UNIT - 4

Electro-Optic Modulators.

Electro optic Effect

The application of an electric field across a crystal may change its refractive indices This electric field may induce birefringence in an isotropic crystal or change the birefringent property of doubly refracting crystal

[birefrigence: In crystalline materials such as Calcite quartz, KDP are optically anisotropic ie velocity of propagation in such materials depends on the direction of propagation and state of polarization of light. The refractive index of these crystals varies with direction and such crystals are called birefringent a doubly refracting]

This is known as the electro optic effect. If the refractive index varies linearly with the applied electric field, it is known as the pockel's effect. and if the variation in refractive index is proportional to the square of the applied electric field. It is called Kerr Effect.

The change in the refractive index 'n' as a function of the applied electric field E can be given by the equation of the form

$$\Delta\left(\frac{1}{n^2}\right) = rE + pE^2$$

E — Applied Electric field.

r — linear electro optic Coefficient

P — quadratic electro optic Coefficient.

Longitudinal Electro optic Modulator.

The effect of an electric field across a crystal showing Pockel's or linear electro optic effect depend on the crystal structure and symmetry.

Consider the case of Potassium Di Hydrogen Phosphate (KDP), a widely used electro optic crystal. KDP is a uniaxial birefringent crystal. and z axis is chosen as the optic axis of the crystal

Uniaxial crystal are transmissive optical elements in which the refractive index of one crystal axis is different from the other two crystal axes ($n_i \neq n_j = n_k$) [This unique axis is called extraordinary axis and is also called as optic axis]

Longitudinal configuration.

Let us consider a longitudinal configuration.

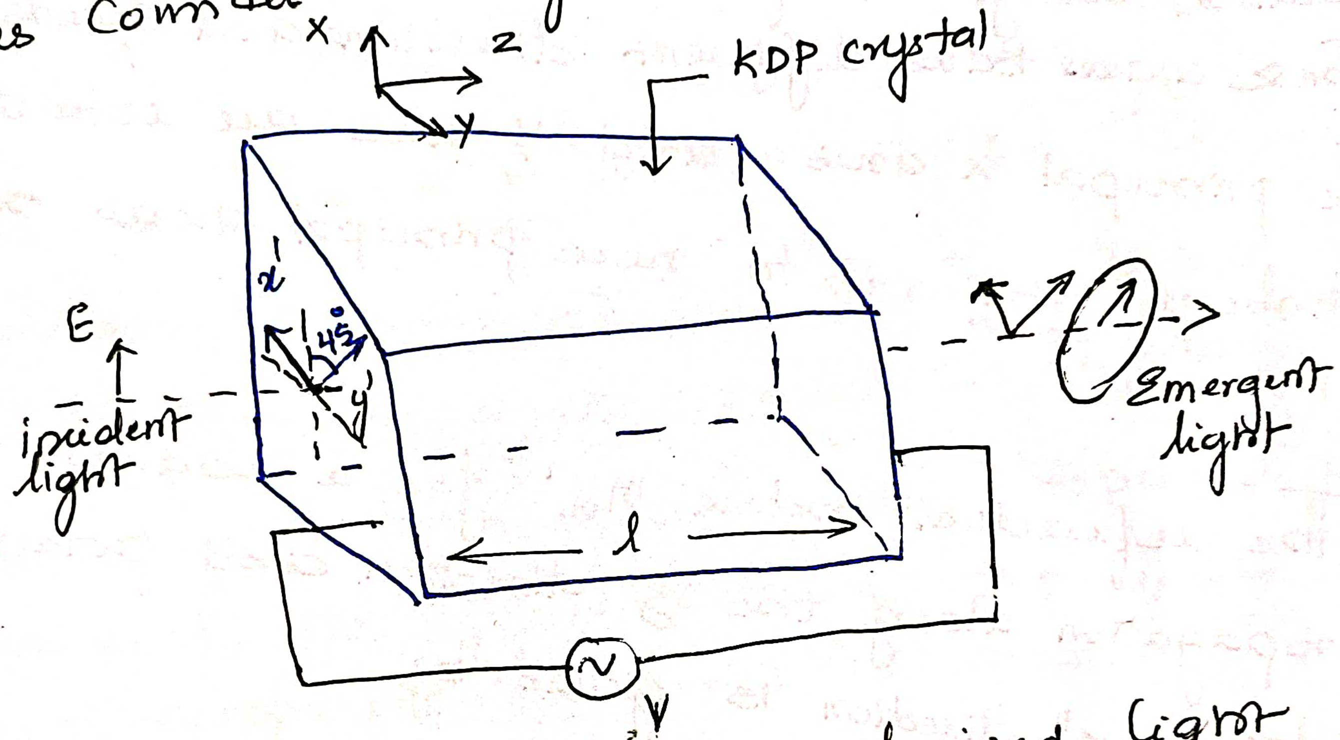


Fig shows a beam of plane polarized light propogating along the z axis of a KDP crystal subject to an external electric field applied in the same direction.

In the absence of electric field, the incident wave polarized normal to the z axis will propagate as a principal wave with an ordinary refracting index n_o [because KDP is uniaxial and optic axis is z]

Upon applying electric field KDP becomes biaxial

[Biaxial crystal is an optical elemt which has 2 optic axes. when a light beam passes through a biaxial crystal, the light beam splits in to two fractions, being both fractions are extraordinary waves These waves have different directions and speeds]

The principal x axis and y axis are rotated through 45° in to new principal axes x' & y'

The refractive index $n_{x'}$ for a wave propagation along the z direction and polarized along x' direction is given by

$$\cancel{n_{y'} = n_o - \frac{1}{2}} \quad n_{x'} = n_o + \frac{1}{2} n_o^3 r_{63} E_z \quad (1)$$

r_{63} — electro optic Coefficient.

The refractive index $n_{y'}$ for a wave polarized in y' is given by

$$n_{y'} = n_o - \frac{1}{2} n_o^3 r_{63} E_z \quad (2)$$

The components incident wave is represented by the equation

$$E = E_0 \cos(\omega t - kz) \quad (3)$$

The components along the x' and y' direction is given by

$$E_{x'} = \frac{E_0}{\sqrt{2}} \cos(\omega t - kz) \quad (4)$$

$$E_{y'} = \frac{E_0}{\sqrt{2}} \cos(\omega t - kz) \quad (5)$$

and these components will become out of phase as they propagate through the crystal. If the crystal thickness along the propagation direction is l, the phase change experienced by the 2 component at z = l is given by

$$\phi_{x'} = k n_{x'} l = \frac{2\pi}{\lambda} n_{x'} l \quad (6)$$

$$\phi_{y'} = k n_{y'} l = \frac{2\pi}{\lambda} n_{y'} l \quad (7)$$

Substituting (1) in (6)

$$\phi_{x'} = \frac{2\pi}{\lambda}\left(n_0 + \frac{1}{2} n_0^3 r_{63} E_z\right) l$$

$$= \frac{2\pi}{\lambda} l n_0 \left(1 + \frac{1}{2} n_0^2 r_{63} E_z\right) \quad (8)$$

Assuming $2\pi l n_0/\lambda = \phi_0$ and $\pi l n_0^3 r_{63} E_z/\lambda = \Delta\phi$

equation (8) becomes

$$\phi_x' = \phi_0 + \Delta\phi \quad \text{--- (9)}$$

Similarly substituting eqn (2) in eq (7)

$$\phi_y' = \frac{2\pi}{\lambda} l n_0 \left(1 - \frac{1}{2} r_{63} n_0^2 E_z\right)$$

$$\phi_y' = \phi_0 - \Delta\phi \quad \text{--- (10)}$$

$$\Delta\phi = \frac{\pi}{\lambda} l r_{63} n_0^3 E_z = \frac{\pi}{\lambda} r_{63} n_0^3 V \quad \text{--- (11)}$$

[where $V = E_z l$ applied voltage]

The extra phase shift $\Delta\phi$ for each component is directly proportional to the applied voltage V.

If V is made to oscillate with frequency ω_m ie, $V = V_0 \sin \omega_m t$, the phase shift $\Delta\phi$ will also vary sinusoidally and the maximum value will be $\pi r_{63} n_0^3 V_0/\lambda$

The net phase shift between the two waves with the polarized in the x' and y' direction with the application of voltage V is given by

$$\phi = \phi_{x'} - \phi_{y'} = 2\Delta\phi \quad \text{—— (12)}$$

$$= \left[\phi_0 + \Delta\phi - (\phi_0 - \Delta\phi)) \right]$$

In general, the super position of 2 plane polarized waves that are perpendicular to each other produces an elliptically polarized wave. The wave emerging at $z = l$ is elliptically polarized. If the superposition gives a phase ~~of~~ difference of integral multiples of π, the emergent beam will be plane polarized and if phase difference is an odd integer multiple of $\pi/2$, the emergent beam is circularly polarized.

