Module 17 : Integrated Optics II

Lecture : Integrated Optics II

Objectives

In this lecture you will learn the following

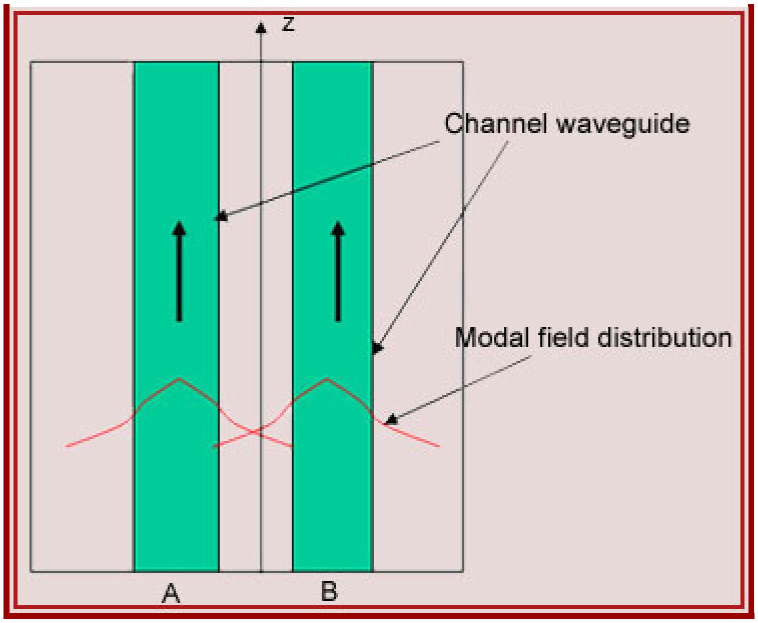
- Directional Coupler
- Passive Devices
- Equal Power Divider
- Active Devices
- Optical Cross-Connect
- Wavelength Filter or Wavelength Router

Directional Coupler

- Directional coupler is one of the very important devices which can be used for various applications like, optical amplitude modulator, power tapping, power divider, wavelength filter, optical switch, optical multiplexer, optical cross-connect and so on.

- Here we first develop the basic understanding of the directional coupler and then we will study its implementation in an integrated form.

- The directional coupler consists of two channel optical waveguides placed close to each other so that their fields can interact with each other as shown in Fig.



- Let us say we excite only on of the waveguides (say A). The modal field of the waveguide A will be intercepted by waveguide B. Since there has to be continuity of the fields at the boundary of the waveguide B, some fields will get induced inside waveguide. However, being a bound structure, any arbitrary field can not get induced inside waveguide B, it has to be modal field. The modal field will have distribution similar to that of the modal field of waveguide A. The induced filed of waveguide will interact back with waveguide A.

- So on the whole the fields of the two waveguides will start interacting. Moreover, the modal field of the waveguide will be propagating and therefore would need power. But the power has been supplied to waveguide A only, since we excited only waveguide A. In other words, waveguide B will tap power from waveguide A.

- The important thing to note is there is exchange of power between two waveguides due to overlapping of the field outside the waveguide. This is called evanescent mode coupling.

- With this qualitative understanding now we can analytically investigate the power exchange between two channel waveguides.

- Let us say that the modal propagation constants for the two waveguide are β_1 and β_2 respectively. Then in absence of mutual interaction the complex fields on the waveguide will be given as

$$a = a_0 \; e^{-j\beta_1 z}$$

and

$$b = b_0 \; e^{-j\beta_2 z}$$

Where, a_0, b_0 are amplitudes of the modal fields on the two wave guides. The two fileds satisfy the differential equations,

$$\frac{da}{dz} = -j\beta_1 a$$

And

$$\frac{db}{dz} = -j\beta_2 b$$

- Now in the presence of the other waveguide the fields are coupled. The governing equations therefore become

$$\frac{da}{dz} = -j\beta_1 a - j\kappa b$$

And

$$\frac{db}{dz} = -j\beta_2 b - j\kappa a$$

Where, κ is **the coupling coefficient** between the two waveguides.

