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UNIT 1
PRINCIPLES OF OPTIC FIBRE COMMUNICATION

$\boxed{\text{CO - 1}}$: Demonstrate the importance of optical technology in communication, light propogation and fibre structure parameters

DEFINITION :

- It is line communication - Tx and Rx are connected by solid guided medium
- Transparent medium where information is generated in form of light/photon

REQUIREMENTS OF EXISTING TERRESTRIAL COMMUNICATION

- Attenuation / Path loss min : results in longer repeater spacing
- Larger Bandwidth and bit rate capacities & better BER performance.
- Convinient end devices : Compatible devices
- Signal Security

OPTICAL FIBRE COMMUNICATION SASTISFIES THESE ALL

DIFFERENT GENERATIONS OF OFC

PARAMETERS	G1	G2	G3	G4	G5
$\lambda(\mu m)$	0.8 window 1	1.3 window 2	1.55 window 3	1.45-1.62 Extended window	1.53 to 1.55 Window 3
Semiconductor Materials	GaAs - direct Si, Ga - indirect Conventional devices (homojunction)		InGaAs, InAlAs Multilayered (Heterojunction)		
Rb	45Mbps	100Mbps -1.7Gbps	10Gbps	10Tbps	40-160Gbps to improve ISI
Repeater Spacing	10km	50km	100km	>10000km	>100,000km
	MM fibre			SM fibre.	

→ HISTORICAL DEVELOPMENT

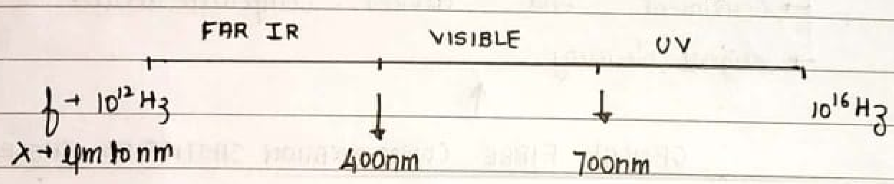
* hand signalling
* smoke and fire – Africa and Europe
* Lanterns and torches
* Photophone
* Laser communication

→ LIMITATIONS

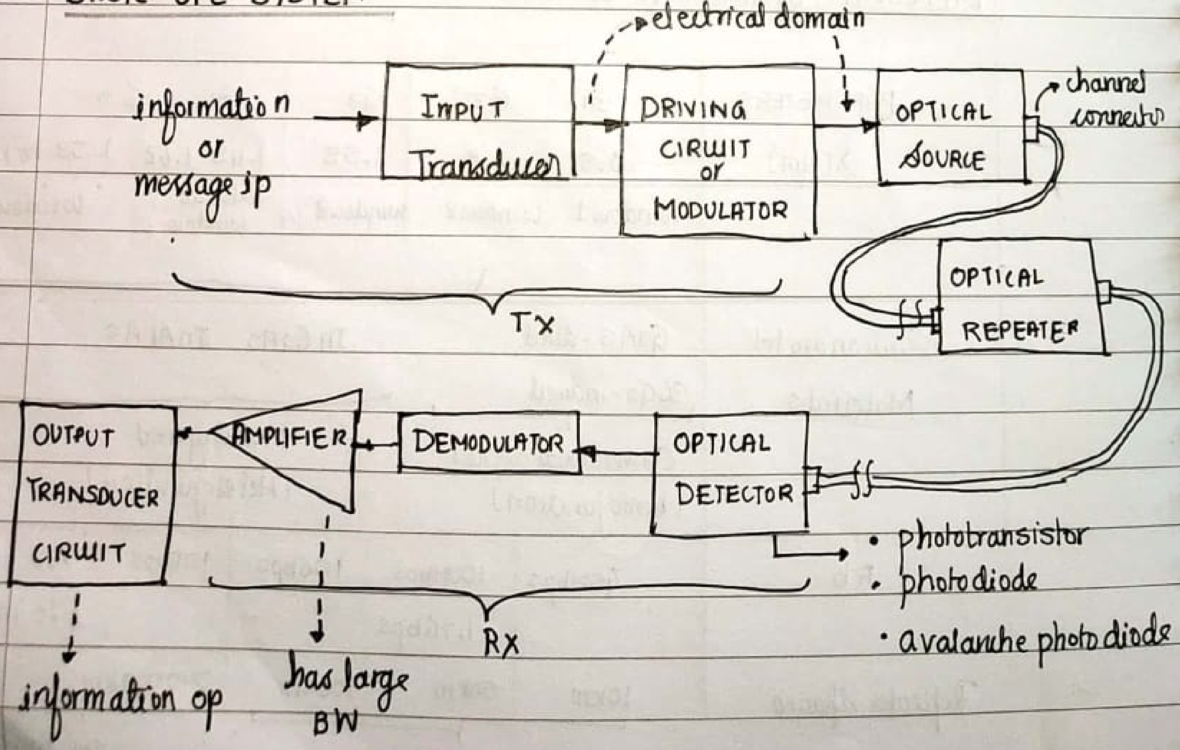
* ~~Radi~~ Rectilinear propogation
* Environmental dependancy
* Distance of communication
* distortions, noise, interference

03/08/2018

OPTICAL FREQUENCY SPECTRUM



→ BASIC OFC SYSTEM



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ADVANTAGES OF OPTICAL FIBRE

1. Large Bandwidth capability.
   - 2×10^{12} Hz to 3.7×10^{12} Hz
     [5 to 10% of f_c (which will be in THz)]
   - IOT, Broadband, audio applications

2. LOW ATTENUATION
   - plastic/conventional fibers, $\alpha < 1$ dB/km
   - all glass/hallide fibers, $\alpha \simeq 0.1$ to 0.01 dB/km
   - higher bit rate transmission with minimum ISI
   - larger ~~spot~~ repeater spacing

3. IMMUNE TO INTERFERENCES (EMI and RFI
   - Since fibers are made of insulating material like glass or fibers, System is free from cross talk.
   - Free from electrical hazards like O.C / S.C / earthlooping etc

4. SMALL SIZE AND LIGHT WEIGHT

   Characteristics: Diameter will be few 10s of μm. A fiber spool can weigh upto few kgs.
   - on board applications like satellites.

5 HIGH TENSILE STRENGTH: Duct applications (underground cabling)

6. IMMUNE TO CHEMICAL AND ENVIRONMENTAL EFFECTS
   - Under sea cabling: salt water affects normal cables.
   - no oxidation or rusting.

7 SIGNAL SECURITY AND EASIER FAULT FINDING.
   - fault detection is easy (using OTDR) and other equipments.

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→ DISADVANTAGES OF OPTICAL FIBRE

1. Complex splicing process.
2. Large number of distortion - attenuation loss, scattering loss, absorption loss
3. Low power sources
4. In duct applications, after critical radius of bending, fiber core gets damaged.
5. Additional losses in fibres are high
   - a) scattering
   - b) bending losses
   - c) absorption
   - d) connectors and couplers
   - e) splicing losses
6. Under lateral strain/stress, single mode slicing is damaged (proper cabling)

→ APPLICATIONS:

1. Telephone trunking
   within cities for landlines.
2. Fiber Sensors
   - instrumentation
   - medical applications
   - manufacture processes
3. Japan - +130v [Highly interactive audio systems]
   multimedia communication
4. Fiber communication is used in
   - underground railway
   - mines
   - earthquake engineering.

EXPERIMENTS.

1. Communication circuits
   - filters
   - modems
   - attenuation
   - TDM/FDM
2. F.O.C
3. Microwaves and Antennas
4. Simulation

⇒ CYCLE - I

1. m-derived LPF - T type (II order)
2. m-derived HPF - λ type (II order)
3. mixer circuits
   - additive
   - product
   - diode
   - transistor.
4. BASK
   - discrete
   - kit
5. BFSK
   - discrete
   - kit
6. BPSK
   - discrete
   - kit

I EXPERIMENTS 1 and 2 : m-derived filters

- Aim
- Components/equipments
- Theory required
  - passive filters

- comparision of passive and active filters
- applications
- advantages of m-derived filters
- filter parameters.

→ DESIGN: with f_c, f_o, m-factor

→ PRACTICAL ASPECTS:
- conduction
- tabulation
- frequency response (normalised frequency response attenuation v/s normalised frequency)
- parameters
  - → attenuation
  - → roll-off
  - → 3 dB bandwidth
- graphs.

→ INFERENCES

* Each experiment carries 40 MARKS

P1 → PREPAREDNESS

P2 → VIVA

P3 → CONDUCTION

P4 → REPORT

P5 → RESULT ANALYSIS

- SLE:

1. Active filters
2. Simulation
3. Digital filters

EXPERIMENT 3 : MIXER CIRWITS

→ Theory required :
- principle of heterodying
- SHR principle
- concepts of IF, image frequency
- distortions in mixers
- mixer parameters.

→ DESIGN : rig-up
- diode
- transistor

EXPERIMENT 4, 5 and 6 : DIGITAL MODULATION (Modems)

→ Theory required :
* principle of modulation
  - analog
  - digital
* need of modulation
* advantages of digital modulation
* applications
* parameters
* comparision of modulation formats.

SLE :

1. LABVIEW
2. SIMULINK
3. MATLAB.

OPTICAL FIBER WAVEGUIDES

→ Two forms of geometry
- → circular : optical fibres
- → rectangular : planar waveguides

→ To study the behaviour, we use the principle of ray and geometric optics
- laws of reflection – Snell's law
- refraction
- bending around corners etc

→ Optical signals behaves in same manner as electromagnetic waves.

→ Laws like Maxwell's equations are applicable to find field components. Even wave equation of propogation in dielectrics are applicable.

→ Wave propogation is by TE and TM waves

→ Field components are found using Boundary conditions

$$E_{tan} = H_{normal} = 0$$

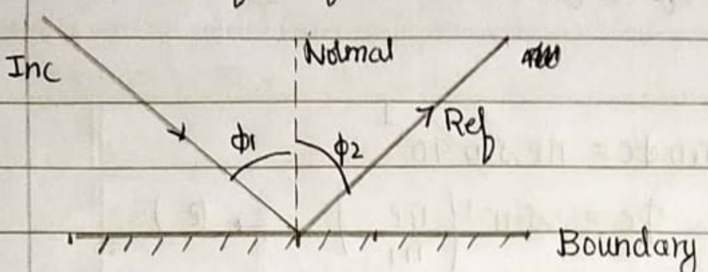
→ Hybrid modes are present in waveguide HE and EH modes.
[Traces of H and E field present along the direction of propogation]

→ To quantify the field parameters of waveguide, we consider
$f_c(\lambda_c)$, λ_g, v_g, v_p, Z_{TE} or Z_{TM} or Z_{EH} or $_{HE}$.

RAY PRINCIPLES:

1. RECTILINEAR PROPOGATION OF LIGHT

2. Principle of Reflection:



$\phi_1 = \phi_2$

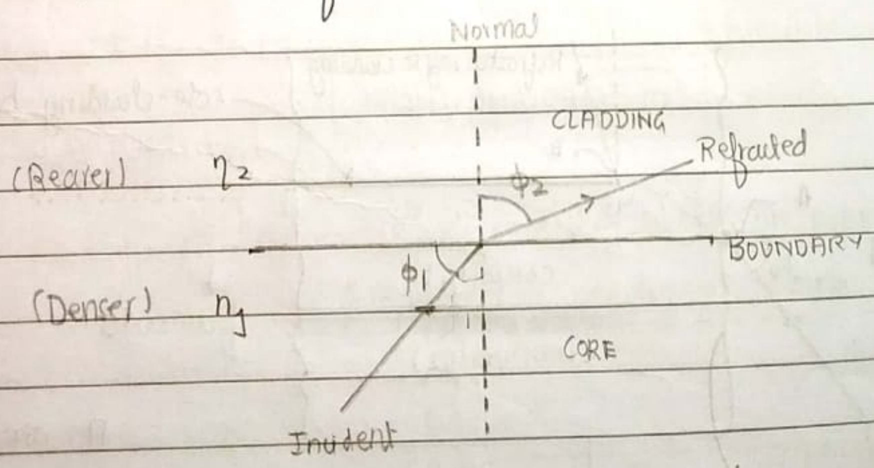
3. Principles of Refraction

Bending of rays when light propogates from one medium to another (bending can be towards normal of surface or away depending on R.I of media)

4. Snell's law

If signal propogates from one media to another of varying RI, then

→ Relates R.I of two mediums wrt incident and refracted angles.



$\boxed{n_1 > n_2}$

$$\left.\begin{aligned} \eta_1 \sin\phi_1 &= \eta_2 \sin\phi_2 \\ n_1 \cos\theta_1 &= n_2 \cos\theta_2 \end{aligned}\right\} \text{"Snell's law"}$$

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* If ray propogates from denser to rearer medium, it bends away from the normal as $\phi_1 \uparrow$ $\phi_2 \uparrow$

For $\phi_1 = \phi_c$ = critical angle of incidence
$\phi_2 = 90^\circ$ (just grazes the boundary)

$\therefore$ from (a), $\boxed{\begin{aligned} n_1 \sin\phi_c &= n_2 \sin 90^\circ \\ \phi_c &= \sin^{-1}\left(\frac{n_2}{n_1}\right) \rightarrow (2) \end{aligned}}$

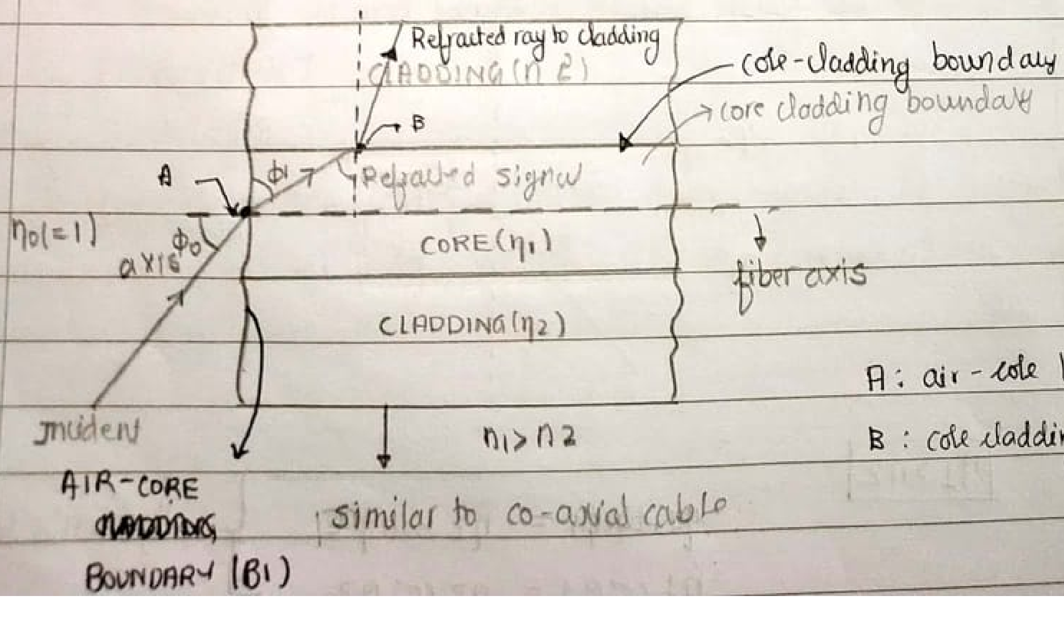
→ for ϕ_1 → incident angle > critical angle (ϕ_c), ray will undergo TOTAL INTERNAL REFLECTION (TIR)
↓
used in optical fibre for wave propogation

→ CONDITIONS FOR TIR are.

* $\eta_1 > \eta_2$ (RI of core > RI of cladding)
* $\phi_1 > \phi_c$ (incident > critical)

→ ACCEPTANCE ANGLE :

SIDEVIEW OF FIBRE



A : air-core boundary
B : core cladding boundary

For air-core boundary (B1) ie at point 'A'

$$\eta_0 \sin\phi_0 = n_1 \sin\phi_1 \rightarrow (1)$$

angle of incidence at core-cladding boundary defines whether ray is refracted or TIR (Total internally reflected)

THURSDAY But $\phi_1 = 90^\circ - \phi_c$ 9/8/18

where $\phi_c \rightarrow$ critical angle of incidence at core cladding boundary for TIR

$$\eta_0 \sin\phi_0 = \eta_1 \sin(90^\circ - \phi_c)$$

$$\boxed{n_0 \sin\phi_0 = n_1 \cos\phi_c}$$

or

$$\sin\phi_0 = \eta_1 \cos\phi_c \quad [\because \eta_0 = 1 \text{ for air}]$$

WKT, $\sin\phi_c = \dfrac{n_2}{n_1}$

equation (2) becomes,

$$\sin\phi_0 = \eta_1 \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2}$$

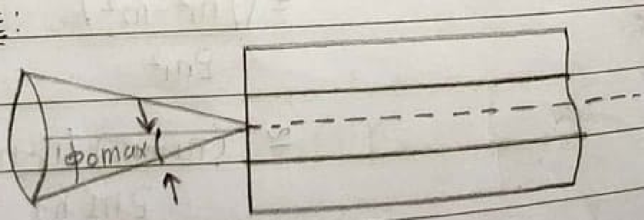
$$\boxed{\sin\phi_0 = \sqrt{n_1^2 - n_2^2}}$$

→ if ϕ_0 is maximum, then TIR is possible.

$$\boxed{\sin\phi_{0_{max}} = \sqrt{n_1^2 - n_2^2}}$$

→ ϕ_{0max} = ACCEPTANCE ANGLE OF FIBER for which ray propogates in core region.

→ ACCEPTANCE CONE:



$\phi_{o\,max}$: half cone angle of acceptance cone within which TIR is possible, otherwise ray will be refracted to the cladding region.

* NUMERICAL APERTURE :

- Determines the light gathering capability of the fiber which is a fractional number.
- defined as

$$\boxed{NA = \sin\phi_{o\,max} = \sqrt{n_1^2 - n_2^2}}$$

- Smaller the value of numerical aperture, it is difficult to couple the light.
- Multimode fibers have larger numerical aperture compared to single mode fibers.

* Δ [FRACTIONAL CHANGE IN R.I]

- For TIR, $n_1 > n_2$
- Amount by which n_1 must be greater than n_2 is determined by Δ (measured in %)

$$\boxed{\Delta = \frac{(N.A)^2}{2n_1^2}}$$

$$= \frac{\left(\sqrt{n_1^2 - n_2^2}\right)^2}{2n_1^2}$$

$$\simeq \frac{(n_1+n_2)(n_1-n_2)}{2n_1\, n_1}$$

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$$\boxed{\Delta \simeq \frac{n_1 - n_2}{n_1} \times 100}$$

$[\because n_1 \approx n_2$

$2n_1 \approx n_1 + n_2]$

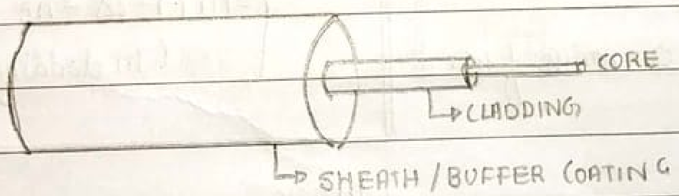
$$\boxed{N.A = n_1 \sqrt{2.\Delta}}$$

⇒ RAY TRACING IN FIBRES:

* Geometric optics helps in determining path of ray inside fiber.
* Principle of reflection, refraction and diffraction are used for tracing.
* In optic fiber, we consider 2 types of rays
  (i) Meridonial rays
  Rays confined to one plane (generally near fibre axis core)

  (ii) Skew rays.
  Confined to multiple planes.

⇒ FIBER STRUCTURE:



- Function characters of (sheath)
  - provides tensile strength to the fiber.
  - prevents radiation of ~~fibre~~ signal out of fibre
  - prevents surface contamination.

- CLASSIFICATION OF FIBERS:

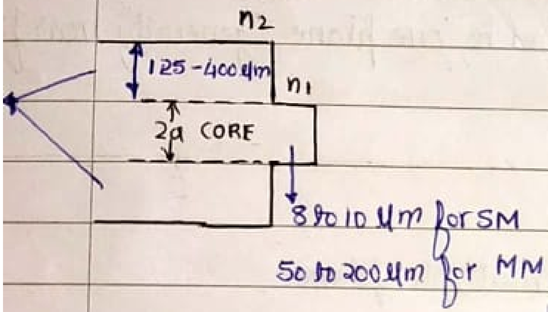
CLASSIFICATION OF OPTIC FIBERS

1. CLASSIFICATION 1 :

Based on :
- Refractive index profile
- Variation of refractive index profile across cross section of fiber.

CLASSES :
1) SIF
2) GRIN
3) COMPOSITE PROFILE

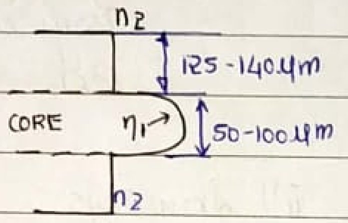
SIF



RI for $r<a$, $\eta = \eta_1$
$r>a$, $\eta = n_2$

where
a = radius of core

GRIN



$$n(r) = \begin{cases} n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right] & \text{for } r<a \\ \text{(within core)} & \\ = n_1\sqrt{1-2\Delta} \simeq n_2 & \text{for } r>a \\ \text{(in cladding)} & \end{cases}$$

where,

α = profile index no which defines number pattern

Ex: $\alpha = \infty \rightarrow$ SIF
$= 2 \rightarrow$ parabolic
$= 3 \rightarrow$ triangular
$= 10 \rightarrow$ circular

COMPOSITE

- combination of profile.

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II CLASSIFICATION 2 :

BASED ON : Material of the fibre.

CLASSES :

1. All glass fiber : both core and cladding are made of glass.

2. Plastic fiber : both core and cladding are made of transparent plastic

3. Composite : core is made of glass
cladding is made of plastic.

III CLASSIFICATION 3 :

BASED ON : Modal characteristics
ie. number of modes they support.

CLASSES.

1. Singlemode (SM) or Monomode (MM) or Fundamental mode (FM)

2. Multimode.

IV BASED ON WINDOW REGION OF OPERATION :

CLASSES

- Window 1 : λc → 750 to 800 nm (Shorter wavelength region)
- Window 2 : λc → 1300 to 1350 nm (Medium wavelength region)
- Window 3 : λc → 1500 to 1550 nm (Longer wavelength Region)

V CLASSIFICATION 5

BASED ON : Loss

CLASSES

1.
- low attenuation loss
- high attenuation loss

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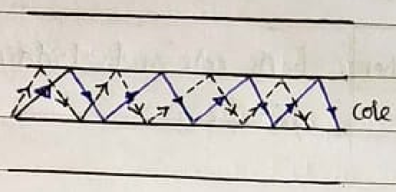
2. | a. Dispersion Shifted fibers
   | b. Dispersion flattened fibers.

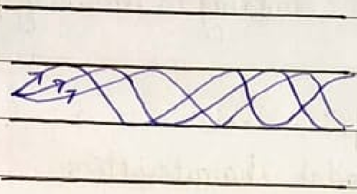
⇒ **RAY BENDING :-**

1. SIF :

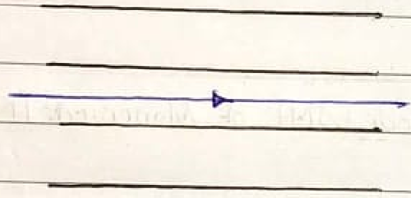


SIF - multimode type.

2. GRIN



3. SM



⇒ **DIFFERENCE BETWEEN SIF and GRIN**

	PARAMETER	SIF	GRIN
1	Numerical Aperture	constant	varies with radius of core
2.	Material	glass/ plastic	glass
3.	Coupling efficiency	higher [50 to 60%]	lower [40 to 50%]
4.	Coupling type	both grating and lenses are used	only lens coupling

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5.	Data Rate	few tens of Gbps	Tbps.
6	Bandwidth - distance product	10 to 20MHz - km	upto 1GHz - km
7.	Pulse spreading	more	less.
8	Source	LED	LED/ Lazer diode LD
9.	Attenuation loss in dB	0.3dB/km (low)	0.6 to 1dB/km (high)
10.	Application	· ALL (Analog local loop) · Telephone trunking	* WAN * LAN

FRIDAY 10/9/2018

⇒ MODES IN OPTICAL FIBERS

— WKT light energy behaves as EMW energy and hence laws of fixed theory can be applied for the analysis.

— Light propogation in the form of a "packet energy" inside the fiber called quantum energy or quanta.

— Energy content of a packet

$\boxed{We = h\nu}$ → frequency of packet (J/

↓

planck's constant

* mode is a regular field pattern (orientation of E & H field according to the crossection of waveguide !

* For cylindrical optic fiber of circular crossection we consider linearly polarised radius.

$$LP_{jm} \begin{cases} \rightarrow TE_{jm} \\ \rightarrow TM_{jm} \\ \rightarrow EH_{jm} \text{ \& } HE_{jm}. \end{cases}$$

* No of modes supported by a fiber depend on the cutoff condition of propogation constant

$$\gamma = \alpha + j\beta$$

where,

γ = propogation constant

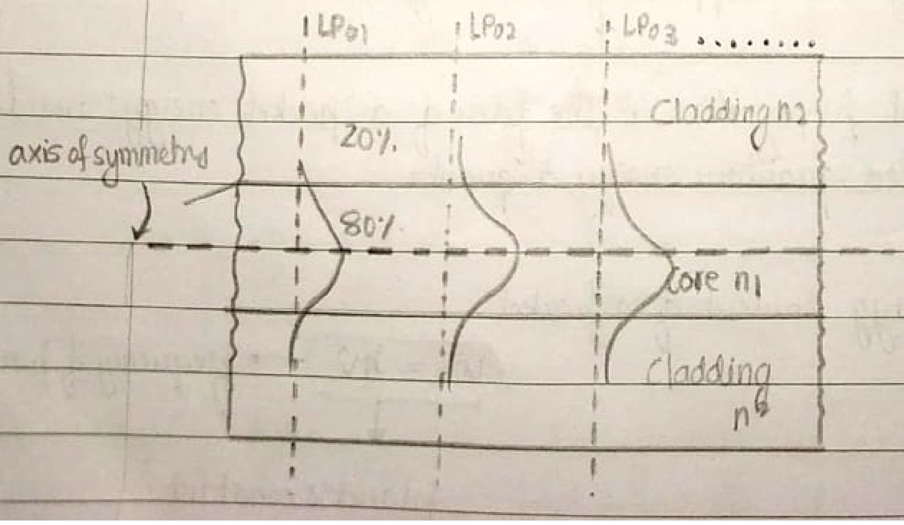
α = attenuation constant

β = phase constant

→ Generally for wave propogation $\alpha = 0$,

$\therefore \gamma = j\beta$

* order of mode is nothing but the number of zero crossings for the E-field according the crossection of waveguide.



* optical energy exhibhits oscillatory behaviour inside core and it gets attenuated in cladding region (exponential decay)

* for lower order modes, most of the energy will be confined inside the core.

* As order increases more and more energy enter cladding region.

* Energy inside core constitutes desired modes of energy in cladding, constitutes "leaky modes" or "undesired modes"
  Since they result in loss of energy.

* Mode cutoff frequency or wavelength determines the single mode or multimode operation of a fiber.

* More specifically, it is defined in terms of "V-number or normalized parameter".

For a SIF

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

$$= \frac{C}{\lambda}\sqrt{n_1^2 - n_2^2}$$

where $C = 2\pi a$ = circumference

a = radius

$$V = \frac{C\,(NA)}{\lambda}$$

* As λ determines the cutoff condition be single mode or multimode operation

ie as $\lambda \to \lambda c$

$V \to Vc$

if $V \leq Vc = 2.45$

then it is monomode or single mode or fundamental mode of operation

otherwise for

$V > 2.405$, it is multimode

$$\boxed{\lambda_c = \frac{2\pi a}{2.405}\sqrt{n_1^2 - n_2^2}}$$

→ Number of modes supported by a

$$SIF = M \simeq \frac{V^2}{2}$$

$$GRIN = N \simeq \frac{V^2}{4}$$

ie $\boxed{M = \frac{N}{2}}$

$$\boxed{\frac{P_{cladding}}{P} = \frac{4}{\sqrt{3M}}}$$

→ COMPARISION BETWEEN SINGLEMODE (SM) AND MULTIMODE (MM)

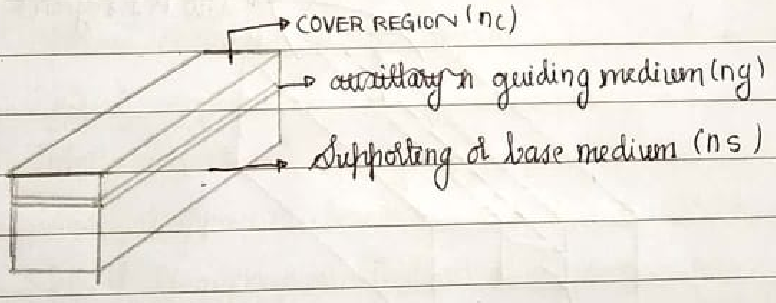
PARAMETER	SM	MM
→ Core diameter (2a)	Small (8–12μm)	large (50–200μm)
→ Source used	LD	LED
→ No of modes supported	mono or single	many
→ Predominant loss	intramodal (loss within mode)	intermodal loss between modes.

Numerical Aperture	Small [0.2 to 0.45]	large [1.5 to 0.8]
Coupling of the signal	difficult (coupling losses high)	easier (coupling losses small)
Splicing	complex	Simple.
Type of index profile	SIF	SIF / GRIN
Bandwidth and bitrate	higher	Smaller
Applications	long haul	Short haul.

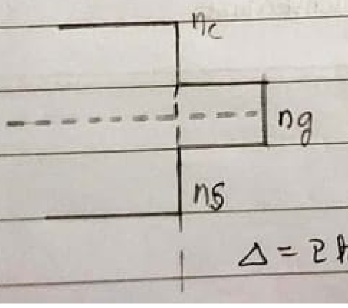
1/8/2018 SATURDAY

PLANAR WAVE GUIDE

- Slab waveguide
- channel waveguide.



- A thin film acting as light guiding medium is sandwiched between two other medium with low R.I.

