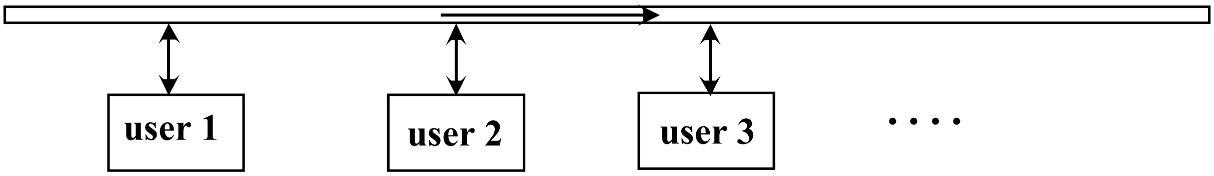
# SECTION 7:

# MULTIPLEXING TECHNIQUES, NETWORKS, and DEVICES

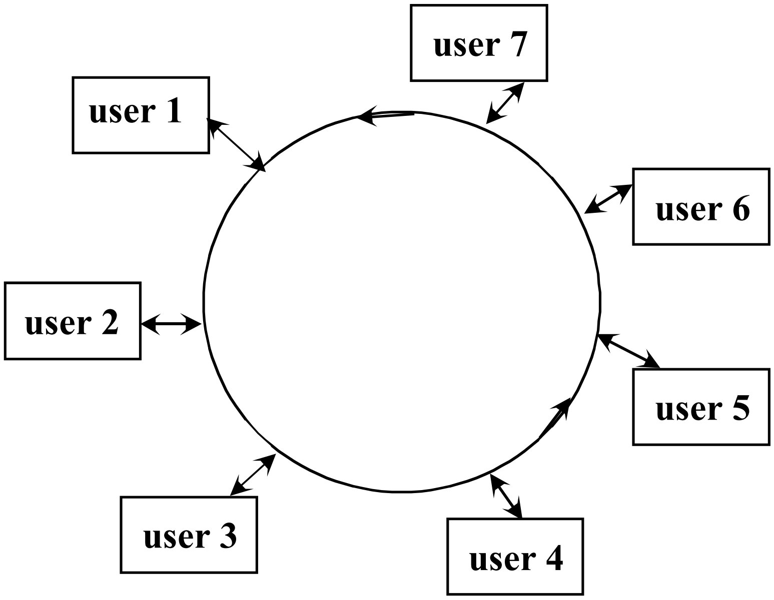
## BASIC NETWORK TOPOLOGIES

1. ***Bus – Backplane***



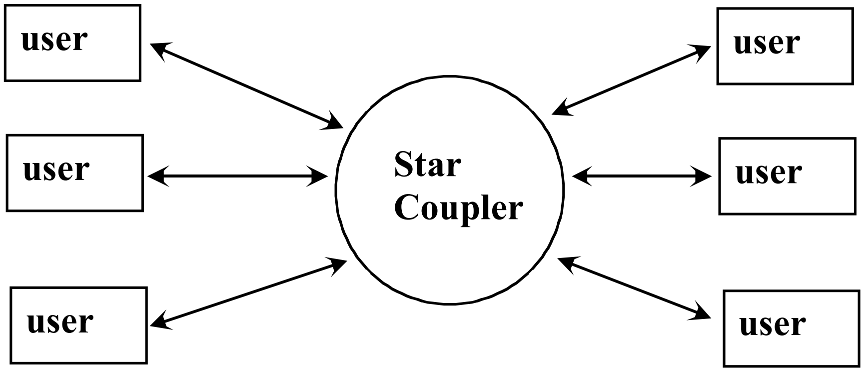
- Issues of contention for accessing the bus

2. ***RING***



- Individual passive optical tap is required for each node.
- Similar to BUS Network in this regard.
- Approach becomes intolerable for large node networks.

3. ***STAR NETWORK***



- The signal from each signal is mixed in the *star coupler* and broadcast to all other users on the coupler.

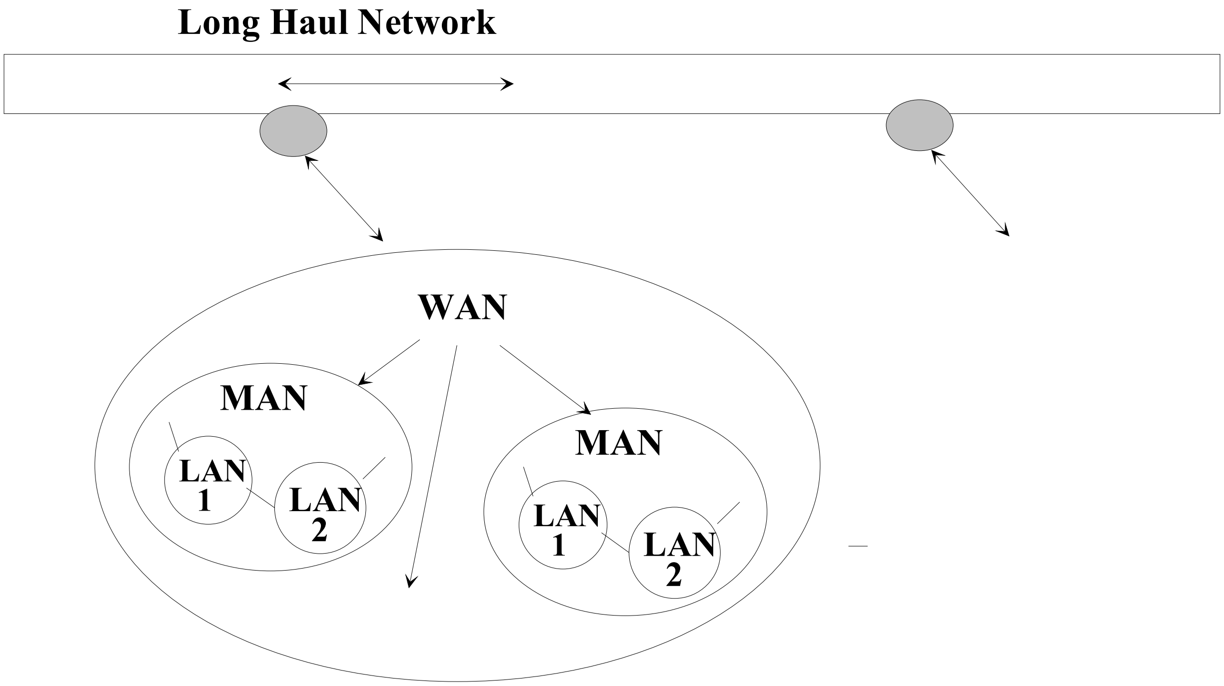
## <u>OPTICAL NETWORK TERMINOLOGY</u>

- SONET/SDH- *Synchronous Optical Network* later called *Synchronous Digital Hierarchy*- This standard defines a synchronous frame structure for transmitting time division multiplexed signals.

