UNIT-5 - OPTOELECTRONIC INTEGRATED CIRCUITS

Introduction

Optics provides the advantage of large bandwidth parallelism and reconfigurable configurations. But Optics does not provide input-output isolation as electronic devices do and it can be difficult to focus multiple beams in a parallel system. It is therefore logical to couple electronic and photonic devices resulting in optoelectronic integration.

An important aspect of optical communication systems and computing systems is the interconnect medium. (1) The performance of conventional electrical interconnects affected by increase in reactance and reflections due to impedance mismatch at the higher frequencies. (2) Multilevel board technology is developed where chip to chip communication is achieved through via holes in the wafers. But at high frequencies the performance is poor. (3) An alternative solution is optical interconnect medium which can take the form of free space, integrated optical waveguide or optical fibers. (4) Optical interconnects and transmission media provide large bandwidths and high speed data transmission, immunity to mutual interference and crosstalk and freedom from capacitive loading effects. The large bandwidth results in system size reduction, reduced system power

Optoelectronic integrated circuits involve integration of electronic and optical components and optical interconnects. The monolithic integration of electronic and optical devices on the same chip will lead to *high speed, *high sensitivity, *compactness and *reliability all at low cost.

Integration has challenges too.

⇒ device may have different layer structures and it should be of high quality.

⇒ Compatability

⇒ Impedence matching between devices & devices and interconnects.

Need for integration: Hybrid and Monolithic Integration.

Integration of electronic and optoelectronic devices arisis from the following facts

⇒ Speed and bandwidth

→ functionality and multifunction capabilities

⇒ Compactness

⇒ low parasitics

Two forms of opto Electronic Integration -

* Hybrid
* Monolithic.

Hybrid: discrete devices or separate functional blocks or chips are connected using electronic or optical interconnects.

⇒ Adv : * possibility of using high performance discrete devices as components.

⇒ Disadv * lack of compactness
* enhance parasitic effects in interconnects
* bonding & lead wires.

Monolithic Integration : All active and passive component are fabricated on the same chips.

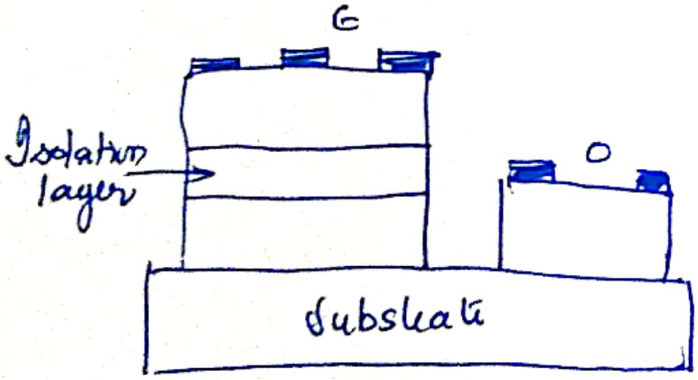
Disadv
The heterostructures and processing steps of the different components of a OEIC can be different and is a real challenge.

Adv * Reduced size
* Reduction of parasitics
* higher circuit speed and Bandwidth.

Monolithic integration can be achieved in 2 Configuration
⇒ Vertical
⇒ horizontal.

Vertical scheme : Both electronic & optical device structures are epitaxially grown sequentially with an isolation layer in between.

⇒ Disadv : lack of planarity

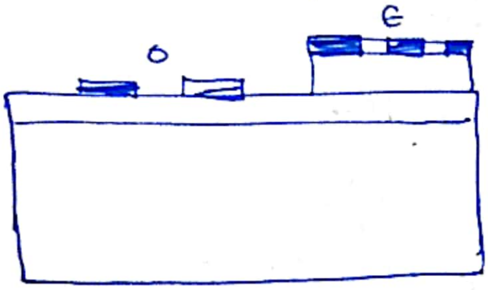


⇒ Vertical Scheme

The horizontal scheme is classified into

→ Planar compatible
→ planar regrown

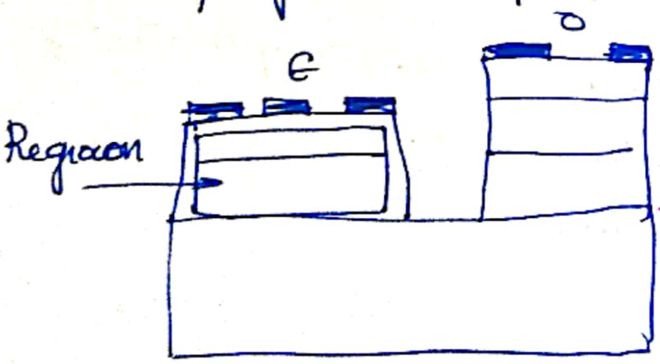
Planar Compatible



planar compatible → both devices are made from the same hetero structure

planar compatible.

Planar Scheme: One of the devices is selectively regrown after growth of the first device. Although this technique provides a large freedom in the choice of device heterostructures, the regrown interface can have a large density of traps and other electrically active defects that can affect the performance of the regrown device.



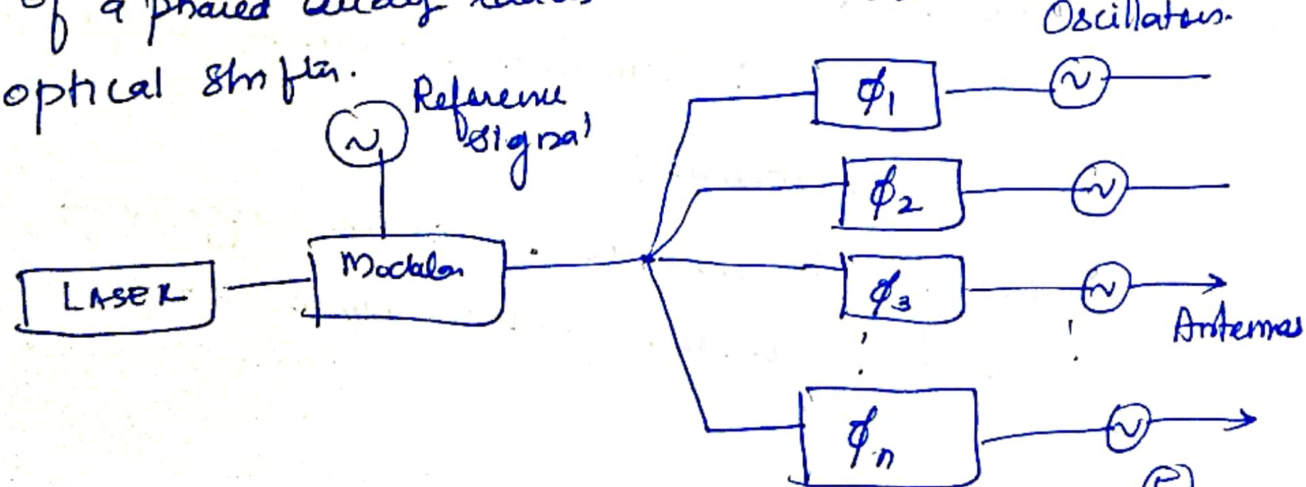
→ Planar scheme using regrowth

Applications of Optoelectronic Integrated Circuits.

1. Telecommunications: The objective of OEIC is to bring systems to the home and individual subscribers in the form of telephone links and broadcast cable TV. This implies that optoelectronic technologies to be extended to the subscriber loop. These systems will necessitate the development of lasers with frequency control and tunability and wavelength selective detectors and receivers. The data transmission rate of several gigabits/sec will be attained in these circuits and systems.