Directional Coupler (contd)

- The coupling coefficient is a complicated function of many parameters like, the width of the waveguide, refractive index of the waveguide, separation between the waveguide, the mode, and wavelength of operation.

- The two coupled equations can be solved by differentiating one equation with respect z and substituting from the other. We therefore get differential equation for the fields on the two waveguides as

$$\frac{d^2 a}{dz^2} + j(\beta_1 + \beta_2)\frac{da}{dz} + (\kappa^2 - \beta_1\beta_2)a = 0$$

And

$$\frac{d^2 b}{dz^2} + j(\beta_1 + \beta_2)\frac{db}{dz} + (\kappa^2 - \beta_1\beta_2)b = 0$$

- General solutions of these equations can be written as

$$a(z) = \left\{ A_1 \cos(\alpha z) + A_2 \sin(\alpha z) \right\} e^{-j\beta z}$$

And

$$b(z) = \left\{ B_1 \cos(\alpha z) + B_2 \sin(\alpha z) \right\} e^{-j\beta z}$$

Where A_1, A_2, B_1, B_2 are the arbitrary constants to be evaluated from the boundary conditions. And we have defined

- Average propagation constant $\beta = (\beta_1 + \beta_2)/2$,

  And

  $$\alpha \equiv \left(\frac{\Delta\beta}{2}\right)^2 + \kappa^2, \qquad \Delta\beta\,\Delta\beta = (\beta_1 - \beta_2).$$

- For obtaining the arbitrary constants we apply the boundary conditions.

- Since we excite waveguide A at say z = 0, and no excitation to waveguide B at z = 0, We have boundary conditions,

  At z = 0, $a(0) = 1, \quad b(0) = 0$ (normalized)

- The fields on two waveguides can the be written as

$$a(z) = \left\{\cos(\alpha z) + j\frac{(\Delta\beta/2)^2}{\alpha}\sin(\alpha z)\right\}e^{-j\beta z}$$

$$b(z) = \left\{-j\frac{\kappa}{\alpha}\sin(\alpha z)\right\}e^{-j\beta z}$$

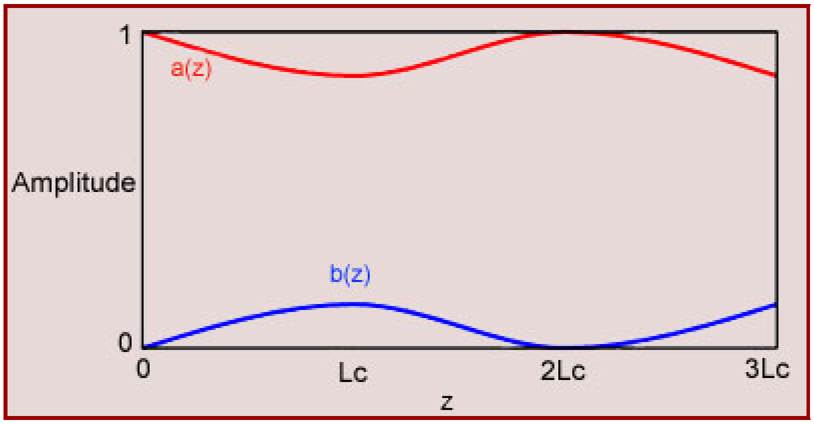
Directional Coupler (contd)

Important Observations

(1)
Both waveguides have traveling waves with average phase constant β.

(2)
The amplitude of both waves vary in amplitude as they travel along the waveguides.

