Lecture: 28

Integrated Optics
In this discussion, we shall study, the second major class of components of Wavelength Division Multiplexed (WDM) systems- integrated optical devices. As the name suggests, these devices are fabricated on a wafer. In other words, optical wave-guiding structures are created on a substrate and the resulting structure looks like an integrated circuit thereby called as integrated optical devices. The light from an optical fiber is coupled into the integrated optical device; after some modification of the properties of the input light by this device, the output light is re-launched into an optical fiber for further propagation. This, however, is a very crude idea about the functioning of integrated optical devices and we shall discuss these devices in little more detail in the subsequent sections.

At the heart of any integrated optical device, there is a phenomenon known as the electro-optic effect. There are certain materials, whose dielectric constant (refractive index) can be changed by application of proper electric or magnetic fields. Materials whose dielectric constants get altered due to application of electric field are called as electro-optic materials; materials whose dielectric constants change on application of magnetic field are called magneto-optic materials. In our discussion, we shall deal with electro-optic materials only. This effect of change of the dielectric constant (refractive index) of a material by the application an electric field is known as the electro-optic effect. Two of such materials which have undergone detailed research are- Lithium Niobate (LiNbO$_3$) and Gallium Arsenide (GaAs). Lithium Niobate is a rather lossy medium, but has a high electro-optic coefficient whereas, Gallium Arsenide has low electro-optic coefficient. The electro-optic coefficient of a material is an indicator of the responsivity (amount of change in refractive index) of the material to the application of electric field. Due to the high electro-optic coefficient, Lithium Niobate is often used as material for fabrication of integrated optical devices.

Lithium Niobate is an anisotropic material (refractive index of the material is different in different directions) wherein, the change of the refractive index depends upon the relative directions of the applied electric field and the axis of the crystal. Without delving into the vector details of such changes, the change in the refractive index \( n \) of Lithium Niobate on the application of an appropriate electric field \( E \) is given by:

\[
\Delta n = \left( \frac{n^3}{2} \right) rE
\]  

(28.1)

Where \( r \) is the electro-optic coefficient of Lithium Niobate and is dependent on material properties. Using this notion, the characteristics of light can be altered, when light propagates through Lithium Niobate.

The very basic device which uses a substrate of Lithium Niobate is the Optical Phase Modulator. The structural detail of an optical phase modulator fabricated on a Lithium Niobate substrate is depicted in figure 28.1 below. As shown in the figure, a semi-circular optical wave-guiding structure known as the channel wave-guide is fabricated on a substrate of Lithium Niobate. There are various ways of fabrication of channel wave-guide such as ion-implantation, etc. The channel wave-guide is surrounded by Lithium Niobate on one side and by air on the top. The refractive index of the channel wave-guide region is
higher than its surrounding media (air and Lithium Niobate). Thus, the channel waveguide, along with the surrounding air and substrate material form a composite structure analogous to the core and cladding of an optical fiber. The light propagates through the channel waveguide in much the same way as in case of an optical fiber.

Continuous wave (CW) light enters from one side of the modulator and after traveling through the channel waveguide comes out at the other end of the device. However, there is a phase change between the input and the output signals as the light travels inside the channel waveguide. This phase change depends on the length L and the phase constant ‘β’ of the channel waveguide. Two metallic strips known as electrodes are deposited on same substrate parallel to the channel waveguide as shown in the above figure. These metallic regions act as electrodes, to which appropriate voltage is applied.
On application of voltage to these electrodes, electric field is generated. This electric field changes the dielectric constant of the channel waveguide (due to electro-optic effect) and as a result the phase constant of the channel waveguide region changes. Due to this change in ‘β’ the phase difference between the input and the output optical signal changes and thus the phase of an input optical signal can be modulated in accordance to the applied voltage to the electrodes. The output optical signal from the optical phase modulator is called as phase shift keyed (PSK) light. This, in principle, is the working of an optical phase modulator. Depending on the nature and distribution of applied voltage V, there can be various nature and amounts of phase changes that can be brought in the signal. In the figure above, we have shown a rectangular voltage waveform applied to the electrodes and consequently there would be two different amounts of phase changes corresponding to the two amplitude levels in the applied voltage.

