

Module 16 : Integrated Optics I

Lecture : Integrated Optics I

Objectives

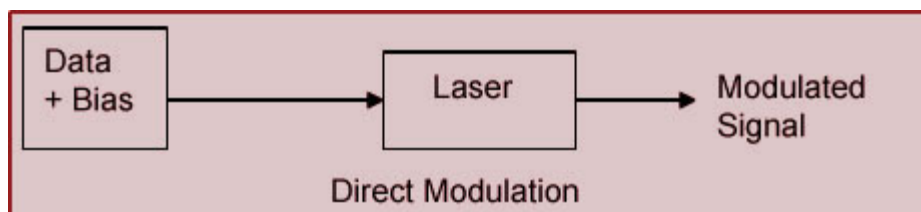
In this lecture you will learn the following

- Introduction
- Electro-Optic Effect
- Optical Phase Modulator
- Optical Amplitude Modulator
- Mach-Zehnder Interferometer
- Extinction Ratio and Chirp in Amplitude Modulator

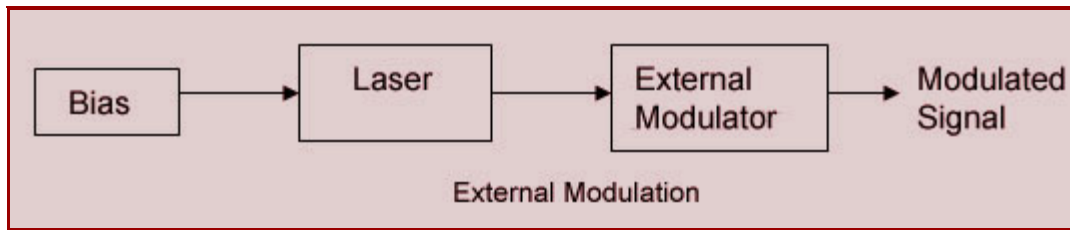
Introduction

- Integrated optical devices or alternatively called the photonic integrated circuits, are the important dives in high speed coherent optical communication. They can various functions like, phase, amplitude, and polarization modulation, and also wavelength filters.
- The main material which made these devices possible is Lithium Niobate (LiNbO_3).

- In the early optical systems where the data rate was low, the lasers were modulated
- directly by combining the data signal with the bias of the laser diode. The advantage of the direct modulation system was is simplicity.



- Beyond the data rates of 1-2 GHz, the complex dynamics of the coupling of electrons and photons within the laser cavity cause undesirable frequency variations, known as chirps. In presence of chirp, the signal gets distorted as propagates on the optical fiber.
- For high data rates a better option would be the external modulation. In this scheme, the laser operates on a constant bias producing a narrow line width continuous optical carrier. The data is imposed on the optical carrier by the modulator, external to the laser cavity.



- By decoupling the process of light generation and modulation the performance of the transmitter may be improved.
- The external modulation has following attractive features.
 - (1) Broad modulation bandwidth
 - (2) Large extinction ratio
 - (3) Excellent spectral purity
 - (4) High optical power handling capability
 - (5) Low modulation distortion
 - (6) Fabrication yield and reproducibility.

Electro-Optic Effect

- There are certain materials, called the electro-optic material whose dielectric constant changes when they are subjected to an electric field. Change in dielectric constant due to electric field is called the electro-optic effect or the Pockel effect.

- The parameter which characterizes the electro-optic material is called the electro-optic coefficient.
- The most widely used electro-optic material is the Lithium Niobate since it has a large electro-optic coefficient. Lithium Niobate is a uni-axial crystalline material. The change in the dielectric constant therefore depends upon the magnitude of the electric field, and orientation of the electric field with respect to the crystal axis. In fact the electro-optic material is an anisotropic material and hence its dielectric constant is a tensor.
- The electro-optically induced change in the dielectric tensor can be written as

$$\Delta \epsilon = \begin{pmatrix} -r_{22}E_y + r_{13}E_z & -r_{22}E_x & r_{51}E_x \\ -r_{22}E_x & r_{22}E_y + r_{13}E_z & r_{51}E_y \\ r_{51}E_x & r_{51}E_y & r_{33}E_z \end{pmatrix}$$