The voltage $V = V_\pi$ required to introduce a phase shift of π between the two polarization components is called half wave voltage.

$$\phi = \pi = \frac{2\pi}{\lambda} r_{63} n_0^3 V_\pi$$

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

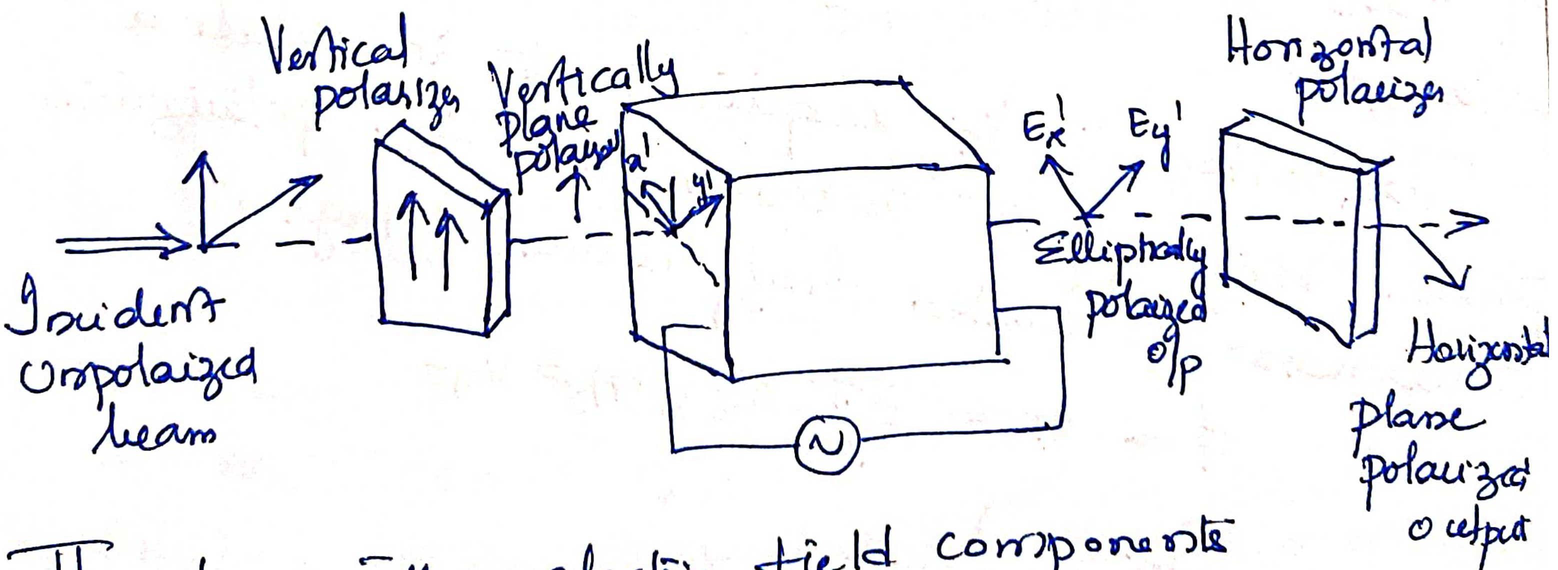
The half wave voltage is a significant parameter of an electro optic modulator.

The equations for the components of the coau emerging from the crystal polarized in the x' and y' direction is written as

$$E_{x'}(z=l) = \frac{E_0}{\sqrt{2}} \cos(\omega t + \Delta\phi) \quad (13)$$

$$E_{y'}(z=l) = \frac{E_0}{\sqrt{2}} \cos(\omega t - \Delta\phi) \quad (14)$$

If a plane polarizer is put at the output end of KDP crystal and orient at right angles to the polarizer producing the original plane polarized beam.



The transmitted electric field components is given by $-E_{x'}/\sqrt{2}$ and $E_{y'}/\sqrt{2}$

$$\therefore E = \frac{E_0}{2}\left[-\cos \omega t + \Delta\phi + \cos(\omega t - \Delta\phi)\right]$$

[By applying equs (13) & (14)]

$$E = E_0 \sin\Delta\phi \sin\omega t$$

The intensity of transmitted beam may be obtained by averaging E^2 over a complete period $T = \frac{2\pi}{\omega}$ Thus the intensity

$$I = \frac{1}{T}\int_0^T E^2 dt = \frac{\omega}{2\pi}\int_{t=0}^{2\pi/\omega} E_0^2 \sin^2\Delta\phi \sin^2\omega t\, dt$$

$$\boxed{I = \frac{E_0^2}{2}\sin^2\Delta\phi} \quad \text{— (15)}$$

$$I = I_0 \sin^2\Delta\phi = I_0 \sin^2(\phi/2) \quad \text{— (16)}$$

where $I_0 = \frac{E_0^2}{2}$ [Amplitude of intensity of incident beam.

Substituting $\Delta\phi = \frac{\pi}{\lambda} r_{63} n_0^3 V$ in (16)

we get

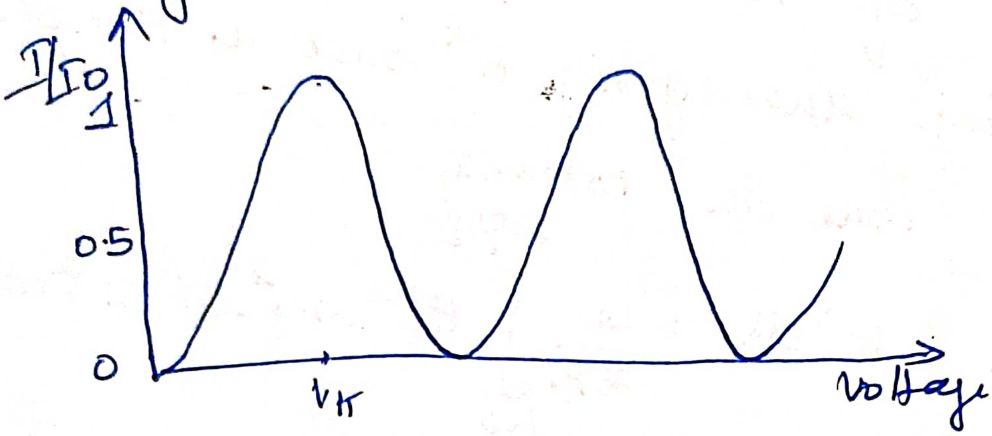
$$\frac{I}{I_0} = \sin^2\left(\frac{\pi}{\lambda} r_{63} n_0^3 V\right) \quad \text{— (17)}$$

$$\frac{I}{I_0} = \sin^2\left(\frac{\pi}{2}\frac{V}{V_\pi}\right)$$

[where $V_\pi = \frac{\lambda}{2 n_0^3 r_{63}}$]

where V_π is the voltage required for maximum transmission ie $I = I_0$

In general, the transmittance of the modulator can be altered by changing the voltage applied across the crystal. The variation of I/I_0 as a function of applied voltage V is shown in fig



Such a system is called Pockels electro optic amplitude modulator.

When a voltage is applied, the phase difference

$$\phi = \frac{\pi}{2} + 2\Delta\phi = \frac{\pi}{2} + \pi\frac{V}{V_\pi}$$

Substituting the value of ϕ in eqn

$$I = I_0 \sin^2(\phi/2)$$

$$\frac{I}{I_0} = \sin^2(\phi/2) = \sin^2\left(\frac{\pi}{4} + \frac{\pi}{2}\frac{V}{V_\pi}\right)$$

$$\cancel{\frac{I}{I_0}} =$$ ~~for $V << V_\pi$~~

which shows that the transmitted intensity varies linearly with the applied voltage V

Transverse Electro Optic Modulator

Fig shows an electro optic modulator in the transverse mode of operation, where the direction of propagation of light is perpendicular to the direction of the applied field.

