Unit-5
Fiber Optical Receiver

- Optical Detectors-PIN diode and APD diodes –Photo detector noise, SNR, –Comparison of Photo detectors – Fundamental Receiver Operation – Design of Analog Systems- Design of Digital Systems.
- **WDM COMPONENTS:** Coupler/Splitter, Isolators and Circulator, Mach Zehnder Interferometer, Fabry Perot Filter and Optical MEMS switches

Optical Receivers

- Optical receivers convert optical signal (light) to electrical signal (current/voltage)
  - Hence referred 'O/E Converter'
- Photodetector is the fundamental element of optical receiver, followed by amplifiers and signal conditioning circuitry
- There are several photodetector types:
  - Photodiodes, Phototransistors, Photon multipliers, Photo-resistors etc.

Photodetector Requirements

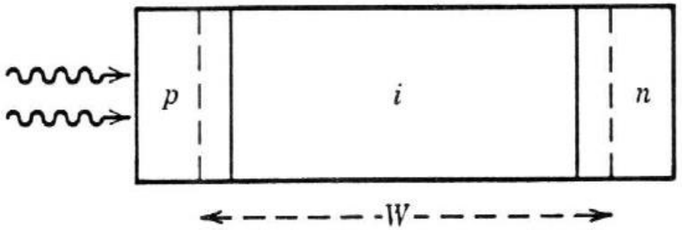
- High sensitivity (responsivity) at the desired wavelength and low responsivity elsewhere → high wavelength selectivity
- Low noise and reasonable cost
- Fast response time → high bandwidth
- Insensitive to temperature variations
- Compatible physical dimensions
- Long operating life

Photodiodes

- Due to above requirements, only *photodiodes* are used as photo detectors in optical communication systems
- Positive-Intrinsic-Negative (*pin*) photodiode
  - No internal gain
- Avalanche Photo Diode (*APD*)
  - An internal gain of *M* due to self multiplication
- Photodiodes are sufficiently *reverse biased* during normal operation → no current flow, the intrinsic region is fully depleted of carriers

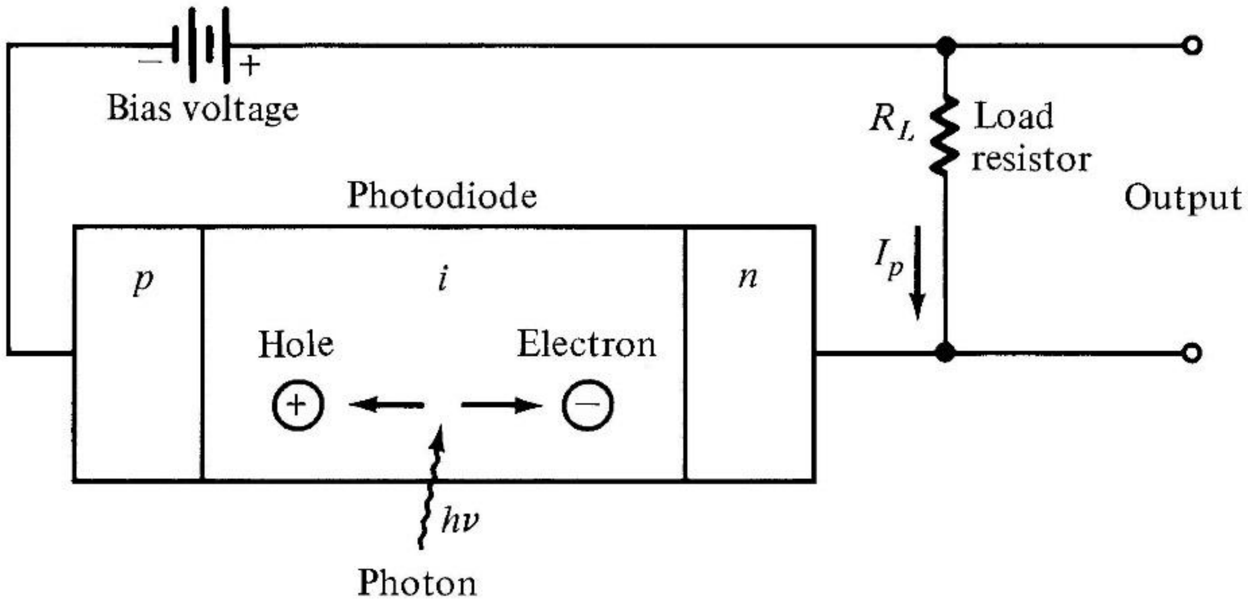
Photodiodes

- Two types of photodiodes commonly used
    - PIN (*p*-type, intrinsic, *n*-type) diodes, and
    - Avalanche photodiodes (APDs)



- PIN Photodiode
    - the thickness of the depletion region is controlled by *i*-layer, not by the reverse voltage
    - most of the incident photons absorbed in the thick *i*-layer - high η
    - large electric field across the *i*-layer - efficient separation of the generated electrons & holes
    - The *p* and *n* layers are extremely thin compare to *i*-layer - diffusion current is very small
    - The increase in the *i*-width reduces the speed of a photodiode
- The speed of response of the photodiode is limited by
    - the time it takes to collect the carriers (drift time)
    - the capacitance of the depletion layer (RC time constant of the detector circuit)

Basic *pin* photodiode circuit



- Incident photons trigger a *photocurrent* I_p in the external circuitry by pumping energy

Photocurrent ∝ Incident Optical Power

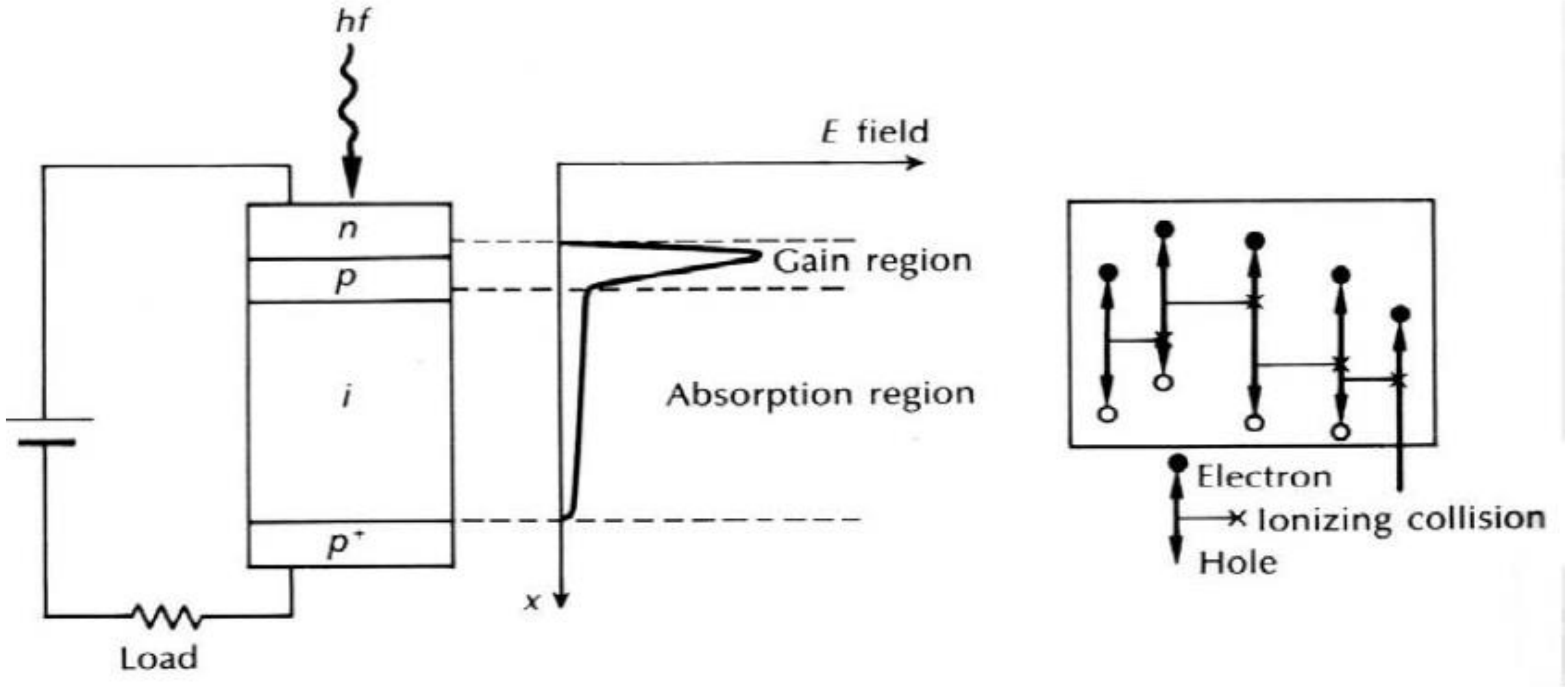
Avalanche photodiodes (APDs)

- It is a photodiodes with internal gain
- An additional layer is added in which secondary electron-hole pairs are generated through impact ionization.
- Internally multiplied the primary photocurrent before it enters the input circuitry of the following amplifier.
- Commonly used structure: Reach-through APD (RAPD)
- The RAPD is composed of a high-resistivity p-type and p+ (heavily doped p-type)

Avalanche Photodiode (APD)

- The internal gain of the APD is obtained by having a high electric field that energizes photo-generated electrons and holes
- These electrons and holes ionize bound electrons in the valence band upon colliding with them
- This mechanism is known as impact ionization
- The newly generated electrons and holes are also accelerated by the high electric field
- They gain enough energy to cause further impact ionization
- This phenomena is the avalanche effect

APD:

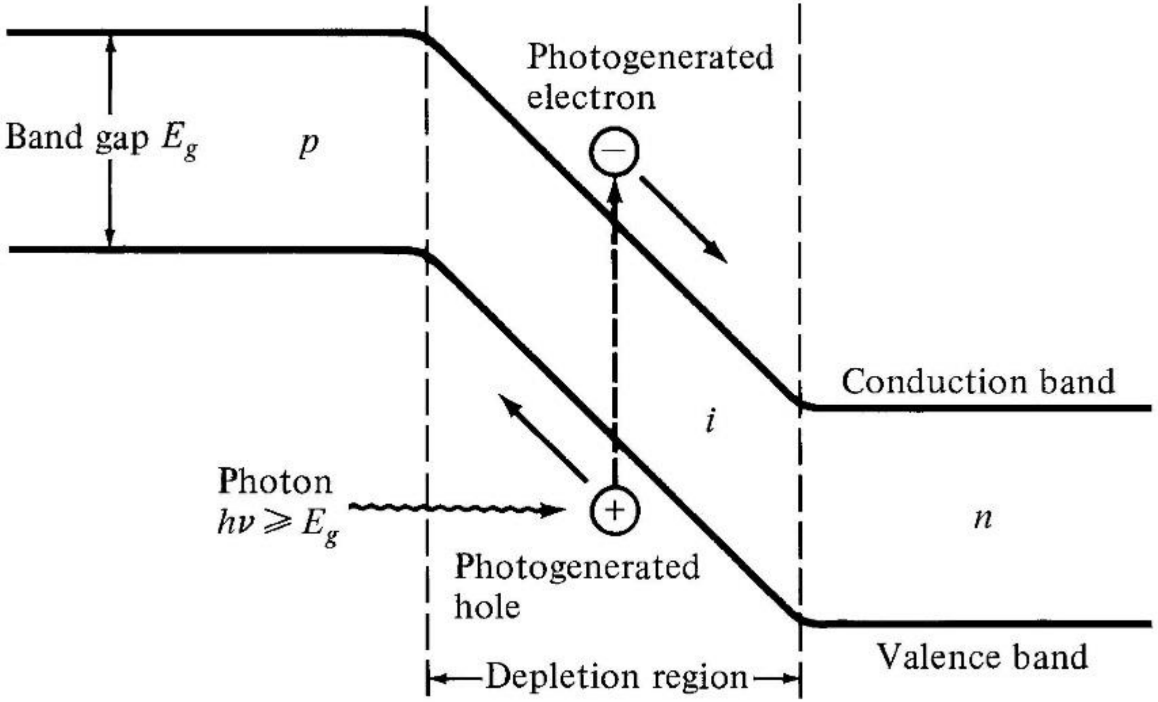


hf
n
p
i
p^+
Load
E field
Gain region
Absorption region
x
Electron
Ionizing collision
Hole

APD Vs PIN

- APD has high gain due to self multiplying mechanism, used in high end systems
- The tradeoff is the ‘excess noise’ due to random nature of the self multiplying process.
- APD’s are costly and need high reverse bias voltage (Ex: 40 V)
- APD’s have the same excess noise at longer wavelengths, but they have an order of magnitude lower avalanche gain.

pin energy-band diagram



$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}\ \mu\mathrm{m}$$

Cut off wavelength depends on the band gap energy

- Responsivity: is a parameter to determine the transfer characteristic of a photodetector.

