Unit-2

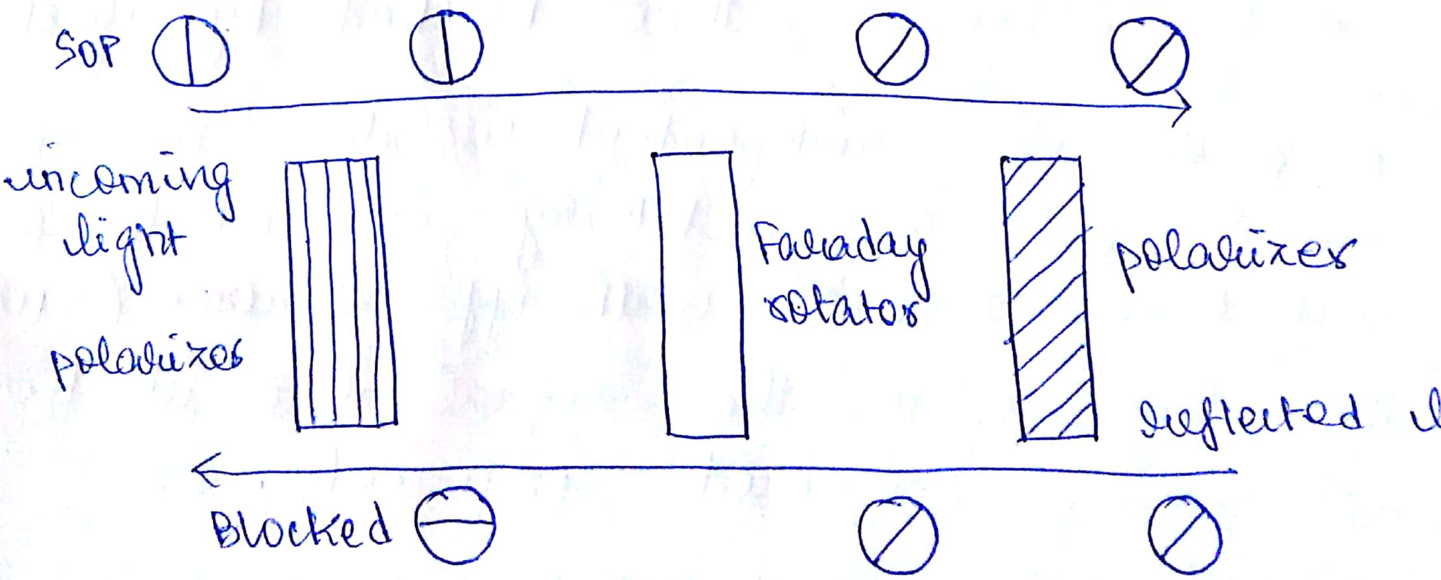
Q.1 What are Isolators and Circulators? Explain the principle of working of an Isolator.

Ans: * An isolator is a device whose main function is to allow transmission in one direction through it but blocks all transmission in the other direction.

* Isolators are used in systems in front of optical amplifiers and lasers primarily to prevent reflections from entering these devices which would otherwise degrade their performance.

* The 2 key parameters of an isolator are insertion loss, which is the loss in the forward direction, and which should be as small as possible, & its isolation, which is the loss in the reverse direction, & which should be as large as possible.

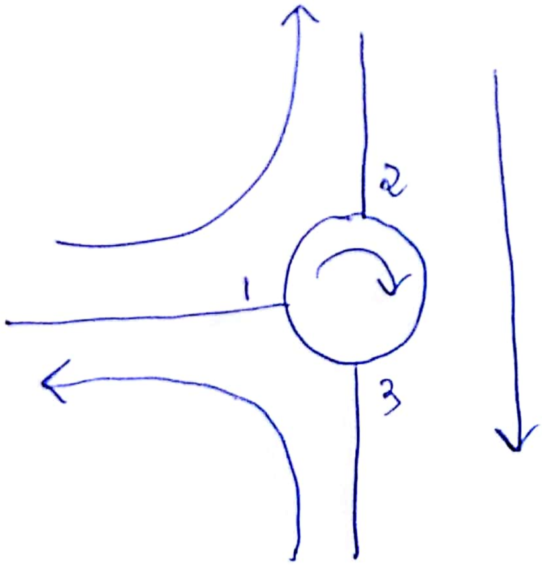
* The principle of operation of an isolator is shown below that works for a particular SOP



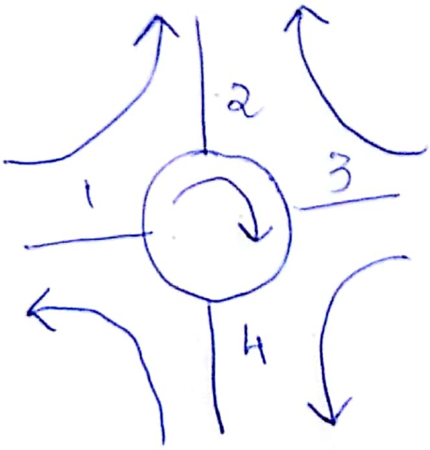
- Assume that the input light signal has the vertical state of polarization (SOP) shown in figure
- It is passed through a polarizer, which passes only light energy in the vertical SOP & blocks light energy in horizontal SOP.
- The polarizer is followed by a Faraday rotat
A Faraday rotator is an assymmetric device, made of crystal that rotates the SOP, clockwis by 45° regardless of the direction of propagation.
- The Faraday rotator is followed by another polarizer that passes only SOPs with this 45 orientation. Thus the light signal from left t right is passed through the device without a loss.
- On the other hand, light entering the device the right due to a reflection, with the sa 45° SOP orientation, is rotated another 45° by Faraday rotator, & thus blocked by first pola

- A polarization independent isolator has an inpu signal with an arbitrary SOP which is fir sent through a spatial walk-off polarizer (SWP). The SWP splits the signal into its two orthogonally polarized components.