- OC-xx *Optical Carrier;* STM-xx *Synchronous Transfer Module* – each bit rate is a multiple of the lowest level OC-1 or STM-1 bit rate.

| SONET | SDH | B(Mb/s) | Channels |
|---|---|---|---|
| OC-1 | | 51.84 | 672 |
| OC-3 | STM-1 | 155.52 | 2016 |
| OC-12 | STM-4 | 622.08 | 8064 |
| OC-48 | STM-16 | 2488.32 | 32256 |
| OC-192 | STM-64 | 9953.28 | 129024 |
| OC-768 | STM-256 | 39813.12 | 516096 |

# FIBER OPTIC NETWORK LAYOUT



***Long Haul Network*** – Provides signal transmission link between distant regions within a country, countries, and continents. (BUS)

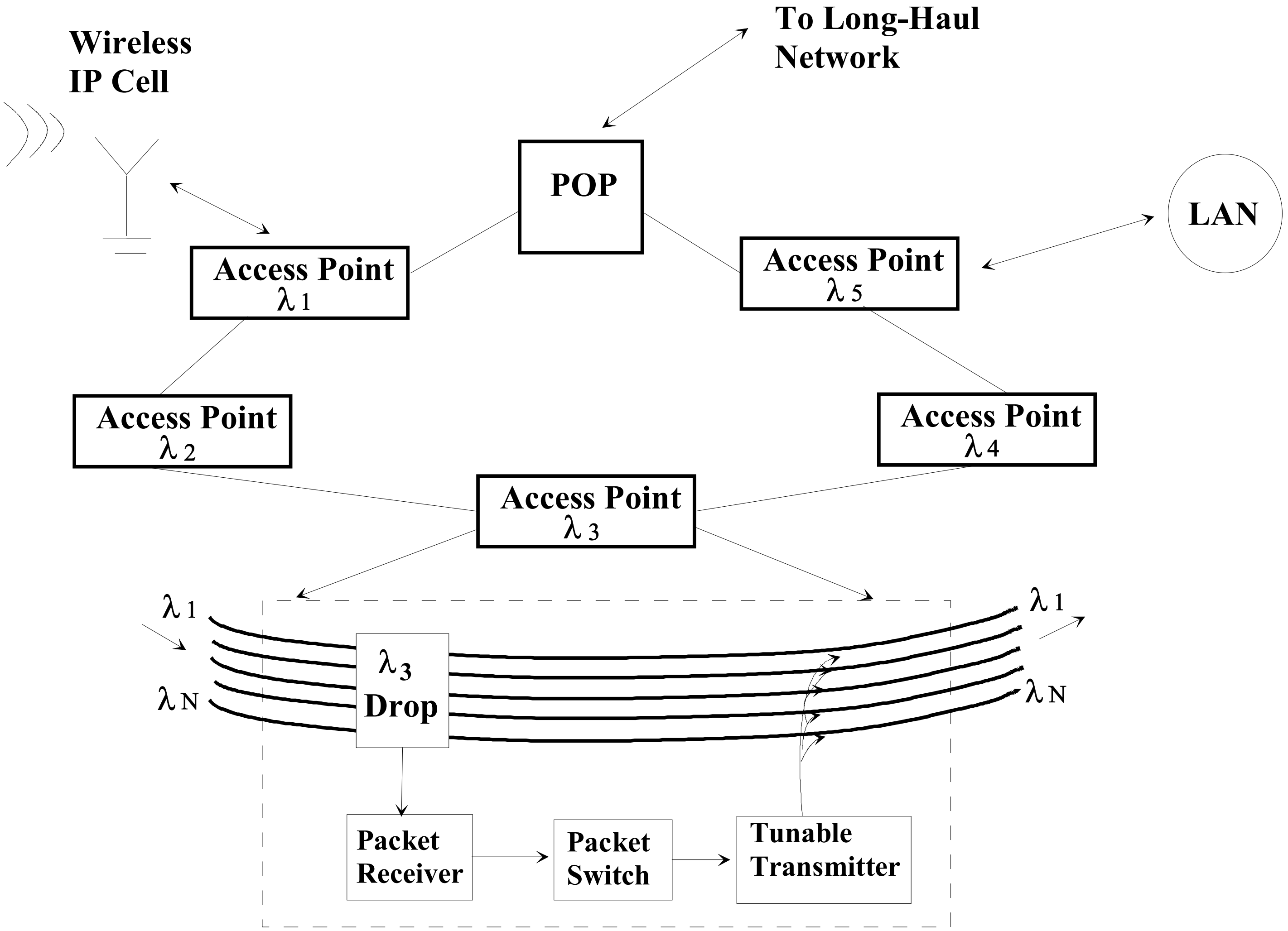
***Wide Area Network*** – Connects significant portion of a country (hundreds of kilometers). (STAR)