2. RADAR Applications: The schematic of a microwave or millimeter wave phased array radar systems is shown in fig.

A phase shifted and modulated optical signal is injection locked to a free running microwave or millimeter wave oscillators which form one element of a phased array radar. It is efficient to use optical shifter.



The modulated and phase shifted signal is coupled by injection looking to a microwave oscillator, which forms a single element of the phased array. Each element of the phased array consists of source, modulator, phaseshifter a waveguide and an oscillator. These devices can be combined by hybrid integration, but for the compactness and ruggedness, it is desirable to realize the array by monolithic integration. Such radars will be used on the ground or aircrafts and in satellites.

Materials and Processing for OEICs.

The choice of materials used to synthesize them for OEICs are based on following requirements

→ Operating wavelength

→ lattice matching constraints.

→ Choice of devices

→ The local area networks, computer interconnect & optical information processing depends on GaAs materials.

→ InP based materials will be applicable to OEICs for long distance fiber communication.

⇒ InP based materials will be more applicable to OEICS for long distance communication.

⇒ Another method is heteroepitaxy or use of mismatched materials that include III – V or II – VI compounds materials that include III-V or II-VI Compounds and InP based on similar semiconductor or GaAs and InP based Compounds on Si

The fabrication of lower dimensional quantum confinement structures such as quantum wires and quantum boxes will involve epitaxy followed by nanolithograph. The desirable feature sizes are 100-400 A° which can be achieved by electron beam lithography with very advanced electron optics and masked ion beam lithography.

Fabrication of optical devices on chips will require advanced dry etching capabilities, particularly for etching of mirrors and integrated optical components. planar circuits can be fabricated using regrowth. Conventional regrowth produces an interface with a large density of defects which can prove to be detrimental to the operation of the regrown device or whole circuit..

An alternate possibility is insitu etching, patterning and processing followed by growth.

Integrated Transmitters and Receivers.

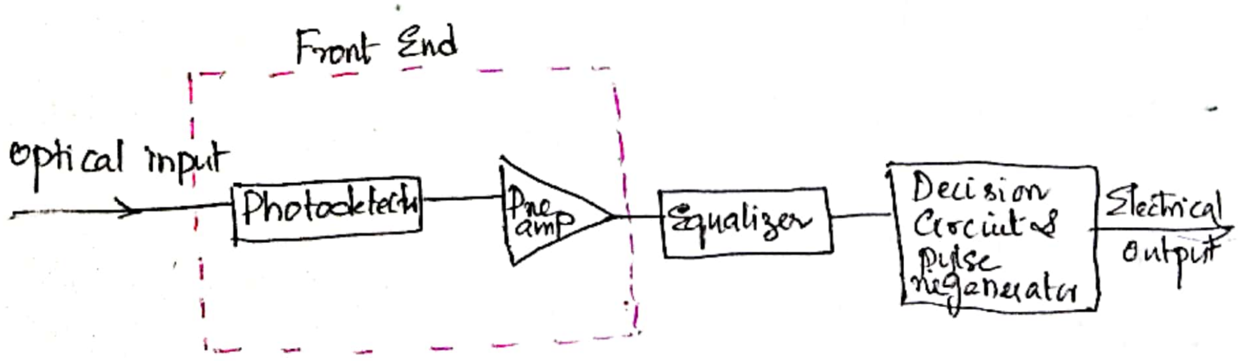
Front End Photoreceivers

In the design of a optical fiber communication system the key element is the receiver. The basic purpose of the receiver is to detect the incident light and convert it into an electrical signal containing the information impressed on the light at the transmitting end.

The performance characteristics of a photoreceiver are Operating bandwidth and sensitivity and dynamic range. Sensitivity plays a vital role in the number of repeaters in long range communication system.

The receiver sensitivity is defined as the minimum amount of optical power level needed at the receiver input so that SNR (signal to noise ratio) is greater than a given value.

Front end photoreceiver Block diagram.



⇒ The first 2 blocks consists of photodetector and low noise amplifier and these two are considered as front end of the photoreceiver.

⇒ The rest of the circuit perform

⇒ * Equalization → Compensate for the average range of expected channel amplitude & delay

⇒ * pulse Shaping

⇒ * gain Control functions.

⇒ Multiple stages of amplifications are included to increase the gain of the Signal.

⇒ The overall performance of the circuit is dictated by front end, which consists of a photodiode and a single stage amplifier.

⇒ The desirable features of the photodetector are

⇒ * high quantam Efficiency

⇒ * low Capacitance

⇒ * Small response time

⇒ * low dark current.

⇒ Commonly used photodiodes are PIN photodiodes, Avalanche photodiode and Metal-Semiconductor Metal photodetector.

⇒ For the Preamplifier It is important to have

⇒ * high output gain

⇒ * Minimum input Capacitance

⇒ * minimum parasitic resistance

⇒ * Minimum leakage current

FETs and BJTs can be used as Preamplifier.

Figure illustrates the monolithic integration of an $In_{0.53}Ga_{0.47}As$ photodiode with a $In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$ modulation doped FET by regrowth on InP

The MODFET consists of a layer of undoped low band gap material forming a heterojunction with a highly doped high band gap material. Due to the difference in the electron affinities of the two layers, electrons are transferred from the high band gap material to the low band gap material to form a quasi two dimensional electron gas. The main advantage of such a structure is that the electrons are separated from their parent donors and Coulombic scattering is greatly reduced. This results in higher carrier mobility and drift velocity. A high bandgap undoped spacer layer is added between the highly doped high band gap layer and the undoped low band gap layer to separate the electrons from their parent donors.

MODFET has an advantage in the proximity of the channel to the gate.

The noise figure and noise temperature exhibited by MODFETs are lower than other FETs.

The InGaAs/InAlAs/InP is superior candidate compared to GaAs/AlGaAs system for MODFET which allows increased confinement of the carriers in the quasi 2 dimensional electron gas and higher mobility and peak velocity in the InGaAs layer.

Selection of the integration scheme for the photodetector and low noise amplifier is important.

Three types of integration are

- ⇒ low-input impedence design
- ⇒ high input impedence design
- ⇒ transimpedence design.

The high input impedence design requires equalization circuit to extend the value of BW

The transimpedence design is very popular as no equalization is required.