* Circulator :-



(a) 3-port circulator



(b) 4-port circulator

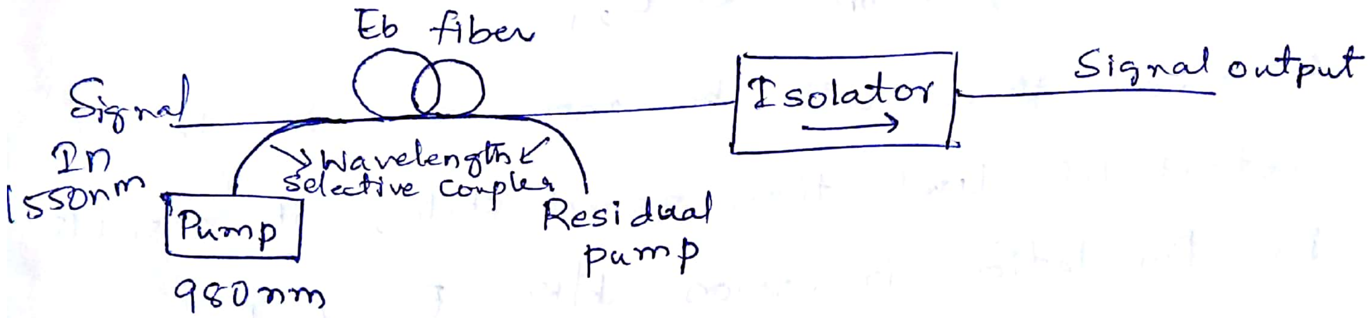
- The principle of operation of a circulator is similar to that of an isolator, but that it has multiple ports, typically 3 or 4 ports as shown in figure.

In a 3-port circulator, an input signal on port 1 is sent out on port 2, and input signal on port 2 is sent out on port 3, and input signal on port 3 is sent out on port 1.

Question : Explain with neat sketch - Erbium doped fiber amplifier.

Answer : Erbium- doped Fiber Amplifier : (EDFA)

* EDFA is a type of optical network works on principle of Stimulated Emission which causes amplification of incoming light.
* The Erbium ion Er^{3+} is used for process.
* General EDFA configuration



* The Basic operation of EDFA is a 3 staged Energy ~~process~~ leveled process.

1. Stark Splitting :

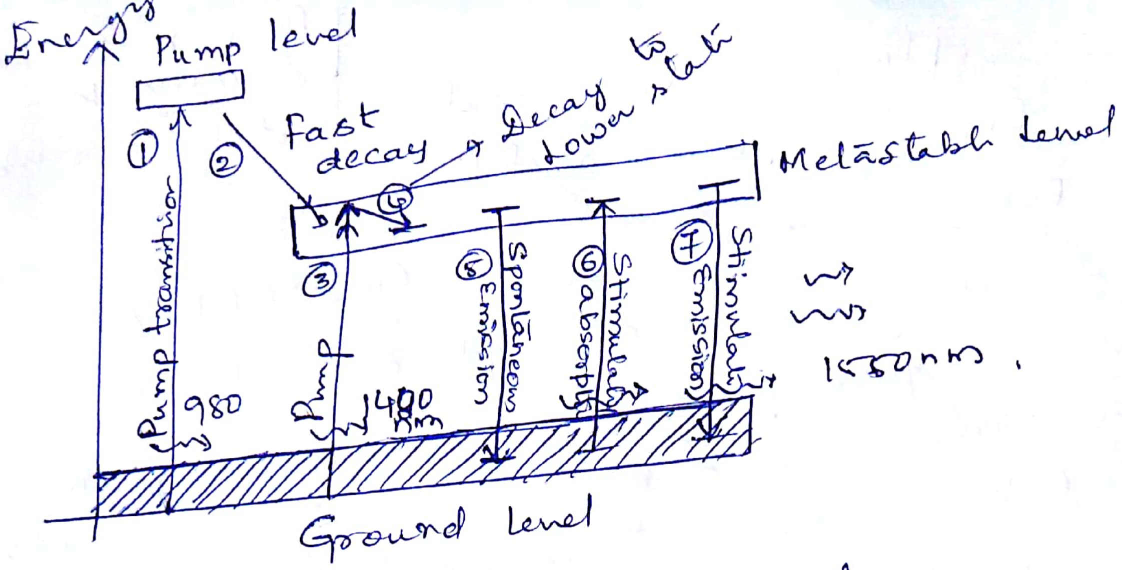
An Isolated ion of Erbium is split into multiple energy levels

Each Stark splitting level is spread into a band.

2. Thermalisation :

Erbium ions are distributed in the various levels within the band.

* Capable of Amplifying several wavelengths simultaneously.



When 980nm pump is used
$\tau_{32} \approx 1\mu sec \ll \tau_{21}$

* Since there will be more ions in the metastable level than ground state, it results in population inversion b/w E_2 & E_1

* we can amplify 1530 - 1570 nm signals when 1480 nm pump is used, the absorption from the bottom ~~~~ of E_1 to the top of E_2

* 1480 nm pump is less efficient

* Less population inversion.

