UNIT- IV

• Electro-Optic Effect -

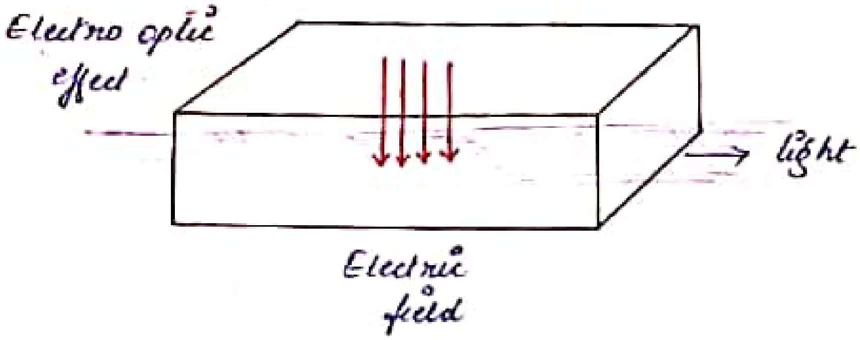
Certain materials change their optical properties when subjected to an electric field. This is caused by forces that distort the positions, orientations or shapes of the molecules constituting the material. The Electro-optic effect is the change in the refractive index resulting from the application of a dc- or low frequency electric field. The dependence of the refractive index on the applied electric field takes one of the two forms -

↳ The refractive index changes in proportion to the applied electric field, in which case, the effect is known as the linear electro-optic effect or the Pockels effect.

↳ The refractive index changes in proportion to the square of the applied electric field, in which case the effect is known as the quadratic electro optic effect or the Kerr effect.

The change in the refractive index is typically very small. Nevertheless, its effect on an optical wave propagating a distance much greater than a wavelength of light in the medium can be significant. Materials whose refractive index can be modified by the means of an applied electric field are useful for producing electrically controllable optical devices.

Light transmitted through a transparent plate of controllable refractive index undergoes a controllable phase shift. The plate can be used as an optical phase modulator.



Herein, a steady electric field is applied to an electro-optic material, changes its refractive index. This, in turn, changes the effect of the material on light travelling through it. The electric field therefore, controls the light.

In general, the change in refractive index n as a function of the applied electric field E, can be given by an equation of the form,

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

Where,

r is the linear electro-optic coefficient

P is the quadratic electro-optic coefficient

• Electro Optic Modulators -

Electro optic modulators are usually built with electro optic crystals exhibiting the Pockets effect. The transmitted beam is phase modulated with the electric signal applied to the crystal. Amplitude modulators can be built by putting the electro optic crystal between two linear polarizers or in one path of a Mach - Zehnder interferometer. Additionally, amplitude modulators can be constructed by deflecting the beam into and out of a small aperture such as a fiber.

An Electro optic modulator (EOM) is an optical device in which a signal controlled element exhibiting the electro-optic effect is used to modulate a beam of light. The modulation may be imposed on the phase, frequency, amplitude or polarization of the beam.

• Phase Modulators -

A Phase modulator is an optical modulator which can be used to control the optical phase of the laser beam.

Frequently used types of phase modulators are electro-optic modulators based on pocket cells, and liquid crystal modulators, but it is also possible to exploit thermally induced refractive index changes or length changes of an optical fiber or induce length changes by stretching. Various kinds of phase modulators are used within the area of integrated optics, where the modulated light propagates in waveguides.

- Important Properties of Phase modulators are -
  - the amount of phase modulation which can be achieved
  - the required drive voltage.
  - the modulation bandwidth which can be of many GHz for electro optic modulators, and far less for devices based on thermal effects or using liquid crystal material
  - the optical bandwidth in which the device can be used
  - the device aperture limiting the beam radius of the modulated beam.
  - the outer dimensions of the device.

- Applications - Some examples of applications of phase modulators are -
  - A phase modulator within a laser resonator of a single frequency laser can be used for wavelength tuning or for active mode locking of a laser.
  - Various kinds of interferometers and setups for spectroscopic measurements require phase modulators, often with a periodic drive signal.
  - In data transmitters of optical fiber communication systems, phase modulators can be used for encoding the transmitted information. An example is a method of phase shift keying

• Directional Coupler -

The implementation of WDM or (DWDM) requires some optical components that do not need any external control for their operation. These are primarily used to split, combine or tap off optical signals. The prime components of this category are Couplers, multiplexers and demultiplexers.

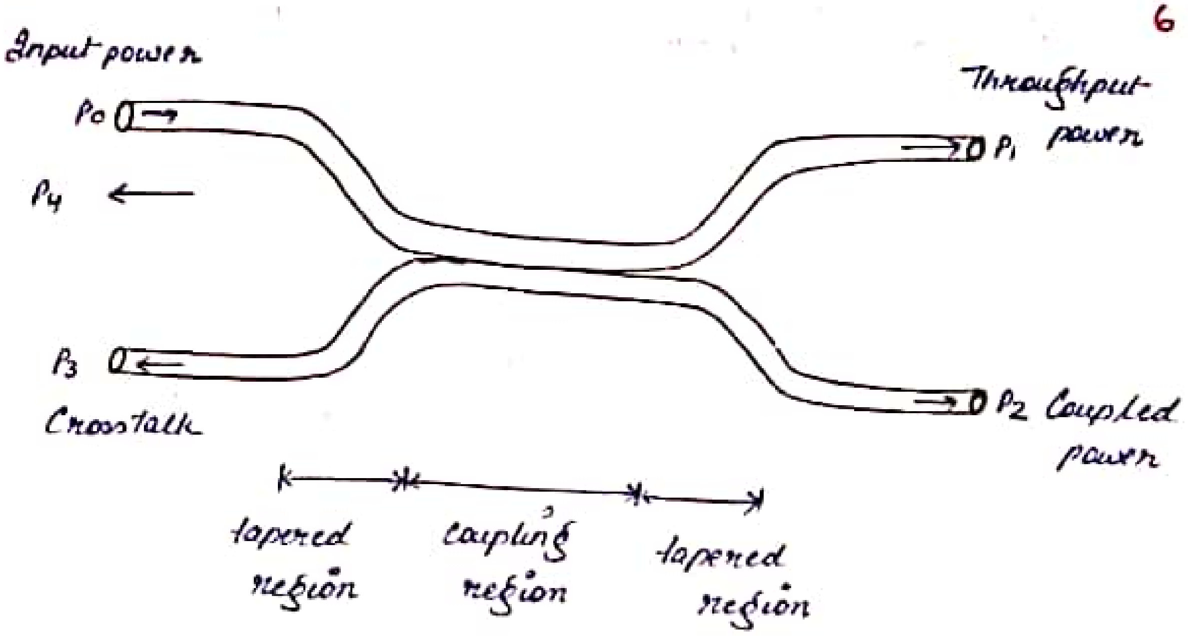
Couplers are the devices that are used to combine and split optical signals. A simple 2×2 coupler consists of two input ports and two output ports. It can be made by fusing two optical fibers together in the middle and then stretching them so that a coupling region is created. Such devices can be made wavelength independent over a wide spectral range.

Thus, an optical signal launched at input port 1 maybe split into two signals that can be collected at output ports 1 and 2.

The fraction of the power available at the output ports is called the Coupling ratio.

A device with a 50:50 coupling ratio is called a 3dB-coupler as 50% of the input power is coupled to each output port.

It can be used as a Power Splitter. A coupler with the coupling ratio of 1:99 can be used as an optical tap.



A 2x2 Fiber-optic Coupler

Here, P_0 is the input power, P_1 is the throughput power, P_2 is the power coupled into the second fiber. The parameters P_3 and P_4 are extremely low signal levels, resulting from backward reflections and scattering.

The V-parameter of an optical fiber is given by -

$$\boxed{V = \frac{2\pi a}{\lambda} n_1 \sqrt{2\Delta}}$$

where,

$2a$ is the core diameter

n_1 is the core index

λ is the wavelength of light propagating through the fiber

Δ is the relative refractive index difference

As the input light P_0 propagates along the taper in fiber 1 and into the coupling region, there is a significant decrease in the

V- number. Thus, the optical power propagating through the core of a single mode fiber will be less confined.

If two identical single mode fibers are used to make a 2X2 coupler, the power in a single mode propagating through the core of the first fiber will couple to that in the core of a second adjacent fiber in the coupling region. By controlling the distance between the fibers, it is possible to obtain a desired coupling ratio. Such couplers are called Directional Couplers, because the fibers allow the launched light to pass through them in one direction. If the device allows the light to pass through in two opposite directions, it is called a Bidirectional Coupler.

Assuming that the above mentioned 2X2 coupler is lossless coupler and the two single mode fibers are identical, the power P_2 coupled from the first fiber into the second fiber over an axial length 'z' is given by,

$$P_2 = P_0 \cdot \sin^2(kz)$$

where, P_0 is the power launched at input port 1

K is the coupling coefficient

Assuming that the power is conserved, one can write the following expressions for the power P_1 delivered to the output port 1,

$$P_1 = P_0 - P_2 = P_0\left[1 - \sin^2(kz)\right] = P_0 \cdot \cos^2(kz)$$

This shows that the phase of the driven fiber always lags 90°
behind the phase of the driving fiber.

The performance of a directional coupler may be specified in terms of the Splitting ratio or the Coupling ratio, defined as follows -

$$\text{Coupling Ratio } (\%) = \left(\frac{P_2}{P_1 + P_2}\right) \times 100$$

$$\text{Coupling Ratio } (dB) = -10 \log_{10} \left(\frac{P_2}{P_1 + P_2}\right)$$

So fare we have assumed that the coupler is loss less. However, in a practical device of this type, some power is always lost when the signal passes through it. There are two basic parameters related to the loss - i.e the Excess loss and the Insertion loss.