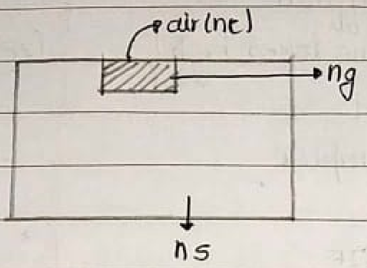


$\Delta = 2$ to 5%

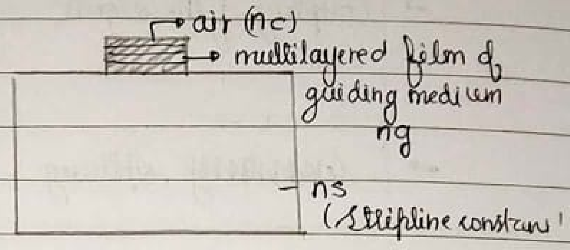
* ~~Loss~~ Radiation loss from top and bottom portion of guiding medium

* Prism and grating focussing methods are used for optical coupling

a)

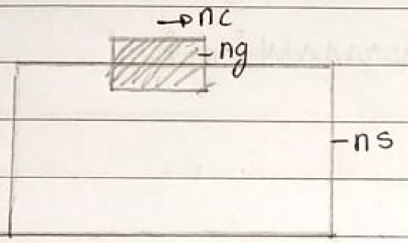


BURRIED SLAB WAVEGUIDE

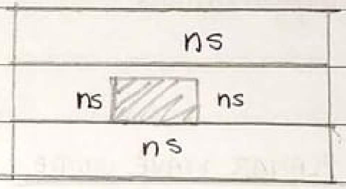


BRIDGE SLAB WAVEGUIDE

Sattelite Application ←

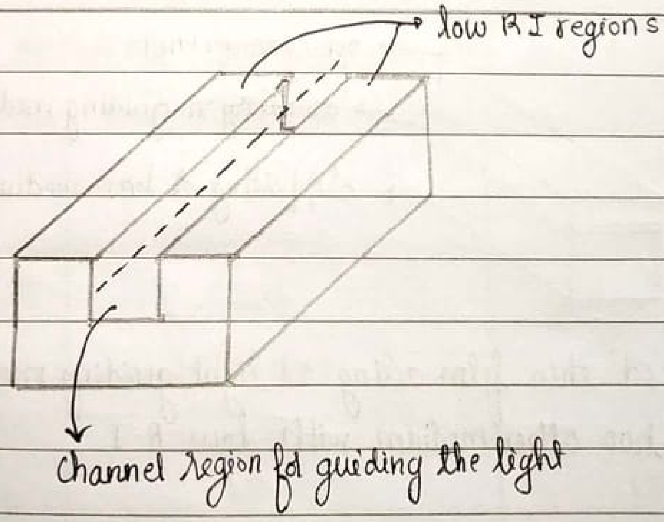


LOADED SLAB WAVEGUIDE



EMBEDDED SLAB WAVEGUIDE

b)



CHANNEL WAVEGUIDE

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→ MATERIALS USED IN FABRICATION :

* $LiNbO_3$ - Lithium Niobate
* $LiTnO_3$ - Lithium Tantalum Trioxide.
* NbO_5 - Niobium pentaoxide
* ZnS - Zinc Sulphate
* ZnO - Zinc Monoxide.

→ Direct band gap materials like GaAs, GaAlAs, GaInP, GaP etc (Alloy materials)

→ FABRICATION METHODS :

1) RF Sputtering
2) Titanium diffusion method
3) Ion exchange and implantation methods.

→ APPLICATIONS OF OPTICAL SLAB WAVEGUIDE :

1. Optical MUX or DE-MUX
2. Machzander modulation
3. Optical cross connects or switches
4. Optical couplers
5. Interferometers
6. Mode strippers or cleaners.
7. Optical frequency multipliers or dividers.
8. IOC [Integrated optic circuits]

Nishi Hara

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PROBLEMS

1. A SIF has a refractive index of 1.5 at core and cladding R.I of 1.47.
a) Find the critical angle of incidence at the core-cladding interface for TIR,
b) maximum entrance angle at fibre core axis to cater TIR (acceptance angle)
c) Numerical aperture and fractional change in RI.

Solution:

a) Critical angle $\phi c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$= \sin^{-1}\left(\frac{1.47}{1.5}\right)$

$= 78.52°$

b) Numerical aperture ~~for~~ $NA = \sqrt{n_1^2 - n_2^2}$

$= 0.298$

c) Acceptance angle $\phi A = \sin^{-1}(NA)$

$= 17.36°$

d) Fractional change $\Delta = \frac{n_1 - n_2}{n_1} \times 100$

$= 2\%$

/8/2018

OPTIC FIBRE CABLES:

There are few set of optical fibres and copper cable bunched together.

1. To source the repeater
2. As trunk lines for voice traffic between cities.

Structure depends on the type of application like

- underground or direct
- suspension on pole
- underwater

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Design considerations

1. Maximum allowable lateral bond which produces lateral stress and strain.
2. Static fatigue causes contraction or expansion of fibers (20% to 40%)
3. Temparature of operation
4. Environmental condition.

To bear the lateral road reinforcement are provided in the cabling

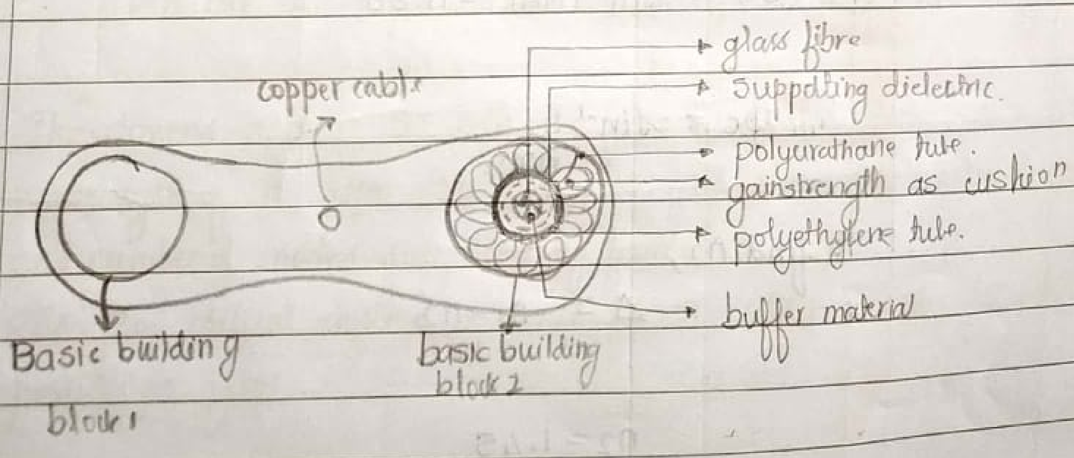
* Steelwire or wire mesh casing but prone to EMI and RFI. To overcome this before encapsulation with ~~mettatic~~ metallic tube, compressible jackets like Invar, Kelvar are provided.

* Resins and polymers of high tensile strength can be used as protective jackets.

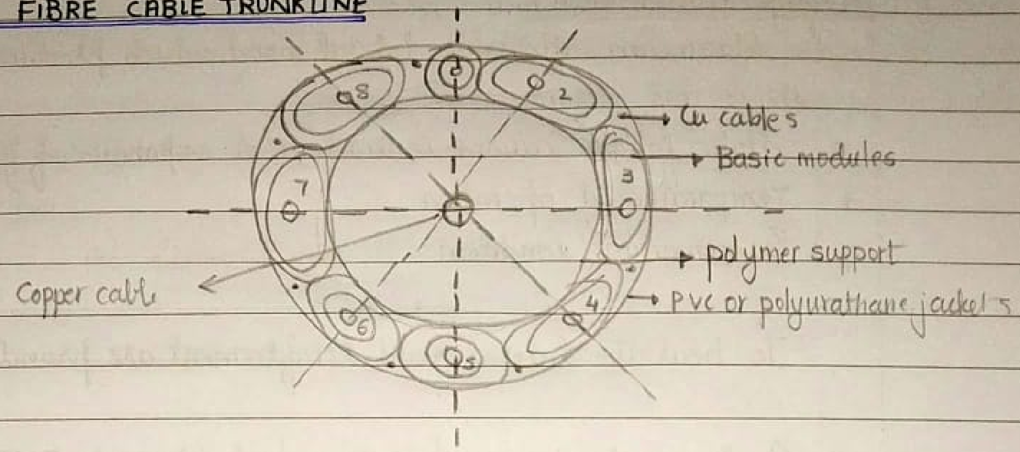
* In duct applications, radius of curvature of bending is important because it results in "mode coupling losses".

* Dermic coating of SM fibers is important in cabling. It takes care of cabling strain or abration.

1.2 FIBRE CABLE



2.8 FIBRE CABLE TRUNKLINE



PROBLEM :

1. A SIF has a relative refractive index difference of 1% , core RI is 1.46, If the fibre is operating at 850nm. Find numerical aperture, acceptance angle, critical angle of incidence and cladding refractive index. If Δ is changed to 2% , compute the above parameters and infer about each of them.

For a SIF,

(i) $\Delta = 1\%$

$$NA \simeq n_1\sqrt{2\Delta}$$
$$= 1.46\sqrt{2(0.01)}$$
$$= 0.21$$

$$\theta_A = \sin^{-1}(NA) = 11.88^\circ$$

$$\phi_c = \sin^{-1}\frac{n_2}{n_1}$$

To find n_2,

$$\Delta \simeq \frac{n_1 - n_2}{n_1}$$

$$n_2 = 1.45$$

$$\phi_c = \sin^{-1} \frac{1.45}{1.46}$$

$$= 81.78^\circ$$

(ii) $\Delta = 2\%$

$$NA = n_1 \sqrt{2\Delta}$$
$$= 1.46 \sqrt{2(0.02)}$$
$$= 0.29$$

$$\theta_A = \sin^{-1}(NA)$$
$$= 16.97^\circ$$

$$n_2 = 1.46$$
$$\phi_c = 78.52^\circ$$

INFERENCES :

- There is a marginal increase in NA as Δ increases. This implies better coupling of the signal is possible which enhances light gathering capability.
- Other parameters have decreased.

Q. If wavelength is increased to 1350nm, what are the new parameters of fibre and what is the inference?

All the above parameters are independent of wavelength of operation

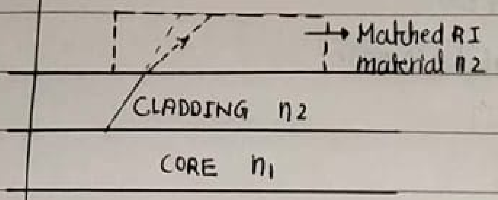
2. The dimension of a SI core of a fibre is 80μm with $\Delta = 1.5\%$ at a wavelength of 0.85μm. If $n_1 = 1.48$, find above parameters, V-number and number of modes supported by fibre.
Also find critical angle of incidence for air-core boundary for which TIR is possible in fibre.

LEAKY MODES

These are unwanted modes that propogate in cladding region due to refraction.

To avoid leaky modes:

1. Use matched index mode



A buffer material of RI n2 is placed above the cladding which absorbs unwanted signals in the cladding so that leaky modes are avoided

2. MODE STRIPPER

Matched buffer material is placed above cladding such that cladding modes also propogates in buffer materials over a short distance and gets attenuated.

SM GRIN FIBRES

As in step index fiber, here also we can define V-number which defines cut off condition for SM operation

In step index fiber, V is constant for the given profile. But for GRIN fiber, it varies with 'α' (profile index number)

For $\alpha = 2$, (parabolic profile)

$V \simeq 3.53$

For $\alpha = 1$, (triangular profile)

$V \simeq 4.38$

Generally, $(V_{cutoff})_{GRIN} \simeq 2.405\sqrt{1+\frac{2}{\alpha}}$ → improvement fiber

$= (V_{cutoff})_{SIF}\sqrt{1+\frac{2}{\alpha}}$

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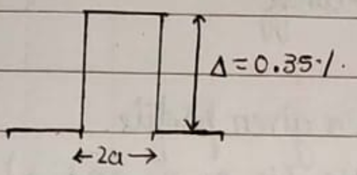
∵ V of GRIN > V of SIF, larger core dimension possible for single mode operation in GRIN fibers. Due to this better coupling or higher coupling efficiency, easier splicing, small bending loss etc.

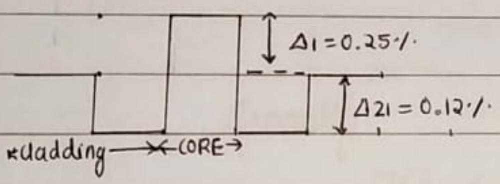
DESIGN OPTIMIZATION OF SM FIBRES :

Performance of SM fibers can be compared by design optimization

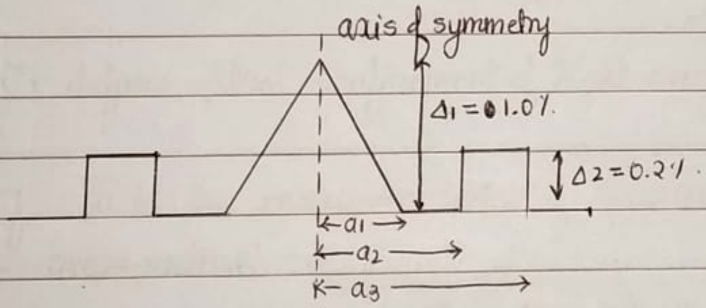
(a) By varying RI profile of fibre ($\lambda = 1300$ nm)



MATCHED RI



∴ DEPRESSED PROFILE



∴ TRIANGULAR DEPRESSED PROFILE

b) By varying dispersion characteristics of fiber

Two types of dispersion
- waveguide and material
- intra and inter modal

(i) Dispersion shifted : By proper fabrication, dispersion, minimum point is shifted to attenuation minimum point of fiber

(ii) Dispersion flattened fibre

Make uniform dispersion along a given window region of operation.

(c) By varying cutoff wavelength of fiber

$$\lambda_c = \frac{2\pi a}{V_{cutoff}} (NA)$$

- But, V is constant for a given profile.
- By varying 'a' and NA (ie n_1, n_2 and Δ), design optimization is possible.

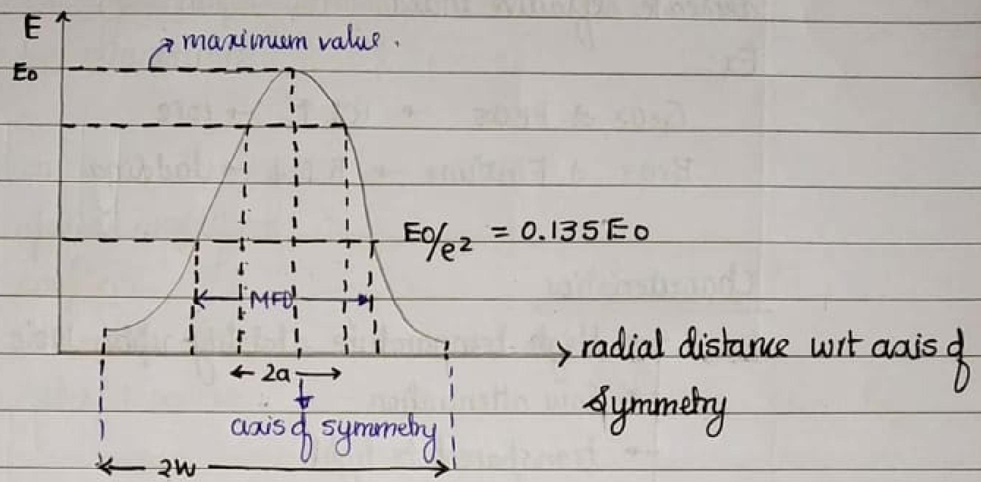
SATURDAY

18/8/18

MFD : MODE FIELD DIAMETER :

This is an important parameter of a fiber used to define the light distribution of a given mode wrt E-field.

- Random nature of light is analysed by principles of proability, assumming Gaussian distribution of light.



. Generally

MFD > physical dimension of core (ie. 2a)

- It defines optical confinement of light energy.

- If 'w' is the maximum radius of Gaussian distribution (or Gaussian beam radius)

$$\boxed{MFD = d_f \simeq 2\sqrt{2}\,w}$$

→ FIBRE MATERIALS.

- Important Considerations for medium selection
  1. Must be able to fabricate sufficiently long length of fibre with good tensile strength and low attenuation loss.
  2. Material must be transparent to given wavelength of operation.
  3. Compatible materials of small Δ must be used for core & cladding.

We can use "glass and plastic"

I. GLASS FIBRES :

- Silica or Sand is heated to a high temparature to get "vitrious silica" → intrinsic glass.

- Dopents in the form of oxides, selenides are added to increase or decrease refractive index.

Ex:

GeO_2 or P_2O_5 → RI ↑ → core

BrO_3 or Fluorine → RI ↓ → cladding

Characteristics

→ High temparature stability upto 100°c
→ low attenuation
→ transparent to light
→ good chemical durability.

Types of glass fibres

(a) Hallide glass fibres

→ fluoride material glass
→ ZBLAN : gold coloured material
· combination of ($ZrF_4 + BaF_2 + LaF_3 + AlF_3 + NaF$)

Characteristic : high temparature tolerance upto 200°C
- not sensitive to UV and IR radiations
- high tensile strength 10GPa
- low attenuation 0.1 to 3dB/km

Application : optical sensors.

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2. ACTIVE GLASS FIBRE :

- incorporating rare earth materials like Erdium & Neyodymimum into vitrous glass enhances optical properties like
  - phase attenuation
  - light amplification
  - retardation
- Application
  - optical amplifiers
  - couplers
  - connectors
  - interferometers.

3. CHALGENIDE FIBRES :

- Material exhibhits non linear property.
- Materials include
  - Sulphur
  - Selenium
  - Tellurium
- Application :
  - optical switches
  - optical discs
  - phase changers etc

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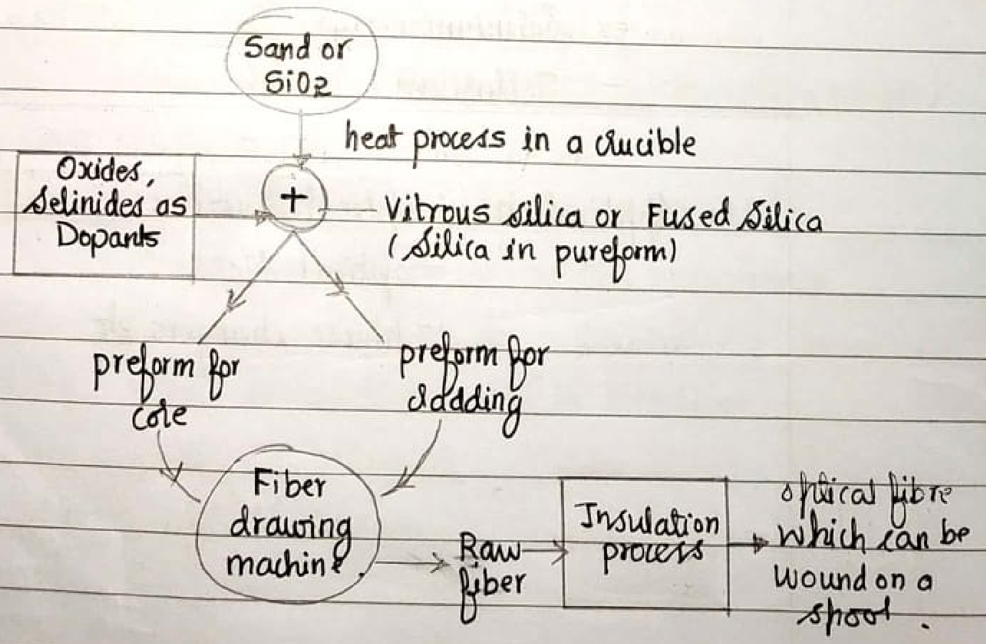
II PLASTIC FIBRES

- Polymer materials transparent to light are used in fabrication.
- PMMA POF : Poly methylene metha Acrylate polymer optic fibre.
- PFP POF : Per flurinate polymer
  - → high tensile strength
  - → larger bandwidth
  - → core diameter 10 to 20 times that of glass fibres
  - dis → higher attenuation.
- Application :
  - → cable TV
  - → short distance applications.

THURSDAY 23/08/2018

FABRICATION OF FIBRE :



PROCESSES OF FABRICATION :

1. OVPD : Outside vapour phase deposition.

2. VAD : Vapour phase axial deposition

3. MCVD : Modified chemical vapour deposition

4. PCVD : Plasma activated CVD

5. DCM : Double crucible method.

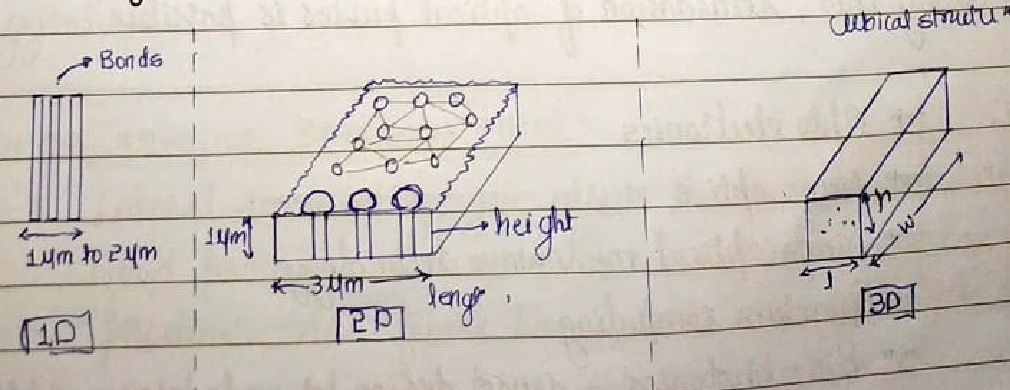
Generally there are two forms of fabrication
a) Direct fabrication
b) Indirect fabrication.

→ PHOTOMIC CRYSTALS :

- They are artificial multidimensional periodic structure of photons of quantum energy.

- BP : "Band of photons" is an optical theory used to understand the photonic crystals.

- For analysis, consider 1D, 2D and 3D



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Optical crystal lattice consists of "Brillouin" structure or zones. of unit cells which are of nm dimension

* Behaviour of light through photonic crystals are analysed by transforming Maxwell's equations to Eigen value vectors' equations.

* Applying periodic boundary condition and solving using computational methods.

* Photonic band gap energy or forbidden band gap is required to shift photons from valence to conduction band.

* If in a photonic crystal, photonic band gap is predominant (similar to semiconductor in materials) light cannot propagate through this level.

* By constructing dense forbidden gap, photonic crystals, light retardation is possible ie free space velocity of light ie $3 \times 10^8 ms^{-1}$ is changed to "zero"

This is called "light stopping condition" in photonic crystals.

* Super prism phenomenon is manifestation of scattering of light in a forbidden gap. where light propagation is possible without any guiding medium ie. concept of negative refraction, negative dielectric constants

* Using this, retardation of optical pulses is possible.

APPLICATIONS:
- → Opto electronics
- → Nano optics
- → Nano optical microwave technology
- → Quantum computing
- → Bio-photonics - sensor design for endodermy application.

- nano acoustics
- nano lasers
- photonic integrator circuit chips.

- SPECIALITY FIBRES OR HIGH PERFORMANCE FIBRE:

By considering parameters like attenuation, dispersion, polarization, tensile strength etc we can design special fibres.

1. DISPERSION COMPENSATED FIBRE
   - Dispersion shifted fibre
   - dispersion flattened fibre.

- large bandwidth - GHz
- large bandwidth - distance product - GHz km
- large bit-rate

2. POLARISATION MAINTAINING FIBRE:

- Waveguide imperfections, intrinsic-extrinsic absorption, attenuation and bending alters mode patterns or linear polarisation pattern.

- This reduces the optical power output over the given link length.

- Using proper fabrication processes "polarization can be conserved throughout the link length" in optical interferometers, optical sensors, gyroscope.

3. HIGH TENSILE STRENGTH FIBRE:
   - Lateral stress or fatigue affects the modal characteristics.
   - Good protective coating is necessary to prevent core deformation.
   - "pristine" silica fibres have tensile strength of 7 to 10 Gpa.

* Epoxy crylate, Urathane crylate are the coating materials used to produce compressible jackets for fibres.

* Underground duct applications.

* Satellite transponders.

4) LARGE NUMERICAL APERTURE FIBRES :-

By reducing R·I of cladding and propotionally R·I of core fractional refractive index (Δ) can be optimised.

(0.8 to 0.97 possible)

normal (0.3 to 0.7)

Important in optical amplifiers
laser amplifiers
opto couplers.

5) DND {DIRECT NANO PARTICLE DEPOSITED} FIBRE.

Incorporating rare earth materials enhances optical properties of fiber.

6) MACROHOLE FIBRES or MICRO STRUCTURED FIBRES

Using the "forbidden band gap" in photonic crystal, velocity modulation is possible.

7) MULTICORE FIBRES :

* Using multi coaxial cores, cladding loss can be minimized.

* Used in image fibres.

(c) ... if $\Delta = 0.1\%$?

3. Light traveling in air strikes a glass plate with an angle of incidence of 57°. If the reflected and refracted beams make an angle of 90° with each other,...
   (a) ... calculate the refractive index of the glass.
   (b) What is the critical angle for this material if the light travels from glass into air?
4. A point source of light is located 1 m below a water-air interface. Find the radius of the light circle seen by an observer positioned over the source (outside of the water). The refractive index of water is 1.333.
5. (a) Consider a fiber with a 100 μm core diameter and a 140 μm cladding diameter. If $n_1 = 1.48$ and $\Delta = 1\%$, calculate the V-parameter if the operating wavelength is 850 nm.
   (b) ... if the wavelength is 1300 nm?
   (c) Find the value of V at a wavelength of 850 nm if the diameter of the core is 50 μm?
6. (a) Calculate the number of modes for each case described in the previous problem.
   (b) Calculate the percentage of the optical power that is carried in the cladding for each case described in the prior problem.
7. (a) Calculate the numerical aperture of a step-index fiber having a core index of 1.47 and a cladding index of 1.45.
   (b) Find the value of the largest angle made by a ray that is accepted by the fiber if the outer medium is air.
   (c) ... if the outer medium is water? ($n = 1.33$)
8. (a) Determine the mode parameter V at 820 nm for a step-index fiber with a 50 μm core diameter, $n_1 = 1.47$ and $n_2 = 1.45$.
   (b) How many modes will propagate in this fiber at 820 nm?
   (c) ... at 1300 nm?
   (d) What percentage of the optical power is flowing in the cladding for each operating wavelength? Pd
9. (a) Find the core diameter required to ensure single-mode operation of a step-index fiber with $n_1 = 1.485$ and $n_2 = 1.480$ at a wavelength of 820 nm. At 1300 nm?
   (b) What are the NA and θ_{max} for this fiber?
10. (a) Design a single-mode step-index fiber for operation at 1300 nm with a fused silica core ($n_1 = 1.458$). Find n_2 and the diameter of the core.
   (b) Is the fiber still single-mode at 820 nm? If not, how many modes are there?
   (c) Calculate the cutoff wavelength λ_c.
11. (a) Consider a step-index fiber with a core diameter of 50 μm, a core index of 1.450, and a fractional index difference of 1.3%. Find the values of the V-parameter and NA of the fiber if the operating wavelength is 820 nm.
   (b) Does the number of modes in the fiber increase or decrease if n_1 increases?
   (c) ... if λ increases?
12. A step-index fiber has $n_{core} = 1.450$, $n_{cladding} = 1.440$, and will operate at 820 nm.
   (a) Find the diameter of the core that will ensure single-mode operation.
   (b) If the core diameter is 50 μm, how many modes will the fiber have?
   (c) Calculate the numerical aperture of the fibers in parts (a) and (b).

(8)

13. Calculate V and the numerical aperture of a step-index multimode fiber if $n_1 = 1.450$, $\Delta = 1.3\%$, $\lambda_0 = 0.82\ \mu m$, and $a = 25\ \mu m$.

14. Design a single-mode fiber (with $V = 2.3$) for operation at 1300 nm with a fused silica core ($n_1 = 1.458$). The numerical aperture of the fiber is to be 0.10.

    (a) Find the cladding index n_2 and the radius a of the fiber.

    (b) Calculate the approximate number of modes in the fiber for operation at 820 nm.

15. Using a computer, plot the power-law refractive index profile from n_1 to n_2 vs. radial position for $g = 1, 2, 4, 8$ and ∞. Assume a core diameter of 50 μm, $n_1 = 1.480$, and $\Delta = 1.00\%$.

16. (a) Calculate the number of modes in a 50/125 graded-index fiber having a parabolic index (i.e., $g = 2.0$), $n_1 = 1.485$ and $n_2 = 1.460$ at an operating wavelength of 820 nm.

    (b) ... at a wavelength of 1300 nm?

    (c) Calculate the number of modes in an equivalent step-index fiber at both wavelengths.

17. Prove Eq. 2.15 on page 19 by applying Snell's law at the fiber input face for the ray that meets the critical angle condition at the core-cladding interface. For generality, assume that the medium outside the fiber has an index n_0 and then check the equation for $n_0 = 1$.

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(B) Fibers with internal electrodes :

Including nano structure electrodes in fibre, both optical and electrical properties can be optimised.

Applications :

- Defence, ONGC, ISRO where signal security is important.
- Realization of optical filters.
- Nano optical MUX or DE-MUX
- Nano fiber sensors.
- fiber for broadband and internet applications.
- Submarine hydrophones.

QUESTIONS

1. Numerical aperture of SIF is 0.2 and it supports approximately 1000 modes at a wavelength of 850nm. Find the core diameter, if wavelengths are changed to 1320 and 1550nm. How many modes will the fibre support and what is the inference?

2. Core diameter of SIF is 50μm, $\eta_1 = 1.48$, $\Delta = 0.01$. If operating wavelength is ~~1300~~ 1350nm, find normalized frequency parameter, number of ~~f~~ modes supported by fibre and cutoff wavelength for single mode operation. If Δ is reduced to 0.3%, what happens to number of modes in fibre and what fraction of power propogates in cladding.

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2 TRANSMISSION CHARACTERISTICS OF OPTICAL FIBRE, SOURCES & DETECTORS 24/8/18

CO2: EXPLAIN AND ANALYSE THE PRINCIPLES OF SIGNAL DEGRADATION IN OPTICAL FIBRE, SOURCE AND DETECTOR WITH NECESSARY MODELLING.