* Higher Noise figure

Advantages :

1) Availability of high power pump lasers
2) All fiber device, polarization independent, ease to couple, reliable
3) Simple
crosstalk.

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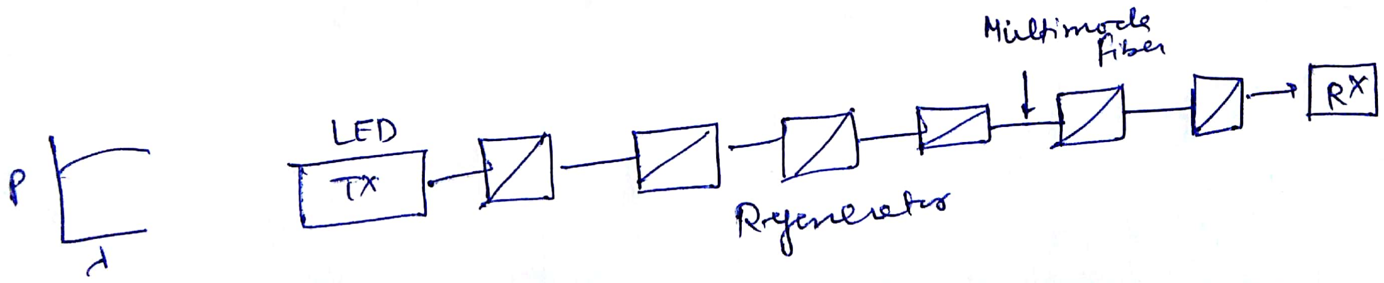
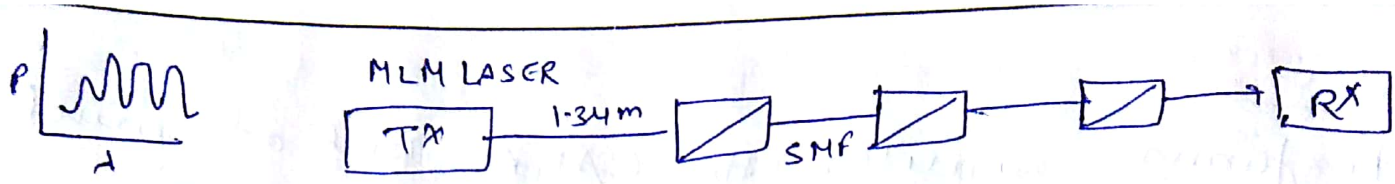
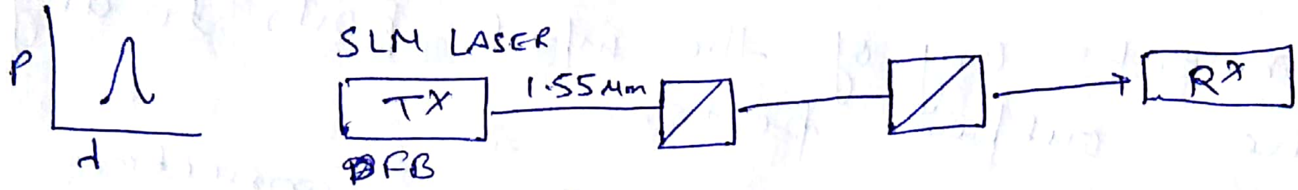
System & Network Evolution

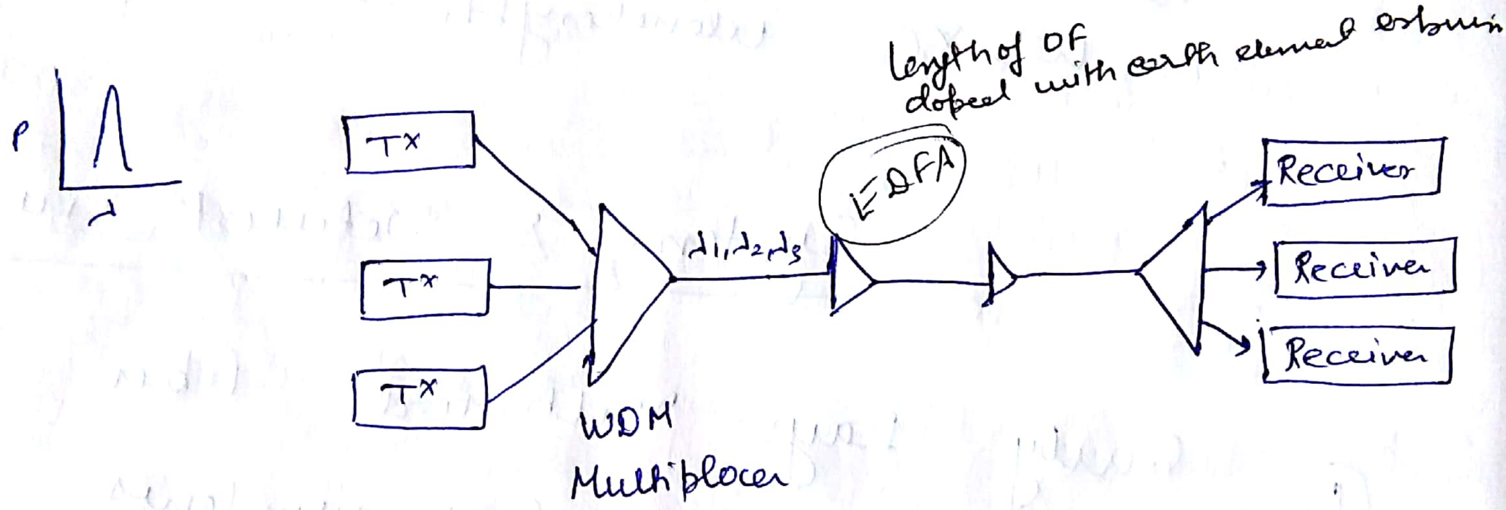
① Early Days Multimode fiber

- → Three low loss windows (0.8, 1.3 & 1.55 μm)
- → Regenerator
- → LED & Detectors
- → LED & MLM (Multilongitudinal mode) LASER
- → intermodal dispersion (pulses travel at diff speed)









→ Small core diameter 8 to 10 μm

→ Chromatic dispersion

→ The high chromatic dispersion at 1.55 μm motivated the development of dispersion-shifted fiber.