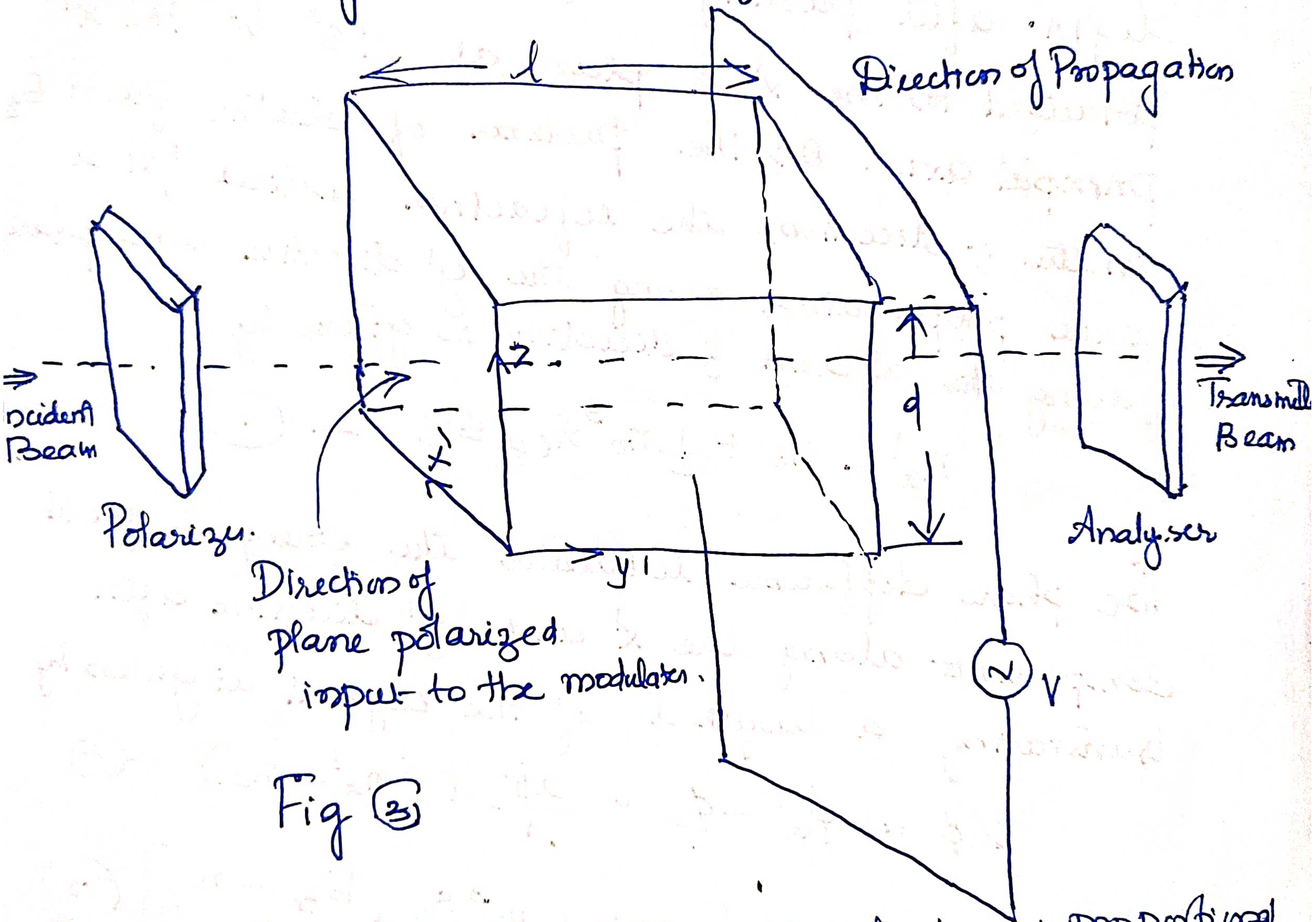


Fig ③

Here the phase difference which is proportional to the electric field and crystal length can be increased by using longer crystals.

In fig ③ the input wave is plane polarized at an angle of 45° to the x' direction and propagated in the y' direction. The electric field is applied along the z direction. The analyzer is placed with its pass axis normal to the [illegible] of the polarizer.

Assume that an electric field is applied along the z direction and the direction of propagation is along the y' induced principal axis. The Incident light after passing through the polarizer is plane polarized in the x'-z plane at 45° to the x' principal axis. In the presence of electric field E_z in the z direction, the refractive indices for a wave propagating along the y' direction and polarized along the x' and z direction is given by

$$n_x' = n_o + \frac{1}{2} n_o^3 r_{63} E_z \quad — (1)$$

The phase difference between the emergent field components along the x' and y' direction after traversing a length l of the crystal is given by

$$\Delta\phi = \phi_x' - \phi_z = \frac{2\pi}{\lambda} l \, (n_x' - n_z) \quad — (2)$$

$$= \frac{2\pi l}{\lambda} \left[n_o + \frac{1}{2} n_o^3 r_{63} E_z - n_e \right] \quad (3)$$

$$[n_z = n_e]$$

$$\Delta\phi = \frac{2\pi l}{\lambda} (n_o - n_e) + \frac{\pi}{\lambda} r_{63} n_o^3 \left(\frac{V}{d}\right) l) \quad — (4)$$

where V is the voltage applied across the width d of the crystal

Even when the applied voltage $V=0$, the finite retardation is given by

$$(\Delta\phi)_{V=0} \; \frac{2\pi l}{\lambda}(n_o - n_e) \quad -(5)$$

This is due to the intrinsic birefringence of the crystal.

⇒ The phase difference (retardation) induced by the external voltage is given by

$$\Delta\phi = \frac{\pi}{\lambda} r_{63} n_o^3 \left(\frac{V}{d}\right) l \quad -(6)$$

⇒ The half wave voltage V_π for this configuration as the voltage required to produce a phase difference of π between the two polarization components (in addition to that produced by intrinsic birefringence)

$$\Delta\phi = \pi = \frac{\pi}{\lambda} r_{63} n_o^3 \left(\frac{V_\pi}{d}\right) l \quad -(7)$$

$$V_\pi = \frac{\lambda}{n_o^3 r_{63}}\left(\frac{d}{l}\right) \quad -(8)$$

and V_π is dependent on $\left(\frac{d}{l}\right)$. Thus the half wave voltage may be reduced by employing long thin crystals.

Problem 1 Calculate the change in refractive index due to longitudinal electro optic effect for a 1cm wide KDP crystal for an applied voltage of 5kV. If the wave length of light being propagated through the crystal is 550nm. Calculate the net phase shift between the two polarization components after they emerge from the crystal. Also calculate V_π for the crystal.

[Assume $n_0 = 1.51$ $r_{63} = 10.5 \times 10^{-12}$ m/v)

Solution

Given $V = 5 \times 10^3$ V

$\lambda = 550 \times 10^{-9}$ m

net phase shift $= \phi = 2\Delta\phi$

$$\Delta\phi = \frac{\pi}{\lambda} r_{63} n_0^3 V$$

$$= \frac{\pi}{550 \times 10^{-9}} \times 10.5 \times 10^{-12} \times (1.51)^3 \times 5 \times 10^3$$

$$\Delta\phi = 0.33\pi$$

$$\therefore \phi = 2\Delta\phi = 0.66\pi$$

The half wave voltage V_0 is given by

$$V_\pi = \frac{\lambda}{2 n_0^3 r_{63}} = \frac{550 \times 10^{-9}}{2 \times (1.51)^3 \times 10.5 \times 10^{-12}} = 7.6\text{kV}$$

Problem 2

A transverse electro optic modulator with a KDP crystal (KD_2PO_4) crystal is operating (Deuterated Potassium dihydrogen phosphate) at a wavelength $\lambda = 550\,nm$. The crystal has length $l = 3\,cm$ and width $d = 0.25\,cm$. The optical constants of the crystal $n_o = 1.51$ and $n_e = 1.47$ a) Calculate the phase difference between the emergent field components with applied voltage $V = 0$ b) the additional phase difference between the emergent field components with $V = 2V$ and half wave voltage V_π for the crystal and $r_{63} = 26.4$

Solution

given $\lambda = 550\,nm$

$l = 3 \times 10^{-2}\,m$

$d = 0.25 \times 10^{-2}\,m$

1) $\Delta\phi$ due to inherent birefringence

$$= \frac{2\pi l}{\lambda}(n_o - n_e)$$

$$= \frac{2 \times 3 \times 10^{-2}}{550 \times 10^{-9}}(1.51 - 1.47)\pi = 4.363 \times 10^{3}\pi$$

2) $$\Delta\phi = \frac{\pi}{\lambda} r_{63} n_o^3 \left(\frac{V}{d}\right) l$$

$$= \frac{\pi}{550 \times 10^{-9}} \times 26.4 \times 10^{-12} \times (1.51)^3 \times \frac{2 \times 10^{-2} \times 3 \times 10^{-2}}{0.25 \times 10^{-2}}$$

$$= 0.396\pi$$

3) $$V_\pi = \frac{\lambda}{n_o^3 r_{63}}\left(\frac{d}{l}\right) = \frac{550 \times 10^{-9}}{(1.51)^3 \times 26.4 \times 10^{-12}} \times \frac{25 \times 10^{-2}}{3 \times 10^{-2}} = 504\,V$$

15

Acousto Optic Modulators.