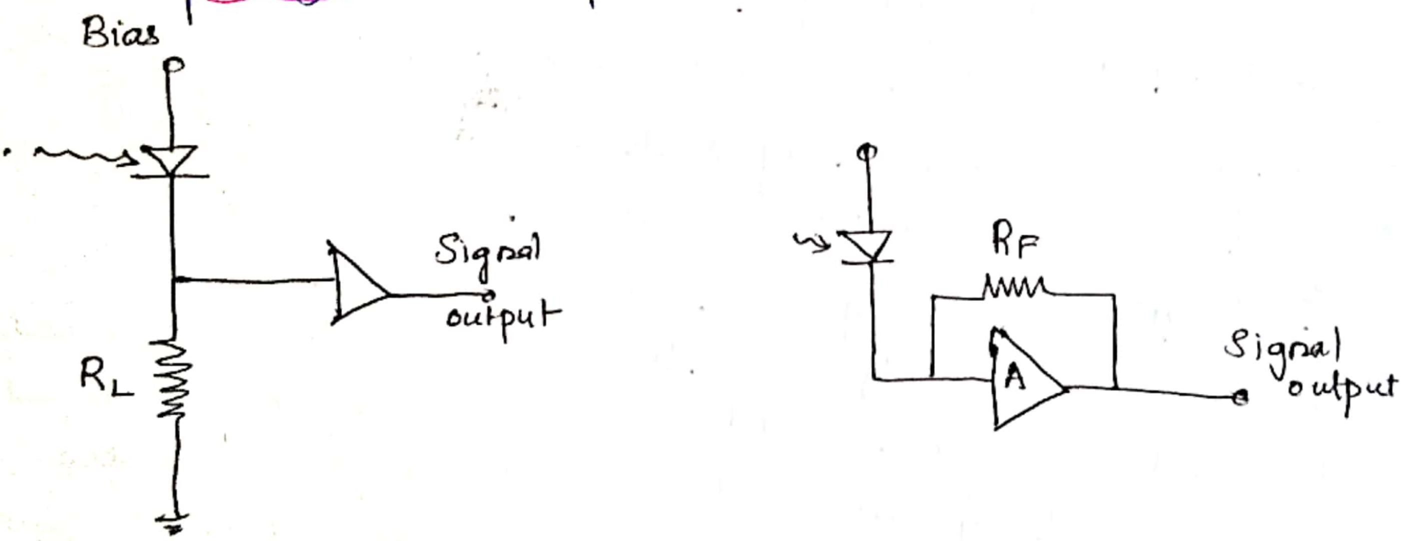
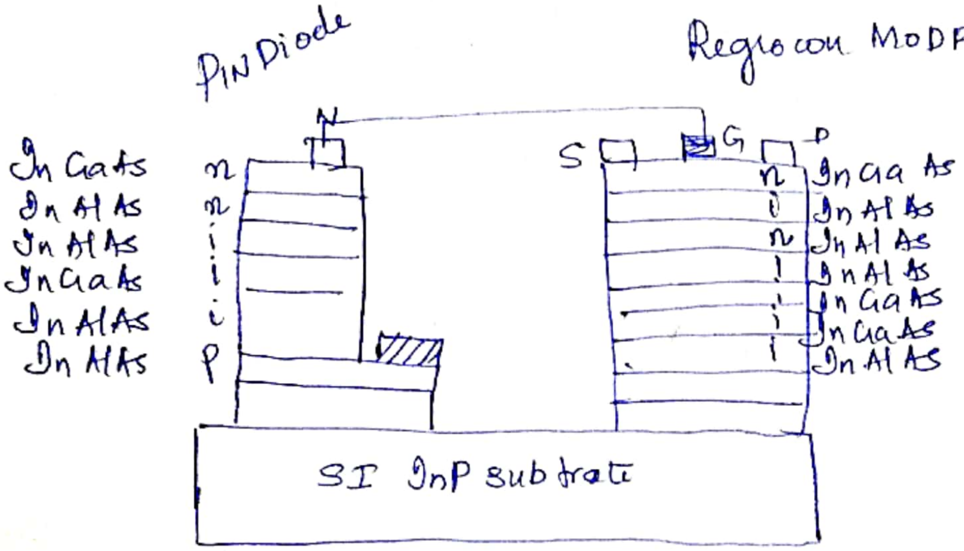


Photo receiver circuit diagrams for low, high and transimpedence designs.

Improvement in device performance can be made by increasing the In composition in the $In_x Ga_{1-x} As$ channel layer. This result in even higher mobilities and peak velocities. The PIN diode is grown in the first epitaxial step and MODFET is grown.



⟹ **Photo receiver Noise**

In a photo receiver 2 important parameters are Noise & Bandwidth.

To optimize performance in terms of these parameters, materials and device design must be carefully tailored.

The front-end noise current of FET can be expressed as

$$i_N^2 = 2q I_{ph} I_{p1} B + \frac{4K_B T}{R_L} I_{p2} B + 2q(I_g + I_D) I_{p2} B$$

$$+ \frac{4K_B T \Theta_m (2\pi C_T)^2 f_c I_f B^2}{g_m} + \frac{4K_B T \Theta_m}{g_m} (2\pi C_T)^2 I_{p3} B^3 + \frac{4K_B T \Theta_m (2\pi C_T)^2}{g_m} \left(\sum_{q=1}^{m} \frac{I_q A_T}{C_T}\right) B^2$$

→ I term → Signal noise associated with photo current I_{pR}

→ II term → Thermal noise due to load resistance

→ III term → Shot noise due to leakage current in the gate. I_g and dark current in the photodiode I_D

→ IV term → noise in FET device f_c → Center frequence

→ V term → noise associated with channel conductance of FET

→ VI term → noise associated with buffer regions or trap in channel.

→ I_{p1}, I_{p2}, I_{p3} — Personick integral

→ I_f, I_x — noise integral, trap integral

→ Θ_m → material related parameter

→ g_m → trans Conductance

→ τ_e → trap Emission time constant

→ A_e → Constant based on trap density and transistor parameters

To minimize noise it is required to have

⇒ low gate leakage current

⇒ low dark current

⇒ low total input capacitance

⇒ high trans conductance

C_T → total capacitance due to

$$\boxed{C_T = C_{gs} + C_j + C_p \quad — (2)}$$

C_{gs} — gate source capacitance

C_j PIN diode capacitance

C_p → parasitic capacitance

At high frequencies, taking the prominent noise source eqn (1) becomes

$$\boxed{\overline{i_N}^2 = \left[4K_BT\left(\frac{I_{p2}}{R_L} + 4\pi^2 \Theta_m B^2 I_{p3} \frac{C_T^3}{g_m}\right)B\right]}$$

(a) The input noise at high frequency is dependent on C_T^2/g_m

For low noise performance C_T should be small & g_m should be large

$$\boxed{C_T = C_{gs} + C_j + C_p}$$

C_j — junction capacitance
C_p — parasitic capacitance } can be kept small.

Both C_{gs} and g_m are related to gate length with decrease of L_g $C_{gs}\downarrow$ and $g_m\uparrow$.

∴ The condition for minimum photoreceiver noise $\boxed{C_{gs} = C_j + C_p}$

(b) The cut off frequency of FET can be increased to minimize the overall photoreceiver noise.

$$\boxed{f_T = \frac{g_m}{2\pi C_{gs}}}$$

The equation for the signal power to noise power (SNR)

$$\boxed{\frac{S}{N} = \frac{m^2 I_0}{2\sqrt{\overline{i_N^2}}}}$$

$I_0 \rightarrow$ dc photocurrent level from the CW light signal P_0

Photoreceiver Bandwidth Considerations

The bandwidth of the receiver are is determined by the transmit time of the carriers in the diode and RC time constant of the circuit.

The frequency response is limited by transit time

The frequency response of a receiver is given by

$$\boxed{J_0(\omega) = J(\omega) H(\omega)}$$

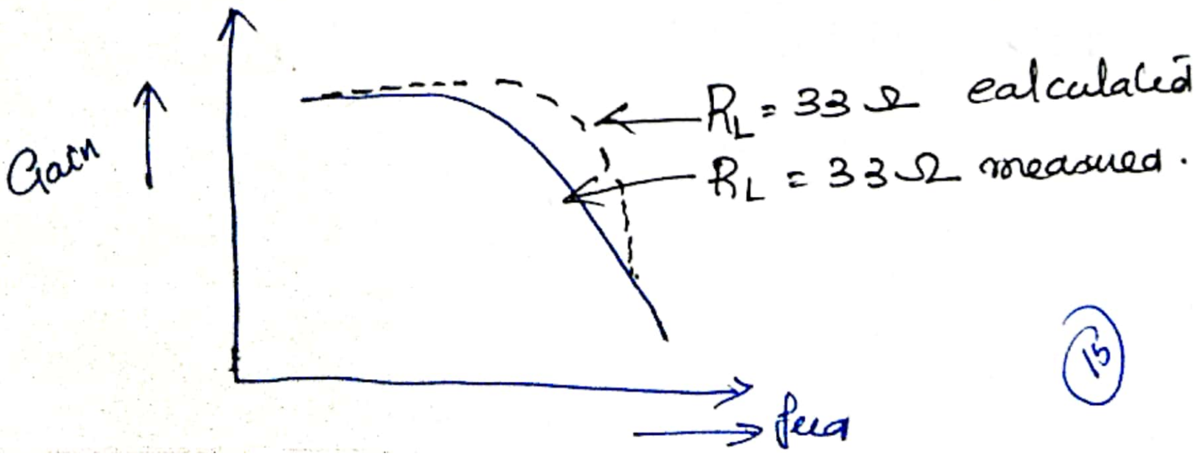
where $J(\omega)$ is the frequency response of PIN photodiode