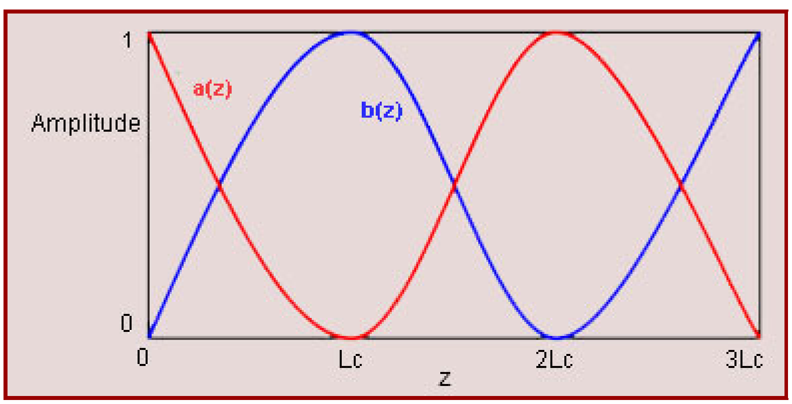
(3)
If the two waveguides are dissimilar i.e. if $\beta_1 \neq \beta_2$, and if $\Delta\beta/2 \gg \kappa$, field amplitude of waveguide A remains almost constant and amplitude of the wave on waveguide B is much less than 1. That is in this situation most of the power remains with waveguide A and a small power is transferred to waveguide B (see Fig).



(4)
If the two waveguides are identical, i.e. if $\beta_1 = \beta_2$, we get $\Delta\beta = 0$, $\alpha = \kappa$ and the fields on the two waveguide become,

$$a(z) = \cos(\kappa z)e^{-j\beta z}$$
$$b(z) = j\sin(\kappa z)e^{-j\beta z}$$

- In this case when $\kappa z = \pi/2$, i.e. when $z = \dfrac{\pi}{2\kappa}$, $a(z) = 0$ and $b(z) = 1$. That means the entire power gets transferred from waveguide A to waveguide B.
- Beyond this distance the power slowly goes back to waveguide A and when $z = \dfrac{\pi}{\kappa}$, the entire power goes back to waveguide A.
- This process continues indefinitely. The power keeps fluctuating between the two waveguides (see Fig.).



- The distance over which the maximum power is transferred to the other waveguide, is called the **Coupling Length,** L_c. The coupling length is related to the coupling coefficient, κ as

$$L_c = \frac{\pi}{2\kappa}$$

- Using this basic phenomenon of mode coupling a variety of devices can be realized.

Passive Devices

- Here passive device means a device whose characteristics can not be changed after the device is fabricated. The passive devices are given in the following. In all cases L denotes the length of the device.

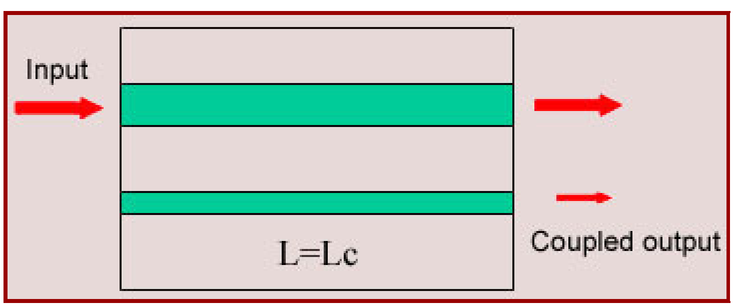
Directional coupler

- The directional couples is a device which couples a small fraction of power from the main waveguide. This device can also be used for tapping of power from the main waveguide.

- The power tapping can be realized in two ways:

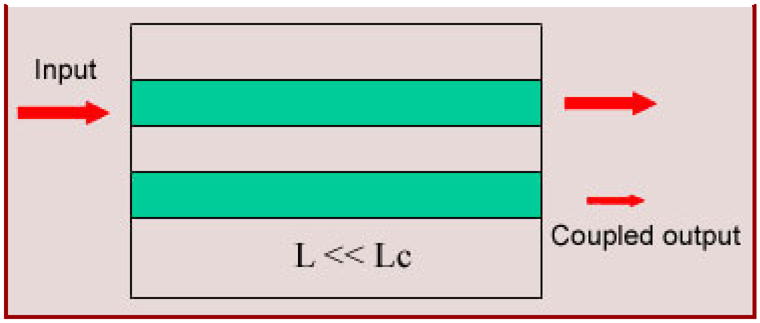
(1)
Making use of dissimilar waveguides . Taking the length $L = L_c$ and $\Delta\beta \gg \kappa$, the coupled field is approximately, $2\kappa / \Delta\beta$. In terms of dB the coupled power is