Acousto - Optic Effect

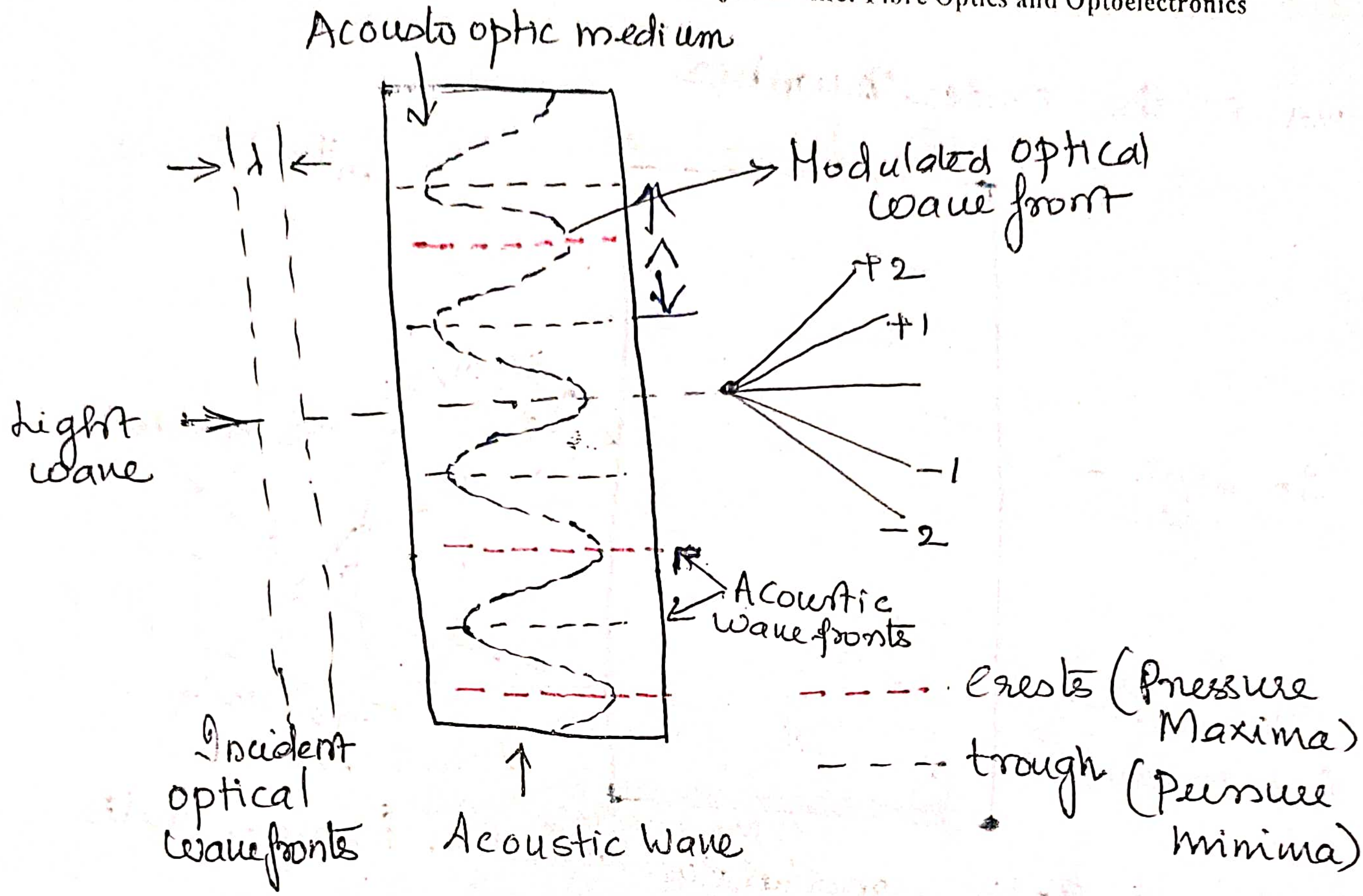
The change in the refractive index of a medium caused by the mechanical strain produced due to the passage of an acoustic wave through the medium is referred to as acousto optic effect.

* [Acoustic waves are a type of energy propagation through a medium by means of compression & decompression]

When a monochromatic light of wavelength λ is incident normally on a acousto-optic medium, in which periodic strain associated with an acoustic wave has produced periodic variations in the refractive index of the medium.

As the light enters the medium, the portion of the incident wavefront near the acoustic wave crests encounters higher refractive index and hence advance with a lower velocity than those portions of the wavefront that encounter acoustic wave troughs. As a consequence, the wavefront in the medium acquires a wave like apperance

The acoustic wave sets up a refractive index grating with in the medium, so that when a light beam falls on it, either multiple order or single order diffraction takes place. The first one is called Raman-Nath diffraction and is observed at low acoustic frequencies and the second one is called Bragg diffraction and is observed at high acoustic frequencies.



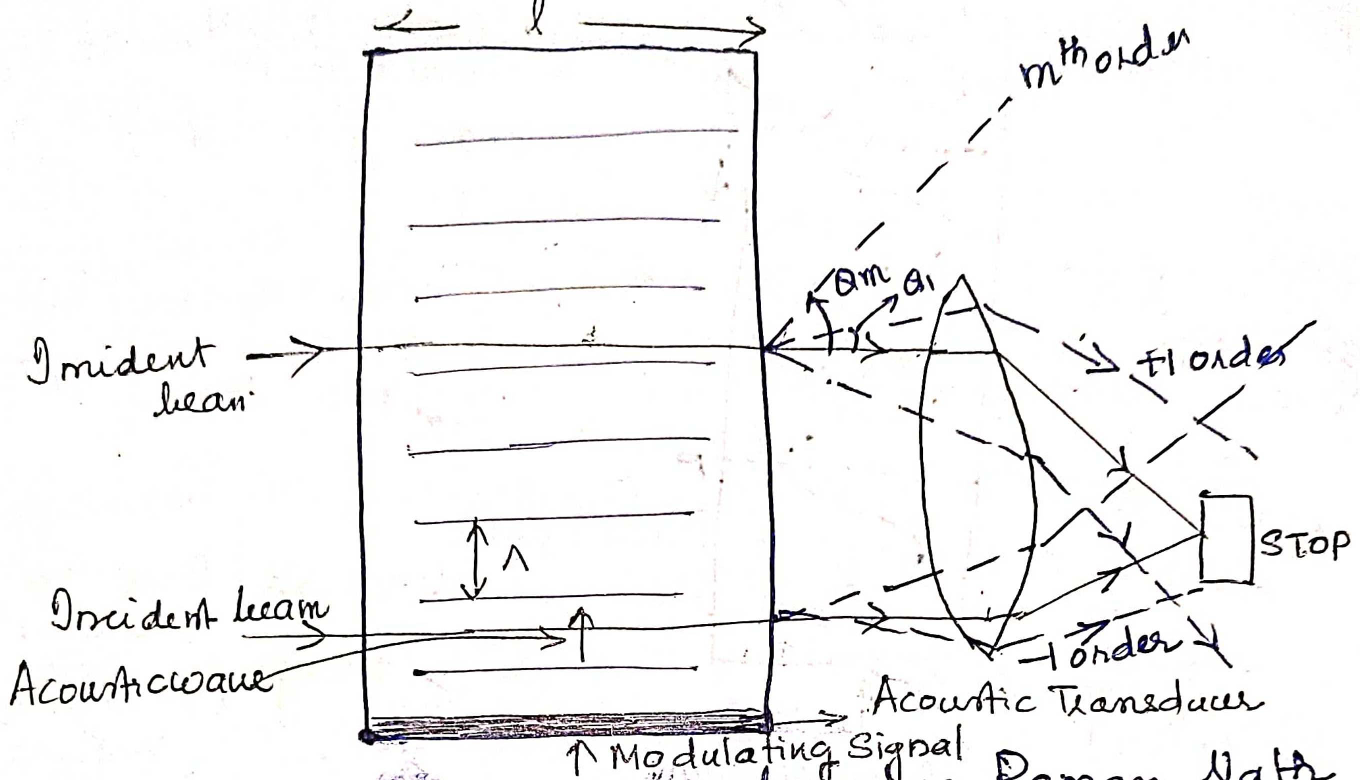
Raman Nath Modulator

In the Raman Nath modulator, the acousto optic diffraction grating is so thin that it behaves almost like a plane transmission grating. The m^{th} order diffracted wave propagates along a direction making an angle θ_m with the direction of the incident beam.

$$\sin\theta_m = m\left(\frac{\lambda}{n_0\Lambda}\right)$$

where n_0 is the refractive index of the medium in the absence of the acoustic wave and $m = 0, \pm1, \pm2, \pm3, \pm4 \ldots$

m is the order number



Acousto optic modulator based on Raman Nath diffraction

In this configuration, the signal carrying the information modulates the amplitude of the acoustic wave propagating through the medium. The light beam incident on the acousto optic medium gets diffracted and the zeroth order beam of the diffracted output is blocked using a stop. For small acoustic powers the relative intensity in the first order is given by

$$\eta = \frac{(\Delta n)^2 L^2 \pi^2}{\lambda^2}$$

where Δn is the peak change in the refractive index of the medium due to acoustic wave and L is the width of the acoustic beam equal to the length