The excess loss is defined as the ratio of the input power to the total output power.

$$\text{Excess loss } (dB) = 10 \log \left(\frac{P_0}{P_1 + P_2}\right)$$

The insertion loss refers to the loss of a particular port-to-port path, defined as the ratio of the power at input port i to the power at output port j.

$$\text{Insertion loss } (dB) = 10 \log \left(\frac{P_i}{P_j}\right)$$

Another performance parameter is Crosstalk, which measures the degree of isolation between the input at one port and the optical power scattered or reflected back into the another input port. That is, it is a measure of the optical power level P_3,

$$\text{Crosstalk} = 10 \log \left(\frac{P_3}{P_0} \right)$$

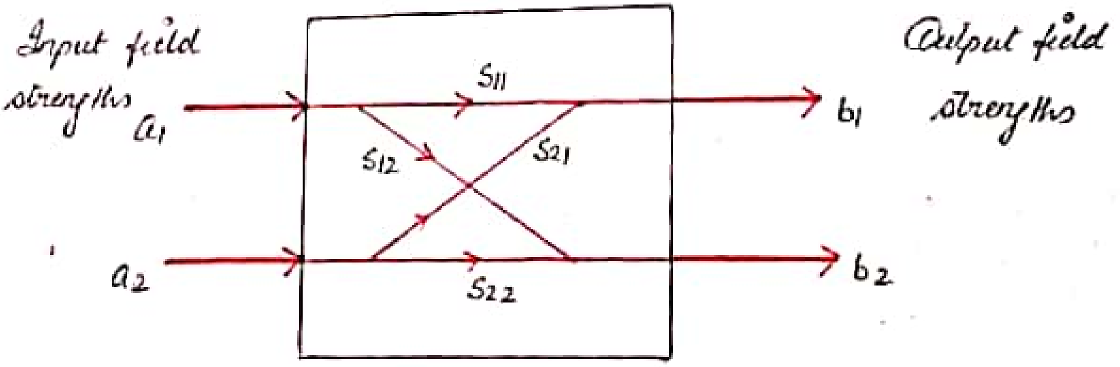
One can also analyze a 2x2 guided wave coupler as a four terminal device that has two inputs and two outputs.

All fiber or integrated optic devices can be analysed in terms of the Scattering matrix (also called as the Propagation matrix) S, which defines the relationship between the two input field strengths a_1 and a_2, and the two output field strengths b_1 and b_2;

$$\boxed{b = S a}$$

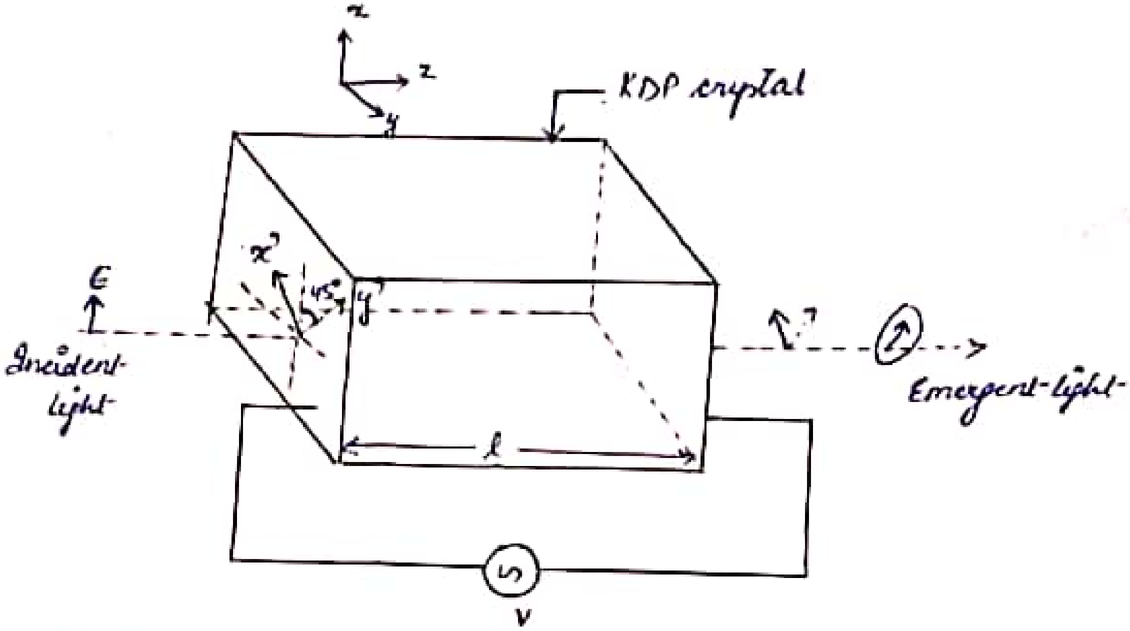
where,

$$b = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \quad a = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad \text{and} \quad S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$



• Longitudinal Electro-Optic Modulator -

Let us consider, a longitudinal configuration. Herein, a plane polarised light is propagated along the optic axis (z-axis) of a KDP crystal (it is an uniaxial birefringent electro optic crystal), which is being acted upon by an external electric field directed along the z-axis.



Upon the application of an electric field, E_z along the z-axis, the crystal no longer remains uniaxial but becomes biaxial.

The principal x-axis and y-axis of the crystal are rotated through 45° into new principal axes x' and y'.

Refractive index $n_{x'}$ for a wave polarised in x' direction is given by,

$$n_{x'} = n_o + \frac{1}{2} n_o^3 r_{63} E_z$$

where, r_{63} is an appropriate Electro-optic coefficient.

Similarly, the refractive index $n_{y'}$ for a wave polarised in y' direction is given by,

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

If the incident wave is represented by, $E = E_0 \cos(\omega t - kz)$

Then the components along x' and y' direction is given by,

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

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

But these components have refractive indices $n_{x'}$ and $n_{y'}$, hence they will become increasingly out of phase as they propagate through the crystal.

Phase change experienced by two components -

$$\phi_{x'} = k n_{x'} l = \frac{2\pi}{\lambda} n_{x'} l$$

$$\phi_{y'} = k n_{y'} l = \frac{2\pi}{\lambda} n_{y'} l$$

Substituting the values of $n_{x'}$, we have;

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

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

$$\phi_{x'} = \phi_0 + \Delta\phi$$

Similarly, substituting for $n_{y'}$, we have;

$$\phi_{y'} = \frac{2\pi}{\lambda} l n_0 \left[1 - \frac{1}{2} r_{63} n_0^2 E_z\right]$$

$$\phi_{y'} = \phi_0 - \Delta\phi$$

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

and $V = E_z l$ is the applied voltage.

If V is made to oscillate with frequency ω_m ie $V = V_m \sin \omega_m t$, the phase shift $\Delta\phi$ will also vary sinusoidally and the peak value will be $\pi r_{63} n_o^3 V_0 / \lambda$. Thus, the electro optic effect may be used for phase modulation.

The net phase shift or total retardation between the two polarised waves in x' and y' direction are -

$$\phi = \phi_{x'} - \phi_{y'} = 2\Delta\phi$$

$$= \frac{2\pi}{\lambda} r_{63} \cdot n_o^3 V$$

We know that the superposition of two plane polarised waves that are perpendicular to each other produces an elliptically polarised wave. Here, the wave emerging at $z = l$ will be elliptically polarised. If the superposition gives a phase difference which is an integral multiple of π, the emergent beam will be plane polarised and if the phase difference is an odd integer multiple of $\pi/2$, the emergent beam will be circularly polarised.

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

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

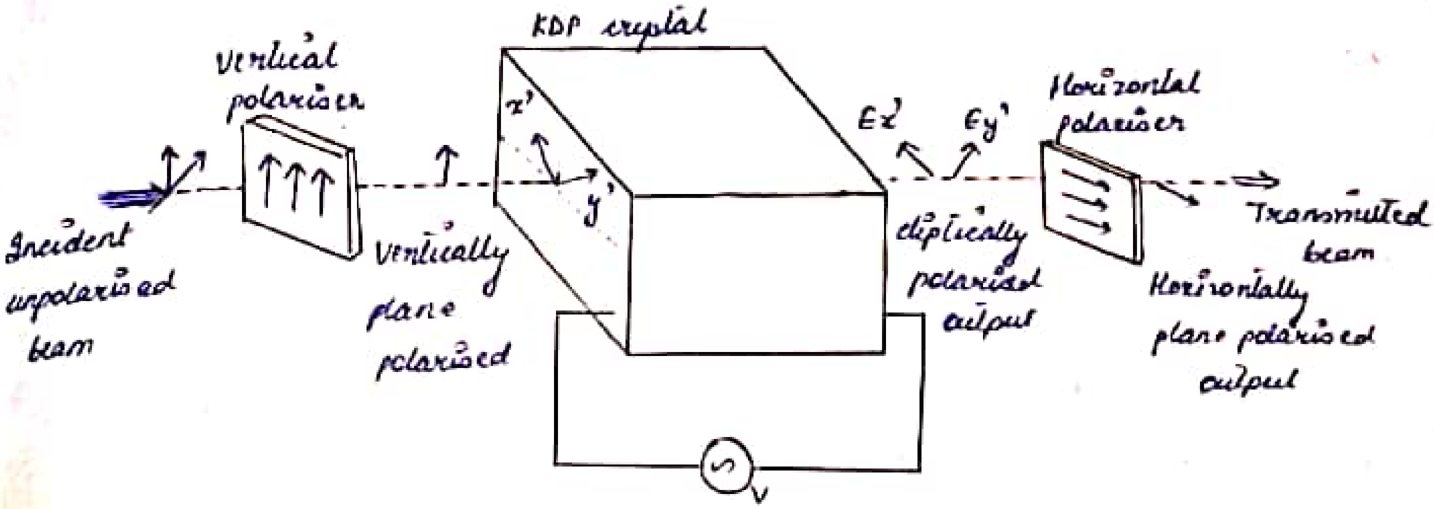
$$V_\pi = \frac{\lambda}{2 n_o^3 r_{63}}$$

The half wave voltage is one of the important parameters of an electro-optic modulator.