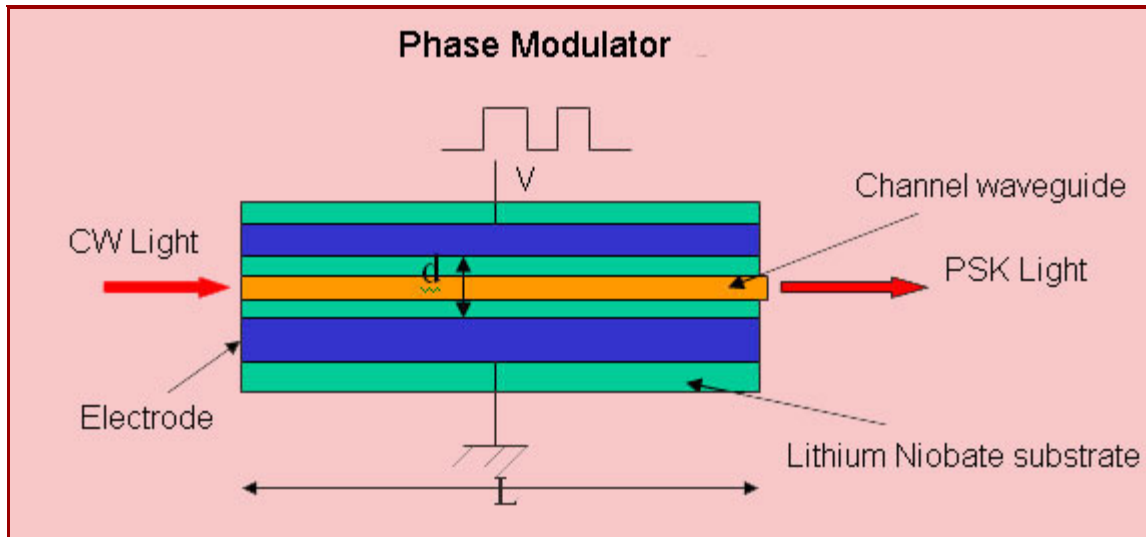
- Where r_{ij} are the electro-optic coefficients. The diagonal terms of the matrix represent electro-optically induced phase change of the propagating signal, and the off-diagonal terms represent the polarization conversion.
- For Lithium Niobate, the highest electro-optic coefficient is r_{33} with a value $31 \times 10^{-12} \text{ m/V}$.
- Since the refractive index of the material is equal to the $\sqrt{\epsilon}$, we can write the change in the refractive index of Lithium niobate as

$$\text{Change in refractive index } \Delta n = \left(\frac{n^3}{2} \right) r E$$

r = Electro Optic coefficient
 E = Electric field

Optical Phase Modulator

- The optical phase modulator is one of the simplest devices which can be made from an electro-optic material.



- The Fig shows a channel waveguide made on a Lithium Niobate substrate. Parallel to the waveguide, the electrodes are laid to apply electric field across the waveguide. The CW light is fed to the channel waveguide at one end and the phase shifted light is taken out from the other end.
- A binary data voltage is applied to the electrodes. The data voltage changes the electric field between the electrodes changing the refractive index of the waveguide. The change in refractive index changes the phase of the light.
- For a binary data, the voltage changes between two levels making the output phase change between two levels.

The phase change is given as

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

- Where, λ is the free-space wavelength of the light, L is the length of the modulator, n is the refractive index of the waveguide material, V is the applied voltage between the electrodes, d is the separation between the electrodes, and r is the electro-optic coefficient, Γ represents the spatial overlap between optical intensity profile and the applied electric field.
- For a binary data the phase change between the two states is π .

Voltage required to get phase change of π rad,
$$V_{\pi} = \frac{\lambda}{n^3 r} \frac{d}{L \Gamma}$$

- For a typical modulator,

$$n = 2.2$$

$$d = 15 \mu\text{m}$$

$$\Gamma = 0.5$$

$$r = 30 \times 10^{-12} \text{ m/V}$$

$$\lambda = 1550 \mu\text{m}$$

We get the **Figure of Merit**

$$V_{\pi} \times L = \frac{\lambda}{n^3 r} \frac{d}{\Gamma} = 14 \text{ V} \cdot \text{cm}$$

Since the data voltages are typically few volts, the length of the modulator has to be few cm. There is no miniaturization possible in realizing integrated optical devices.

Issues in implementation of the Phase shifter:

- (1) As the data frequency increases, the electrode capacitive reactance becomes excessive and the modulation index of the output signal reduces. Therefore as the frequency increases, the electrodes have to be realized in the form a coplanar waveguide.
 - (2) Since the electrode spacing is very small, the electric field between the electrodes is very high and at times could be higher than the break-down field of the medium.
 - (3) The modulating signal and the optical wave travel along the waveguide. However, the optical energy is mostly confined to the dielectric waveguide which has refractive index of about 2.2. The modulating signal fields are not well confined to the substrate. There is substantial field above the substrate. Consequently, the refractive index which the modulating signal electric field sees is different than 2.2. The optical fields and the electric fields hence have different phase velocities. Then we say that there is phase miss-match between the optical and the electric field. With phase miss-match the interaction between the two fields decreases and consequently the modulation efficiency decreases.
- Designing proper waveguides and the electrode structure for achieving good phase matching is fairly involved task.

