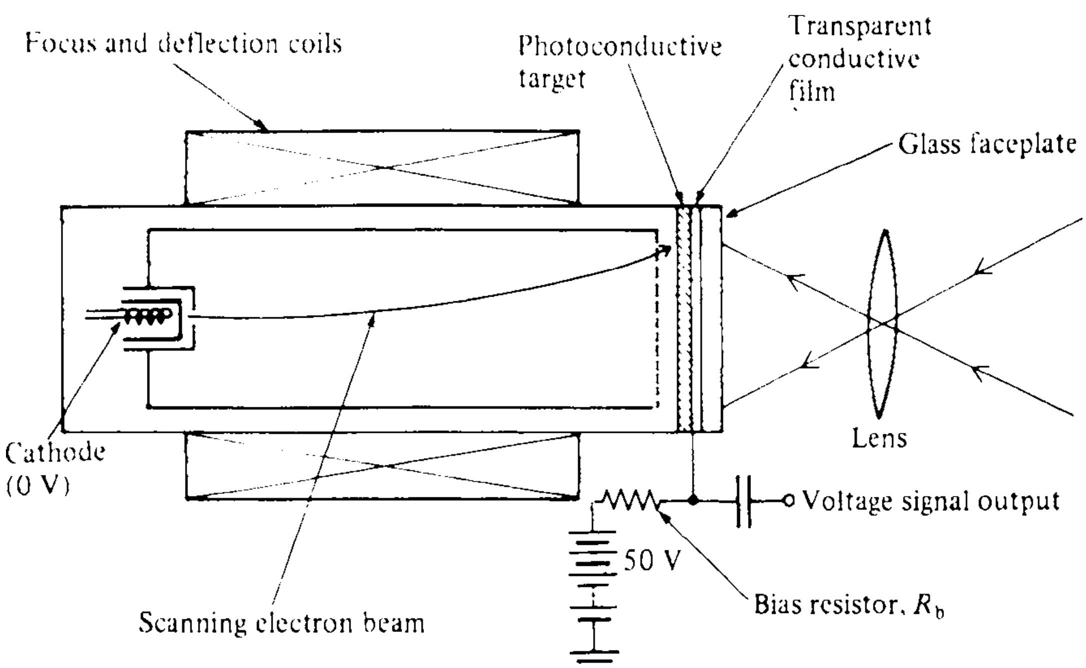


Fig i: Basic Construction of vidicon tube

The optical image is formed on a thin target of semiconducting material (antimony trisulfide is commonly used) that has a transparent conducting layer (usually SnO_2) on the side facing the incident radiation. This conducting layer is connected to a potential of some +50V above ground via a bias resistor. The other side of the semi-conductor target is scanned with an electron beam in the same way as in a CRT. In operation the target acts rather like a ‘leaky’ capacitor. When not illuminated its resistance will be high, and charge will accumulate on opposite faces. The electron beam side will charge up to around cathode potential (0 V), Whilst the other will charge up to around +50 V. Under illumination , however , the resistivity of the target material will be much reduced and the charge on the ‘capacitor’ will leak away (i.e. the capacitor will discharge itself) whenever the scanning beam is not incident on the area in question, when the beam does return to the ‘discharged’ area it will recharge the beam side and a corresponding amount of opposite charge must be supplied via the bias resistor and external bias supply circuit to the other side of the target. The amount of charge flowing will be dependent on how discharged the ‘capacitor’ has become, which in turn, is directly related to the amount of light falling on the target. The output voltage signal is obtained by taking the voltage across the bias resistor.

One of the problems with the vidicon is its relatively high dark current, which gives rise to poor S/N ratio’s at low light irradiances. A device which exhibits very low dark currents is the plumbicon.

This is essentially identical to the vidicon except for the nature of the photosensitive layer.In the plumbicon, this consists of a thin film p-i-n structure formed from lead oxide, PbO. The transparent SnO_2 layer acts as the n-type contact while the other surface has an excess of oxygen, which causes it to be p-type. The region in between (typically 15 □□ thick) is effectively an intrinsic semiconductor. The plumbicon is widely used in colour TV studio cameras. The energy gap of PbO is about 2 Ev so that the red sensitivity of the device is poor; this can be improved by adding a thin layer of PbS

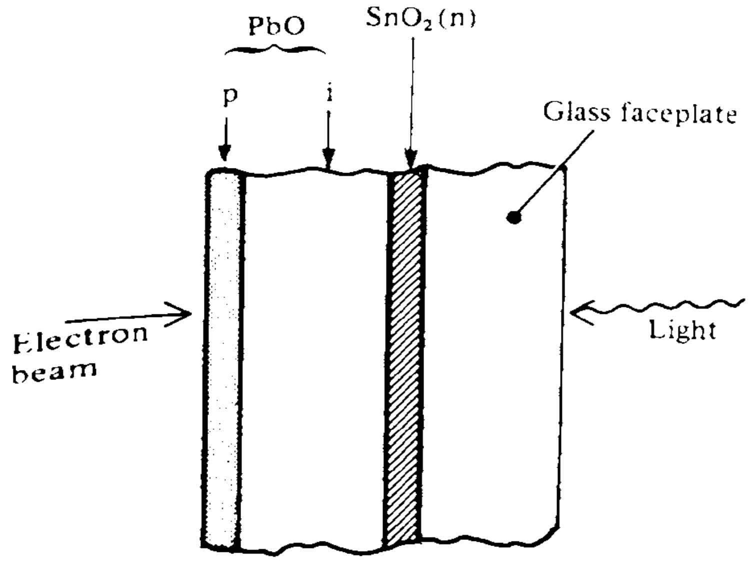


Fig :ii: A lead oxide based p-i-n structure (The Plumbicon)

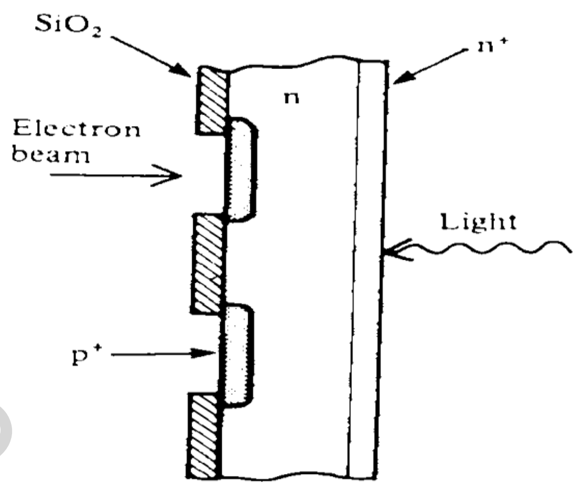


Fig iii: A discrete array of silicon p-n junction diodes

A further development has been the replacement of the lead oxide target layer by an array of silicon diodes. Dark currents are very small, and the devices exhibit very uniform sensitivities over the wavelength range 0.45-0.85 μm with a good tolerance to high light levels.

The P-I-N Photo diode

A structure that results in a good long wavelength response with only relatively modest bias levels is the so called p-i-n structure here the intrinsic region has a high resistivity so that only a few volts of reverse bias are needed to cause the depletion region to extend all the way through to the n region and thus provide a large sensitive volume.

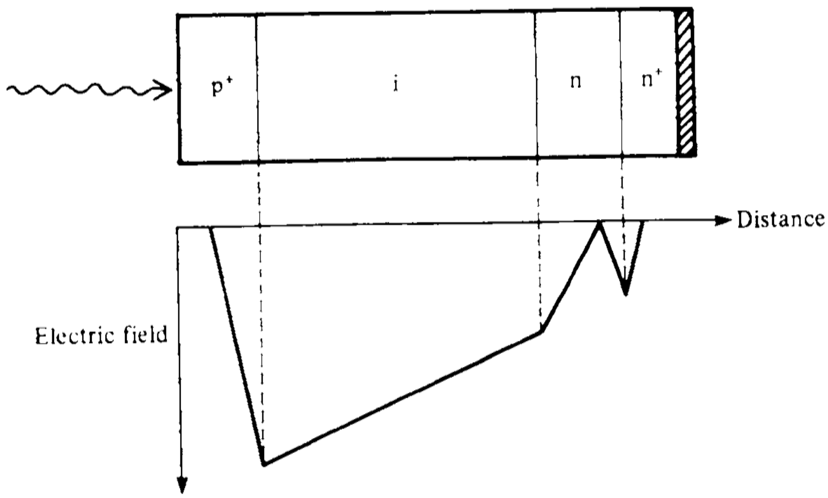


Fig: Electric field distribution with in a p-n structure

In practice, the bias is maintained at a considerably higher voltage than the minimum value and the intrinsic region then remains fully depleted of carriers even at high light levels. The depletion region width in a p-i-n structure is then practically independent of applied voltage and thus much better delineated than in a p-n structure where the depletion region width will vary appreciably with applied voltage. For this reason most simple photodiode structures are of the p-i-n rather than p-n type.

For efficient detection of photos we require that as many as possible are absorbed with in the intrinsic region(p-i-n), If the thickness of the p and i regions are w_p and w_i respectively, and assuming a surface reactance of R, then the fraction F_1 of the incident power that is absorbed within the i layer is given by

$$F_1 = (1 - R)\{\exp(-\alpha w_p) - \exp[-\alpha(w_p + w_i)]\}$$

Assuming that $w_p \ll \alpha^{-1}$, so that absorbtion within the surface p^+ layer may be neglected, we may ensure that most of the incident radiation is absorbed in the i layer by requiring that $w_i \ll □^{-1}$. To be more specific , if $w_i = 2□^{-1}$ then some 86% of the radiation entering the device will be absorbed . silicon p-i-n photodiodes can achieve quantum efficiencies of 80% in the wavelength range 0.8-0.9 □□ . A typical spectral response of a p-i-n silicon photodiode is shown below.

The problem of low detector efficiencies at wavelengths close to the bandgap wavelength can also be addressed by using detectors that are illuminated from the side (parallel to the junction) although these are not commonly available.

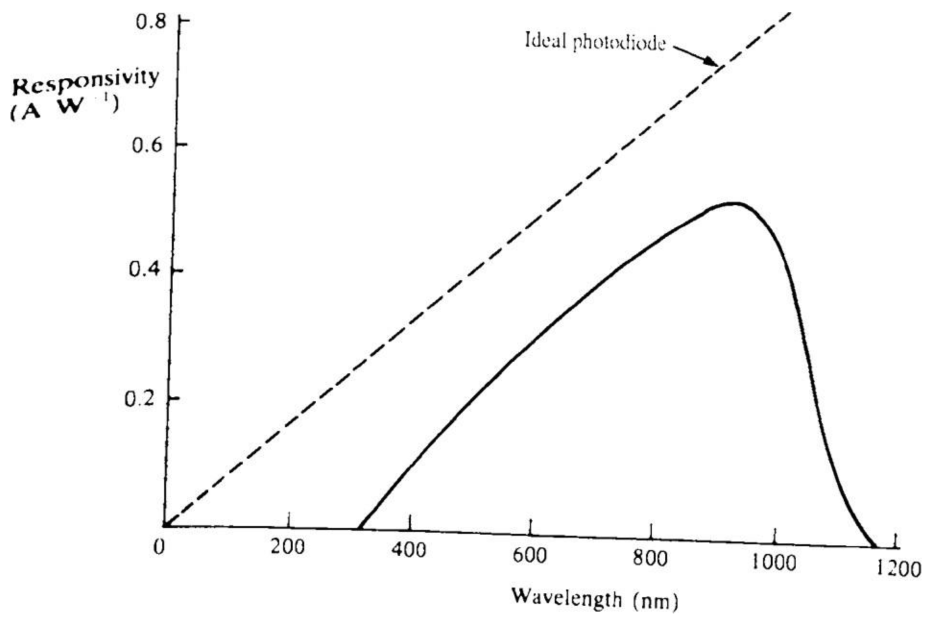


Fig: Typical current responsivity of a silicon photodiode. Also shown is the responsivity of an ideal photodiode with unit quantum efficiency.

<u>photo multiplier tube</u>

In the photomultiplier , the photoelectrons are accelerated towards a series of electrodes (called dynodes) which are maintained at successively higher potentials with respect to the cathode. On striking a dynode surface, each electron causes the emission of several secondary electrons which in turn are accelerated towards the next dynode and continue the multiplication process.

Thus, if on average □ secondary electrons are emitted at each dynode surface for each incident electron and if there are N dynodes overall, then the total current amplification factor between the cathode and anode is given by

$$G= □^{N}$$

Considerable amplification is possible: if we take, for example □ = 5 and N=9 we obtain a gain $2*10^{6}$, Four of the most common photomultiplier dynode configurations are illustrated in figure below. Three of them (venetian blind, box and grid, and linear focussed) are used in ‘end-on’ tubes , these have a semi transparent cathode evaporated onto the inside surface of one end of the tube envelope. The photoelectrons are emitted from the opposite side of the cathode layer to that of the incident radiation. Obviously , in this arrangement the thickness of the photocathode is very critical, if it is too thick , few photos will penetrate to the electron emitting side , whilst if it is too thin few photos will be absorbed.

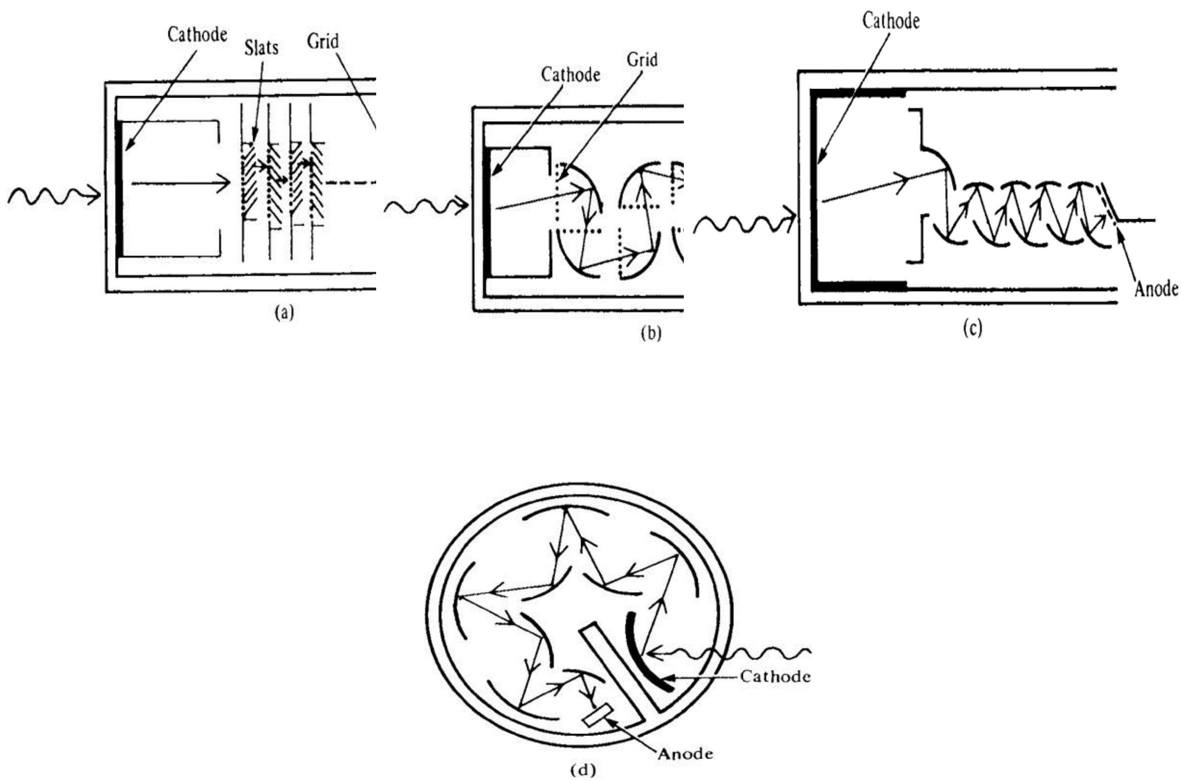


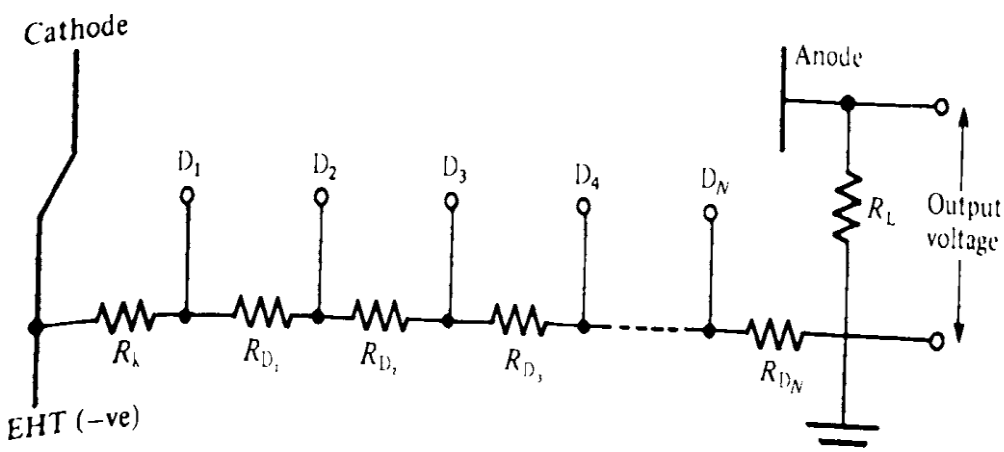
Fig: Dynode structures of four common types of photomultiplier: (a).Venetian blind (b).box and grid (c).Linear focussed and (d).Circular cage focussed, typical trajectories of an electron through the systems are also shown.

In the venetian blind type, electrons strike a set of obliquely placed dynode slats at each dynode stage; the electrons are attracted to the next set of slats b means of the inter dynode potential applied between a thin wire grid placed in front of the slats. This arrangement is compact, relatively inexpensive to manufacture and is very suitable for large area cathodes. The box and grid type (b) is somewhat similar in performance. In both of these, very little attempt is made to focus the electrons, which is in contrast to the linear focused and circular cage focused types (c&d), where some degree of electron focussing is obtained by careful shaping and positioning of the dynodes.

The focussed type have somewhat higher electron collection efficiencies and a much better response to high signal modulation frequencies. The circular cage focussed type is very compact and usually used in conjunction with a side window geometry. In this, the photocathode material is deposited on a metal substrate within the glass envelope and the photoelectrons are emitted from the same side of the cathode as that struck by the incident radiation.

The dynode potentials are usually provided by means of the circuit shown in figure below.

Care must be taken to ensure that the voltage between cathode and the first dynode is large enough to maintain proportionality between cathode current and cathode illumination. Usually a voltage value is recommended for a particular tube, and in some circumstances it may be preferable to use a Zener diode in place of the fixed resistor R_k to



keep the voltage at this value.