In general, the amount of phase change, $\Delta \phi$ undergone by the input optical signal of wavelength ‘λ’ can be expressed as:

$$\Delta \phi = \frac{2\pi}{\lambda} \Delta n L$$

(28.2)

Substituting the value of the change in refractive index $\Delta n$ from equation 28.1 in the equation 28.2 we obtain:

$$\Delta \phi = \frac{2\pi}{\lambda} \left(\frac{n^3}{2}\right) r EL$$

(28.3)

For a given optical signal and phase modulator material, the quantities λ, ‘n’ and ‘r’ are constant. So, the only degree of freedom available to us is the product EL, which we can vary to obtain different phase changes. In practice, we obtain a significant phase change only when both E and L have high values. For obtaining high electric fields, the separations ‘d’ between the two electrodes have to be decreased. Decreasing the value of ‘d’ also reduces the size of the device. However, the size of the device cannot be miniaturized to a great extent and so the length of the device has to be kept sufficiently long so that the product EL has a large value for a significant phase change of the input signal.

For a two amplitude level voltage signal, V as the one shown in the figure 28.1(b) if the lower amplitude level is zero, then the phase change corresponding to the high level of the voltage is given as:

$$\Delta \phi = \frac{2\pi}{\lambda} \left(\frac{n^3}{2}\right) r \left(\frac{V}{d}\right) L$$

(28.4)

If $V_\pi$ is the voltage level for a phase change of π in the input signal, then from equation 28.4:

$$V_\pi = \frac{\lambda}{rn^3} \frac{d}{L}$$

(28.5)

For a lower value of voltage $V_\pi$, the length of the device has to be large because the value of ‘d’ cannot be arbitrarily minimized.
The finite separation between the two electrodes of the phase modulator constitutes a finite capacitance which, together with the internal and external resistances of the source circuitry, builds up a finite RC time constant for the source circuitry which prevents it from being used at higher frequencies. As a remedy to this observation, the metallic electrodes can be considered as transmission lines and can be fed electromagnetically by a high frequency source. However, due to the difference in the frequencies of operation of the source and light propagating through the channel waveguide, the refractive index seen by both the waves are different and as a result, their phase velocities differ. This creates some kind of a velocity mismatch in the system and the phase change of the light signal is no longer linear along the length as suggested in equation 28.4. To mitigate this effect appropriate measures have to be taken which manufacturing of an optical phase modulator so that the phase change stays linearly dependent on the length of the device.

The application of electro-optic material to change the phase of an incoming optical signal is essentially the simplest and the most basic version of an integrated optical device. However, this phase modulation of an optical phase modulator can be further used for amplitude (intensity) modulation of light by implementing it in the principle of interference. This idea, in fact, is the basic principle behind the Mach Zehnder Interferometer. Hence, the PSK output signal of the phase modulator can be converted into an amplitude shift keyed (ASK) optical signal using this device. The figure below shows a schematic of the Mach Zehnder Interferometer: (diagram intended only for understanding and so not practical)

![Mach Zehnder Interferometer](image)

As shown in the figure, two equal-length channel waveguides (lines in Red) are implanted onto a substrate of LiNbO$_3$ along different paths and one of these channel waveguides is used for phase modulation using the electro-optic effect. The input optical signal beam is split into two parts at the two-way power divider and these beams travel equal distances through distinct paths until they recombine by interference at the other end in the beam combiner. However, the phase change in the two beams is different as they travel along the channel waveguides. One beam is allowed to travel undisturbed along the reference path and is known as the reference beam. The relative phase of the reference beam is assumed to be 0. The other beam travels through a phase modulator which...
changes the phase of the beam by some pre-determined amount, say $\theta$ and so, the relative phase difference between the two beams when they arrive at the beam combiner is $\theta$. Depending on the value of $\theta$ these beams interfere either constructively or destructively and the output signal is obtained accordingly.

For a value $\theta=\pi$, the two beams interfere destructively and the Mach Zehnder Interferometer acts as an inverter in case of a digital input at the source of the modulator. The input and output waveforms corresponding to this case are shown below:

![Figure 28.3: Output of Mach Zehnder Interferometer to digital input at the source](image)

Thus using appropriate phase modulator, we may obtain light which is amplitude (intensity) modulated. This kind of amplitude modulated light is known as Amplitude Shift Keyed (ASK) Light.

In practice, at high data rates the optical source is not modulated directly by the modulated signal because it may produce undesirable frequency deviations. Instead, the optical source emits a continuous optical carrier wavelength and this light is fed to a separate modulator (like the Mach Zehnder Interferometer) where it gets modulated by an appropriate modulating signal to get the desired modulated signal as an output.