***Metropolitan Area Network***- Interconnects users in a city and its outlying regions. (RING)

***Local Area Network***- Connects a small number of users in a region of a few kilometers. (RING)

# MAN Example

## *(Stanford's HORNET- Hybrid Opto-Electronic Ring Network)*



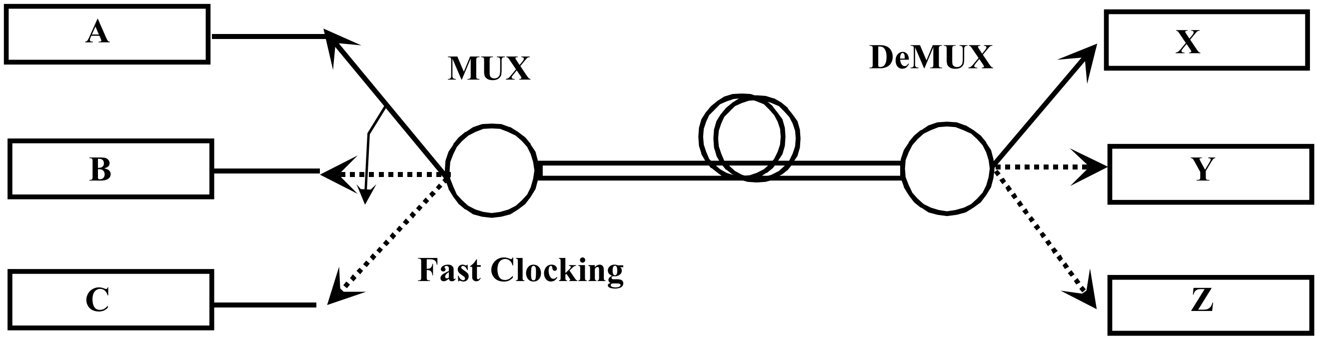
- *POP- Point of Presence* – switches traffic between the ring and the carriers long-haul network.

- *Access Points*- nodes for accessing and sending data to the ring.

- *WDM MAN* – In this architecture *Access Points* are connected in a ring topology. Wavelength Division Multiplexing approach is used to route signals on the MAN. A rapid tunable (<15 ns) laser is used to send data onto the network at an Access Point.

## *MULTIPLEXING TECHNIQUES:*

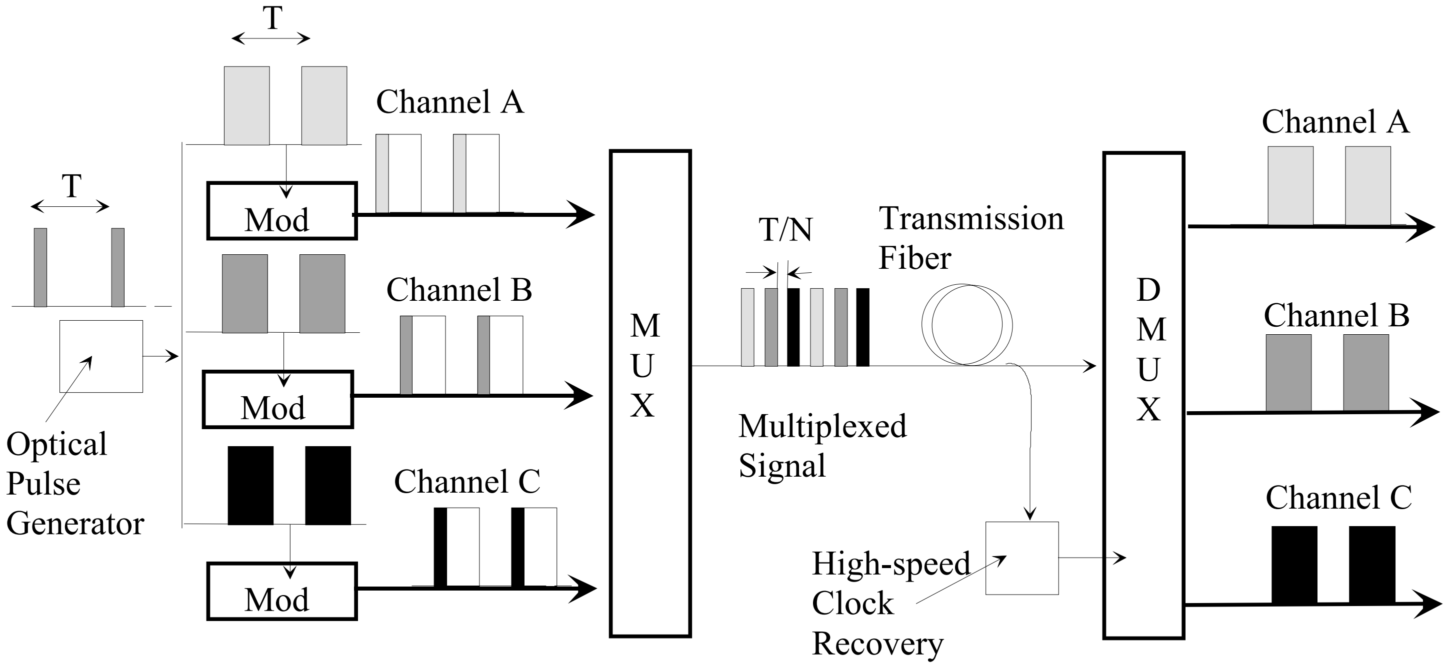
### 1. Basic Time Division Multiplexing (TDM)



- The signal is modulated at a very high bit rate, rapidly sampled by a high speed clock, and then transmitted through the fiber network.

- This scheme is limited by the ability to modulate and sample high bit rate signals ~100 Gbit/s.

## Example: Time Division Multiplexing (TDM) System



- Individual channels are modulated at high data rates (Channels A-C, more would be used in an actual system).

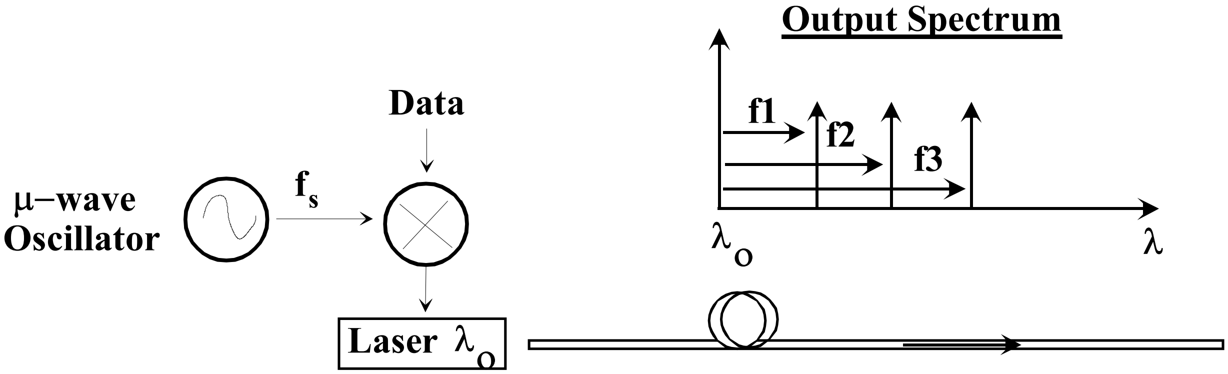
- An Optical Pulse generator forms high-speed pulses at rates less than the period of the transmitted data.