Responsivity ($\Re$)

Quantum Efficiency (η) = number of e-h pairs generated / number of incident photons

$$\eta = \frac{I_p / q}{P_0 / h\nu} \longrightarrow \Re = \frac{I_p}{P_0} = \frac{\eta q}{h\nu} \quad \text{mA/mW}$$

$$\boxed{\Re_{APD} = \Re_{PIN} M}$$

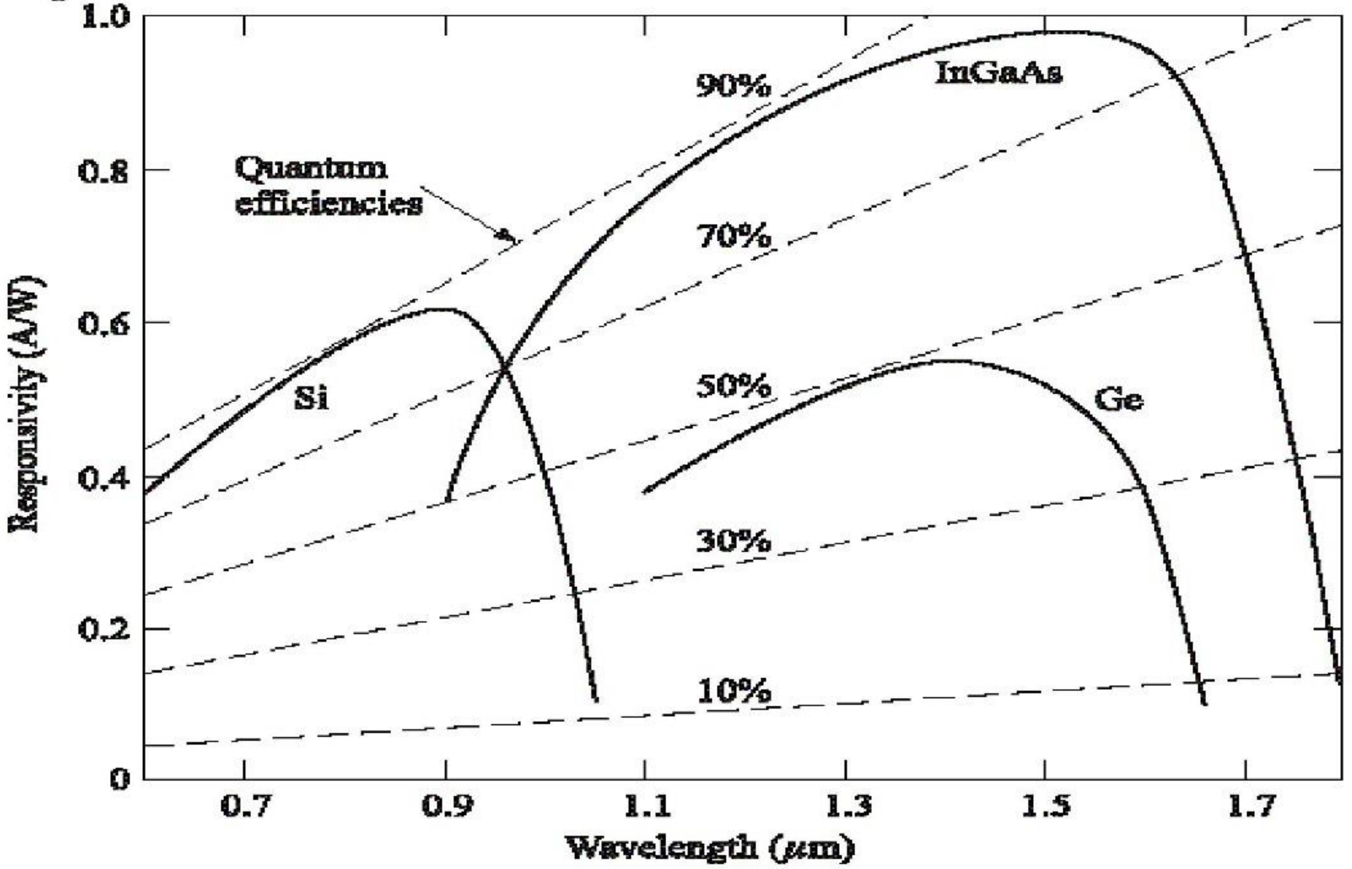
Avalanche PD's have an internal gain M

$$\boxed{M = \frac{I_M}{I_p}}$$

I_M : average value of the total multiplied current
$M = 1$ for PIN diodes

$$\lambda_c = \frac{hc}{E_g}$$

Responsivity



When $\lambda << \lambda_c$ absorption will be low

Signal to Noise Ratio

$$SNR = \frac{\text{Signal power from photocurrent}}{\text{Detector Noise + Amplifier Noise}}$$

For high SNR

- The Photodetector must have a large quantum efficiency (large responsivity or gain) to generate large signal current
- Detector and amplifier noise must be low

SNR Can NOT be improved by amplification

Notation: Detector Current

- The direct current value is denoted by, I_P ; capitol main entry and capital suffix.
- The time varying (either randomly or periodically) current with a zero mean is denoted by, i_p small main entry and small suffix.
- Therefore, the total current Ip is the sum of the DC component I_P and the AC component i_p .

$$\boldsymbol{I}_P = \boldsymbol{I}_p + \boldsymbol{i}_p$$

$$\left\langle i_p^2 \right\rangle = \mathrm{Lim}_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} i_p^2(t)dt$$

Quantum (Shot Noise)

Due optical power fluctuation because light is made up of discrete number of photons

$$\left\langle i_Q^2 \right\rangle = 2qI_p BM^2 F(M)$$

$F(M)$: APD Noise Figure

$F(M) \sim= M^x \; (0 \leq x \leq 1)$

I_p: Mean Detected Current

B = Bandwidth

Dark/Leakage Current Noise

There will be some (dark and leakage) current without any incident light. This current generates two types of noise

Bulk Dark Current Noise $\left\langle i_{DB}^{2} \right\rangle = 2qI_{D}BM^{2}F(M)$

I_D: Dark Current

Surface Leakage Current Noise $\left\langle i_{DS}^{2} \right\rangle = 2qI_{L}B$

(not multiplied by *M*)

I_L: Leakage Current

Thermal Noise

The photodetector load resistor R_L contributes a mean-square thermal (Johnson) noise current

$$\left\langle i_T^2 \right\rangle = 4K_B TB / R_L$$

K_B: Boltzmann's constant = 1.38054 X $10^{(-23)}$ J/K
***T* is the absolute Temperature**

- **Quantum and Thermal are the important noise mechanisms in all optical receivers**
- **RIN (Relative Intensity Noise) will also appear in analog links**

Signal to Noise Ratio

Detected current = AC component (i_p) +
DC component (I_p)

Signal Power = $<i_p{}^2>M^2$

$$SNR = \frac{\left\langle i_p^2 \right\rangle M^2}{2q(I_p + I_D)M^2 F(M)B + 2qI_L B + 4k_B TB / R_L}$$

Typically not all the noise terms will have equal weight

SNR

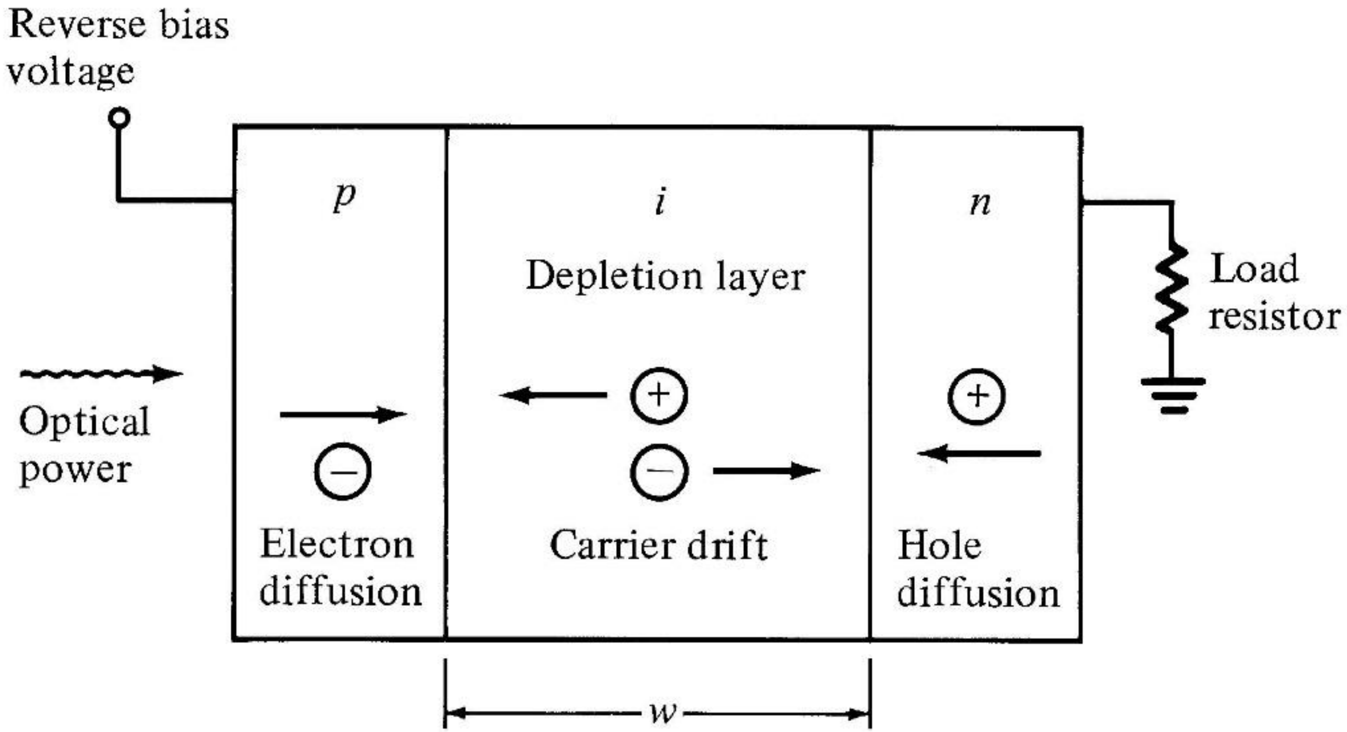
Dark current and surface leakage current noise are typically negligible, If thermal noise is also negligible

$$SNR = \frac{\langle i_p^2 \rangle}{2q(I_p)F(M)B}$$

For analog links, (*RIN*= *Relative Intensity Noise)*

$$SNR = \frac{\langle i_p^2 \rangle M^2}{\left[2q(I_p + I_D)M^2 F(M) + 4k_B T / R_L + (RIN) I_p^2\right] B}$$