→ Dispersion-shifted fiber have zero dispersion in the 1.55 μm wavelength window.

Self Phase Modulation :-

→ SPM arises because the refractive index of the fiber has an intensity dependent component.

→ This non linear R.I causes an induced phase shift that is proportional to intensity of the pulse.

→ Thus different parts of the pulse undergo different phase shifts, which gives rise to chirping of the pulses.

→ Pulse chirping in turn enhances the ~~phase shifts~~ pulse broadning effects of chromatic dispersion.

→ This chirping effect is proportional to the transmitted signal power.

→ In order to understand the effect of SPM, consider a single channel system where the electric field is -

$$\boxed{E(z,t) = E \cos(\omega_0 t - \beta z)}$$

Non-linear dielectric polarization is given by -

$$P_{NL}(x,t) = \epsilon_0 \chi^3 E^3 \cos^3(\omega_0 t - \beta_0 z)$$

$$= \epsilon_0 \chi^3 E^3 \left(\frac{3}{4}\cos(\omega_0 t - \beta_0 z) + \frac{1}{4}\cos(3\omega_0 t - \beta_0 z)\right)$$

Neglecting the component at $3\omega_0$ -

$$P_{NL}(r,t) = \left(\frac{3}{4}\epsilon_0 \chi^3 E^2\right) E \cos(\omega_0 t - \beta_0 z)$$

$$\therefore \beta_0 = \frac{\omega_0}{c}\sqrt{1+\bar{\chi}^{(1)} + \frac{3}{4}\chi^{(3)} E^2}$$

$$n^2 = 1 + \bar{\chi}^{(1)}$$

$$\beta_0 = \frac{\omega_0 n}{c}\sqrt{1 + \frac{3}{4n^2}\chi^{(3)} E^2}$$

$$\beta_0 = \frac{\omega_0}{c}\left(n + \frac{3}{8n}\chi^{(3)} E^2\right)$$

Cross Phase Modulation :-

→ In WDM, intensity dependent nonlinear effects are enhanced since the combined signal from all the channels can be quite intense, even when individual channels are operated at moderated powers.

→ Thus the intensity dependent phase shift and consequent chirping induced by SPM is enhanced because of intensities of the signals in the other channels

→ This effect is called as cross phase modulation (XPM).

$$\boxed{E(r,t) = E_1 \cos(\omega_1 t - \beta_1 z) + E_2 \cos(\omega_2 t - \beta_2 z)}$$

Non linear polarization is given by-

$$P_{NL}(r,t) = \epsilon_0 \chi^{(3)} \left(E_1 \cos(\omega_1 t - \beta_1 z) + E_2 \cos(\omega_2 t - \beta_2 z)\right)$$

Since $(a+b)^3 = a^3 + b^3 + 3a^2 b + 3ab^2$

so $\epsilon_0 \chi^{(3)} \left[E_1^3 \cos^3 \theta_1 + E_2^3 \cos^3 \theta_2 + 3 E_1^2 \cos^2 \theta_1 \, E_2 \cos\theta_2 + 3 E_1 E_2^2 \cos\theta_1 \cos^2 \theta_2 \right]$

where $\theta_1 = \omega_1 t - \beta_1 z$

$\theta_2 = \omega_2 t - \beta_2 z$

$$\Rightarrow E_1^3\left(\frac{1}{4}\cos 3\theta_1 + \frac{3}{4}\cos\theta_1\right) + E_2^3\left(\frac{\cos 3\theta_2}{4} + \frac{3}{4}\cos\theta_2\right.$$

$$+ 3E_1^2\left(\frac{1+\cos 2\theta_1}{2}\right)E_2\cos\theta_2 + 3E_1\cos\theta_1 E_2^2\left(\frac{1+\cos 2\theta_2}{2}\right.$$

$$\Rightarrow \frac{E_1^3}{4}\cos 3\theta_1 + \frac{3E_1^3}{4}\cos\theta_1 + E_2^3\frac{\cos 3\theta_2}{4} + \frac{3E_2^3}{4}\cos\theta_2$$

$$+ \frac{3E_1^2E_2}{2}\cos\theta_2 + \frac{3E_1^2E_2}{2}\cos 2\theta_1\cos\theta_2$$

$$+ \frac{3E_1E_2^2}{2}\cos\theta_1 + \frac{3E_1E_2^2}{2}\cos\theta_1\cos 2\theta_2$$

$$\Rightarrow \left(\frac{3E_1^3}{4} + \frac{3E_1E_2^2}{2}\right)\cos\theta_1$$

$$+ \left(\frac{3E_2^3}{4} + \frac{3E_1^2E_2}{2}\right)\cos\theta_2 + \frac{E_1^3}{4}\cos 3\theta_1 + \frac{E_2^3}{4}\cos\ldots$$

$$+ \frac{3E_1^2E_2}{2}\underbrace{\cos 2\theta_1\cos\theta_2} + \frac{3E_1E_2^2}{2}\underbrace{\cos\theta_1\cos 2\theta_2}$$