- The bit period for these signals is compressed to T/N, multiplexed, and transmitted through optical fiber.

- A high-speed clock and regenerator demodulates the signals.

- ***All optical 3R regeneration*** processes (re-amplifying, re-shaping, and re-timing) can greatly extend the capability of this technique beyond 100 Gb/s). A demonstration of 1.28 Tb/s has been demonstrated (Nakazawa, et.al., Elect. Lett. 2000).

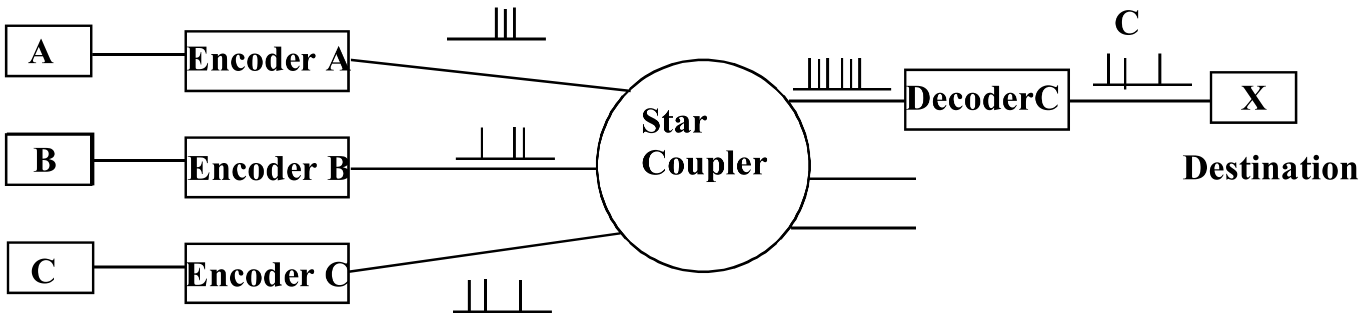
## 2. Sub Carrier Multiplexing



- Multiple digital signals are multiplexed onto one RF signal and then sent at one optical wavelength.
- MUX and DEMUX accomplished electronically not optically.
- Limited by BW of electrical and optical components.
- Can be combined with other multiplexing schemes such as SONET (Synchronous Optical Network) and DWDM to extend transmission capacity.

## 3. CODE Division Multiplexing (CDM)

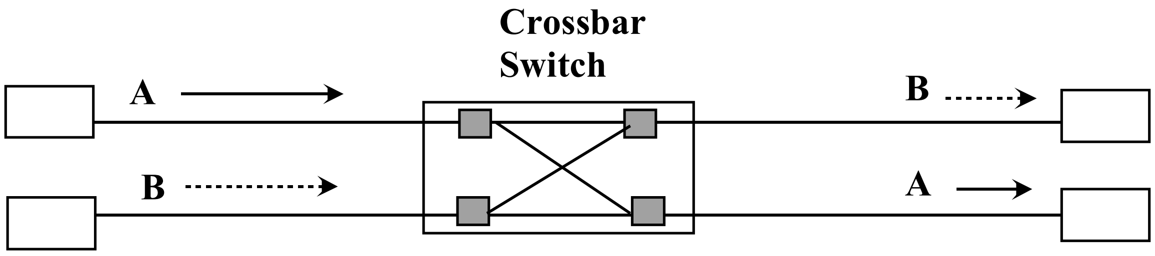
- Each channel transmits its data bits as a coded channel specific sequence over available BW, wavelength, and time slots.



## 4. Space Division Multiplexing (SDM)

- The channel routing path is determined by different spatial positions (fiber locations).

- High BW space switching matrix is formed.

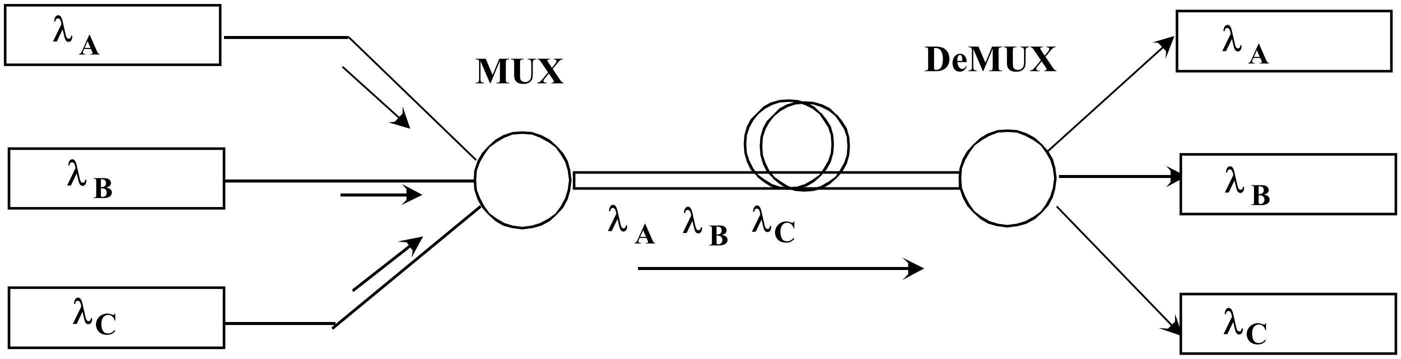


## 5. Wavelength Division Multiplexing (WDM)

- One of the most promising concepts for high capacity communication systems is wavelength division multiplexing (WDM).