$H(\omega) \rightarrow$ Electrical frequence response and it depends on

$\Rightarrow$ diode capacitance
$\Rightarrow$ diode resistance

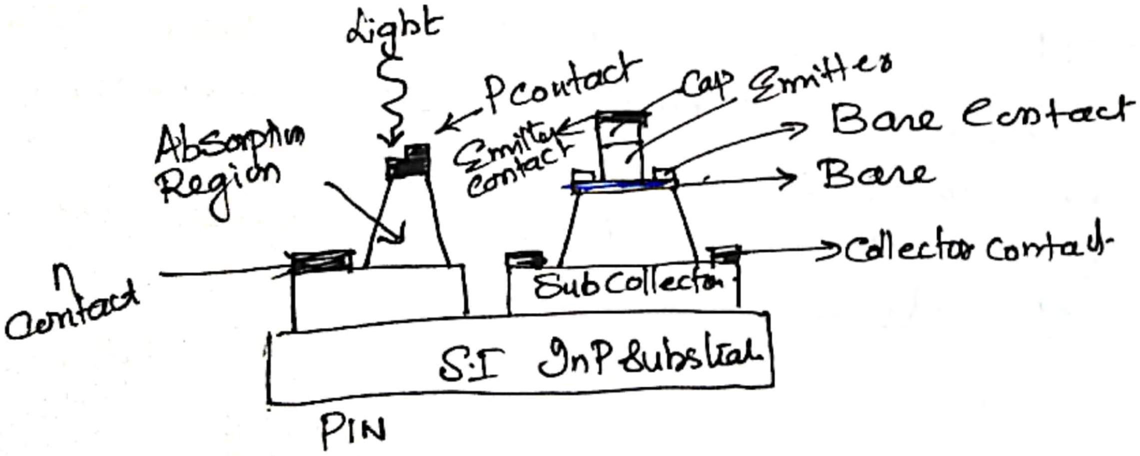
The thickness of the absorption and transist layer of the photodiode should be optimally designed to get good frequency response.

However there is always a tradeoff between bandwidth and noise in the selection of load resistor.



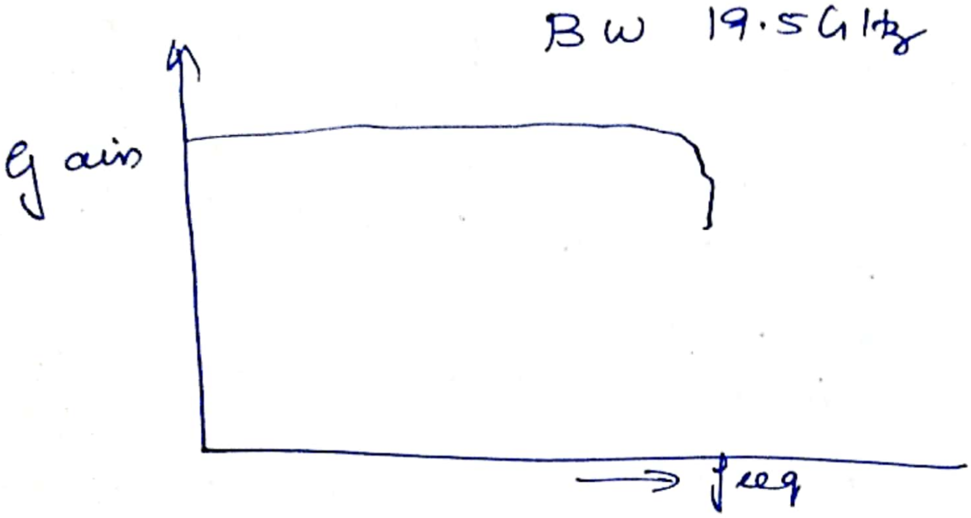
The PIN HBT Photoreceivers

The integration of a PIN HBT photoreceiver involves a single step epitaxy of the HBT from which the PIN modulator was selectively defined by processing. The collector region of the HBT also serves as the i-region of the diode. The two devices are monolithically integrated with the addition of required passive elements. Here to realize a front end photoreceiver the PIN diode serves as the front end photodetector and HBT is the preamplifier. Another advantage of PIN HBT combination is that the sensitivity of HBT based photoreceivers is better than that of FET based photoreceiver. This is because the sensitivity of a FET photoreceiver $\propto B^3$ where as that of HBT is proportional to B^2 [where B is the Bit Error rate]



epitaxial heterostructure

A technique to Enhance photoreceiver response at high frequencies is inductive peaking where an inductor is placed in Series with photodiode at the input of the diode. Typical values of inductors is 2 - 5 nH



Frequency response of a monolithic PIN HBT photoreceiver

OEIC Transmitters.

The integration of a high power LED or a laser with associated Electronics is more Complicated than the fabrication of a photoreceiver and it is due to the fact that laser has more stringent materials and processing requirements than a photodetector.

OEIC Transmitters

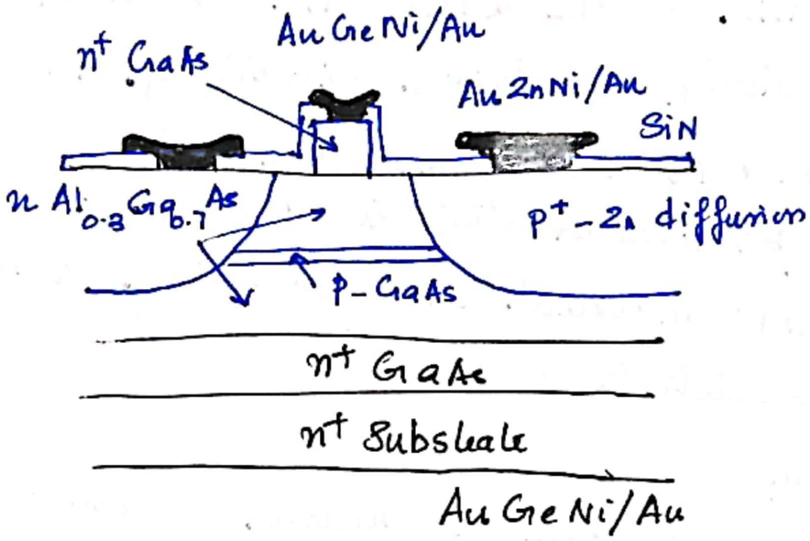
A transmitter circuit includes a light source such as a high power LED or a LASER. Integration of the laser with associated electronics particularly the driver circuitary in the form of a transistor is more complicated than the fabrication of a photoreceiver. This is because LASER has more stringent materials and processing requirements than a photodetector.

Reasons

1. laser structure is nearly 4 μm high, which makes the processing steps for integration with an incompatible heterostructure for the electronic device very difficult.
2. The optical cavity in an edge emitting lasers needs to be defined by two end mirrors.
3. Electrical and optical confinement needs to be achieved in the lateral dimension.
4. Operation of the laser necessitates efficient heat-sinking of the whole chip.