The equations for the components of a wave emerging from the crystal will be,

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

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



The transmitted electric field components will be given by $-E_x'/\sqrt{2}$ and $E_y'/\sqrt{2}$. Thus the above equations becomes;

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

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

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

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

$$= \frac{E_0^2}{2}\sin^2\Delta\phi$$

$$I = I_0 \sin^2\Delta\phi = I_0 \sin^2\left(\frac{\phi}{2}\right)$$

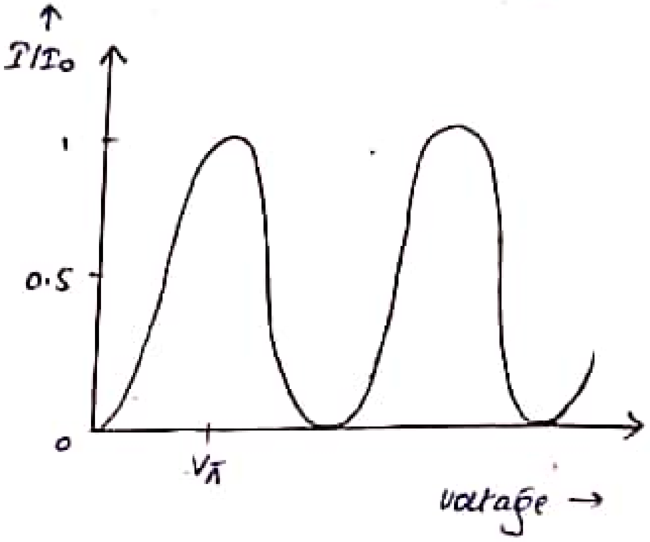
where, $I_0 = \frac{E_0^2}{2}$ is the amplitude of the intensity of the incident beam.

$$\frac{I}{I_0} = \sin^2\left(\frac{\pi}{\lambda} r_{63}\, n_o^3\, V\right)$$

$$\frac{I}{I_0} = \sin^2\left(\frac{\pi}{2}\frac{V}{V_\pi}\right) \quad \text{(using the formula } V_\pi\text{)}$$

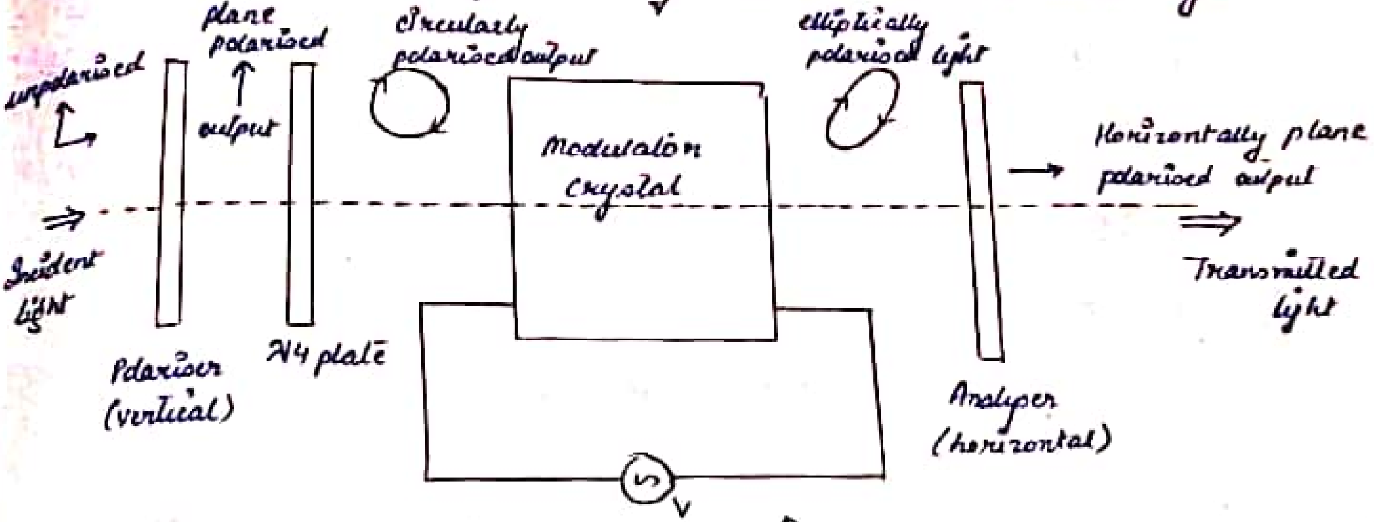
Thus we can also define V_π as the voltage required for maximum transmission i.e. $I = I_0$. In general, the transmittance of the modulator can be altered by changing the voltage applied across the crystal.

The variation of I/I_0 as a function of applied voltage V is shown alongside. Such a system is called Pockels electro-optic amplitude modulator.



If such a modulator is operated around $V=0$, then the output intensity of the modulated beam does not vary linearly with the input signal.

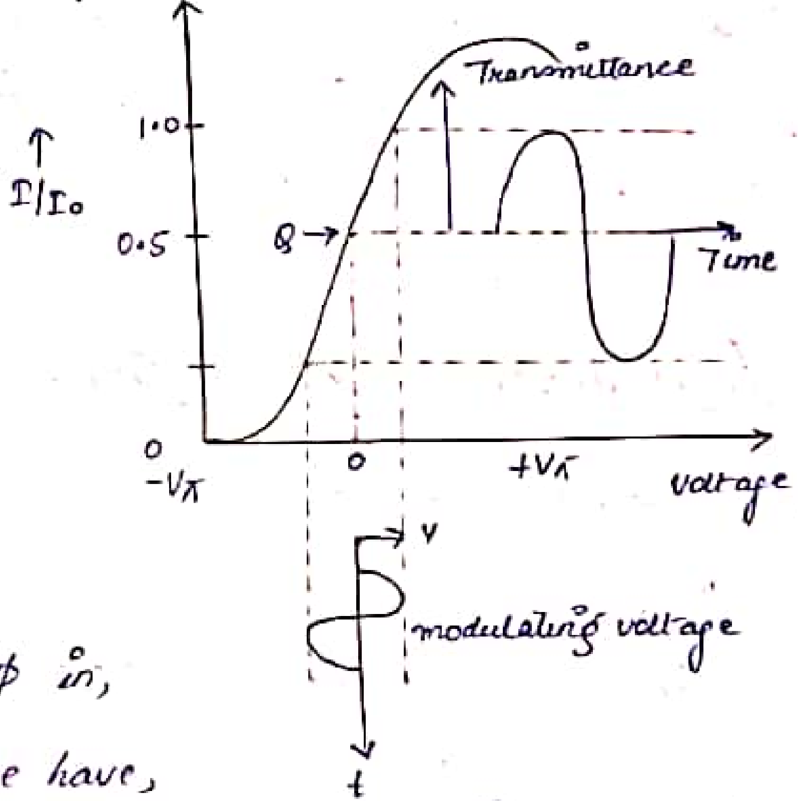
for $V \ll V_\pi$, the transmitted intensity is proportional to V^2. To overcome this problem, we introduce an external bias, so that with no signal, the transmittance of this modulator is 1/2. It is more convenient to bias the modulator, optically to the 50% transmittance point Q, by introducing a quarter wave plate with its fast and slow axes parallel to x' and y' axes of the modulator crystal. The retarder plate introduces a phase difference of $\pi/2$ between $E_{x'}$ and $E_{y'}$.



With this bias, the net retardation ϕ between the two polarised components becomes,

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

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



Substituting the value of ϕ in,

$I = I_0 \sin^2\left(\frac{\phi}{2}\right)$ we have,

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

An almost linear variation of transmittance with applied voltage, when the modulator is operated about Q.