Optical Amplitude Modulator

Once the basic phase modulator is realized, the amplitude modulator can be made using

the interferometer principles.

- An optical amplitude modulator should be characterized for following parameters:

Switchoff voltage-current

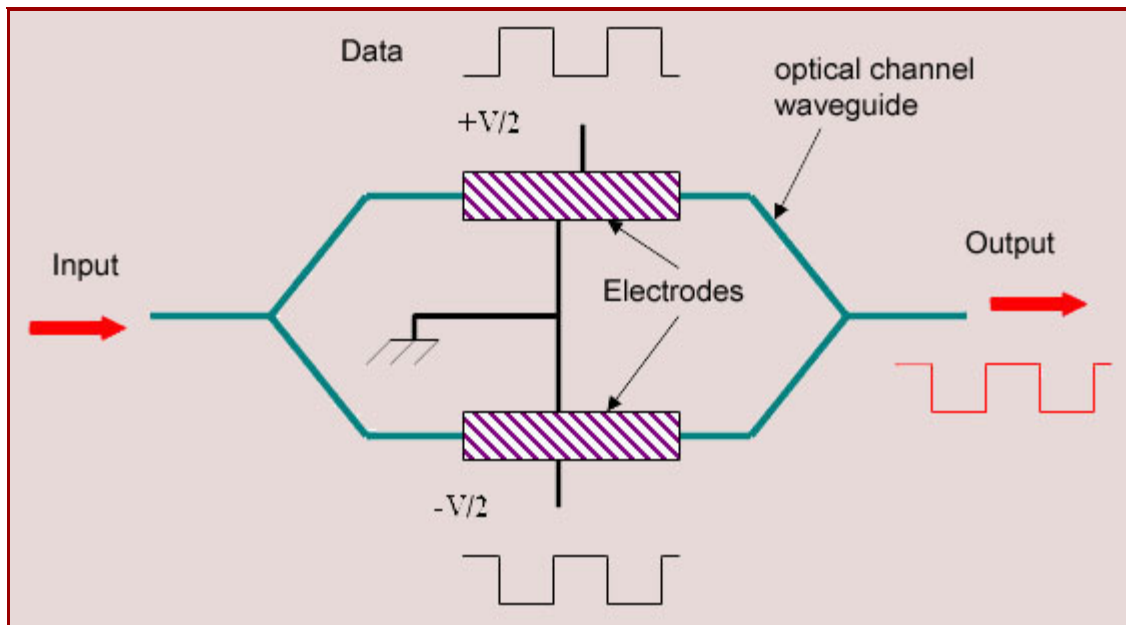
- (a) Switchoff voltage-current
- (b) Extinction ratio
- (c) Frequency response (bandwidth)
- (d) Optical frequency chirp
- (e) Distortion
- (f) Bias voltage stability
- (g) Operating wavelength range
- (h) Polarization dependence
- (i) Input/output fiber connectors
- (j) Insertion loss
- (k) Return loss
- (l) Temperature sensitivity
- (m) Size

- There are two commonly used configurations for the amplitude modulator.

- (1) Mach-Zehnder Interferometer
- (2) Directional coupler

Mach-Zehnder Interferometer

- The Mach-Zehnder interferometer is shown in Fig. It consists of two integrated optical phase modulators (or one phase modulator and one ordinary channel waveguide), and two Y branch couples, one at the input for splitting the signals and other at the output for combining the optical signals.



- The operation of the Mach-Zehnder interferometer can be explained as follows.
- Let the Y junction be a balanced junction meaning it can combine or split power equally. The input Y-junction splits the power equally into two branches to give fields E_1 and E_2 in the two arms of the interferometer (for balanced Y-junction the two fields are equal say E_0).
- Let the data voltage is such that the electrodes introduce a phase shift of $\pm \Delta\phi/2$ in the optical signals in the two branches. We then have

$$E_1 = E_0 e^{+j\Delta\phi/2}$$

$$E_2 = E_0 e^{-j\Delta\phi/2}$$

- The two fields are combined in the output Y-junction to give, out put field

$$E = E_1 + E_2 = E_1 = E_0 e^{+j\Delta\phi/2} + E_0 e^{-j\Delta\phi/2} = 2E_0 \cos(\Delta\phi/2)$$