Response Time in *pin* photodiode

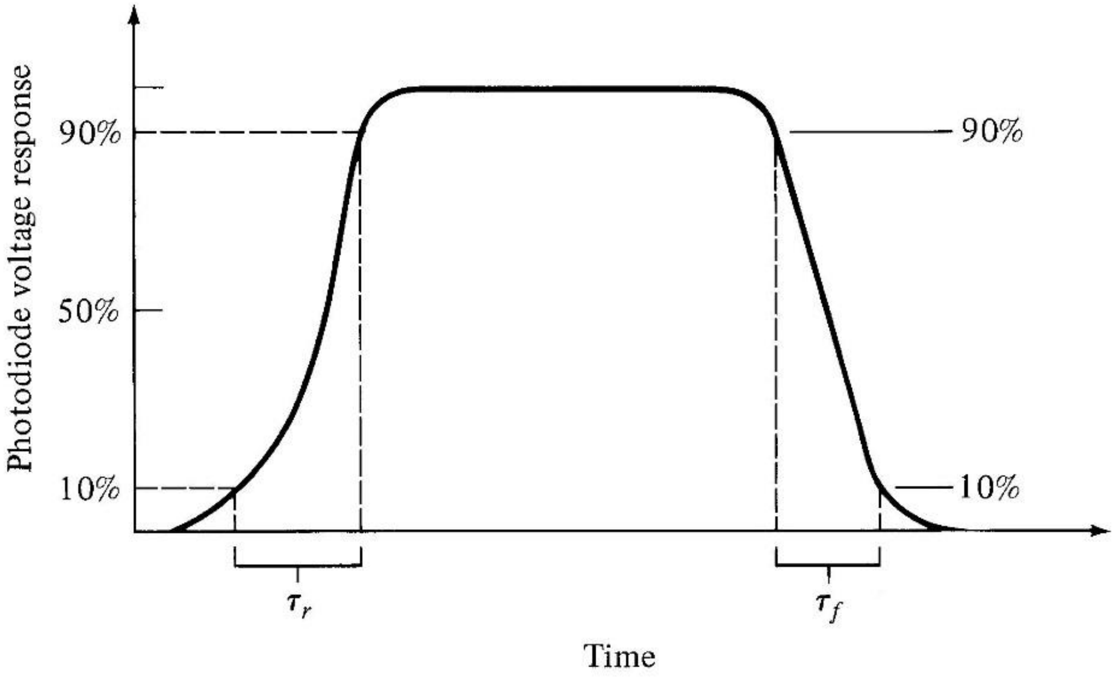


Transit time, t_d and carrier drift velocity v_d are related by

$$t_d = w / v_d$$

For a high speed Si PD, $t_d = 0.1$ ns

Rise and fall times



Photodiode has uneven rise and fall times depending on:

1. Absorption coefficient $\alpha_s(\lambda)$ and
2. Junction Capacitance C_j

$$C_j = \varepsilon_o \varepsilon_r A / w$$

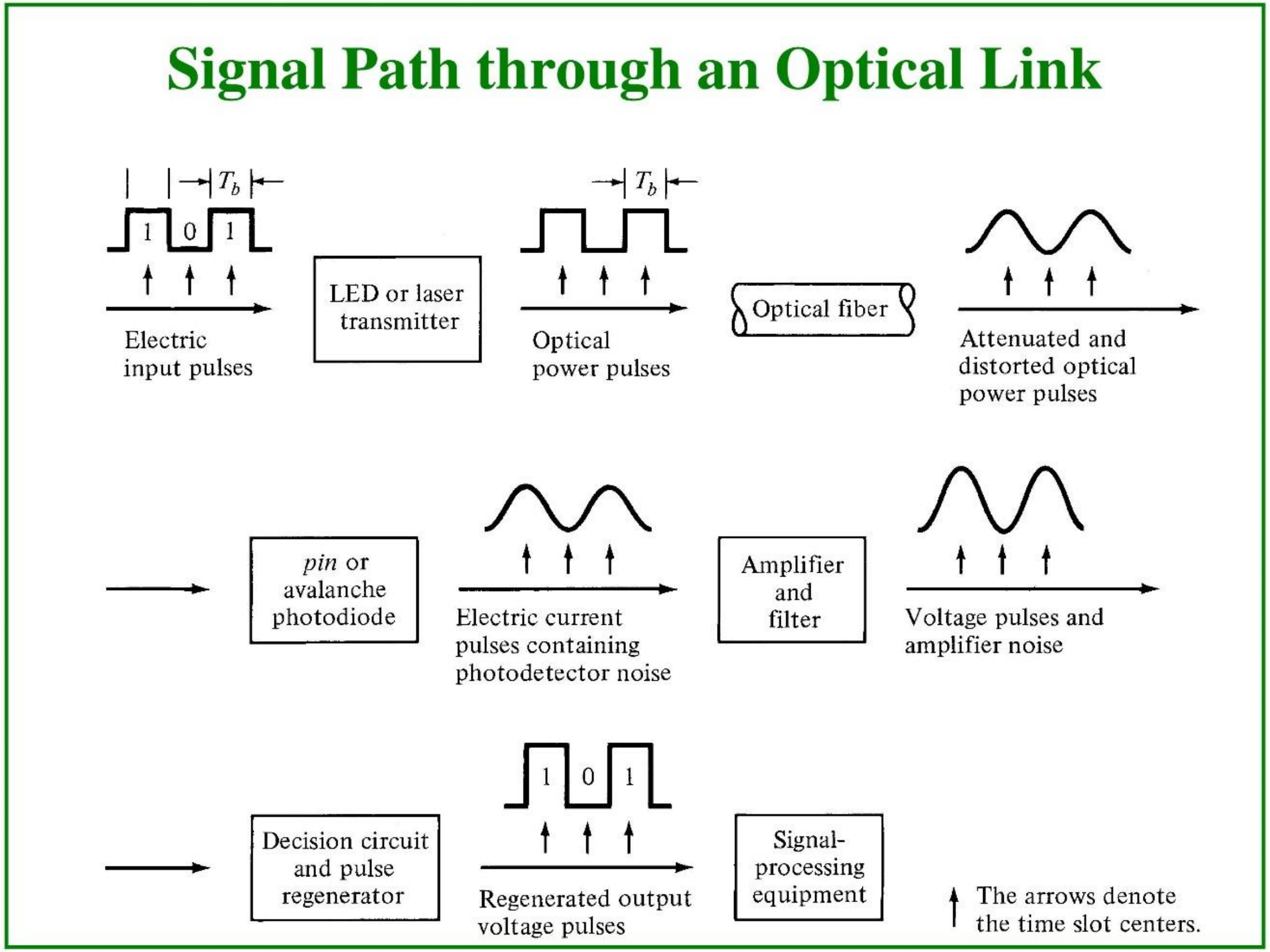
Junction Capacitance

$$C_j = \varepsilon_o \varepsilon_r A \Big/ w$$

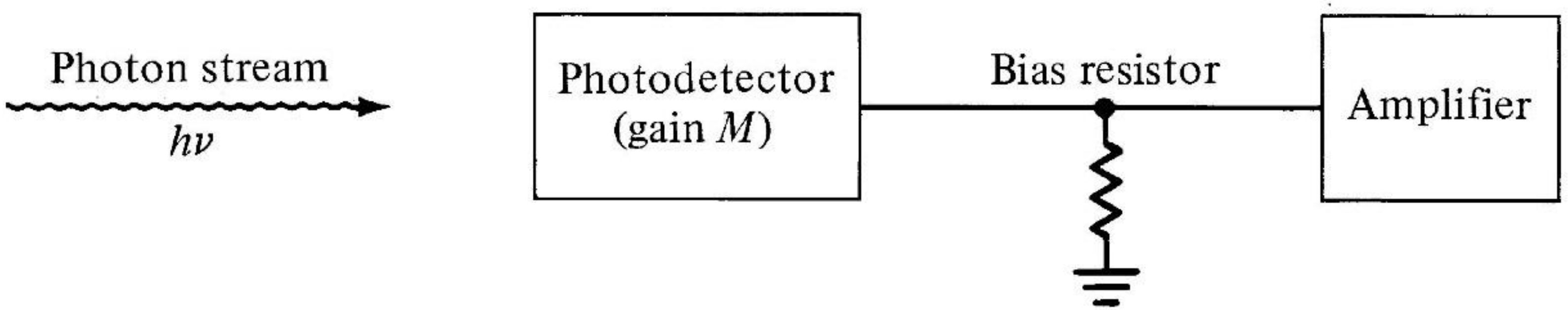
ε_o = 8.8542 x 10(-12) F/m; free space permittivity
ε_r = the semiconductor dielectric constant
A = the diffusion layer (photo sensitive) area
w = width of the depletion layer

Large area photo detectors have large junction capacitance hence small bandwidth (low speed)
→ A concern in free space optical receivers

Fundamental Receiver Operation:



Noise sources and disturbances at an optical receiver



- Photon detection quantum noise (Poisson fluctuation)

- Bulk dark current
- Surface leakage current
- Statistical gain fluctuation (for avalanche photodiodes)

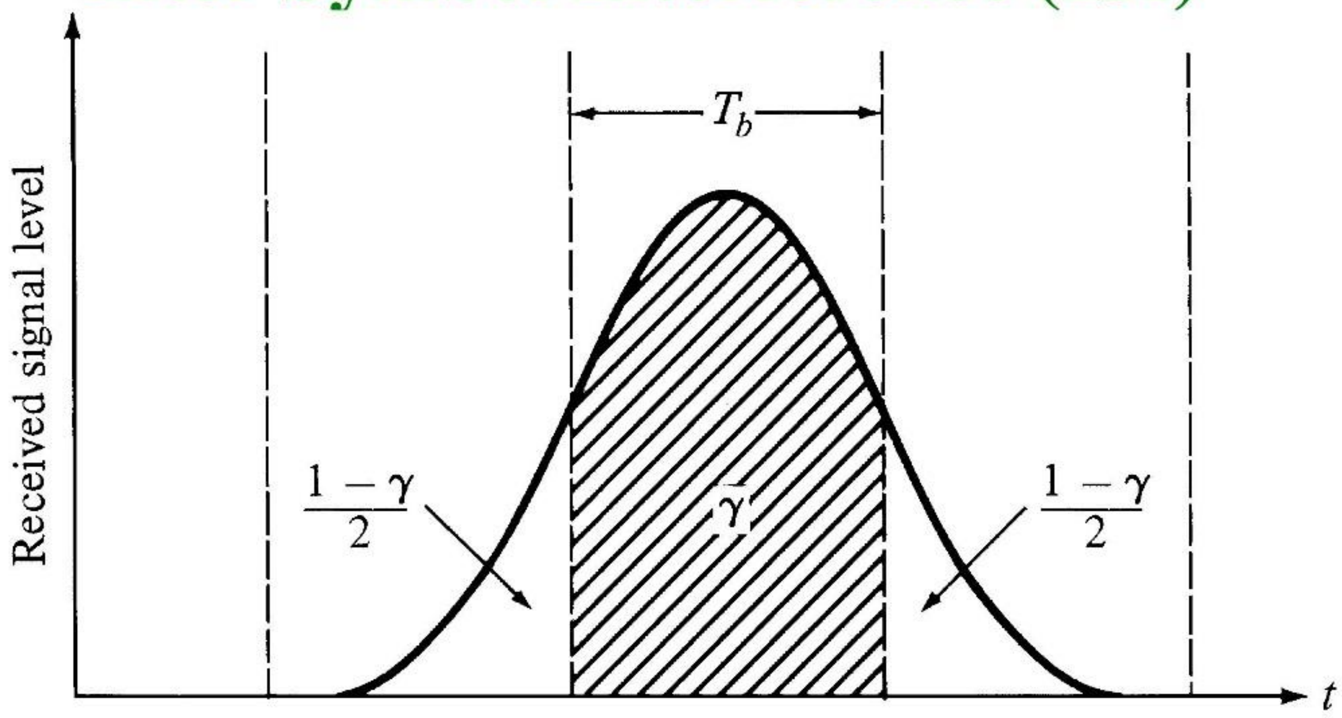
- Thermal noise

- Amplifier noise

Bit Error Rate (BER)