- Signal degradation in optical fibres can be catagorised into two.
  a. within the fibre
  b. outside the fibre.

a. → WITHIN THE FIBRE

1) Attenuation loss of fiber loss
2) Dispersion loss
   - intramodal loss (single mode fibre)
   - intermodal loss (multi mode fibre)
   - polarisation modal loss (PMD)
3) Bending loss
   - macrobending loss
   - microbending loss
4) Scattering loss
   - Rayleigh
   - Raman
   - Brilinouium
(5) Radiation loss
(6) Absorption loss
   - intrinsic
   - extrinsic

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b. OUTSIDE THE FIBRE

i. Coupling or connector loss

ii. Splicing loss.

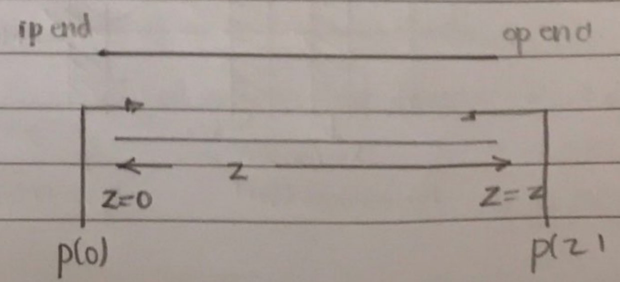
iii. Cabling loss

→ ATTENUATION LOSS

- Reduction in signal strength when optical signal propagates in the fibre, over a given length.

- FACTORS CONTRIBUTING TO ATTENUATION LOSS
  - a. Scattering loss - 90%
  - b. Absorption loss - 8%
  - c. Macrobending loss - 2%
  - d. Material of fibre
    - glass fibre - low attenuation
    - plastic fibre - high attenuation.
  - e. Wavelength or window region of operation.

- Attenuation of fibre can be determined by
  - a. Absolute method
  - b. Cutoff method : a fixed length of 1m is used for testing.



Attenuation in Nepers,

$$\alpha_N = \frac{1}{z} \ln\left[\frac{p(0)}{p(z)}\right] \quad \text{N/unit length} \rightarrow (1)$$

$$\alpha_{dB} = \frac{10}{z} \log\left[\frac{P(0)}{P(z)}\right] \quad \text{dB/unit length}$$

$$\alpha_{dB} \simeq 4.343\,\alpha_N$$

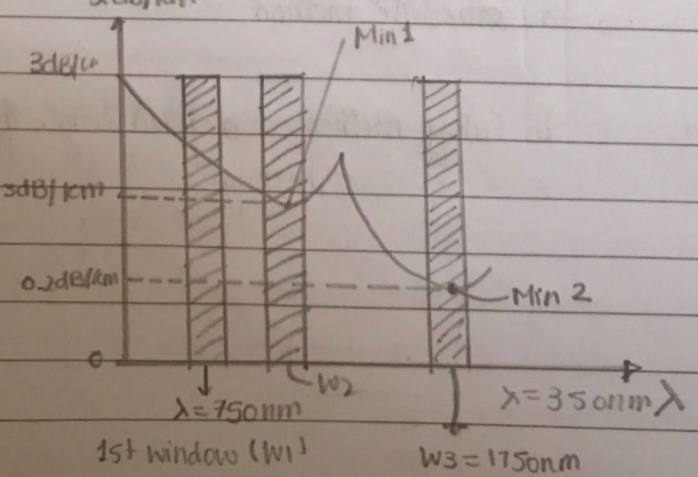
- LEDs, LDs, ILDs are able to ~~detect~~ source power of orders mW or few 10^3 of mWs. Hence better to represent p(0) & p(w) in dBm scale.

- $$P_{dBm} = 10\log\left(\frac{\text{power in mW}}{\text{1mW reference}}\right)$$

  $$1\text{mW} \rightarrow 0\,\text{dBm}$$

- from equation (1), $\frac{P(0)}{P(z)} = e^{\alpha_N z}$

  $$\boxed{p(0)_{dBm} = p(z)_{dBm} - \alpha_N z}$$



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- Fiber must be operated in W3 region to get low attenuation loss.

NUMERICALS:

Q1. Mean optical power launched into a 8 km length of fiber is 12μW and the output power measured is 3μW. Determine i) overall signal attenuation in dB.
ii. Overall signal attenuation for 10 km length optical link using same fiber with splices noticed at 1km intervals (assume each splicing contributes a signal loss of 1 dB)

Solution:

i) Total attenuation loss of fiber,

$$\alpha_{total} = 10 \log \left[\frac{P(0)}{P(8)} \right]$$

$$= 10 \log \left[\frac{12 \mu W}{3 \mu W} \right]$$

$$\alpha_{total} = 6.020 \text{ dB}$$

$\therefore$ attenuation per unit length $= \frac{\alpha_{total}}{\ell} = \underline{0.7525 \text{ dB/km}}$.

where $\ell = 8$ km

ii) for a 10 km length, total attenuation loss

$$\alpha_{10} = (\alpha)(\ell)$$

$$= (0.7525) \times (10)$$

$$\alpha_{10} = \underline{7.527 \text{ dB}}$$

→ There are 9 joints or splices in a link length of 10km (as they are separated by 1km)

$\therefore$ Total loss $= 9\text{dB} = \alpha_j$

$\therefore$ Total attenuation loss $= \alpha_{10} + \alpha_j$

$= 7.527 + 9$

$= \underline{16.527 \text{ dB}}$

25/8/18

2. ABSORPTION LOSS IN FIBRE

- Intrinsic : internal to fibre
- Extrinsic : external to fibre.

- intrinsic is related to material composition
- extrinsic is related to fabrication process.

a. INTRINSIC ABSORPTION :

REASONS : - Inherent characteristics of glass such that it absorbs at a certain wavelength

- Absorption is maximum in UV & IR regions

(i) In UV region because of transitional molecular atoms there will be absorption.

(ii) In IR region (7 to 12 μm) vibration of bonds (streching and contraction of bonds) regulation absorption.

b) EXTRINSIC ABSORPTION :

Reasons :

i) Impurity atoms added to fused silica as dopants causes absorption.

ii)
- Transitional metal ions from one bond to another
- OH ion concentration (expressed in ppb).

Ex : 1 ppb → 10 dB loss

2 ppb → 20 dB loss etc

predominant loss in dopants like cobalt, Ni, Cu, Chromium, Ferrous (Iron)

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- This can be overcome by proper glass fabrication methods

ii) Atomic defects
- Incompletely filled inner shells.
- weak covalent bonds
- missing atoms in crystal structures (even molecules)
- material inhomogenetis - rearer and denser variations.
- ~~unreacted~~ unreacted dopant silica.

iii) OH ion concentration (hydroxide ion concentration)
- peaking is maximum at 750nm, 950nm, 1400nm and are called as 'overtones in windows'

$$\boxed{\alpha_{UV} = \frac{154.2x}{46.6x+60} \times 10^{-2}\ e^{4.13/\lambda} \text{ Nepers.}}$$

where,

x = mole fraction

$$\alpha_{IR} = 7.81 \times 10^{11}\ e^{-48.48/\lambda} \text{ Nepers.}$$

3. SCATTERING LOSS

- Types
  - Rayleigh → predominant (90%)
  - Raman → 10%
  - MIE } → negligible.
  - Brilonium }

→ Reasons for Rayleigh scattering.

i. Microscopic density variations in material of fiber (ie. core)
ii. Composition fluctuations - due to dopants
iii. Structural inhomogeneties in waveguides
(trapped air bubbles, unreacted materials, OH ion concentration etc.)

All the reasons give rise to refractive index variation with λ.

* Rayleigh Scattering :

"Scattering of light in material of path of signal when there are perterbuations of dimensions comparable to wavelength of signal".

Almost similar to sunlight scattering when it enters the atmosphere giving rise to "blue sky".

α due to scattering is difficult to be quantised because of randomness of photons.

FOR GLASS :

EXACT EQUATION

i. $\boxed{\alpha_{scat} \simeq \frac{8\pi^3}{3\lambda^4} (n^2-1)^2 K_B T_f \beta_T}$

where,

$\eta \to$ RI of medium

$K_B \to$ Boltzman's constant

$T_f \to$ Fictive temparature of glass

(Temparature at which molten silica solidifies into glass)

$\beta_T \to$ Isothermal compressibility of glass.

APPROX EQUATION

ii. $\boxed{\alpha_{scat} \simeq \frac{8\pi^3}{3\lambda^4} \eta^8 p^2 K_B T_f \beta_T}$

where,

p : photon elastic constant

From equation (1) and (2), it is clear that except 'λ' all other parameters are constant for a given material.

$\boxed{\alpha_{scat} \propto \lambda^{-4}}$

ie. as $\lambda \uparrow$ $\alpha_{scat} \downarrow$

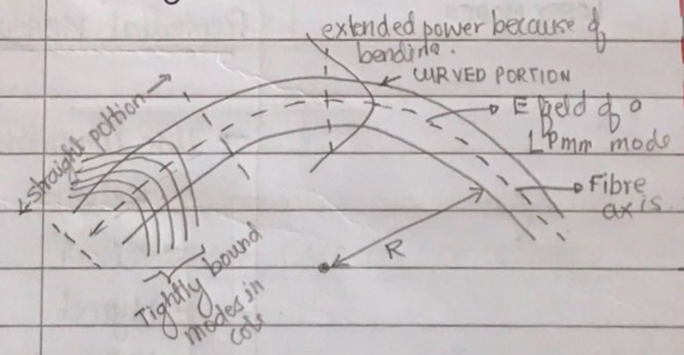
ie. by operating fiber in window 3, longer wavelength region, this loss can be minimised.

WEDNESDAY 29/8/2018

4. BENDING LOSS IN FIBRE

Macroscopic

- If radius of bending >> radius of curve. ie when fibre is used in underground duct application for cabling



Attenuation loss due to bending

$$\alpha_r = c_1 e^{-c_2 R}$$

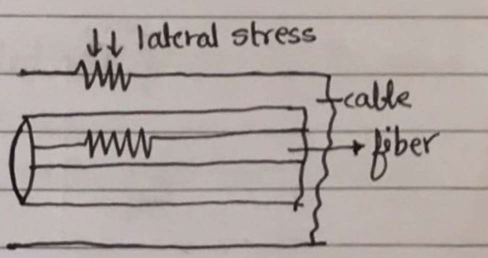
R is the radius of bending

Maximum limitation on bending is expressed in terms of Rc = critical radius of bending

Microscopic

When fibre is incorporated in cable.

- Majorly include waveguide imperfections.
- lateral stress and strain (fatigue) due to cabling.
- Manufacturing defects.



$$\boxed{\text{For SIF, } \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2-n_2^2)^{3/2}}}$$

No of modes in a bent fibre, will be smaller than that in a straight fibre

FOR STRAIGHT FIBRE : $N_0 = \frac{\alpha}{\alpha+2}(n_1 k a)^2 \Delta$

where,

$\alpha \rightarrow$ profile index no (from 2 to ∞)

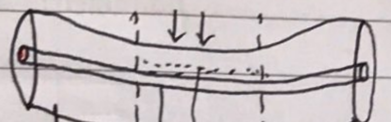
$K = \frac{2\pi}{\lambda}$

FOR BENT FIBRE :

$$N_{eff} \simeq N_{\infty}\left\{1 - \frac{\alpha+2}{2\alpha D}\left[\frac{2a}{R} + \left(\frac{3}{2\eta_2 kR}\right)^{2/3}\right]\right\}$$

$N_{\infty} \downarrow$ attenuation

$\left[\;\right] \downarrow$ LOSSY MODES



Two problems encountered in deformation of curve.

- loss of power in higher order modes.
- Mode coupling occurs between lower order and higher order modes, results in modal loss.

Remedial MEASURES

→ Use compressible jacket
- Kelvar
- Elvar
- Hytrel
- Verasulon

29/8/2018

5. CORE-CLADDING FIBRES.

→ We use slightly different refractive index materials for core and cladding.

→ Hence there will be different attenuation for the two regions.

ie. $n_1 \rightarrow \alpha_1$

$n_2 \rightarrow \alpha_2$

Attenuation loss for a given mode neglecting mode coupling.

$$\alpha_{VM} = \alpha_1 \frac{P_{core}}{P} + \alpha_2 \frac{P_{clad}}{P}$$

$$P_{cladd} = P - P_{core}.$$

- For SIF, $\alpha_{VM} = \alpha_1 + (\alpha_2 - \alpha_1) \frac{P_{cladd}}{P}$

(a)

$$\alpha_{VM}(r) = \alpha_1 + (\alpha_2 - \alpha_1) \frac{P_{core}}{P}$$

- For GRIN, $\alpha_{VM}(r) = \alpha_1 + (\alpha_2 - \alpha_1) \frac{n_1^2(0) - n_1^2(r)}{n_1^2(0) - n_2^2}$

INFORMATION CAPACITY OF FIBRES:

- Optical signal becomes progressively distorted as it propogates through a fibre.
- This is because of pulse spreading characteristic of the fibre (mixing of pulses)

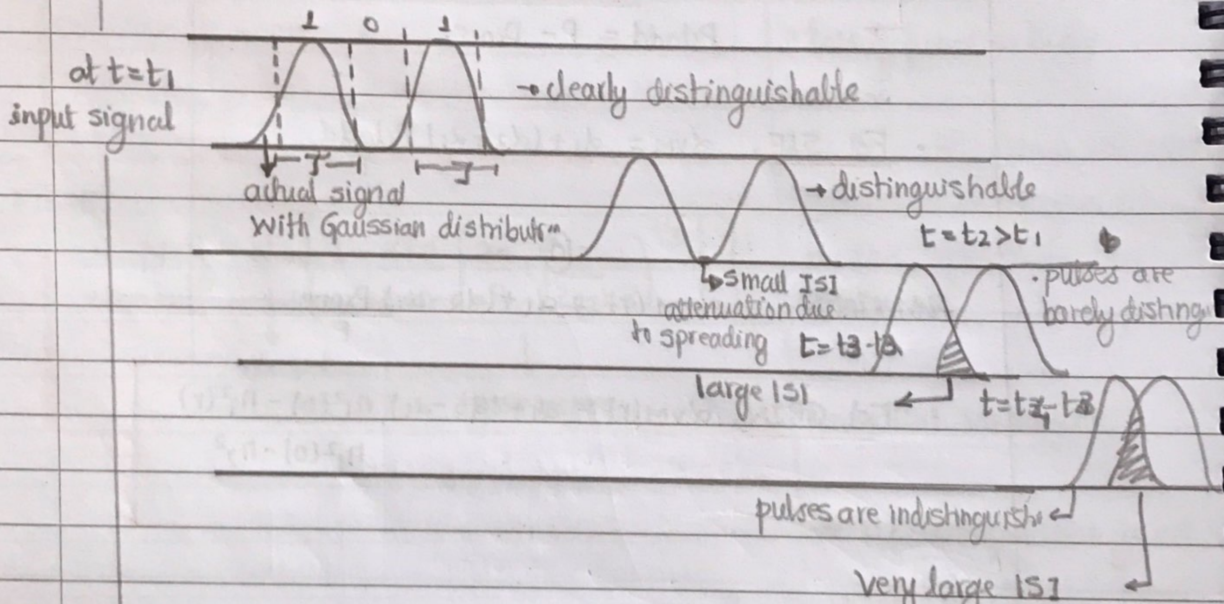
THURSDAY

30 / 8 / 2018

DISPERSION & INFORMATION CAPACITY :

→ **DISPERSION :**

- Spreading of signal in time-domain.
- Spreading is due to difference in propogation times of light rays that takesplace different path during propogation.
- Spreading causes ISI, which limits the information capacity of fiber.
- This distortion can be better studied by considering Vg (group velocity of modes)



- Information capacity of fiber gets limited because of ISI or pulse spreading
  - → Bandwidth - distance product (Modulated bandwidth - distance product)
  - → Optical or electrical bandwidth
  - → Bit rate.

__/__/__

If

$\tau \rightarrow$ average pulse duration (ideal)

$\Delta \rightarrow$ rms pulse width having Gaussian distribution (practical)

Without ISI, maximum bit rate is possible

$$\boxed{B_T \simeq \frac{0.2}{\Delta} \text{ bps}}$$

with tolerable ISI,

$$\boxed{B_T \simeq \frac{1}{2\tau} \text{ bps}}$$

For NRZ transmission,

$$\boxed{B_T = 2B}$$

For RZ transmission

$$\boxed{B_T = B}.$$

GROUP VELOCITY:

→ ASSUMPTIONS:

i. Modulated input signal from source excites all modes.

ii. Each mode contains number of spectral components.

As mode propogates independently & takes different path and hence undergoes different time delay (τ_g) & group delay.

If L is the distance travelled by a mode along the fiber

Hence,

$$\frac{\tau_g}{L} = \frac{1}{V_g}$$

$$\frac{\tau_g}{L} = \frac{1}{c}\frac{d\beta}{dk} \quad \rightarrow (1)$$

where

- $c \rightarrow 3\times10^8$ m/s
- $\beta \rightarrow$ propogation constant
- $k \rightarrow$ phase constant $= 2\pi/\lambda$

Substituting for K and differentiating

K = phase constant $= \frac{2\pi}{\lambda} = \frac{2\pi f}{c} = \frac{w}{c}$

$\frac{\tau_g}{L} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}$ → (2)

$$\boxed{V_g = c\left(\frac{d\beta}{dk}\right)^{-1}}$$

$$\boxed{V_g = \left(\frac{d\beta}{dw}\right)^{-1}}$$

From equation (1) and (2), we can see that, group delay (τ_g) and group velocity (V_g) are functions of λ.
ie.

each spectral component takes different time to travel along the fiber (ie τ_g) and have different velocity (ie V_g). This causes pulse spreading.

Amount of pulse spreading

→ in a fiber is measured in terms of dispersion factor (D)
→ 'D' is a function of spectral width of source (Range of λ over which light output of a source is optimum)

$$\boxed{D = \frac{1}{L}\frac{d\tau_g}{d\lambda} = \frac{d}{d\lambda}\left(\frac{1}{V_g}\right)}$$

↓ spectral width of source

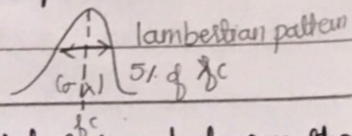
→ unit of D is psec/nm-km

or

psec/km-nm.

DISPERSION IN SINGLE MODE & MULTIMODE FIBRE.

(a) Dispersion in SM fibre is called Intramodal or dispersion within the mode.



(b) Dispersion in MM fibre is called 'Intermodal' or dispersion between the modes.

a) INTRAMODAL OR CHROMATIC OR GROUP VELOCITY DISPERSION (GVD)

In a mode there will be no spectral components, which represents the colour content (chroma) and hence chromatic since modal velocity (v_g) varies wrt λ.

Reasons for dispersion.

(i) Sources have limited or narrow bandwidth, rms spectral width, σ_λ in 5% of central wavelength of output pattern

for LED, $\sigma_\lambda = 40nm$

for LD and ILD, $\sigma_\lambda = 1$ to $2nm$.

(ii) Material dispersion

- RI of material varies wrt λ, this varies τ_g and hence v_g.
- Mathematically, Material dispersion.

$$\boxed{\frac{\tau_g}{L} = \frac{-\lambda^2}{2\pi c}\frac{d\beta}{d\lambda}}$$

where,

$$\beta = \frac{2\pi\eta(\lambda)}{\lambda}$$

Since η varies wrt λ

Hence, τ_g due to material dispersion

$$\boxed{\tau_{mat} = \frac{L}{c}\left(\eta - \lambda\frac{dn}{d\lambda}\right)}$$

RMS pulse spread due to material dispersion,

*

$$\sigma_{mat} = \left| \frac{d\tau_{mat}}{d\lambda} \right| \sigma_\lambda$$

$$\sigma_{mat} = \frac{\sigma\lambda^2}{c} \left| \lambda \frac{d^2 n}{d\lambda^2} \right|$$

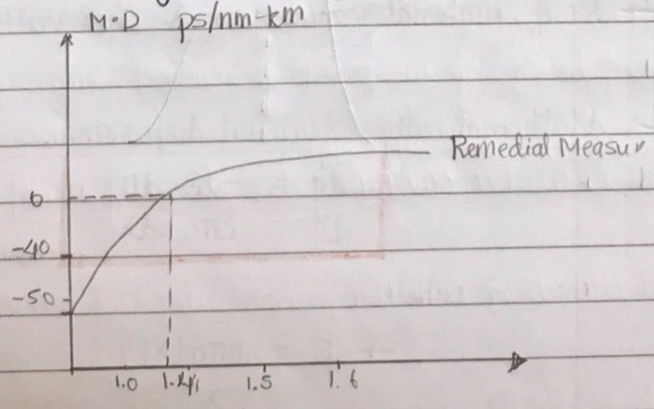
$$\sigma_{mat} = \sigma_\lambda L \underbrace{D_{mat}(\lambda)}_{\text{dispersion factor due to material dispersion}}$$

Hence,

$$D_{mat}(\lambda) = \frac{\lambda}{c} \left| \frac{d^2 \eta}{d\lambda^2} \right|$$

REMEDIAL MEASURES :

- → Use Narrow Spectral Width Sources
- → Operate at higher wavelength



NUMERICAL (ON RAYLEIGH SCATTERING)

__/__/____

Q) Core refractive index of a silica fiber is 1.46, fictive temperature of glass 1400° K). Isothermal compressibility of material $7\times10^{-11}\ m^2/N$, photon elastic constant of material is 0.29

Determine Rayleigh attenuation coefficient at

a. 0.63 μm

b. 1 μm

c. 1.3 μm

Assume, Boltzman constant = $K_B = 1.38\times10^{-23}$ J/m.

Solution :

WKT, $\boxed{\alpha_{scat} = \frac{8\pi^3}{3\lambda^4} n^8 p^2 K_B T_f \beta_T}$; $p = 0.29$

$$\alpha_{scat} = \frac{8\times\pi^3\times(1.46)^8\times p^2\times(1.38\times10^{-23})\times1400\times7\times10^{-11}}{3\lambda^4}$$

$$\alpha_{sat} = \frac{1.9415\times10^{-28}}{\lambda^4} \rightarrow (1)$$

i) for,

a. $\boxed{\lambda = 0.63\times10^{-6}}$

$$\alpha = \frac{1.9415\times10^{-28}}{(0.63\times10^{-6})^4} = 1.232\times10^{-3}\ m$$

b. $\lambda = 1\mu m$, $\alpha = 1.9415\times10^{-4}$ m

c. $\lambda = 1.3\mu m$, $\alpha = 6.7977\times10^{-5}$ m

(ii) at $\lambda = 63\mu m$, $\alpha_s = 1.2\times10^{-3}$ m

then

transmission due to scattering = $\boxed{T_{loss} = e^{-\alpha_s L}}$ **

Let L = 1km

$$T_{loss} = e^{-1.2\times10^{-3}\times1000m}$$

$$\simeq 0.30119$$

Scanned with CamScanner

___/___/_____

Attenuation due to scattering in dB/km

$$\boxed{T_{loss(dB)} = 10 \log \frac{1}{T_s}}$$

$T_{loss(dB)} = +5.2115$
↳ loss

(b) at $\lambda = 1\mu m$, $\alpha = 1.9415 \times 10^{-4}/km$.

$T_{loss} = e^{-\alpha \times L} = 0.8235$

$T_{loss_{dB}} = 0.843 dB$.

(c) at $\lambda = 1.3\mu m$, $\alpha = 6.7977 \times 10^{-5} m$

$T_{loss} = e^{-\alpha \times L} = 0.9342$

$T_{loss(dB)} = 0.295 dB$

INFERENCE,

as λ increases, there is a significant decrease in T_{loss}.

5/9/2018

2. WAVEGUIDE DISPERSION

This occurs because of imbalance of optical powers in core & cladding region.
ie: 80% of power flows in core-~~cladding~~ which is narrow and travels slower.
20% of power flows in cladding which is wide and travels fast.

→ Due to this rate of arrival of signal at output is different.

→ Here R.I is assumed to be independent of λ.

→ Waveguide dispersion delay

$$T_{wg} = \frac{L}{c}\frac{d\beta}{dt}$$

$$= \frac{L}{c}\left\{ \eta_2 + \eta_2 D \frac{d(Kb)}{dK} \right\}$$

b is normalized propogation constant.

$$= \underbrace{\frac{L}{c}\left\{ \eta_2 \right.}_{\text{constant}} + \underbrace{\left. \eta_2 D \frac{d(Vb)}{dV} \right\}}_{\text{Group delay due to waveguide dispersion.}}$$

Intramodal delay,

$$\Delta t_{mod} = T_{max} - T_{min}$$

$$\simeq \frac{n_1 \Delta L}{c}$$

INTERMODAL

→ predominant in multimode fibers

→ For a given wavelength of ~~operation~~ optical signal, different modes have different group velocity ie faster modes can catch up with slower modes as they propogate through the fiber.

→ This causes mode coupling, and the resultant mode travels with average speed.

⇒ POLARISATION MODAL DISPERSION:

→ Occurs due to modal variations over a distance. Important in long distance communication

→ PMD is due to two factors

i. Internal

Geometric irregularities core diameter variations,
material inhomogeneties,
internal stress,
strain.

ii External

- due to cabling of fiber.
- bending
- twisting
- pinching of fiber.

→ Main reason for PMD is birefringenes or bifringence. ie. RI of material depend on direction of polarization.

→ PMD causes variation in v_g and hence spreading.

→ PMD randomly varies wrt. temparature

Delay due to PMD is

$$\langle \Delta \tau_{PMD} \rangle = D_{PMD} / \sqrt{L} \rightarrow ps/\sqrt{km}$$

ensemble

dispersion factor due to PMD.

Typically for a fiber,

$$0.1 < \Delta \tau < 1 \quad ps/\sqrt{km}.$$

—/—/—

Modal dispersion in GRINF :

- Generally GRIN fibers are of multimode type
- Total rms pulse boundary due to modal dispersion is combination of itra and intermodal dispersions.

RMS pulse spreading,

$$\boxed{\sigma = \sqrt{\sigma_{intra}^2 + \sigma_{inter}^2}}$$

Pulse spreading in SIF,

$$\boxed{\sigma_{SIF} \simeq \frac{n_1 \Delta L}{2\sqrt{3}c}}$$

Similarly pulse spreading in GRIN

$$\sigma_{GRIN} \simeq \frac{n_1 \Delta^2 L}{20\sqrt{3}c}$$

$$\frac{\sigma_{SIF}}{\sigma_{GRIN}} = \frac{10}{\Delta} \quad (\text{Typically } \Delta = 1\%)$$

$$= 10^3$$

Similarly

$$\sigma_{GRIN} = \frac{(\sigma_{SIF})}{10^3}$$

Capacity of GRIN fiber is 1000 times better than SIF because of smaller spreading.

Example : For SIF $\sigma_{SIF} = 14 nsec/km$

For GRIN $\sigma_{GRINF} = 14 nsec \times 10^{-3}/km$

Le (EQUILIBRIUM LENGTH)

Mode coupling occurs over an initial length in a waveguide fiber (Le) after which it is insignificant.

If σ_0 = pulse spreading in the absence of mode coupling.
σ_c = pulse spreading under strong mode coupling.

Spreading which causes delay

$$\Delta \tau = L \Delta (\tau/L) \text{ for } L < L_e$$

$$= \sqrt{L L_e}\, \Delta(\tau/L) \text{ for } L > L_e.$$

LABORATORY

1. Design, simulate, demonstrate the working of communication circuits and compare the results

   [mapping
   m-derived filters
   TDM, Mixer
   Attenuators]

2. Setup, simulate, demonstrate the working of few digital MODEMS (using kits/components)

   [ASK, FSK,
   BPSK, QPSK,
   DPSK]

3. Characterize few antenna using available sf-wave (Antenna experiments)

4. Work in groups and use available software / tools to realize an antenna few advanced modulation methods and prepare a document and conclude accordingly

   [PCM, ADM,
   CDMA, antenna]

Evaluation process

→ Each experiment for 40 Marks

AC1	-	PREPAREDNESS	(8 MARKS)
AC2	-	CONDUCTION	(8 MARKS)
AC3	-	VIVA	(8 MARKS)
AC4	-	REPORT	(8 MARKS)
AC5	-	RESULTS, INTEPRETATIONS & CONCLUSION	(8 MARKS)

WRITING FORMAT

AIM :

COMPONENTS :

THEORY :

DESIGN (if any) :

DIAGRAM

CONDUCTION PROCEDURE :

RESULTS, GRAPHS, WAVEFORM, INFERENCE

→ Final lab marks $= \frac{20}{2} = 10$ Marks .

→ CIE → 40 Marks

Total : $40 + 10 = 50$ MARKS .

FORMAT FOR PRINTED

- Calibri
- Headings - 12
- Sub heading - 11
- Text - 10

EXTRA

→ Simulation and testing of antenna .

_/_/_

PROBLEM

Q Multimode SIF has core diameter of 50 μm. Intermodal dispersion is limited to 10nsec/km. Find the numerical aperture of fiber, what is the maximum bit rate possible over a 10 km link length at an operating wavelength of 0.88 μm. Assume R.I of cladding is 1.45

Solution:

(i) ~~Numerical~~ Total pulse spreading

$$\tau = (\text{link length}) \times (\text{pulse spreading/unit length})$$

$$= 10\text{ km} \times 10\text{ nsec/km}$$

$$= 100\text{ns} = 0.1\mu s$$

WKT maximum ~~distance~~ bitrate possible without ISI is

$$B_T \simeq \frac{1}{2\tau} = 5\times10^6$$

For SIF, $\boxed{\sigma_s = \frac{L n_1 \Delta}{2\sqrt{3}c}}$ [IMPO: σ_s for SIF = 14ns/km

But, $\Delta = \frac{n_1 - n_2}{n_1}$

$$\therefore \sigma_s = \frac{L\, n_1 (n_1 - n_2)}{n_1 . 2\sqrt{3}c}$$

$$\boxed{\sigma_s = \frac{L(n_1 - n_2)}{2\sqrt{3}c}}$$

$$\therefore (n_1 - n_2) = \frac{\sigma_s \times 2\sqrt{3}c}{L} = \frac{10\times10^{-9}/\text{km} \times 2\times\sqrt{3}\times3\times10^8 \text{m/s}}{10\text{ km}}$$

$$= 1.039$$

and $n_2 = 1.45$

$\therefore n_1 - n_2 = 1.039$

$n_1 = 2.489$

Numerical aperture $\simeq n_1\sqrt{2\Delta} = 2.27$

Substitute, η_1 value in $\Delta = \frac{n_1 - n_2}{n_1} = \frac{2.489 - 1.45}{2.489} = 0.4174$

Substitute obtained Δ in equation for NA

$NA = 2.27$

(b) V numbers and number of modes separated by fiber.

$$V = \frac{2\pi a}{\lambda}(NA) = \frac{2\pi(50\times10^{-6})(2.27)}{0.88\times10^{-6}} = 810.493$$

$$N \text{ of } M = \frac{V^2}{2} = 328.45\times10^3$$

Q. A light emmiting diode operating at 850nm has a spectral width of $\sigma_x = 45nm$. What is the pulse spreading of signal in nsec/km due to material dispersion. Assume $\left|\lambda^2 \frac{d^2\eta}{d\lambda^2}\right| = 0.0025$

Solution:

Material dispersion, $D_{mat} = -\frac{\lambda}{c}\frac{d^2\eta}{d\lambda^2}$

$M = |D_{mat}| = \frac{1}{c\lambda}\left|\lambda^2\frac{d^2 n}{d\lambda^2}\right|$

M → MD factor; $\left|\lambda^2\frac{d^2 n}{d\lambda^2}\right|$ → 0.0025

at $\lambda = 850nm$

$M = 9.8 psec/nm\text{-}km$

→ Pulse spreading due to material dispersion $= \sigma_{mat} = M \cdot L\sigma_x$

let L → unit distance = 1 km

$= 9.8\times10^{-12}\times1\times45\times10^{-9}$

$= 441 ps/km$

6/8/18

OPTICAL SOURCES:

↳ LED, LD, ILD

Basic requirements of a source are.