Since $\cos A\cos B = \frac{1}{2}\left(\cos(A-B) + \cos(A+B)\right)$

So

$$\left(\frac{3E_1^3}{4} + \frac{3E_1E_2^2}{2}\right)\cos\theta_1 + \left(\frac{3E_2^3}{4} + \frac{3E_1^2E_2}{2}\right)\cos\theta_2$$

$$\cdot\ \frac{3E_1^2E_2}{2}\left\{\frac{1}{2}\cos(2\theta_1-\theta_2) + \cos(2\theta_1+\theta_2)\right\}$$

$$+ \frac{3E_1E^2}{2}\left\{\frac{1}{2}\cos(\theta_1 - 2\theta_2) + \ldots\right.$$

$$\Rightarrow \left(\frac{3E_1^3}{4} + \frac{3E_1E_2^2}{2}\right)\cos(\omega_1 t - \beta_1 z)$$

$$+ \left(\frac{3E_2^3}{4} + \frac{3E_1^2E_2}{2}\right)\cos(\omega_2 t - \beta_2 z)$$

$$+ \frac{3E_1^2E_2}{4}\cos\{2((\omega_1 t - \beta_1 z)) - \omega_2 t - \beta_2 z)$$

$$+ \frac{3E_1^2E_2}{4}\cos(2\omega_1 t - 2\beta_1 z + \omega_2 t + \beta_2 z)$$

$$+ \frac{3E_1E_2^2}{4}\cos(\omega_1 t - \beta_1 z - 2\omega_1 t + 2\beta_1 z)$$

$$+ \frac{3E_1E_2^2}{4}\cos(\omega_1 t - \beta_1 z + 2\omega_1 t - 2\beta_1 z)$$

$$+ \frac{E_1^3}{4}\cos(3\omega_1 t - 3\beta_1 z) + \frac{E_2^3}{4}\cos(3\omega_2 - 3\beta_2 z$$

$$= \epsilon_0 \chi^{(3)} \left[\left(\frac{3E_1^3}{4} + \frac{3E_1E_2^2}{2}\right)\cos(\omega_1 t - \beta_1 z)\right.$$

$$+ \left(\frac{3E_2^3}{4} + \frac{3E_1^2E_2}{2}\right)\cos(\omega_2 t - \beta_2 z)$$

$$+ \frac{3E_1^2E_2}{4}\cos((2\omega_1 - \omega_2)t - (2\beta_1 - \beta_2)z)$$

$$+ \frac{3E_2^2E_1}{4}\cos((2\omega_2 - \omega_1)t - (2\beta_2 - \beta_1)z)$$

$$+ \frac{3E_1^2E_2}{4}\cos((2\omega_1 + \omega_2)t - (2\beta_1 + \beta_2)z)$$

$$+ \frac{3E_2^2E_1}{4}\cos((2\omega_2 + \omega_1)t - (2\beta_2 + \beta_1)z)$$

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$$+ \frac{E_1^3}{4} \cos(3\omega_1 - 3\beta_1 z) + \frac{E_2^3}{4} \cos(3\omega_2 t - 3\beta_2 z)$$

The terms at $2\omega_1 + \omega_2$, $2\omega_2 + \omega_1$, $3\omega_1$ and $3\omega_2$ can be neglected since the phase matching condition will not be satisfied for these term

→ The component of the nonlinear dilectric polarization at frequency ω_1 is -

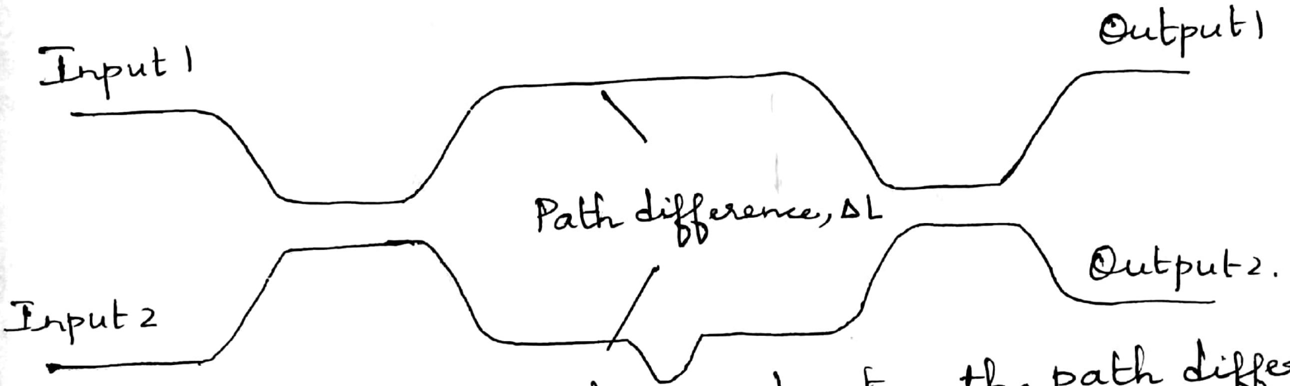
$$\boxed{\frac{3}{4} \epsilon_0 \chi^{(3)} \left[\left(E_1^2 + 2E_2^2 \right) E_1 \cos(\omega_1 t - \beta_1 z) \right]}$$

Due to SPM   CPM

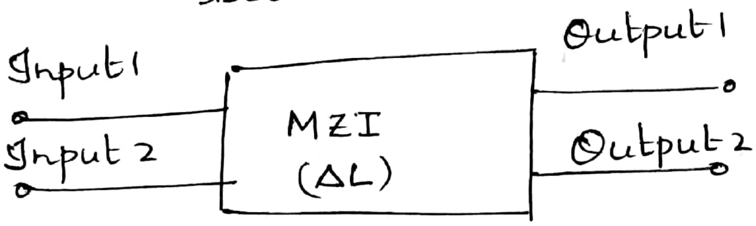
If $E_1 = E_2$, effects of CPM is twice than SPM.