- BER is the ratio of erroneous bits to correct bit
- Estimate of BER often needed to estimate the performance of a communication link
- BER depends on the signal and noise power (Signal to Noise Ratio)
- BER requirement is different for different services and systems
  - Wireless → BER < 10(-6); Optical: BER < 10(-12)
  - Voice → Low BER; Data → High BER

Pulse spreading in digital links that leads to Inter Symbol Interference (ISI)



$$P(t) = \sum_{n=-\infty}^{\infty} b_n h_p(t - nT_b)$$

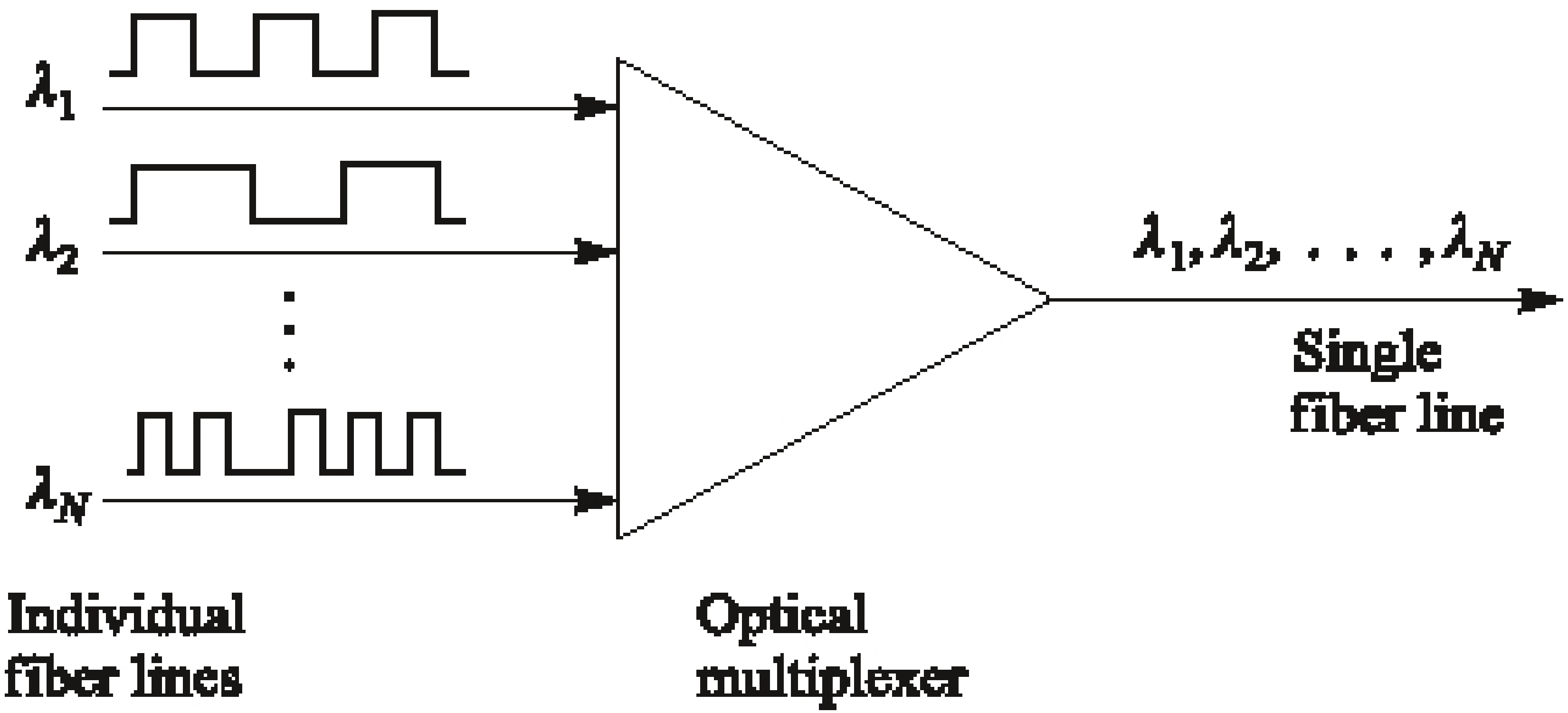
b_n = Data bit (1,0)
T_b = Bit period
h_p = Received pulse shape

Wavelength Division Multiplexer

Why WDM?

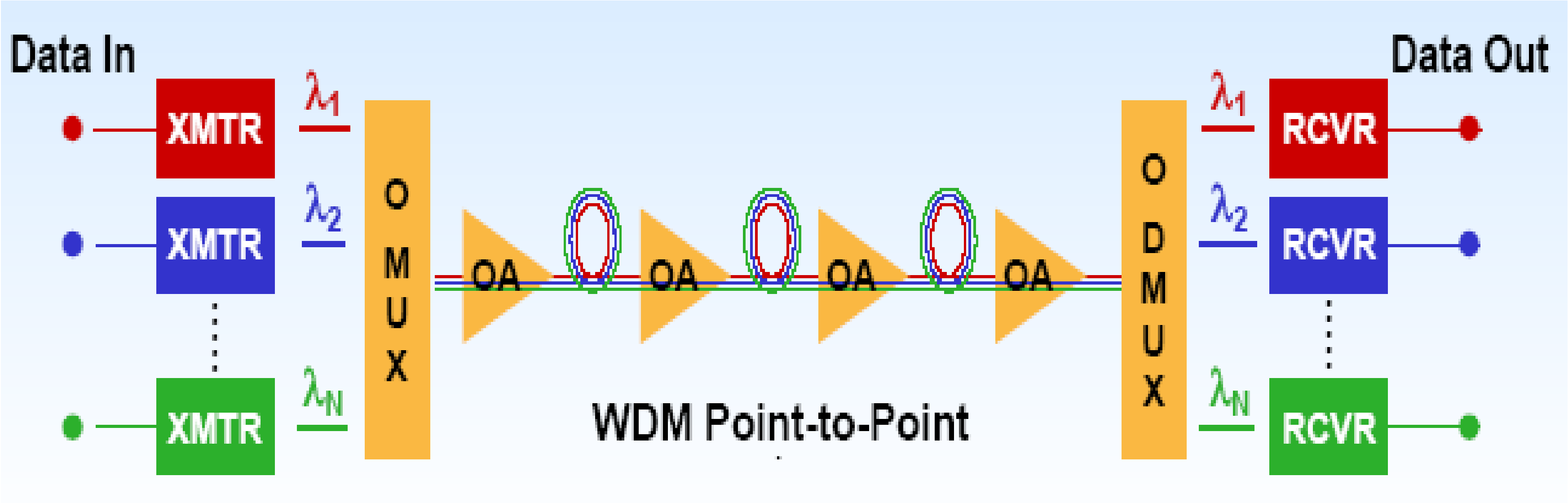
- Capacity upgrade of existing fiber networks (without adding fibers)
- Transparency: Each optical channel can carry any transmission format (different asynchronous bit rates, analog or digital)
- Scalability– Buy and install equipment for additional demand as needed
- Wavelength routing and switching: Wavelength is used as another dimension to time and space

Wavelength Division Multiplexing



Each wavelength is like a separate channel (fiber)

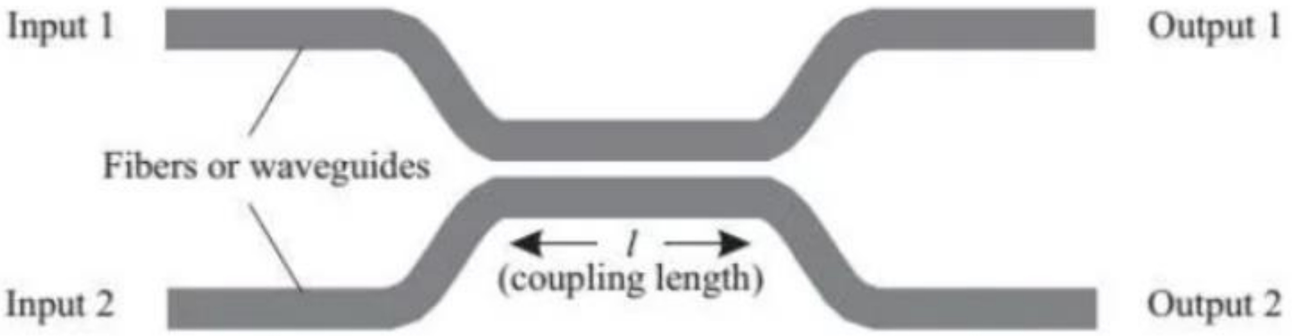
Wavelength Division Multiplexing



- Passive/active devices are needed to combine, distribute, isolate and amplify optical power at different wavelengths

Couplers/ Splitters

- A directional coupler is used to combine and split signals in an optical network.
- A 2×2 coupler consists of two input ports and two output ports.
- The most commonly used couplers are made by fusing two fibers together in the middle—these are called fused fiber couplers.
- A 2×2 coupler, takes a fraction α of the power from input 1 and places it on output 1 and the remaining fraction $1-\alpha$ on output 2.