1. long life span with continuous operation.
2. line output of source must be modulated by wide range of frequencies.
3. Spectral width of source (σ_λ) must match to atleast one of the 3 windings for optimum performance.
4. Source must couple maximum power to fiber ie. maximum coupling efficiency or minimum coupling loss.
5. Spectral width of source must be as small as possible to suit single mode operation, since material dispersion is of function of σ_λ
6. ~~Devi~~ To maximize the efficiency (η), we must use low power supply.
7. Device must exhibit linear characteristics ie drive current as high output power to avoid intermodal distortions, harmonic distorting, Non linear distortion etc, it improves dynamic range of the device.
8. Device must be compatible with fiber and other optical components.
9. To work at high SNR, CNR or better BER, Po of source must be as large as possible.
10. High reliability, light weight and cheaper components.

LIGHT EMMITING DIODE (LEDs)

→ Basic principle : "Electro luminiscence" ie when ~~earth~~ each pair combines together near depletion layer, a photon is released (ie. radiative recombination)

→ Number of photon emmited depends on the number of each pair recombination

To ~~compromise the~~ improve the possibility of radiative recombination in lazer gun and double heterogeneous (DH) junction structures are used ie we improve optical confinement of carriers.

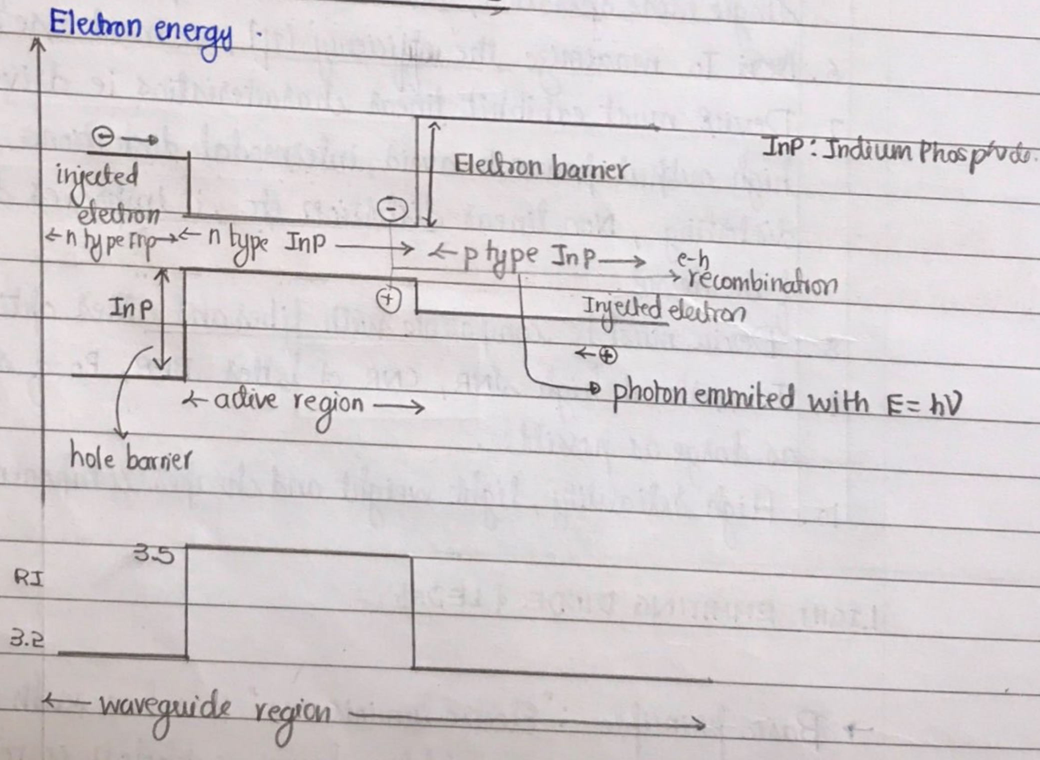
~~Daat~~,

→ CHAPTER 2 NUMERICAL
(continued from before)
If a lazer diode of spectral width 3nm is used as source, what is spreading due to material dispersion and what is inference.

7 Sept 2018

FRIDAY

DOUBLE HETEROGENEOUS STRUCTURE

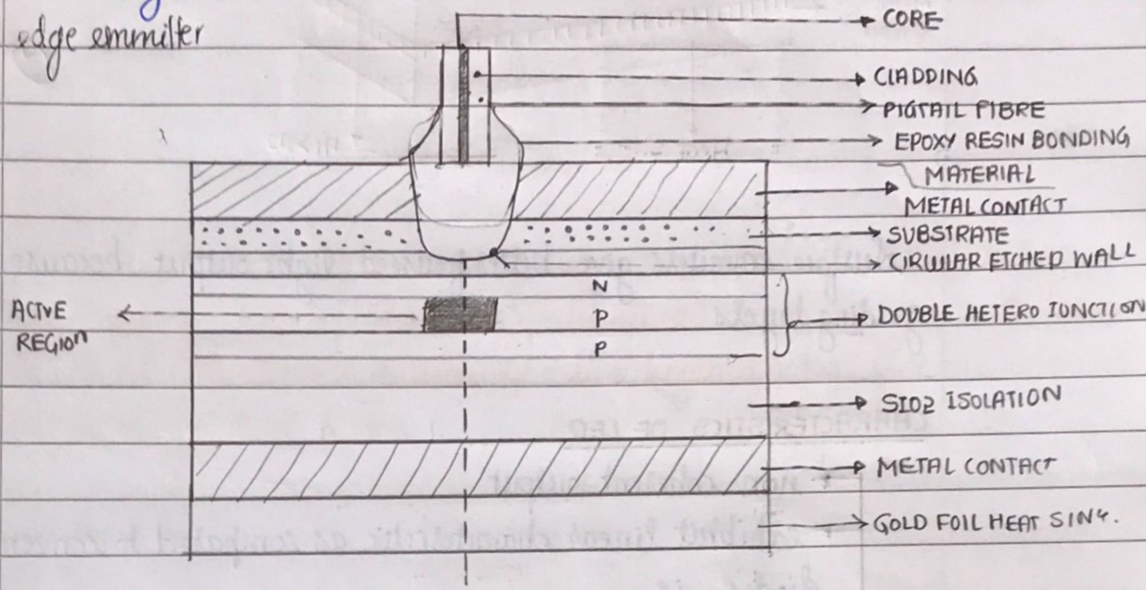


→ Heterogeneous junction is an interface between two adjoining single crystal semiconductor with different bandgap energies (E_g)

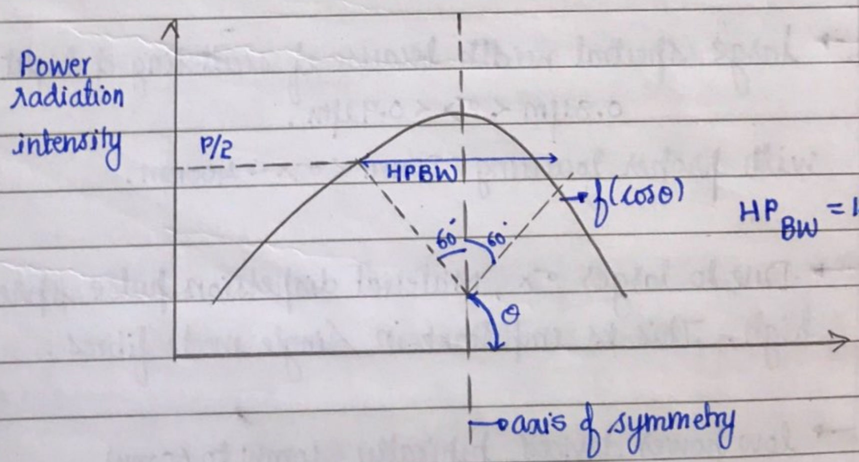
→ Double heterogeneous junction
- isotype (p-p, n-n)
- Anti isotype (p-n)

→ LED types
- surface emmiters
- edge emmiters.

edge emmitter

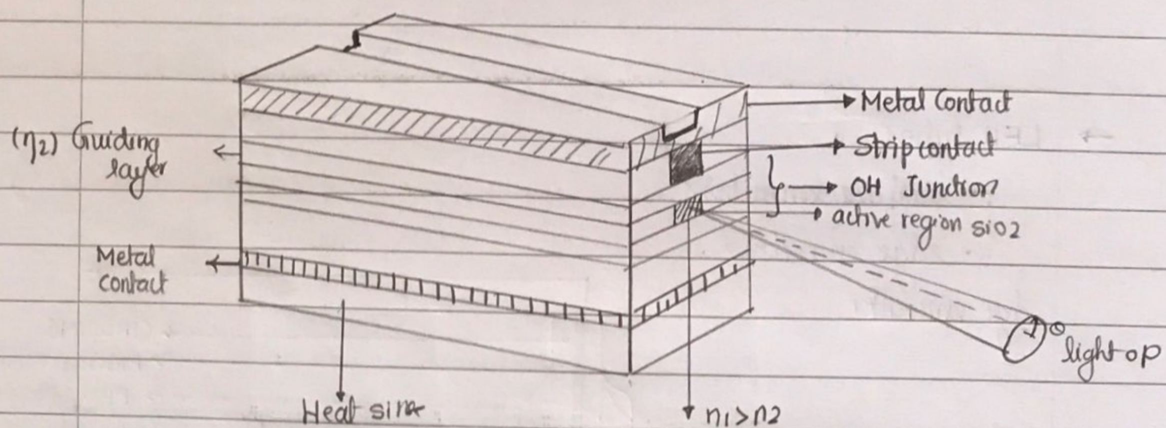


→ RADIATION PATTERN OF LIGHT OUTPUT is '<u>Lamberation</u>'



$HP_{BW} = 120°$

SURFACE EMMITER:



Surface emmiters give better focussed light output because of guiding layers

CHARACTERISTICS OF LED

- non coherent output
- exhibit linear characteristic as compared to conventional diodes ie.

$$\boxed{P_o \propto I_d}$$

- large spectral width because of scattering of light.

  $0.8\mu m < \sigma_\lambda < 0.9\mu m$.

  with proper focussing $25nm < \sigma_\lambda < 400nm$.

- Due to larger σ_λ, Material dispersion pulse spreading is high. This is important in Single mode fibres.
- low power devices, typically 10mW to 60mW.
- More reliable, higher coupling efficiency $\simeq$ 60 to 70%.

→ Temparature sensitivity.

- MATERIALS USED : Direct band gap materials like GaAs, GaInAs, GaP etc, Rarely Si and Ge.

→ Maximum bandwidth 140MHz → 140Mbps bitrate.

→ LEDs are characterised by quantum efficien (η_q) as
  - i. internal
  - ii. external.

NUMERICAL

A SM fibre has cladding RI of 1.48 and $\Delta = 0.2\%$. If operating wavelength is 1320nm. Determine, pulse spread due to waveguide dispersion and what is the total dispersion, for a link length of 10km. Assume waveguide dispersion factor is 0.26.

SATURDAY | 8/9/2018

→ PERFORMANCE PARAMETERS OF LED

1) Quantum efficiency η_q
   - i. Internal
   - ii. external

This determines the high output produced for a given drive current & for a given electron-hole recombination, what will be the number of photons generated.

(i) $$\boxed{\eta_{int} = \frac{R_r}{R_r + R_{nr}} \times 100\%}$$

where

- R_r = Radiative recombination rate
- R_{nr} = non radiative recombination rate.

If η is the RI of the medium,

- T_r = radiative recombination time
- T_{nr} = non radiative recombination time.

then,

$$\boxed{R_r = \frac{n}{T_r}} \text{ and } \boxed{R_{nr} = \frac{n}{T_{nr}}}$$

$$\therefore \boxed{\eta_{int} = \frac{1}{1 + T_r/T_{nr}} \times 100\%}$$

Also if the bulk recombination rate of combination in active region, then

$$\boxed{\frac{1}{\tau} = \frac{1}{T_r} + \frac{1}{T_{nr}}}$$

→ If I is the input drive current for the LED, q is the charge then

$$\boxed{R_r \approx R_{nr} = \frac{I}{q}}$$

$$\therefore \boxed{\eta_{int} = \frac{R_r}{2I/q} \times 100\% \rightarrow \text{(approx)}}$$

for practical LED,

$$\boxed{\begin{gathered} R_r >> R_{nr} \\ \eta_{int} \simeq \frac{R_r}{I/q} \times 100\% \end{gathered}}$$

→ output power internally generated near active region.

$$P_{int} = R_r h\nu$$

ν → frequency of photon

h → Planck's constant

R_r → Radiative recombination rate.

$$= \left[\eta_{int} \times \frac{I}{q} \times h\nu \right]$$

EXTERNAL QUANTUM EFFICIENCY (η_{ext})

Due to opaqueness of guiding layers, some emmitted photons are reflected back, such that actual light output of LED is less than actual light output internally produced.

$$\eta_{ext} = \frac{\text{Actual light output of LED}}{\text{light generated internally}} \text{ or } \frac{\text{photon output of LED}}{\text{photon internally generated.}}$$

∴ Total power output $= P_o = P_{int} \, \eta_{ext}$.

MODULATION BANDWIDTH OF LED :

This is defined as the range of input modulating frequency over which output light of LED can be modulated without distortion.

This depends on the frequency response of LED.

Frequency response of LED depends on.

i. Doping level of active region.
ii. Junction stray capacitance.
iii. Carrier injection life time.

iv. Thickness of region.

Power output of LED can be written as

$$\boxed{P(\omega) = P(0)\left[1+(\omega\tau_L)^2\right]^{-1/2}}$$

$P(\omega)$, power output at given modulating frequency $\omega = 2\pi f$.
$P(0)$, power output without modulation.

Modulation bandwidth can be defined both in electrical and optical domain.

(a) Electrical modulation bandwidth :-

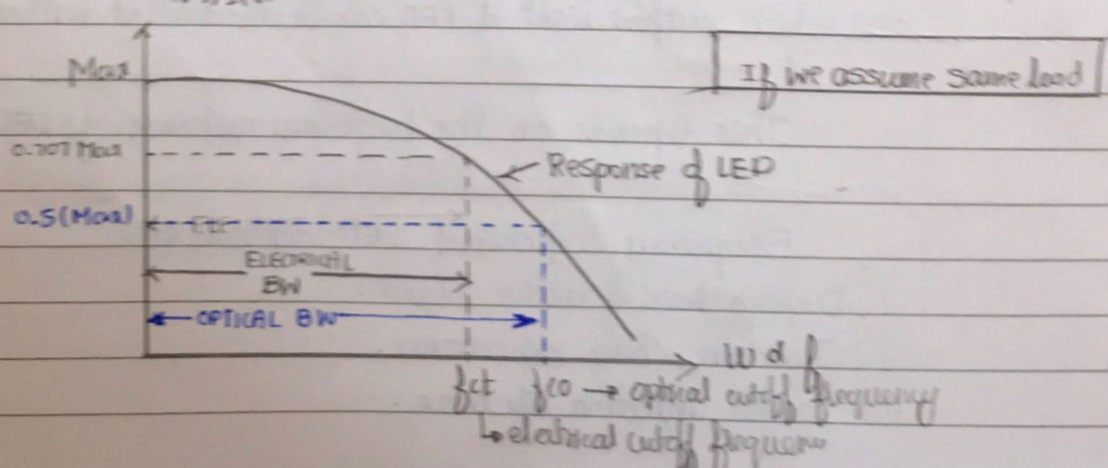
If $P(\omega)$ is the output power with modulation at a drive current of $I(\omega)$, then

$$\boxed{P(\omega) \propto I^2(\omega)}$$

Similarly, if $P(0)$ is the output without modulation with drive current of $I(0)$ then

$$\boxed{P(0) \propto I^2(0)}$$

$$\boxed{R_{electrical} = 10 \log \frac{P(\omega)}{P(0)} = 10 \log \frac{I^2(\omega)}{I^2(0)} = 20 \log \frac{I(\omega)}{I(0)}}$$



Half power point is,

$$\frac{P(\omega)}{P(0)} = \frac{1}{2} = \frac{I^2(\omega)}{I^2(0)}$$

$$\therefore \frac{I(\omega)}{I(0)} = \frac{1}{\sqrt{2}} = 0.707$$

b) Optical modulation bandwidth :

WKT, LED source exhibhits linear characteristics wrt input drive current.

ie

$$\boxed{\begin{array}{c} P(\omega) \propto I(\omega) \\ P(0) \propto I(0) \end{array}}$$

$$\boxed{R_{optical} = 10 \log \frac{P(\omega)}{P(0)} = 10 \log \frac{I(\omega)}{I(0)}}$$

$\therefore$ Half power optical point occurs when

$$\boxed{\frac{P(\omega)}{P(0)} = \frac{1}{2} = \frac{I(\omega)}{I(0)}}$$

LED TYPE	Modulation BW (MHz)	Internal Po generated (mW)	External Po obtained
Surface	60	<4	<0.2
Edge	200	<7	<1.0

14/9/2018

LASER DIODE

→ 2 types
- a. conventional
- b. ILDS (injection LDs)

→ LASER : Light Amplification Stimulated Emmission Radiation.

→ Electrons make transition from one energy level to another in an atom.

→ When they transit from low level to high level, they absorb energy, when they transit from high level to low level, they emit energy.

→ In laser diode, energy will be released in form of photon energy.

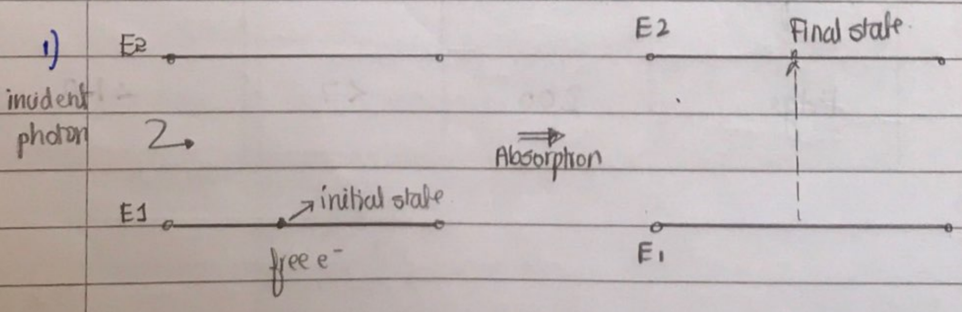
emmision
- spontaneous : few photons are released.
- controlled : more photons are released.

→ In LD, we have to do two things to get controlled emmision.

i. population inversion → making more number of charge carriers to be available at higher energy level.

ii. pumping : lifting charge carriers from low level to high level using an external source

1)



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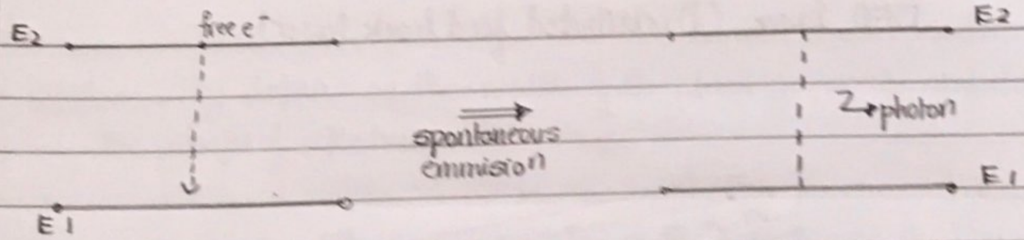

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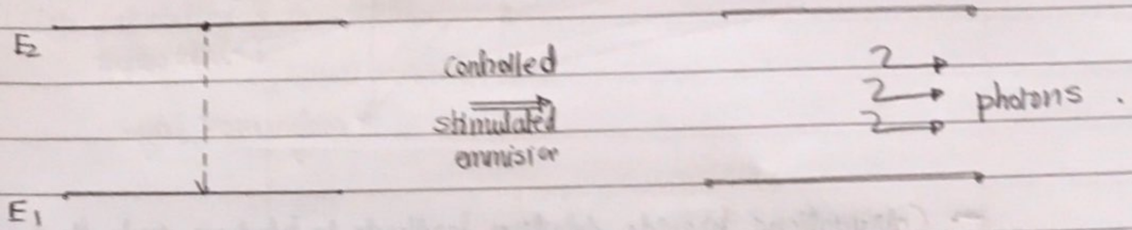
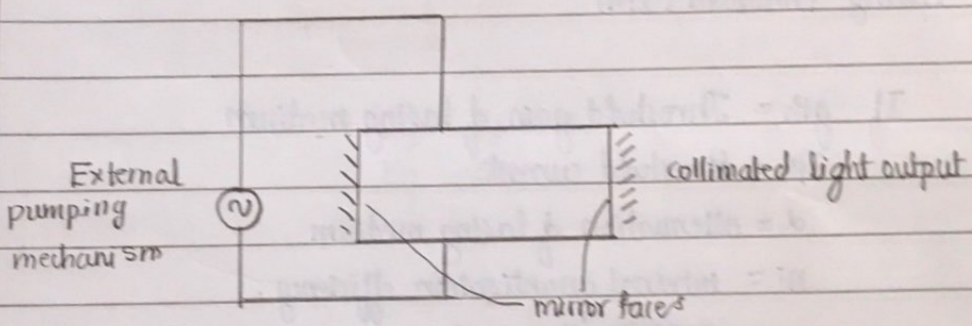
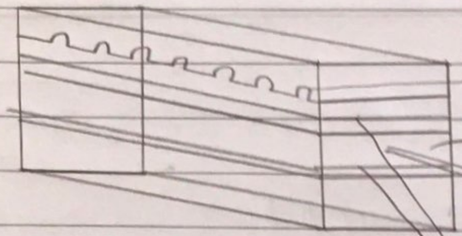


Lasing action is possible to produce a sustained equilibrium by using a "Fabry parrot cavity"



Initially due to spontaneous emmision
- a photon with energy $E = h\nu$ is created.
- photon carrier multiplication is possible because of constant feedback from ~~mirror~~ mirror facets.
- collimated light output is obtained

DFB laser (Distributed feed back laser)



- Corrugations provide selective feedback to photons such that multiplication is possible in the lasing medium.

- Light amplification occurs above some threshold drive current called "Lasing Threshold" (I_{th})

If g_{th} = Threshold gain of lasing medium
I_{th} = threshold current
α = attenuation of lasing medium
η_i = internal quantisation efficiency.
(typically 0.6 to 0.7)

then

$$\eta_{ext} = \frac{\eta_i (g_{th} - \alpha)}{g_{th}} \times 100\%$$

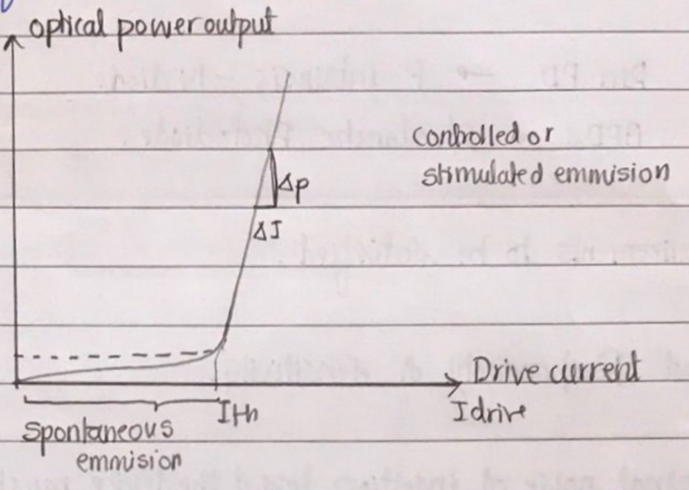
- Like LED, here also TE, TM, LF and hybrid modes are possible.

- modes in LDs are classified as longitudinal, lateral (LAM) and transverse modes (TM)

(i) LM: These are related to length of the cavity and determine the frequency components of the emmited spectrum, many LM are possible $\because L >> \lambda$

ii LAM: They depend on the width of the lasing cavity and determine the shape of spectrum.

iii Transverse modes: They are associated with EMF inside the lasing cavity. These modes are important because, they determine radiation pattern and Ith capability of the source.



$$\eta_{ext} = \frac{q}{E_g}\frac{\Delta P}{\Delta I} \times 100\%$$

$$\simeq 0.8065\,\lambda(\mu m)\,\frac{\Delta P(mW)}{\Delta I(mA)} \times 100\%$$

η_{ext} is typically 15 to 20%.

- mirror facets reflectivity determines the η_{ext}. By properly alligning the mirror facets, η_{ext} can be increased to 30 to 40%.

SINGLE MODE LASERS:

- By exiting only one mode in the cavity, it is possible to get single mode operation (one LM or one TM)
- They are used in long distance communication with SM fibers
- Spectral width drastically reduces to a fraction of λ so that modal dispersion can be reduced

- One limitation of SM fibers lasers is smaller power output (few mw) which requires smaller repeater spacing in long distance communication.

PHOTODETECTORS

These are transducers used at Reciever to convert light from fiber to photocurrent.

Pin PD → P-intrinsic-N diode

APDs → Avalanche Photodiode.

Requirements to be satisfied.

- Good Responsivity or sensitivity.
- Internal noise or insertion loss of the device must be small
- Juntion capacitance of depletion layer (∵ diode is operated in RB mode) must be as small as possible as it determines switching capability of device.
- Diode must have larger bandwidth capability to detect the signal.
- Characteristics must not change with temparature.
- Compatible dimension compared to fibre cross section
- Long continuous operating line.
- Suitable, semiconductors must be available for fabrication.

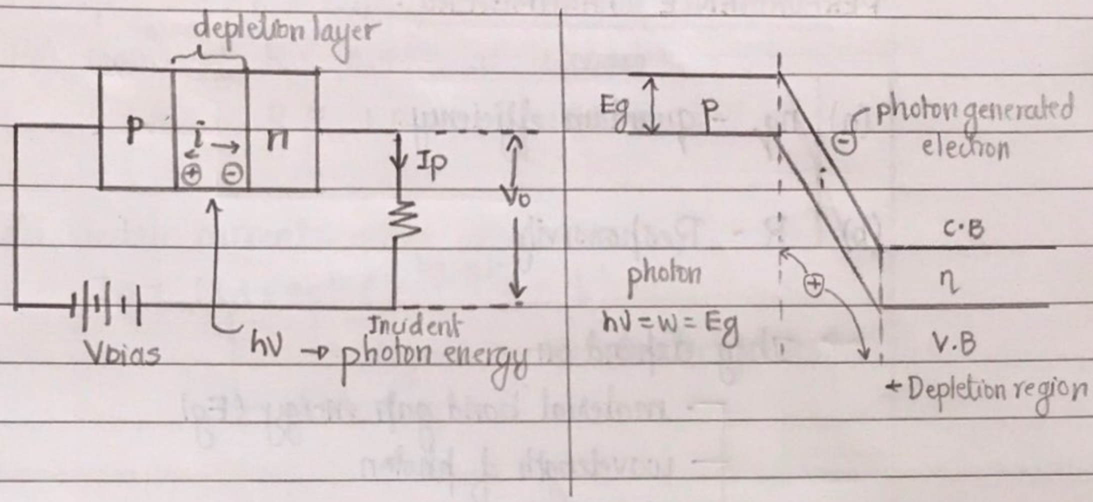
20 / 9 / 2018
THURSDAY

PHOTODETECTORS

- Of two types
  - a. PINS → P intrinsic - N type.
  - b. APDs → Avalanche photo detector.

- CONSTRUCTION

a. PIN photo diode



→ middle region is very lightly doped, such that ~~photodiode is operated in reverse bias region~~ it is almost intrinsic semiconductor. Photodiode is operated in revese bias region

→ E field across the junction is stored to produce electron-hole pairs for given ~~and~~ incident photon with $W >> E_g$.

→ Optical power absorbed by depletion layer is

$$p(x) = P_0 (1 - e^{-\alpha_s(\lambda) x})$$

Here $\alpha_s(\lambda)$ → absorption coefficient of i-region

$p(x)$ is the absorbed power over a distance 'x'

P_0 → incident optical power level.

$$P(w) = P_0 (1 - e^{\alpha w})$$

where w → width of depletion layer.

· Primary photocurrent produced by diode

$$I_p = \frac{q}{h\nu} P_o (1 - e^{\alpha_s w})(1 - R_f)$$

$R_f \rightarrow$ Reflectivity of i region at the point of incidence.

PERFORMANCE PARAMETERS :

(a) η_q - quantum efficiency.

(b) R - Responsivity

→ They depend on

- material band gap energy (E_g)
- wavelength of photon
- doping level
- thickness of depletion layer
- Absorption coefficient.

$$\eta_q = \frac{\text{number of electron hole pairs generated}}{\text{given numbers of incident photons}}$$

$$\eta_q = \frac{I_p/q}{P_o/h\nu} \times 100\%$$

$30\% < \eta_q < 95\%$.