Fig: Dynode biasing circuit using a linear resistor chain

If high anode current are likely, then the last few stages may also be biased using Zener diodes. The photomultiplier responds to light input by delivering charge to the anode. This charge may be allowed to flow through a resistor R_L or to charge a capacitor: the corresponding voltage signal then provides the measure of the input optical signal. If individual pulses need to be examined, then it is important to ensure that the response time of the external circuitry is less than that of the pulse rise time. This usually implies a low value for the load resistor.

ionally photomultipliers have been relatively bulky devices with photocathode diameters of 25mm or more, recent much smaller devices have become available contained in small metal cans with photocathode diameters of 8mm or so.

UNIT – IV

OPTOELECTRONIC MODULATOR

Explain the concept of external modulation and compare with direct modulation.

- In the external modulator scheme, the light output passes through a material whose optical properties can be modified by an external means.
- Depending upon the means used, one can have electro-optic, acousto-optic or magneto-optic modulator.
- The elctro-optic effect is most widely used for high speed applications and compatible with modern electronics.

Briefly explain about the Analog and Digital Modulation

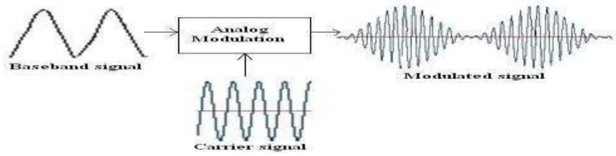
- Modulation is the process by which the waveform of a high frequency carrier wave is modified suitably to transmit information.
- Modulation is classified into two types they are

  i)Analog

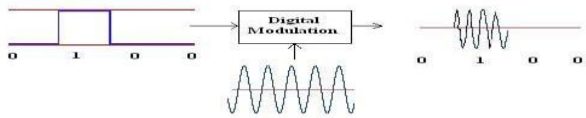
  ii)Digital
- Thus these two classifications of modulation were identified according to the final shape of carrier waveform. This carrier waveform is usually a sinusoidal waveform (i.e.) continuous waveform.
- In Analog modulation, the information signal or waves varies the light from the source, or the high frequency signal in the continuous manner. Thus, both could be sinusoidal. There is always a one to one correspondence between the information signal and the magnitude of the modulated carrier.
- In Digital modulation, discrete changes in the intensity of the carrier caused by the information signal. Information is then transmitted by the high frequency signal as a series of discrete pulses.
- Trough simpler in concept and implementation, analog modulation suffer few practical drawbacks. It requires higher signal to noise ratio at the receiver.
- Analog modulation may be more suitable for low modulation frequencies. Digital

modulation is more suited for large bandwidth optical transmission and reception.

- These can be described in the basic forms of modulation to described the devices basically amplitude and phase modulator. Continuous wave light can be used as external modulator in those both digital and analog schemes.



(a). Analog signal



(b).Digital signal

<u>Explain the concept of birefringence in Uniaxial crystal with necessary diagrams.</u>

- The simplest way of demonstrating birefringence is to allow a narrow band of unpolarized light to fall normally to a parallel sided calcite plate shown in fig.

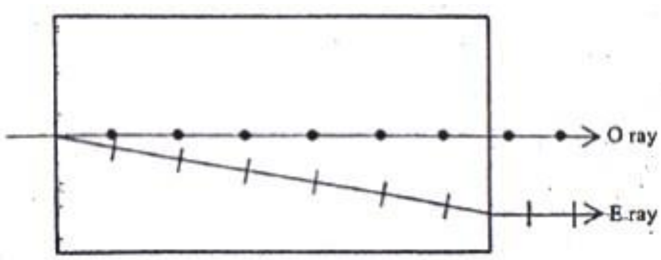


Fig: Double refraction by a birefringent crystal.

- The beam is found to divide into two parts. One the so called ordinary or O ray, passes straight through the crystal and is found to obey Snell's law.
- The other so called extraordinary or E ray, diverges as it passes through the crystal and then emerges parallel to its original direction.
- The ordinary and extraordinary rays are found to have orthogonal direction of polarization.
- We can explain the above and other observation on the propagation of light through the anisotropic crystal quite simply using Huygens construction. Consider a point source of light radiating uniformly inside the crystal. Then for the case of uniaxial crystal, when a short time has elapsed there will be two wave surfaces shown in fig.

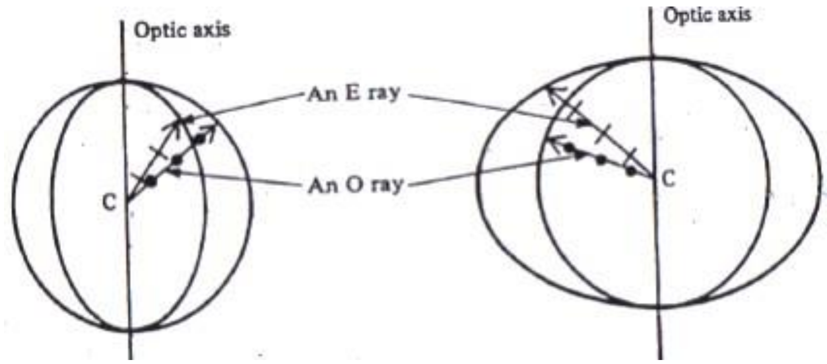
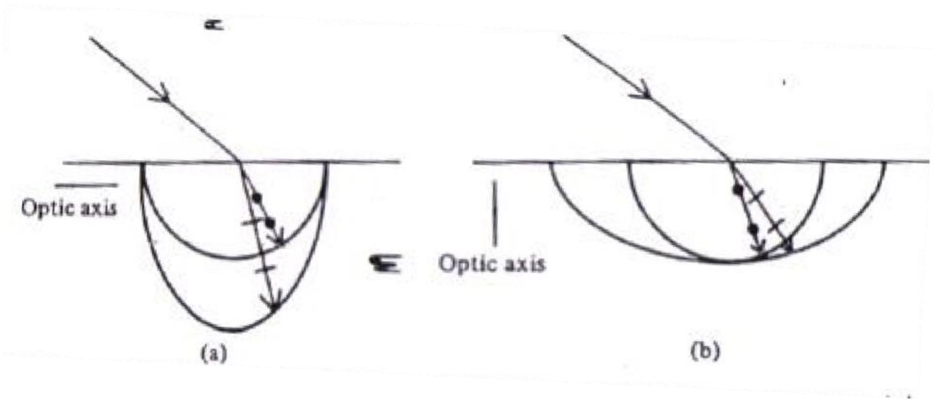


Fig:Huygen's constructions for the E- and O-wave surface for a) positive and b) a negative uniaxial crystal

- In each case one of the wave surface is a sphere. It is found that the light contributing to this wave surface is polarized with its electric vector perpendicular to the optic axis and the principle section.
- The principle section is a plane containing the direction of propagation and optic axis. Thus for light with this polarization the velocity of propagation of wave is the same in all directions.
- Such light gives rise to ordinary rays mentioned above and crystal has an ordinary refractive index η_0 .
- The other wave surface is ellipsoid of revolution which has one of its axes parallel to the optic axis. This wave surface is comprised of light which are polarized orthogonally to the ordinary wave and hence parallel to the principle section, and which give rise to the extraordinary rays.
- At right angles to the optic axis the extraordinary ray velocity is either a maximum, as in negative crystals. The refractive index $\eta_{\square}$,of the crystal for the extraoridinary ray is such that $\eta_{\square} \leq \eta_{\square}$for positive crystal and $\eta_{\square} \geq \eta_{\square}$for negative crystals.
- As the distance from point C to the wave surface are proportional to the velocities of the E and O rays, the wave surface are often called ray velocity surface.

Fig : Double refraction by a negative crystal plate in which a)the optic axis is parallel to the crystal surface and the plane of incidence b) the optic axis is perpendicular to the crystal surface and parallel to the plane of incidence.



- The above figure shows two special cases plane polarized light incident on the surface of a plane parallel plate cut a) with its optical axis parallel to the surface b) with its optical axis perpendicular to the surface.
- We see that for non-normal incidence there will be two diverging rays, the O ray and the E ray.

Explain with neat diagram, the construction of electro optic effect based external modulator. Also deduce the expression of modulated light.

- When an electric field is applied across, an optical medium the distributon of electrons within it is distorted so that the polarizability and hence the refractive index of the medium changes anisotropically.
- The result of this elecro-optic effect may be to introduce new optic axes into naturally doubly refracting crystal.
- The change in refractive index as a function of the applied field can be obtained from an equation of the form,

$$\Delta \left(\frac{1}{□^2}\right) = □□ + □□^2$$

- Where □ is the linear electro optic coefficient and □ is the quadratic electro optic coefficient.
- In the case of the pocket effect, the precise effects of the applied electric field depends on the crystal structure and symmetry of the material under consideration.
- n through a crystal such as KDP with its plane of polarization at 45° to the induced axes □′and □′ shown in fig.

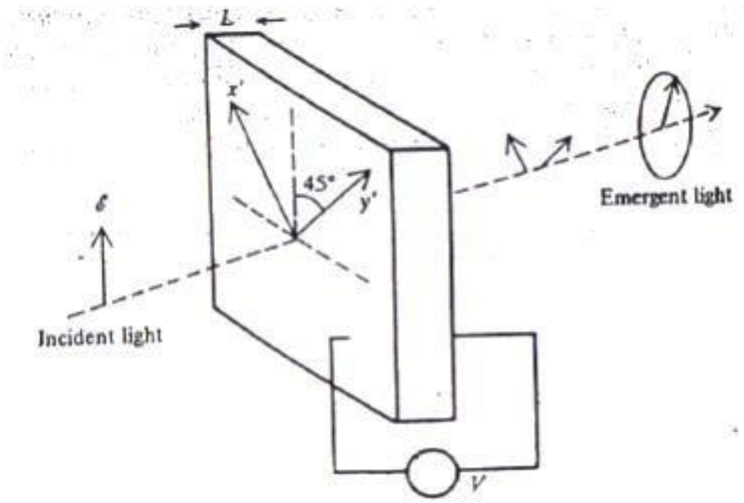


Fig : Beam of plane polarized light incident on an electro optic crystal plane subjected to a voltage V will be resolved into components along $\square'$ $\square\square\square$ $\square'$ the induced principle direction

$$\square_{\square'} = \frac{\square_0}{\sqrt{2}}\square\square\square(\square\square - \square\square)$$

and

$$\square_{\square'} = \frac{\square_0}{\sqrt{2}}\square\square\square(\square\square - \square\square)$$

- thus if the crystal is of thickness L the phase change of the two componenets will be,

$$\square_{\square'} = \frac{2\square}{\square}\square_{\square'}\square$$

and

$$\square_{\square'} = \frac{2\square}{\square}\square_{\square'}\square$$

- sub $\square_{\square'}$ value in the above eqn, $\square_{\square'} = \frac{2\square}{\square}\square_0\square(1+\frac{1}{2}\square\square_0^2\square_\square)$

or

$$\square_{\square'} = \square_0 + \square_\square$$

and $\square_{\square'} = \frac{2\square}{\square}\square_0\square(1-\frac{1}{2}\square\square_0^2\square_\square)$ or

$$□_{□'} = □_0 − □_□$$

- Where $□_□ = \frac{□}{□} □□□_0^3 □_□ \frac{□}{□} □□_0^3 □$

- The net phase shift or total retardation, between the two waves resulting from the application of the voltage V is seen to be,

$$□ = □_{□'} − □_{□'} = 2□□ = \frac{2□}{□} □□_0^3 □$$

and the emergent light will be in general be elliptically polarized.

- The componenet of the wave emerging from the electro – optic crystal can now be written as,

$$□_{□'} = \frac{□_0}{\sqrt{2}} □□□(□□ + □□)$$

and

$$□_{□'} = \frac{□_0}{\sqrt{2}} □□□(□□ − □□)$$

- The phase shift □□ for each component depends directly on the applied voltage V. so that we can vary the phase shift by varying the voltage applied to the given crystal.
- From the fig the transmitted electric field components will be $−\frac{□_{□'}}{\sqrt{2}}$ and $\frac{□_{□'}}{\sqrt{2}}$ that is we can write the transmitted electric field as,

$$□ = \frac{□_0}{\sqrt{2}}[□□□(□□ + □□) − \frac{□_0}{\sqrt{2}} □□□(□□ − □□)]$$

or $□ = −□_0 □□□\ □□\ □□□\ □□$

- Thus the irradiance of the transmitted beam, which is given by averaging $□^2$ over a complete period $□ = \frac{2□}{□}$ can be written as,

$$□ = \frac{□}{2□} \int_0^{2□/□} □^2 □$$

Or

$$□ = □_0 □□□^2\ □□ = □_0 □□□^2 \left(\frac{□}{2}\right)$$

- Where $\square_0$ is the irradiance of the light incident on the electro-optic crystal. Sub $\square$ value in the above eqn then the transmittance as a function of applied voltage is given by,

$$\frac{□}{□_0} = □□□^2 \left(\frac{□□□□_0^3□}{□}\right)$$

Which can be written as, $$\frac{□}{□_0} = □□□^2 \left(\frac{□ □}{□ □_□}\right)$$

- Where $□_□ = \frac{□}{2□□_0^3}$ is the voltage required for the maximum transmission . i.e) $□ = □_0$.

$□_□$ is often called the *half wave voltage*.

Discuss in detail the principle and operation of a photonic switch based on self electro optic Device (SEED). **[Nov/Dec - 2015]**

- Since the QCSE involves a quadratic Stark effect, large electric field are necessary for any useful shift of the absorption edge.
- At the correspondingly large bias values, the MQW diode also behaves as an optical detector.
- Optical detection in a MQW involves
  - i) absorption of the incident photons.
  - ii) recombination of some of the photo-excited electron-hole pairs.
  - iii) tunneling and thermionic emission of electron and hole through the barriers in
  - iv) opposite direction and their collection at the contact regions to generate the external photocurrent.
- At low field the tunneling rate is small and the recombination process dominates, result in very small photocurrent.
- At higher fields, the tunneling rate is enhanced and the photocurrent follows the absorption spectra of the MQW.
- The photocurrent is given by, $$□_{□h} = \frac{□ □_{□□□} □(□)□}{h□}$$
- Where, V is the applied bias, $h□$ is the incident photon energy, $□_{□□□}$ is the incident optical power
- It is easy to see that the bias dependence of the photocurrent follows that of absorption coefficient. The internal quantum efficiency of a MQW structure has been shown to be approximately unity at field above 10 kv/cm at room temperature.

- At appropriate wavelength a strong negative differential resistance (NDR) region is observed in the photocurrent versus bias voltage relationship of a p-i(MQW)-n structure.
- This arise because the photocurrent results from the change in absorption coefficient of the MQW due to QCSE.
- The NDR occurs where the Heavy Hole (HH) and Light Hole (LH) peaks cross the photon energy of the input light. As long as electron and hole densities in the quantum well are less than 10^{11}□□2 .
- To develop a number of photonic switching and logic devices, the first and most important of these is called the Self Electro optic Effect Device (SEED).
- This device exhibit photonic switching, bistability, and optically induced oscillations due to negative differential resistance in the photocurrent. The basic SEED circuit with series resistor shown in fig.

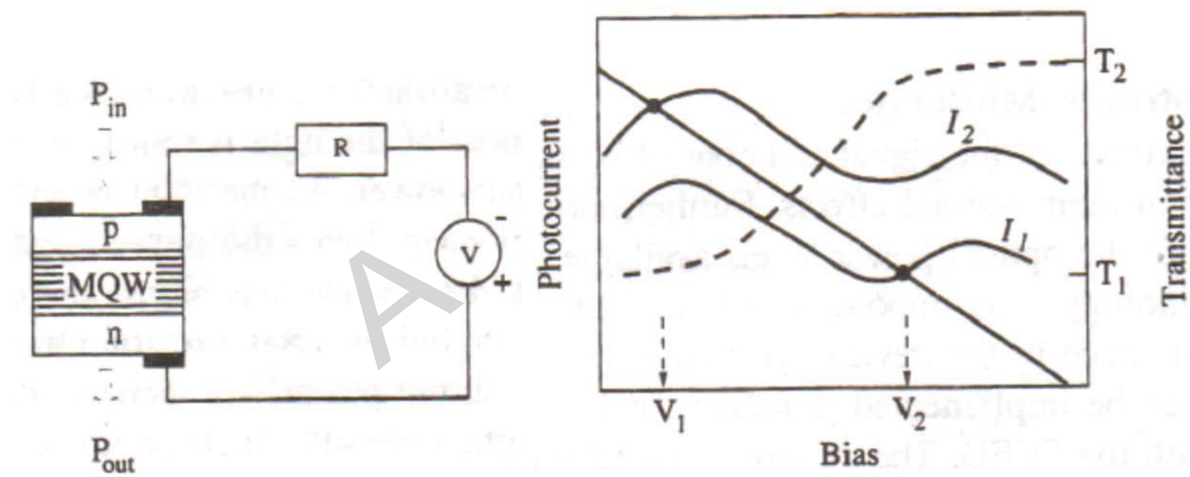


Fig:a) SEED circuit with feedback resistor b) its excitonic switching property

- The switching action is demonstrated in fig. the light intensity changes from I_2 to I_1 . the voltage across device shift from V_1 to V_2, causing a transmittance change from T_1 to T_2.
- The general principle of the SEED is that the photocurrent flowing through the circuit, including the series resistor, change the voltage across the modulator, which in turns influences its absorption and transmission. As a consequence the photocurrent is changed.
- For low-input power, most of the light is transmitted and the output power increases in proportional to the input power.

- As the light intensity increases, the photocurrent increases and voltage drop across the series resistance will increase. Since the bias voltage remains constant, the reverse bias across the diode decreases, which shift the HH absorption peak to higher energies and transmission drops.
- As the input power increases further, the output power will increase again. Such the photonic switching can also be illustrated with two beams, one for transmission and one for control.

Explain the concept of Bipolar controller Modulator.

- In the SEED, the path and effect of the signal and control beam are the same and are therefore indistinguishable in their internal effects.
- Inorder to make the SEED more compatible with the optical power level available in optoelctronic integrated circuit (OEIC) technology, it is important to have gain in the circuit.
- One scheme that can be implemented to achieve gain is to correct a bipolar phototransistor in series with the SEED.
- The control or switching beam is incident on the transistor, while the signal is incident upon the transmitted through the SEED, which function as a modulator.
- Gain can also be realized by using a heterojunction bipolar transistor (HBT) with a MQW in the base collector region. This device provides a number of advantages.
- Since a transistor operates vertically, a large uniform transverse electric field can be applied to the collector base junction to cause the QCSE.
- Incorporate of the MQW in the collector region effectively allows the realization of a $\square^{+} - \square(\square\square\square) - \square^{+}$ modulator by selective etching of the emitter and so the control signal on the HBT and the information signal on the modulator can be physically separated.
- More importantly the entire structure of the $\square - \square^{+} - \square(\square\square\square) - \square^{+}$ MQW_HBT and the $\square^{+} - \square(\square\square\square) - \square^{+}$modulator can be realized by single-step epitaxy.