$$20\log(2\kappa / \Delta\beta)$$



(2)
Identical Waveguides : In this case by changing the length of the device the coupled output can be changed. The coupled power in dB is

$$20\log\left[\sin\left(\frac{\pi L}{2L_c}\right)\right]$$

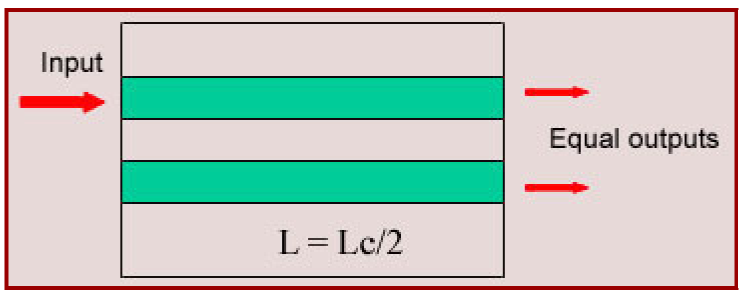


Equal Power Divider

- In this case of course the two waveguides have to be identical. Now taking $L = L_c / 2$, we get

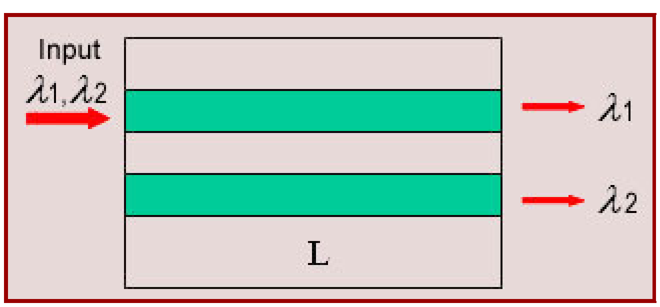
$$a(z) = 1/\sqrt{2}, \quad b(z) = 1/\sqrt{2}$$

The power is therefore equally divided between the two waveguides.



Wavelength Filter

- Since the coupling coefficient and hence the coupling length is a function of wavelength, we can design the coupler is such a way that L/L_{c1} is odd and L/L_{c2} is even, where L_{c1} and L_{c2} are the coupling lengths at the two wavelengths λ_1 and λ_2 respectively.



- Then wavelength λ_1 will appear at the output of waveguide A, and λ_2 will appear at the output of waveguide B. The two wavelengths can therefore be separated by the directional coupler.

Active Devices

- As mentioned above, the coupling coefficient is a function of the refractive index of the channel waveguide as well as the refractive index of the substrate.

- If therefore fabricate a directional coupler on an active substrate like Lithium Niobate, the refractive index of the waveguide and consequently the coupling coefficient of the directional coupler can be changed dynamically by application of the electric field to the waveguide.

- Because of the dynamic control of the coupling coefficient we can develop a variety of new devices as given in the following.

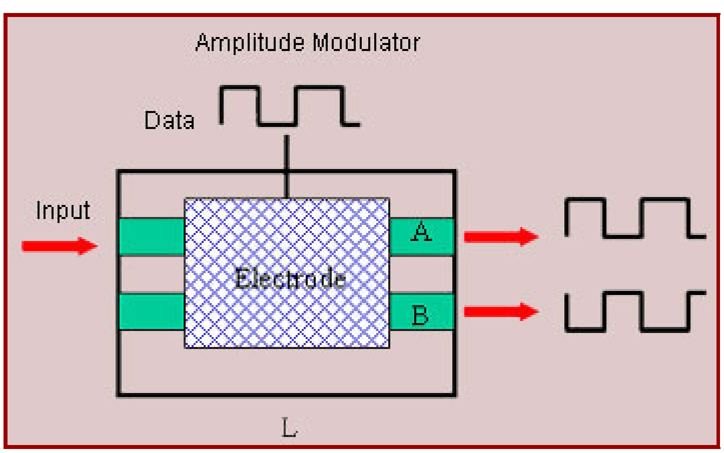
Amplitude Modulator

- For a directional coupler, if the length is equal to the coupling length, the power in completely transferred to waveguide B. And if the length is equal to twice the coupling length, the power returns back to waveguide A.