Q.2 Explain Mach-Zehnder Interferometer with its principle of operation.

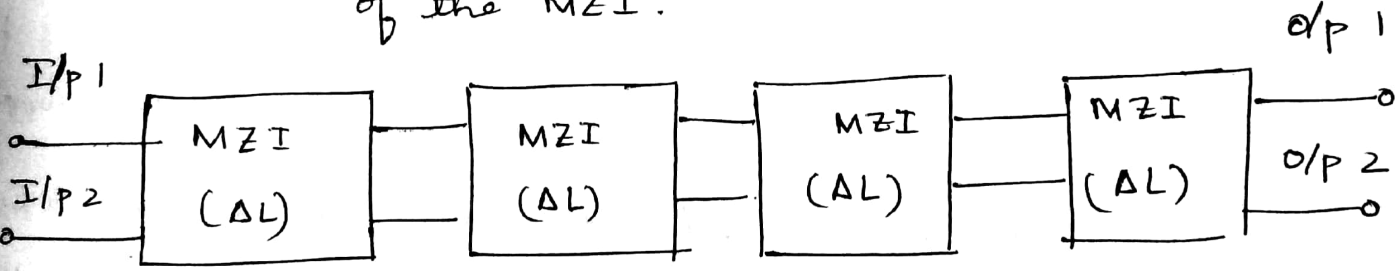
- A Mach Zehnder interferometer is an interferometric device that makes use of two interfering paths of different length to resolve different wavelength.
- They are typically constructed in integrated optic and consist of two 3db directional couplers.
- A substrate is ~~used~~ usually silicon and the waveguide and cladding regions are silica (SiO_2).



(a) - ΔL denotes the path difference between the two arms.



(b) - Block diagram representation of the MZI.



(c)

(c) A block diagram of a four stage Mach-Zehnder interferometer, which uses different path length differences in each stage.

<u>Principle of Operation</u>

> The operation of MZI ~~has~~ as a de-mux, so only one input (say i/p 1). After the first directional coupler, the input power is divided equally between the two arms of the MZI. But the signal in one arm has the phase shift of $\pi/2$ w.r.t the other. The signal in lower arm ~~lacks~~ lags the one in upper arm by $\pi/2$. Since, there is length difference of ΔL between the two arms, there is a further phase lag of $\beta \Delta L$ introduced in the signal in the lower arm.

> In the 2nd directional coupler, the signal in the lower arm undergoes another phase delay of $\pi/2$ in going to the 1st o/p relative to the signal from upper arm. Thus, the total relative phase difference between the two signals is ~~parallel~~ to $\pi/2 + \beta\Delta L + \pi/2$. At the o/p directional coupler ~~At~~ the total relative phase difference is $\beta \Delta L$.

If $\beta \Delta L = K\pi$, when K is odd, the signals add in phase at first output. whereas at second o/p they are in opp. phase and