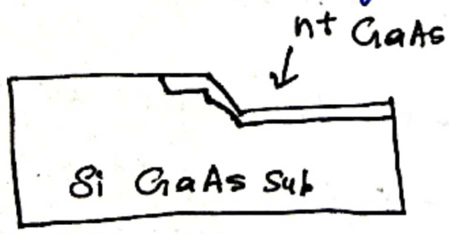
With all the above disadvantages it is worth while to integrate the component devices to ensure a higher modulation bandwidth. The latter is ensured by the close proximity of the devices and the associated reduction of parasitics from the devices and interconnects.

An OEIC transmitter using the same hetero structure for the laser and the driver transistor. However the optimization of performance both devices is better if separate optimized structures are used.



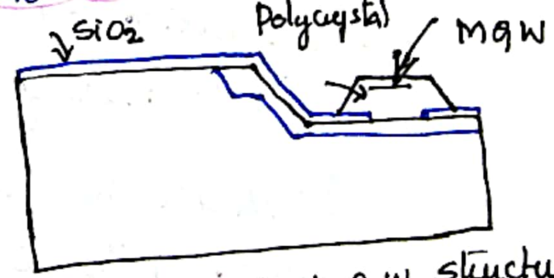
Cross sectional diagram of a double heterojunction bipolar transistor which also function as a transverse junction injection Laser.

Early transmitter circuits consisted of a single edge emitting laser, whose facet was created by cleaning integrated with a single transistor MESFET as shown in fig. The cross section of a laser MESFET



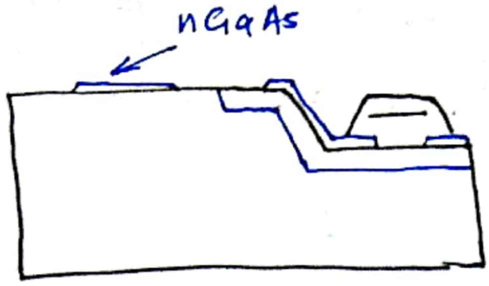
Groove etching growth of Contact layer

1



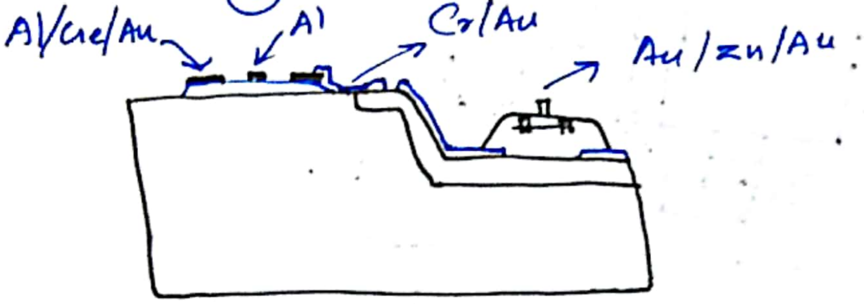
Growth of MQW structure

2



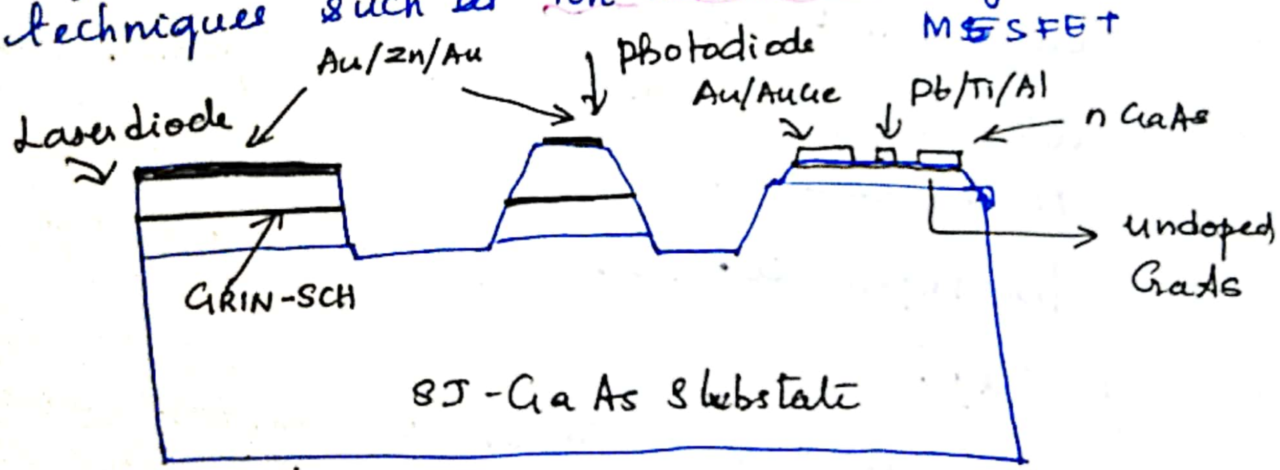
Growth of FET layer.

3



Ridge formation, Contact formation.

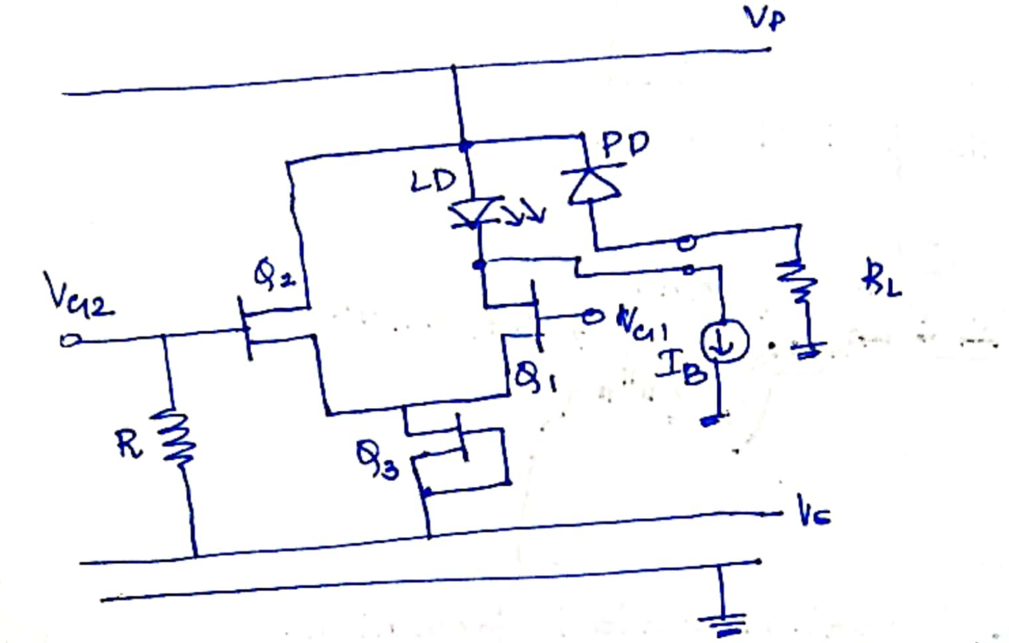
More Recently, LASER facets are formed on chip by microcleaving or by using dry etching techniques such as ion beam etching.



⇒ The circuit contains a photodiode for monitoring the laser output power.

⇒ Laser is a SQW GRIN SCH device.

The circuit diagram of a Single Channel LASER MESFET transmitter is shown below



The equivalent circuit includes three FETs and 50 Ω load resistance R_L

The identical FETS labelled Q_1 and Q_2 form a differential amplifier or current source which is used for common mode rejection and noise reduction.