For $V << V_\pi$,

$$\frac{I}{I_0} \simeq \frac{1}{2}\left(1 + \frac{\pi V}{V_\pi}\right)$$

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

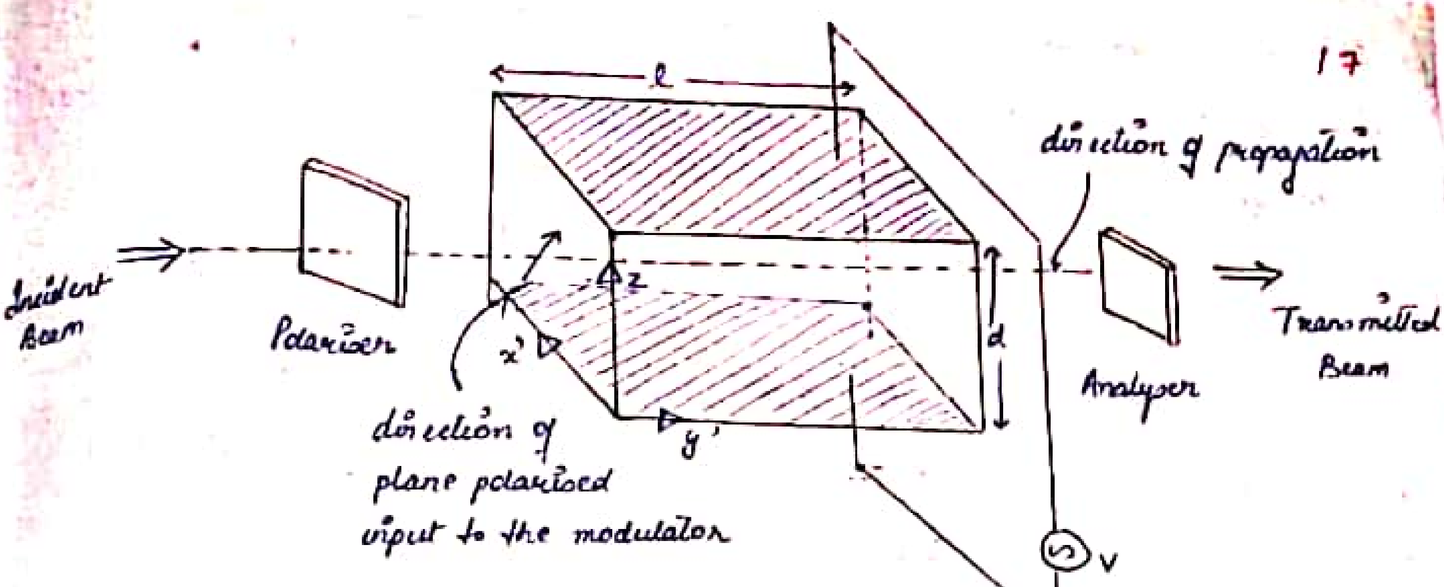
If a small sinusoidally varying voltage of amplitude V_0 and frequency ω_m is applied to the modulator, then the intensity of the transmitted beam will also vary sinusoidally with frequency ω_m.

$$\frac{I}{I_0} \approx \frac{1}{2}\left[1 + \frac{\pi}{V_\pi} V_0 \sin \omega_m t\right]$$

In this amplitude modulator, the voltage and hence the electric field is applied along the direction of propagation of the optical beam, and hence it is called a longitudinal electro optic modulator.

• Transverse Electro - Optic Modulator -

In the Transverse mode of Electro-optic modulator, the direction of propagation of light is perpendicular to the direction of the applied field. The advantages of this configuration are that, electrodes do not obstruct the beam as in the case of longitudinal modulator and the retardation, which is proportional to the electric field and the crystal length, can be increased by using longer crystals.



In the presence of an electric field E_z in the z-direction, the refractive indices for a wave propagating along y'-direction and polarised along x'-direction and z-direction are,

$$n_{x'} = n_o + \frac{1}{2} n_o^3 r_{63} E_z.$$

$$n_z = n_e$$

Thus the phase difference, along x' and y'-direction will be;

$$\Delta\phi = \phi_{x'} - \phi_z = \frac{2\pi}{\lambda} . l \, (n_{x'} - n_z)$$

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

$$= \frac{2\pi}{\lambda} l \, (n_o - n_e) + \frac{\pi}{\lambda} r_{63} \; n_o^3 \left(\frac{V}{d}\right) . l$$

where, V is the voltage applied across the width d of the crystal. Also, when the applied voltage $V=0$, there is a finite retardation, given by,

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

This is due to the intrinsic birefringence of the crystal. Thus the retardation induced by the external voltage is given by,

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

Half wave voltage (V_π) for this configuration can be defined as the voltage required to produce a phase difference of π between the two polarisation components.

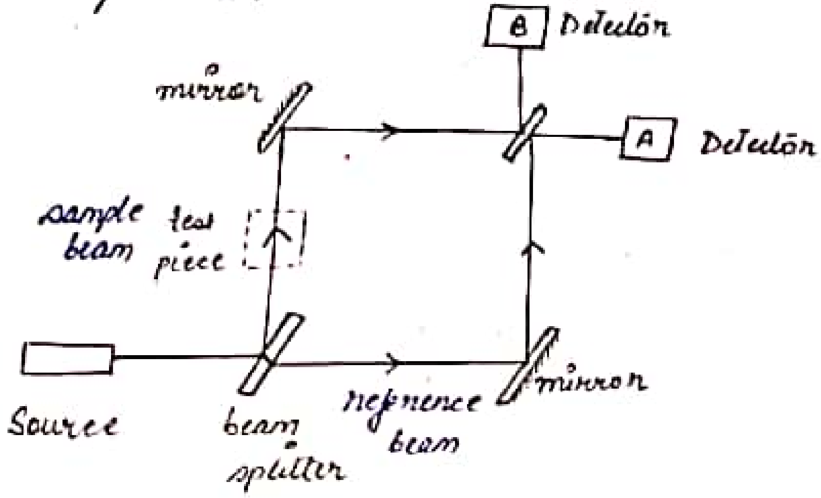
$$\Delta\phi = \pi = \frac{\pi}{\lambda} r_{63}\, n_o^3 \left(\frac{V_\pi}{d}\right) \cdot l$$

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

In contrast to the longitudinal modulator, V_π in this case is not independent of the length l of the modulator crystal, but depends on the ratio d/l. Thus the half wave voltage may be reduced by employing long thin crystals.

• Mach Zehnder Interferometer –

The Mach Zehnder is an amplitude splitting interferometer that consists of two beam splitters and two fully reflecting mirrors. Light from an extended source passes through the first beam splitter resulting in two light waves traversing equal and separate optical paths. The two paths are later recombined with a set of mirrors at a second beam splitter in which the resultant beam is then passed to an observation plane where the interference fringes are recorded. The effectiveness of the Mach Zehnder Interferometer is solely based off the equal optical path lengths that the two light paths travel before being recombined. Any difference between the two optical paths can be introduced by a slight tilt of any of the beamsplitters.



• Working Principle -

Setup - A collimated beam is split by a half silvered mirror. The two resulting beams (i.e the sample beam and the reference beam) are each reflected by a mirror. The two beams then pass a second half-silvered mirror and enter the two detectors as shown in the fig. above.

Properties -

- The half silvered mirror is just a crummy mirror, it only reflects half the light incident on it, refracting the other half through it. Such mirrors are sometimes called one way glass or a Beamsplitter.

- Speed of light in glass is significantly less than the speed of light in air / vacuum. The index of refraction of air is mo almost exactly 1 whereas, the index of refraction is of the order of 1·5 or so.
- When a light ray is incident on a surface and the material on the other side of the surface has a higher index of refraction, then the reflected light ray is shifted in its phase by exactly one half a wavelength.
- The index of refraction of a perfect mirror can be thought of as infinite. Thus light reflected by a mirror has its phase change by one half a wavelength.
- When a light ray is incident on a surface and the material on the other side of the surface has a lower refractive index, then the reflected light ray does not have its phase changed.
- When a light ray goes from one medium to another medium, its direction changes due to refraction but no phase change occurs at the surfaces of the two mediums.
- ~~When a light ray travels~~

Observing the effect of a Sample -

In the absence of a sample, both the sample beam (SB) and the reference beam (RB) will arrive in phase at detector 1, yielding constructive Interference. Both SB and RB will undergo a phase shift of (1x wavelength + k) due to two front-surface reflections and one transmission through a glass plate.

The sample beam is -

(a) reflected by the front of the first beam splitter, giving a phase change of one half a wavelength

(b) reflected by the upper left mirror, giving a further phase change of one half a wavelength.

(c) transmitted through the upper right beam splitter, giving some constant phase change.

The reference beam is -

(a) transmitted through the lower left beam splitter, giving some constant phase change.

(b) reflected by the front of the lower right mirror, giving a phase change of one half a wavelength.

(c) reflected by the front of the second beam splitter, giving a phase change of one half a wavelength.

Adding up all the contributions for the two paths, we see that the light entering detector 1 is in phase.

At detector 2, in the absence of a sample, the sample beam and the reference beam will arrive with a phase difference of half a wavelength, yielding a complete destructive interference. The reference beam arriving at detector 2 will have gone a phase shift of (0.5 X wavelength + 2k) due to one front surface reflections and two transmissions. The sample beam arriving at detector 2 will have undergone a (1X wavelength + 2k) phase shift due to two front surface reflections, one rear surface reflection and two transmissions. Therefore, when there is no sample only detector 1 recieves light.

If a sample is placed in the path of a sample beam, the intensities of the beams entering the two detectors will change,

- **Applications** -

(1) Mach-Zehnder Interferometer are used in electro optic modulators, electronic devices used in various fiber optic communication application.