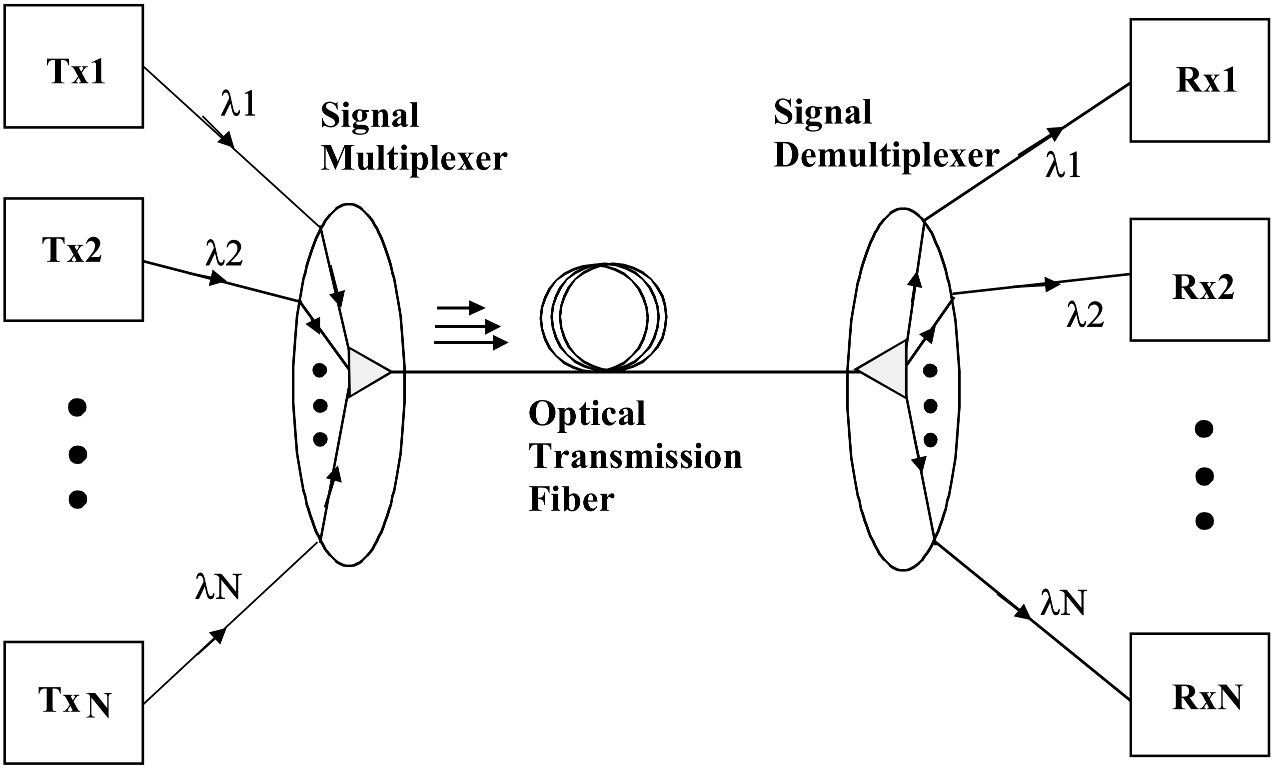
- Each communication channel is allocated to a different frequency and multiplexed onto a single fiber. At the destination wavelengths are spatially separated to different receiver locations.

- In this configuration the high carrier bandwidth is utilized to a greater extent to transmit multiple optical signals through a single optical fiber.



## *WAVELENGTH DIVISION MULTIPLEXING (WDM) Systems:*

- A basic *point-point* communication configuration is illustrated below:



- For single frequency *point-point* links the bit rate is limited ~100 Gb/s due to dispersion. This is well below the capability of the optical carrier frequency.

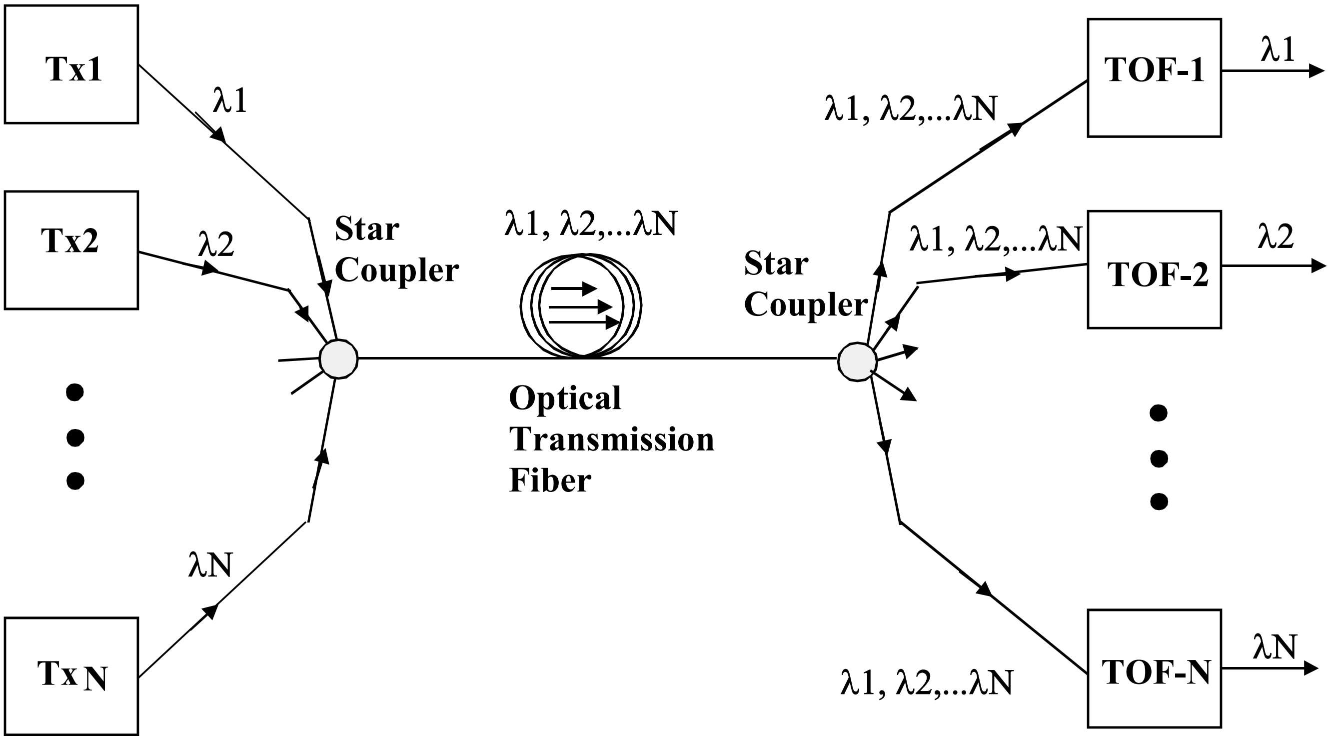
- WDM can increase the total bit rate of point-to-point systems.