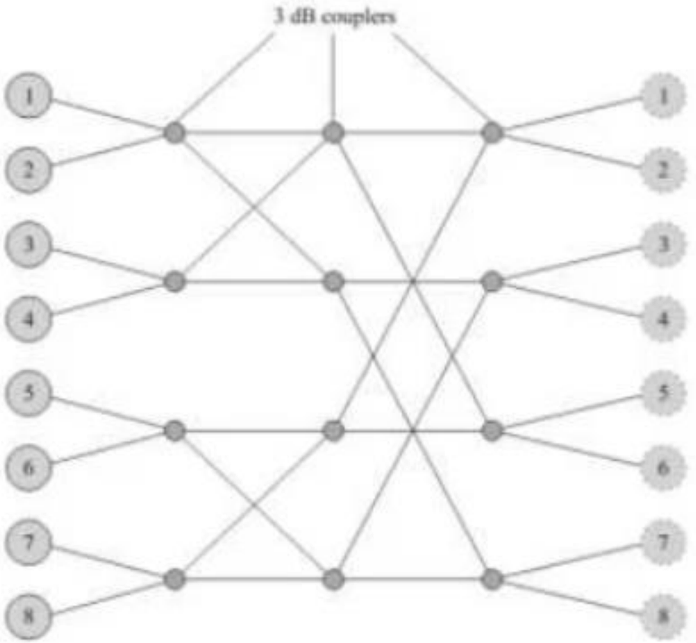


Couplers/ Splitters

- Similarly, a fraction $1-\alpha$ the power from input 2 is distributed to output 1 and the remaining power to output 2.
- We call α the "coupling ratio".
- The coupler can be designed to be either wavelength selective or wavelength independent (sometimes called wavelength flat) over a usefully wide range.
- **Wavelength- independent device**, α is independent of the wavelength.
- **Wavelength selective device**, α depends on the wavelength.
- **3 dB coupler,** a coupler can be used to distribute an input signal equally among two output ports if the coupling length(l), is adjusted such that half the power from each input appears at each output. Such a coupler is called a 3 dB co**upler.**

Couplers/ Splitters

- An n×n star coupler is a natural generalization of the 3 dB 2×2 coupler.
- It is an n-input, n-output device with the property that the power from each input is divided equally among all the outputs.
- An n×n star coupler can be constructed by suitably interconnecting a number of 3 dB couplers.
- A star coupler is useful when multiple signals need to be combined and broadcast to many outputs.
- Couplers are also used to tap off a small portion of the power from a light stream for monitoring purposes or other reasons.



Couplers/ Splitters

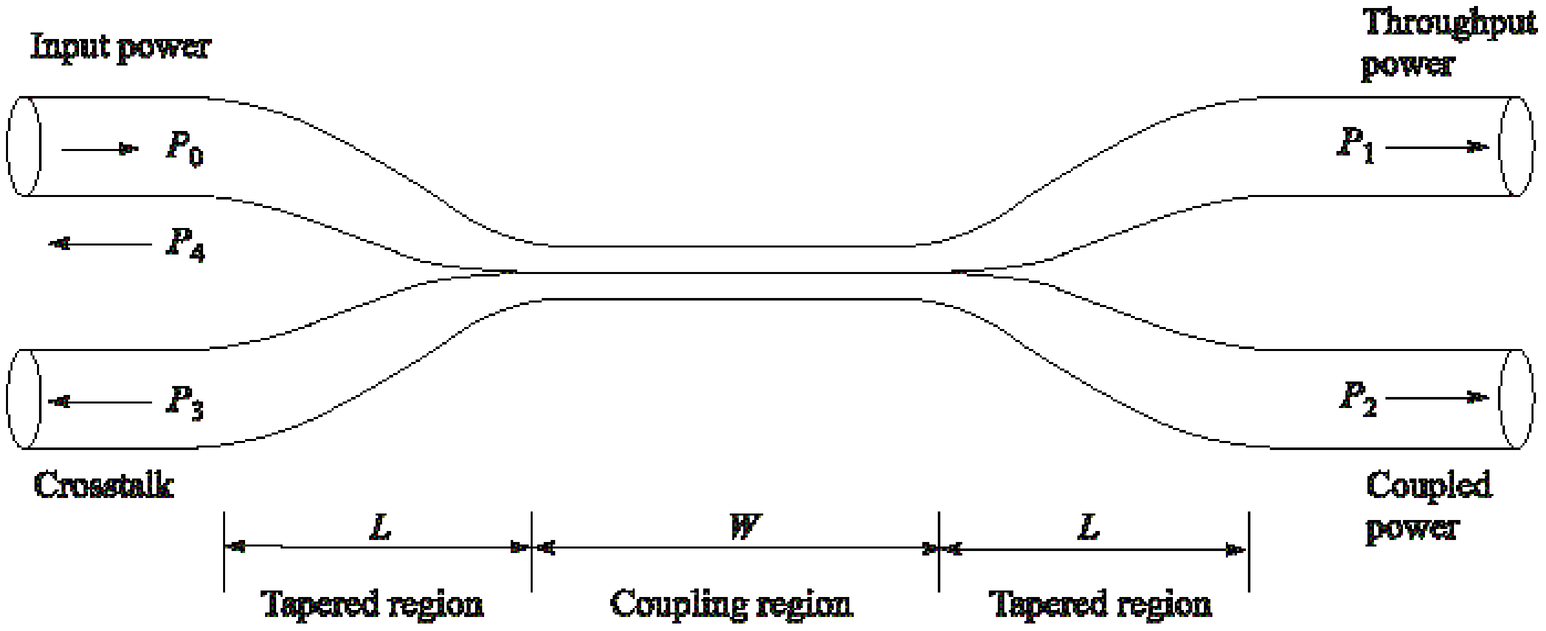
- A coupler can be made wavelength selective, meaning that its coupling coefficient will then depend on the wavelength of the signal.
- Such couplers are widely used to combine signals at 1310 nm and 1550 nm into a single fiber without loss.
- These types of couplers are used for optical amplifiers.

- Couplers and most other passive optical devices are reciprocal devices in that the devices work exactly the same way if their inputs and outputs are reversed.
- In many systems there is a need for a passive non reciprocal device.

Couplers: Principle of Operation

- When two waveguides are placed in proximity to each other, light "couples" from one waveguide to the other.
- This is because the propagation modes of the combined waveguide are quite different from the propagation modes of a single waveguide due to the presence of the other waveguide.
- When the two waveguides are identical, light launched into one waveguide couples to the other waveguide completely and then back to the first waveguide in a periodic manner.
- A 3 dB coupler the coupling length must be chosen to satisfy $\kappa l=(2k+1)\pi/4$, where k is a "non-negative integer", l denotes the "coupling length", The quantity κ is called the "coupling coefficient".

Fused-Biconical coupler OR Directional coupler



- *P3, P4* extremely low (-70 dB below Po)
- Coupling / Splitting Ratio = *P2/(P1+P2)*
- If $P_1=P_2$ → It is called 3-dB coupler

Fused Biconical Tapered Coupler

- Fabricated by twisting together, melting and pulling together two single mode fibers
- They get fused together over length *W;* tapered section of length *L;* total draw length = $L+W$
- Significant decrease in *V*-number in the coupling region; energy in the core leak out and gradually couples into the second fibre

Definitions

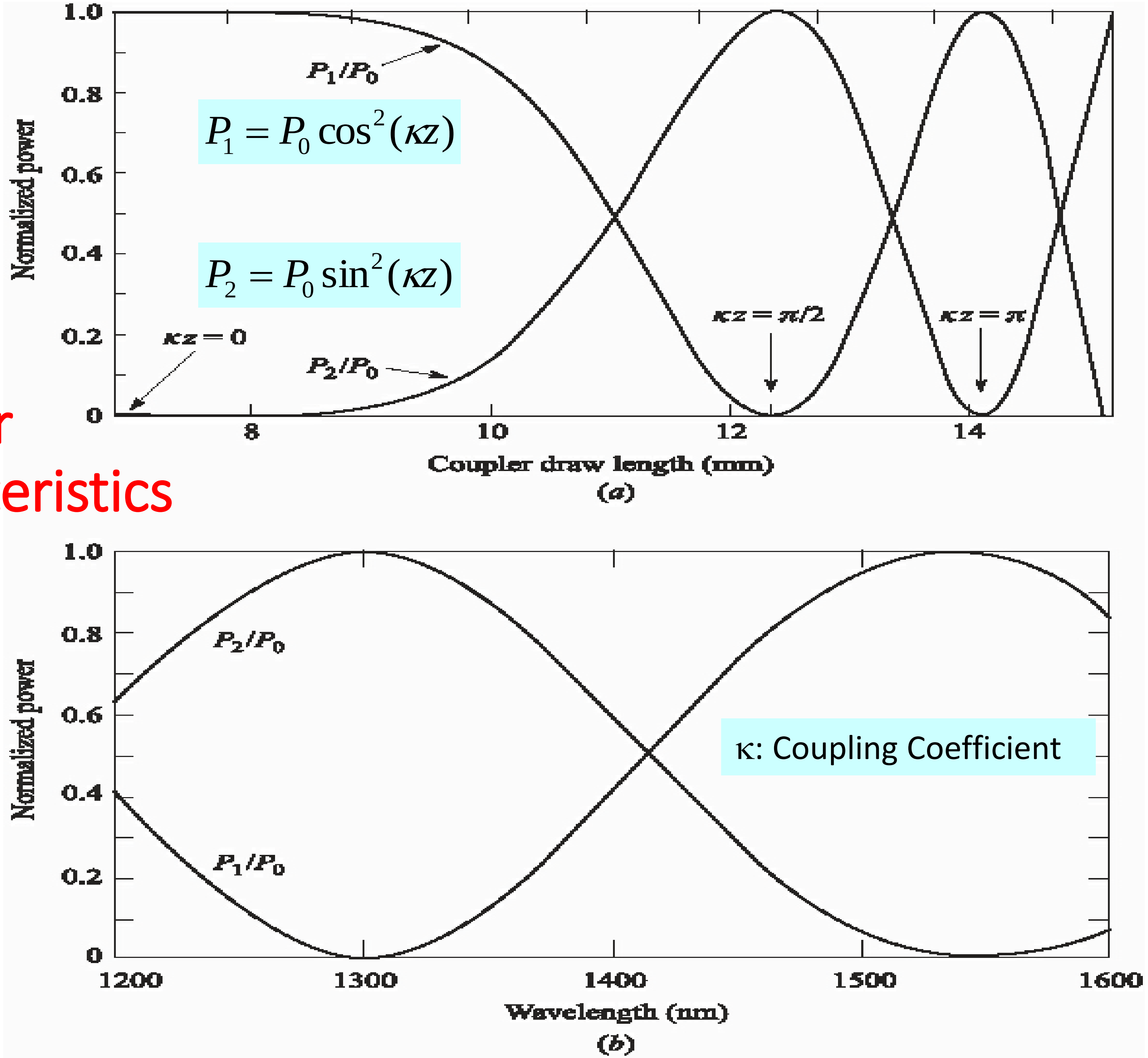
Splitting (Coupling) Ratio $= P_2/(P_1+P_2)$

Excess Loss $= 10\ \mathrm{Log}[P_0/(P_1+P_2)]$

Insertion Loss $= 10\ \mathrm{Log}[P_{in}/P_{out}]$

Crosstalk $= 10\ \mathrm{Log}(\mathrm{P}_3/\mathrm{P}_0)$

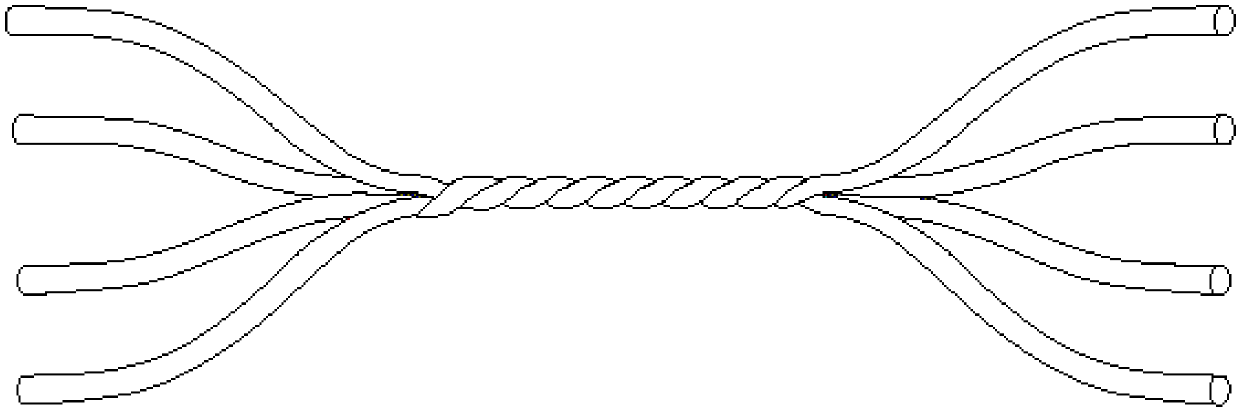
Coupler characteristics



Coupler Characteristics

- power ratio between both output can be changed by adjusting the draw length of a simple fused fiber coupler
- It can be made a WDM de-multiplexer:
  - Example, 1300 nm will appear output 2 (p2) and 1550 nm will appear at output 1 (P1)
  - However, suitable only for few wavelengths.