→ mainly depend on 'w', by ↑w, η_q can also be increased. But R comes down due to depletion layer capacitance, hence compromise between both

$\Rightarrow$ R = photocurrent generated / for incident optical power

$$= \frac{I_P}{P_0} = \frac{\eta q}{h\nu} = 30\%$$

For Si → R = 0.65 A/W at 900nm
For Ge → R = 0.45 at 1300nm
For GaAs → R = 0.9 at 1300nm
R ≃ 1.0 at 1550nm

→ Photo electric current

$$I_P = (I_d + I_s)(e^{Vq/nKT} - 1)$$

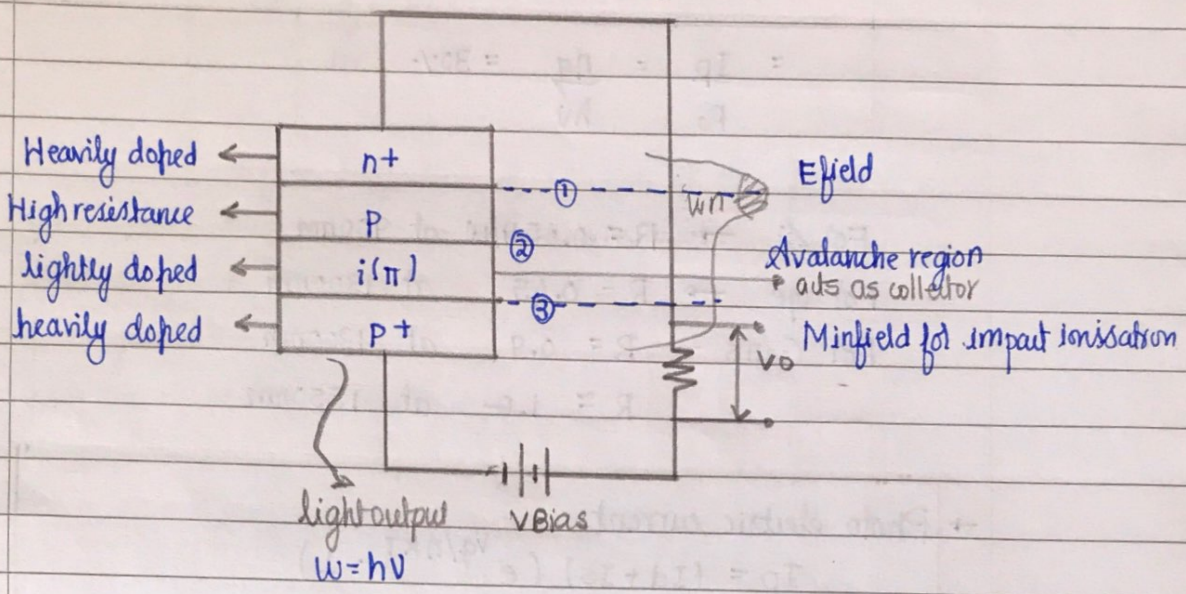
I_s ↳ signal current due to photons.
I_d ↳ dark current

Cutoff wavelength (λ_c)

- Any semiconductor material absorbs photon upto certain λ_{max}, which defines cutoff wavelength λ_c.
- Accordingly $\boxed{\lambda_c \simeq \frac{hc}{E_g} = \frac{1.24}{E_g}}$, where λ_c is in μm and E_g is in eV.
- λ_c is inversely proportional to E_g ie as $E_g \downarrow$ $\lambda_c \uparrow$

b) APD (Reach through structure)

· There are photodetectors with internal gear.



Main principles are
- Impact ionisation

• Avalanche x^n photo generated carriers travel into high field region where e-h pair has sufficient energy to release electron from covalent bonds by impact ionisation.

• These carriers gain sufficient level due to strong field, due to collision further x^n (transmission) of carriers possible.

• Photodiode is operated above breakdown region.

• Most of Vbias appears across junction ①

• Due to strong field, depletion layer widens and reaches to π region.

• These are photodiodes with internal gain.

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- If input is the unmultiplied photocurrent, Im is the multiplied photocurrent due to internal gain of photodiode then $M = I_m / I_P$

Internal gain of transmission factor of diode.

In APDs both coupling efficiency η_q and ~~Responsivity~~ are functions of 'M'

Example: $R = R_0 M$

R_0 → Responsivity of PIN PD.

Similarly $\eta_q = \eta_0 M$

Problem

Example: for GaAs photodiode,

$\eta_q = 60\%$

$\lambda = 900nm$

$P_0 = 0.5\mu W$

$I_m = 10\mu A$. Find M

Solution:

multiplied photocurrent ↲ $I_M = RP_0$ for APD

$$= \frac{\eta_q . P_0}{h\nu} = \frac{\eta_q \lambda}{hc} . P_0 = \frac{0.65 \times 1.6 \times 10^{-19} \times 900 \times 10^{-7} \times 0.5 \times 10^{-6}}{6.625 \times 10^{-34} \times 3 \times 10^{8}}$$

$$= 0.2 \mu A$$

COMPARISION OF PHOTODETECTORS

i) Comparision of Source :

	PARAMETER	LED	LD
i)	Principle	Radiative Recombination	Stimulated emmision.
ii)	Output beam	Non coherent	Coherent
		← Lambertian	→

iii	rms spectral width ($\sigma\lambda$) in nm	20 - 100	1 - 5
iv	data rate possible	low (Mbps)	very high. (Gbps)
v	transmission link length	shorter	longer.
vi.	coupling efficieny	very low	very high
vii.	compatible fibres	MM, SIF, GRINF	SM - SIF, GRINF Some extent MM GRINF
viii	lifetime (Hours)	2×10^5	1.4×10^4
ix.	Temparature sensitivity	very low	very high
x	Optical power output	linearly varies with drive current	linearly varies only above threshold.
xi	Drive current requirements (mA)	50 - 100 (peak)	$I_{th} \rightarrow$ 5 to 40.
xii	λ Range (over which source is operated)	0.66 to 1.65 μm	0.78 μm to 1.65 μm
xiii	Application	LAN, ALL (analog local loop) ↓ short distance communication	long distance communication

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Self Study.

* Compare PIN photodiode and APDs along similar lines.

22/9/2018

NOISE IN PHOTODETECTORS

- Photodetector is the first stage in an optical reciever which must introduce minimum internal noise and insertion loss.

- These parameters are important since they determine SNR or CNR of an optical Reciever.

SNR of reciever = Signal power from photocurrent of detector / PD noise power → amplifier noise power.

For larger SNR, denominator must be as small as possible.

→ IMPORTANT NOISE SOURCES IN PHOTO DETECTOR ARE

i) Quantum or Short noise.

Incident photon on the depletion region layer surface produces, random generation of photoelectrons which gives rise to this noise.

MSV of this current is given by

$$\langle i_Q^2 \rangle = \underbrace{\langle \sigma_Q^2 \rangle}_{\text{Variance}} = 2qI_PBM^2F(M)$$

Where

q = charge

I_p = dc ~~current~~ value of photocurrent

B = Bandwidth of reciever

F(M) = noise figure associated with avalanche process $= M^x$

where x: depends on material of fiber

M: Multiplication factor

NOTE: for P.W PhotoDetector, $M = 1$ and $F(M) = 1$

2) Bulk ~~dark~~ dark current :

When no light falls on the R.B p-n junction of detector, due to thermally generated carrier this noise current flows. This noise is further amplified in APDs due to avalanche transmission.

RMS value of this current is

$$\langle i_{DB}^2 \rangle = \sigma^2_{DB}$$
$$= 2q \underbrace{I_D}_{\text{DC value of dark current}} M^2 F(m) B$$

3) Surface dark current or leakage current.

This occurs because of

- surface defects
- surface contamination
- bias voltage variations
- surface area
- doping level.

$$\boxed{\langle i^2_{DS} \rangle = \sigma^2_{DS} = 2q \underbrace{I_L}_{\text{DC value}} B}$$

All the ~~noise~~ above noise sources are internal to a photodetector, hence total RMS noise current from photodetector is

$$\boxed{\begin{aligned} \langle i_N^2 \rangle &= \langle i_Q^2 \rangle + \langle i_{DB}^2 \rangle + \langle i_{DS}^2 \rangle \\ \sigma_N^2 &= \sigma_Q^2 + \sigma^2_{DB} + \sigma^2_{DS} \end{aligned}}$$

4) Photodetector noise current : Load resistance thermal noise

- Generally this will be thermal noise contributed by R_L.

$$\langle i_T^2 \rangle = \sigma_T^2 = \frac{4K_BTB}{R_L}$$

5. Avalanche transmission and impact congesion noise in APD.

PHOTODETECTOR RESPONSE TIME(t_d)

This is defined as the ability of time taken by photo detector to convert incident photons into equivalent photogenerated carriers.

- t_d depend on,
  - (i) Transit time of photo carriers in depletion region.
  - ii) Diffusion of carriers generated outside the depletion region.
  - iii) T-RC time constant
    - R → Total resistance associated with detector circuit
    - C → Total capacitance associated with detector circuit.
  - iv) Absorption coefficient of depletion layer.
  - v) Depletion layer width
  - vi) Mobility of charge carriers
  - vii) Rise time and fall time.

$$\boxed{t_d = \frac{W}{v_d}}$$

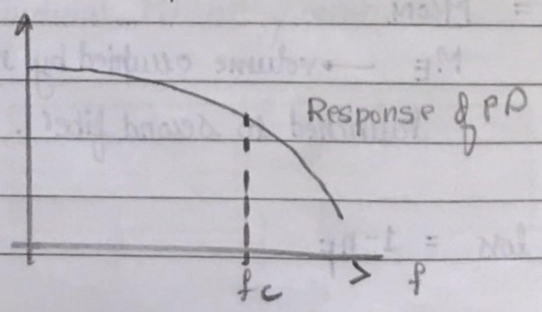
W → width of depletion layer

v_d → carrier drift velocity

→ few tens of nanosecond.

Bandwidth of Reciever depends on the bandwidth of photo detector

$$\boxed{B = \frac{1}{2\pi R_T C_T}}$$



Wednesday

26/9/2018

UNIT 3 : FIBER CONNECTORS, COUPLERS AND OPTICAL RECIEVERS.

CO3: Demonstrate necessary skill set related to the analysis of optical reciever and passive components.

FIBER ALLIGNMENT :

To build an optical link we require a long length fiber (few 10^3 or 100^3 of km)

- For this interconnection, fiber is necessary.
- Two types of interconnection
  - (i) permanent : done by splicing of fibers
  - (ii) temporary : using couplers or ~~dem~~ connectors.
    → also called demountable.

COUPLING EFFICIENCY

1. TYPES :
   - i. fiber to fiber
   - ii. fiber to circuit or device.
   - iii. device or circuit to fiber.

i. Fiber to fiber coupling efficiency.

"The fraction of energy coupled from one fiber to another proportional to the common mode volume (M_{com})"

$$\eta_F = \frac{M_{com}}{M_E}$$

M_E → volume occupied by number of modes which are launched to second fiber.

Coupling loss $= 1 - \eta_F$

MECHANICAL MISALIGNMENT :-

Several parameters are to be considered in fiber connectivity

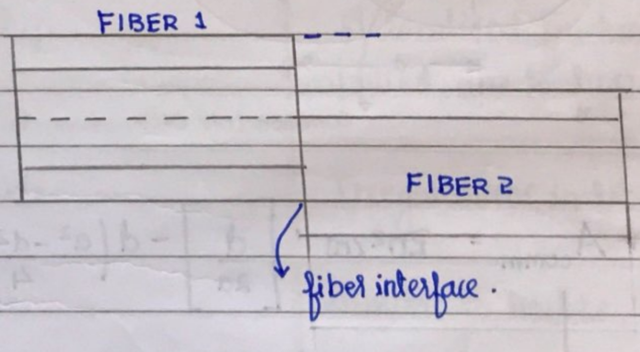
- type of fiber
  - i) a. Single mode
    b. Multimode
  - ii) Glass
    Plastic
    Composite.

→ Numerical Aperture of fibers and acceptance angle.

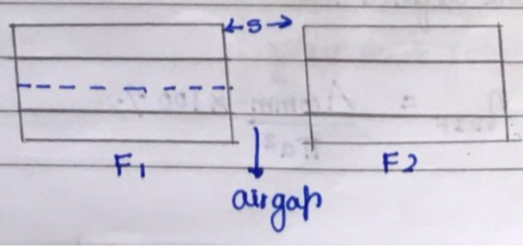
→ To minimize coupling loss between fibres, proper allignment is necessary.

→ Three types of mechanical misalignment

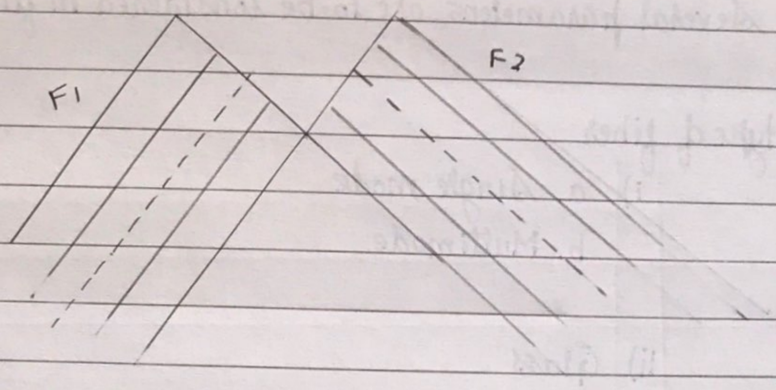
a. lateral or axial M·A



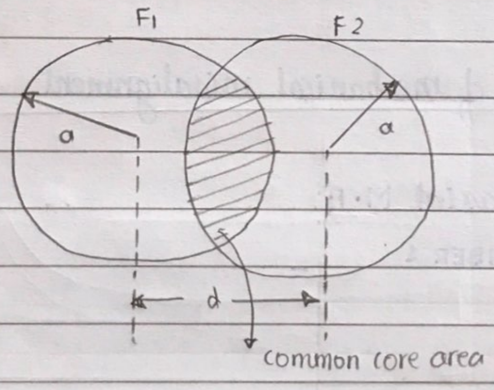
b). longitudinal Misallignment.



c) Angular Misallignment



- Among the 3 types, axial misallignment is most common which reduces the actual core area of the fibers.
- Hence there will be power loss, modal loss and smaller coupling efficiency.



$$A_{comm} = 2n^2 \cos^{-1}\left[\frac{d}{2a}\right] - d\left(a^2 - \frac{d^2}{4}\right)^{1/2}$$

Based on this coupling efficiency of connected fibers are defined.

$$\eta_{SIF} = \frac{A_{comm}}{\pi a^2} \times 100\,\%$$

- power coupled to GRINF due to axial Misallignment

$$P_{GRINF} = P\left(1 - \frac{\delta d}{3\pi a}\right)$$

$\left(1 - \frac{\delta d}{3\pi a}\right)$ → factor of reduction

P → power in first fiber.

→ During splicing, if stress applied is not properly controlled, then there maybe defect in splices.

→ Some of the types of defects are.

	DEFECT TYPE	DESCRIPTION
1)	LIP	A short protrusion that prevents the fiber tips to come in contact with one another.
2)	Roll-off	Rounding edge of fiber.
3)	Chip	A localised fracture due to large stress applied due to fusion of fiber.
4)	Hackle	Irregularities in fibers ends.
5)	Mist	Similar to hackle, but occurs in axial direction
6)	Step	Abrupt disconnectivity in end facets.
7)	Shattering	Very weak joint due to fracture

Thursday

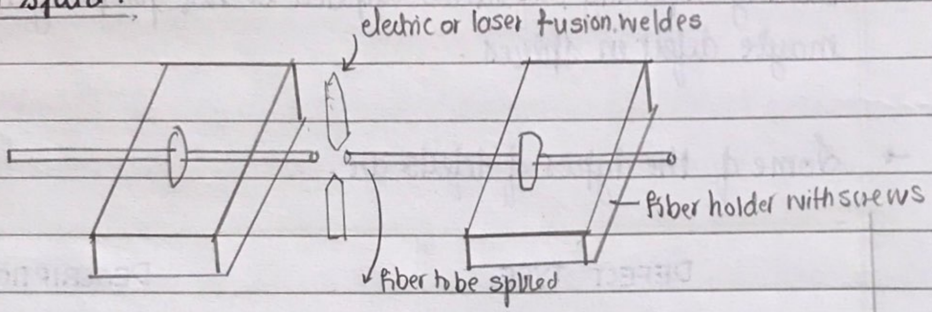
27/9/2018

FIBER SPLICES :

Different methods are → permanent splice.

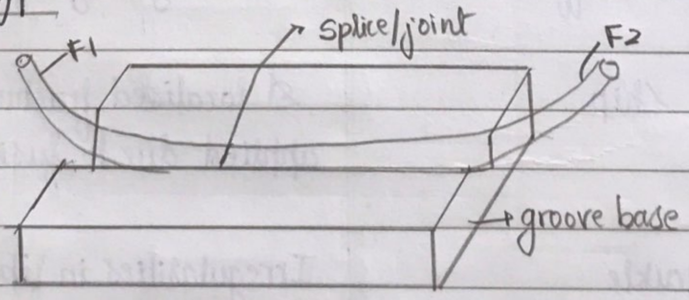
a. Fusion splice
b. V-groove mechanical splice } demountable type.
c. Elastic tube splice

a. Fusion splice.



- produces low splice loss < 0.6dB
- for good splice joints alignment is important
- avoid over heating.

ii) V-groove type



· prepared fibers are butted together in V-groove.

· then they are bonded with adhesive material

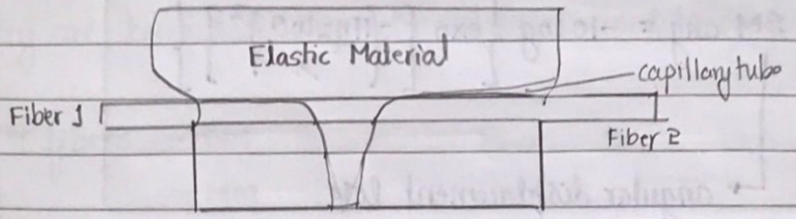
· Splice loss depends on

i) alignment of fibers

ii) air gap produced near joint

__/__/__

c) Elastic fiber splice.



- capillary tube size is smaller than dimension of fiber
- fibers are pierced into the capillary and kept for sometime to make a joint/splice.
- Tube performs automatic lateral, longitudinal and angular allignments
- This type is used for MM fiber

⇒ SM splicing:

- In long distance communication we use SM fibers. Hence number of SM fibers must be spliced together to get required link length.
- Lateral or axial offset loss is important
- Splicing loss depends on
  - i. type of mode propogation
  - ii. polarization
  - iii. power content of a mode.

· For Gaussian shaped mode field pattern, splicing loss is

$$\underbrace{SM\,lat}_{\text{lateral displacement loss}} = -10\log\left\{\exp\left[\left(-\frac{d}{W}\right)^2\right]\right\}$$

d: lateral displacement

W: mode field diameter of beam

__/__/__

Similarly

$$SM\ ang = -10\log\left\{\exp\left[-\left(\frac{\pi \eta_2 w\theta}{\lambda}\right)^2\right]\right\}$$

→ angular displacement loss

Example : A SM fiber has

$\eta_1 = 1.47$

$\eta_2 = 1.465$

$2a = 9\,\mu m$

$d = 1\,\mu m$

$\theta = 1°$ → convert to radians before substitution.

Calculate both lateral displacement loss and angular displacement loss ?

Assume Gaussian distribution with

$w = a[0.65 + 1.619V^{-3/2} + 2.879V^{-6}]$

WKT, for a SM fiber $V \simeq 2.405$

$L_{SM\,lat} = 0.177$ dB → (i)

$SM_{ang} =$ ~~0.0000~~ 0.406 dB → (ii)

Assume $\lambda = 1.3\,\mu m$

$w = 0.45\,\mu m$ dB → (iii)

INFERENCE : ~~Angular~~ Angular misallignment loss is more than ~~angular~~ lateral misalignment loss in fiber.

FIBRE OPTIC CONNECTORS

They are temporary connecting devices used to connect.

- fibers – SM
  – MM
- fibers to circuits and vice-versa
- cross connects in telecommunication networks
- channel connectors
  - → single channel
  - → multi channel.

Important requirements to be satisfied by a device to be used as connector

(a) LOW COUPLING LOSS :
- conform stringent allignment tolerances
- loss must not change, even after a number of connects or disconnects

(b) COMPATIBILITY AMONG MANUFACTURERS:
- ie. interchangability possible.

(c) Easy assembly, installation by service technician.

(d) low environmental sensitivity ie device must tolerate moisture, corrosion, dust, temp variation etc

(e) low cost and reliable.

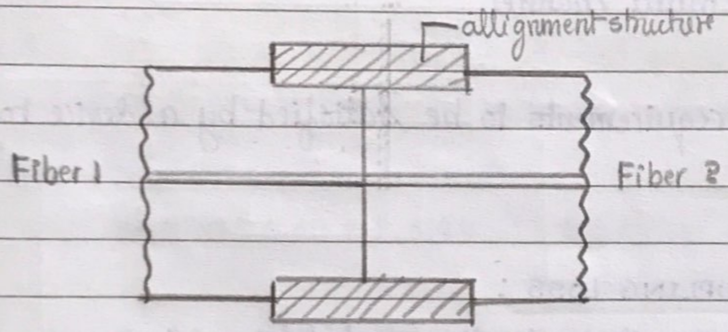
- Coupling mechanism is of two types.

| i. | Butt joint connections
| ii | Expanded beam connectors.

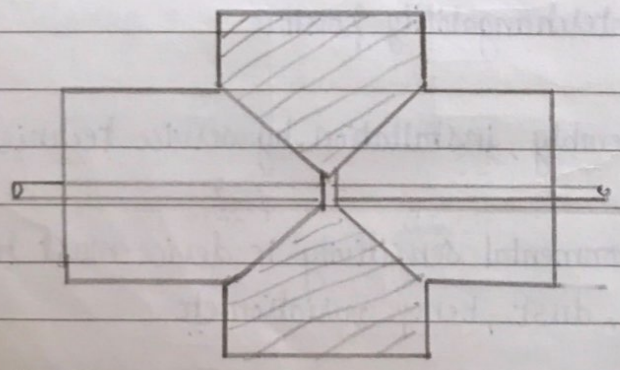
i. BUTT JOINT CONNECTIONS

→ employ metal or ceramic or moulded plastic ferrula tips of ~~moulded plastic~~ fibers which can be easily into a sleeve.

→ sleeve is of two types
| a. | straight sleeve
| b | tapered sleeve.

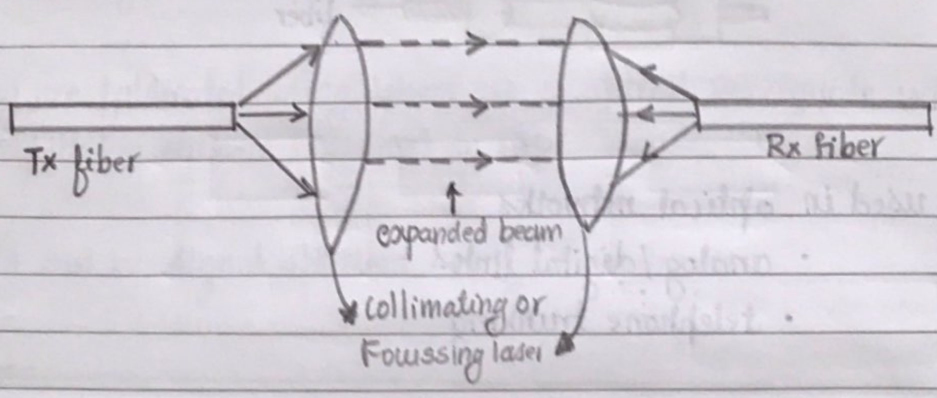


Straight sleeve



Tapered sleeve

iii Expanded beam

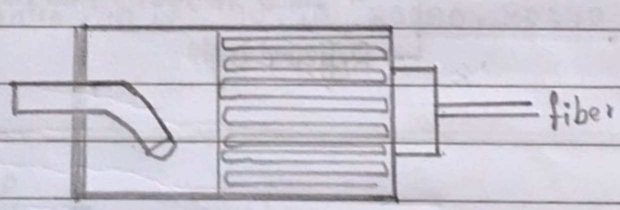


Different types of connectors available are.

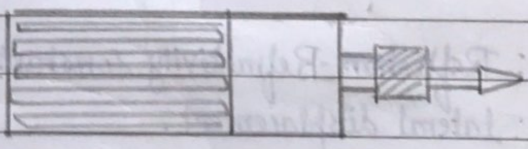
- SMA906
- ST
- Biconical
- Ferrula connector (FC)
- D4
- HMS-10

- SC - subscriber channel connector
- FDDI
- ESLON
- EC/RACE
- LC
- MT

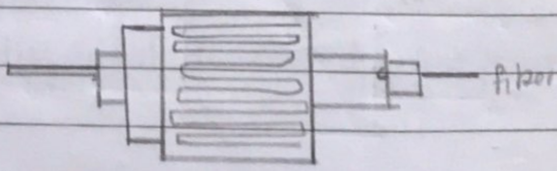
BNC:



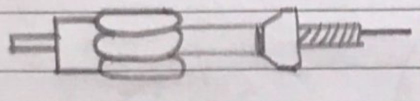
BICONICAL



FERRALE



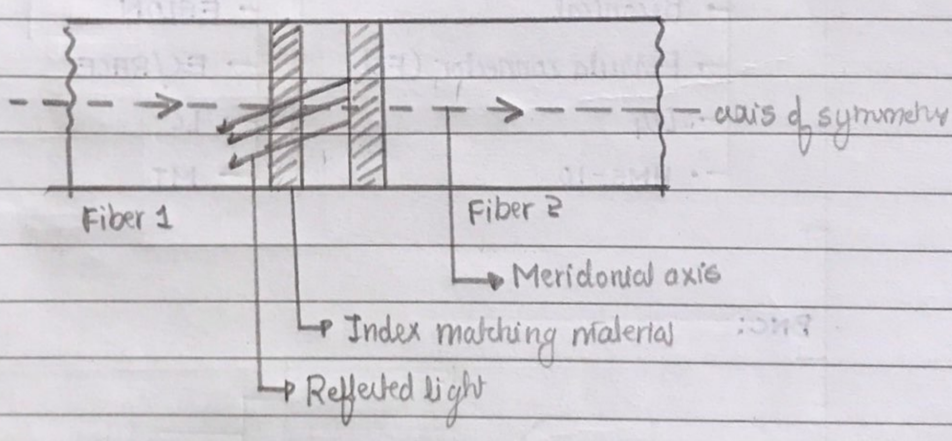
SMA



- used in optical networks
  - analog / digital links
  - telephone trunking

⇒ CONNECTOR RETURN LOSS :-

- Important loss in a connector used to quantify reflection at fiber joints.



Return loss

$$R_L = -10 \log \left[2R \left[1 - \cos\left(\frac{2\pi n_1 d}{\lambda} \right) \right] \right]$$

where

R : ~~Reflection~~ Refractivity constant of index matching material

d : lateral displacement.

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Saturday

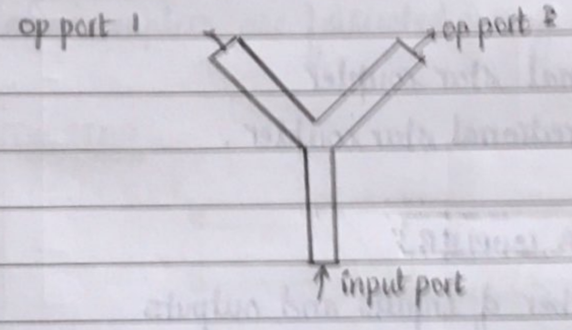
29/9/2018

FIBER COUPLERS:

- They are temporary passive components used to connect fibers.
- They are fabricated using fibers ~~are~~ or optical waveguide with materials, like Lithium Niobate ($LiNbO_3$) or InP
- They can be signal splitters or signal combiners.

TYPES:

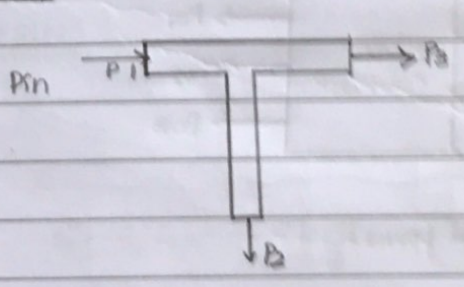
i) Y-COUPLERS or TAP COUPLER:



- used to split the input signal power over two output ports.
- split ratio can be, 10:90, 20:80, 30:70, 50:50 etc

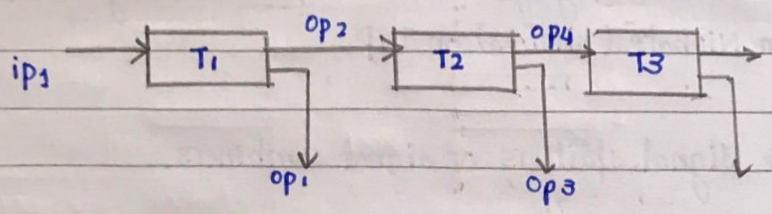
  50:50 → 3dB.

ii) T COUPLER



- used in power taps
- used in Hierarchial division of input power

Advantages of T and Y couplers is that, it is easily terminated in with standard connectivity ST, ST, LC etc

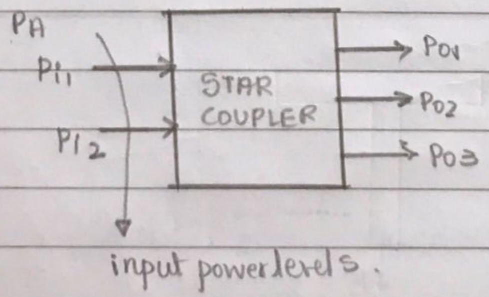


iii) STAR COUPLER :

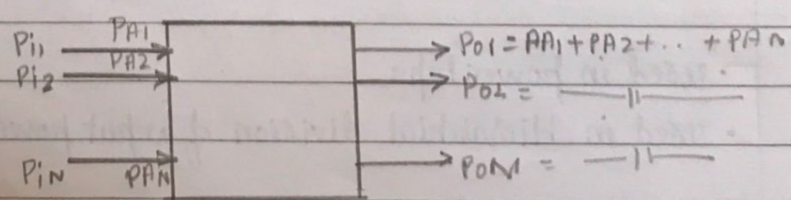
There are two types
i. directional star coupler
ii. non directional star coupler.

a. DIRECTIONAL STAR COUPLER :

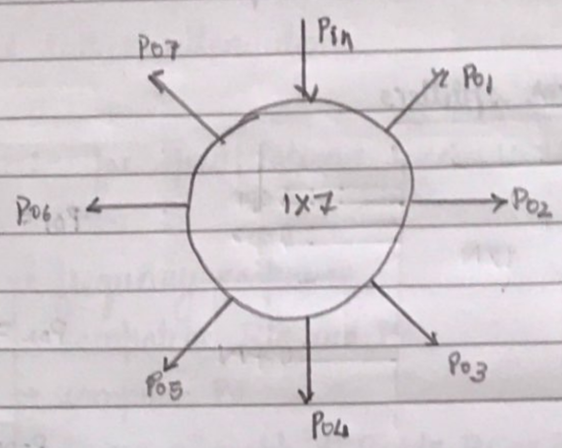
- It has number of inputs and outputs
- Mixing of input signal takes place irrespective of λ, power level, polarization etc
- Combined signal is distributed among the output ports (equally)
- They are bidirectional.