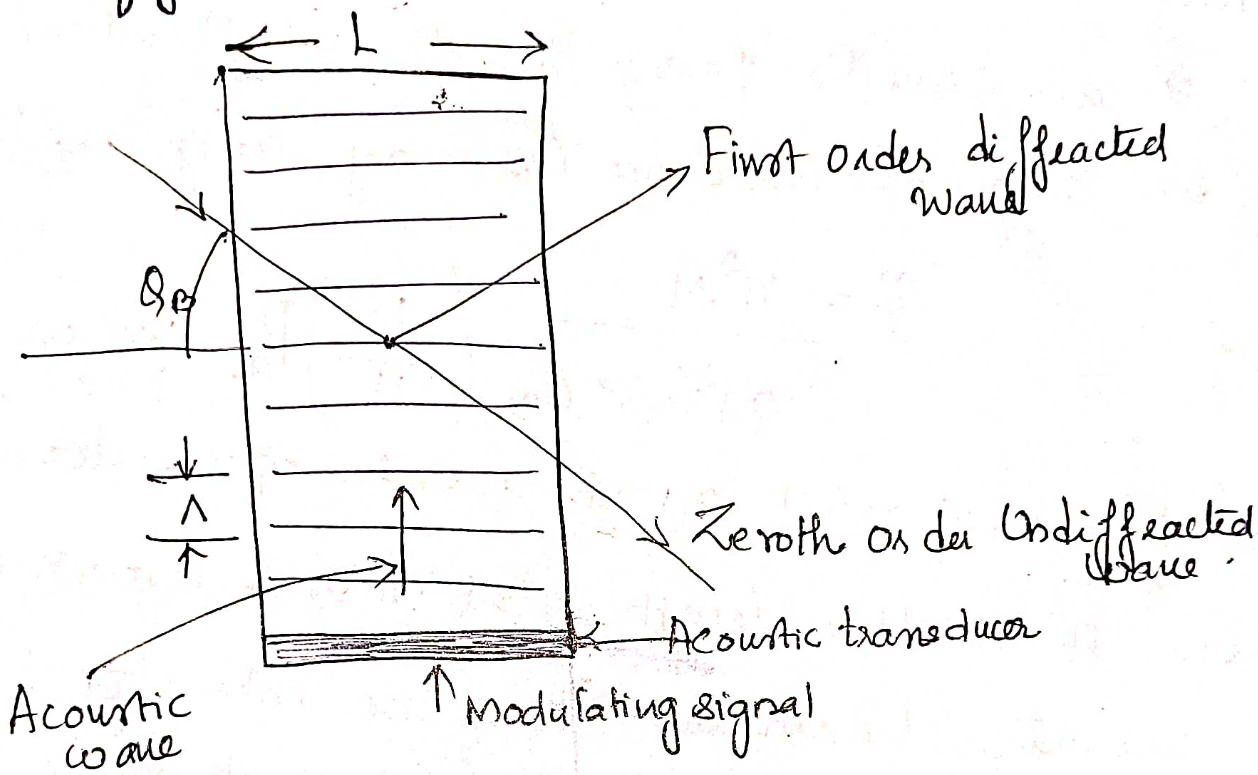
For small acoustic power P_a, the diffraction efficiency for an angle of incidence θ_B may be given by

$$\eta = \frac{\pi^2 M}{2\lambda^2 \cos^2 \theta_B}\left(\frac{L}{H}\right)P_a$$

where M is the figure of merit of the acousto optic device, and L and H are the length and height respectively of the acoustic transducer. Thus the intensity of the diffracted beam is directly proportional to the acoustic power and hence modulation of the acoustic power will lead to corresponding modulation of the diffracted beam.

Bragg Modulator

The configuration of a Bragg modulator is shown in fig



An acousto optic modulator based on Bragg diffraction

In the Bragg regime, the interaction length 'L' is larger, so the acoustic field creates a thick grating inside the medium. When the light beam is incident at an angle θ, it is reflected by successive layers of the acoustic grating. Diffraction occurs for an angle of incidence $\theta - \theta_B$ order the condition $\sin\theta_B = \lambda / 2 n_0 \Lambda$

of the medium. It can be shown that $(\Delta n)^2$ is proportional to the acoustic power. Thus if the acoustic wave is amplitude modulated, the first order diffracted beam will be intensity modulated.

Problem

A typical acousto optic cell of a Raman Nath modulator contains water. A piezo electric crystal bonded to the cell generates an acoustic wave of frequency 5MHz in water. The velocity of the acoustic wave in water is $1500\,ms^{-1}$ and the thickness of the cell is 1cm. If a He-Ne laser beam ($\lambda = 633\,nm$) is incident on the cell, calculate the a) angle between the first order diffracted beam and the direct beam and b) Relative intensity of the diffracted beam in the first Order if $\Delta n = 10^{-5}$.

Solution

Given $m = 1$

$\lambda = 633\,nm$

n_0 (1.33 for water)

$$\sin \theta_m = m\left(\frac{\lambda}{n_0 \Lambda}\right)$$

$$\Lambda = \frac{\text{Velocity of acoustic waves}}{\text{frequency}} = \frac{1500}{5\times10^6}$$

$$= 300\times10^{-6}\, m$$

$$= 300\, \mu m$$

$$\sin \theta_m = 1\left(\frac{633\times10^{-9}}{1.33\times300\times10^{-6}}\right)$$

$$\theta_1 = \sin^{-1}\left(\frac{633\times10^{-9}}{1.33\times300\times10^{-6}}\right)$$

$$\boxed{\theta_1 = 0.09^\circ}$$

$$\text{Intensity} = \frac{\pi^2 (\Delta n)^2 L^2}{\lambda^2} = \frac{\pi^2\times(10^{-5})^2\times(1\times10^{-2})^2}{(633\times10^{-9})^2}$$

$$\boxed{\eta = 0.246}$$

Optical Amplifiers

When setting up an optical link, one formulates a power budget and add repeaters when the path loss exceeds the available power margin. To amplify an optical signal with a conventional repeater, one performs photon to electron conversion, electrical amplification, retiming pulse shaping, and then electron to photon conversion. Though this process works well for moderate speed single wavelength operation, It can represent a data transmission bottle neck for high speed multiple wavelength systems. Hence to eliminate transmission delay problems optical amplifiers are developed. These devices operate completely in the optical domain to boost the power levels of multiple light wave signals over spectral bands of 30 nm and more.

Three fundamental amplifier types

- Semiconductor Optical Amplifiers (SOA)
- Doped fiber amplifiers (DFA)
- Raman amplifiers.

- Basic Applications and Types of Optical Amplifiers

In line Optical Amplifiers.

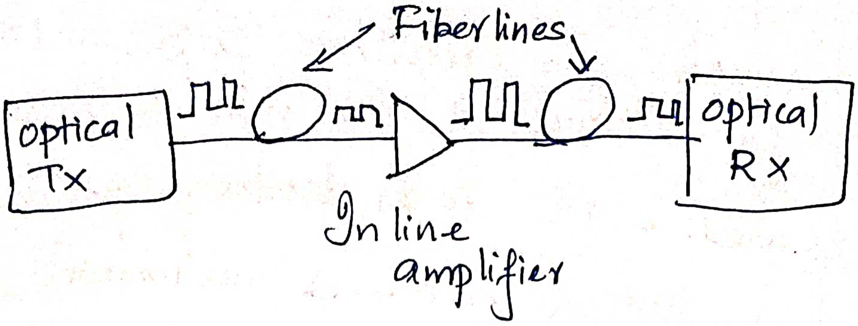
In single mode link, the effects of fiber dispersion is small so that main limitation to repeater spacing is fiber attenuation. Such a link does not necessarily require a complete regeneration of a signal, simple amplification of the optical signal is sufficient. Thus an inline optical amplifier can be used to compensate for transmission loss and increase the distance between regenerative repeater.

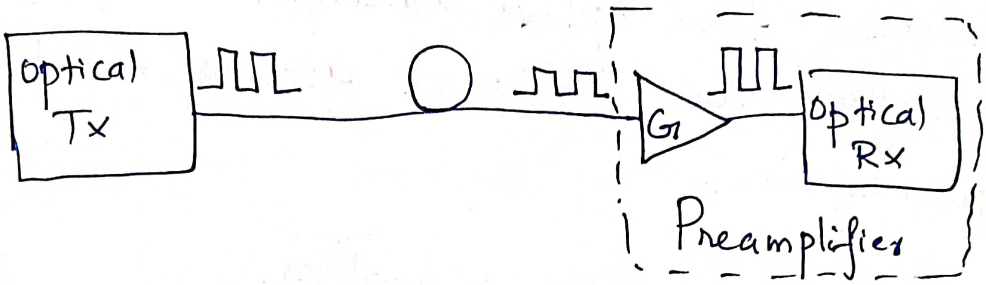
Preamplifier

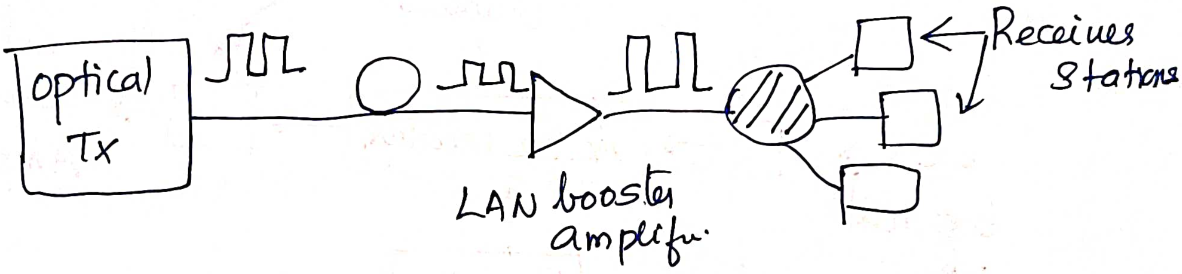
Fig b shows an optical amplifier being used as a front end preamplifier for an optical receiver. Thereby a weak optical signal is amplified before photo detection so that the SNR degradation caused by thermal noise in the receiver electronics can be suppressed. Compared with other front end devices such as avalanche photodiodes or optical heterodyne detectors, an optical preamplifier provides a large gain factor and a broader bandwidth.