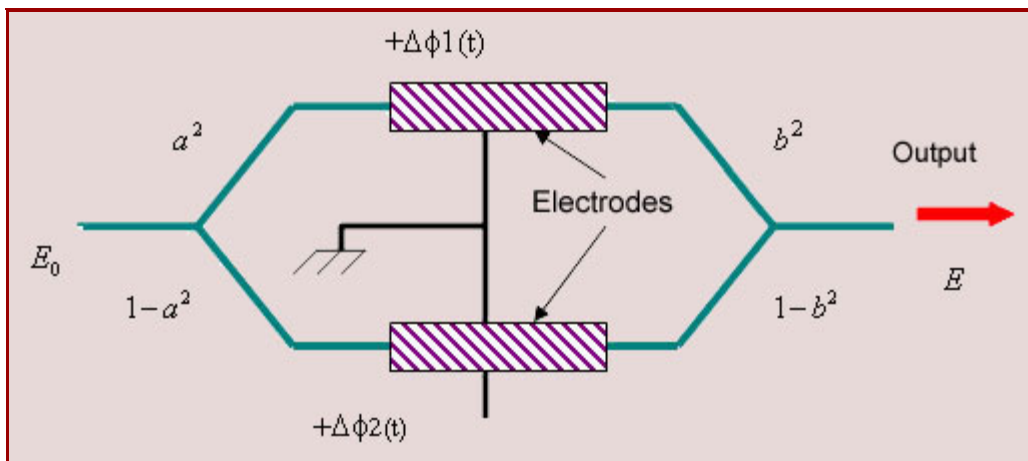
- Intensity of the light $I \propto |E|^2$. The output light intensity therefore is

$$I \propto |E|^2 \propto \cos^2(\Delta\phi/2)$$

- For binary data, the phase changes between 0 and π , and the output intensity changes from $2E_0$ to 0.
- Note:** The optical amplitude modulated signal is inverted with respect to the data.

Extinction Ratio and Chirp in Amplitude Modulator

- For an ideal Mach Zehnder interferometer the basic components, the Y-junctions and the phase shifters are perfect and there is no problem of extinction ratio and chirp. However, in practice, the Y-junctions do not have equal power division and the phase shifts are not conjugates of each other. In the following we see how the imperfect Y-junction and the phase shifter affects the extinction ratio and chirp.



- Let the input Y-junction divides the power in the ratio $a^2/(1-a^2)$ and the output Y-junction divides the power in ratio $b^2/(1-b^2)$ as shown in Fig. Let us assume that the phase shifters in the two arms produce phase shifts $\Delta\phi_1$ and $\Delta\phi_2$ respectively. If we now assume that the two arms of the interferometer different losses L_1 and L_2 respectively, the output field in general can be obtained as

$$E = E_0 \left\{ abL_1 e^{j\Delta\phi_1(t)} + \sqrt{(1-a^2)} \sqrt{(1-b^2)} L_2 e^{j\Delta\phi_2(t)} \right\}$$

- It is difficult to see from this expression what is the effect of the parameters on the extinction ratio and chirp. Let us therefore make it simple to assume that only input Y-junction is not perfect, every other things are ideal. That is, $b^2 = 1/2$, $L_1 = L_2$, $\Delta\phi_1 = \Delta\phi_2$.

We then get

$$E = \frac{E_0 b L_1 e^{j\Delta\phi(t)}}{\sqrt{2}} \left\{ a + \sqrt{1-a^2} e^{-j2\Delta\phi(t)} \right\}$$

- Now for the binary data $\Delta\phi_1 = \pm\pi/2$, and therefore the output extinction ratio is

$$ER = \frac{a + \sqrt{1-a^2}}{a - \sqrt{1-a^2}}$$

We can note that when $a = 1/2$, the extinction ratio is ∞ .

- In practice extinction ratio of 30 dB are achievable which indicates that power splitting ratio of the Y-junctions is better than 46/54.
- For investigating chirp in the output, let the Y-junctions be ideal, i.e. $a^2 = b^2 = 1/2$. Also the losses in the two arms are equal. The output then is

$$E = \frac{E_0 L_1}{2} \left\{ e^{j\Delta\phi_1(t)} + e^{j\Delta\phi_2(t)} \right\} = \frac{E_0 L_1}{2} \left\{ e^{j[\Delta\phi_1(t) + \Delta\phi_2(t)]/2} \right\} \cos \left[(\Delta\phi_1 - \Delta\phi_2)/2 \right]$$

- The output is amplitude as well as phase modulated. However if the two arms are driven with complementary waveforms, i.e. $\Delta\phi_1 = -\Delta\phi_2$, the phase modulation term is identically zero.

Recap

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Congratulations, you have finished Module 16. To view the next lecture select it from the left hand side menu of the page