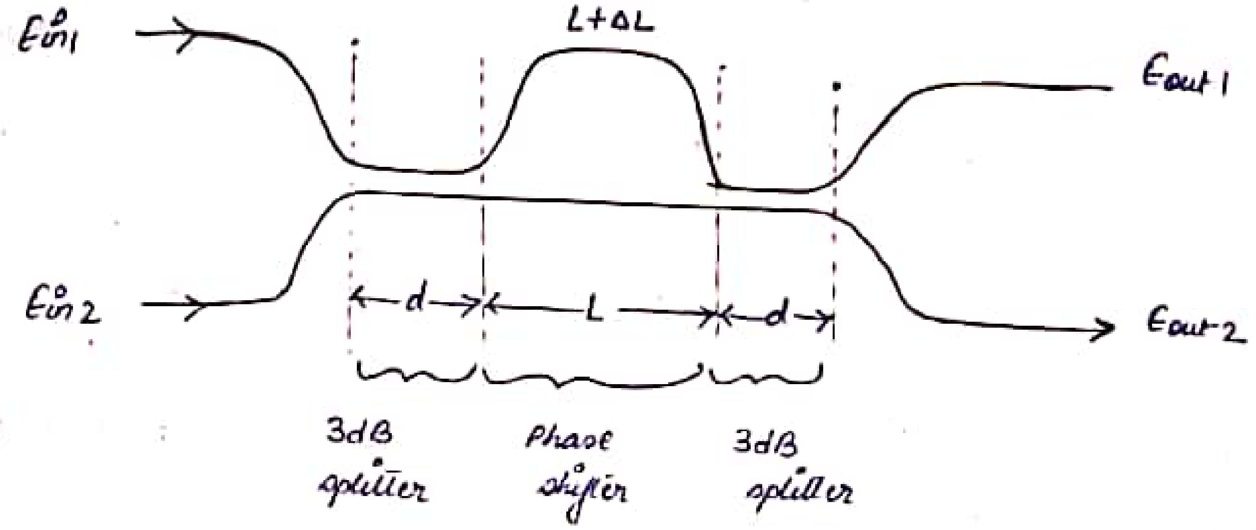
(2) Mach-Zehnder modulators are incorporated in monolithic integrated circuits and offer well behaved, high bandwidth electro optic amplitude and phase responses.

(3) They are also used to study one of the most counter intuitive predictions of quantum mechanics, the phenomenon known as Quantum entanglement.

(4) It is frequently used in the fields of aerodynamics, plasma physics and heat transfer to measure pressure, density and temperature changes in gases.

Mach-Zehnder Interferometer Multiplexer - 23 (Keiser)

2x2 Mach Zehnder Interferometer consists of three stages: an initial 3-dB directional coupler which splits the input signals, a central section where one of the waveguides is longer by ΔL to give a wavelength dependent phase shift between the two arms, and another 3-dB coupler which recombines the signal at the output.



The function of this arrangement is that, by splitting the input beam and introducing a phase shift in one of the paths, the recombined signals will interfere constructively at one output and destructively at another. The signals then finally emerge from only one output port.

The propagation matrix $M_{coupler}$ for a coupler of length d is,

$$M_{coupler} = \begin{bmatrix} \cos kd & j\sin kd \\ j\sin kd & \cos kd \end{bmatrix}$$

Where, k is the coupling coefficient.

Since, we are considering a 3dB coupler, which divides the power equally then, $2kd = \pi/2$

$$\therefore \quad M_{coupler} = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix}$$

In the central region, when the signals in the two arms come from the same light source, the output from these two guides have a phase difference of $\Delta\phi$, given by;

$$\Delta\phi = \frac{2\pi n_1}{\lambda} L - \frac{2\pi n_2}{\lambda}(L + \Delta L)$$

This phase difference can arise either from a different path length or through a refractive index difference if $n_1 \neq n_2$. Hence, we take both arms to have the same index $n_1 = n_2 = n_{eff}$, then, $\Delta\phi = k\,\Delta L$

where,
$$k = \frac{2\pi n_{eff}}{\lambda}.$$

Input - Output Waveguid - Couplers

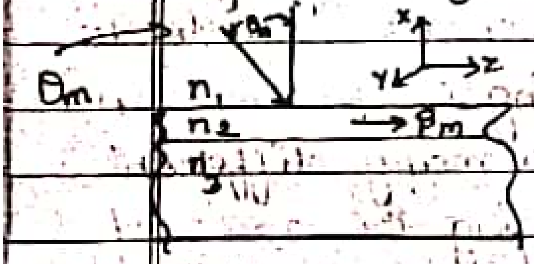
Prism Couplers

Transverse coupling can be used only when a cross-sectional End-face of waveguide is Exposed.

For coupling to occur, it is nessessary that the components of the ~~waves in z direction be the same in both~~ phase velocities of the wave in the z-direction be the same in both the waveguid & beam. Thus, a phase-match condition must be satisfied ; which requiries,

$$\beta_m = k n_1 \sin\theta_m = \frac{2\pi}{\lambda_0} n_1 \sin\theta_m .$$

For a waveguide mode : $\beta_m > k n_1$



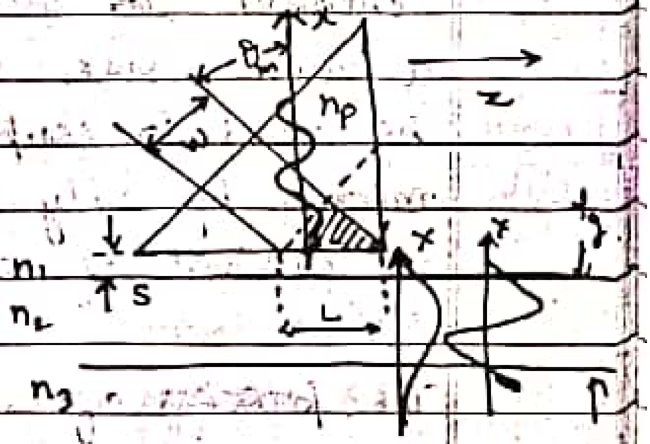


Fig: Diagram of a prism coupler.

m = 0 & m = 1 waveguide in z-direction are shown coupling → modes

One solution to the problem of phase matching is to use a prism, as sho

A beam of light of width 'w' is directed into the face of the prism, which has $n_p > n_1$. The beam is totally internally reflected at $n_p - n_1$ interface, seting up an standing wave mode in the prism. This mode is stationary in x-direction, but moves in the z-direction with phase constant β_p. In the waveguide, various guided modes can exist, ~~moving~~ in z-direction moving with phase angle β_m.

$\beta_p = \beta_m$; when θ_m is choosen.

The condition for matching of 'β' terms is:-

$$\frac{2\pi n_p}{\lambda_0} \sin\theta_m = \beta_m$$

Athough 'θ_m' must be carefully choosen ~~to~~ in order to couple to a given mode. A single prism can be used to couple to many different modes by only changing the angle of incident of optical beam. (θ_m)

The process of coupling energy via the overlapping mode, while the incident beam tends to be totally internally reflected in the prism, is some-times called optical tunneling.

Of course, the condition -

$$\theta_m > \theta_c = \sin^{-1}\left(\frac{n_1}{n_p}\right)$$

must also be satisfied if total internal reflection is to occur in the prism.
where θ_c = critical angle.

↳ Because of the size of the prism, the interaction b/w prism & waveguide modes can occur only over length 'L'.
The theory of 'weakly couple interface' give the condition for total internal reflection :

$$KL = \pi/2$$

where,

k = Coupling cofficient depends on n_p, n_1 & n_2 & spacing 's'.

↳ The length require for complete ~~comp~~ coupling is given by :

$$L = \frac{w}{\cos\theta_m} = \frac{\pi}{2K} \qquad \boxed{K = \frac{\pi \cos\theta_m}{2w}}$$

↳ This condition for complete coupling assumes the amplitude of the electric field is uniform over the entire width of the beam.

Since all the spetial harmonics of Each mode are coupled to form the complete surface wave field in the grating region; Energy introduced from ~~one~~ any ~~harmonic~~ spetial harmonics is eventually coupled into the fundamental (v=0) harmonic as it travels to right and past to the grating region.

Adv:

↳ The grating coupler can be used to selectively transfer the Energy from optical beam to particular waveguide mode by properly choosing the angle of incident.

↳ The grating can also be used as an output coupler.

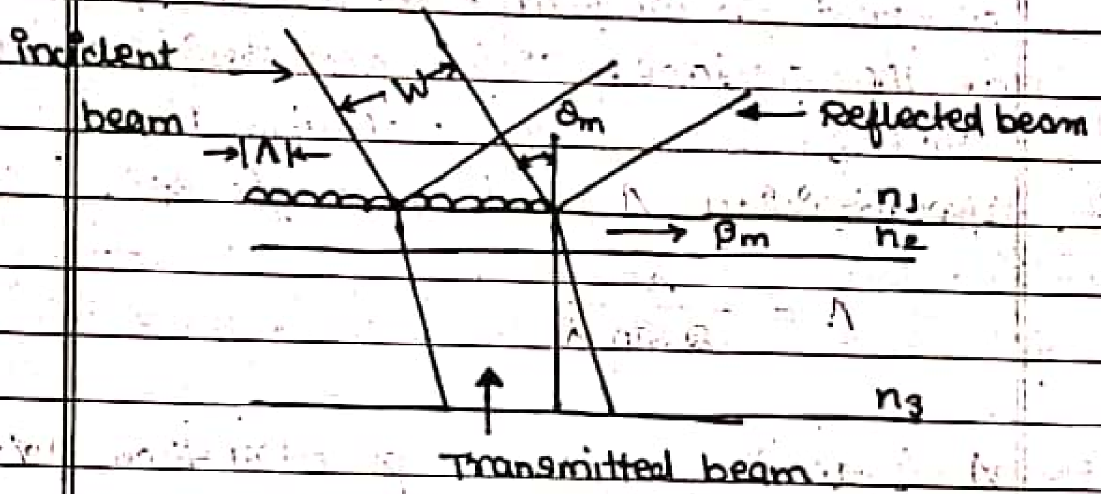
↳ The principle Advantage of grating coupler is that, once fabricated, it's 'coupling efficiency' remains constant & is not altered by vibration.