- The schematic of the integrated MQW-HBT along with its equivalent circuit is shown in fig.

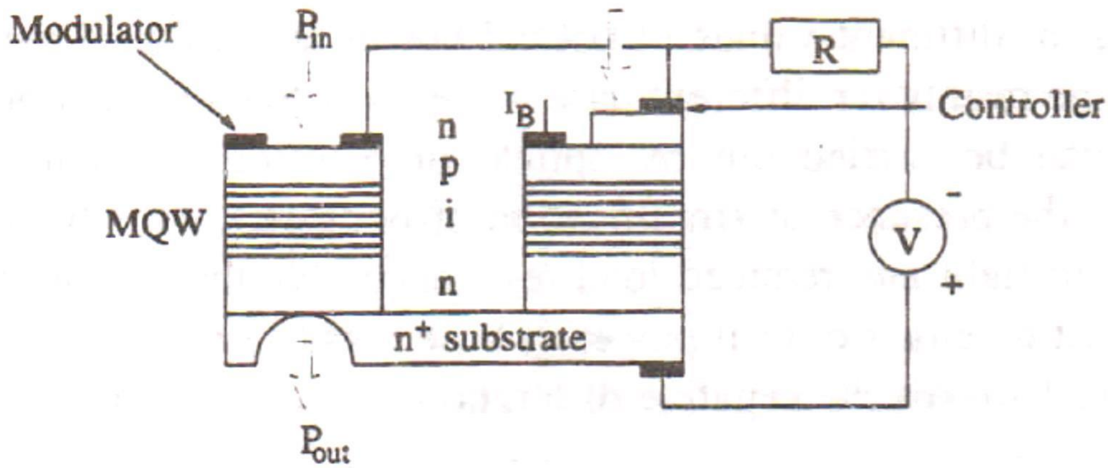


Fig:Schematic illustration of integrated controller-modulator

- The transisitor amplifies the photocurrent generated in the MQW and provides a voltage feedback to the MQW-HBT by changing its collector-base voltage.
- The modulator and controller are connected in parallel and the load is connected in series with the modulator and controller. the parallel connection of the controller and the modulator allows the sum of the input signals in these devices to control the modulation of light.
- The structure is therefore very compatible with OEIC application. An important point to realize is that amplification of the photocurrent by transistor action allows low-power photonic switching.

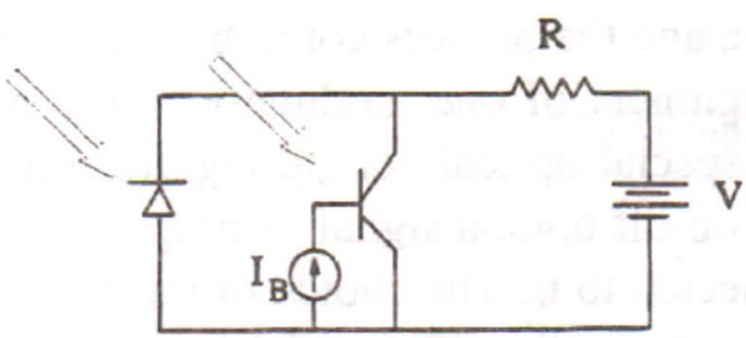


Fig : Equivalent Circuit

- The fig shows the measured output characteristics for two different switching conditions. In the figure the load lines are shown also.
- In one application the change in light input in the controller would alter the light passing through the modulator. The modulated light would then be a light input to the next controller stage and the process could be continued. It would be very useful for special optical computing architectures.
- Another class of application would involve an on-off optical signal to simply change the optical state of one or more modulator connected to it.

Optoelectronic Amplification:

- In the use of the controller-modulator (C-M) circuit for amplification of an optical signal, a photon energy approximately 15 meV below the excitation peak at zero bias is usually choosen.
- The transmittance voltage curve for this choice is shown in fig.

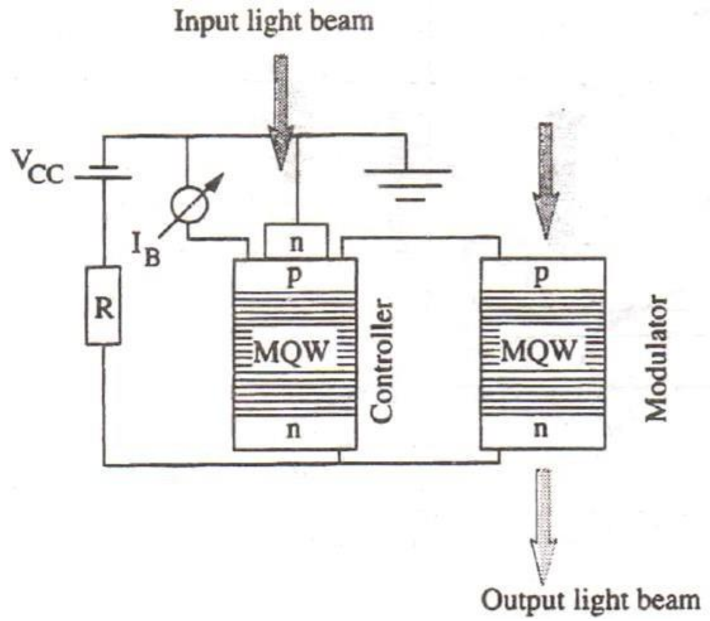


Fig : Demonstration of optoelecrtonic amplification : circuit configuration.

- The large gain of the controller will allow a small change in the controller input intensity to produce a large change in the modulator output.
- The improved gain resulting frim the large base current allow a larger amplification. Such opto electronic amplification can find important application in optical system.

Programmable Memory Device:

- The MQW-HBT can be operated in a single flip flop programmable memory element.
- The controller-modulator, consists of a single memory cell, can be conceived to form an element of a larger two-dimensionalarray.
- The operation principle of the device are schematically shown in fig below
- The high voltage point $□_□$also corresponds to high transmittance through the MQW region, and the low voltage stable point at $□_□$corresponds to a low transmittance.
- If the base current is made non-zero the load line has only one stable point A and when the base current is restored to $□_□^0$, the stable point at base $□_□$is set.
- If the base current is made higher $□_□^1$, there is again only one stable operating point at B. now when the holding base current $□_□^0$is restored the low voltage point $□_□$is choosen.
- This device is fully compatible with HBT digital technology and only requires a constant uniform optical illumination. Also it is very simple in that it requires only one transistor.
- The bistable flip flop characteristics, demonstrating the switching and holding behavior of a GaAs/AlGaAs MQW device

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Tunable Thershold Logic Gates:

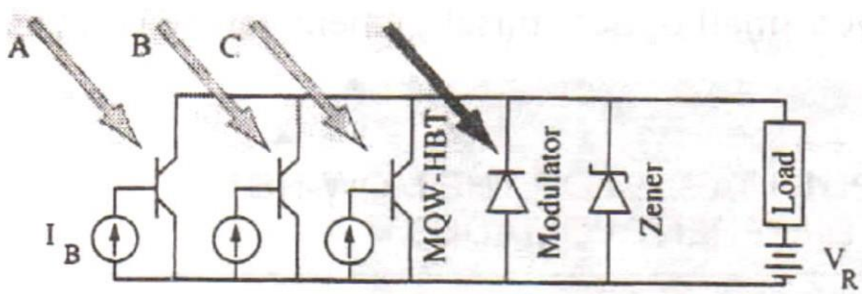


Fig :Circuit diagram of thresholding gate with 3 controller and a modulator

- The fig shows the circuit diagram of an MQW-HBT threshold gate. For operation of the gate the wavelength of the light should be above the excitonic peak, so that the complete heavy-hole response appears in the photocurrent spectrum of the MQW-HBTs.

- The p-i(MQW)-n diodes or modulator in parallel with the MQW-HBTs are used to modulate light of the same wavelength.
- The photocurrent of the modulator also passes through the load, but the electronic gain of MQW-HBTs ensures that this photocurrent is much smaller than that of the MQW-HBT.
- Fig shows the experimental output characteristics for 3-input threshold gate.

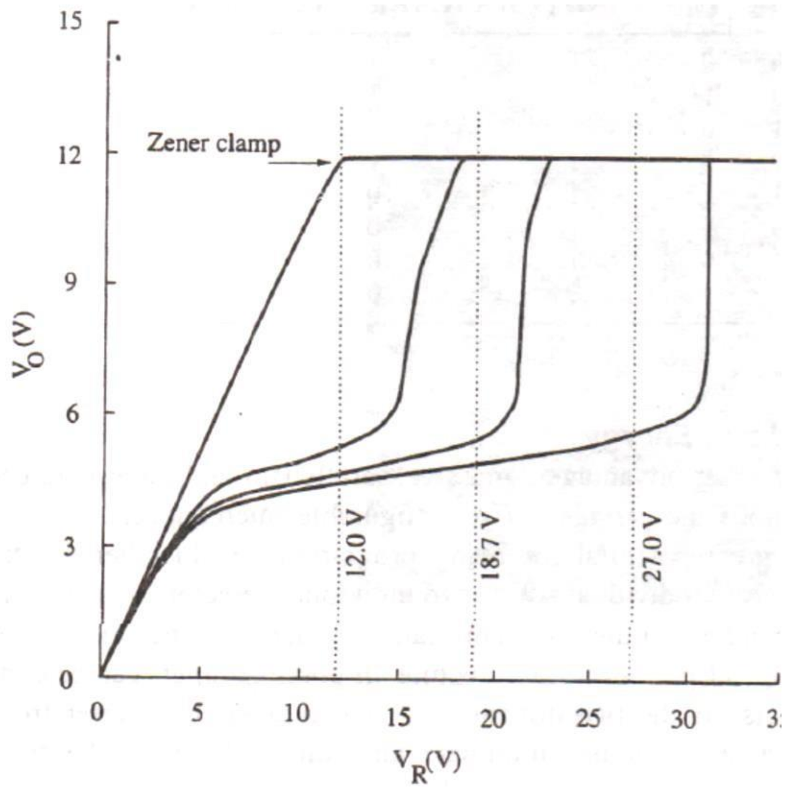


Fig : Output Characteristics of gate

- The Zener diode connected in parallel with the MQW-HBT prevents damage from accidental high voltages. A tunable laser is used as the light source.
- When none of the MQW-HBT are illuminated the output voltage increases linearly with the supply voltage, as there is no current in the circuit and hence no potential drop across the load.
- from the figure it is seen that for a 12 V supply the output is 1 when none of the input are 1, but become 0 when any of them is 1. This is the NOR function.
- For the supply voltage of 18.7V, the circuit is an INVERSE CARRY gate as the output is 0 when output is 0 when two or more of the input are 1, and otherwise the output is 1.

- When supply voltage is about 27V the gate output is 0 whenever all of the input are 1. Hence the gate now perform the NAND operation.

BIREFRINGENCE AND THE ELECTRO-OPTIC EFFECT:
APPLICATION TO PHASE MODULATION

- The constitutive relations in material media are

$$D = \epsilon_0 E + P$$

$$B = \mu_0 H + M$$

- Where P and M are the electric and magnetic polarization vectors.
- In anisotropic media, the induced polarization due to the change in the distribution of electron within it will depend, in magnitude and direction, on the direction of the applied field. Thus,

$$P_i = \epsilon_0 \sum \chi_{ij}^{e} E_j$$

- Where χ_{ij}^{e} is known as the susceptibility tensor and P and E are usually complex amplitudes of harmonic, time varying quantities. The choice of axes with respect to the crystal structure becomes very important in defining χ_{ij}^{e}.

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \epsilon_0 \begin{bmatrix} \chi_{11}^{e} & \chi_{12}^{e} & \chi_{13}^{e} \\ \chi_{21}^{e} & \chi_{22}^{e} & \chi_{23}^{e} \\ \chi_{31}^{e} & \chi_{32}^{e} & \chi_{33}^{e} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$$

- It is also used to keep in mind the corresponding relation

$$\epsilon_{ij} = \epsilon_0 (1 + \chi_{ij}^{e})$$

- If the coordinate axes are chosen in such a way that the off-diagonal elements of the susceptibility tensor vanish, then these directions define the principal dielectric axes of the crystal.

$$P_x = \epsilon_0 \chi_{11}^{e} E_x$$

$$\epsilon_{11} = \epsilon_0 (1 + \chi_{11}^{e})$$

- The phase velocity of the propagating beam will depend on the direction of the polarization of the electric field. This phenomenon is known as birefringerence. This is the basis of electro – optic modulation and the phenomenon can be used to make efficient field induced phase modulator with appropriate crystals.

- The phenomenon of birefringerence and two resulting polarizations are very convenient described by what is called the index ellipsoid and it is expressed as,

$$\frac{\square^2}{\square^2_{\square\square}} + \frac{\square^2}{\square^2_{\square\square}} + \frac{\square^2}{\square^2_{\square\square}} = 1$$

- Where $\square_{\square\square}, \square_{\square\square}, \square_{\square\square}$ are the indices in the direction of the major axes of the ellipsoid.
- The direction of the major and minor axes of the ellipse is the two polarization direction. The wave propagating in the two directions are sometimes called as ordinary and extraordinary rays.
- This induced birefringence is the electro-optic effect, which is the change in the refractive index of the crystal in the direction of the ordinary and extraordinary rays due to the application of an electric field.
- The field dependent change in the refractive index can be expressed by the equation,

$$\square\left(\frac{1}{\square^2_{\square}}\right) = \square^1 + \square^{\square}\square^2$$

- Here $\square^1$ is called the linear electro-optic coefficient and $\square^{\square}$ is called the quadratic electro-optic coefficient.
- If $\square^1$is very large, the corresponding electro-optic effect is called the pockels effect. If $\square^{\square}$

is large and makes the quadratic term dominant. The pockels effect is accurately defined by the equation,

$$\square\left(\frac{1}{\square^2_{\square}}\right) = \sum_{\square=1}^{3} \square^1_{\square\square}\,\square_{\square}$$

- First we will discuss the operation on the linear electro optic modulator. A possible experimental configuration is shown in fig.

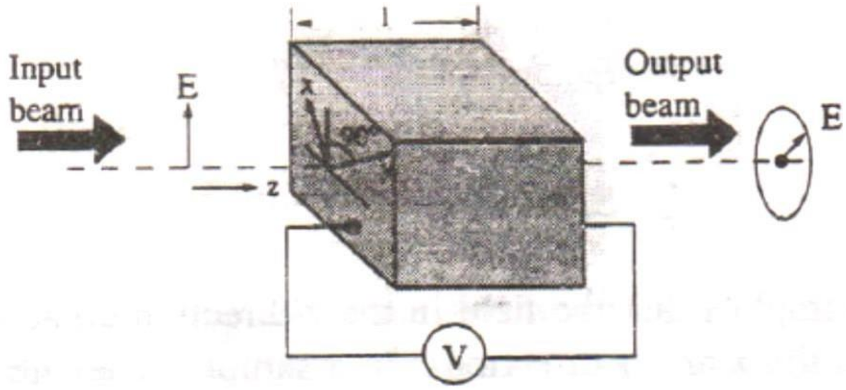


Fig:Electro optic phase modulation

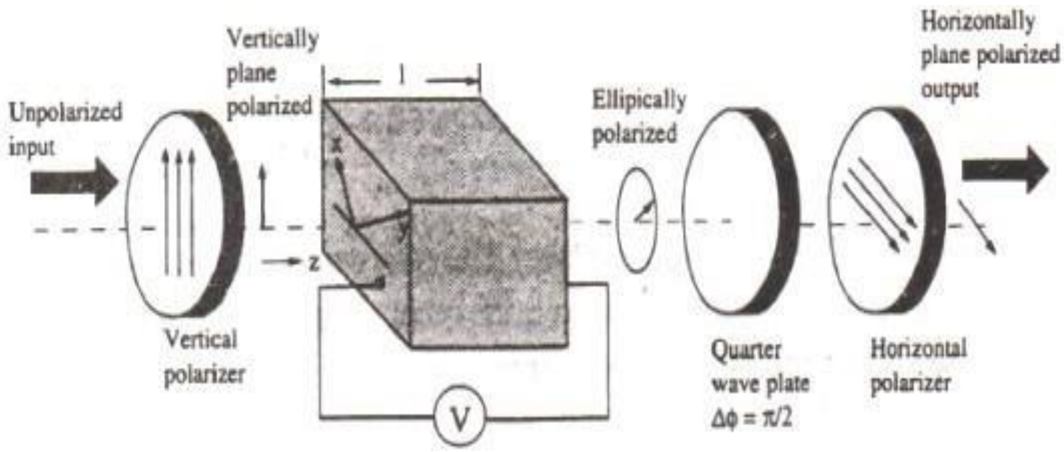


Fig :Electro optic amplitude Modulation.

- If the wave incident at z=0 is described by $E = E_0 e^{i\omega t}$, then the polarized componenet along the two principle axes x and y are each,

$$E_x = E_y = \frac{E_0 e^{i\omega t}}{\sqrt{2}}$$

- When the electric field is applied in the Z-direction, the pockels effect in the limit of a small refractive index change can be expressed as,

$$\Delta\left(\frac{1}{n_i^2}\right) = -\frac{2\Delta n_i}{n_i^3} \sum_{j=1}^{3} r_{ij} E_j$$

- Where E_z is the applied electric field in the z-direction. The refractive index change along the principle axes and be written as,

$$n_{xx} = n_0 + \frac{n_0^3}{2} r_{13} E_z$$

2 □□ □

$$n_{x'x'} = n_{0} - \frac{n_0^3}{2} r_{63} E_z$$

$$n_{z'z'} = n_{zz}$$

- The two different refractive indices along the privileged direction (x and y) cause the two wave to travel with different propagation constant, which are described by,

$$E_{x'} = \frac{A_0}{\sqrt{2}} e^{i\left(\omega t - \frac{2\pi}{\lambda} n_{x'x'} z\right)}$$

$$E_{y'} = \frac{A_0}{\sqrt{2}} e^{i\left(\omega t - \frac{2\pi}{\lambda} n_{y'y'} z\right)}$$

- In the sample of length l, the phase difference at the output plane between the two component is given by,

$$\Delta\phi(l) = \frac{2\pi}{\lambda}\left(n_{x'x'} - n_{y'y'}\right) l$$

$$= \frac{2\pi}{\lambda} r_{63} n_0^3 E_z l$$

Electro – optic amplitude modulation:

- If the phase shift between the two component at the output is $\frac{\pi}{2}$, then the linearly polarized wave is changed to a circularly polarized wave at the output.

$$E_{x'} = \frac{A_0}{\sqrt{2}} \cos \omega t$$

$$E_{y'} = \frac{A_0}{\sqrt{2}} \cos\left(\omega t - \frac{\pi}{2}\right) = \frac{A_0}{\sqrt{2}} \sin \omega t$$

- Similarly if the phase change is $\Delta\phi = \pi$, then the component of the output are,

$$E_{x'} = \frac{A_0}{\sqrt{2}} \cos \omega t$$

$$E_{y'} = -\frac{A_0}{\sqrt{2}} \cos \omega t$$

- It can be easily shown that the ratio of the input and output intensities. Or the modulator index is given by,

$$\frac{I_{out}}{I_{in}} = \sin^2\frac{\Delta\phi}{2}$$

$$= \square\square\square^2 \left(\frac{\square\;\square}{2\;\square_\square}\right)$$

- This eqn forms the basis of the pockels electro optic amplitude modulator. The variation of the transmission with voltage is shown in fig.