- So design a directional coupler on an active substrate such that when the electric field is not applied, $L = L_c$, and when the electric field is applied, $L = 2L_c$.

- Take the output only from one of the waveguides. The output will vary in accordance with the applied field and we will get amplitude modulation.

- A schematic of the amplitude modulator is shown in Fig.

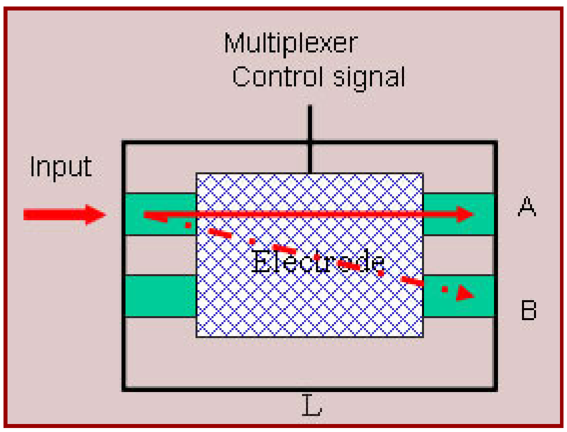


Optical Switch

- By using the same lay out as used for the amplitude modulator, we can realize an optical switch. Instead of data if apply the control voltage to the electrode, the output at any port can be switched ON or OFF. Of course the two outputs are complement of each other, so when one port is OFF the other will be ON and vice versa.

Optical Multiplexer

- The same amplitude modulator structure can be used as an 1:2 multiplexer. By applying the control voltage to the electrode, the input signal can be connected to port A or port B as shown in Fig.



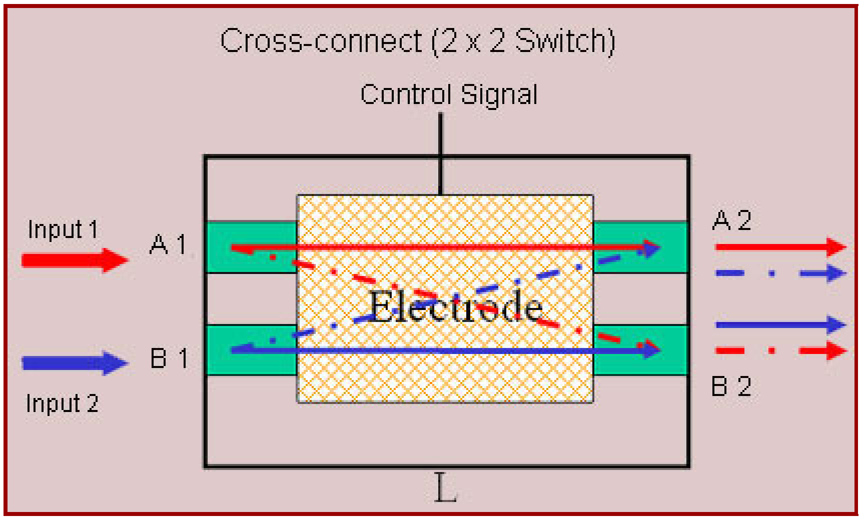
Optical Cross-Connect

- The optical cross-connect is a very important device of a modern optical switching system. A 2x2 optical cross-connect or switch forms the basic module of a switching system.

- Up till now we had only one input. Let now have 2 inputs connected to the two waveguides of the directional coupler. Signal 1 is connected to waveguide A and signal 2 is connected to waveguide B as shown in Fig.

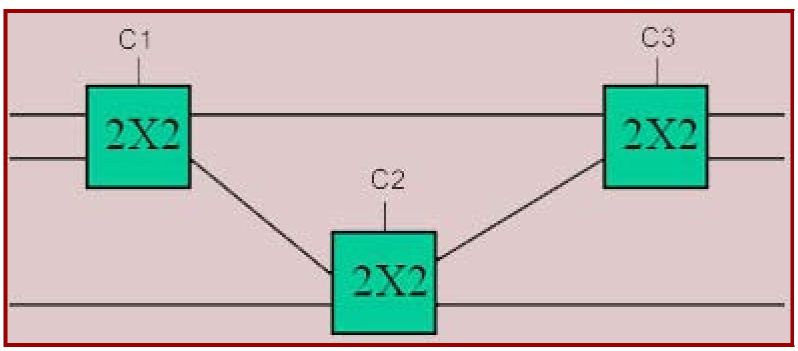
- If signals and 1 and 2 are incoherent, their flow on the directional coupler will not be affected by each other.