↳ The grating coupler can be used on high-index semiconductor ~~materia~~ waveguides for which it is difficult to obtain suitable 'prism pattern'.

DisAdv:

↳ unlike a prism, the grating does not operate on total internal Reflection.

- It is highly angle dependent, the grating coupler can not be used with divergent beam of semiconductor laser.
- It is very difficult to fabricate, requires sophisticated masking & Etching techniques.



Grating Fabrication:

The grating structure may be formed either by masking or Etching the waveguide. The most difficult part of this process is defining the pattern of closely space grating pattern.

Therefore, grating are generally produced by using an optical interference process sometimes called holographic process.

Advantages:

(i) The prism coupler is frequently used in Integrated optics applications because of its versatility.

(ii) It can also be use as Either Input or output coupler.

(iii) Can be use as an analytical tool to determine the relative power in Each waveguid mode.

(iv.) Prizm can also be moved along the length of the waveguide to determine losses.

DisAdv.

① Care must be taken to apply machanical force on the prizm during Each measurments.

② The greater disadv. of prizm coupling is that the n_p must be not only greater than n_1 but also greater than n_2. $n_p > n_1, n_2$

③ Semiconductor waveguide having Indices ≈ 3 or 4, are more difficult to couple with prizm.

④ The incident beam must be highly collimated.

Adv. ⇒ Prizm coupler are very useful in laboratory applications.

Grating Couplers :

The grating coupler, like 'prizm coupler' functions to produces the 'phase maching' b/w the waveguid & an unguided optical beams which is incident at an oblique angle t/r the surface of waveguide.

Basic Theory of the Grating Coupler :

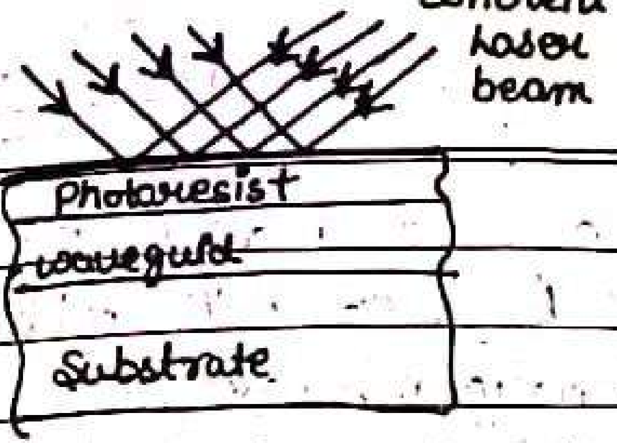
Because of its periodic nature; the grating perturbs the waveguide modes in the periodic grating pattern, thus causing each of them to have a 'set of spatial harmonics' with z- direction propogation, given by –

$$B_v = \beta_0 + \frac{v2\pi}{\Lambda}$$

where, $v = 0, \pm 1, \pm 2 \ldots$
Λ = periodicity of grating.

The fundamental factor β_0 is approximately equal to β_m of particular mode in the waveguide region not covered by the grating. Because of the –ve values of v, the phase maching condition can not be satisfied so that

$$\beta_v = kn_1 \sin\theta_m \qquad (\beta_m > kn_1)$$



Holographic photoresist Expose.

In this process: the substrate consist the waveguide is first coated with photo-resist. Then the resist is expose using an interfarience pattern generated by coherent laser beams combination, directed at the surface. Simple geometric conside-rations shows" the relation b/w periodicity Λ & beam angle α'.

$$\Lambda = \frac{\lambda_0}{2 \sin \alpha}$$

Λ is limited to value greater than $\lambda_0/2$ while in case of ractangular prism:

$$\Lambda = \frac{\lambda_0}{2n \sin \alpha}$$

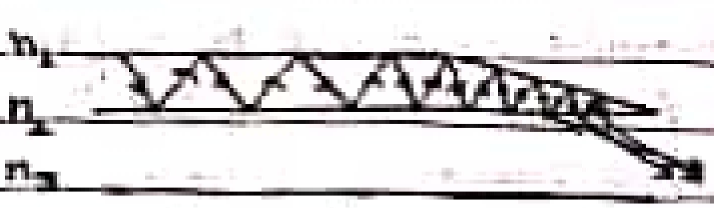
n – index of ~~[illegible]~~ refraction of the prism material.

Once the photoresist has been Exposed, we produce the required mask on waveguide surface, either by chemical or ione beam etchim to produce the grating.

Tapered Couplers :

The tapered coupler is based on the principle, that a waveguide which is below the 'cutoff transfer energy' into radiation modes. The waveguide thickness is tapered in the coupler region to produce a reduced-height waveguide with a decreasing cutoff wavelength.

A 'guided wave' incident on the tapered coupler, undergoes zig-zag bounces with the angle of incident steadily decreasing. When the angle of incidence become less than ~~cut-off~~ critical angle, the total internal refraction takes place & thus the energy of beam is refracted back to substrate. The energy from subsequent rays ~~are~~ also refracted out of the waveguide in same manner. So upto 70% coupling efficiency is obtain. 30% loss is mostly due to scattering into air.



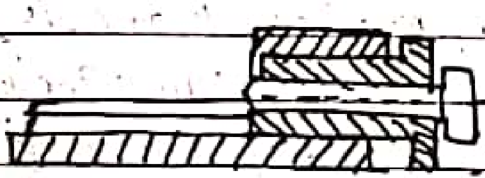
: Fig. of a Tapered coupler.

* The 3 parts (Types) of Tapered coupler

(i) Butt Coupling:

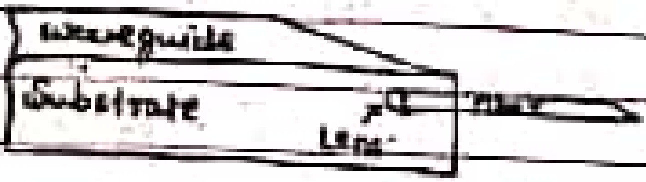
The fiber may be directly butted in the waveguide, without any interfacing device, in an End-on alignment. If the cross-sectional area of the fiber core & the waveguide are closely mached, high Efficiency of coupling can be achived.

A index ~~match~~ matching fluid can be used to reduce reflection loss at ~~guides~~ the interface. The greates problem with the butt coupling approach is, it is Extremly difficult to establis & maintain correct alingment, since both the fiber core & waveguide typically have micro sized dimensions.



(ii) Tapered Film Fiber Couplers:

This process uses a tapered section of waveguide to couple to a fiber. The fiber is inserted into a cylindrical hole, drilled into the substrate, just below the wave-guide. The hemispherical End of this hole is filld with a high-Index material to produce a lens. light wave coupled out of the thin film waveguide into the substrate are collected by the fiber. Reasonably good efficiency ~~into the~~ is ~~substrate~~ obtainable in the case of multimode fibers with a large acceptance angle.



(iii) Grating Fiber coupler.

This grating is done to couple between a single mode fiber & a sputtered glass waveguide. In this case the cladding was not removed, but the fiber was heated and draw to reduce its cross-section by 1/3rd from the original diameter of 18 um. This reduction in cladding thickness permitted optical tunneling of Energy, while the grating provides phase matching.

Adv:

↳ It is simple to fabricate & function & reasonably well as an output coupler.

↳ It forms a divergence beam.

Date:
Page:

↳ can also be use as a input Coupler

↳ It spreads over an angle of 1-20°.

Disadv:

↳ Divergent beam, produced by it, is sometime inconvenient to use.

↳ In order to obtain high Efficiency, one would have to construct a converting input beam.

Application -: One practicle application of the tapered coupler is may be in coupling a thin film waveguide to an opticle fiber, since the End of the fiber can be located very close to the waveguide & the End face can be shaped to Improve the coupling Efficiency.

FBG

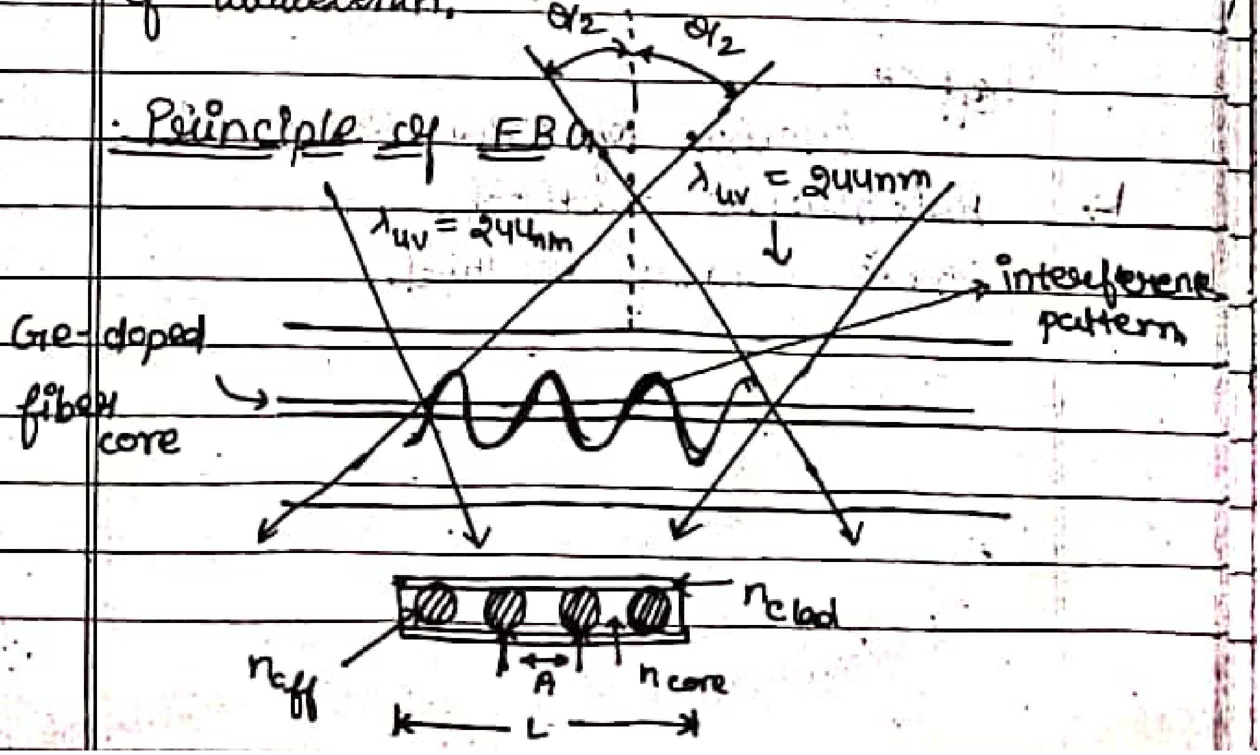
(Fiber brag grating)