- For N channels with bit rates $B_1$, $B_2$, …, $B_N$ transmitted simultaneously over a fiber of length L, the bit rate-length product becomes

$$B-L=\left(B_1+B_2+\ldots+B_N\right)\cdot L$$

- **Another type of network takes the form of *broadcast and select* system and is illustrated below.**

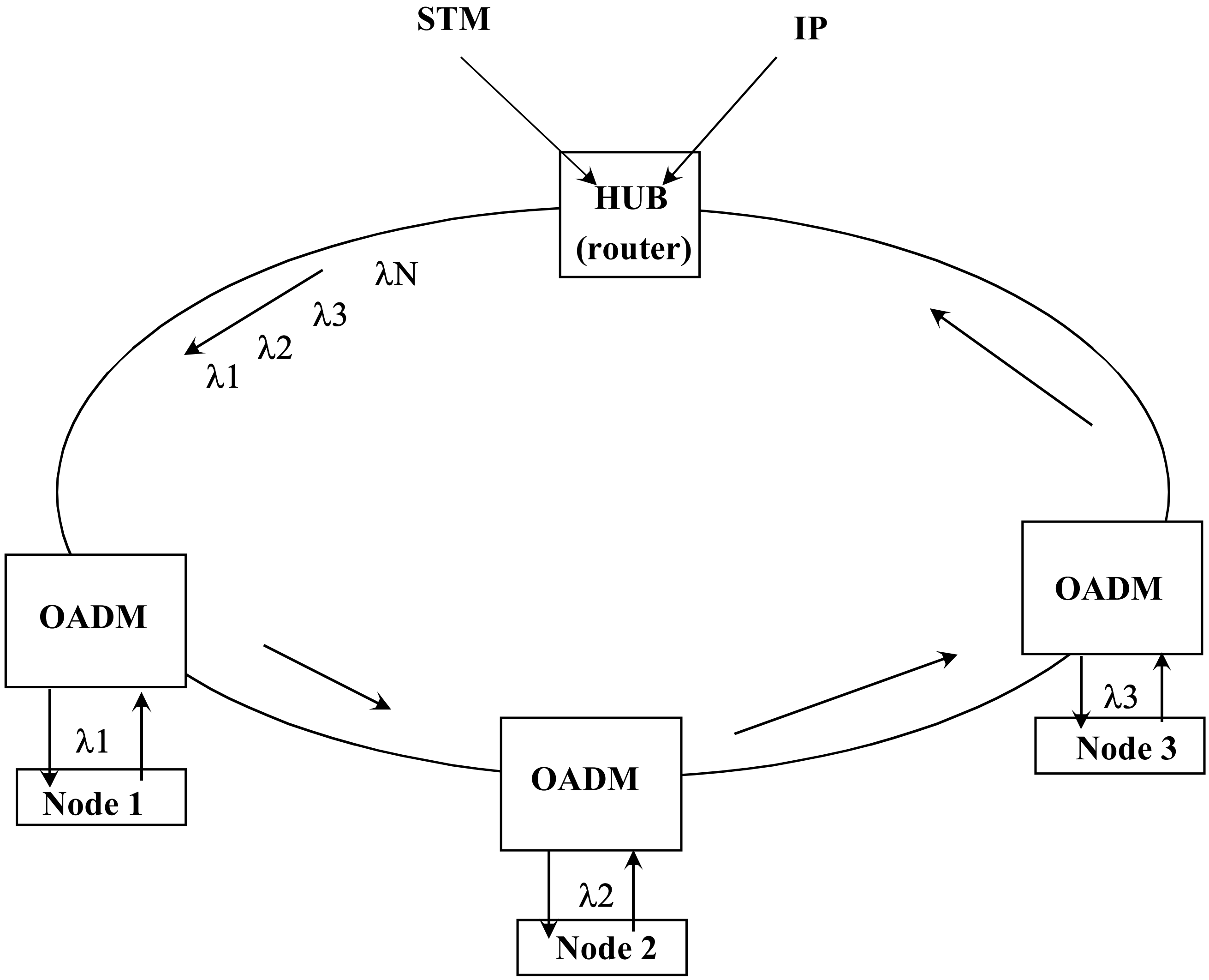
- This type uses a *star coupler* to mix signals of different wavelengths and wavelength tunable filters to extract the information.



- Although the power is decreased by a factor of 1/N this loss can be offset with the use of an optical amplifier prior to the second star coupler.

  - During the past few years dense WDM (DWDM) systems have been proposed and are being developed. These systems have wavelength separations on the order of 0.3 – 0.8 nm.