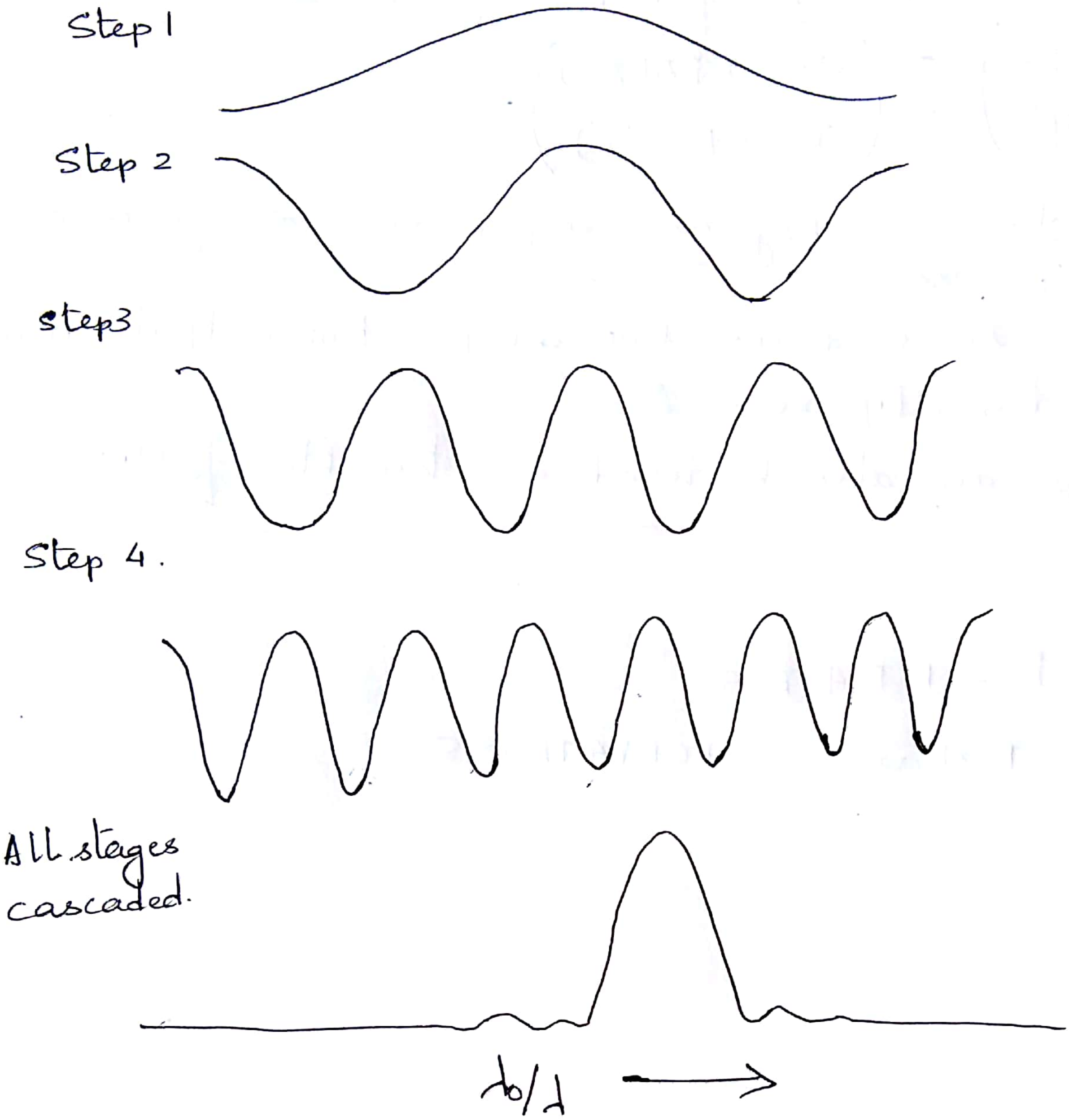


Fig1:- Transfer functions of each stage of a multistage MZI.

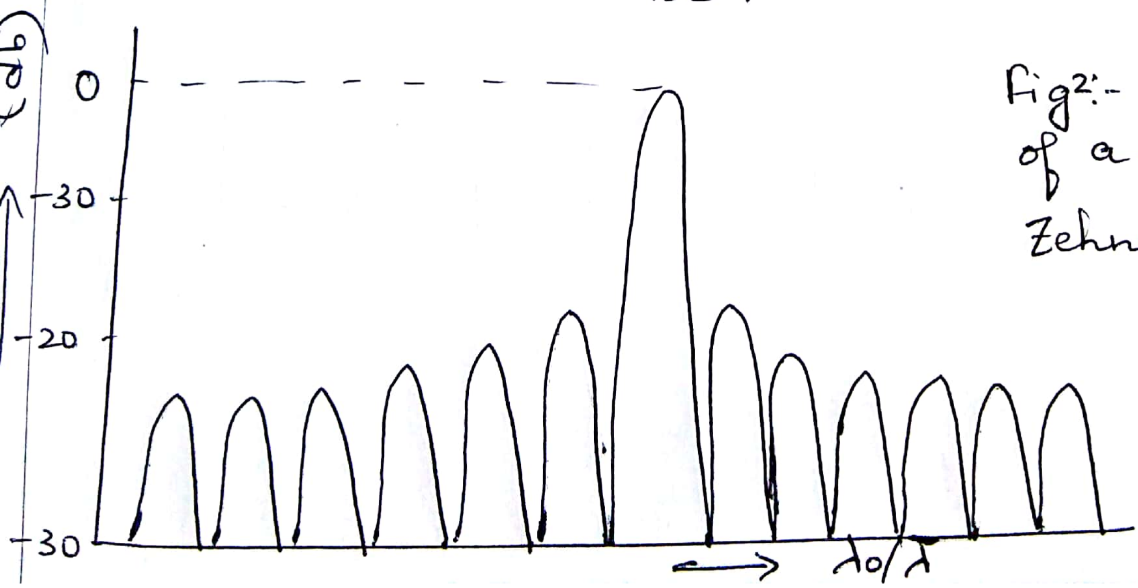


Fig2:- Transfer functi
of a multistage Mach
Zehnder interferomete

The power transfer function of MZI is

$$\begin{pmatrix} T_{11}(f) \\ T_{12}(f) \end{pmatrix} = \begin{pmatrix} \sin^2(\beta \Delta L/2) \\ \cos^2(\beta \Delta L/2) \end{pmatrix}.$$

<u>Applications</u> - They are useful as both filters and multiplexers

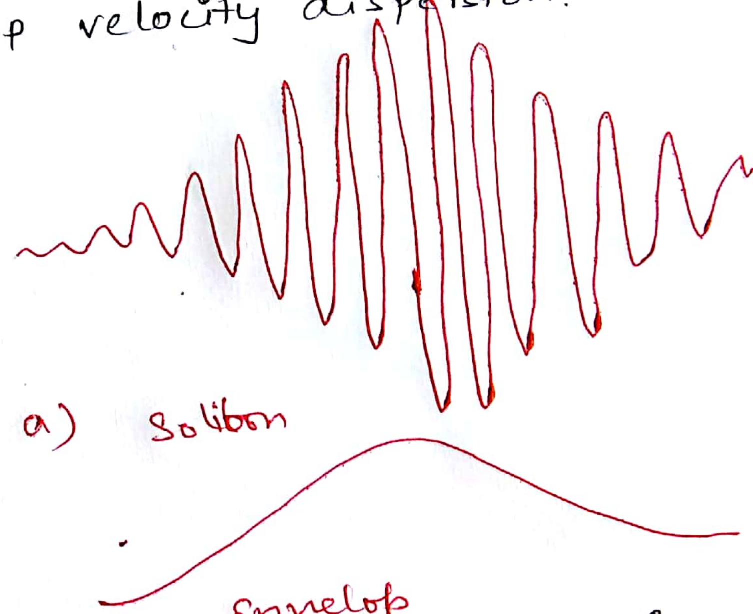
> They are used as two input, two output multiplexers and demultiplexers.