The Fiber brag grating is a periodic structure fabricated inside the core of the optical fiber. The periodicity could be machanical like variation of the core diameter or, it could be Electrical like variation of the refractive index of the core.

In FBG two identical counter propagating modes get coupled and the Energy is transfered from forward travelling to backward traveling ~~code~~ mode.

In periodic structure like FBG the coupling of energy b/w different co-propagating & counter-propagating modes of the fiber takes place always. The mode coupling phenomenon is a strong function of wavelenth.

Principle of FBG:



According to the mode coupling phenomenon the 2 modes show strong coupling if they satisfies Bragg condition:-

$$\beta_1 - \beta_2 = 2\pi / \Lambda$$

where, β_1 & β_2 = Phase constant of the 2 modes.
Λ = periode of variation of refractive index.
m = Integer (defines order of diffraction)

↳ If we take two identical counter propagation modes, $\beta_2 = -\beta_1$
& the Bragg differection condition:

$$2\beta_1 = 2m / \Lambda$$

↳ The Bragg condition then gives the wavelength called Bragg wavelength λ_B given as-

$$\lambda_B = 2 n_{eff} \Lambda$$

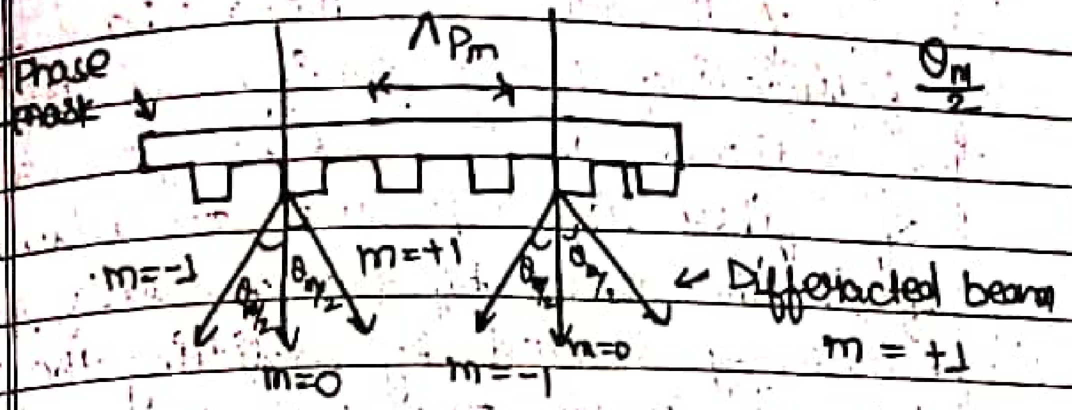
Method of F.B.G. Fabrication:

↳ Holographic method.
↳ Phase grating method.

One of the most effective methods for fabricating Bragg gratings is Kolographic method. In this method ~~a~~ section of fiber is expressed or illuminated from the side, by two mutually coherent beam's, generated by splitting the light from UV laser. The both beams suffers approximatelly equal path length & interfase in a region surrounding by a portion of the fibers. Actually there 2 coherent beams are, after splitting through fiber, goes opposite, near to 2 saturated mirrors on both the side, they get a reflection over there & then collected at combination of fiber.

The fringes run perpendicular to the long axis of the fiber. The angle of interfacing must be adjusted to achive the the fring spacing, that will be appropriate for IR wavelengths.

Phase grating method



For this method a 'master phase grating' is made usually by Etching grooves in a plate of glass.

profile The phase grating will have a close approximation to a square wave profile with an optical path length.

Phase grating has no zero order & no even order. The transmitted light being dominated by the two first order which contain more than 80% of transmitted light. The two first order interference in the fiber, creating a problem with a period that is half the period of the master grating.

Application

↳ Narrow band filtering
↳ Fiber laser
↳ Raman Amplifier
↳ WDM ADD/ Drop / mux / Demux
→ Gain Equilizer

Wavelength converter
Mode converter
Phase conjugater.

Adv:

(1.) It minimise 'recording laser coherent' requirement.

(2.) The fringe period created is not affected by small changes of the laser wave length.

DisAdv.

Once the master grating has been generated there is no easy way to change the period of FBG.

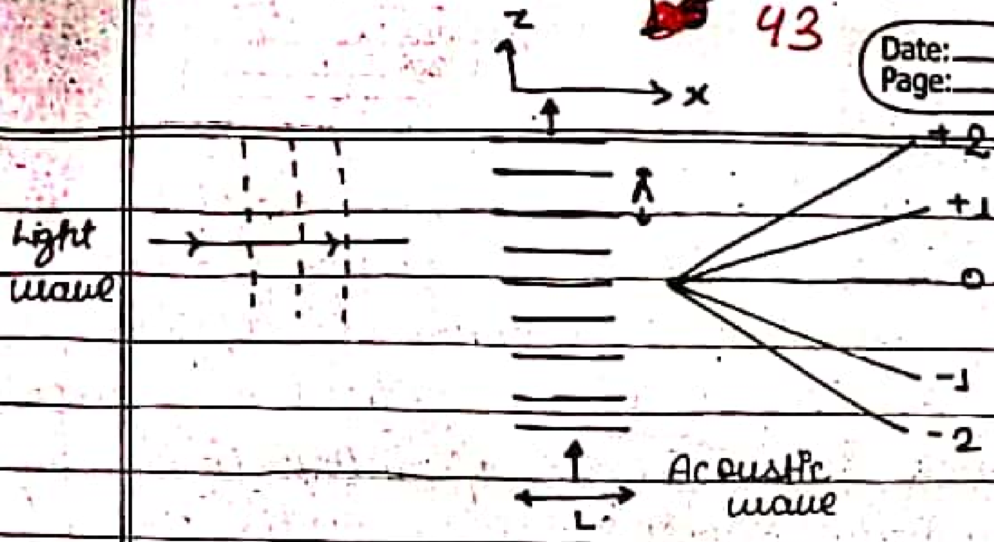
Acousto-optic Effect:

The acousto-optic Effect is the change in the refractive Index of a medium caused by the machonical strain produced by an acoustingc wave. Since the strain varies periodically in the acoustic wave. the refractive Index of the medium also varies periodically to a refractive index grating. when a light beam is Incident on such a refractive Index grating, differaction takes place & this produces Either any multiple order differaction or single order diffraction.

↳ The former one is refferred to as Raman-Nath diffraction & is usually observed at low acoustic frequency.

↳ The latter one is analogous to Bragg diffraction of X-Rays in crystal & is refferred to here also as Bragg diffraction; this is usually observed at high acoustic frequency.

The Interaction between acoustic waves and light waves is used in a no. of applications such as an acoustooptic modulators, deflectors, frequency shifters for hetrodyning, spectrum analysers, Q-switching & mode locking in lasers.



Raman- Nath and Bragg regine of Acoustic Effects :

As discussed, when an acoustic wave propagate in a medium, the periodic strain associated with the acoustic wave generates a periodic refractive index variation in the medium. This periodic refractive index grating has the same period as the acoustic wave & is also propagates at the same velocity as the acoustic wave. Typically the refractive index variation are about 10^{-4} around the mean refractive index value.

Even though this is very small change, that of the acoustoptic interaction which can be quite larger due to the interaction length between the optical & acoustic wave being very large compared to the wavelength of the light wave.

when a light wave is allowed to fall on such a refractive index grating, it undergoes diffraction & depending on the wavelength of the optical & acoustic waves & the length of interaction, one may have either multiple order (Raman-Nath) or single order (Bragg) diffraction

↳ If the length of interaction 'L' b/w the optical & acoustic wave satisfies:

$L << k/K^2 = \Lambda^2 n_0 / 2\pi\lambda_0$

$K = 2\pi/\Lambda$, $k = 2\pi n_0/\lambda_0$

Λ = acoustic wave length
n_0 = Refractive index of medium
λ_0 = free space optical wavelength

↳ Then the incident light wave diffracts into multiple orders. This is referred to as Raman-Nath diffraction

On the other hand, if $L >> k/K^2$ then, only one diffraction order is produced & that too only when the so-called Bragg condition is satisfied:

The corresponding angle of incidence 'θ' is close to

$$\theta_B = \sin^{-1}(\lambda_0/2n_0\Lambda)$$

This is referred to Bragg diffraction.