GENERAL



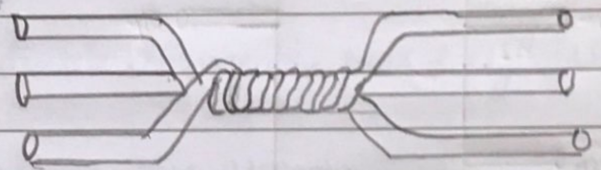
b) NON DIRECTIONAL



Po1 ..... Po7 have same power level as input power.

→ Star couplers are fabricated using fibers.

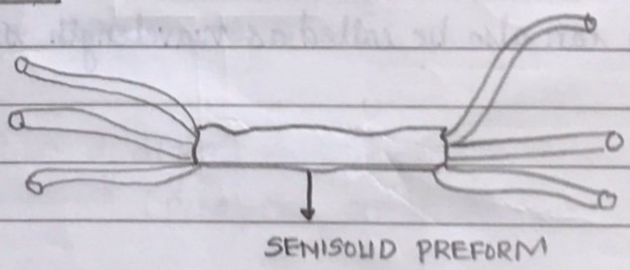
(i) TWISTED



ii) HEATED OR FUSED

Same as in twisted, but is heated using ~~gap~~ gas laser in the middle.

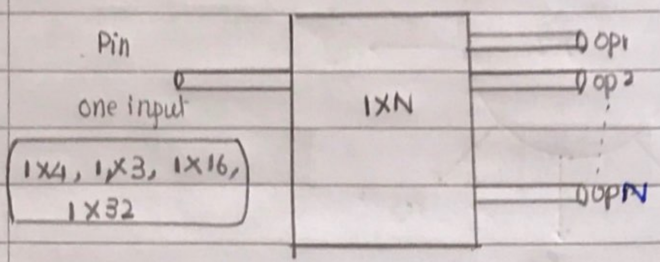
iii. TAPERING



TREE COUPLERS :

Also called 1XN or NX1 couplers which are bidirectional

i. These are power splitters



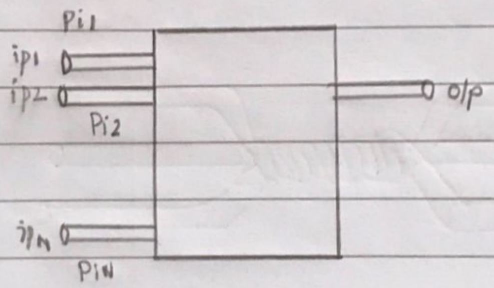
$P_{01} = \frac{P_{in}}{N}$

$P_{02} = \frac{P_{in}}{N}$

⋮

$P_{0N} = \frac{P_{in}}{N}$

ii. Power Combiners



$P_0 = P_{i1} + P_{i2} + \ldots P_{iN}$.

WDM COUPLERS {WAVELENGTH DIVISION MULTIPLEXING}

- It separates or combines signals, based on their wavelength
- They can also be called as wavelength splitters or combiners.

Lab cycle - 02.

1. T or π attenuation
2. Bridged lattice attenuation

Design :- for specifications like 10dB, 20dB, 30dB, 40dB etc

- frequency response
- compatible Rin and Ro
- compute Po
- Draw a graph of Po v/s RL or Ro.

3) TDM (using both TDM kit and discrete components)

- Find, frame time, slot time and bit time.
- for discrete components, MUX 3 signals (sine, square, pulse)
- Determine TDM efficiency.

4) Antenna characterisation using a μ-wave bench set

- Radiation pattern
- Directivity and Direction gain
- Rr
- HPBW and BWFN.

5) Simulation of digital modulation
(PCM, DM, QPSK, DPSK)

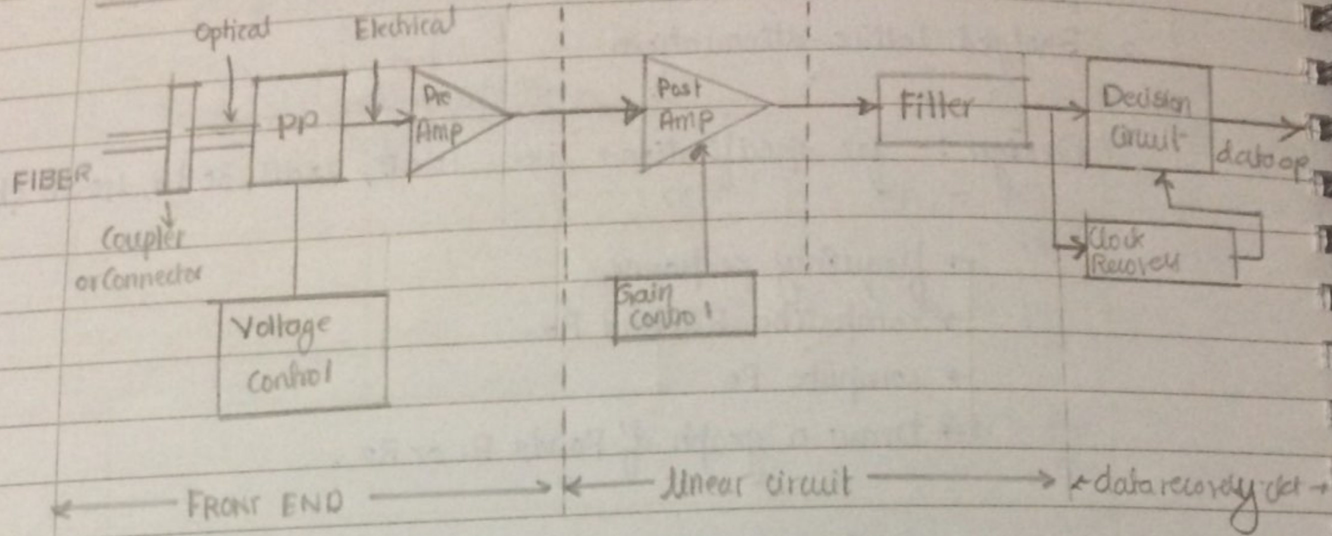
6) Self learning : Design a simple antenna and characterise it.

- monopole/dipole
- dish
- Yagi-Uda array
- μ-strip
- horn
- slot

Wednesday 3/10/2018

X for test

OPTICAL RECIEVER



- Weak signal from ~~photodetector~~ fiber is coupled to the photodetector, through a connector/coupler.

- Based on the input optical power ~~input~~ level, bias condition (reverse bias) of photodiode is varied to absorb maximum optical power through depletion region.

- pre amplifier and photodetector determine the front end selectivity of Rx ie amplifier must have sufficient gain and bandwidth to handle input signals.

THREE TYPES OF PRE AMPLIFIERS USED

i. LOW IMPEDANCE (LZ):

- operates with $R_b = 50\Omega$
- Photodetector and amplifier must introduce minimum shot noise/thermal noise.
- FET amplifier with neutralization is used to reduce the input capacitance of amplifier
- $\tau = R_b C_{amp}$ and $B = \frac{1}{2\pi\tau}$

→ large bandwidth is possible with small T but sensitivity and gain are small.

→ care must be taken to prevent standing between photodetector and amplifier.

b) HIGH IMPEDANCE AMPLIFIER

→ To minimize the dark current, surface leakage current and other noises use FET and high frequency BJT.

→ High gain is possible, but bandwidth gets reduced due to large T

→ Take precaution against oscillations or instability in the system due to high gain.

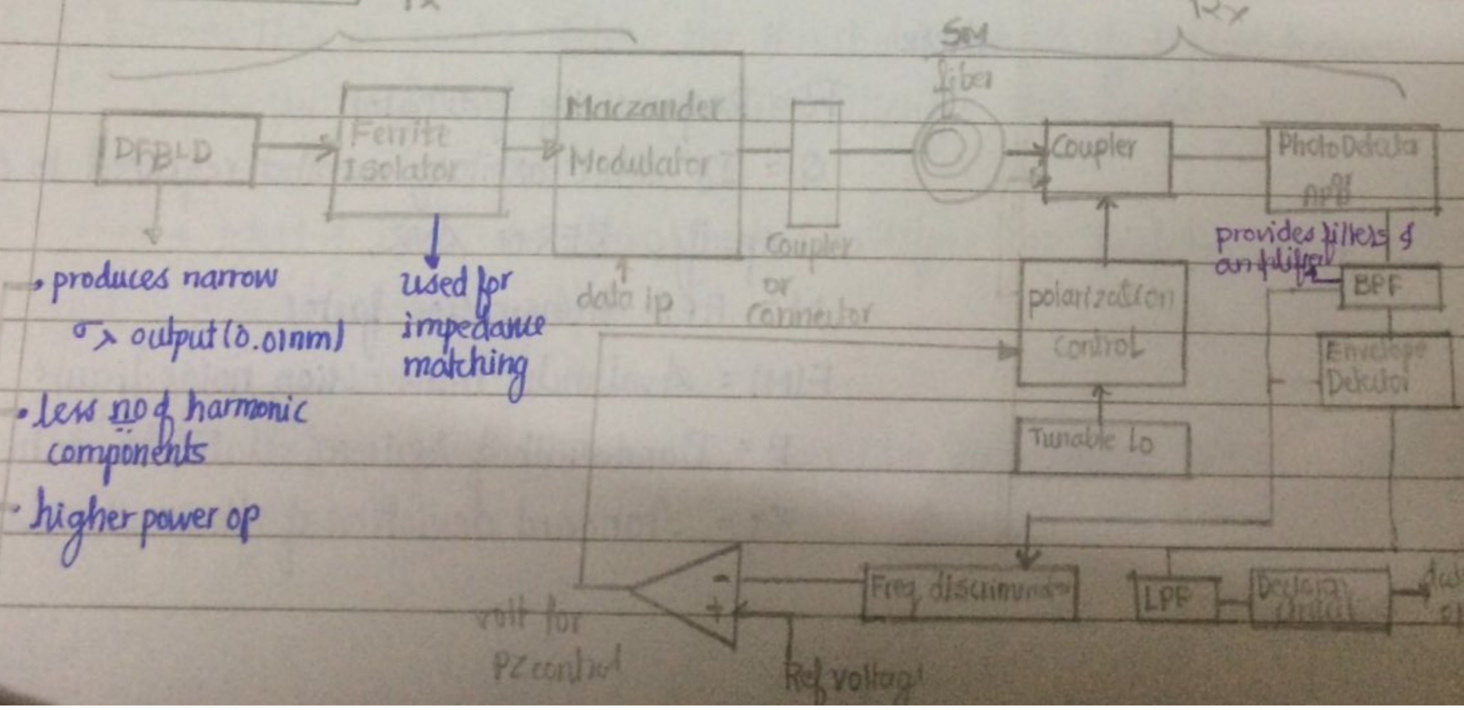
→ Use compensators to improve bandwidth of amplifier to a value greater than signal bandwidth.

c) TRANSIMPEDANCE (TZ)

- use some negative feedback to overcome distortions.
- use compensation between gain and error performance required.

HETRODINE RECIEVER

⇒ ASK MODEM :-



OPTICAL RECIEVER PERFORMANCE :

Defined in terms of sensitivity, fidelity, bandwidth, noise performance, BER or CNR or SNR performance.

(PERFORMANCE)

(a) RECIEVER SENSITIVITY.

- Minimum power an optical reciever can detect in the presence of noise.
- Also defined as minimum average optical power required to achieve a specific BER or SNR
- Three cases of BER or SNR is defined for reciever.
  - → worst case
  - → threshold
  - → best case.

- Minimum power detectable by a reciever

$$P_{sensitivity} = \frac{QM}{R}\left[\frac{qMF(M)BQ}{2} + \sigma_T\right] \quad \to (1)$$

where

R = Responsivity of detector

Q = Is some arbitary number required to achieve specific BER or SNR.

M = APD transmission factor

F(M) = Avalanche transmission noise figure.

B = Bandwidth of reciever related to data rate.

σ_T = Standard deviation of thermal noise

$$\sigma_T = \sqrt{\frac{4KBT}{R_L} F_n \frac{B}{2}}$$

$\Rightarrow$ F_n = Noise figure of reciever

Equation holds good for APD (Avalanche photodetector) reciever, in case of pin diode optical reciever M and F(M) will be 1.

QUESTION:

Find the sensitivity of an optical reciever which uses a load resistance of 200 Ω at T = 300K. Reciever noise figure is 3dB, standard deviation of thermal noise = $9.1 \times 10^{-12} \sqrt{B}$. If in ~~case~~ GaAs photodetector is used with responsivity 0.95 A/w at 1550nm.

Assume BW = 1GHz for BER = 10^{-9}, Q = 7 arbitary ~~if detector is~~

If detector is an APD with internal gain of 10, noise figure 5. Also find reciever sensitivity in terms of dBm.

$$\boxed{\text{Sensitivity in dBm} = 10 \log \frac{P_{sensitivity}}{1mW}}$$

QUANTUM LIMIT:

→ This is also a reciever performance which defines reciever sensitivity.

→ This is used to define the threshold values of signal power required for ~~determining~~ detection with specific BER or SNR.

→ Most of the times this is used to define the performance of digital reciever system

→ To define quantum limit we consider maximum BER performance.

i. Proalility of error of a digital optical reciever is

$$\boxed{P_e = e^{-N} = 10^{-9}}$$

Solve for $\bar{N} = 9 \ln 10 = 20.7 \simeq 21$

ie atleast 21 photons/pulse is required to achieve a BER of 10^{-9}.

BAND GAP ENERGY OF A MATERIAL :

$$\boxed{E_g = 20.7 \frac{h\nu}{\eta q}} \quad \rightarrow (1)$$

If P_0 is the quantum limit of power required for a BER of 10^{-9} then,

$$E_g = P_0 \tau$$

where,

$$\frac{1}{\tau} = \frac{B}{2} \quad \rightarrow (2)$$

$\downarrow$

Assuming equal number of 0s and 1s in the bit stream

From (1) and (2), LHS are same, RHS can be equated

$$\boxed{P_0 \tau = P_0 \frac{2}{B} = 20.7 \frac{h\nu}{\eta q}}$$

$\therefore$ Quantum limit of detection

$$P_0 = \frac{20.7 h\nu}{2\eta q} . B$$

$$= \frac{20.7 h c}{2\eta q \lambda} . B$$

$\because \ \nu = \frac{c}{\lambda}$

For APDs, generally $\eta_q = 1$.

Example

Determine the quantum limit of digital reciever operating at 850nm. with a bandwidth of 10MHz. (in terms of dBm).

$$(Q.L)_{dBm} = 10 \log \frac{P_o}{1mW}$$

NOTE: FOR PRACTICAL DIGITAL RECIEVER, QUANTUM LIMIT WILL BE 10 to 20dB GREATER THAN THE THRESHOLD VALUE. THIS IS REQUIRED TO COMPENSATE

→ NON LINEAR DISTORTIONS

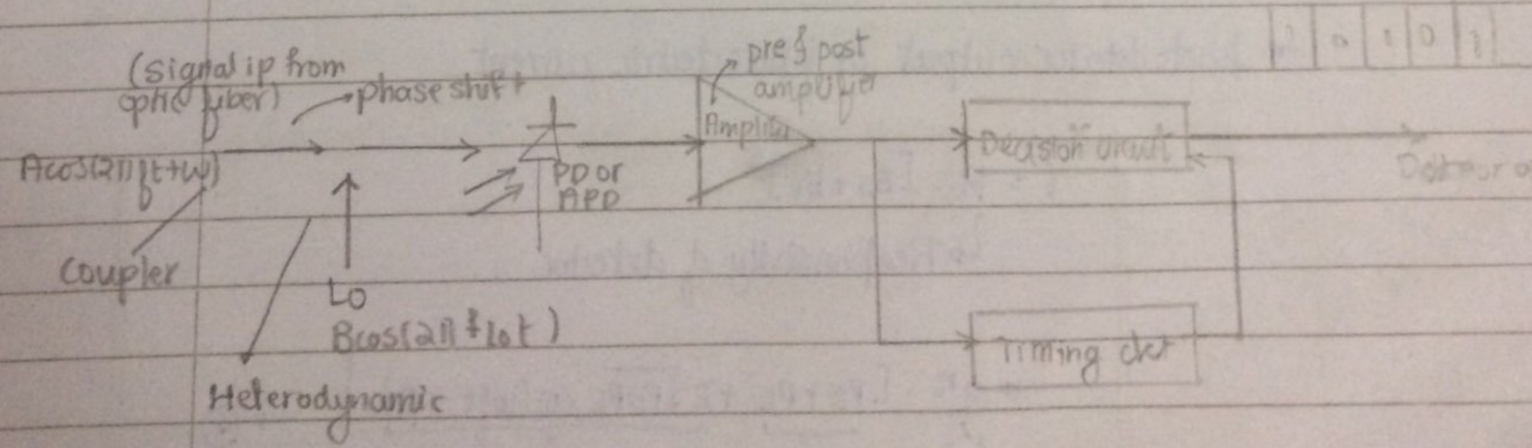
→ OTHER NOISE EFFECTS

- SHOT NOISE
- DARK CURRENT NOISE
- LEAKAGE NOISE

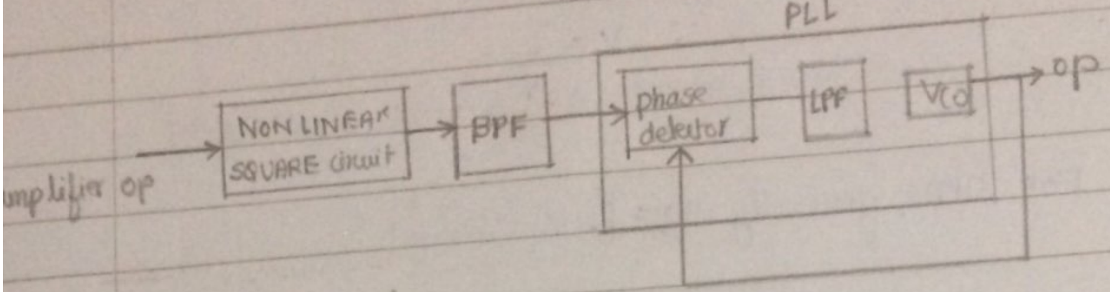
: Self Study : EYE DIAGRAM

Saturday Oct 6/2018

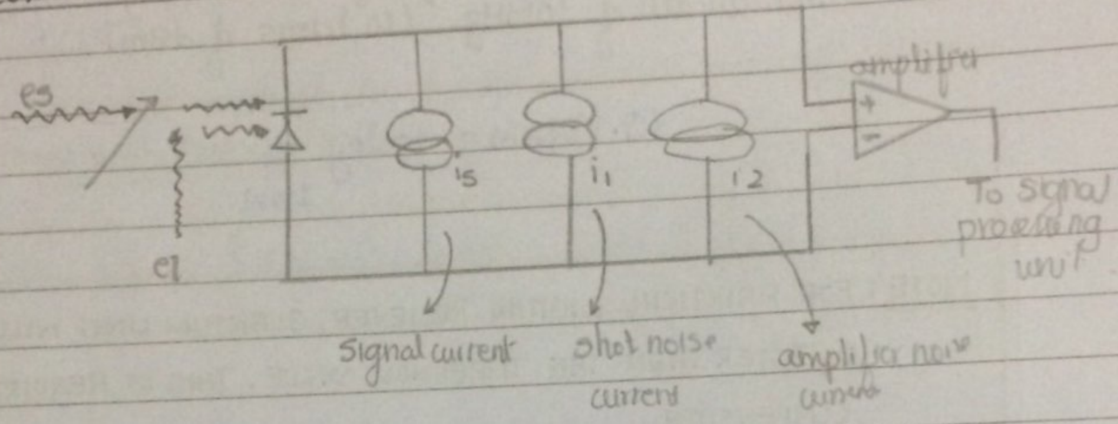
COHERENT DETECTOR RECIEVER (ASK or IM)



TIMING CIRCUIT.



Coherent detector with various noise sources :



→ In coherent system, optical carrier amplifier, frequency and phase are modulated by digital data (RZ or NRZ)

→ To types of coherent detection
- homodyne - direct detection
- heterodyne - IF detection.

$$e_s = E_s \cos w_s t$$
$$e_L = E_L \cos(w_L t + \phi)$$

→ photodetector output or photoelectric current

$$i = R\,[E_s + E_L]^2$$

↳ Responsivity of detector.

$$= \frac{q\eta}{h\nu}\left[\underbrace{P_s + P_L}_{I} + \underbrace{2\sqrt{P_s P_L}\cos(w_{if}t + \phi)}_{II}\right] \rightarrow (*)$$

where

$w_f = w_L \simeq w_S$, then IF frequency

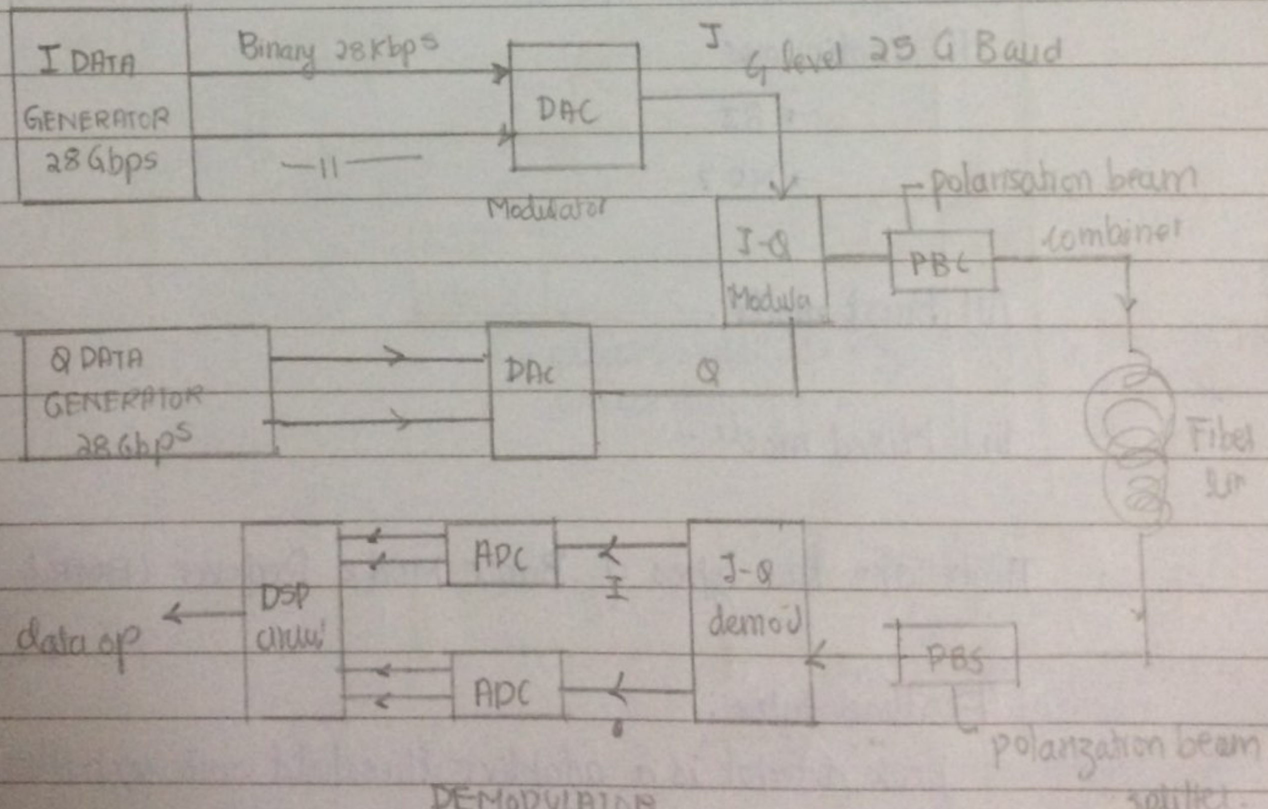
$$\left.\begin{aligned} P_S &\propto |E_S|^2 \\ P_L &\propto |E_L|^2 \end{aligned}\right\} \rightarrow \text{NORMALISED POWERS.}$$

For a coherent reciever, generally $\text{II} > \text{I}$ from eq ⊛

$$i \simeq \frac{qn}{h\nu}\left[2\sqrt{P_S P_L}\cos(w_f t + \phi)\right]$$

$$\simeq \frac{qn}{h\nu}\left[2\sqrt{P_S P_L}\cos(w_{AF}\, t)\right] \text{ for homodyne.}$$

COHERENT QAM MODEM (16 QAM) - (8bit/symbol)



BURST MODE RECIEVER (BMR)

- Recievers can handle different types of packets with
  - → varying power levels (similar to ASK)
  - → varying phase shift (similar to PSK)
  - → varying λ^2 (similar to FSK)

ie. they handle packet by packet data

- Applications in high speed data transmission systems.

  Ex:
  - → PON: Passive optical Networks using TDMA/CDMA
  - → optical bus network
  - → WDMA optical network
  - → Multichannel, parallel optical data links
  - → Supervisory systems for under sea, landline, long haul ED transmission systems

- Data types used in OFC are.

  (i) continuous
  - → RZ
  - → NRZ

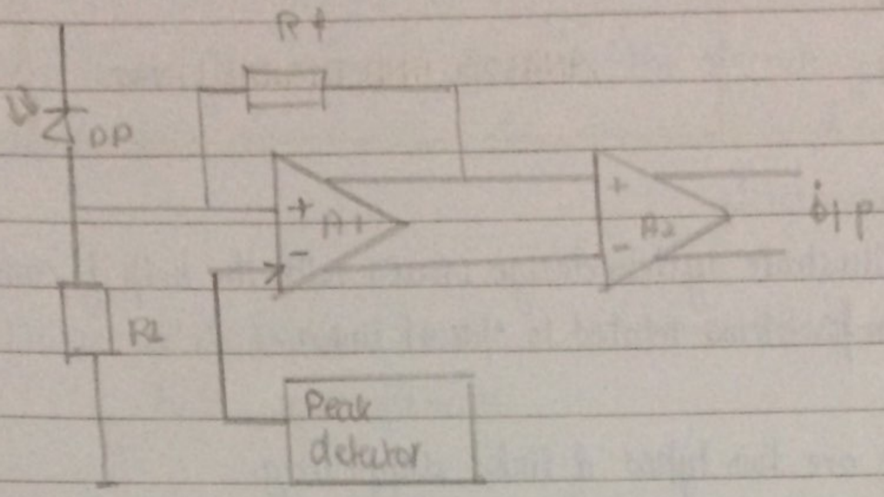
  (ii) Burst mode.

  (ii) Mixed mode.

- There are two types of Burst Mode Reciever (BMR)

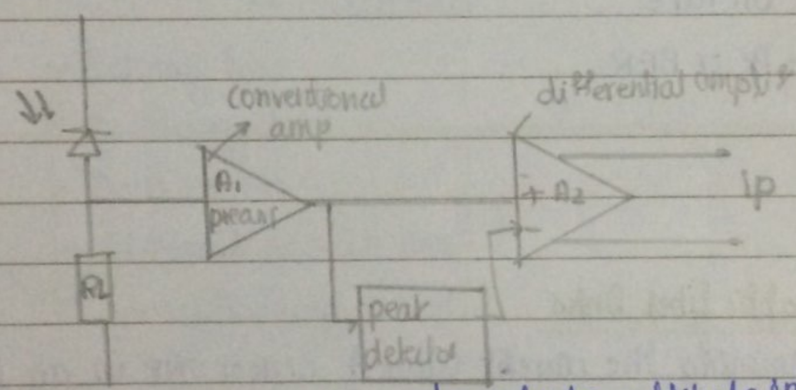
a) Feedback type:

peak detector is a adaptive threshold gain controller to prev instability in an amplifier



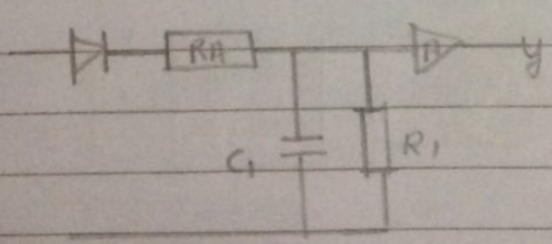
Advantages of trans impedance amplifier
- wide dynamic range
- sufficient gain and bandwidth
- no equalization circuits required.
- less susceptible to other noises.

b) Feed forward type.



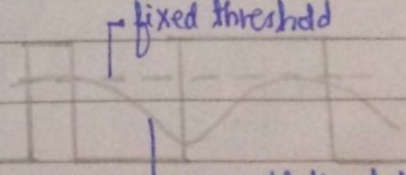
↳ extracts amplitude information of packets to correct gain of A 2

⇒



amplifier input capacitance & resistance

$T_1 = R_f C_1$
$T_2 = R_1 C_1$
↓
must be properly selected to overcome NL distortion



fixed threshold

↳ variable threshold / adaptive threshold

UNIT 04	ANALOG AND DIGITAL LINKS	11 October 2018 Wednesday

CO4:

Illustrate system design issues with the help of case studies and design problems related to optical links.