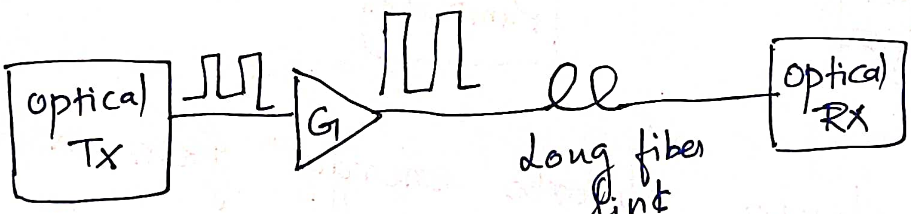
Power Amplifier

Power or booster amplifier applications include placing the device immediately ~~to~~ after an optical transmitter to boost the transmitted power. This serves to increase the transmission distance by 10-100 km depending on the amplifier gain and fiber loss. As an example using this technique









Power (booster) Amplifier.

Amplifier Types

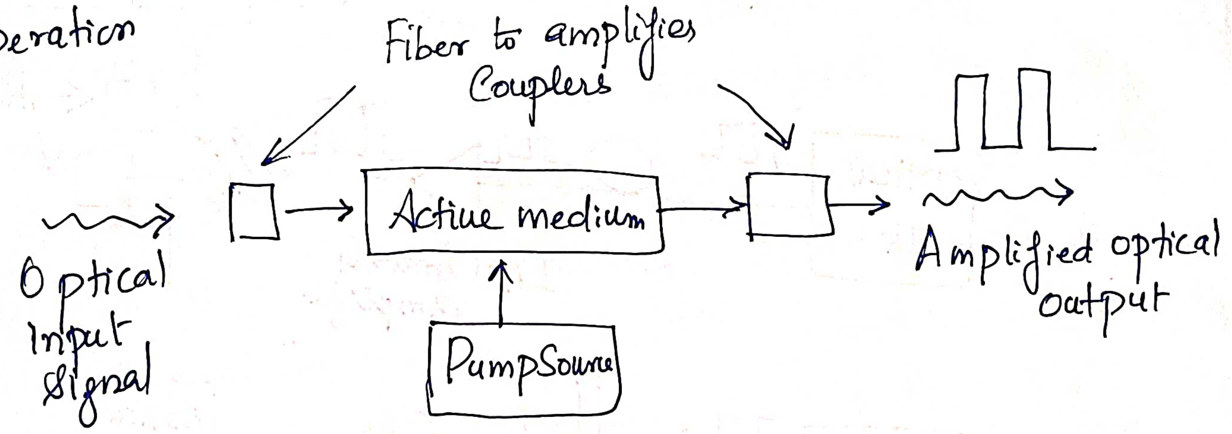
The three main optical amplifier types can be classified as ⇒ semiconductor optical amplifiers (SOAs)

⇒ active fiber or doped fiber amplifier (DFA)

⇒ Raman amplifier.

All optical amplifiers increase the power level of incident light through a stimulated Emission or an optical power transfer process. In SOA and DFA the mechanism for creating population inversion that is needed for Stimulated Emission to occur is the same as used as in laser diodes. Optical amplifier does not have optical feedback mechanism for lasing to take place. Thus optical amplifier can boost incoming signal levels, but it cannot generate a coherent optical output by itself

Operation



⇒ The device absorbs energy from an electrical external source called pump.

⇒ The pump supplies energy to electrons in an active medium, which raises them to higher energy levels to produce a population inversion.

⇒ An incoming signal photon will trigger these excited electrons to drop to lower levels through a Stimulated Emission process.

⇒ Since one incoming photon stimulates a cascade effect in which many excited electrons emit photons of equal energy as they drop to ground state the result is an amplified optical signal.

In Raman amplifier there is a transfer of optical power from a high power pump wavelength to lightwave signals at longer wavelengths. This mechanism is done without the need for a population inversion process.

⇒ Alloys of semiconductor materials from groups III & V make up the active medium in SOAs

⇒ These devices can be made to work in O band and C band

⇒ It can be integrated easily on same substrate as other optical devices and circuits

⇒ They consume less power, fewer components and are more compact

⇒ SOAs has more rapid gain response.

DFAS

In DFA the active gain medium ~~in the~~ for operating in S - C - L bands is created by lightly doping a silica fiber core with rare earth elements such as erbium (Er) Ytterbium (Yb) thulium (Tm) DFA operating in O band is achieved through doping fluoride based fibers with elements such as neodymium (Nd)

⇒ Ability to pump the devices at several different wavelengths.

⇒ low coupling loss to compatible size fiber transmission medium.

highly transparent to signal format & bit-rate.
Immune from interference effects

Semiconductor Optical Amplifiers.

A SOA is essential InGaAsP laser that is operating below its threshold value and the gain can be selected by varying the composition of the InGaAsP. The optical signal travels through the device only once. During the single passage the signal gains energy and emerges intensified at the other end of the amplifier.

SOA Construction is similar to a resonator cavity structure of a Laser diode. The SOA has an active region of length 'L' width 'w' and height 'd'. The reflectivities are lower in order for the optical signal to pass through the amplification cavity. Low reflectivities are achieved by depositing thin layers of silicon oxide, silicon nitride or titanium oxide.

External Pumping

External Current injection is the pumping method used to create the population inversion needed for having a gain mechanism in SOAs. Thus the sum of the injection, stimulated Emission and spontaneous recombination rates gives the rate equation that governs carrier density $n(t)$ in the excited state

$$\Rightarrow \frac{\partial n(t)}{\partial t} = R_p(t) - R_{st}(t) - \frac{n(t)}{\tau_r} \quad -(1)$$

$$\Rightarrow \text{where } R_p(t) = \frac{J(t)}{qd} \quad -(2)$$

$R_p(t) \Rightarrow$ external pumping rate from the current density $J(t)$ in to an active layer of thickness d, τ_r is the combined time constant from spontaneous emission and carrier recombination mechanisms.

$$R_{st}(t) = \Gamma a v_g (n - n_{th}) N_{ph} = g v_g N_{ph} \Rightarrow (3)$$

Where $\Gamma \Rightarrow$ optical confinement factor

$a \Rightarrow$ gain constant

$n_{th} \Rightarrow$ threshold carrier density

$N_{ph} \Rightarrow$ photon density

$g \Rightarrow$ overall gain per unit length.

If the optical amplifier is of width w and thickness d, then optical signal of power P_s with photons of energy $h\nu$ and group velocity V_g

$$\text{Photon density is } N_{ph} = \frac{P_s}{V_g h\nu wd} \quad -(4)$$

In steady state $\frac{\partial n(t)}{\partial t} = 0 \therefore R_p = R_{st} + \frac{n}{\tau_r} \quad -(5)$

and the steady state gain per length

$$g = \frac{\frac{J}{qd} - \frac{n_{th}}{\tau_s}}{V_g N_{ph} + 1/\Gamma a \tau_s} = \frac{g_o}{1 + \frac{N_{ph}}{N_{ph\,sat}}}$$

[where $N_{ph\,sat} = \frac{1}{\Gamma a V_g \tau_s}$

$$g_o = \Gamma a \tau_s \left(\frac{J}{qd} - \frac{n_{th}}{\tau_s}\right)$$

where g_o is the gain ~~for~~ per unit length in the absence of signal].

Amplifier Gain

⇒ Amplifier Gain is defined

$G = \frac{P_{s\,out}}{P_{s\,in}}$ where $P_{s,in}$ and $P_{s,out}$ are input and output powers of the optical signal being amplified.

$$G = \exp\left[\Gamma(g_m - \bar{\alpha})L\right] = \exp g(z)L$$

where Γ ⇒ optical confinement factor in the cavity, g_m ⇒ material gain coefficient

$\bar{\alpha}$ ⇒ absorption coefficient

$g(z)$ ⇒ gain/unit length.

SOA Bandwidth

A general expression for the cavity gain G_c as a function of signal frequency f is given by

$$G_c(f) = \frac{(1-R_1)(1-R_2)G}{\left(1-\sqrt{R_1R_2G}\right)^2 + 4\sqrt{R_1R_2G}\sin^2\phi}$$

G – single pass gain

$R_1, R_2 \rightarrow$ i/p & o/p facet reflectivities

$\phi = \pi(f-f_0)/\Delta f_{FSR}$ where f_0 is the cavity resonance frequency

$f_0 \Rightarrow$ cavity resonance frequency

Δf_{SR} = free spectral range of SOA

$$B_{SOA} = 2(f-f_0) = \frac{2\Delta f_{FSR}}{\pi}\sin^{-1}\left[\frac{1-\sqrt{R_1R_2}\,G}{2\left[\sqrt{R_1R_2}\,G\right]}\right]^{1/2}$$

ERBIUM DOPED FIBER AMPLIFIER

The optical fiber amplifiers use optical pumping. In this process one uses photons to directly raise electrons into excited states. The optical pumping process requires three or more energy levels.