Fused-Fiber Star Coupler

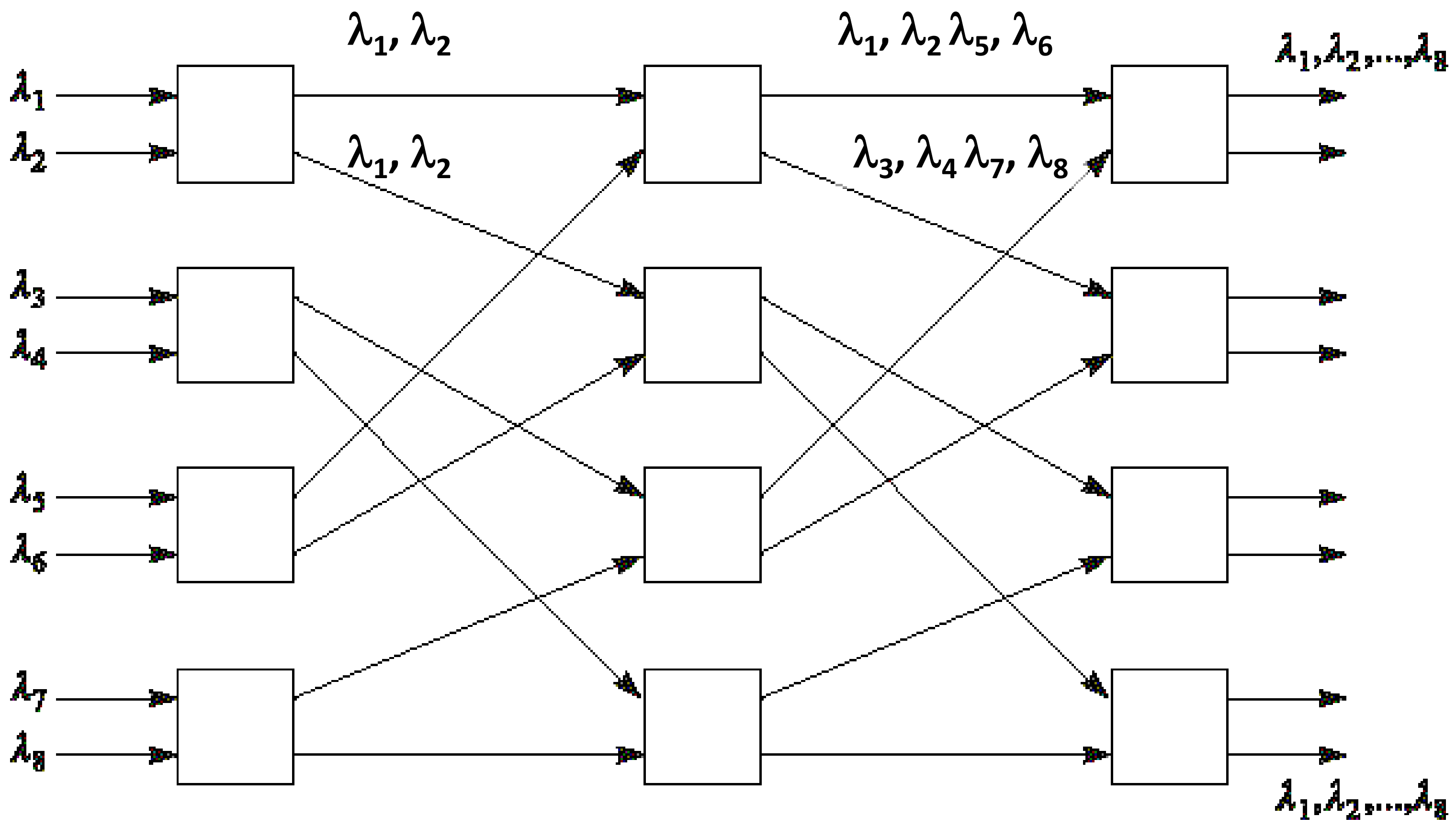


Splitting Loss = -10 Log(1/N) dB = 10 Log (N) dB

Excess Loss = 10 Log (Total P_{in}/Total P_{out})

Fused couplers have high excess loss

8x8 bi-directional star coupler by cascading 3 stages of 3-dB Couplers



Number of 3-dB Couplers $N_c = \frac{N}{2} \log_2 N$

(12 = 4 X 3)
Try Ex. 10.5

Isolators and Circulators

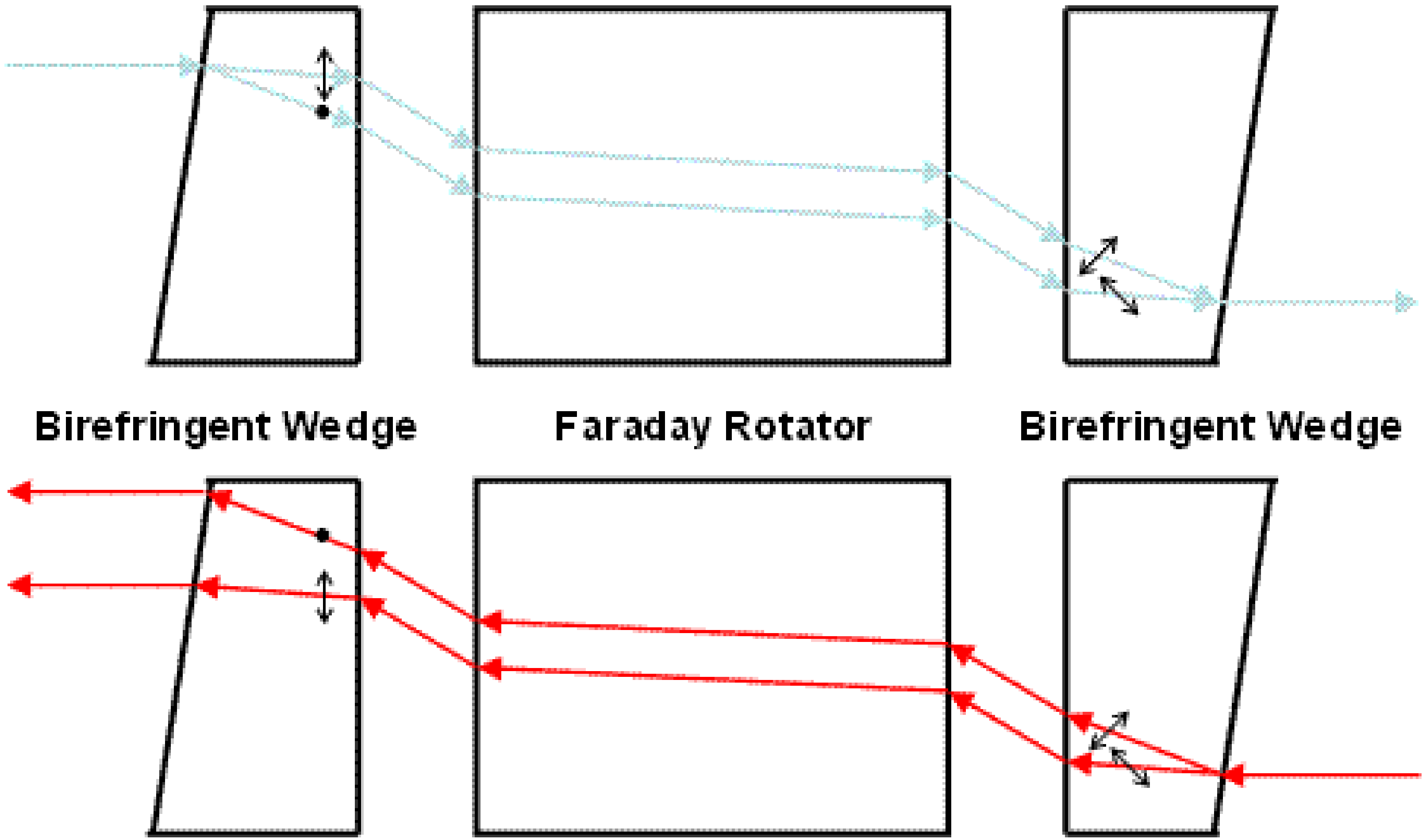
- Isolators, main function is to allow transmission in one direction through it but block all transmission in the other direction.
- Isolators are used in systems at the output of optical amplifiers and lasers primarily to prevent reflections from entering these devices, which would otherwise degrade their performance.
- The two key parameters of an isolator are its insertion loss, which is the loss in the forward direction and which should be as small as possible, and its isolation,which is the loss in the reverse direction and which should be as large as possible.

(a) (b)

Isolators and Circulators

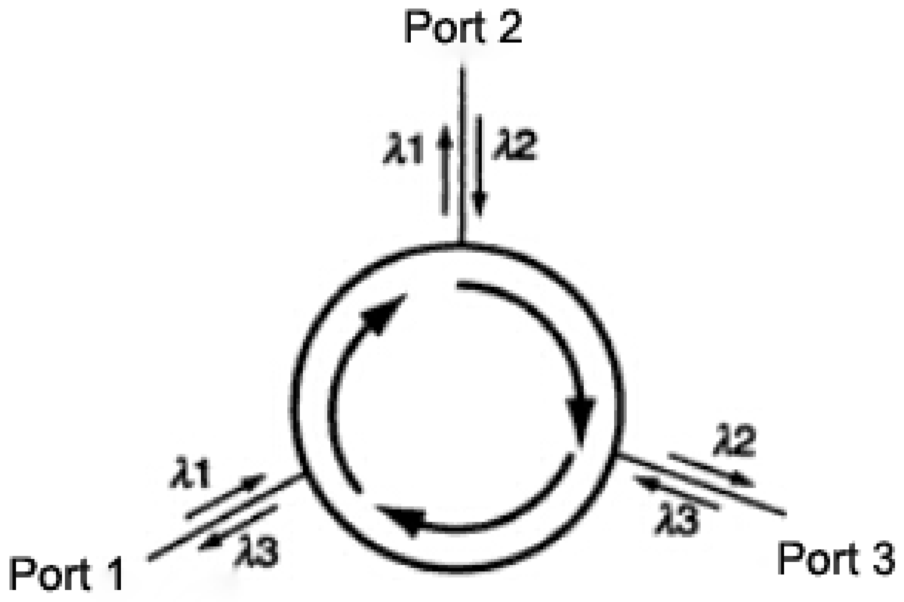
- A circulator is similar to an isolator, except that it has multiple ports, typically three or four.
- In a three-port circulator, an input signal on port 1 is sent out on port 2, an input signal on port 2 is sent out on port 3, and an input signal on port 3 is sent out on port 1.
- Circulators are useful to construct optical add/drop elements.
- Circulators operate on the same principles as isolators.