- There are two types of links supporting
  - a. SCS : Single carrier systems
  - b. MCS : Multi carrier systems

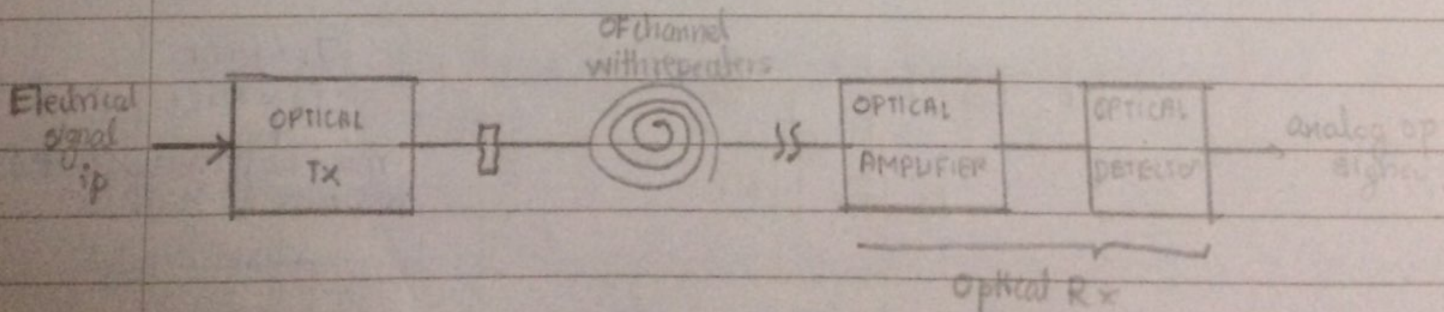
- Analog systems characterised by,
  - Bandwidth
  - CNR & SNR

- Digital systems are characterised by,
  - bit rate
  - Pe or BER

THURSDAY 12/10/2018

Analog optic fiber links

- Determining the correct value of CNR or SNR is an important task in link analysis.
- Signal power is easily estimated but noise estimation is complex.



Tx :

- Non linear distortion - based on the operating part of the active device
  ↓
  determined by driver circuit
- Harmonic distortions : due to non linear operation there will be harmonic components.
- Clipping action of active device due to limited spectral width.
- $\boxed{\text{RIN : Relative Intensity Noise}}$

Channel :

→ This is the fiber link

- Attenuation loss or path loss
- Absorption loss
- Modal loss
  - → intramodal
  - → intermodal
- Bending loss
- Scattering loss
- GVD in MM
- MD and W.D in SM
- core-cladding losses

Rx : DETECTOR NOISES

- → Shot noise
- → Thermal noise
- → leakage noise
- → Dark current noise
- → Surface noise
- → Amplifier noise.
- → APD gain noise.

RIN :

Light intensity output of LD exhibhits fluctuations in frequen and phase even when operated above threshold region.

- Two fundamental reasons for this noise are.
  - (i) e-h recombination results in random shot noise.
  - (ii) Transition from spontaneous emmision to stimulated emmision near the threshold is not smooth.

- Among the two factors, second one is dominant.

- Mean Square Value of RIN current is

$$\langle i^2_{RIN} \rangle = \underbrace{\sigma^2_{RIN}}_{\text{Variance}} = RIN\,(R_0\bar{P})B$$

where,

$$RIN = \frac{\langle (\Delta P_L)^2 \rangle}{P_L^2} = \frac{\text{MSV of fluctuations of intensity}}{\text{Average laser intensity}} \quad dB/Hz$$

- CNR due to only RIN noise, $= \frac{C}{\sigma^2_{RIN}}$

- At 1550nm for DFD laser diode, $-152 < RIN < -156$ dB/Hz

- RIN also depends on the drive current at the input

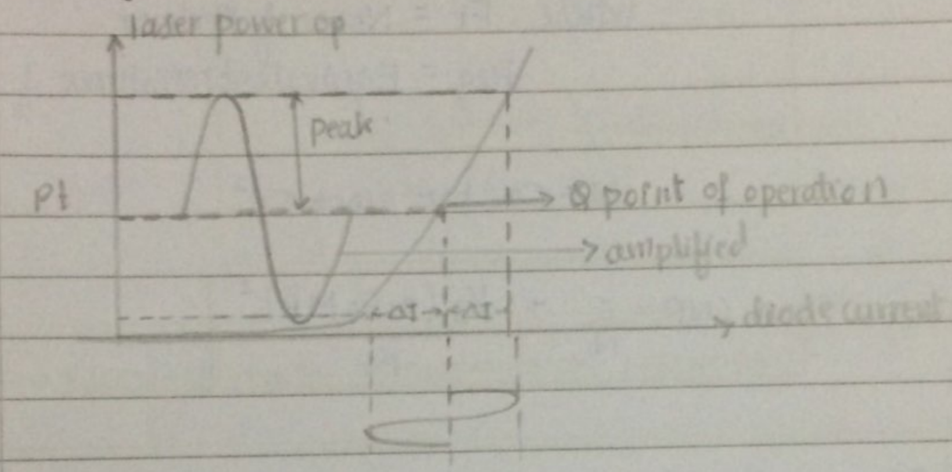
$$\boxed{RIN \propto \left(\frac{I_B}{I_{th}} - 1\right)^{-3}}$$

RIN ↓ as injection current ↑

- CNR can be represented in two forms.
  - (i) in terms of 'm' → modulation index.
  - (ii) only in terms of C & N power

Friday — 13 Oct 2018

Analog link and CNR estimation



- Q point is selected in the middle of characteristic curve to avoid non linear distortion

- power output of LD corresponding to drive current is

$$P(t) = P_t\,[1 + m\,s(t)]$$

where,

$m \to$ modulation index $= \dfrac{P_{peak}}{P_t}$ ($< .5$)

- Transmitted power from laser source is detected by a photodetector at the reciever.

$$C = \frac{1}{2}(m\,R_0\,M\bar{P})^2$$

R_0 → unit gain responsivity of photo detector

- Noise power = N = Noise contributed by detector + Noise of amplifier.

(i) PD noise = $N_D = \langle i_N^2 \rangle = \sigma^2_N$

(ii) RIN = NR = $\langle i_{RIN}^2 \rangle = \sigma^2_{RIN} = RIN(R_0\bar{P})B$

(iii) Thermal noise = $\langle i_p^2 \rangle = \sigma_T^2 = \frac{4K_BT}{R_{eq}} BF_t$

where, F_t = Noise of Reciever
R_{eq} = Equivalent resistance of amplifier

$$N = \sigma_N^2 + \sigma^2_{RIN} + \sigma_T^2$$

$$\therefore CNR = \frac{C}{N} = \frac{\frac{1}{2}(mR_0M\bar{P})^2}{N}$$

⇒ Performance of analog fiber link, is based on CNR

- There are 3 limits, defined for this CNR based on signal strength is recieved by photodetector.

a) limit-1 : When input signal is very weak then thermal noise of amplifier is predominant compared to other noises.
ie

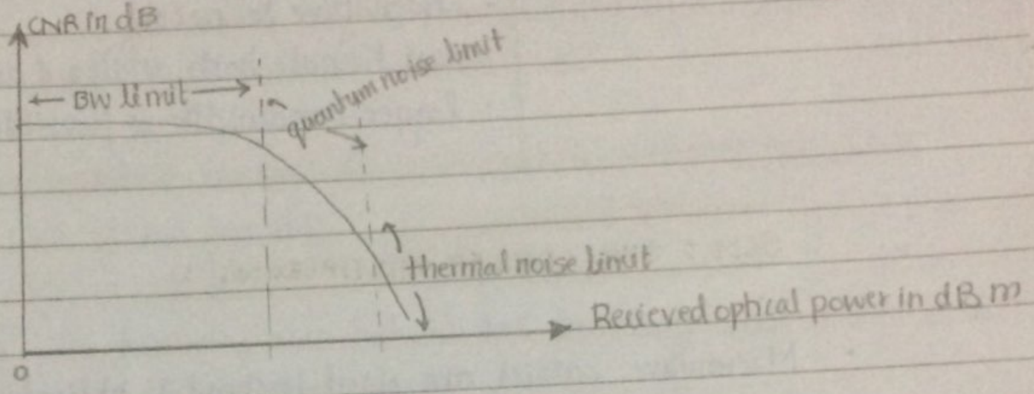
$$N \simeq \sigma^2_T \Rightarrow (CNR)_{lim\,1} = \frac{C}{\sigma_T^2}$$

(b) limit 2 : For well designed photodetectors, bulk and surface dark currents are negligible at a verge of signal strength

$$(CNR)_{limit\,2} = \frac{\frac{1}{2}(m^2R_0\bar{P})}{2q\,F(M)\cdot B}$$

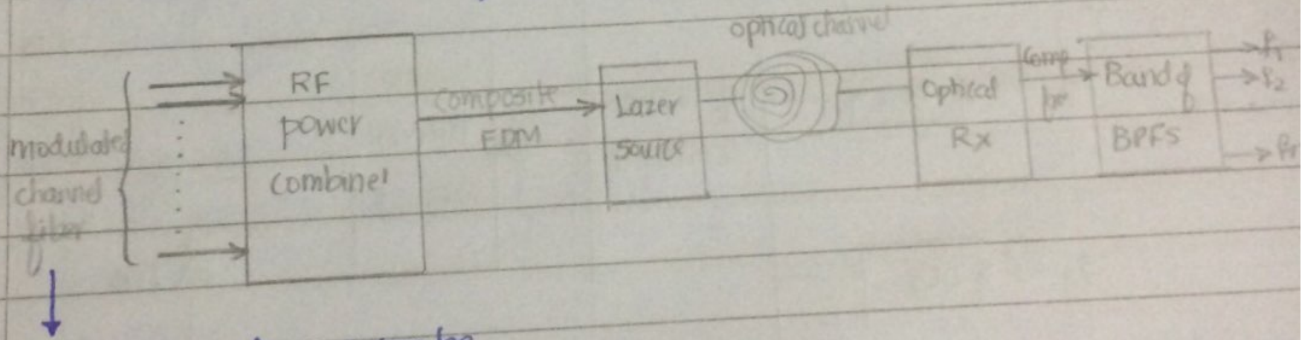
(c) limit 3 : For strong input signals, RIN is predominant

$$\boxed{(CNR)\ \text{limit}\ 3 = \frac{1}{2}\frac{(MM)^2}{RIN \cdot B}}$$



⇒ MULTI-CHANNEL TRANSMISSION METHODS :

- To better use the available bandwidth of fiber, Multiplexing technique is used to transmit information.



modulation schemes can be
VSB-AM, FM, SCM

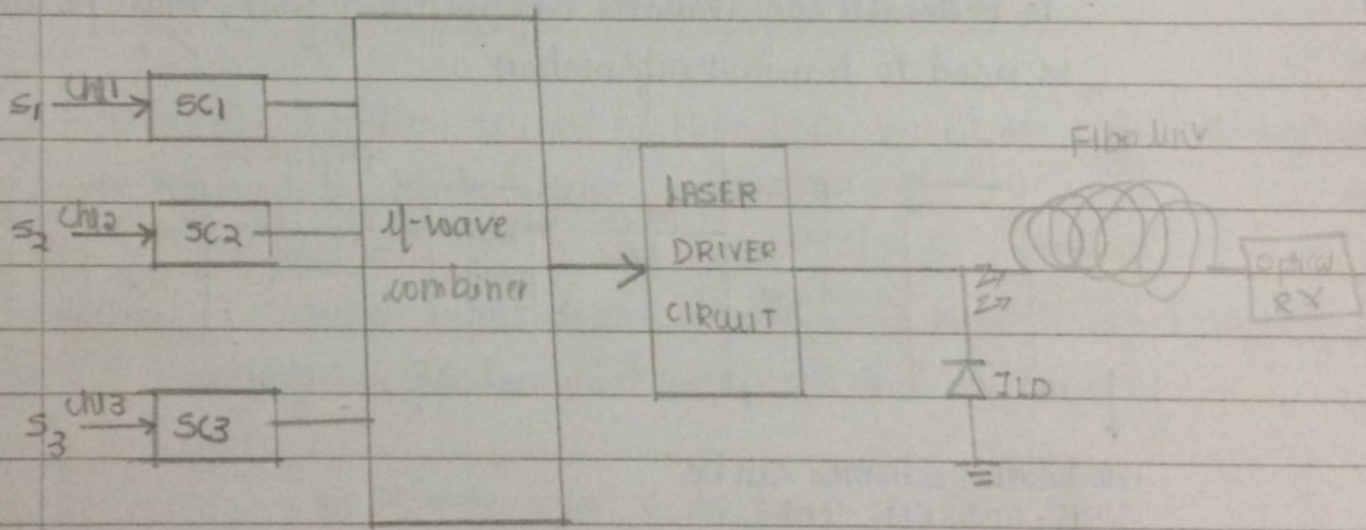
	MODULATION FORMAT	CHARACTERISTICS
1.	VSB-AM	· cost effective · compatible with OFC systems · very sensitive to noise and NL distortions.
2	FM	· requires larger bandwidth than AM · provides highest CNR

	· Better noise suppresion · minimum non linear distortion.
SCM	· operates at higher frequency than AM & FM · insensitive to noise · can handle both analog & digital signals. · larger bandwidth is possible

SCM : SUB CARRIER MULTIPLEXING :

13/10/2018

- Microwave carrier are used instead of optical carrier for modulating the different channel.
- If signals are transmitted over an optical fiber than bw > 10GHz.



ADVANTAGES :

- wide bandwidth available
- flexibility for upgradation of components/equipments
- useful in multimedia communication for number of users
- used in network monitoring management systems.

Scanned by CamScanner

ROF or RF OF :

- ROF : Radio over optical fibers
- (Principle) : "light ~~super~~ signal is modulated by a microwave carrier and transmitted over fiber".

- provides wireless coverage in area where wireless backhaul or reverse link is not possible.

- Example : In tunnels, area behind tall buildings, mounting and secluded array like jungles, desert, sea etc

ADVANTAGES :

- low path loss : Since fiber is used as the medium.
- no EMI and RFI on the links.
- Fadings eliminated - both short term and long term
- noise effects reduced.

APPLICATIONS

- 3G, 4G, 5G and LTE of mobile systems
- Wi-Fi
- CATV
- RF - L band communication between base station or ground s and polar ~~bit~~ orbit sattelites.
- FTTA : Fiber To The Antennas
  ie fiber is used as the interconnecting link between Tx / antenna.

Scanned by CamScanner

ADVANTAGES OF FTTA :

- Better coupling - Avoid standing waves
- Protection of system against lightning
- in mobile systems, simple base station design is possible.

DIGITAL LINKS :

Important considerations in link design.

- We use line coupling methods to power the randomness, redundancy and signal security.
- FEC can be used (FORWARD ERROR CORRECTION) codes are used to get better end to end fidelity
- Pe and BER are limited by noise and dispersion effects
- Use of SM fibers for long distance communication.
- In high speed applications (rate > 400Mbps) consider the effects of
  - modal noise
  - spectral noise
  - mode partition noise
  - laser chirping
  - reflection noise.
- Selecting proper wavelength for transmission - fixing λ from 3 windows

  This has bearing on the fo
  - link length
  - σ_λ
  - scattering of losses
- Optimising the performances of Tx, link and Rx

Generally optimise at last 2 unit

→ Selection of photodetector for QL of detection of detector with good sensitivity – PDS $\left[\frac{PIN}{APDS} \right.$

24 25/OCT/2018

Example for Analog link power budget

Compute the maximum link length and various power margins.

DATA AVAILABLE:

→ $BER = 10^{-9}$ (ie. one bit will be in error for 10^9 bits Ix)

→ Data Max = $B_{T max}$ = 200Mbps

→ Operating wavelength $\lambda = 850nm$

→ Soure → GaAlAs LED = power output of $P_S = -13dBm$ (average power level)

→ Fiber core diameter = 50μm

→ Detector in PIN PD, sensitivity = –42dBm (P_{min})

→ 1dB coupling loss between source and fiber.

→ 1dB coupling loss between fiber and photodiode.

→ System loss margin = 6dB

→ Attenuation of fiber is = 3.5dB/km (composite plastic fiber)

SOLUTION:

→ Total power loss that occurs between source and destination

$$P_L = P_S - P_R$$

$$= -13dBm - (-42dBm)$$

$$= 29dBm.$$

→ Neglecting the splicing, coupler and connector losses (not given)

P_L = Loss of coupling at soure + Loss of coupling at detector + power margin + attenuation loss of fiber

$$29dB = 1dB + 1dB + 6dB + \underbrace{(3.5)L}_{\alpha_F \cdot L}$$

∴ Maximum link length possible = L = 6km.

There are two methods by which power budget of an analog link can be represented.

(i) conventional method

(ii) spread sheet method.

COMPONENT/ LOSS PARAMETER	OUTPUT/ SENSITIVITY/ LOSS	POWER MARGIN IN dB
LED power output (Ps)	-13dBm	
PIN PD sensitivity (Pn)	-42dBm	
Allowable loss (Ps - Pa)		29dBm
Connectivity loss at ip and output	1dB each	29dB - 2dB = 27dBm
Loss Margin tolerable	6dB	27 - 6dB = 21dB
loss due to fiber attenuation and others will be		21dB.

RISE TIME BUDGET :

→ This gives dispersion limitations of optic fiber used in digital links.

→ Total rise time for the digital link in

$$t_{sys} = \left(\sum_{i=1}^{N} t_i^2 \right)^{1/2} \quad \rightarrow (1)$$

where t_i → rise time contributed by each of the components of link.
N = Number of components in the link

→ In digital links we consider four basic parameters for determining rise time budget.

(i) t_{tx} → transmitter rise time
(ii) t_{GVD} → Group velocity dispersion rise time
(iii) t_{mod} → modal dispersion rise time.
(iv) t_{rx} → Reciever rise time

} MM fibers of SIF or GRIN

For single mode fibers, GVD is the only dispersion and no other dispersion.

→ Rise time specifications for a digital link is based on data format like NRZ or RZ, considering various factors.

- For NRZ, Total transitional time degradation < 70% of T(bit time)
- For RZ, Total transition time degradation < 35% of T (bit value time)

$$\boxed{T = \frac{1}{\text{Bit rate}}}$$

(i) t_{tx} :- (TRANSMITTER RISE TIME)

This is associated with driver circuits of the source and source equalisation circuit.

- Generally, this is specified based on
  - → window region of operation
  - → types of source
  - → $\sigma\lambda$

t_{rx} (RECIEVER RISE TIME)

Several considerations are

- * types of PD → PIN
  → APD
- * Responsivity and wavelength
- * Modulation Bandwidth
  - Electrical } 3dB
  - optical
- * Modulation format
- * Front end passive and active circuits
- * Response of Reciever front end is modeled as a Low Pass filter with step input.

$$g(t) = [1 - \exp(-2\pi B_{rx} t)]\, u(t)$$

$u(t)$ → step input

B_{rx} → 3 dB bandwidth of Rx

→ $u(t) = 1$ for $t \geq 0$
$= 0$ for $t < 0$

- * Generally rise time of reciever is defined as the transition time of response to change from 10% to 90% of amplitude levels.

Approximately $\boxed{t_{rx} \simeq \dfrac{350}{B_{rx}}}$

if B_{rx} is in MHz, then t_{rx} will be in nsec ii (tGVD : (GROUP VELOCITY DISPERSION RISE TIME))

This is very diffiuult to ~~accurately~~ be computed accurately for a link because

- → number of splices or joints
- → even if we use same fiber there will be microvariations in R.I profile, modal characterisation, dispersion characteristics etc which cummulatively gets added.
- → mode mixing and spreading characteristics of fiber further complicate the calculations.
- → fiber misallignment losses further adds to this complication.

→ Finally GVD rise time is a function of dispersion factor, which depends on whether fiber is dispersion compensated / flattened or shifted type.

26-10-18

$$\boxed{t_{GVD} \cong |\Delta| L \sigma_\lambda}$$

where,

Δ : Average dissipiation factor

L : link length

σ_λ : spectral width.

Considering two types of fibers,

(i) Non dispersion shifted fibers

$$D(\lambda) = \frac{\lambda S_0}{4}\left[1 - \left(\frac{\lambda_0}{\lambda}\right)^4\right]$$

where,

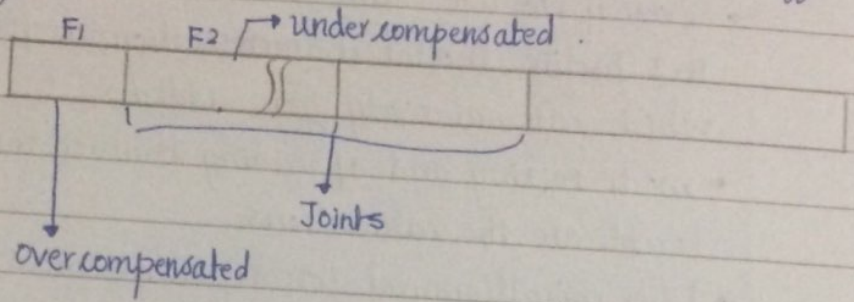
S_0 : Slope of the dispersion curve

λ_0 : zero dispersion wavelength

(ii) For dispersion shifted fibers

$$\boxed{D(\lambda) = (\lambda - \lambda_0) S_0}$$

To make D even over the given link length, splice different dispersion fibers together



* Bm : Modal dispersion bandwidth :

It is the wavelength region over which D is uniform for a given length.

- $$B_m(L) = \frac{B_0}{L^q}$$

  where,

  $B_m \rightarrow$ Bandwidth over 1 km of fiber

  $0.5 < q < 1 \rightarrow$ loading factor

  typically $q \simeq 0.7$

- Bandwidth of fiber connector expressed in terms of optical or electrical bandwidth

  optical $\rightarrow$ (3dB)

$\rightarrow$
$$\boxed{f_{3dB} = B_{3dB} = \frac{0.44}{t_{FWHM}} = B_m}$$

$\rightarrow$ $t_{FWHM} \rightarrow$ Rise time resulting from modal dispersion or (full width half max rise time)

$$f_{3dB} = B_{3dB} = \frac{0.44}{t_{FWHM}} = \frac{0.44}{t_{mod}} = B_m$$

$$\therefore t_{mod} = \frac{0.44}{B_m} = \frac{0.44 L^q}{B_0}$$

If B_m is in MHz, t_{mod} is in nsec,

then,

$$\boxed{t_{mod} = \frac{440 L^q}{B_0}}$$

- Total rise time budget for the given digital link is

$$\rightarrow t_{sys} = \left[\sum_{i=1}^{4} (t_i^2)\right]^{1/2}$$

$$\rightarrow t_{sys} = \left[t_{tx}^2 + t_{mod}^2 + t_{GVD}^2 + t_{rx}^2\right]^{1/2}$$

$$= \left[t_{tx}^2 + \left(\frac{440 L^q}{B_0}\right)^2 + (D L \sigma_\lambda)^2 + \left(\frac{350}{B_{rx}}\right)^2\right]^{1/2}$$

NOTE:

- For SM fibers in window 1, $D = D_{mat}$
- In windows 2 and 3, D further gets reduced.

NUMERICAL:

Consider a digital link, which uses LED source with spectral width of 40n… having NRZ input data, approximate rise time of transmitter is 15nsec material dispersion related rise time degradation is 6 nsec above the transmitter rise time. Approximate link length is 6km, with a bandwidth of 25MHz. Rise time degradation corresponding to reciever system is 14nsec. Assume $q = 0.7$ and average modal dispersion rise time is around 3.9nsec. What is the rise time budget for this digital link and what is the inference?

$$t_{sys} = [(15\,nsec)^2 + (21\,nsec)^2 + (3.9\,nsec)^2 + (14\,nsec)^2]^{1/2}$$
$$\simeq 30\,nsec$$

Inference

Starting with rise time budget, WKT for window 1 digital links maximum limit on rise time degradation must be < 35 nsec (ie 35% of T). Hence given digital link degradation is well within prescribed limits.

HOMEWORK

$D = 0.07$ nsec/ ~~km~~ nm-km

$L = 8$ km

Window 3 region

$\sigma_\lambda = 2nm$ for ILD

$B_0 \simeq 50MHz$

Saturday — 27 OCT 2018

TRANSMISSION DISTANCE IN SINGLE MODE FIBERS

Link length depends on

(a) λ of operation

(b) Attenuation of fiber

(c) Type of source at its σ_λ

(d) Detector Sensitivity

(e) Type of Data
- → NRZ
- → RZ

(f) power output source

(g) GVD

(h) Datarate

For SM fibers, GVD is predominant and hence no other dispersion

$$t_{GVD} = |D| L \sigma_\lambda$$

Scanned by CamScanner

Example: SM fiber at 1550nm

$D_{average} = 2.5$ psec/nm-km $= 2.5\times10^{-3}$ sec/m-km

Compute link length for

(a) RZ data, $\sigma\lambda = 3.5$nm LD source, $B_{Tmax} = 200$Mbps.

t_{GVD} is limited to 35% of bit time.

Solution: I

$t_{GVD} = 35\% \cdot \frac{1}{B_{Tmax}}$

$= (35\%)\left(\frac{1}{200\times10^{6}}\right) = 1.75$nsec

Bit time $= T = \frac{1}{B_{Tmax}} = \frac{1}{200\times10^{6}} = 5$nsec

$1.75\text{nsec} = (2.5\times10^{-3})L(3.5\times10^{-9})$

$\therefore L = 200$m

II Instead of multimode LD source, if we use SM LD source $\sigma\lambda = 1$m

(a) $t_{GVD} = 35\%\left(\frac{1}{200\times10^{6}}\right) = 1.75$nsec

$L_{RZ} = 700$m

(b) $t_{GVD} = 1.4$nsec

$L_{NRZ} = 560$m

CONCLUSIONS :-

(i) As $\sigma\lambda \downarrow$, $L \uparrow$ for both RZ and NRZ data

(ii) For RZ and NRZ having smaller link lengths larger data rate is possible because of reduced GVD.

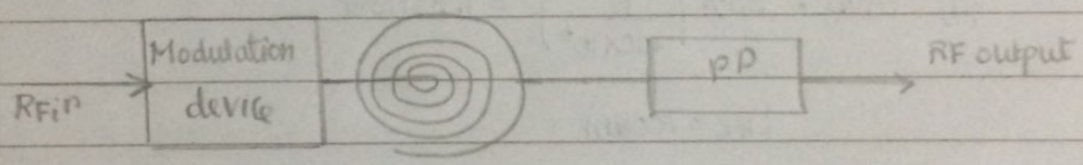
: If D is reduced by 10 fold, find the improvement in 'L'

MWP : MICROWAVE PHOTONICS :- (MICRO PHOTONS)

- This is inter disciplinary which integrates microwaves and photonics.
- Using photonic crystals, we can increase & enhance microwave systems. based on SWAP system
  ↳ Size, Weight And Power
- Improvements wrt
  - a. Bandwidth
  - b. Range (Dynamic Range)
  - c. Reducing power requirements
  - d. Reduction in IL (Insertion loss)
  - e. Reflection, impedance matching requirement can be eliminated.

FRIDAY 2/11/2018

HEART OF MICROWAVE PHOTONICS IN THE MICROWAVE LINK :



FUNCTIONALITIES :

i. TIME DELAY :

- * Rise time constraints
- * Time delay of active devices

ii. PHASE SHIFT :

- * Phase compensation for long distance communication to preserve mode patterns.

* micro active components in the circuit introduces unwanted phase change

iii. FILTERING OF UNWANTED FOR COMPONENTS

iv. FREQUENCY CONVERSIONS

Microwave range to optical range converssions and vice versa.

v. MODULATION FORMATS FOR TRANSMISSION

Most of the links use IMDD (Intensity Modulation Direct Detection)

⇒ Modulation is of two types

(a) DIRECT : Information signal is converted to optical signal and is modulated using an optical carrier (MM)

(b) INDIRECT : Modulation is done at microwave frequency and then translation is done.

CW → Continuous wave modulation
EOM → Electric optical modulators are used.

★ Other advantages:

- → Constant attenuation over a given window
- → Large dynamic range (increased tunalility)
- → Immune to EMI/RFI

★ PARAMETERS

i) link gain
ii) Dynamic range (SFDR → Spurious Frequency Dynamic Range)
iii) NF
iv) Fidelity and Sensitivity

APPLICATIONS OF MICROWAVE PHOTONICS

- GHz - THz frequency generators / function generators
- HSWN : High Speed Wireless Networks
- WSN : Wireless Sensor Networks used in IoT
- Radar and Satellite Communication.
- Cellular mobile system
- CATV / HDTV
- Distributed and multiple antenna system etc MIMO
- OSP : optical Signal processing
- Optical Computing
- Medical imaging and endoscopy applications.

MODAL NOISE

- Various discontinuities in the connecting medium alters the modal patterns
- This happens in
  - i) couplers/connectors/jumpers
  - ii) Splices

- Due to changes in the modal pattern, mean optical power level reduces which affects Quantum limit of detection.

- Variation in power levels create variations in CNR, Pe and BER performances and also increases power penalties

Main reason for increased power penalties are
(a) Modal noise
(b) Laser chirping
(c) Spectral broadening effects
(d) Mode partition noise effects.

- Modal noise generally occurs in coherent single mode lasers when signal is coupled to multimode fibers. (ie modal compatibility between two)

- Not important if Bit Rate B_T for 100Mbps upto 400Mbps
  But critical if $B_T > 400$Mbps.

- Frequency and wavelength variations of the source.

- Mechanical vibrations

---

3 Nov 2018

Modal noise depends on BER performance

Example : APD is the detector $\lambda = 1200$nm

$B_T = 280$Mbps

If 'M' is the number of spectral components (speckles) incident on APD

Then if $M_1 = 2910$ (very large for dominant LD mode)
then BER $= 10^{-6}$ no power penalty required or no modal losses detected

$M = 50$ (Reduced speckles)
To achieve BER $= 10^{-6}$, we need 1dB additional power penalty

Similarly

$M = 20$

to achieve BER 10^{-6} we need 2dB additional power penalty.

REMEDIAL MEASURES :

1. Use non coherent source like LED where MN is completely avoided.
2. Use LD source with more number of ~~longitudin~~ longitudinal spectral components.
3. As far as possible avoid mechanical vibrations
4. Keep mode compatibility between source and fibre & use large numerical aperture fiber which generally supports MM operation where 'M' will be sufficiently large.
5. Use all SM source fiber etc such that IM dispersions can be avoided.