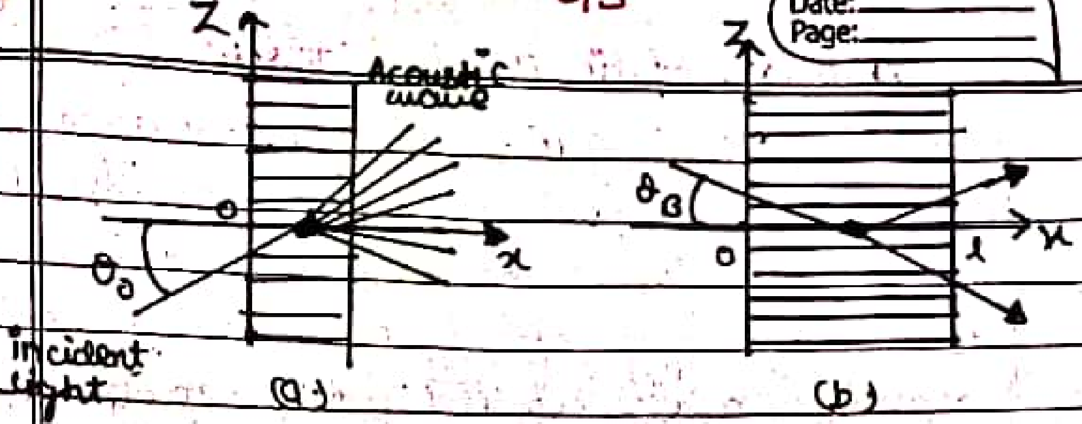


Fig: Differaction of Ramman-Nath (a). and Bragg (b).

Acousto optic modulators:

An acousto-optic modulator (AOM) is also called a Bragg cell, uses the acoustooptic effect to diffract ~~the~~ & shift the frequency of light wave using sound wave (usually at radio freq.)

They are used in lasers for Q-switching, telecommunications for single modulation and in spectroscopy for frequency control. A piezo-electric transducer is attached to a material such as glass. An oscillating electric signal drives the transducer to vibrate, which creates sound waves in the material. These can be thought of as expension & compression of planes, that changes the index of refraction.

The two main modulators used are:

↳ Rammon-Nath acoustopptic modulator.

↳ Bragg modulator.

Rammon-Nath :- The signal carrying the information modulates the amplitude. The amplitude of the acoustic wave propagating through the medium. The light beam incident on the cell is diffracted & at the output, the zero order beam is blocked using a stop. Fig. shows that the diffraction efficiency in the first order is given by;

$$\eta = J_1^2 (k_0 \Delta n L) \approx \pi^2 (\Delta n)^2 L^2 / \lambda_0^2$$

where; Δn = peak change in refractive index (causes by a propagating acoustic wave)

L = length of interaction

& we have assumed $k_0 \Delta n L << 1$. Thus,

$$\because 2n\Delta n = \Delta\epsilon / \epsilon_0 = n^4 \bar{p} \bar{S}$$

$$\therefore \eta = \pi^2 \left(\frac{n^4 \bar{p} \bar{S}}{2n} \right)^2 L^2 / \lambda_0^2$$

$$= \frac{\pi^2}{L^2 \lambda_0^2} \frac{n^6 \bar{p}^2 \bar{S}^2}{4}$$

If we now use $P_a = I_a L H$

$$= \frac{1}{2} \rho V_0^3 \bar{S}^2 L H$$

we will obtain;

$$\eta = \frac{\pi^2 M_2}{2 \lambda_0^2} \left(\frac{L}{H} \right) P_a$$

$\eta \propto \frac{1}{P}$

where M_2 is figure of merit.
From last eq we see that for small acoustic power, 'η' is proportional to P_a & hence as the acoustic beam is modulated, the diffracted power will also be correspondingly modulated. To obtain low acoustic powers M_2 should be large & aspect ratio L/H should also be large.

One of the main drawback of Raman-Nath interaction is the restriction on the length of interaction. we find here

wavelength

$$L << n\Lambda^2 / 2\pi\lambda_0 = n v_s^2 / 2\pi\lambda_0 f^2$$

$\Lambda = \frac{v_s}{f}$ → velocity

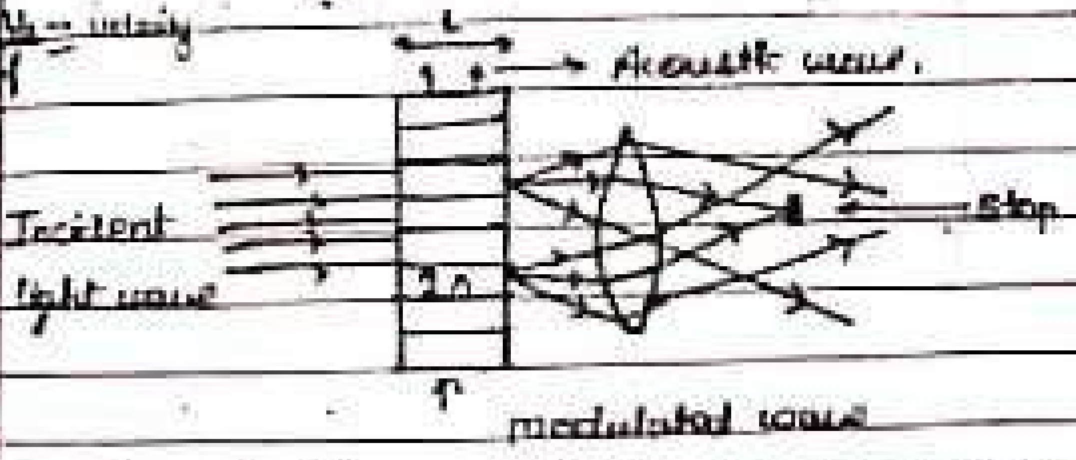


fig: An Acoustooptic modulator based on Raman-Nath diffraction.

Thus RNM can be used at relatively low acoustic frequency & hence with limited modulation bandwidth.

Bragg Modulator:

For higher carrier frequency & higher bandwidths, Bragg diffraction modulators are preferred. ~~These will~~

When the interaction length satisfies the condition ;

$$L >> n V_a^2 / 2\pi \lambda_0 f^2$$

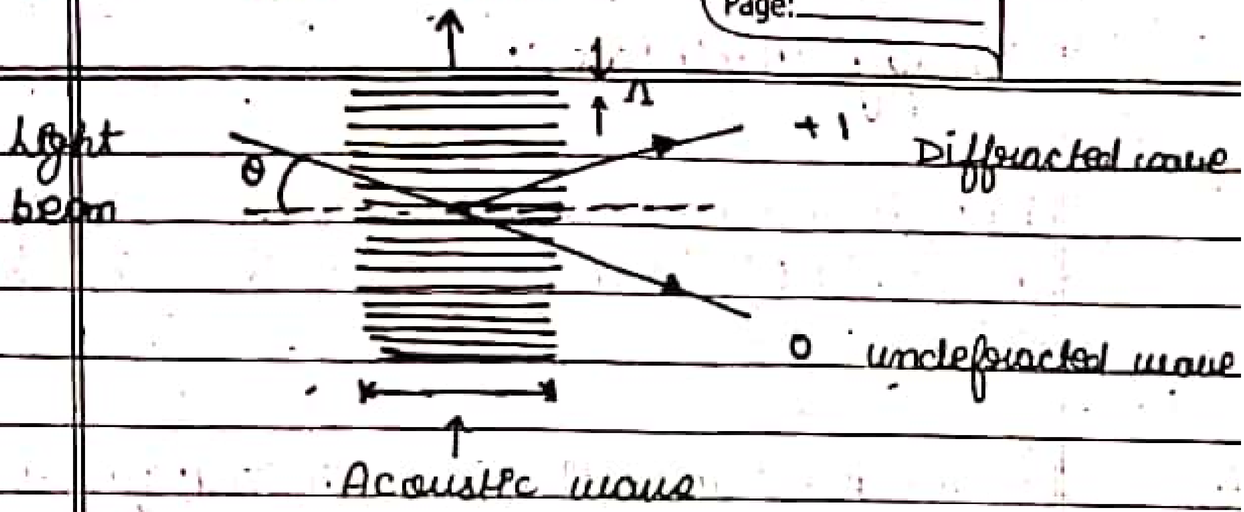
The acoustoppic interaction is in the Bragg regime. In this regime the light wave incident (must be) at the Bragg angle θ_B, In order to coupled to the differacted wave.
The diffraction efficiency for incidente at the Bragg angle is given by -

$$\eta = \sin^2 \left[\frac{\pi}{\lambda_0 \cos\theta_B} \left(\frac{M_2}{2} \frac{L}{H} P_a \right)^{1/2} \right]$$

For small acoustic power, this eqn becomes -

$$\eta \simeq \frac{\pi^2 M_2}{2\lambda_0^2 \cos^2\theta_B} \left(\frac{L}{H} \right) P_a$$

Which is almost the same as in Ramman Nath modulator efficiency.



The intensity of the diffracted ~~p~~ light is perportional to the acoustic power & hence variation in acoustic power will leads to the corresponding variation in the diffracted beam intensity. Fig. shows the typical configuration of a Bragg diffraction ~~grating~~ modulator.

A before for a low acoustic power requirement the material must have the high figure of merit & the aspect ratio (L/H) should be large.

Frome ~~last~~ second last eq^n one can calculate the acoustic power required for complete coupling from the incident to the diffracted wave.