The inputs at the respective Gates are V_{G1} and V_{G2}.

The FET Q_3 acts as a constant current source and provides the drive current. The current source I_B is a dc source to bias the laser at threshold, the inputs at V_{G1} and V_{G2} are small signal modulated signals. The photodiode PD acts as a monitoring device. If the transconductance of the two FETs is g_m and the slope in the lasing portion of the light current characteristic is 'S', the output power P_{out} of the laser

$$\boxed{P_{out} = \frac{g_m S}{2}(V_{a1} - V_{a2})}$$

The detector will be almost transparent to the laser output since the emission of a laser occur at energies slightly below the absorption edge of the material.

Equivalent Circuit of Integrated Transmitter.

The internal limit to the modulation bandwidth of a laser is set by relaxation oscillation frequency f_r. The modulation bandwidth can be increased by a large photon density in the cavity and a short photon life time.

The modulation bandwidth is achieved by driving the laser well above threshold which is a critical issue due to heat dissipation.

The power dissipation in a laser

$$\boxed{\begin{aligned} P_d &= P_{in} - P_{out} \\ &= I_B\left(\frac{h\nu}{q} + I_B R_s\right) - \frac{h\nu}{q}(I_B - I_{th})\eta_p \end{aligned}}$$

$\Rightarrow$ $\eta_p \rightarrow$ power efficiency

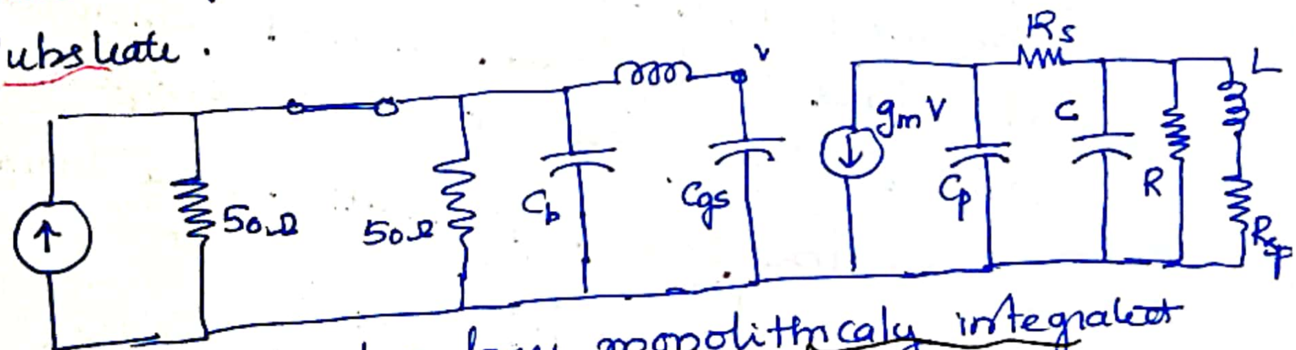
$\Rightarrow$ $I_B \rightarrow$ bias current

$\Rightarrow$ $R_s \rightarrow$ series resistance in the circuit

Power dissipation can be kept small for a large drive current if the series resistance and threshold current are small and C_p is large.

The intrinsic model of a laser diode can be represented by an RLC circuit that has a resonant frequency $\boxed{f = \frac{1}{2\pi\sqrt{LC}}}$

Noise sources due to the shot noise of electrons and photons are incorporated. The combined impedance of this RLC circuit is smaller than those of parasitic circuit elements. The extrinsic limit to the internal modulation frequency is set by these parasitic elements. The most important parasitic elements are the series resistance of the diode R_s, the bond wire inductance L_b and the parasitic capacitance C_p between the bonding pad and ground plane. The capacitance is reduced by fabricating the LASER diode on a semi insulating substrate.



The eq. circuit of a laser monolithically integrated with a FET.

An advantage of having the FET in the circuit is the impedance matching. The modulating high frequency input is fed to the gate of the FET, which is terminated with a 50Ω resistance and the laser is matched to 50Ω input through the FET. This enhances the modulation B.W. Usually 2 inputs are fed to the laser. two inputs are fed to the laser. a dc current for biasing and ac modulating input. A high frequency bias T circuit is used to separate the two inputs.

Complex Circuit and Arrays

⇒ As high data rate local area networks are being installed in an increasing number of locations due to merging of a high density of fibers in each of these locations, it becomes necessary to use multiple opto electronic devices or arrays for reducing component cost and weight.

An array consists of an assemblage of identical devices monolithically integrated on the same chip.

Array can serve a variety of different needs.

⇒ * One or two dimensional arrays of identical sources provide larger output power and with proper design, near single longitudinal mode characteristics.

⇒ * If the respective phases are progressively tuned, then a phased array of sources can be used for electronic beam steering.

⇒ * Wavelength tunability is also possible in 2 dimensional array of sources.

* ⇒ Arrays of opto electronic devices are used for transmission, routing and reception of signals in optical fiber systems.

* ⇒ For eg: in star networks, information from several locations are brought in at the node of the ~~star~~ and rerouted again.

Arrays are useful in parallel architectures such as in interconnection of Computers. Parallel data transmission between the computers becomes more efficient than Serial data transmission where by downloading time of data is considerably reduced.

For eg: In the transmitter (4 Channel) Consisting of GRINSCH-SQW GaAs/AlGaAs lasers integrated with 2 μm gate GaAs MESFET. In this array interval between lasers is 1mm and chip size is $4 \times 2\ mm^2$. The circuit operates up to bit rate of 2 gigabits/sec. The crosstalk between the Channels is less than −20dB at a frequency of 600 MHz.

Optical Control of Microwave Oscillators.

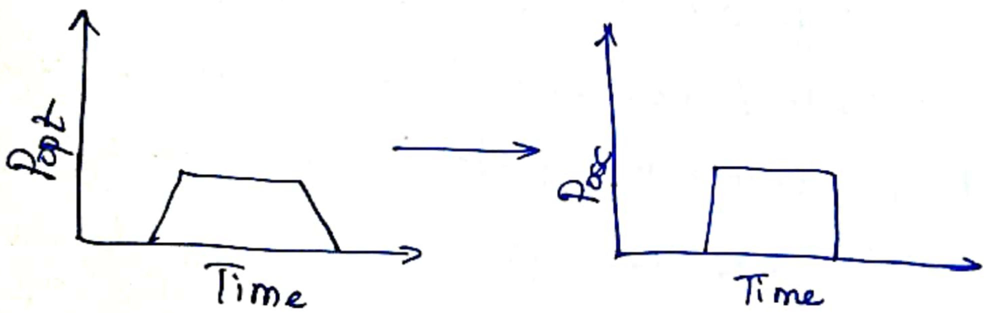
The use of optical signals to Control high Speed electronic Circuits is advantageous due to wide bandwidth of the optical control signals and their inherent isolation from radio frequency signals. Optical signals can be routed via light weight fibers or monolithically integrated optical wave guides without affecting signals transmitted on microwave waveguides. Microwave optical links also allow remote Control of antennas. This allows moving personnel and expensive Control equipment to be located at the Command center rather than at the antenna. It is useful in cellular telephone transmission or

Cable television where a transmitting antenna is located in remote or inconvenient locations. Similarly fiber optic links have been used in microwave measurements and instrumentations, where optical fibers overcome the limitations on phase stability by coaxial cables.