Another important integrated optical component that is used in a WDM system is an optical coupler which is used couple light traveling along one path (waveguide) to one or more different path(s) (waveguide(s)). Also, light coming from multiple paths may be distributed again to single/multiple path(s) using an optical coupler. There are two main types of optical couplers. The first one is Fused Fiber Star Coupler which is shown below:

![Figure 28.4: Fused Fiber Star Coupler.](image)
As seen from the figure, multiple optical fibers are twisted together and then heated over a flame at the twisted region until their cores fuse into one-another. The twisted region then becomes one single region through which light from all the input optical fibers travel simultaneously. At the output, each output optical fiber receives all the input wavelengths that travel through the fused region as shown in the above figure. This device is a very crude device and is not wavelength selective. The light from different sources gets combined and on the output side each detector receives all the wavelengths. The basic block diagram of a fused star coupler, thus, looks like:

![Figure 28.5: Block diagram of Fused Star Coupler](image)

As the figure shows, the input powers $P_1, P_2, ..., P_N$ on the input get combined and on the output side each output channel gets an amount of power given by $(P_1 + P_2 + ... + P_N)/N$ which is $1/N^{th}$ of the total input power. For proper detection, this $1/N^{th}$ of total input power has to be greater than the minimum average required power by the detector. This fact suggests that the number of inputs and outputs cannot be arbitrarily increased. In other words, there is a limitation to the increase in the number of input and output channels. But, whatever may be the number of inputs and outputs, the basic operation of the device remains the same. This device finds its ideal application in passive distribution networks of WDM systems.

The second type of optical coupler which is, in fact, more important than a star coupler, is the Directional Coupler. The schematic of this type of coupler is shown below:

![Figure 28.5: Direction Optical Coupler](image)
As shown in the above figure, two cladding-removed optical fiber cores, if brought very close to each other, start interacting with one another through their evanescent fields and such interactions result in coupling of energy from one optical fiber core to the other. This is the basic principle behind the construction and working of a directional coupler. The integrated form of a directional coupler consists of two channel waveguides developed close to one another on the same substrate of LiNbO$_3$ as shown in the figure 28.6 below.

![Figure 28.6: Integrated Directional Coupler](image)

Two channel waveguides A and B are fabricated in close proximity to each other on a substrate of LiNbO$_3$ and the channel waveguide A is excited with an optical source and B is not. For convenience of comprehension, let us assume both channels A and B to have exactly identical characteristics. Due to modal propagation of light in the channel waveguide A, evanescent fields will extend into the substrate material. These Evanescent fields, which in principle extend upto infinity, are now intercepted by the second channel waveguide B. This interception results in induction of similar modal distribution of fields in B which propagate along B with the same phase and group velocity as in A. The energy needed for waves to propagate in B is coupled from the energy in A. Thus, we see that if two channel waveguides are brought very close to each other, energy propagating in one gets coupled into the other. This observation seems to be a contradiction to the notion of data security in the optical fibers that we earlier mentioned as an advantage. However, one should note that, power coupling can take place only when two optical fiber cores, without their claddings, are brought close to each other. If the cladding of the optical fiber is intact, there is almost no evanescent field outside the cladding that is available for coupling.

To have qualitative understanding about the phenomenon of power coupling, let us consider the figure 28.7 below. It shows the field distributions in the two channel waveguides A and B as power flows along the positive z direction. At $z=0$, the entire power is confined in the channel A and the modal field distribution of the wave is shown in the figure. This modal field distribution may be assumed to be a superposition of an equivalent even (red) and an odd (blue) field as shown. As the wave starts to propagate along the
channel A, power starts coupling from channel A to channel B as shown by the power flow curve in the figure. Then, at a point $z=Z_1$, it so happens that the relative phase difference between the even and the odd fields becomes $180^\circ$ and at this point the superposition of the fields causes the entire power of the channel A to exist in channel B. As the wave further moves power re-couples with channel A and this cycle of power coupling from one channel to the other goes on until the wave reaches the output of the channel. If we locate our detector at $z=Z_1$ at the output of channel A, we would find very little power at that point in the channel A as the entire power initially launched into channel A gets coupled to channel B at $z=Z_1$. This, superficially, explains the principle of operation of a directional coupler in a qualitative manner. In the subsequent discussions, we shall have a detailed qualitative analysis of a directional coupler.