  Fig pg 461

- for small signal modulation ,the modulator is usually biased at some point, say S, and a small signal modulating voltage is superimposed.
- The total phase difference between the componenet at the output of the output polarizer is,

$$\square\emptyset_{\square\square\square\square\square} = \frac{\square}{2} + \square\emptyset$$

- The transmission in this case is given by,

$$\frac{\square_{\square\square\square}}{\square_{\square\square}} = \square\square\square^2 \left[\frac{\square}{4} + \frac{\square\;\square}{2\;\square_\square}\right]$$

$$= \frac{1}{2}\left[1 + \square\square\square\;\frac{\square\square}{\square_\square}\right]$$

-
- Thus if a modulating voltage $\square_0\square\square\square\square\square$ is applied to a modulator around the bias point $\frac{\square_\square}{2}$ determined by a quarter wave plate, the transmitted intensity intensity is given by,

$$\frac{\square_{\square\square\square}}{\square_{\square\square}} = \frac{1}{2} + \frac{\square\square\;\square\square\square\square\square}{2\square_\square}$$

$\square$

  - Where $\frac{\square\square_0}{\square_\square}$ should be $\ll 1$. if the condition $\frac{\square\square_0}{\square_\square} \ll 1$ is not fulfilled, the output will contain higher order harmonics of $\square$.

- The electro optic modulators that we have considered until now are called *longitudinal electro optic modulator*, since the electric field is applied in the same direction as the optic beam.

- Where d is the thickness of the crystal. In isotropic crystal such as GaAs $\square_{\square 0} = \square_{\square\square}$ and

$$|\square\emptyset| = \frac{\square\square}{\square\square}\, \square^{3}_{\square 0}\, \square^{1}_{41}\, \square$$

- A typical GaAs electro optic modulator is shown in fig.

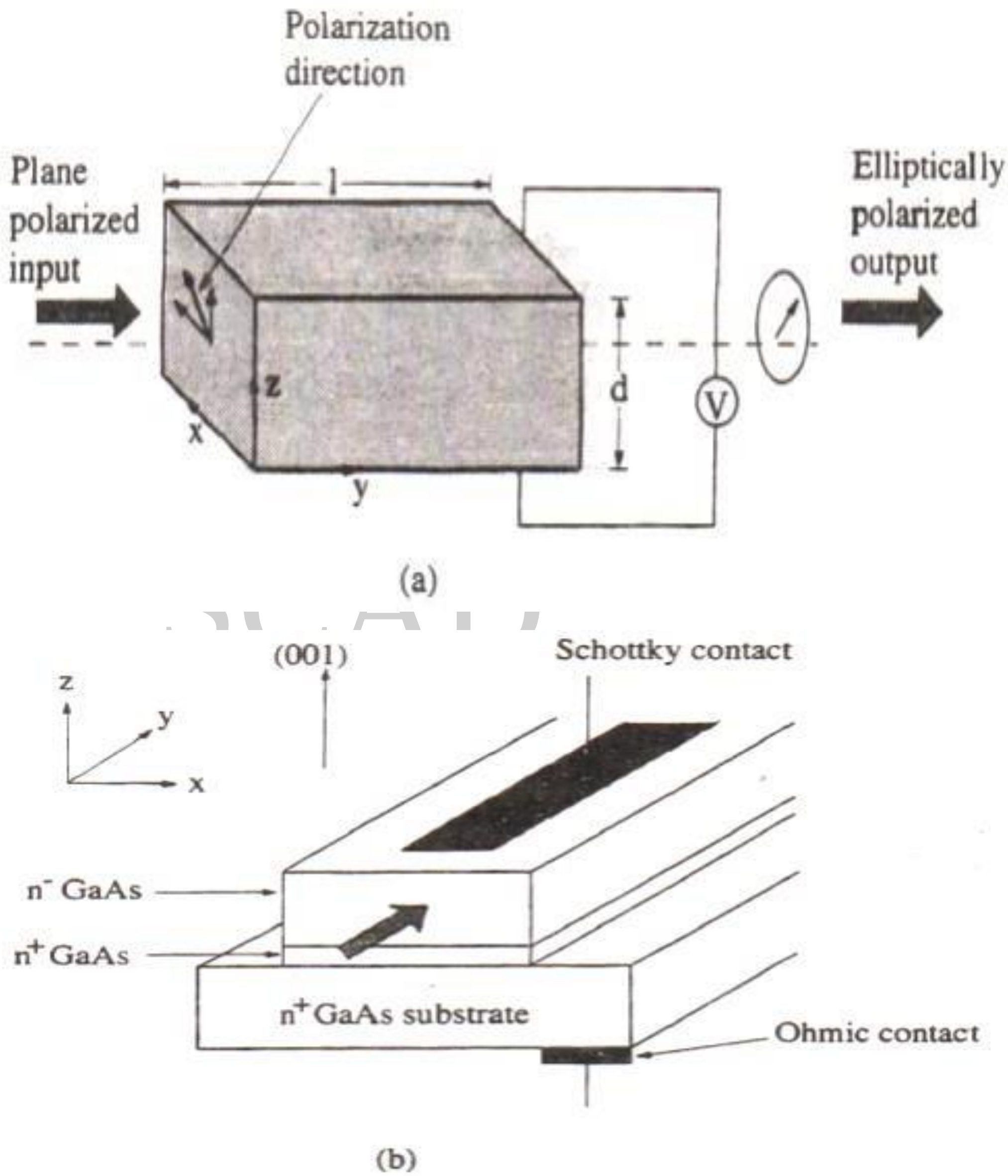
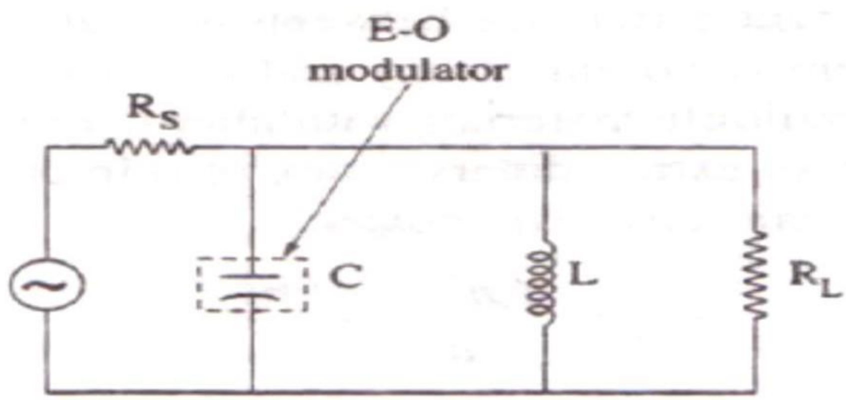


Fig : a) Geometry of transverse electro-optic modulator and b)schematic of a GaAs waveguide modulator.

- Such rigid waveguide structure are fabricated by lithiography, wet and dry etching and appropriate contact formation after first cleaving the sample along the 011 direction. The bias is applied by means of a reverse biased p-n junction or schottky diode along (001) direction.
- The external limitation is imposed by the capacitance and series resistance of the device. Therefore the device area has to be small and the series resistance resulting from the contact has to be minimized.
- The problem is alleviated by using a circuit as shown in the fig.



- The value of the inductance L is choosen to satify the condition,

$$\omega_0^2 = 4\pi^2 f_0^2 = \frac{1}{LC}$$

- Such that at resonance $(\omega - \omega_0)$the impedance is equal to the load resistance R_L,which is choosen to be much larger than R_s.

The quadratic Electro-optic Effect: Quantum well Modulators

- In the quantum wells, the elecro-optic is different from that in bulk semiconductors, where the linear term is dominant.
- In a quantum well hetrostructure, there will be a strong interaction of the electric field with the optical wave.
- This was described as the quantum confined strack effect (QCSE). Which is a quadratic effect with respect to electric field. In other words the transition energies vary quadratically with electric field.

- As a result the absorption coefficient and refractive indices will vary quadratically with electric field. Thus it is expected that the quadratic electro optic effect will be pronounced in quantum well.
- The refractive indices in the directions of ordinary and extraordinary rays can be written as,

$$n_{TE} = n_0 - \frac{1}{2} n_0^3 s_{12} E^2$$

$$n_{TM} = n_0 - \frac{1}{2} n_0^3 s_{11} E^2$$

- Where s_{12} and s_{11} are the quadratic elecro optic coefficients. Accordingly the phase shift is given by,

$$\Delta\emptyset = \frac{\pi}{\lambda} n_0^3 (s_{12} - s_{11}) E^2$$

- If the linear electro optic effect is also present, the total phase change is given by,

$$\Delta\emptyset = \frac{\pi l}{\lambda} n_0^3 [r_{41} E + (s_{12} - s_{11}) E^2]$$

- Here s_{12} and s_{11} are the electro optic coefficients describing the index ellipsoid for the quadratic effect.

Modulation by carrier injection : The BRAQWET modulator

- In these device the injection of free carriers change the refractive index. This effect can be quite pronounced if the junction current is of the order of a few tens of milliamperes.
- Carrier injection can also be used in a quantum well to quench the band-edge absorption. This id done in a device called the *Blockaded Reservoir and Quantum well Electron Transfer* (BRAQWET) modulator.
- Carrier injection into the quantum well is usually done by transfer or modulator-doping from an adjacent large bandgap doped semiconductor with the help of an applied bias across a n-i-n structure.

- It is important to note that while the QCSE modulator the oscillator strength is only moved spectrally, in this device the existing oscillator strength is switched on and off completely.
- The band diagram of the active region of a BRAQWET modulator at zero applied bias shown in fig.

  Fig: Transmission-voltage characteristics of BRAQWET modulator

- Since the electron transfer across the spacer is a very fast process, very high modulation speeds are expected with the device. It has been found that BRAQWET modulators are free from the speed limitations imposed by recombination times and other carrier dynamics that are typically present in current injection band filling device.
- The carrier population in the quantum well, when the bond state $\square_1$is below the Fermi level is given by,

$$\square = \frac{\square^{*}}{\square h^2}(\square_1 - \square_{\square})$$

- Due to the nature of the planar doped barrier which is used to shift the height of the quantum well relative to the electron reservoir, the offset in energy levels

  e applied voltage.

- It can be shown that a linear relationship between the applied voltage bias voltage and the optical absorption coefficient results.

$$\square(\square) = \square_0 + \square\square$$

- Where $\square_0$ is the zero-bias absorption coefficient and B is a constant.
- The transmitted power of a BRAQWET amplitude modulator is given by,

$$\square = \square^{-\square_0\square}\,\square^{-\square\square\square}$$

5. i) Explain the Magneto-Optic Devices:

- The presence of magnetic field may also affect the optical properties of some substances thereby giving rise to number of useful devices.
- In general however an electric field are easier to generate than magnetic fields, electro-optic devices are usually preferred to magneto optic effect.

Faraday Effect:

- This is the simplest magneto-optic effect and the only one of real interest for optical modulators, it concerns the change in refractive index of a material subjected to a steady magnetic field.
- When a beam of plane polarized light passes through a substance subjected to a magnetic field, its plane of polarization is observed to rotate by an amount proportional to the magnetic field component parallel to the direction of propagation.
- This is very similar to optical activity which results from certain material having different refractive indices $\eta_{\square}$ and $\eta_{\square}$ for right and left circularly polarized light.
- In the faraday effect the sense of rotation of the plane of polarization is independent of the direction of propagation. This is in contrast to optical activity where the sense of rotation is related to the direction of propagation.
- The rotation of the plane of polarization is given by,
- We can also express □ in terms of the refractive indices $\eta_{\square}$ and $\eta_{\square}$,

$$\square = \frac{2\square}{\square}(\eta_{\square} - \eta_{\square})\square$$

- A faraday rotator used in conjunction with a pair of polarizers acts as an optical isolator which allows a light beam to travel through it in one direction but not in opposite one.
- It may therefore be used in laser amplifying chains to eliminate reflected, backward travelling waves, which are potentially damaging. The construction of a typical isolator is shown in fig.

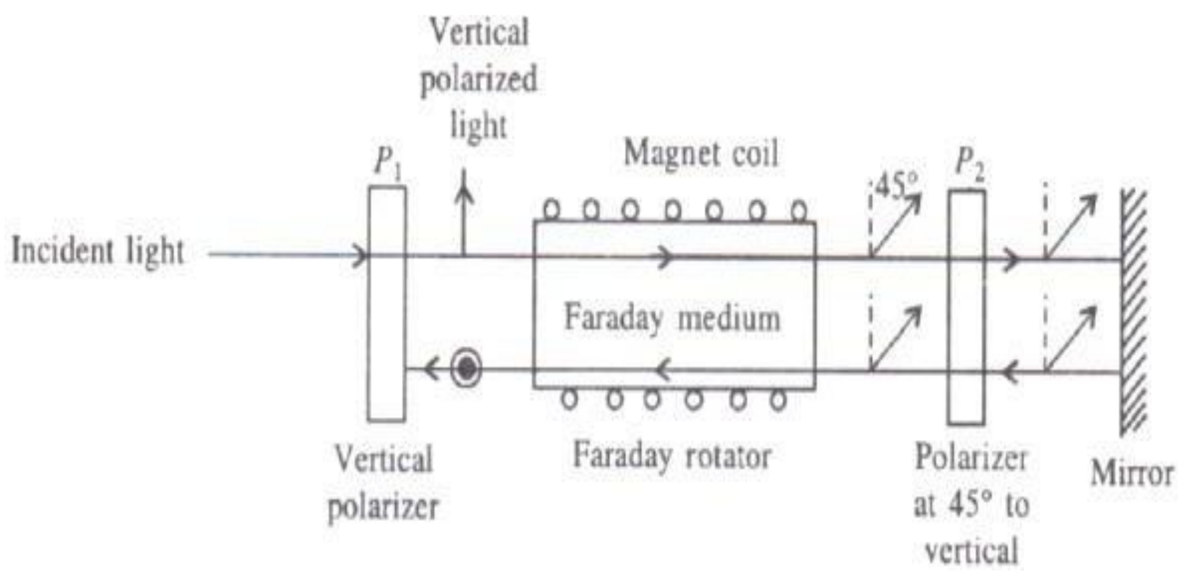


Fig: optical isolator based on the Faraday effect.

- Light passing from left to right is polarized in the vertical plane by polarizer □$_1$. The faraday rotator is adjusted to produce a rotation of 45^0 in the clockwise sense.
- The second polarizer □$_2$is set as 45^0 to □$_1$, so that it will transmit light emerging from the rotator.
- One potential application of magneto-optic currently receiving attention is large capacity computer memories. Such memories must be capable of storing very large amounts of information in a relatively small area and permit very rapid readout and preferably random access.
- Writing may be achieved by heating the memory elements on the storage medium to a temperature above the curie point using a laser beam. To read the information the irradiance of the laser beam is reduced and tehn directed to the memory elements.

5.i) Explain about Acoustic optic effect:

- The acousto-optic effect is the change in the refractive index of a medium caused by the mechanical strains accompanying the passage of an acoustic (strain) wave through the medium.
- The strain and hence the refractive index varies periodically with a wavelength □ equal to that of the acoustic wave. The refractive index changes are caused by the photoeleastic effect which occurs in all materials on the application of mechanical stress.
- We consider the monochromatic light wave , wavelength □ incident upon a medium in which an acoustic wave wave has produced sinusoidal variation of wavelength Λ in the refractive index.
- The situation is shown in fig where the solid horizontal lines represent acoustic wave peaks(pressure maxima) and the dashed horizontal line represent acoustic wave throughs (pressure minima).

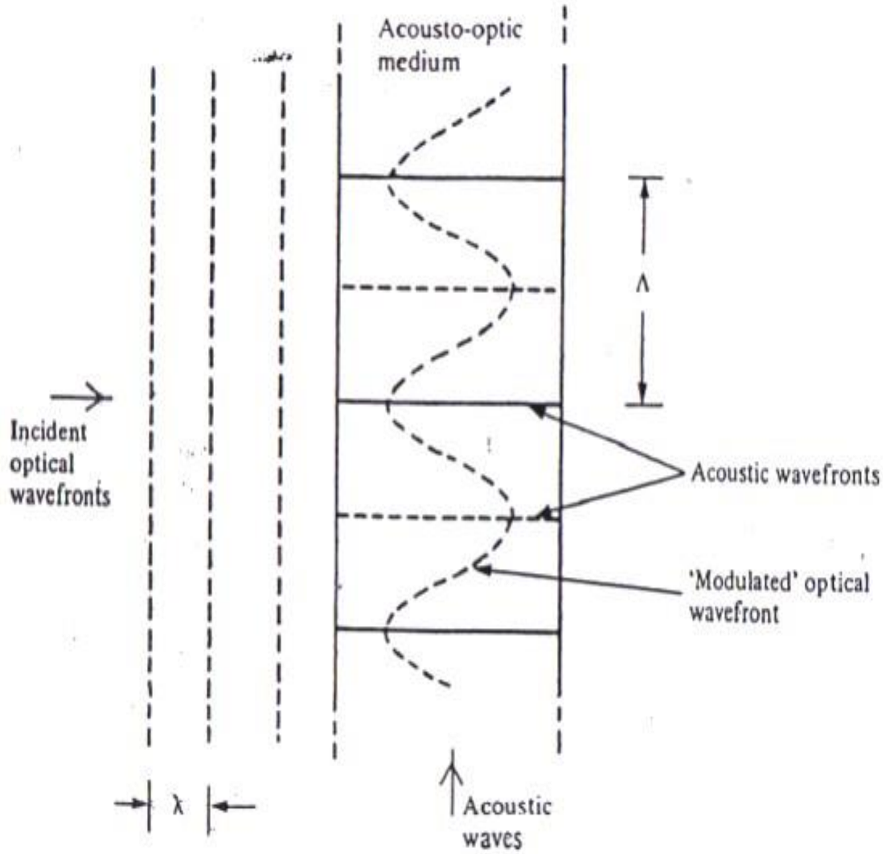


Fig:Schematic illustration of acousto-optic modulation.

- The wavefront in the medium therefore soon acquires the wavy appearance shown by the dashed curve. The acoustic wave velocity is very much less than the light wave velocity, so we may consider the variation in the refractive index to be stationary in the medium.
- As element of the light wave propagate in a direction normal to the local wavefront, almost all the wave element will suffer a change in direction leading to a re-distribution of the light flux, which tends concentrate near the regions of compression.
- There are two main cases of interest namely i) *the Raman-Nath regime* ii) *the Bragg regime.*
- In *Raman-Nath regime* the acoustic diffraction grating is so thin that the diffracted light suffers no further redistribution before leaving the modulator. The light is diffracted as from a simple plane grating such that

$$\square\square_0 = \Lambda \square\square\square\ \square_{\square}$$

- Where m=0,±1,±2,… is the order and θ_m in the correspondence angle of diffraction as shown in fig.