The optical control of microwave oscillators can be realized in 3 forms

⟹ Optical Switching
⟹ Optical tuning
⟹ Optical injection locking

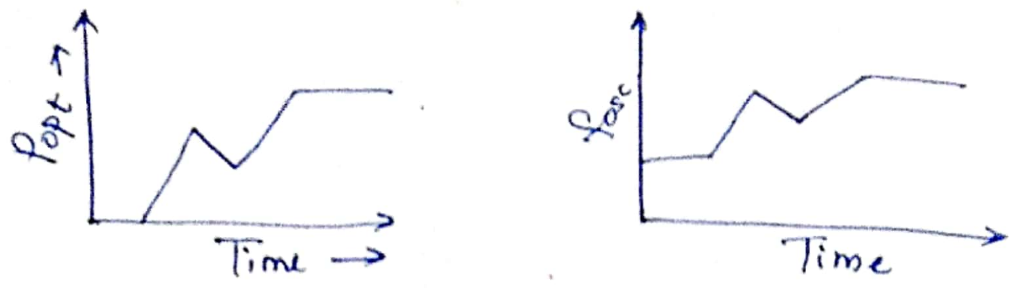
Optical Switching.



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/off the controlled oscillator.

Optical tuning

With optical tuning, the intensity of the input light controls the output frequency of the oscillator.



Optical tuning

Optical injection locking

It refers to the use of a high frequency modulated optical control signal to fix the frequency of a free running oscillator. When in locked 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 signal. The phase offset varies by $\pm 90°$ over the injection locking bandwidth ω_{max}. The injection locking bandwidth ω_{max}. The injection locking bandwidth and phase error are given by

$$\boxed{\begin{aligned} \omega_{max} &= \frac{\omega_0}{2Q}\sqrt{\frac{P_{inj}}{P_0}} \\ \phi &= \sin^{-1}\left(\frac{\omega_{lock} - \omega_0}{\omega_{max}}\right) \end{aligned}}$$

⇒ ω_0 → free running oscillation frequency

⇒ ω_{lock} → injection locking frequency

⇒ P_{inj}, P_0 → injected power & oscillator o/p power

Q – Quality factor,

Q provides a measure for loss in resonant circuit and is defined as

$$\boxed{Q = \omega \times \frac{\text{average energy stored}}{\text{energy loss / second}}}$$

Guided Wave Devices

Guided wave components are required for routing optical signals on a chip and also for the functions of directional coupling, filtering and modulation.

Waveguides and Couplers.

A waveguide is a region of dielectric through which light is propagated, surrounded by dielectric regions or air having a smaller dielectric constant. Therefore it is essential to employ techniques that will effectively and selectively create regions 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 carriers is expressed by

$$\boxed{\Delta n_x = -n \lambda_0^2 q^2 / 8\pi^2 \varepsilon_0 n_x m^* c^2}$$

Opto Electronic Integrated Circuits Contd...

where $n_r \rightarrow$ refractive index of the undoped semiconductor at a free space wavelength λ_0

For eg

$$\boxed{\begin{aligned} n &= 1\times 10^{19}/cm^3 \\ \lambda_0 &= 1\mu m \\ \Delta n_r &= -0.02 \end{aligned}}$$

This change in refractive index is large enough for light confinement. (1) Based on this principle waveguides can be produced either by growth of an undoped epitaxial layer on a highly doped substrate or by implantation damage.

(2) In the second scheme, the waveguide-cladding layer interface is not well defined since the implantation profile is not rectangular.

In the epitaxial technique, the interface is more abrupt.

At the top of the guide, optical confinement is provided by the index change at the semiconductor air interface. Guiding is also achieved by compositional variation in vertical direction. The index difference and optical confinement in this case are made possible by the different bandgaps.

(3) For obtaining single mode guiding and propagation it is necessary to delineate the guiding region in the lateral direction by causing an index change. This is achieved in a ridge waveguide, a buried channel guide or a strip loaded guide.

① Finally, the lateral waveguide dimensions are delineated by wet or dry etching or combination of both. A dry etching process such as ion milling or reactive ion etching which provides control is followed by a wet etching process which smoothe the surface.

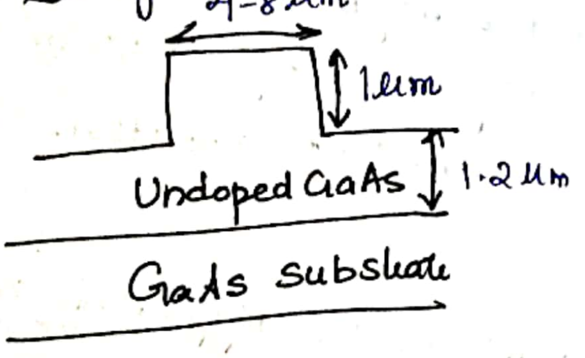
② Buried channel waveguides can be created by a variety of techniques. Simplest technique is for eg A GaAs waveguide is grown epitaxially and delineated and a higher index AlGaAs confining layer is regrown by LPE or MOCVD. Selective diffusion or ion implantation can also be used.

③ A more novel technique is diffusion induced disordering. A multiquantum well guiding layer is first grown epitaxially. It is then masked selectively and the regions adjacent to the guiding region are doped by diffusion, by implantation and annealing or by diffusion. Either process converts the ordered MQW or superlattice structure into a disordered random alloy, usually with a low refractive index providing optical confinement.

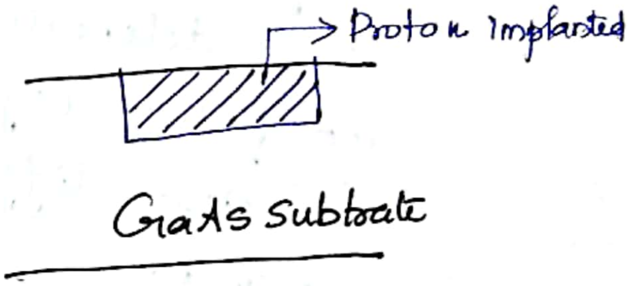
④ Strip loaded guide: The formation of a dielectric or metal stripe on the guiding layer allows the refractive index of the semiconductor underneath it and confines light. This is attributed to the spatial variation of the dielectric constant generated by stresses originating in the dielectric or metal stripe. The strain fields in the semiconductor, below the stripe, penetrate to a depth of 2-3 μm and therefore suitable for guiding.

Techniques for fabricating wave guides.

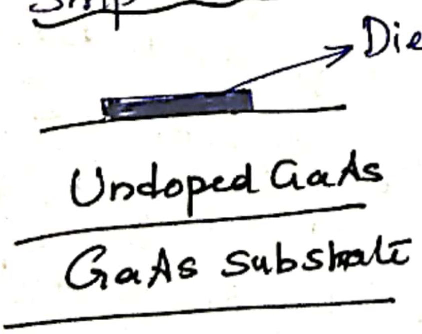
(a) Ridge

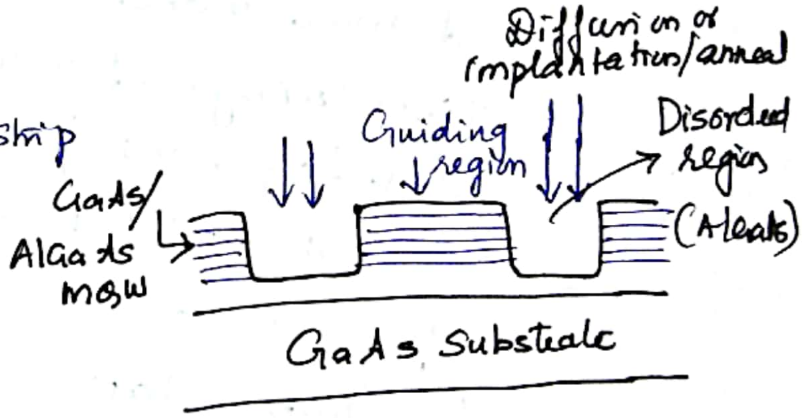


(b) Buried channel by Implantation.