- When $L = L_c$ signal 1 is connected B2, but at the same time signal 2 will be connected to A2 as shown by dotted lines and arrows. This state is called the cross-state ($\otimes$ state) of the switch.



- When $L = 2L_c$, signal 1 gets connected to A2 and signal 2 gets connected to B2 as shown by thick lines and arrows. This state is called the bar-state (= state) of the switch.

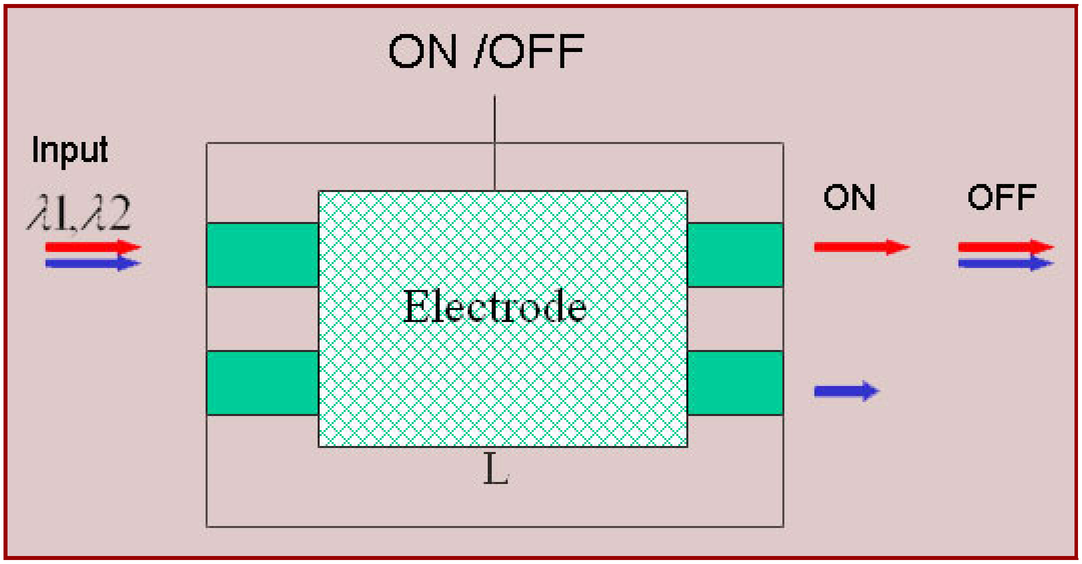
- Using the basic 2X2 switch a complex multiple input multiple output switch architecture can be built. For example a 3X3 non-blocking switch using basic 2X2 modules is shown in Fig. A non-blocking switch is the one where connection between any input-output pair is possible irrespective of the other connections as long as the given input-output pair is free for connection.



Wavelength Filter or Wavelength Router

- Using the same principle as used for passive optical filter, we can make a an active optical filter.

- The principle is similar to that of the optical switch except now the coupling is wavelength dependent. So if we design a coupler such that when no voltage is applied to the device, the coupler length is even multiple of coupling lengths at both wavelengths, whereas when the voltage is applied, the coupler length becomes even multiple of the coupling length of one wavelength but odd multiple of coupling length for the other wavelength. The two wavelengths will then appear at the two ports at the output.



- **OFF** L / L_{c1} and L / L_{c2} are even

  ON L / L_{c1} is even, L / L_{c2} is odd

Recap

In this lecture you have learnt the following

- Directional Coupler
- Passive Devices
- Equal Power Divider
- Active Devices
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- Wavelength Filter or Wavelength Router

Congratulations, you have finished Module 17. To view the next lecture select it from the left hand side menu of the page