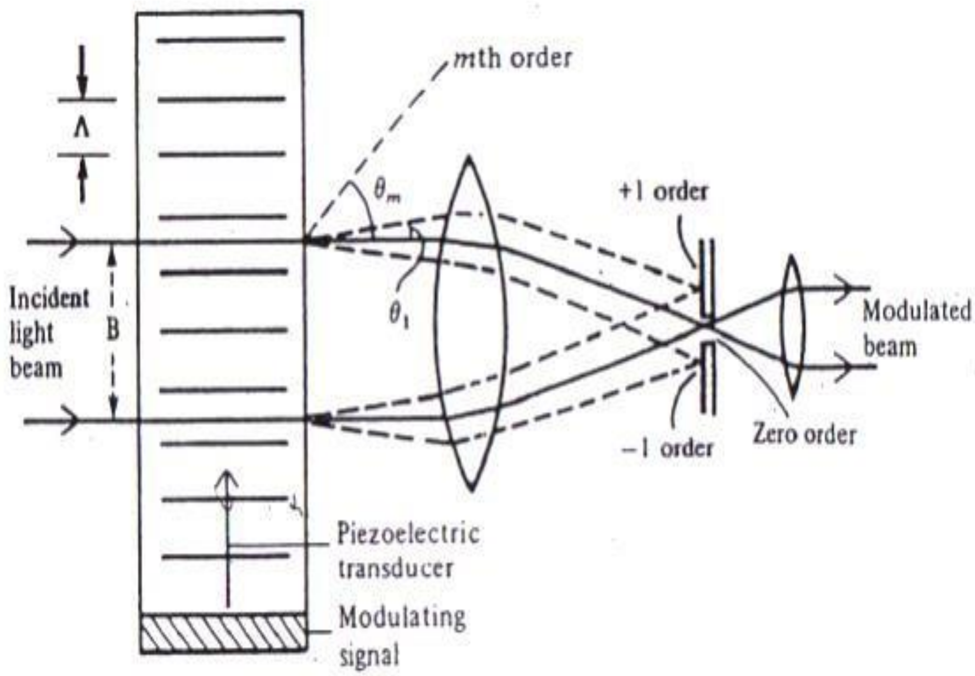


Fig:Geometry for Raman-Nath acousto-optic diffraction grating modulation.

- The irradiance I of the light in these orders depends on the ruling depth of the acoustic grating, whichis related to the amplitude of the acoustic grating.
- The fraction of light removed from the zero order beam is

$$\eta = \frac{I_0 - I}{I_0}$$

- Where I_0 is the transmitted irradiance in the absence of the acoustic wave. Thus amplitude variations of the acoustic wave are transformed into irradiance variation of the optical beam.
- Consider a plane wave front incident on the grating planes at an angle of incidence θ_i as shown in fig. significant amounts of light will emerge only in those direction in which constructive interference occurs.
- The conditions to be satisfied are i) light scattered from a given grating plane must arrive in phase at the new wavefront and ii)light scattered from successive grating planes must be an integral number of wavelengths.

- The first of these conditions is satisfied when $□_□ = □_□$, where $□_□$ is the angle of diffraction. The second condition requires that,

$$\sin □_□ + \sin □_□ = \frac{□□}{\Lambda}$$

- Where $□ = 0,1,2 \ldots$ the two conditions are simultaneously fulfilled when.

$$□ \; \sin □_□ = \sin □_□ = \frac{□}{2\Lambda}$$

- The diffraction is similar to that obtained with a plane grating, but only for special angles of incidence; the angle of incidence must equal the angle of diffraction.

UNIT V

OPTOELECTRONIC INTEGRATED CIRCUITS

Explain any two applications of OEIC in detail.

One of the primary areas where photonic devices and OEICs will make an impact is telecommunications, driven by the large bandwidth and light weight of optical fiber

.The object is to bring fiber system to the home and individual subscribers in the form of telephone link and broadcast cable TV.

- This implies that optoelectronic technologies have to be extended to the subscriber loop. These systems will necessitate the development of lasers with precise frequency control and tenability and wavelength-selective detectors and receivers.

  Similar requirements also hold for optical computing system. However, since link over shorter distances are needed for this application.

- Optoelectronic integration is also important for radar application .The schematic of a microwave or millimeter wave phased-array radar system shown in fig.

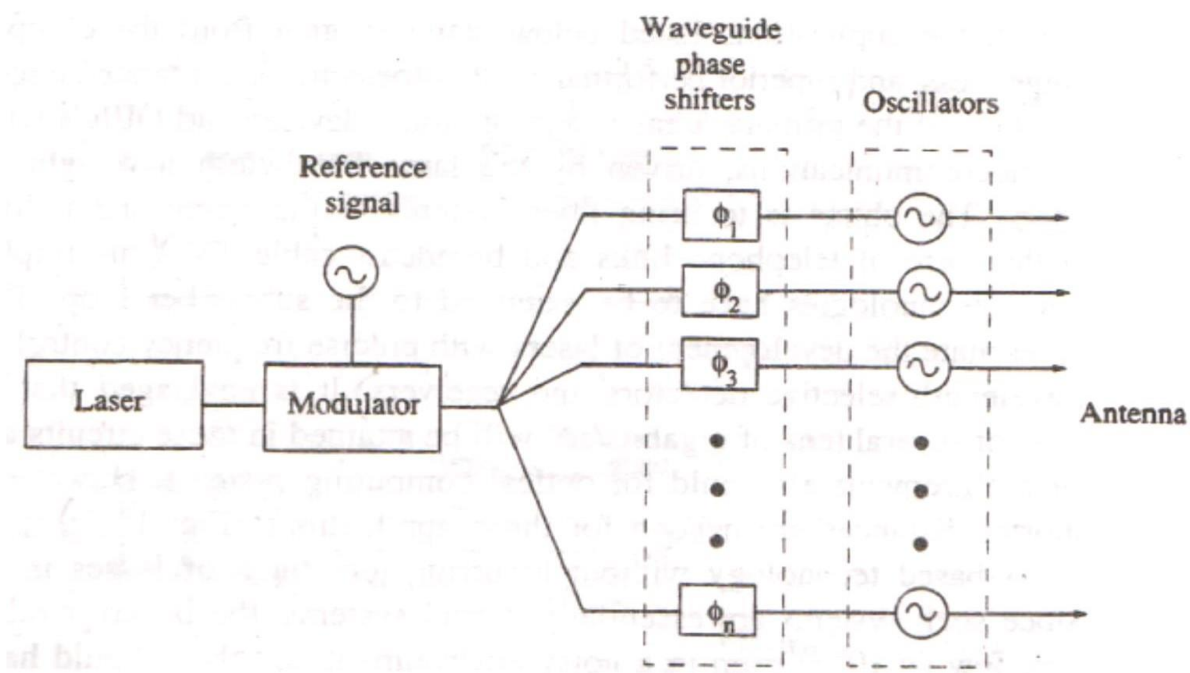


Fig: **Schematic block diagram of an optoelectronic phased array antenna sysytem**

- In principle, a phase-shifted and modulated (high frequency) optical signal is injection locked to a free-running microwave, or millimeter-wave oscillator, which forms one element of phased-array radar.
- Beam steering in such radars is achieved by incorporating a progressive phase shift $\Delta\Phi$ between successive elements.
- The modulated and phase-shifted signal is couple by injection locking to a microwave oscillator, which forms a single element of the phased array.
- Each element of the phased array therefore consists of a source, a modulator, a phase-shifter, a waveguide, and a oscillator. These devices can be combined by hybrid integration, but for the sake of compactness,(since the phased array will contain many radiating elements) and ruggedness, it is more desirable to realize the array by monolithic integration. The resulting OEIC chip, even for a single element, is extremely complex .Such radar will be used on the ground on aircrafts("smart skins"),and in satellites.

Explain the importance of Optoelectronic Integration

An optoelectronic device is an good example of the complementary and collaborative role of electrons and photons to perform a single function – emission or detection.

- Electrons and photons interact effectively in a direct bandgap semiconductor to produce optoelectronic conversion.
- As in any optoelectronic devices where electrons and photons are involved in producing the device characteristics ,it is possible to envision ,in a large sense ,an optoelectronic system in which multiple function are separately performed by electronic and optoelectronic devices. Such a system, by analogy with the integrated circuit(IC), can be called an OEIC.
- Electronic function such as switching or amplification can be combined with detection and also light transmission in such an integrated chip.

- The need for integration arises from a variety of need speed and bandwidth, functionality and multifunction capabilities, compactness, low parasitic, to name few.
- There are two principal forms of optoelectronic integration—hybrid and monolithic. In hybrid integration , as the name suggests ,discrete devices on separate functional block or chip are connected using electronic(lead) or optical(fiber) interconnects
- An advantage of such hybrid integration is the possibility of using high-performance discrete devices as component.
- The disadvantages are lack of compactness and enhanced parasitic effects in terms of interconnects, bonding and lead wires.
- In monolithic integration all active and passive components are fabricated on the same chip. However unlike silicon ICs in which almost all the parts are made with the same material and some processing steps, the hetrostructure and processing steps of the different components of OEIC can be different.
-
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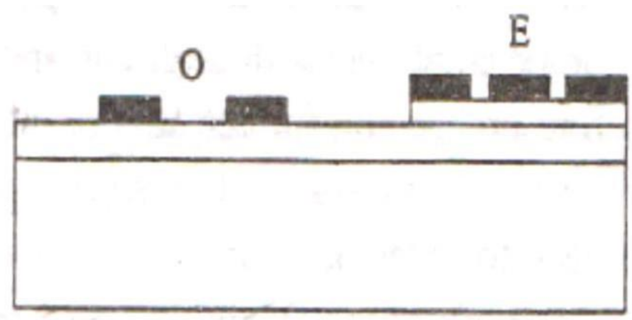


Fig: (b) Planar Compatible Schame

- where both devices are made from the same hetrostructure or planar regrown shown in fig (c).

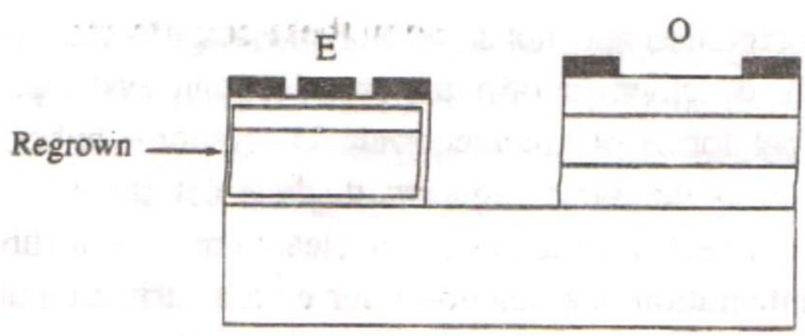


Fig: (c) Planar scheme using regrowth

- where one of the device is selectively regrown after growthof the first device. Although this technique provide a large freedom in the choice of device hetrostructures, the grown interface can have a large density of traps and other electrically active defects that can affect the performance of the regrown device.

2. Draw the diagram of a PIN diode and HBT integrated front end photo receiver and explain its operation. [May/June-2013]

- Depending on the compatibility of material used and desired device and circuit characteristics, there are other possible combinations of photodetectors and amplifiers which can form a monolithically integrated front end photoreceiver circuit.
- The important point to realize is that the integration involved a single step epitaxy of the HBT, from which the p-i-n modulator was selectivey defined by processing.
- The collector region of the HBT also serves as the i-region of the diode.
- The same scheme can be conveniently used to realize a front-end photoreceiver and the HBT is the preamplifier.
- Another compelling reason for using a PIN-HBT combination stems from noise and sensitivity considerations.
- The sensitivity of the HBT based photoreceiver is better than a FET-based photoreceiver at high frequencies.
- This is because the sensitivity of a PIN-FET receiver is proportional to B3 where B is the bit rate while the sensitivity of a PIN-HBT is proportional to B2.
- The epitaxial layer structure, equivalent circuit of a transimpedance amplifier design and the photomicrograph of a fabricated circuit with the active and passive element shown in fig.

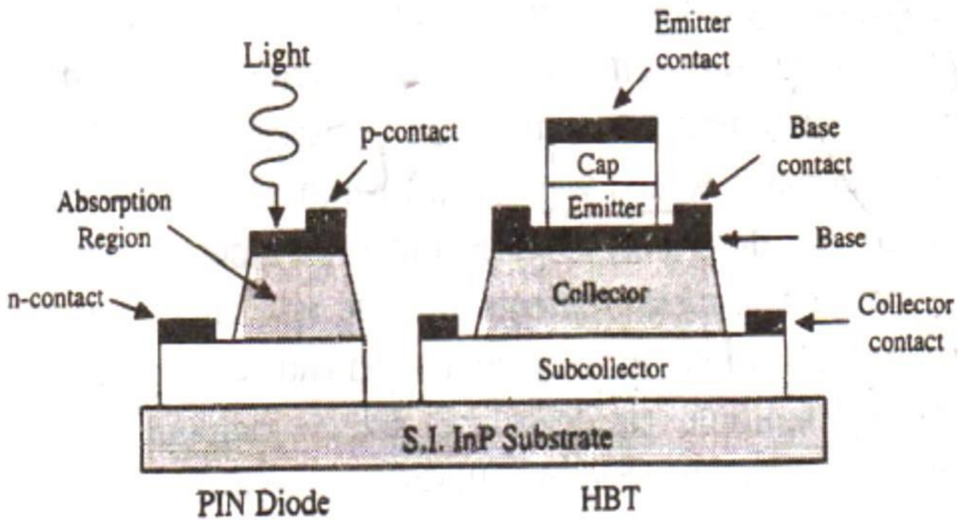


Fig:The PIN-HBT front-end photoreceiver – epitaxial heterostructure

- A valuable technique to enhance photoreceiver response at high frequencies is inductive peaking, where an inductor is placed in series after the photodiode at the input of the amplifier or in other circuit locations.

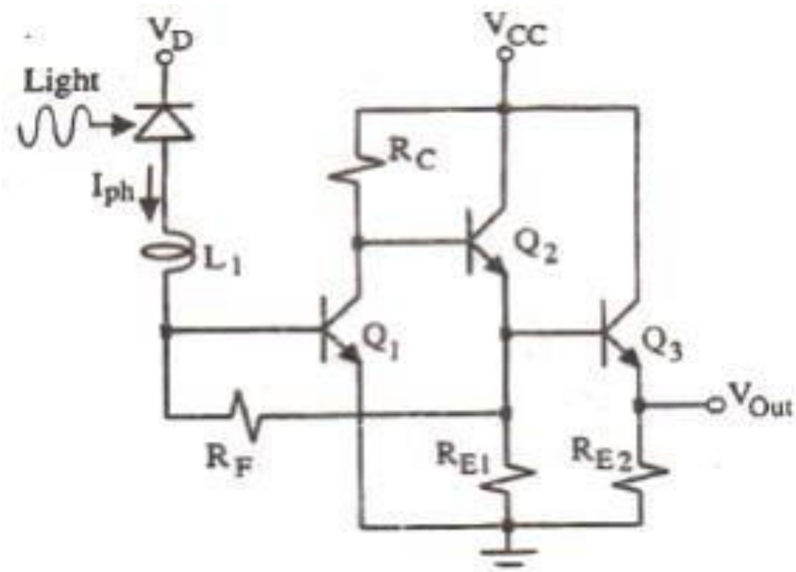


Fig: **The PIN-HBT front-end photoreceiver – Equivalent Circuit.**

- Digital optical communication systems require optical time domain measurements to characterize system pulse performance.
- These measurements include both single and multi-valued waveforms.
- Multi-valued waveform measurements, commonly called eye diagrams, include pulse parameter mask, extinction ratio an jitter.
- Eye diagrams are formed by overlaying multiple single-valued pseudo-random binary sequence (PRBS) waveforms on the displayed an oscilloscope or eye diagram analyzer.

- In general , the more open the eye is, the lower the likelihood that the system may mistake a “1” bit for a “0” bit, or vice versa .
- The eye diagram opening width, the time between the zero-to-one/one-to-zero crossings, shows the time interval over which the signal may be sampled without error due to intersymbol interference.

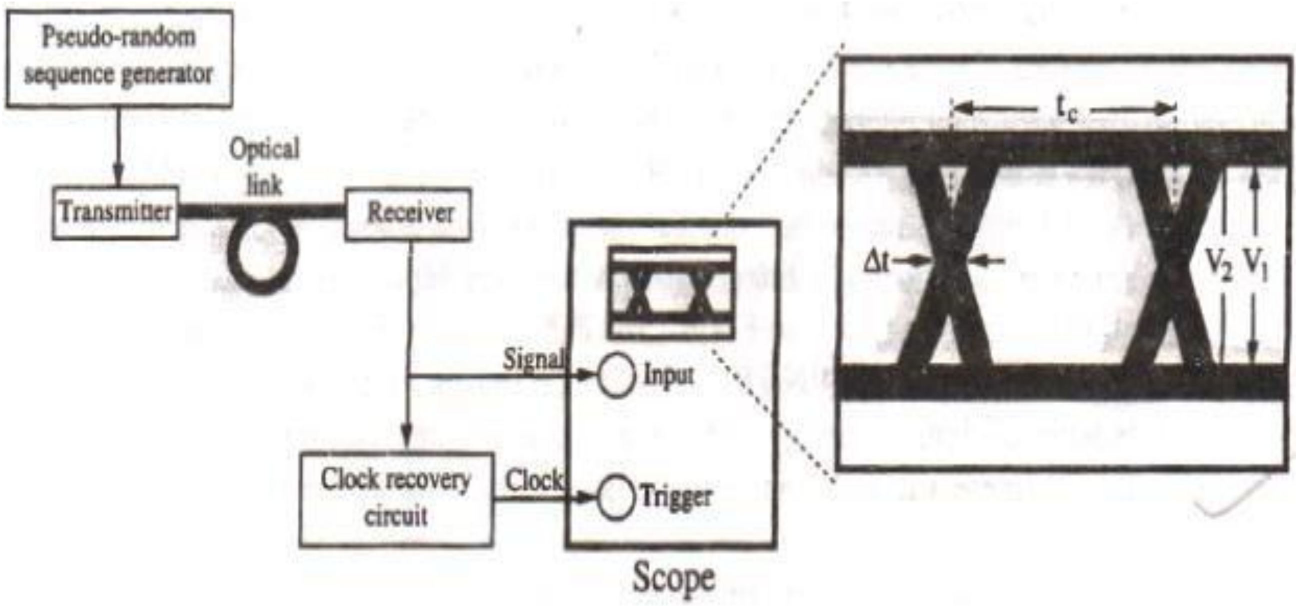
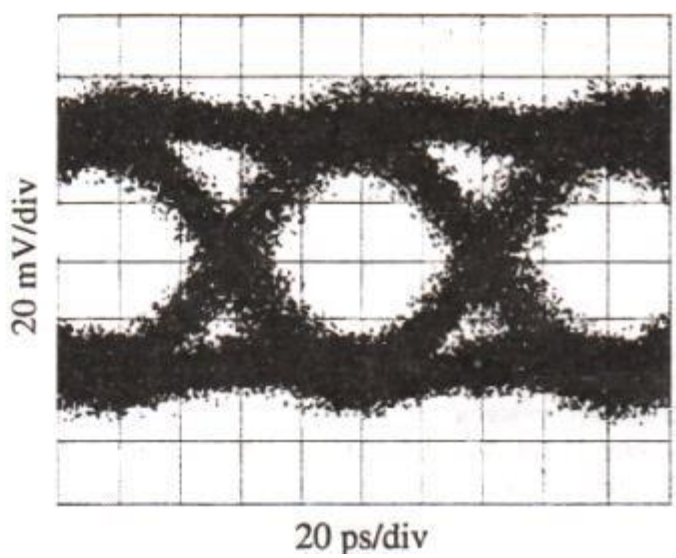


Fig:Measurement of the eye diagram of a photoreceiver.