⇒ The top energy level to which the electron is elevated initially must be energetically above the desired final emission level

⇒ After reaching its initial excited state, the electron must quickly release some of its energy to drop to a slightly lower energy level. A signal photon can then trigger the excited electron sitting in this new lower level into stimulated emission, whereby the electron releases its remaining energy in the form of a new photon with a wavelength identical to that of a signal photon.

Since the pump photon have a higher energy than the signal photon, the pump wavelength is shorter than the signal wavelength.

Working of EDFA.

The working of EDFA can be explained using energy band diagram.

The erbium atoms in silica are Er^{3+} ions, which are erbium atoms that have lost three of their outer electrons.

The transitions of the outer electrons in these ions to higher energy states is known as raising the ions to higher energy levels.

⇒ The two principal levels for telecommunication applications are a meta stable level and the pump level.

The term metastable means that the lifetimes for transitions from this state to the ground state are very long compared to the lifetimes of the states that led to this level.

To understand the various energy transitions and photon emission ranges, Consider the following conditions:

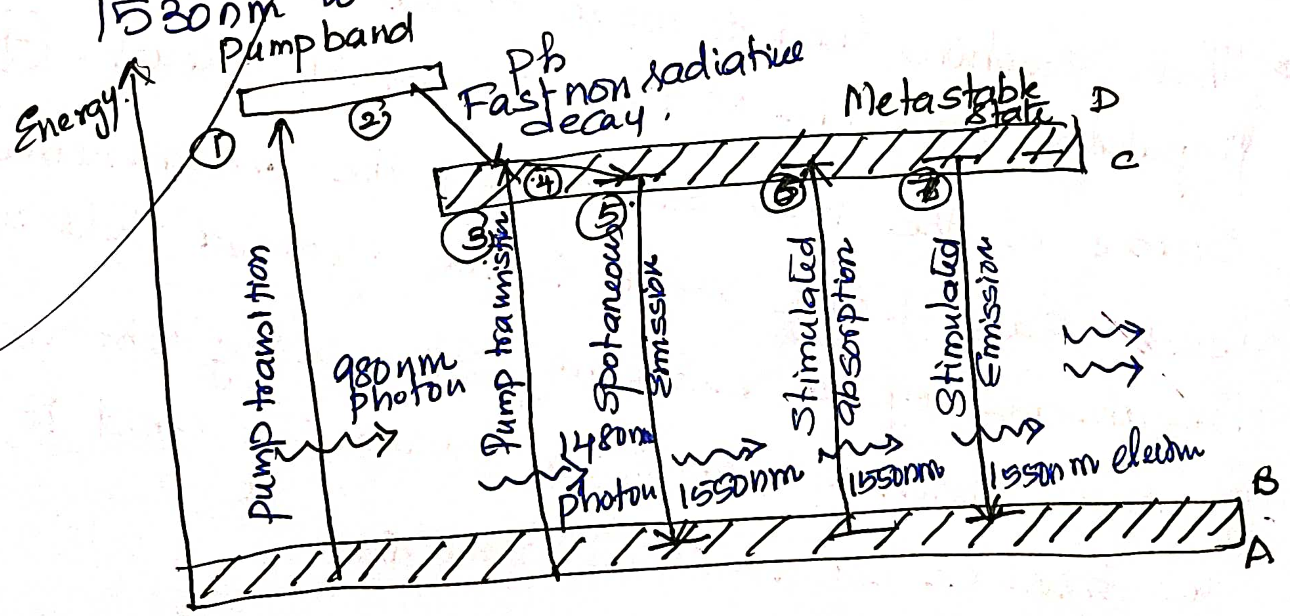
⇒ The pump band shown in the top left exists at a 1.27 eV separation from the bottom of the ground state. This energy corresponds to a 980 nm wavelength.

⇒ The top of the metastable band is separated from the bottom of the ground state band by 0.841 eV. This energy corresponds to a 1480 nm wavelength.

⇒ The bottom of the metastable band is separated from the bottom of the ground state band by 0.814 eV. This energy corresponds to a 1530 nm wavelength.

⇒ The bottom of the metastable band is separated from the top of the ground state band by 0.775 eV. This energy corresponds to a 1600 nm wavelength.

The possible pump wavelengths are 980 nm and 1480 nm. The photons emitted during transitions of electrons between possible energy levels in the metastable and ground state bands can range from 1530 nm to 1600 nm.



→ In normal operation a pump laser emitting 980nm photons is used to excite ions from the ground state to the pump level ⟶ process ①

→ These excited ions decay very quickly from the pump band to the metastable band — ② During this decay excess energy is released as phonons or mechanical vibrations in the fiber

→ With in the metastable bands, the electrons of the excited ions tend to populate the lower end of the band. They are characterized by very long fluorescence time of 10ms

→ Another possible wavelength is 1480 nm. The energy of these pump photons is very similar but slightly higher to the signal photon energy

The absorption of a 1480 nm pump photon excites an electron from the ground state directly to the lightly populated top of the metastable level, as indicated by transistion process ③

→ These electrons tend to move down to the more populated lower end of the metastable level. ④

→ Some of the ions sitting at the metastable level can decay back to the ground state in the absence of an externally stimulating photon flux as shown by transistion process ⑤ and it is known as Spontaneous Emission.

Two or more types of transisition occurs when a flux of signal photons that have energies corresponding to the bandgap energy between the ground state and metastable level passes through the device.

A small portion of the external photon will be absorbed by ions in the ground state, ~~there by Emitting a new photon of the same energy, wavevector and polarization as the incoming signal photon.~~ which raises these ion to the metastable level — (6)

In the stimulated Emission, a signal photons triggers an excited ion to drop to the ground state there by Emitting a new photon of the same energy wave factor and polarization as the Incoming signal photons (7)

The absorption and Emission respones of an EDFA depend on the ⇒ Composition of the host glass
⇒ type of dopants such as Ge & Al in glass

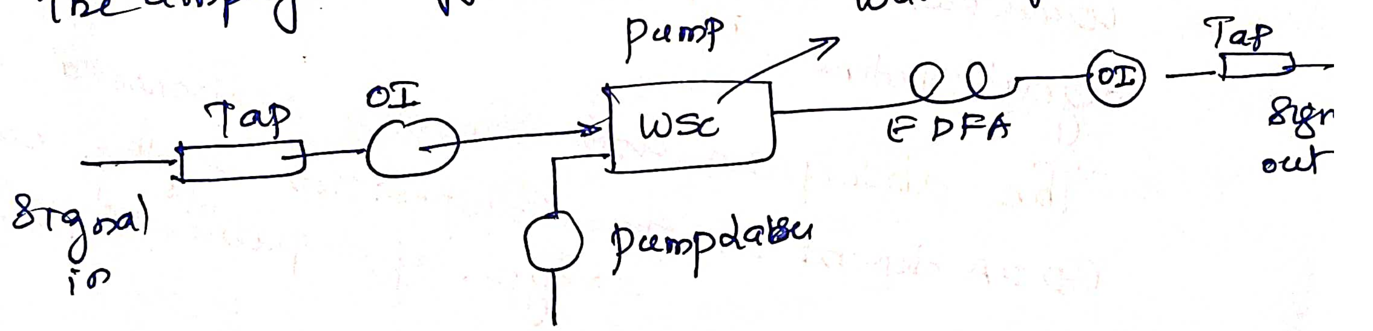
EDFA Architecture.

An optical fiber amplifier consists of
→ doped fiber
→ one or more pumplaser
→ passive wavelength couples
→ optical isolators
→ tap Couplers

The dichroic (a wavelength) coupler handles either 980/1550 nm or 1480/1550 nm wavelength combination to couple both the pump and signal optical power efficiently in to fiber amplifier.

The tap couplers are wavelength insensitive. The are generally used on both sides of the amplifier to compare the incoming signal with the amplified output.

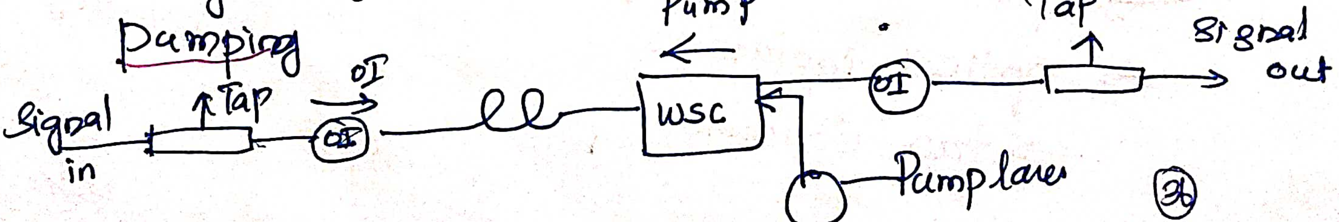
The optical isolators prevent the amplified signal from reflecting back in to the device where it could increase the amplifier noise and decrease the amplifier efficiency.