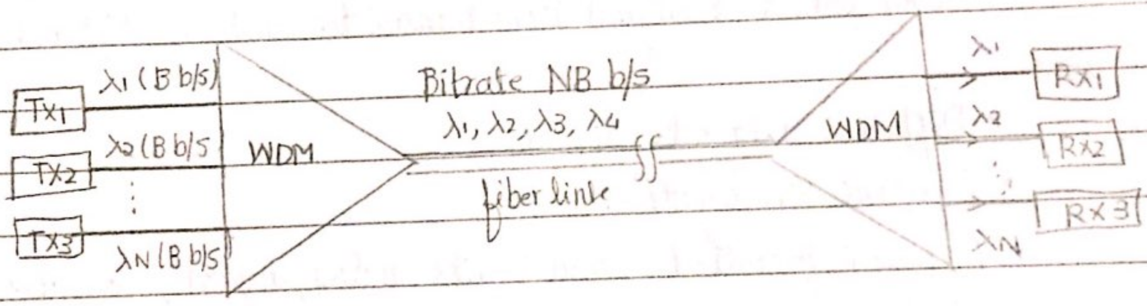
UNIT 5 - WAVELENGTH DIVISION MULTIPLEXING & NETWORKS

3 NOV 2018
SATURDAY

CO5 : Demonstrate awareness about emerging trends in the field of optical communication and networking.

WDM PRINCIPLES :

→ It is basically a FDM system,
→ Many different wavelength signals are simultaneously transmitted through channel or fiber.
→ WDM is generally implemented in W2 and W3 regions because
  i. Attennae is small
  ii. Using dispersion shifted or flattened fiber, minimum dispersion can be obtained.
→ Proper guard band spacing is required to overcome inter channel interference.



WDM FEATURES ARE :

(i) CAPACITY UPGRADE :

- point to point link capacity can increase many fields which increases spe efficiency (η)

- Number of wavelengths can be multiplexed depending on data rate of individual channel.

Example :

- If $B_T = 2.5$ Gbps
  $N = 32$

- * $B_T = 10$ Gbps
  $8 < N < 10$

- * According to ITU specifications
  B_T of fiber = 2 Tbps (theoritical)
  B_T of fiber available = 80 Gbps (practical)
  ↓
- Due to various constraints like E/O conversion at transmitter
  O/E conversion at reciever.

using number of electrical circuits.

(ii) IMPROVED TRANSPARENCY :

Any format of signal from transmitter can be multiplexed.

- Different data rate signals.
- Different wavelength signals
- Different formatted signals like analog, digital, SX, HDX, FDX, of fast etc.

(iii) FLEXIBILITY OF WAVELENGTH ROUTING.

Using optical routing devices like routers, network switching wavelength addressing is possible

WAVELENGTH SWITCHING :

- Reconfiguration of optical layer possible
- Unwanted delays in switching can be reduced.
- Switching speed can be increased
- Key components are
  - Add/drop MUX
  - Optical Cross Connect
  - Wavelength convertors

Some more devices required to implement WDM are

- Optical power splitters or combiners
- Tunable optical sources
- Tunable optical wavelength filters
- Optical amplifiers
- Directional couplers.

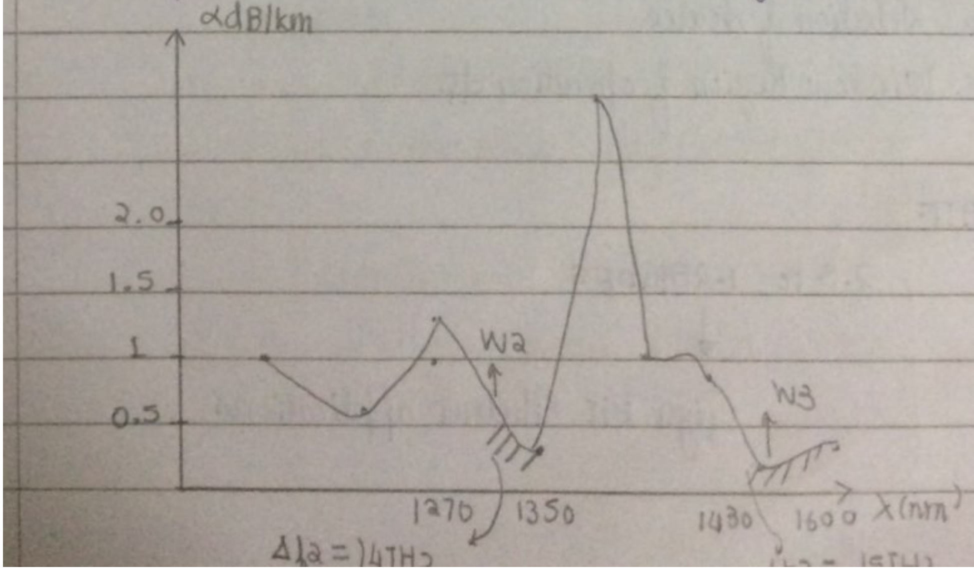
OPERATION PRINCIPLES OF WDM :

(i) OPTICAL ~~SOURCE~~ SENSORS

- DFB layer
- $\sigma\lambda = 10^{-3}$ nm
- Guard Band spacing 0.4 to 1.6nm

Considering ~~gifts~~ drifts in peak emmision wave

- length, temparature/bias variations, aging etc



- While selecting the window region of operation consider minimum fiber attenuation and also use dispersion shifted / flattened fibers to keep both losses at minimum level.

- Total optical bandwidth available in W2 and W3 is 29 THz ($\approx$ 30THz)

- $\Delta V = \left(\frac{c}{\lambda^2}\right)|\Delta\lambda|$

  $|\Delta\lambda|$ → RMS spread spectral width of source.

  ΔV → optical Bandwidth

- Channel spacing depends on the operating window
  (x) 1552 nm : Spacing can be 100 GHz (0.8nm)

  Both attenuation and spacing can be 50 GHz (0.4nm)

  Dispersion loss are minimum spacing can be 200 GHz (0.6nm)

- Normally if spacing is 100 to 200 GHz it is normal WDM if spacing is ≤ it is DWDM.

- WDM STANDARDS :

  ITU under its G.615 charter has given specifications for WD

  This includes
  - a. Bit Rate (x) Channel spacing
  - b. Selection of Source
  - c. Window Region of operation etc

⇒ BIT RATE

2.5 to 1.259 Gbps

↓

Giga bit Ethernet applications

Unidirectional and Bidirectional operation

Link length

40km and 80km

Number of WDM channels

1271-1611

Channel ~~Spreading~~ Spacing

20nm

- Guide Operation of WDM is possible (similar to frequency range system) to improve channel capacity and spectral intensity, spacing can be 100GHz, 50GHz, 20GHz
  - ↳ overlay

12.5 and 6.25GHz
  - ↳ underlay.

CLASSIFICATIONS

WDM
- Normal
  - → W1 & W2 with Bandwidth ≃ 20THz
- Coarse
  - → provides 16 channels ~~according~~ across multiple window additionally using silica fibers.
- Dense WDM
  - → Uses C Band (1530-1565nm)

→ Conventionally we use EDFA for WDM with improved gain and narrow bandwidth, nowadays we use Raman amplifier.

↓

Operates in 'L' band region (1565 to 1625 nm)

↓

W3

Hence capacity of WDM system can be doubled.

⇒ **APPLICATIONS OF WDM :**

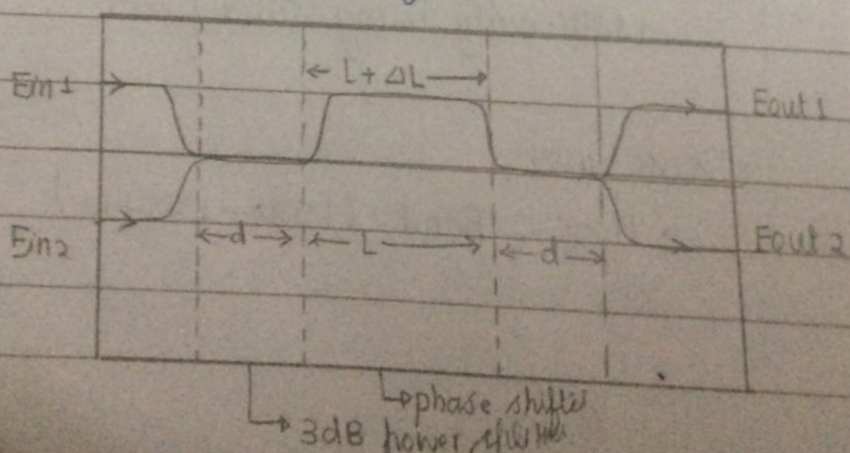
- Ethernet LAN
- Storage area network
- CATV
- Enterprises network.

Saturday

10/11/2018

MACH - ZENDER INTERFEROMETER MUX :

Used to construct wavelength dependant MUX.



MZI consists of 3 stages

- two 3dB couplers for power splitting
- a phase shifter to introduce the phase shift between the curves.
- Extra length ΔL in one of the path in phase shifter, introduces a phase shift such that drive power combining at the output, the two powers can combine constructively or destructively.
- Fiber material and bending losses are neglected.
- Propogation of passive optical components are expressed in terms of propogation matrix 'M'.
- For coupler length 'd',

$$M_{coupler} = \begin{bmatrix} \cos kd & j\sin kd \\ j\sin kd & \cos kd \end{bmatrix}$$

$k =$ coupling coefficient

- For a 3dB coupler (which splits the input power into two equal output powers)

$$2kd = \frac{\pi}{2}$$

$$kd = \frac{\pi}{4}$$

$$M_{coupler} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}$$

· Phase difference or shift introduced between 2 lines is

$$\Delta\phi = \frac{2\pi n_1 L}{\lambda} - \frac{2\pi n_2 (L+\Delta L)}{\lambda}$$

→ n_1, n_2 are R·Is of the two lines

If two lines / waveguides are ~~small~~ same $\eta_1 - \eta_2 = \eta_{eff}$

$$\Delta\phi = K\Delta L$$

where

$$K = \frac{2\pi \eta_{eff}}{\lambda}$$

- $\Delta\phi$ corresponding to 'M' matrix is

$$M_{\Delta\phi} = \begin{bmatrix} e^{j\frac{K\Delta L}{2}} & 0 \\ 0 & e^{-j\frac{K\Delta L}{2}} \end{bmatrix}$$

- Output and input of MZI are related by 'M' matrix

$$\begin{bmatrix} E_{out,1} \\ E_{out,2} \end{bmatrix} = M \begin{bmatrix} E_{in1} \\ E_{in2} \end{bmatrix}$$

where

$$M = M_{coupler} \, M_{\Delta\phi}$$

$$\therefore M = j \begin{bmatrix} \sin\left(\frac{K\Delta L}{2}\right) & \cos\left(\frac{K\Delta L}{2}\right) \\ \cos\left(\frac{K\Delta L}{2}\right) & -\sin\left(\frac{K\Delta L}{2}\right) \end{bmatrix}$$

- If $E_{in,1}$ is at λ_1
  $E_{in,2}$ is at λ_2

$$\therefore E_{out,1} = j\left[E_{in,1}(\lambda_1)\sin\left(\frac{K\Delta L}{2}\right) + E_{in,2}(\lambda_2)\cos\left(\frac{K\Delta L}{2}\right)\right]$$

Similarly

$$E_{out,2} = j\left[E_{in,1}(\lambda_1)\cos\left(\frac{K\Delta L}{2}\right) - E_{in,2}(\lambda_2)\sin\left(\frac{K\Delta L}{2}\right)\right]$$

Where $k_j = \frac{2\pi \eta_{eff}}{\lambda_j}$ $\quad j = 1 \text{ \& } 2$

Optical power at outputs are given by

$$P_{out,1} = E_{out,1} \cdot E_{out,-1}^{*}$$

Similarly

$$P_{out,2} = E_{out,2} \cdot E_{out,2}^{*}$$

normalized parameters.

- Cross products are neglected, since ~~the~~ these wavelengths will be outside the PB of individual fibers/waveguides.

$$Z = \underbrace{|Z|}_{\text{magnitude}} e^{j\overbrace{\phi}^{\text{phase}}}$$

$$\therefore P_{out,1} = \sin^2\left(\frac{K_1 \Delta L}{2}\right) P_{in,1} + \cos^2\left(\frac{K_2 \Delta L}{2}\right) P_{in,2}$$

$$P_{out,1} = \cos^2\left(\frac{K_1 \Delta L}{2}\right) P_{in,1} + \sin^2\left(\frac{K_2 \Delta L}{2}\right) P_{in,2}$$

- Power output from a given point is based on relative phase differences

ie

if $\frac{K_1 \Delta L}{2} = \pi$, $\frac{K_2 \Delta L}{2} = \frac{\pi}{2}$

then output from port 2 is obtained similarly.

Optical power at outputs are given by

$$P_{out,1} = E_{out,1} \cdot E_{out,1}^*$$

Similarly

$$P_{out,2} = E_{out,2} \cdot E_{out,2}^*$$

normalized parameters.

- Cross products are neglected, since ~~there~~ their wavelengths will be outside the PB of individual fibers/waveguides.

$$Z = |Z| e^{j\phi}$$

$|Z|$ → magnitude, ϕ → phase.

$$\therefore P_{out,1} = \sin^2\left(\frac{K_1 \Delta L}{2}\right) P_{in,1} + \cos^2\left(\frac{K_2 \Delta L}{2}\right) P_{in,2}$$

$$P_{out,1} = \cos^2\left(\frac{K_1 \Delta L}{2}\right) P_{in,1} + \sin^2\left(\frac{K_2 \Delta L}{2}\right) P_{in,2}$$

- Power output from a given point is based on relative phase differences

ie

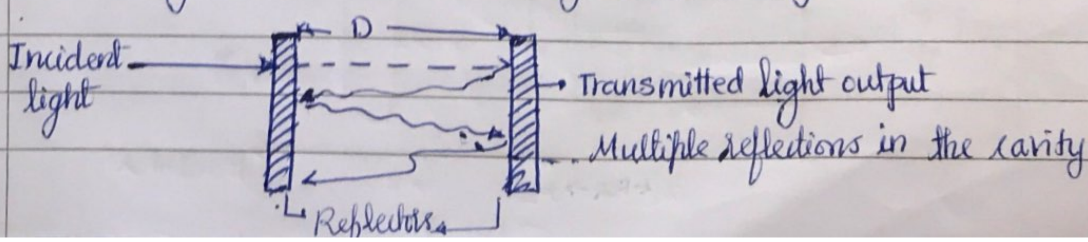
if $\frac{K_1 \Delta L}{2} = \pi$, $\frac{K_2 \Delta L}{2} = \frac{\pi}{2}$

then output from port 2 is obtained similarly.

Wednesday. 14/11/2018

THIN FILM FILTER

- These are band pass filters used to select particular 'λ' from band of 'λs'
- They are based on "Fabry - Parot Cavity"



- This filter selects a particular
  - → λ based on cavity reasonance
  - → Round trip distance of reflected waves is generally integer multiple of λ (ie $n\lambda$) where $n = 1, 2, 3 \ldots$

- This is a bilateral device, light waves gets added if they are in phase.

FILTER PARAMETERS

(a) T(Transmission Parameters)

"Ability to select a particular wave length from a given set of wavelengths"

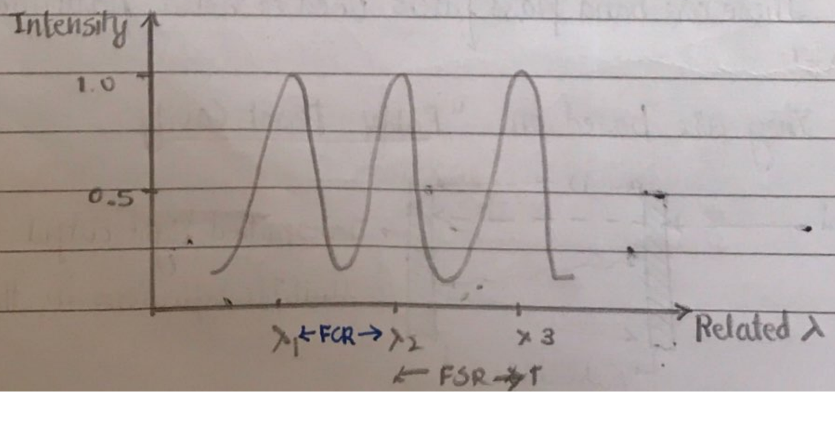
$$T = \left[1 + \frac{4R}{(1-R)^2} \sin^2\left(\frac{\phi}{2}\right) \right]^{-1}$$

where,

- R → ~~Reflectaty~~ Reflectivity of the mirrors
- ϕ → Round trip delay of the waves related to optical for $f = \frac{2\pi}{\lambda}$
- $\phi = \left(\frac{2\pi}{\lambda}\right)(2\eta D \cos\theta)$
- η = RI of the medium
- θ = angle of normal to the incoming light beam

→ Filter exhibits multiple reasonance and is hence called multi reasonance filter.

- Number of passbands produced depends on the condition $N\lambda = 2\eta D$



→ As R ↑ , the Band pass filter characteristics becomes more selective & sharper.

(b) FSR (FREE SPECTRAL RANGE)

This defines the spacing between the reasonant ~~carriers~~ curves or inter λ spacing. Very important in WDM application.

$$\boxed{FSR = \frac{\lambda^2}{2\eta D}}$$

(c) FWHM (Full Width Half Maximum)

This defines the passband width of the filter and also gives ~~information~~ information regarding number of λs that can be accomodated in the P.B.

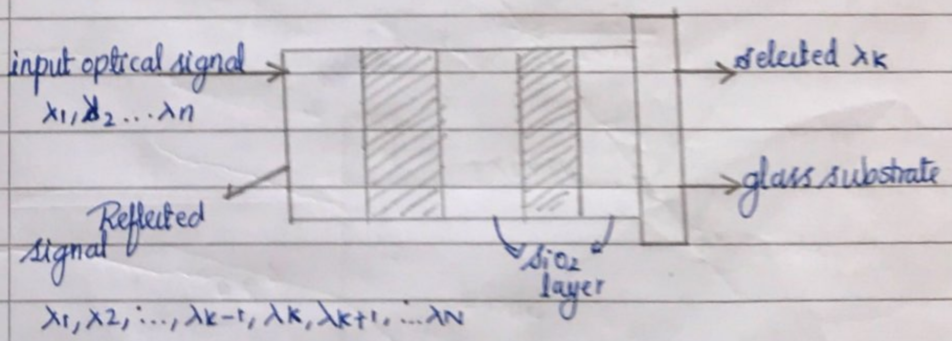
$$= \frac{FSR}{FWHM}$$

This is also called "Finesse" of the filter

$$\boxed{F = \frac{\pi\sqrt{R}}{rR}}$$

PRACTICAL CONSIDERATION :

Implemented by depositing multilayer thin coatings of alternatively low ~~voltage~~ or high RI regions on a glass substrate.



- Selectivity depends on number of layers. As number of layers ↑ it improves selectivity but PMD also increases.

Scanned with CamScanner

Specifications :

- Two types of bandwidths are possible.
- Narrow Band

  Bandwidth = 50GHz

  → smaller λ spacing
- Wide Band

  Bandwidth = 80GHz

  → wider λ spacing.

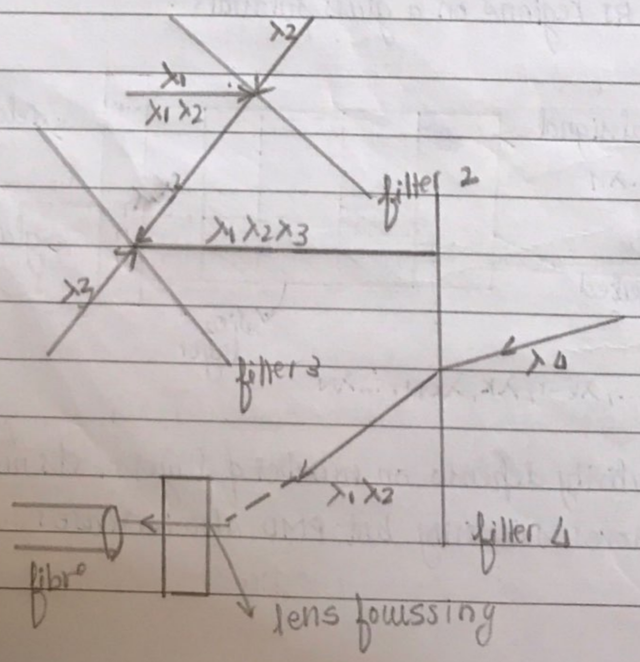
Parameter :

(a) I·L < 3.5dB
(b) Chromatic design < 50 ps/nm
(c) PMD loss < 0.2 psec
(d) Isolation between successive wavelengths is > 25 dB
(e) Optical return loss > 45dB
(f) Polarization dependant loss < 0.2dB

⇒ APPLICATIONS OF TFF :

Wavelength of the MUX/ DE-MUX for separately or combining 'N', λs we require (N-1) filters.

Example :



NOTE : TO IMPLEMENT A DEMUX JUST REVERSE THE ARROWS .

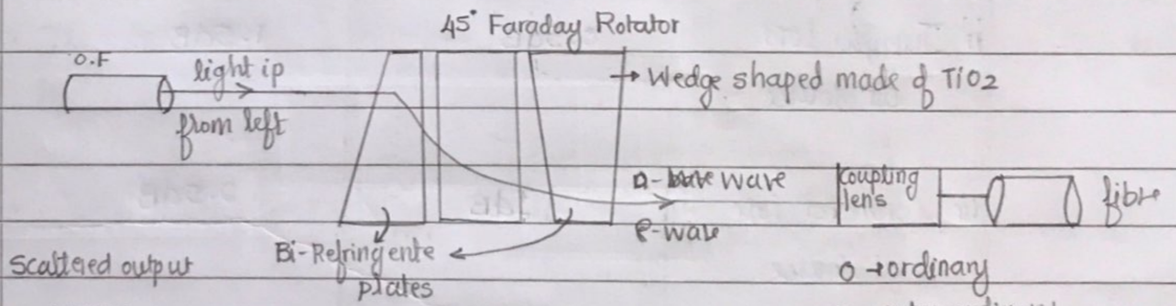
ISOLATORS AND CIRCULATORS :

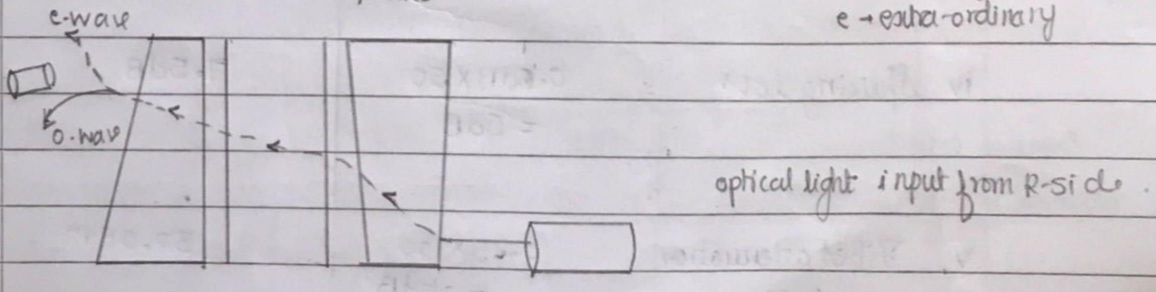
Their working is based on polarization and are hence called "(POLARISATION SENSITIVE DEVICES)"

- A light wave is a combination of parallel and perpendicular vibrations of wave which forms two orthogonal plane of polarisation states.
- Faraday rotators is a device which rotates SOP (state of polarisation) by a specific angular waves.
- Walk off polarizer made of bi-refringent materials splits incident light to parallel and perpendicular waves.
- Half wave plate polarizer (HPP) rotates SOP clockwise by 45° when signal travels L to R & counter clockwise by 45° when signal travels from R to L.

i) ISOLATOR

- Allows signal only in one direction used to isolate and protect I/O sources.





Specifications :

- Central wavelength around which isolator operates : 1350 to 1550nm
- Peak isolation loss loss ≃ 40dB
- I.L < 0.5dB (loss informed direction or coupling loss)
- PD loss < 0.1dB
- PMD < 0.25 psec .

Friday — 23 Nov 2018

Solution to test III pattern :-

Available power at the output of ILD = $P_0 = 4mW \times \eta_q$

$= 4mW \times 0.8$

$= 3.2mW$

$= 5.05dB$

Spread sheet for power budget

COMPONENT	LOSSES	MARGIN
i Source-Fiber coupling loss	1dB	1dB
ii Jumper loss at source	0.5dB	1.5dB
iii Connector loss at source	1dB	2.5dB
iv Splicing loss	0.1dB × 50 = 5dB	7.5dB
v. Fiber attenuation loss	0.25 × 100 = 25dB	32.5dB

Connector loss at reciever	1dB	33.5dB
Jumper loss at reciever	0.5dB	34dB
fiber to detector coupling loss	1dB	35dB
power available at input of detector	5.05dBm - 35dBm = -30dBm	-
power margin available	-30dB - (-40dBm) = 10dB	

power available at the input detector is 10dB more than the requered power, detection is possible

TOF : Tunable optic fibers

- They are the key components of WDM and DWDM networks used to select the channels at Rx

- Fabricated by (MEMS) or (Braggs grating) methods

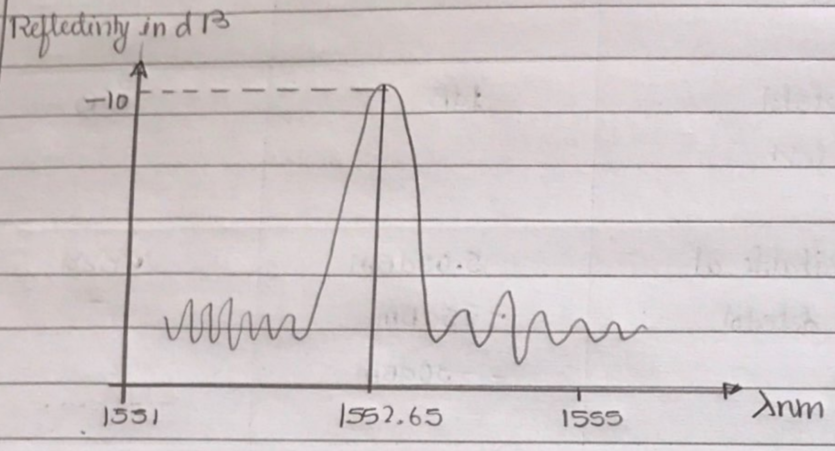
  MEMS ↓ Wideband BPF

  Braggs grating ↓ Narrowband BPF

- MEMS technology used ~~[illegible]~~ epitaxially grown semiconductor mirror facets on a single substrate, where using actuators one of the ~~mirrors~~ mirrors facet can be varied.

→ This varies B and hence λ can be varied.

→ Bragg's grating filters are reflective type using reflective materials, unwanted wavelengths are rejected and only desired λ can be selected.



→ BGF use streching and relaxing process of spacing between the periodic RI profiles, that varies RI and hence λ can be varied.

→ Alloy glass is used for fabrication.

If λ_c is centre wavelength of grating then,

$$\boxed{\lambda_c = 2\eta_{eff}\,\Lambda}$$

↳ period of grating index variations.

If grating is streched

$$\boxed{\Delta\lambda = 2\eta_{eff}\,\Delta\Lambda}$$

→ Streching and contraction can be done by
- → Thermomechanical method
- → piezo electric method
- → stepper motor

__/__/__

- TOF are used in II and III window regions
(SC and L band)

SPECIFICATIONS

- Tunable range : 1nm – 100nm ($\Delta\lambda$)
- channel spacing (FSR) ≃ 150nm • typical
- Selectivity of channel width = 0.2nm to 50nm
  - 0.2nm → narrow band
  - 50nm → wide band.
- I·L < 3dB in the tunable range
- Tuning speed (TS) = 10nm/μsec (typical)

DISADVANTAGE

- large bias voltage = 40V

APPLICATIONS

- Gain tilt monitoring of components in optical Amplifier (OA)
- Optical performance monitoring of survivable optical networks
- Reciever of DWDM and WDM networks
- Suppression of ASE (Amplifier Spontaneous noise in EDFA)

Saturday 24/11/2018

Optical networks:

These networks came into existence because of the requirement in

- commerce - Banks
- ~~banks~~ finance - Markets/Malls
- education
- ~~Scientists~~ scientific
- Research
- Medical
- Healthcare

- national and international security
- entertainment

Infrastructure requirements :

- High end terminal equipments / computers / peripherals .
- large storage devices
- high speed channels
- large bandwidth
- BER performance
- low interference / Noise .

Two types of optical networks

i) SONETS
- Synchronous optical networks
- Standard by ANSI used in North America .

ii) SDH
- Synchronous Digital Hierarchy
- ITU
- Rest of the globe

SDH formats are based on

(a) Speed

SDH level	Actual line rate in Mbps	Common or commercial rate in Mbps
STM-1	155.52	155
STM-2	622.08	622
-16	2488.32	2.5 Gbps
-64	9953.28	10 Gbps
-256	39813.12	40 Gbps

based on link by that and wavelength of operation.

Transmission distance / λ	fiber type	SDH terminology
$\leq$ 2km	G.652	Inter office (I.1)
upto 15km - 1310nm	G.653	Short haul (S.2)
upto 15km - 1550nm	G.653	Short haul (S.2)
upto 40km - 1310nm	G.655	long haul (L.3)
upto 80km - 1550nm	G.655	long haul (L.3)
upto 120km - 1550nm	G.655	very long haul (V.4)
upto 160km - 1550nm	G.655	ultra long haul (U.5)

→ G.652 to G.655 Optical fiber cables

→ GRIN-MM : non dispersion shifted

→ GRIN-SM : dispersion shifted

→ operated at 1310nm and 1550nm windows.

attenuation min dispersion minimum.

→ Attenuation Criteria (dB/km)

0.5 to 3.5 at 1310nm → Short Haul

0.2 to 0.35 at 1510nm → long haul, very long haul, ultralong haul

→ BER performance.

for

$B_{T}max = 1Gbps$ $BER \simeq 10^{-10}$

$B_T > 1Gbps$ $BER \simeq 10^{-12}$

→ Sources:

- monomode or singlemode ILD^3 & DFBLD^3
- $\sigma\lambda$ → rms 0.1 to 0.2nm in DWDM

  2nm to 20nm in WDM

· In SH communication
multilayered LEDs ie DH structure are used.

Detectors:
→ APDs with $M \simeq 10$ for ~~kan~~ long haul, very long haul and ultra long haul communication
→ $M \simeq 100$ for short haul
→ low noise devices
· Bulk current noise
· Surface leakage noise.