- The optical transmitter sends a pseudo-random equence of binary digits to the receiver via the optical link.



- The received signal, and a clock waveform generated by the receiver from the received signal are fed to the sampling oscilloscope. Two parameters that define the eye diagram are eye closure and jitter.

$$\text{Percentage eye closure} = \left(1 - \frac{\square_1}{\square_2}\right) * 100$$

- The central open region of the eye diagram of the eye diagram is a measure of the BER of the circuit.
- It gives a probability of the circuit in making correct decisions regarding incoming zeros and ones.
- In conclusion, the PIN-HBT photo receiver is a simple and versatile OEIC which is capable of demonstrating to note that the dominant noise sources are the base current and the feedback resistor.

Front-end photo receivers

- In the design of an optical-fiber communication system ,whether for use in long-distance communication or for bussing ata over short distances, and operating at low or high data rates, a key element is the receiver.

  The basic purpose of the receiver is to detect the incident light and convert in to electrical signal containing the information impressed on the light at the transmitting end.
- Sensitivity plays a vital role in deciding the number of repeaters needed in long-haul communication system.

- The receiver sensitivity is defined as the minimum amount of optical power level needed at the receiver input so that the signal –to-noise ratio is greater than a given value.
- The block diagram of photoreceiver circuit is shown in fig.

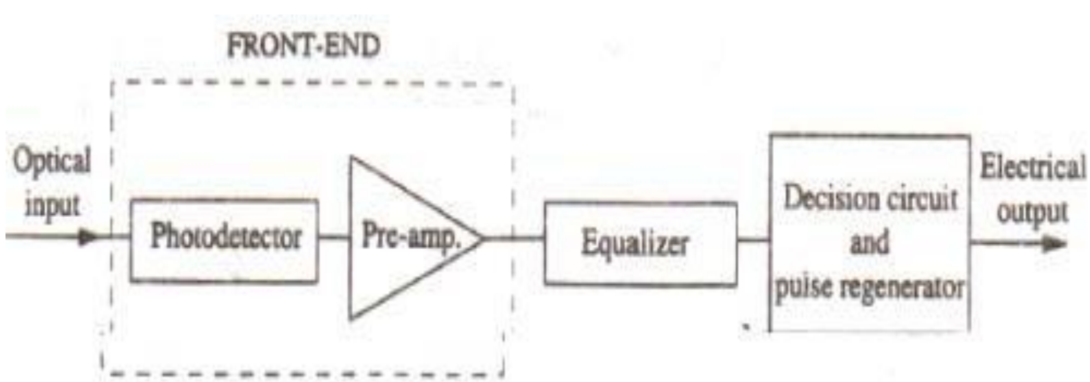


Fig : **Block diagram of a photoreceiver circuit.**

- The first two blocks consisting of the photo detector and the low-noise preamplifier are considered the front end of the photo receiver.
- While the rest of the circuit performance equalization, pulse shaping and gain control functions.
- Also, in most photo receiver circuits multiple stages of amplification are included to increase the gain of the signal.
- The overall performance of the circuit is mostly dictated by the front end,which consists of a photodiode and a single-stage amplifier.
- Avalanche photodiodes, PIN photodiodes,and metal-semiconductor-metal(MSM) photodetectors are among the mostcommonly used photodetectors for this application.
- For the preamplifier circuit, low noise with high output gain are very important because it is the first stage of amplification.
- Both field-effect transistors (FETs) and bipolar transistors have been used in the preamplifier circuit.

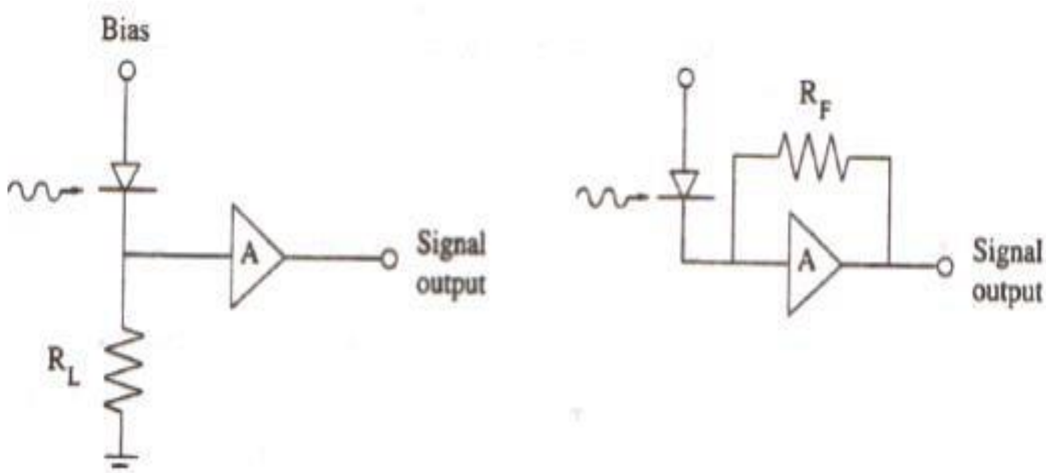


Fig: Photoreceiver circuit diagram for a) low,high b) transimpedance design

- Three types of integration are commonly used and are shown in fig, the low-input impedance design, the high input impedance design, and the transimpedance design.
- The high-input impedance design requires the addition of an equalization circuit to extend the value of the bandwidth due to the large RC time constant.
- The transimpedance design is probably the most popular because no equalization is usually required.

- A field-effect transistor can also be used as an active feedback element , replacing the passive resistor and increasing the impedance value to as high as 80K. This significantly reduces the overall themal noise.

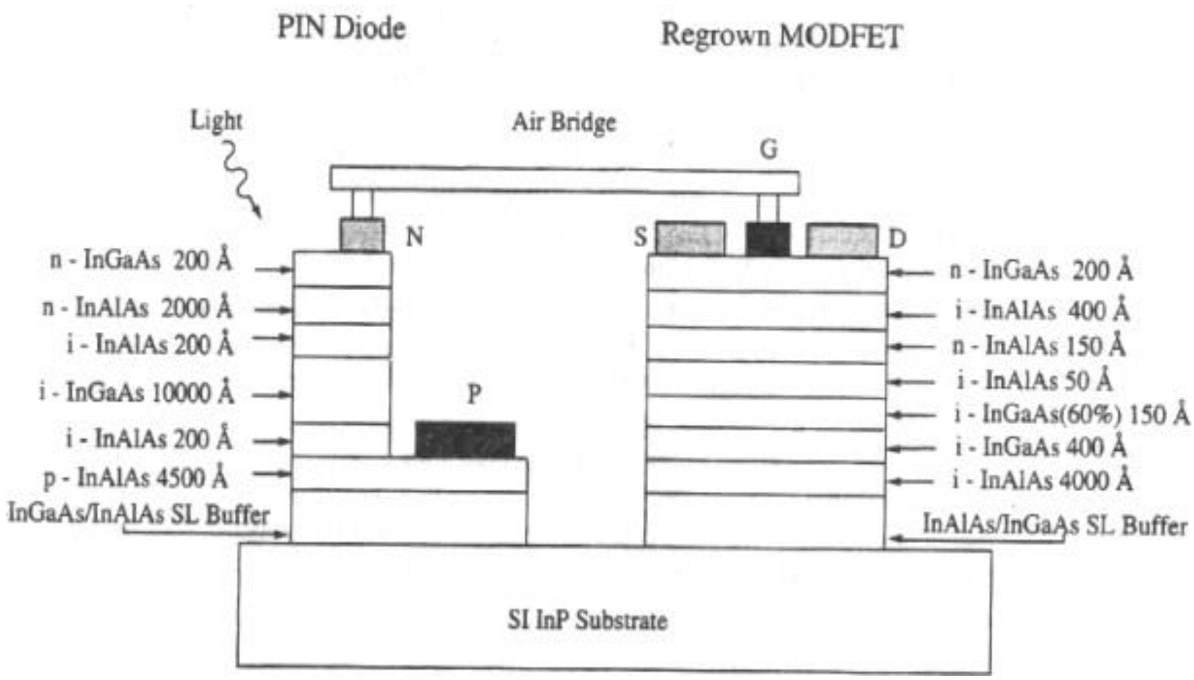


Fig: InP-basedfront-end photoreceiver utilizing MBE regrowth

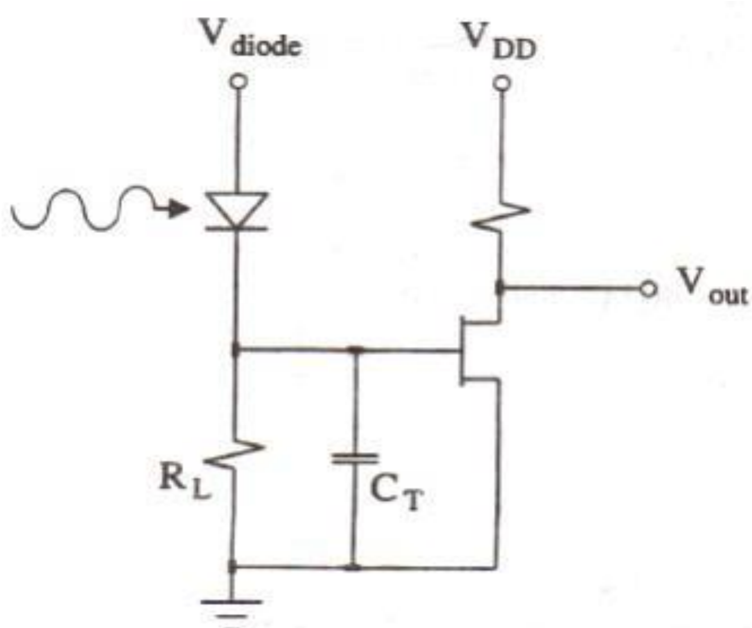


Fig: Equivalent circuit of PIN-FET photo receiver

- The above Figure schematically illustrates the monolithic integration of an In0,53 Ga0,47 As photodiode with a In0,53Ga0,47As/In0,52Al0,48As modulation doped FET (MODFET) by regrowth on InP.
- The MODFET consists of a layer of undoped low-bandgap material forming a heterojunction with a highly doped high-bandgap material.
- Due to the difference in the electron affinities of the two layers , electrons are transferred from the high-bandgap material to the low-bandgap material to form a quasi two-dimensional electron gas(2DEG).
- The main advantage of such a structure is that the electrons are separated from their parent donors and the coulombic scattering is greatly reduced. This results in higher carrier mobility and drift velocity.
- Typically a high-bandgap undoped spacer layer is added between the highly doped high bandgap layer and the undoped low-bandgap layer to further separate the electrons from their parent donors.
- Furthermore ,the noise figures and noise temperature exhibited by MODFET are lower than other FETs.
- The InGaAs/InAlAs/InP heterostructure system is a superior candidate compared to the GaAs/AlGaAs system for the MODFET.

3. Discuss the noise performance in Integrated photo receivers.

- Noise and bandwidth are important parameters of a photo receiver circuit.
- For simplicity, we will consider the integration of a FET with a PIN diode.
- The fourth term represents the i/f noise in the FET device, where $\square_0$ is the noise corner frequency.
- The fifth term represents the noise associated with the channel conductance of the FET.
- The sixth term is due to noiseresulting from traps in the channel or buffer regions. $\square_{\square 1}$, $\square_{\square 2}$ and $\square_{\square 3}$ are known as the personick integrals and $\square_{\square}$ and $\square_{\square}$ are the I/f noise integral and trap integral respectively.
- $\square_{\square}$ is a materials related parameter , $\square_{\square}$ is the FET transconductance`
- $\square_{\square}$ is trap emission time constant and $\square_{\square}$ is a constant dependent on trap density and

transistor parameters.

- This term is proportional to the cube of the bandwidth of the circuit and the square of the total capacitance , $\square_{\square}$ is given by

$$\square_{\square} = \square_{\square\square} + \square_{\square} + \square_{\square}$$

- Where the terms on the right-hand side represent the gate-source capacitance in the FET, the PIN diode capacitance and the parasitic capacitance .
- At high frequencies, taking the dominant noise sources in to account, the input noise current of the FET preamplifier is given by

$$\overline{\square^2_{\square}} = [4\square_{\square} \square_{\square} \left(\frac{\square_{\square}}{\frac{2}{\square_{\square}}} + 4\square^2 \frac{\square^2_{\square} \square^2_{\square}}{\square_{\square}} \square^3 \right)] \square_{\square}$$

- For low-noise performance , $\square_{\square}$ should be small and $\square_{\square}$ large.
- It may be noted that both $\square_{\square\square}$ and $\square_{\square}$ are related to the gate length $\square_{\square}$ of the transistor.
- With increase of $\square_{\square}$, $\square_{\square\square}$ decreases and $\square_{\square}$ increases. It has been shown that the condition for minimum photoreceiver noise yields

$$\square_{\square\square} = \square_{\square} + \square_{\square}$$

- The cutoff frequency $\square_{\square}$ of the transistor is given by
- Where $\square$ represents the modulation index and $\square_0$ is the cw light input power ,then the signal to noise ratio is

$$\frac{\square}{\square} = \frac{\square^2 \square_0}{2\sqrt{\overline{\square^2_{\square}}}}$$

- Where $\square_0$ represents the dc photocurrent level from the cw light signal, $\square_0$. the equations given above can be used to evaluate the noise performance of practical photoreceiver circuits.

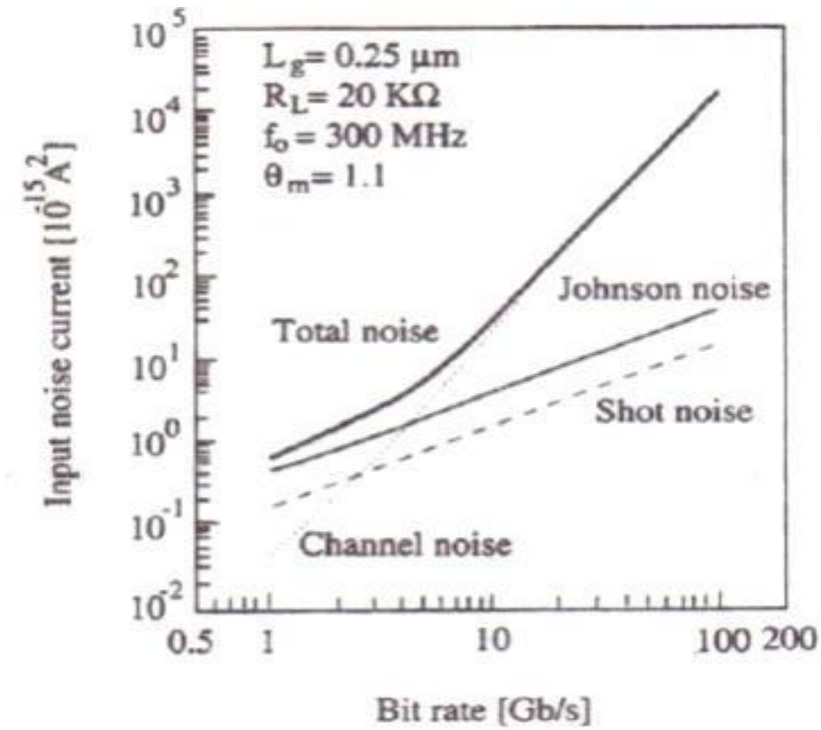


Fig : Calculated noise spectral density vs Bit rate.

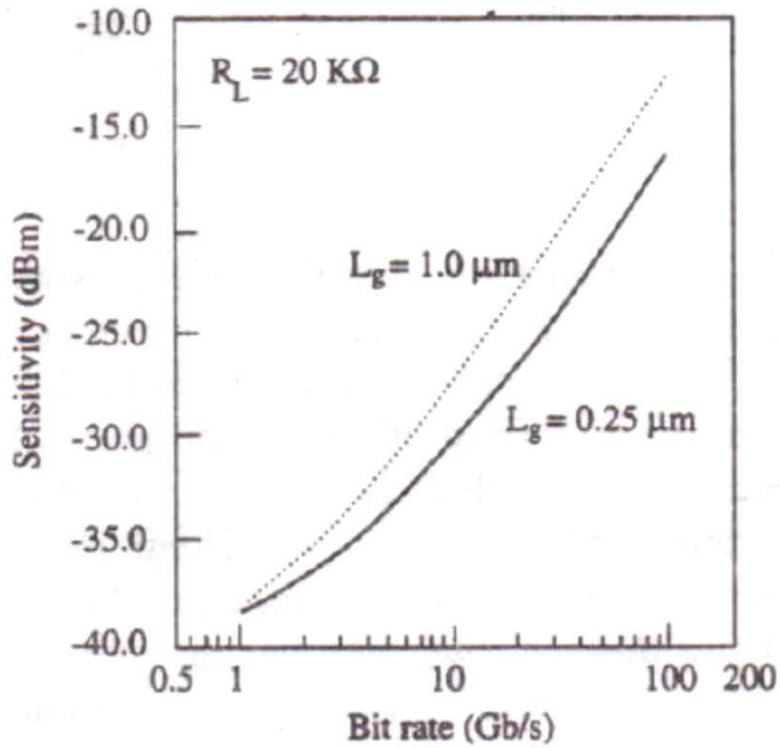


Fig : Calculated sensitivities vs Bit rate.

Photoreceiver bandwidth considerations

- The most important parameters that determine the bandwidth of the receiver are the transit time of the generated carriers in the diode and the RC time constant of the circuit.
- The frequency response of the PIN photodiode, J(□) limited by transit time consideration .
- The electrical frequency response, H(□) of the overall circuit includes the diode capacitance and resistances.
- The frequency response for the complete receiver can then be expressed as

$$\square_0(\square) = \square(\square)\square(\square)$$

- The thickness of the absorption and transit layer of the photodiode should be optimally designed.
- For thicknesses of 1 um or less of this layer the electrical circuit frequency response typically determines the overall frequency response of the photoreceiver .