> They can also be used as tunable filters.

Solitons are narrow pulses with high peak power special shapes.

The most commonly used soliton pulses are called fundamental solitons.

- These pulses can propogate for long distances with no change in shape.
- Soliton pulses take advantage of nonlinear effects in silica, specifically SPM, to overcome the pulse broadening effects of group velocity dispersion.



Types:

1) Fundamental solitons
2) Higher order solitons
3) Dispersion managed solitons.

1) Fundamental solitons :

The family of pulses that undergo no change in shape are called fundamental solitons.

2) Higher order solitons :

Those that undergo periodic changes in shape are called higher-order solitons

3) Dispersion managed solitons :

The significance of solitons for optical communication is that they overcome the determental effects of chromatic dispersion completely.

⇒ Bragg gratings are widely used in fiber optic communication systems. In general, any periodic perturbation in the propagating medium serves as a Bragg grating. This perturbation is usually a periodic variation of the refractive index of the medium. Bragg gratings can be used to make a variety of devices such as filters, add/drop multiplexers, and dispersion compensators. Here the Bragg grating is formed by the propagation of an acoustic wave in the medium.

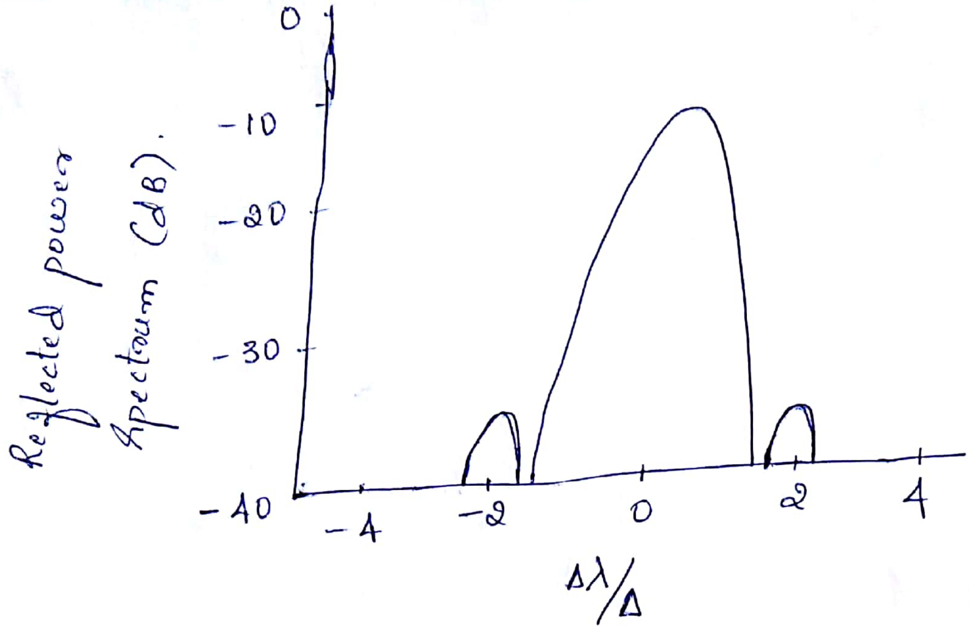
Principle of operation

Consider two waves propagating in opposite direction with propagation constants β_0 & β_1. Energy is coupled from one wave to another if they satisfy the Bragg's phase matching condition.

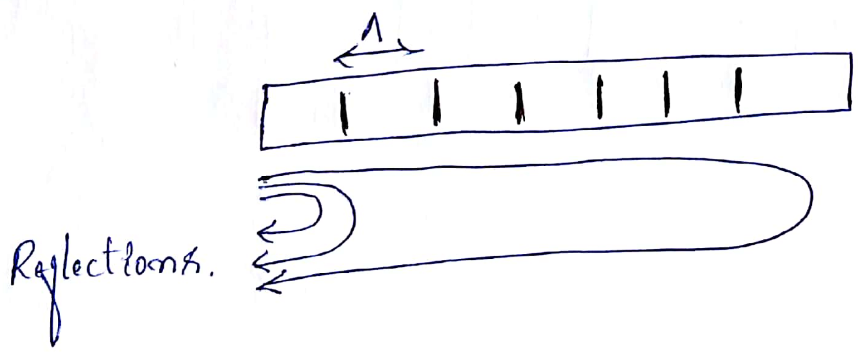
$$|\beta_0 - \beta_1| = \frac{2\pi}{\Lambda}$$

where Λ is period of grating.

In Bragg's grating energy from the forward propagating mode of a wave at the right wavelength is coupled ~~back~~ into a backward propagating mode.



The reflection efficiency decreases as the wavelength of incident wave is detuned from the Bragg wavelength. thus if there are several wavelengths are transmitted into fiber Bragg grating, the Bragg wavelength is reflected while the other wavelengths are transmitted.



The operation of Bragg grating is a periodic variation index. The incident wave reflected from each period of the grating. This reflections add in phase when the path length in wavelength λ_0 each period is equal to that. This is equal to the incident wavelength λ_0.

$n_{eff} \times \Lambda = \lambda_0/2$ which is Bragg's Condition.