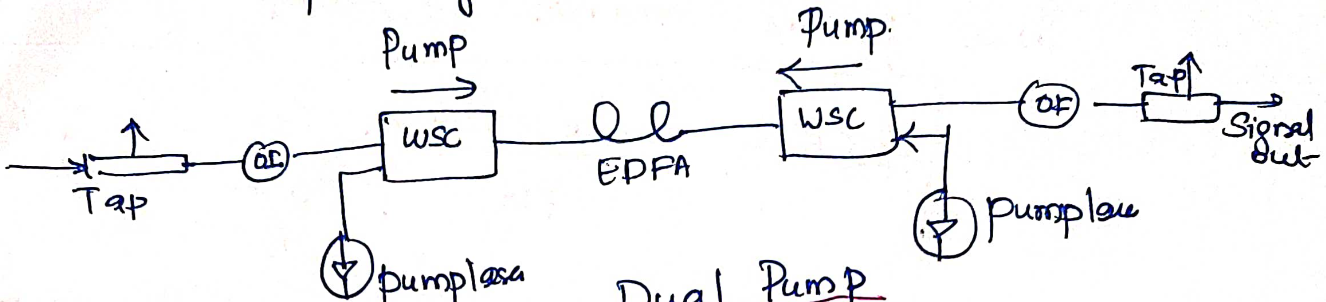
Co directional pump.

The pump light is injected from the same direction as the signal flow.

If the pump power in the opposite direction to the signal flow, which is known as counter directional pumping



One can employ single pump source or use dual pump schemes with resultant gains +17 dB and +35 dB respectively.



Dual Pump

Counter directional pumping $\longrightarrow$ high gain

Co directional pumping — better noise performance.

EDFA Power Conversion Efficiency and Gain

The input and output signal powers of an EDFA can be expressed in terms of principle of energy conversation

$$\boxed{P_{s,out} < P_{s\,in} + \frac{\lambda_p}{\lambda_s} P_{p\,in}} \quad \text{—} (1)$$

$P_{s\,out}$ — output signal power

$P_{s\,in}$ — input signal power

$\lambda_p, \lambda_s \Rightarrow$ pump & signal wavelength

$P_{p\,in}$ = input pump power.

from eqn (1) the maximum output signal power depends on the ratio λ_p/λ_s

For pumping scheme to work $\lambda_p < \lambda_s$ and to have an appropriate gain it is necessary that $P_{sin} < P_{pin}$

Then power conversion efficiency

$$\boxed{PCE = \frac{P_{sout} - P_{sin}}{P_{pin}} \approx \frac{P_{sout}}{P_{pin}} \le \frac{\lambda_p}{\lambda_s} \le 1} \quad (2)$$

Amplifier Gain G

Assuming there is no spontaneous emission

$$\boxed{G = \frac{P_{sout}}{P_{sin}} \le 1 + \frac{\lambda_p P_{pin}}{\lambda_s P_{sin}} \quad — (3)}$$

when the input signal power is very large

$P_{sin} >> \left(\frac{\lambda_p}{\lambda_s}\right) P_{pin}$ is close to unity (max amplifier gain)

from eqn (3) to achieve maximum gain G the input signal power cannot exceed

$$\boxed{P_{sin} \le \frac{\left(\frac{\lambda_p}{\lambda_s}\right) P_{pin}}{G-1} \quad — (4)}$$

In addition to pump power gain depends on fiber length also. The maximum gain in a three level laser medium of length L

$$\boxed{G_{max} = \exp(\rho \sigma_e L) \quad — (5)}$$

ρ — rare earth element concentration
$\sigma_e \rightarrow$ signal emission cross section
L — fiber length.

when determining the maximum gain equs
3 and 5 should be considered together
EDFA gain is given by lowest of two gain expression

$$\boxed{G \leq \min \left\{ \exp(\rho \sigma_e L),\ 1 + \frac{\lambda_p}{\lambda_s} \frac{P_{p\,in}}{P_{s\,in}} \right\}} \rightarrow (6)$$

and the maximum possible EDFA output power is given by min of two expression

$$\boxed{P_{s,out} \leq \min \left\{ P_{s,in} \exp(\rho \sigma_e L),\ P_{s\,in} + \frac{\lambda_p}{\lambda_s} P_{p\,in} \right\}} \rightarrow (7)$$

Raman Amplifiers:

A Raman Optical amplifier is based on a nonlinear effect called Stimulated Raman Scattering (SRS) which occurs in fibers at high optical powers. The SRS effect is due to an interaction between an optical energy field and the vibrational modes of the lattice structure in a material.

An atom absorbs a photon ~~of~~ at a particular energy and then releases another photon at a lower energy that is at a longer wavelength than that of the absorbed photon. The energy difference between the absorbed and released photons is transformed into a phonon which is a vibrational mode of the material. The power transfer to higher wavelengths occurs over a broad spectral range of 80 to 100 nm. The shift to a particular longer wave length is referred to as Stokes Shift for that wavelength.

(or)

Raman Scattering.

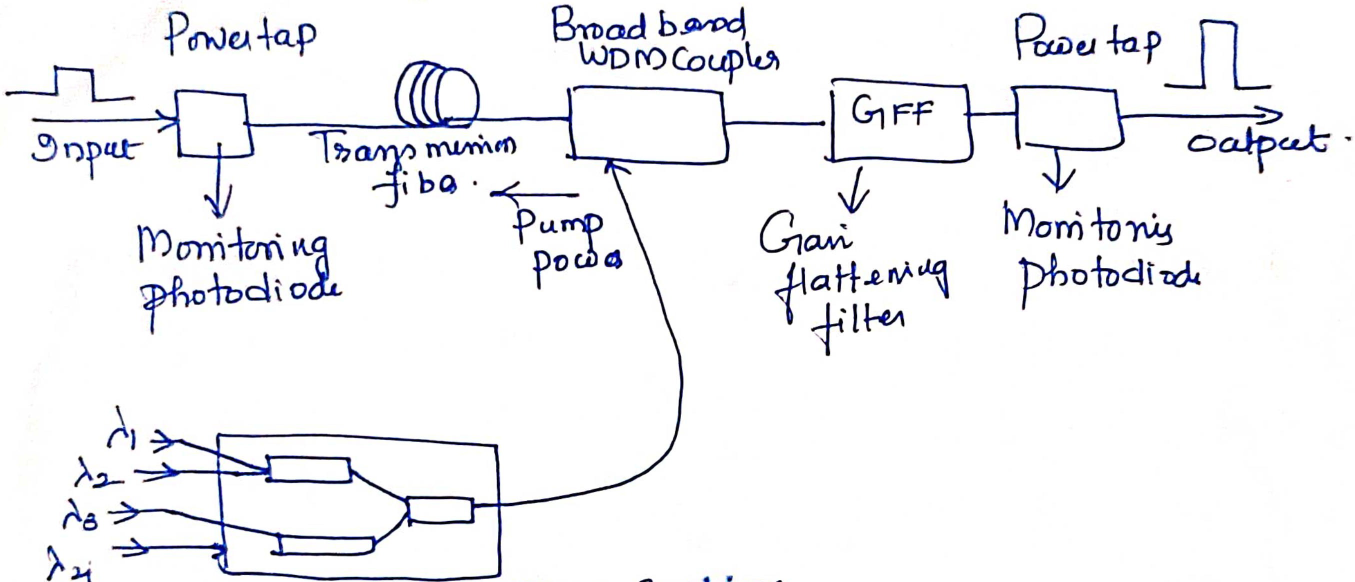
When the light quantum of energy $h\nu$ and wavelength $\lambda = C/\nu$ with a molecule as a collision satisfying the law of conservation of energy. In this encounter, the light quantum suffers a loss of energy and hence appears in the spectrum as a radiation of increased wavelength λ'. This is called Stoke's shift. The molecule which takes up the energy is transported to a higher level of rotation or vibration. This phenomenon is called normal Raman Scattering.

The Raman gain mechanism can be achieved through a lumped a distributed amplifier.

In the lumped Raman amplifier, a spool of about 80 m of small core fiber along with appropriate pump lasers is inserted into the transmission path as a distinct packaged unit.

For the distributed Raman amplifier application, optical power from one or more Raman pump lasers is inserted in to the end of the transmission fiber towards the transmitting end. This process converts the final 20 to 40 km of the transmission fiber in to a preamplifier.

Fig shows the set up for a typical Raman amplification system.



14 xx nm pump-pump combiner

Here figure shows the set up for a typical Raman amplification system. Here a pump combiner multiplexes the outputs from four pump lasers operating at different wavelengths on to a single fiber. These pump power couplers are referred to popularly as 14XX nm pump - pump combiner. This combined pump power then is coupled into the transmission fiber in a counter propagating direction through a broadband WDM coupler. The difference in the power level measured between the two monitoring photodiodes gives amplification gain. The gain flattening filter is used to equalize the gains at different wavelengths. [The gain flattening filter is used to flatten or smooth out unequal signal intensities over a specified wavelength range]