- In many designs, he noise is the main concern because equalization can be used in later stages of the photoreceiver, thereby increasing the effective bandwidth of the photoreceiver.

- The calculated and measured electrical frequency response of a PIN-MODFET front end photoreceiver circuit is shown in fig.

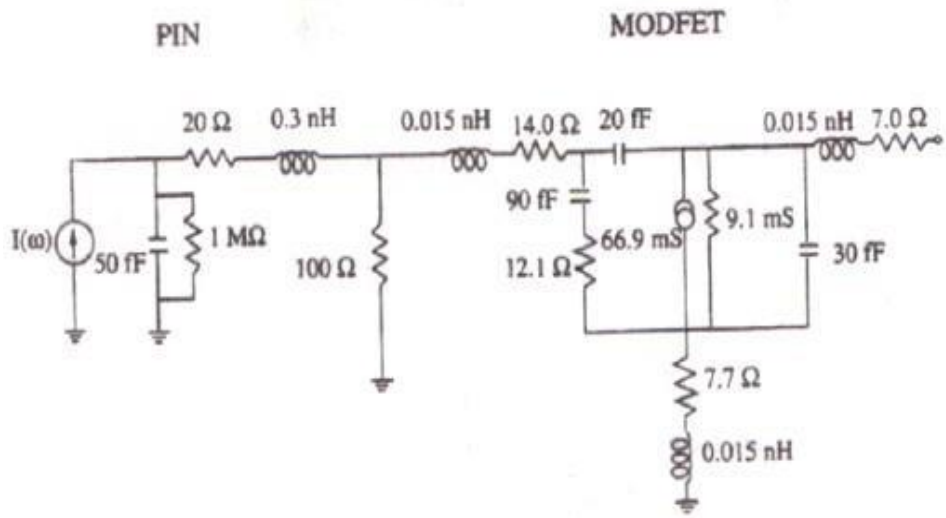


Fig:Equivalent circuit model for a low input impedance PIN-MODFET.

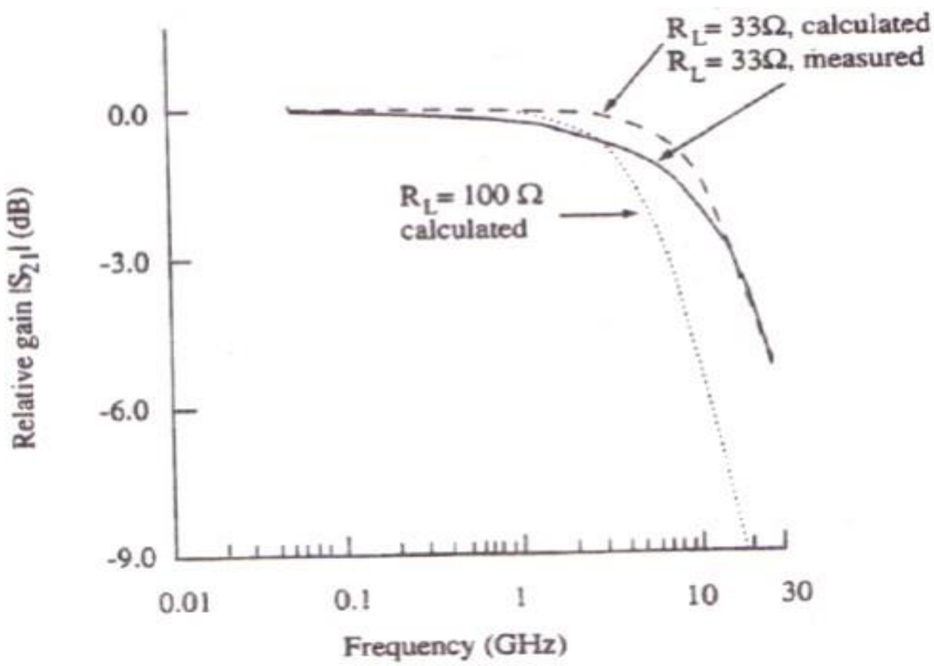


Fig:Calculated and measured frequency response of the circuit.

Describe the fabrication process of an opto electronic integrated transmitter circuit by molecular beam epitaxy regrowth.

- A transmitter circuits includes a light source such as a high-power LED or a laser.
- Integration of the laser with the associated electronics particularly the driver circuitry in the form of a transistor is more complicated than the fabrication of a photoreceiver.
- This is because the laser has more stringent materials and processing requirements than a photodetector.
- First,the laser structure is nearly 4μm high,which makes the processing steps for integration with an incompatible heterostructure for the electronic device very difficult.
- Second, the optical cavity in edge-emitting laser needs to be defined by two end mirrors. Third, electrical and optical confinement needs to be achieved in the lateral dimension. Finally, the operation of the laser necessitates efficient heat sinking of the whole chip.
- In spite of these disadvantages it is worthwhile to integrate the component devices to ensure a higher modulation bandwidth.
- An OEIC transmitter using the same heterostructure for the laser and the driver transistor is shown in fig.

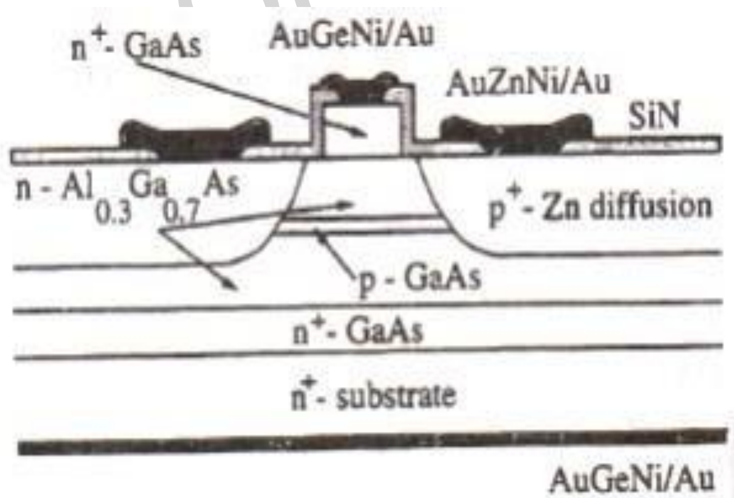
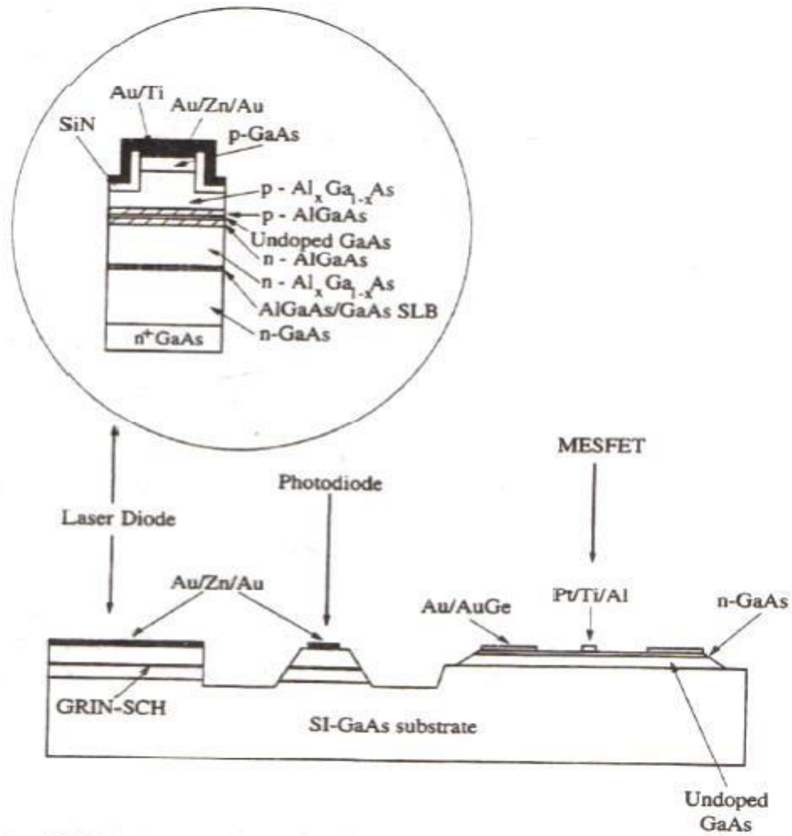


Fig:Schematic cross-sectional diagram of double hetrojunction bipolar transistor which also function as a transverse-injection laser.

- Early, transmitter circuits consisted of a single edge-emitting laser, whose facet was created by cleaving, integrated with a single transistor.

- More recently, laser facets are formed on-chip by microcleaving or by using dry-etching techniques such as ion beam etching.



- The circuit also contains a photodiode for monitoring the laser output power. The laser is a SQW GRIN-SCH device.

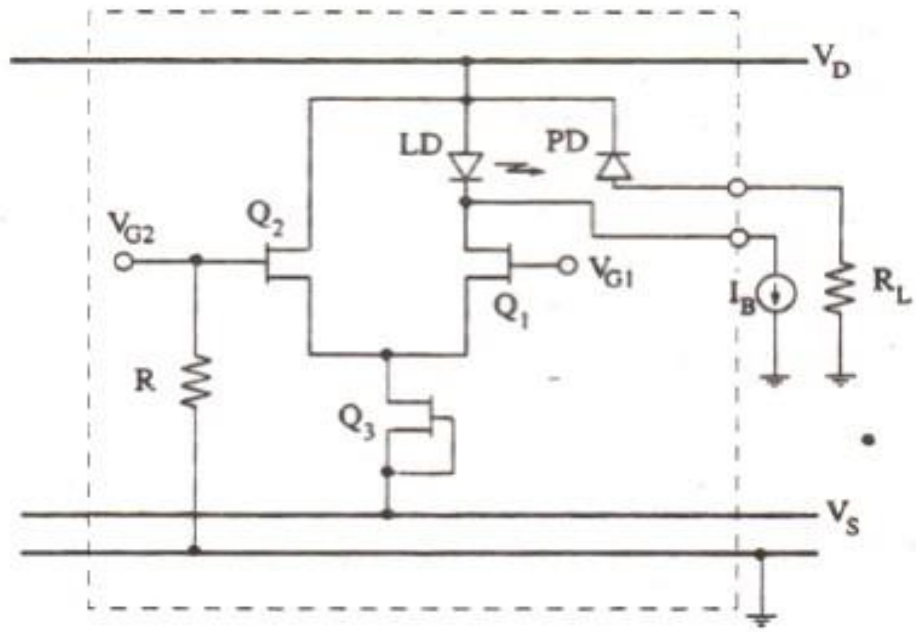


Fig:Circuit diagram of single channel laser-MESFET transmitter.

- The figure 12.22 shows the corresponding equivalent circuit, which includes three FETs and a 50 ohm input load resistance.
- The identical FETs labeled Q1 and Q2 form a differential amplifier or current source to provides the advantages of common mode rejection and noise reduction. The inputs at the respective gates are VG1 and VG2.
- The FET labeled Q3 acts as a constant current source and provides the drive current.
- The current source IS is a dc source to bias the laser at threshold, remembering that the input at VG1 and VG2 are small-signal modulated signals.
- If the transconductance of the two FETs is gm and the slope in the lasing portion of the light-current characteristics is S the output power, Pout of the laser can be simply expressed as,

$$P_{out} = \frac{g_m S}{2}(V_{G1} - V_{G2})$$

Equivalent circuit of integrated transmitter

- The internal limit to the modulation bandwidth of a laser is set by the relaxation oscillation frequency, f_r.
- The modulation bandwidth can be increased by a large photon density in the cavity and a short photons lifetime.
- a laser can be expressed as,

$$\square_{\square} = \square_{\square\square} - \square_{\square\square\square}$$

$$= \square_{\square}\left(\frac{h\,\square}{\square} + \square_{\square}\,\square_{\square}\right) - \frac{h\,\square}{\square}\left(\square_{\square} - \square_{\square h}\right)\eta_{\square}$$

- Here $\eta_{□}$ is the power efficiency, □$_{□}$ is the drive current and □$_{□}$ series resistance in the circuit.
- It is clear that the power dissipation can be kept small, even for a large drive current, if the series resistance and threshold current are small and $\eta_{□}$ is large.
- Noise sources, due to the shot noise of electrons and photons, are also incorporated in this equivalent circuit. However, in practice, the combined impedance of this RLC circuit is smaller than those of parasitic circuit element.
- The extrinsic limit to the internal modulation frequency is set by these parasitic element.
- The most important parasitic element are the series resistance of the diode, R_s, the bondwire induction L_b, and the parasitic capacitance C_p between the bonding pad and ground plane.
- This capacitance is drastically reduced by fabricating the laser diode on a semi-insulating substrate.
- The equivalent circuit of a laser monolithically integrated with a FET.

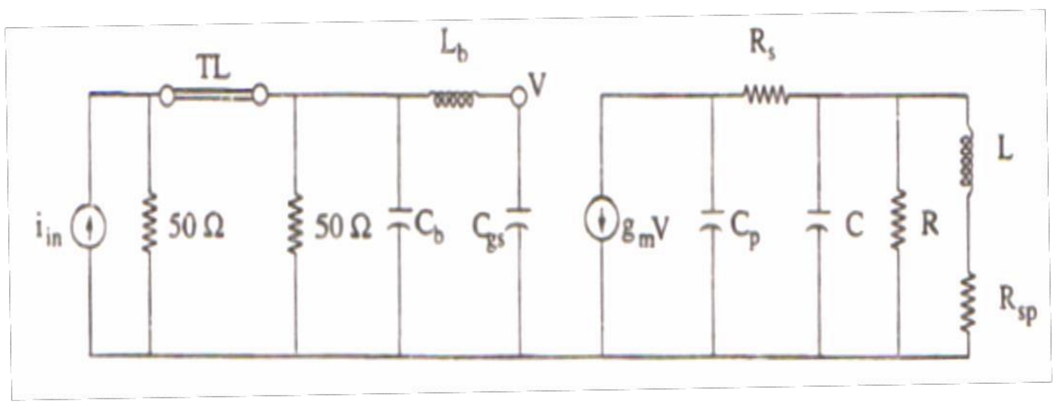
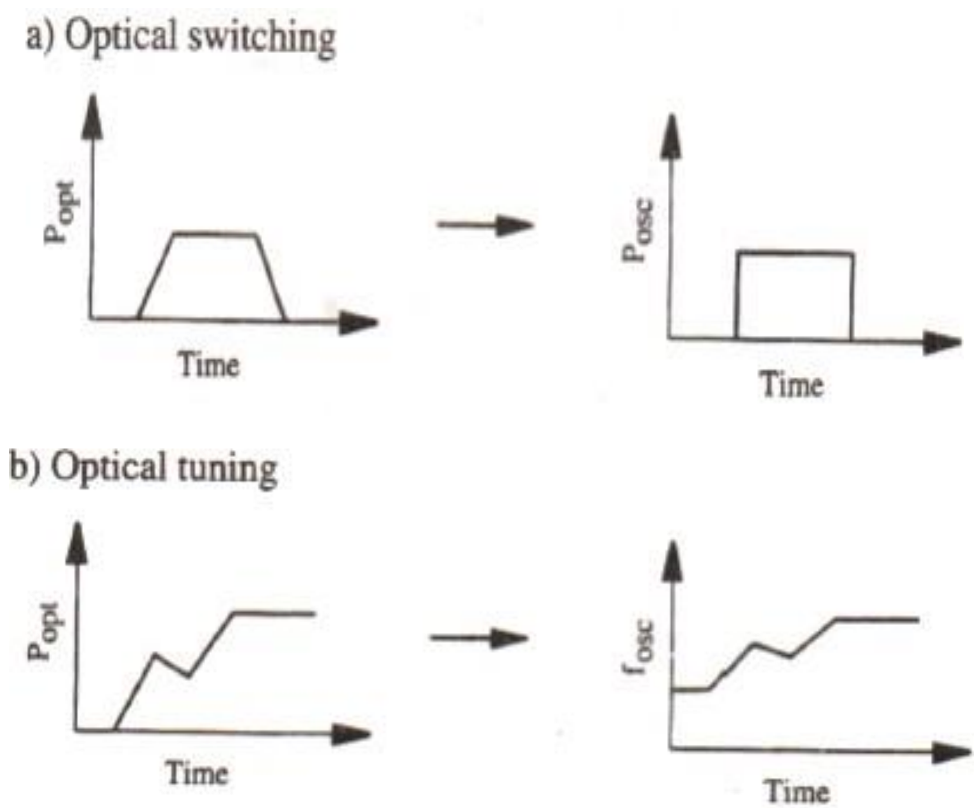


Fig:Equivalent circuit of a junction laser monolithically integrated with a FET drive

Optical control of microwave oscillators

- The photoelectronic phased array antenna system is an example of the application of optical of high-speed electronic circuits.
- The use of optical signal to control high speed electronic circuits is advantages due to the wide bandwidth of the optical control signals and their inherent isolation from radio frequency signals.

- Optical signals can be routed via lightweight fibers or monolithically integrated optical waveguide without affecting signals transmitted on microwave waveguides.
- Microwave-optical links also allow *remote control of antennas.*
- This scheme can become extremely useful in cellular telephone transmission or even cable television where a transmitting antenna is located in remote or inconvenient locations.
- The optical control of microwave oscillators can be realized in one or more of three basic forms: optical switching, optical tuning, and optical injection locking.



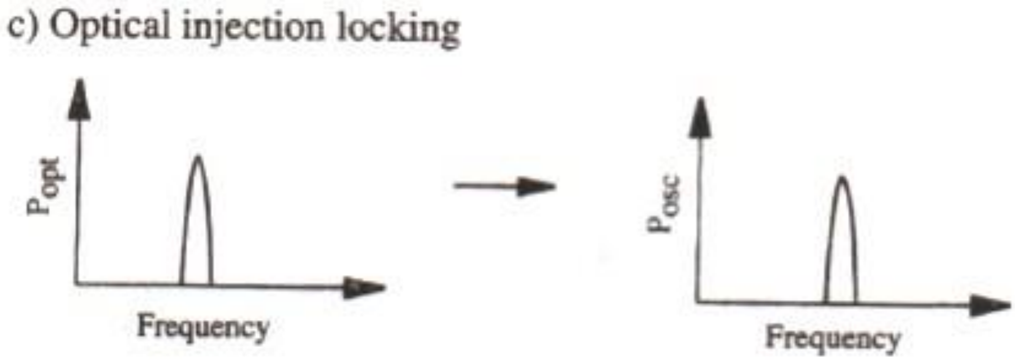


Fig : Optical control of microwave oscillators. a) optical switching b) optical tuning c) optical injection locking.