(c) Strip loaded.





For any application, it is necessary to ensure that the guides provide low propagation loss. If the guides are made of high quality, defect free epitaxial layers, then the major sources of loss are surface scattering and absorption. Therefore etching and formation techniques is critical in the fabrication of low loss waveguides. The value of γ which determines the insertion loss of a waveguide is mainly determined by free carrier absorption and scattering at bulk and surface imperfections. ∴ Material quality and processing is important in determining γ.

Transmission of optical power in the guide is given by $\boxed{P(z) = P(0)e^{-\gamma z}}$

from which the guide loss is

$$\mathcal{L} = 4.3\gamma \ (dB/cm)$$

Low loss waveguides have values $\mathcal{L}$ ranging from 0.1 to 1 dB/cm

Directional Coupler.

The directional coupler consists of two parallel waveguides between which the transfer of optical energy occurs due to the overlapping of waveguide modes. This energy exchange requires that the light propagating 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

$$\boxed{\begin{aligned} P_1(z) &= \cos^2(kz)e^{-\gamma z} \\ P_2(z) &= \sin^2(kz)e^{-\gamma z} \end{aligned}}$$

Here z is the direction of propagation and

k is the coupling constant

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

→ b → extinction Coefficient

→ d → separation between the guides

→ W → width of each guide

→ β_z, β_y → mode propagation constants in the propagation and transverse directions.

The coupling length of a directional coupler L_c is defined as length at which total transfer of power takes place

$$\boxed{L_c = \left(m + \frac{1}{2}\right)\frac{\pi}{k} \quad m = 0, 1, 2 \ldots}$$

Active Guided Wave Devices.

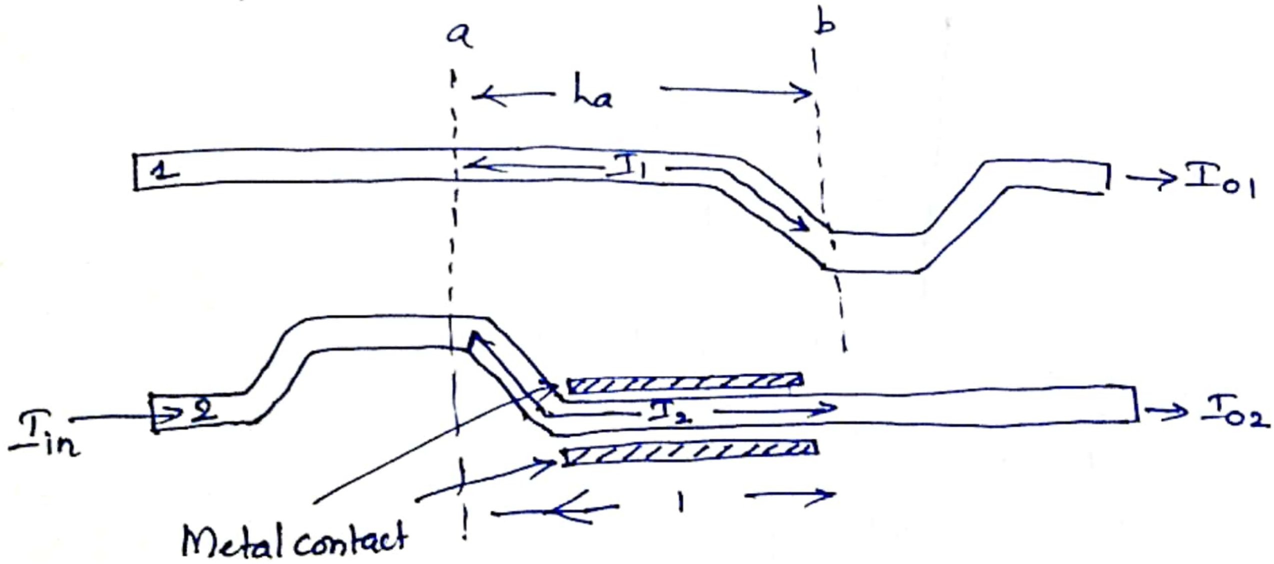
The integrated optical components which are quasi passive or active guided wave components that can be integrated in OEICs with active optoelectronic devices.

Examples of active wave guided devices are laser and electro optic modulator.

Other active guided wave devices are modulators, interferometers and filters.

MACH ZEHNDER INTERFEROMETER

A simple guided wave modulation/switching device based on the electro optic effect is the Mach Zehnder interferometer. 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. Materials growth and processing is such that the tapers are very gradual to reduce bend losses and that there is spatial uniformity.



Schematic of guided wave Mach Zehnder interferometer with input and output 3 dB couplers

With no applied bias to the schottky diode

the phase shift in the two arms is equal and at the output coupler the two waves interfere constructively and all the power appears at the output.

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 fields at point a are given by

$$\boxed{\begin{array}{l} E_{1a} = 0 + j\sin\frac{\pi}{4} = j/\sqrt{2} \quad \text{— (1)} \\ E_{2a} = 0 + \cos\frac{\pi}{4} = \frac{1}{\sqrt{2}} \quad \text{— (2)} \end{array}}$$

At point b, the field is phase shifted due to propagation over the length l_a and

$$\boxed{\begin{array}{l} E_{1b} = \frac{j}{\sqrt{2}} \exp\{jkn_2 l_1\} \\ E_{2b} = \frac{1}{\sqrt{2}} \exp\left[jk\left[n_2 l_2 + \frac{\partial n_2}{\partial V} lV\right]\right] \end{array}}$$

In the second equation the electro optic effect is taken in to account due to the bias V applied to the Schottky diode over a length l. ∴ Unequal lengths l_1 and l_2 will introduce a phase difference

$$\boxed{\Delta\phi_1 = kn_2(l_2 - l_1)}$$

between E_1 and E_2 while the electro optic effect introduces an additional phase shift

$$\boxed{\Delta\phi_{EO} = kl\frac{\partial n_2}{\partial V} V = \frac{\pi l}{\lambda d} n_{2o}^3 \gamma_{ij} V}$$

d — thickness of the wave guide.

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

$$\boxed{E_{o1} = \frac{-j}{2} \exp(jk n_3 l_1) \left[1 + e\{j(\Delta\phi_1 + \Delta\phi_{EO})\}\right]}$$

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

$$\boxed{I_{o1} = \frac{1}{2}\left[1 + \cos(\Delta\phi_1 + \Delta\phi_{EO})\right]}$$

The output from arm 2 is

$$\boxed{I_{o2} = \frac{1}{2}\left[1 - \cos(\Delta\phi_1 + \Delta\phi_{EO})\right]}$$

If the device 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 $I_{o1} = 1$ and $I_{o2} = 0$. On the other hand, the phase shift produced by the application of a bias is π and $\Delta\phi_1 = 0$ then $I_{o1} = 0$ and $I_{o2} = 1$. The modulation index is Only and the corresponding bias is given by

$$\boxed{V_\pi = \frac{\lambda d}{l n_{3o}^3 r_{ij}}}$$

which is the same as guided wave

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

The switch energy of the device is given by $E_s = \frac{1}{2} C V_\pi^2$ where C is the capacitance of the schottky diode. The switching speed is limited by the RC time constant of the electrode structure. The output power can be controlled in a tunable manner by varying the voltage. For W = 2-3 μm and l → few mms the voltage required for $\Delta\phi = \pi$ is of order of few volts in compound semiconductor devices