Polarization independent Isolator

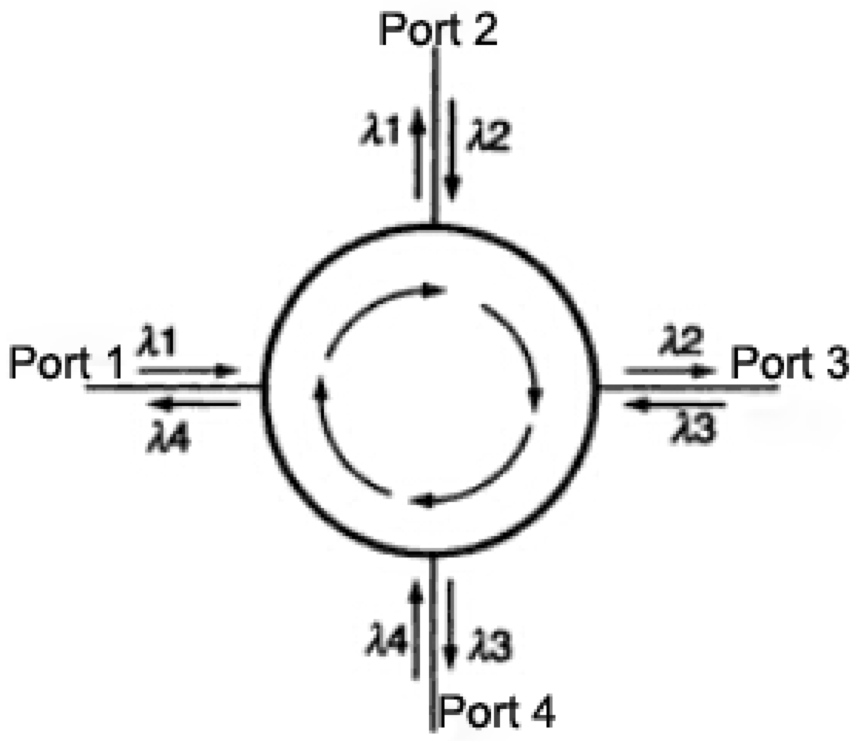


- The polarization independent isolator is made of three parts, an input birefringent wedge (with its ordinary polarization direction vertical and its extraordinary polarization direction horizontal), a Faraday rotator, and an output birefringent wedge (with its ordinary polarization direction at 45°, and its extraordinary polarization direction at −45°).
- Light traveling in the forward direction is split by the input birefringent wedge into its vertical (0°) and horizontal (90°) components, called the ordinary ray (o-ray) and the extraordinary ray (e-ray) respectively. The Faraday rotator rotates both the o-ray and e-ray by 45°. This means the o-ray is now at 45°, and the e-ray is at −45°. The output birefringent wedge then recombines the two components.
- Light traveling in the backward direction is separated into the o-ray at 45, and the e-ray at −45° by the birefringent wedge. The Faraday Rotator again rotates both the rays by 45°. Now the o-ray is at 90°, and the e-ray is at 0°. Instead of being focused by the second birefringent wedge, the rays diverge.
- Typically collimators are used on either side of the isolator. In the transmitted direction the beam is split and then combined and focused into the output collimator. In the isolated direction the beam is split, and then diverged, so it does not focus at the collimator.
- Figure 3 shows the propagation of light through a polarization independent isolator. The forward travelling light is shown in blue, and the backward propagating light is shown in red. The rays were traced using an ordinary refractive index of 2, and an extraordinary refractive index of 3. The wedge angle is 7°.

3 port and 4 port Circulator

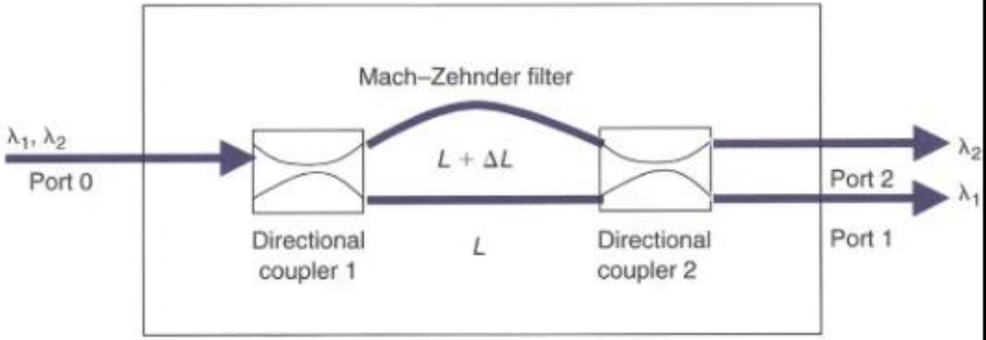


(a) A 3-port circulator



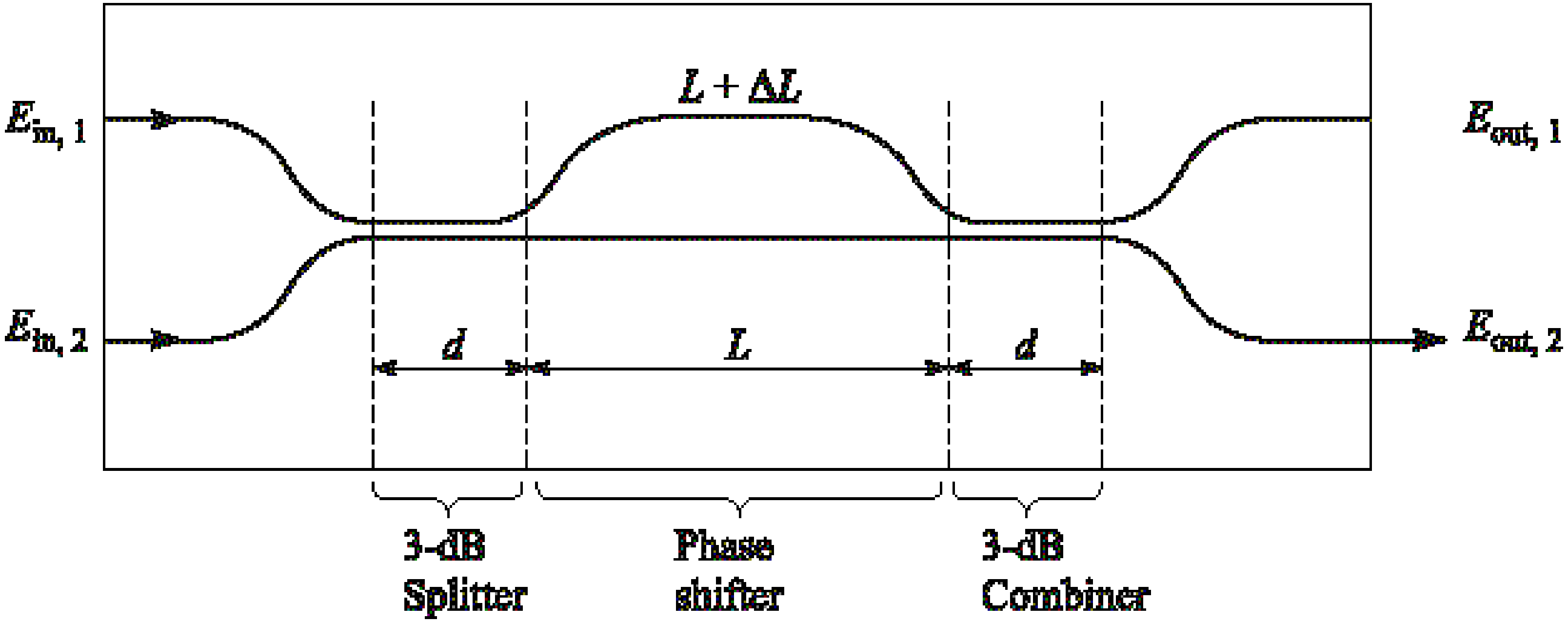
(b) A 4-port circulator

Mach-Zehnder Interferometer



- Uses two couplers
  - The coupling ratio can be different
  - A phase difference between two optical paths may be artificially induced
  - Adjusting ΔL changes the phase of the received signal
- Because of the path difference, the two waves arrive at coupler 2 with a phase difference
- At coupler 2, the two waves recombine and are directed to two output ports
  - each output port supports the one of the two wavelengths that satisfies a certain phase condition
- Note:
  - $\Delta f = C/2n\Delta L$
  - $\Delta \Phi = 2\pi f.\Delta L.(n/c)$

Basic Mach-Zehnder Interferometer



Phase shift of the propagating wave increases with ΔL,
Constructive or destructive interference depending on ΔL

Mach-Zehnder Interferometer

Phase shift at the output due to the propagation path length difference:

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

If the power from both inputs (at different wavelengths) to be added at output port 2, then,

$$\pi = 2\pi n_{eff}\left[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right]\Delta L$$

Applications:

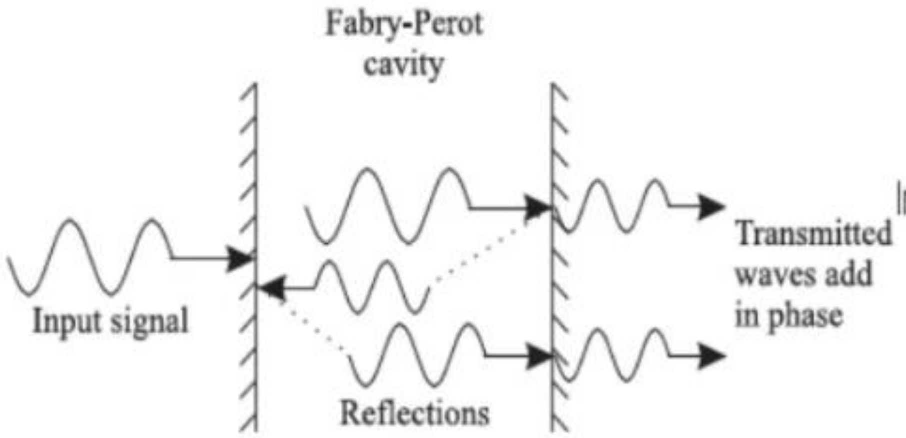
— wideband filters (coarse WDM) that separate signals at1300 nm from those at 1550 nm

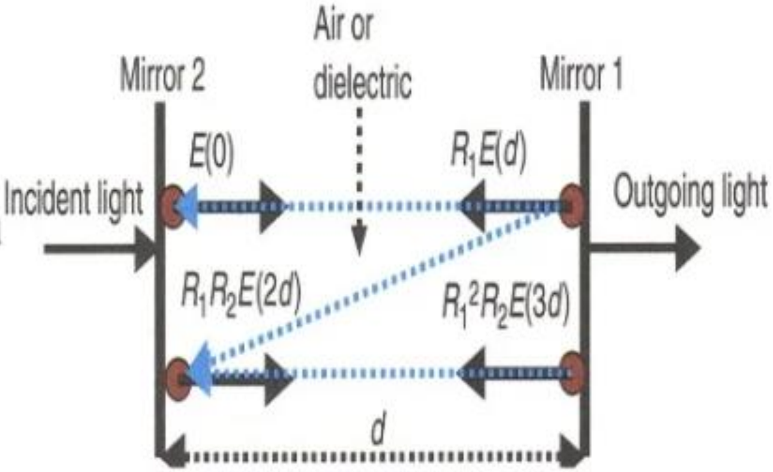
— narrowband filters: filter bandwidth depends on the number of cascades (i.e. the number of 3-dB couplers connected)

Fabry-Perot Filters

A cavity with highly reflective mirrors parallel to each other (Bragg structure)

- Acts like a resonator
- Also called FP Interferometer
- Used in lasers





Fabry Perot Filter:

- A cavity of length L with intensity reflectivity R has an intensity transmittiance of

$$\frac{I_T}{I_{inc}} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(\delta/2)}$$

with

$$\delta = \frac{4\pi nL\cos\theta}{\lambda}.$$

- The transmittance is maximum whenever

$$\delta = 2m\pi.$$

- Therefore the frequency is maximum whenever

$$\nu_m = m \frac{c}{2nL\cos\theta}$$

with θ the angle of the beam relative to the surface normal within the cavity.