## ***DWDM RING TOPOLOGY***

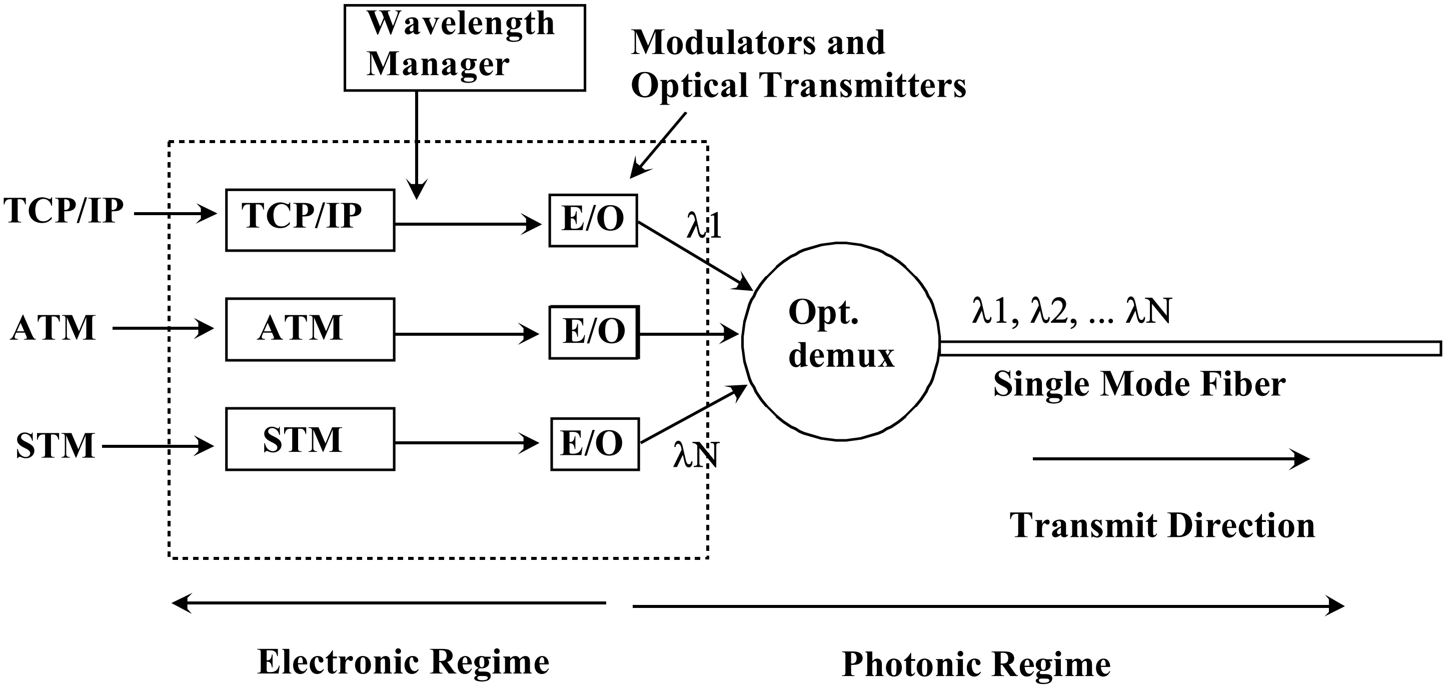


STM – Synchronous Transport Module

IP – Internet Protocol

OADM – Optical ADD-Drop Multiplexers

- The HUB acts as a controller to route information over the network.



TCP/IP – Transmission control protocol/internet protocol

ATM – asynchronous transfer mode

STM – synchronous transfer mode

## ***DWDM COMPONENT DEVELOPMENT***

- From the previous overview a number of critical components are required for the realization of DWDM communication systems. These include:

1. Sources with stable narrow band emission wavelengths

2. Tunable optical filters

3. ADD-Drop Filters

4. Broadband Optical Amplifiers

5. Optical Cross Connects

- In addition there are a number of important support components that also must be developed. These include:
    a. Optical Directional Couplers
    b. Wavelength Filters
    c. Optical isolators
    d. Optical Equalizers
    e. Polarizers, rotators, circulators
    f. Wavelength Interleavers

- System and component development is focused on operation within two low loss wavelength bands in silica fibers. These include the *C*- and *L*- bands.

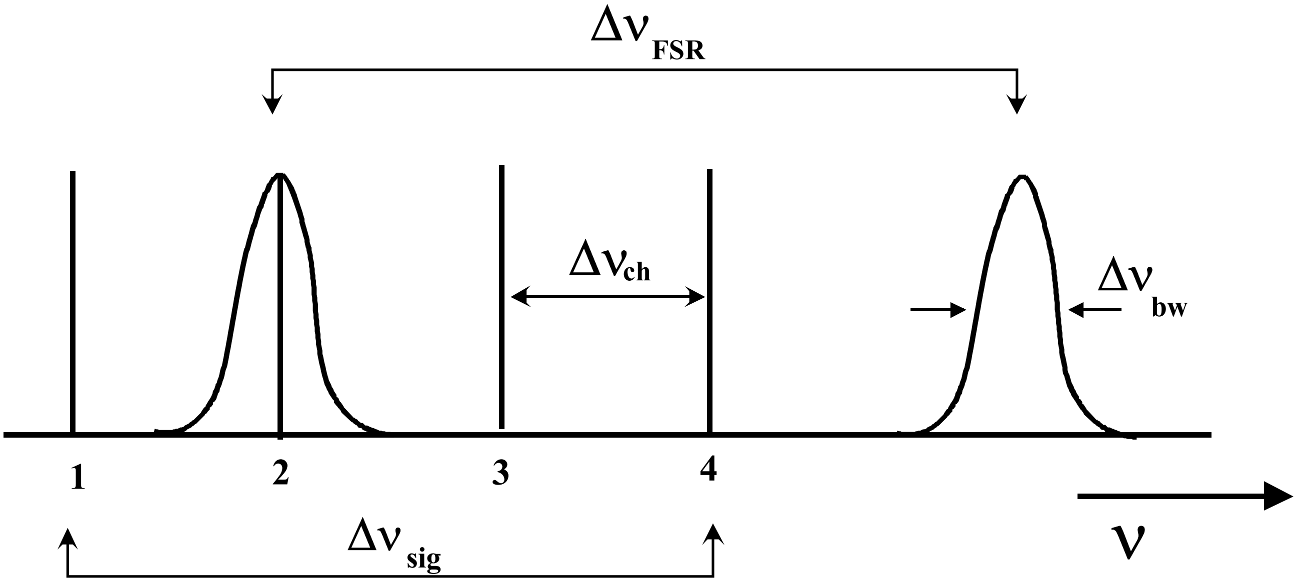
***S-Band: (1480-1520 nm)***
***C-Band: (1521-1560 nm)***
***L-Band: (1561-1620 nm)***

## ***OPTICAL TECHNOLOGIES FOR DWDM:***

- Thin Film Filters
- Micro Electro Mechanical Systems – switches and cross connects
- Passive Optical Elements (POE): waveguides, arrayed waveguide gratings AWGs, star couplers, grating devices
- Acousto-Optic devices – Bragg cells, tunable optical filters
- Micro-resonator structures – resonant grating filters, ring filters
- Functional Fiber Components – Bragg gratings and Doped Fibers
- High speed optical modulators – Mach Zehnder interferometers
- Liquid Crystal Devices
- Temperature Tunable Integrated Waveguide Devices

**Optical Filters:**

- The wavelength selective mechanism of filters is typically based either on *interference* or *diffraction*. The basic characteristics of the filter selection process are illustrated below.