- With optical switching, the intensity of the input light controls the output power of the oscillator primarily applied in a non-linear fashion for turning on and off the controlled oscillator.
- With optical tuning, the intensity of the input light controls the output frequency of the oscillator.
- Optical injection locking refers to the use of the high-frequency modulated optical control signal to fix the frequency of a free-running oscillator.When in locking condition, the oscillator will oscillate at the same frequency as the injection locking signal.
- There will be a phase offset Φ between the oscillator's output signal and the injected signals.
- The phase offset varies by ± 90º over the injection locking bandwidth W_{max}.
- The injection locking bandwidth and phase error are given by,

$$W_{max} = \frac{\omega_0}{2Q}\sqrt{\frac{P_{inj}}{P_0}}$$

and $$\phi = \sin^{-1}\left(\frac{\omega_{inj} - \omega_0}{W_{max}}\right)$$

- Where ω_0 is the free running oscillator frequency, ω_{inj} is the injection locking frequency, P_{inj} and P_0 are the injected power and oscillator output power and Q is the quality factor of the oscillator.
- Q provides a measure for loss in the resonant circuit and is defined as,

□ = □ * (□□□□□□□□ □□□□□□□ □□□□□□) / (□□□□□□□ □□□□ / □□□□□□□)

- The tuning and injection locking characteristics of an HBT-based oscillator circuit are depicted in above eqn.

4. Explain the principles and operation of

i) Waveguide Coupler

ii) Waveguide interferometer

iii) Active directional coupler switch

- It should be evident by now that in complex OEICs it would be advantageous to have optical waveguide and other passive or quasi-passive optical components monolithically integrated with the active components: source, detectors, modulators and electronic devices.
- Conceivable one could use optical fibers, but the applications of these would be limited from both the point of view of integration, and that of functionality.
- Guided wave components are required for routing optical signals on a chip and also for the function of directional coupling, filtering, and modulation.
- The study of these devices made with suitable dielectric materials falls in the realm of integrated optics, which has been discussed in detail in several texts.
- In this section, the properties of some simple and essential guided wave components that are important for OEICs are briefly described.

Waveguides and couplers

- A waveguide is a region of dielectric through which lights is propagated, surrounded by dielectric regions or air having a smaller dielectric constant.
- Therefore, to form a guide, it is essential to employ techniques that will effectively and selectively create region of varying refractive index.
- The simplest technique of delineating a guiding region is by introducing free carriers.

- This is because in a semiconductor material with a large density of free carriers the refractive index is lowered from that in pure material due to the negative contribution of the free-carrier plasma to the dielectric constant.
- The lowering of the refractive index due to free carrier is expressed by,

$$\Delta n_f = -\frac{N e^2 \lambda_0^2}{8\pi^2 \epsilon_0 n_r m^* c^2}$$

- Where n_r is the refractive index of the undoped semiconductor at a free-space wave length λ_0.
- This change in refractive index is large enough for light confinement. Based on this principle waveguide can be product either by growth of an undoped epitaxial layer on a highly doped substrate, or by implantation damage.
- In the second scheme, the waveguide-cladding layer interface is not well defined, since the implantation profile is not rectangular, but Gaussian.
- Guiding is also achieved by compositional variation in the vertical direction, such as that by GaAs-AIGaAs heterojunctions, an the index difference and optical confinement in this case are made possible by different bandgaps. Example were seen in the design of edge-emitting LEDs and lasers.

- In the first, the lateral waveguide dimension are delineated by wet-or dry-etching, or a combination of both.
- A dry-etching process such as ion-million or reactive ion etching, which provides control, is followed by wet-etching process, which smoothes the surface. Buried channel wavelength can be created by variety of techniques
- The simplest one conceptually is by regrowth where, for example, a GaAs waveguide is grown and delineated and higher-index AlGaAs confining layer is regrown by LPE or MOCVD.
- It is then mask selectively and the regions adjacent to the guiding region are doped by implantation and annealing or by diffusion.
- Either process converts the ordered MQW or superlattice structure into a disordered random alloy, usually with a lower refractive index, providing lateral optical confinement. The last type of waveguide structure is the strip-loaded guide.The formation of a dielectric or metal stripe on the guiding layer alters the refractive index of the semiconductor underneath it and confines light.

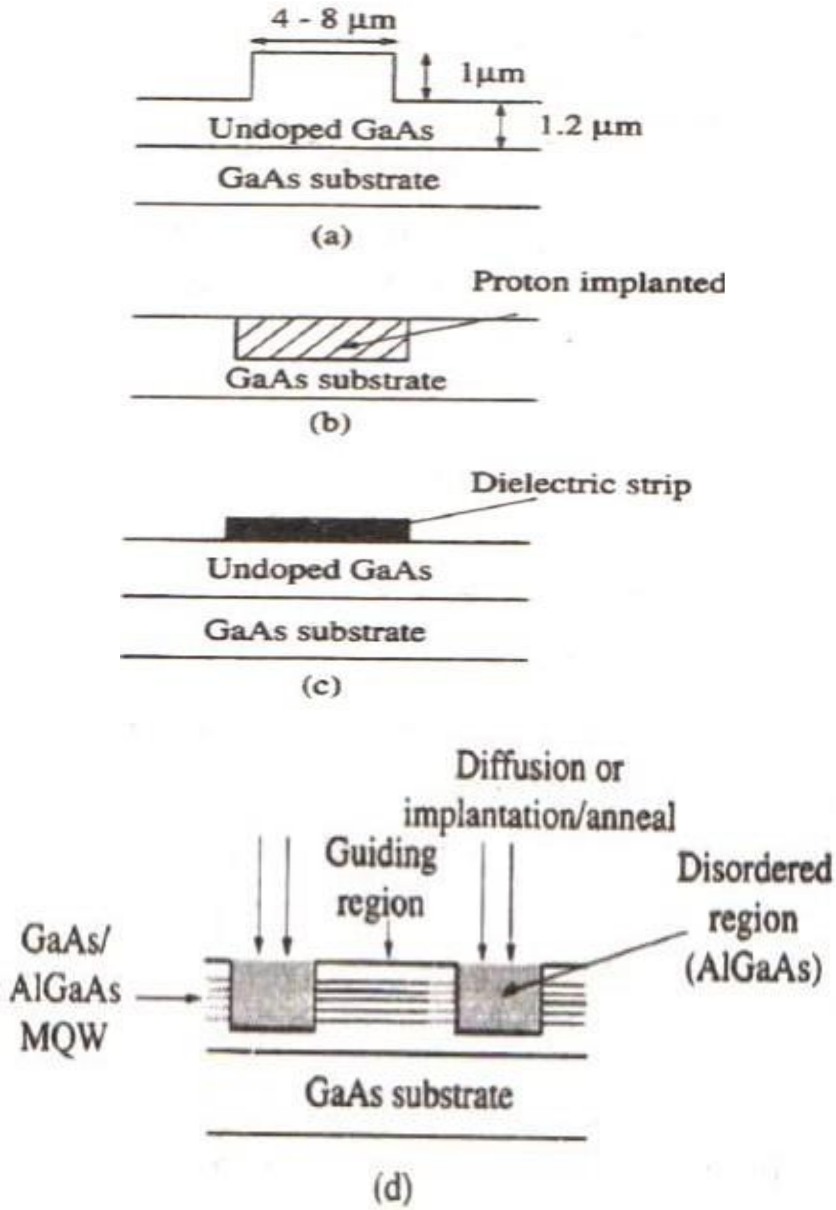


Fig:Techniques for fabrication waveguide. a) rigid b)buried channel by implantation c) strip loaded d) disordered MQW

- The strain fields in the semiconductor, below the stripe, penetrates to a depth of 2-3μm and, therefore, is suitable for guiding.
- These strain fields have been calculated theoretically and observed experimentally.

- For any application it is necessary to ensure that the guides provide low propagation loss.
- If the guide are made of high-quality, defect-free epitaxial layer, then the major source of loss are surface scattering and absorption.
- Therefore, etching and formation techniques become critical in the fabrication of low-loss waveguide..
- The value of γ, which determines the insertion loss of a waveguide, is mainly determine by free-carrier absorption and scattering at bulk and surface imperfections.
- Therefore, material quality and processing become important in determining γ. Transmission of optical power in the guide is given by,

$$P(z) = P(0)e^{-\gamma z}$$

- The directional coupler consists of two parallel waveguide between which the transfer of optical energy occurs due to the overlapping of waveguide modes.
- This energy exchange requires that the light propagation in both guides have nearly the same velocity and propagation vector.
- If these parameters in the two channels are exactly identical, then the power propagating in the two guides is given by,

$$P_1(z) = P_0\cos^2(kz)e^{-\gamma z}$$
$$P_2(z) = P_0\sin^2(kz)e^{-\gamma z}$$

- Here z is the direction of propagation and k is the coupling constant given by

$$k = \frac{2\beta_y^2 b e^{-bd}}{\beta_z w(\beta_y^2 + b^2)}$$

- where b is called the extinction coefficient, d is the separation between the guides, w is the width of each guide, and β_z and β_y are the mode propagation constants in the propagation and transverse direction, respectively.
- The coupling length of a directional coupler, l_c, defined as the length at which total transfer of power takes place, is given by

$$l_c = \left(m + \frac{1}{2}\right)\frac{\pi}{k}, \qquad m = 0,1,2\ldots$$

- It should be remembered that in real couplers the two guides may not be identical, and the propagation constants may differ by a small amount $\Delta\beta_z$.
- The coupling constant is then given by

$$\kappa_c^2 = \kappa^2 + \left(\frac{\Delta\beta_z}{2}\right)^2$$

- The photomicrograph of a straight ridge waveguide dual-channel coupler is shown in

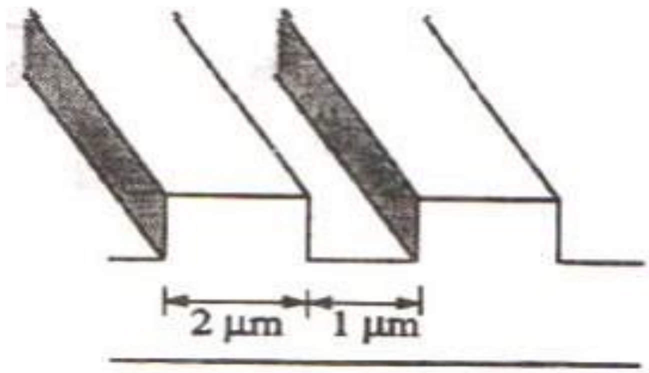


Fig:Photomicrograph of a GaAs dual channel single mode rigid waveguide coupler with w=2μm and d=1.5 μm.

- For the bends to be nearly loss-free the radius of curvature at the bend must be much larger then λ, the wavelength of the light propagating in the guide.

- Finally, there are various forms of leaky guides and couplers where the index of the coupling region is so adjusted that most of the radiation leaks out into an optical detector or other such device.
- Other passive components that are required in integrated optics are lenses, mirrors, and gratings, for the purposes of beam focusing, reflection, and filtering.
- Branching networks divide optical power among two or more outputs or combine power from two are more inputs.
- An important commonly used branching networks is the waveguide γ-structure, shown in fig, which can be used as a symmetric power divider or combiner.
- The mode at various points of propagation are also illustrated for the symmetric combiner in fig.

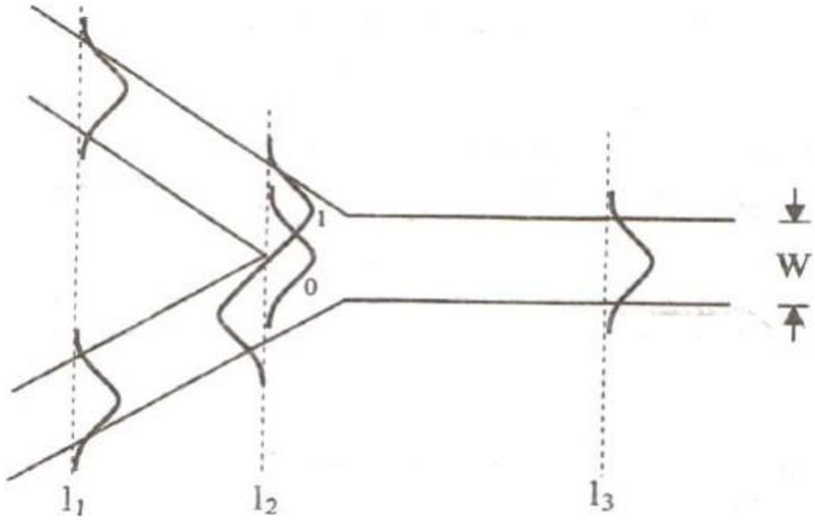


Fig:Symmetric waveguide Y-combiner.

- At point l_1, the two arms are uncoupled and behave as independent single mode guides, supporting the lowest order mode.
- Near the taper, the structure transition from a single waveguide of width 2w (at l_2) to a waveguide of width w. At l_2, therefore, both the symmetric and antisymmetric modes are supported.
- As these propagated towards point l_3 the antisymmetric mode is cut off and its energy is radiated into the substrate. At l_3, single mode characteristics are again restored.
-
- Foe equal inputs intensities in the two arms, the Y-combiner essentially behaves like the 3-db direction coupler.
- More complex various of directional couplers and Y-structures are shown in fig.

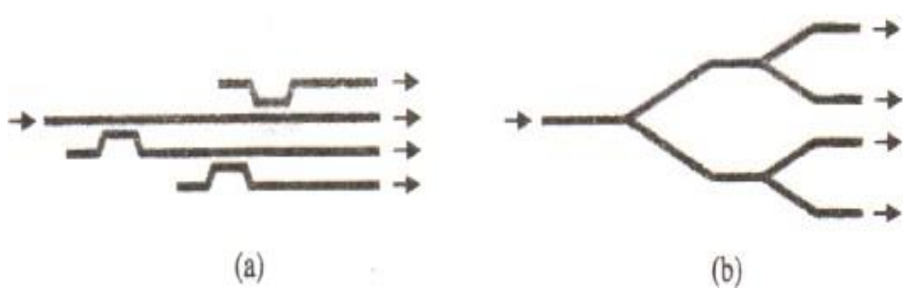


Fig:Power splitter based on directional couplers and Y-structure.

Active guided wave devices

(or)

Describe about the guided wave Mach-Zehnder interferometer.

- The integrated optical components describes in the previous section are essentially passive, and are used for routing optical signals.
- There are also quasi-passive or active guided wave components that can be integrated in OEICs with active optoelectronic devices.
- Example of active guided wave devices that we have already learned about are the laser and the electro-optic modulator.
- There are other active guided wave devices that are used as modulators, interferometers, and filters.
- These have been traditionally designed with materials with a large electro-optic coefficient, such as lithium niobate.
- A simple guided-wave modulations/switching devices based on the electro-optic effects is the *mach-zehnder interferometer*, shown in figure.

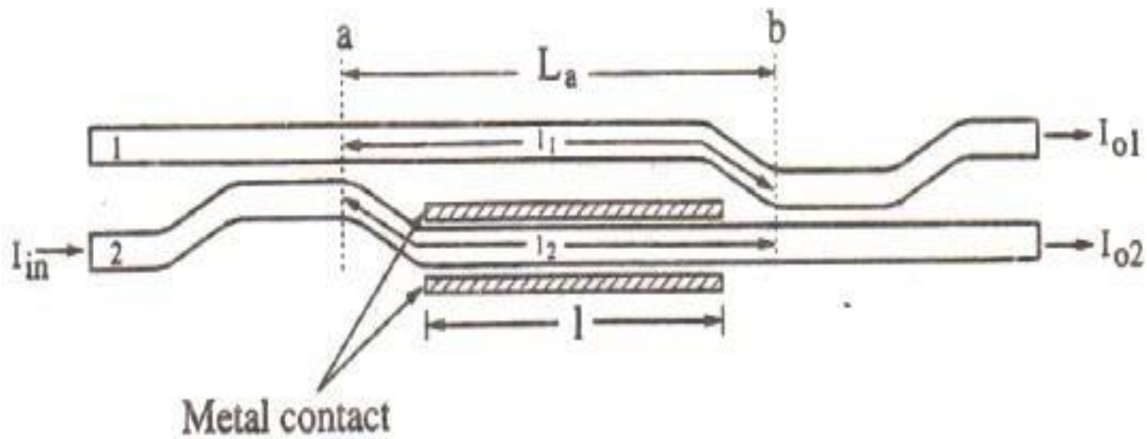


Fig: Schematic of guided wave Mach-Zehnder interferometer with input and output 3-dB couplers.

- The incoming optical beam is split equally between the two branches of the input coupler and then recombined at the coupler at the other end.
- Care must be taken in material growth and processing such that the tapers are very gradual to reduce bend losses, and that there is spatial uniformity.

- It is assumed that the electric field of the input to one arm has unity amplitude and zero phase.
- Then according to coupled-mode theory, the field at point a are given by,

$$E_{1a} = 0 + j\sin\frac{\pi}{4} = \frac{j}{\sqrt{2}}$$

$$E_{2a} = 0 + \cos\frac{\pi}{4} = \frac{1}{\sqrt{2}}$$

- At point b, the field is phased shifted due to propagation over then length L_a and

$$E_{1b} = \frac{j}{\sqrt{2}}\exp\{-j\beta_e l_1\}$$

$$E_{2b} = \frac{1}{\sqrt{2}}\exp\{-j[\beta_e l_2 + \frac{\Delta\beta_e}{\Delta V} V L_a]\}$$

- Therefore, unequal length l_1 and l_2 will introduced a phase difference

$$\Delta\phi_L = \beta_e(l_2 - l_1)$$

- Between E_1 and E_2, while the electro-optic effect introduces an additional phase shift

$$\Delta\phi_{EO} = L_a\frac{\Delta\beta_e}{\Delta V}V = \frac{\pi}{\lambda_0} n^3 r_{33} V$$

- The output coupler recombines the fields E_{1b} and E_{2b} to give the field at output of arm 1 as

$$E_{01} = -\frac{j}{2}\exp(-j\beta_e l_1)[1 + \exp\{-j(\Delta\phi_L + \Delta\phi_{EO})\}]$$

- Taking the square of the magnitude of the field yields the output intensity from arm 1 as

$$I_{01} = \frac{1}{2}[1 + \cos(\Delta\phi_L + \Delta\phi_{EO})]$$

- Similarly, it can be shown that the output from arm 2 is

$$I_{02} = \frac{1}{2}[1 - \cos(\Delta\phi_L + \Delta\phi_{EO})]$$

- If the devices is lossless, then the sum of I_{o1} and I_{o2} is equal to the input intensity regardless of the relative phase shift between arms 1 and 2.
- If $l_1 = l_2$ and no bias is applied, then $I_{01} = 1$ and $I_{O2} = 0$.

- If, on the other hand, the phase shift produced by the application of a bias is π and $\Delta\Phi_t = 0$, then $I_{01} = 0$ and $I_{02} = 1$.
- The modulation index in this case is unity and the corresponding bias is given by

$$\square_{\square} = \frac{\square\square}{\square\square^{3}\,\square^{1}_{\square 0\,\square\square}}$$

- The subscript π denotes a half-wave phase shift and V_π is also called the half-wave voltage.