- The spacing between adjacent modes is therefore:

$$\Delta\nu_{FSR} \equiv \nu_{m+1} - \nu_m = \frac{c}{2nL\cos\theta}.$$

- The signal channel bandwidth can be defined as:

$$\Delta \nu_{sig} = N S_{ch} B \ ,$$

where N are the *number of channels*, S_{ch} is the *normalized channel spacing* ($S_{ch} = \Delta\nu_{ch}/B$, and B is the *bit rate*.

- Typically $\Delta\nu_{bw} \sim B$

$$\therefore N < \frac{\Delta \nu_{FSR}}{S_{ch}\Delta \nu_{bw}} = \frac{F}{S_{ch}} \ ,$$

where $F = \Delta\nu_{FSR}/\ \Delta\nu_{bw}$ is the *finesse* of the filter.

- For a loss less filter the finesse is

$$F = \frac{\pi\sqrt{R}}{1-R}.$$

- The number of channels for FP filters is limited to 50-100 due to the limited *finesse* of practical FP filters (F~100).

- FP filters can be cascaded to increase the effective finesse (F~1000).

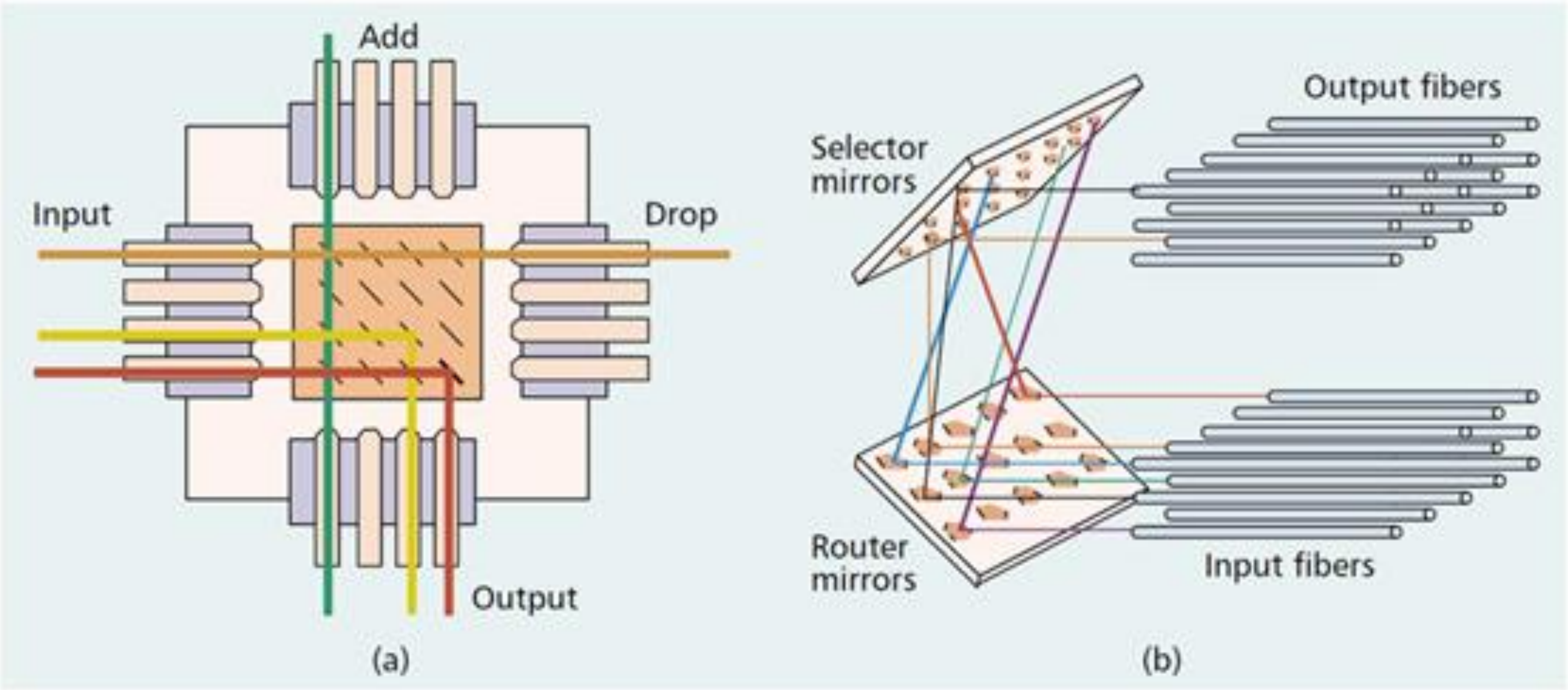
- Note that varying the *cavity length* or the *refractive index* can change the *pass band wavelength*. Either or both parameters can be changed by mechanical or electrical means to form a *tunable filter*.

Optical MEMS switches

- Optical switch is a device that converts an optical signal from one optical channel to another optical channel within a certain range.
- It has one or more selectable transmission windows.
- Fiber optic switch is one of the core devices for optical cross-connection, optical add/drop multiplexing, network monitoring and automatic protection system.
- Its implementation technologies are diverse, including: mechanical optical switches, thermo-optical switches, acousto-optic switches, electro-optical switches, magneto-optical switches, liquid crystal optical switches and MEMS optical switches.
- The traditional switch with electricity as the core is gradually unable to meet the demand for high-speed and large-capacity optical communication, which is why the all-optical switch appears in the market.
- Among them, MEMS optical fiber switches are widely used due to their small size, low power consumption, and good scalability.

- What is MEMS? MEMS is shot for Micro-Electro-Mechanical System, which refers to a micro-device or system that can be mass-produced and integrate micro-machines, micro-actuators, signal processing and control circuits. The preparation process of micro-mechanical structures includes photolithography, ion beam Etching, chemical etching, wafer bonding, etc.
- MEMS is driven by electronic technology, such as electrostatic attraction, electromagnetic force, electrostriction, and thermocouple. Among all the driving mechanisms of MEMS devices, the electrostatic attraction structure is the most widely used due to its simple preparation, easy control and low power consumption.
- The MEMS optical switch is to engrave a number of tiny mirrors on the silicon crystal. The microarray is rotated by electrostatic force or electromagnetic force to change the propagation direction of the input light, thereby realizing the on and off function of the light path.

Working principle of MEMS optical switch

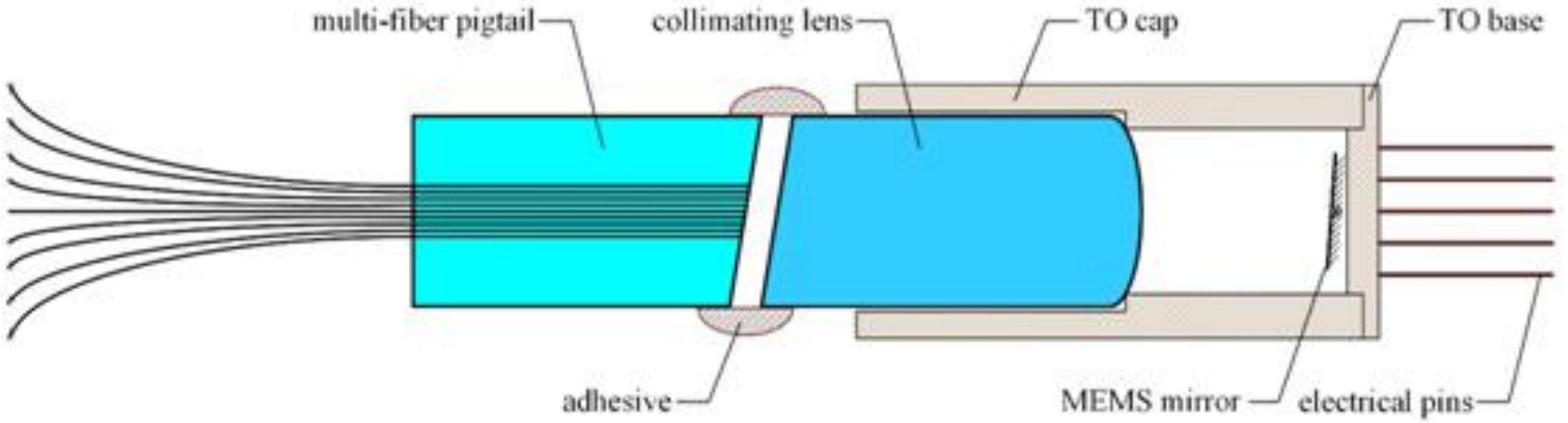


Generally speaking, MEMS based optical switch can be divided into two types in terms of spatial structure:Fig (a) 2D switches and Fig(b)-3D switches.

- The rotating mirror of the 2D MEMS optical switch is monolithically integrated on the silicon substrate through surface micromechanical manufacturing technology, and the collimated light is connected to the designated output terminal through the rotation control of the micro mirror.
- When the micro mirror is horizontal, the light beam can pass through the micro mirror.
- When the micro mirror rotates perpendicular to the silicon substrate, it will reflect the light beam incident on its surface, so that the light beam can pass through the corresponding output port of the micro mirror.
- In the 3D MEMS optical switch, the micro mirror can rotate arbitrarily along two axes, so different angles can be used to change the output of the optical path. These arrays usually appear in pairs, and the input light reaches the first array mirror. It is reflected to the mirror surface of the second array, and then the light is reflected to the output port.

Structure of MEMS Fiber Optic Switch

Fiber optic switch is a multiport device. The port configurations include 2×2, 1×N, N×N. Optical switch with N×N ports is usually called OXC (optical cross connect). The structure of a MEMS-based 1×N optical switch is shown in Fig, which consists of a MEMS torsion mirror, a collimating lens and a multi-fiber pigtail. The MEMS mirror is usually assembled on a TO base, then the collimating lens is joint to the sub-assembly through the TO cap. Finally, the multi-fiber pigtail is actively aligned to the sub-assembly.



- **The advantages of MEMS switch**

The MEMS optical switch can realize the comprehensive remote control of the all-optical network, and has the main advantages of high integration, low power consumption and low cost.

MEMS optical switches have the advantages of mechanical optical switches, such as low insertion loss, low crosstalk, low polarization sensitivity, high extinction ratio, high switching speed, small size and easy large-scale integration of waveguide switches.

This will be the mainstream direction for the development of large-capacity switching optical network switches.

- **The applications of MEMS fiber optic switch**

MEMS optical switches and the switch arrays have a wide range of applications in optical communications.

Its application scope mainly includes: optical network protection switching system, light source control in optical fiber test, real-time monitoring system of network performance, optical device test, construction of switching core of OXC equipment, optical add/drop multiplexing, optical test, optical Sensing system, etc.