- The mode spacing of the optical filter $\Delta\nu_{FSR}$ must be narrow enough to transmit one of the signal frequencies without passing adjacent channel fre+quencies. In addition the channel spacing must be greater than the BW of the individual channels. Therefore

$$\Delta\nu_{FSR} > \Delta\nu_{ch} > \Delta\nu_{bw}$$

## 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:

$$\Delta\nu_{sig} = NS_{ch}B\ ,$$

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

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

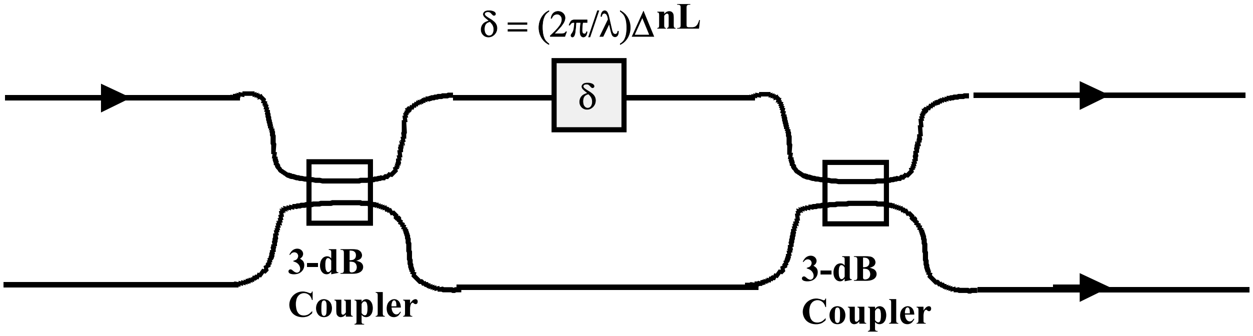
- The number of channels for FP filters is limited to 50-100 due to the limited *finesse* of practical FP filters (F~100).
- FP filters can be cascaded to increase the effective finesse (F~1000).
- Note that varying the *cavity length* or the *refractive index* can change the *pass band wavelength*. Either or both parameters can be changed by mechanical or electrical means to form a *tunable filter*.

**Mach Zehnder Filters:**

The basic form of a *Mach Zehnder interferometer* (MZI) is shown below.

- In its basic form two 3-dB couplers are connected forming an interferometer.

- An incident beam is split into two fiber paths and then recombined with the second 3-dB coupler.



- A phase shifting device is placed in one arm of the interferometer. The shift can be accomplished by changing the *optical path length* (ΔnL) in one arm of the interferometer.

- This will effectively produce a time delay ($\tau$) between the phase of the light propagating in each arm of the fiber interferometer where $\tau = \Delta(nL)/c$.

- The coherent addition of the two beams results in a change in the intensity transmitted through an arm of the interferometer

$$T(\nu) = \cos^2(\pi\nu\tau).$$

- It is possible to *cascade MZIs*. The transmittance of a chain of M interferometers is

$$T(\nu) = \sum_{m=1}^{M} \cos^2\left(\pi\nu\tau_m\right),$$

where $\tau_m$ is the delay for the m$^{th}$ interferometer.

- Schemes have been developed in which the time delays are made to successively block alternate channels.

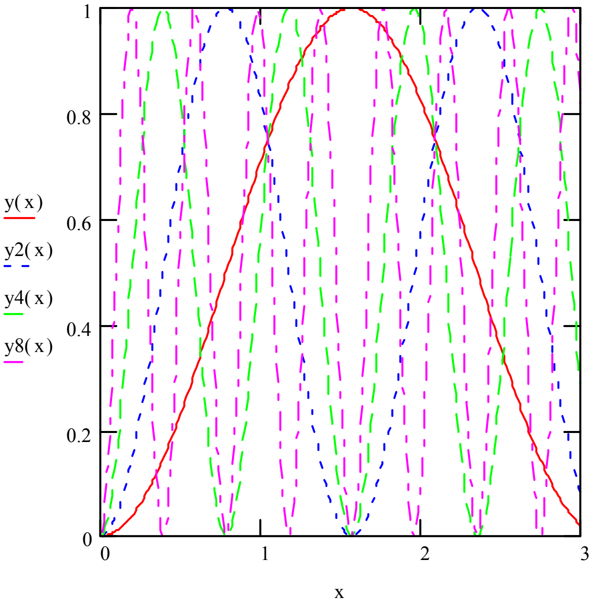
- This technique greatly increases the filtering properties of the resultant interferometer.

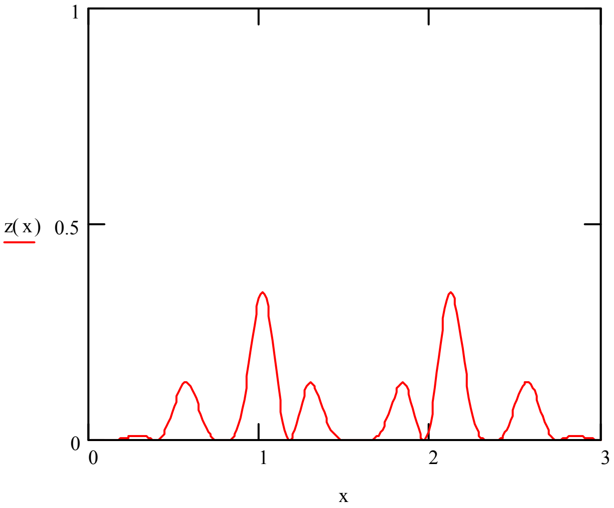
- A 10 stage MZI has been constructed that has an equivalent Fabry Perot finesse of 1600.

  - The required delay times for a cascaded interferometer system with channel spacing of $\Delta\nu_{ch}$ are

$$\tau_m = \frac{1}{2^m \Delta\nu_{ch}}.$$

  - Four Stage MZI filter





## Grating Based Filters:

Optical gratings in the form of distributed Bragg reflectors (DBR), distributed feedback (DFB) gratings as discussed previously in the context of semiconductor lasers, fiber Bragg gratings, or acousto-optic gratings can be used for wavelength selection and multiplexing.

- Wavelength selective devices can be fabricated in InGaAsP/InP materials consisting of a planar waveguide and a section with an etched DBR or DFB grating.

- The wavelength selectivity of the grating section can be electrically tuned by applying a voltage to electrodes fabricated over the grating section.

- The voltage induces electrorefraction that changes the Bragg wavelength.

## *Acousto-Optic Filters*

- The tuning range achieved with etched gratings and voltage induced electrorefraction changes is relatively small.

- Larger tuning ranges (>100 nm) can be achieved using acousto-optic filters. The only filter that can currently be used to select several wavelengths simultaneously.

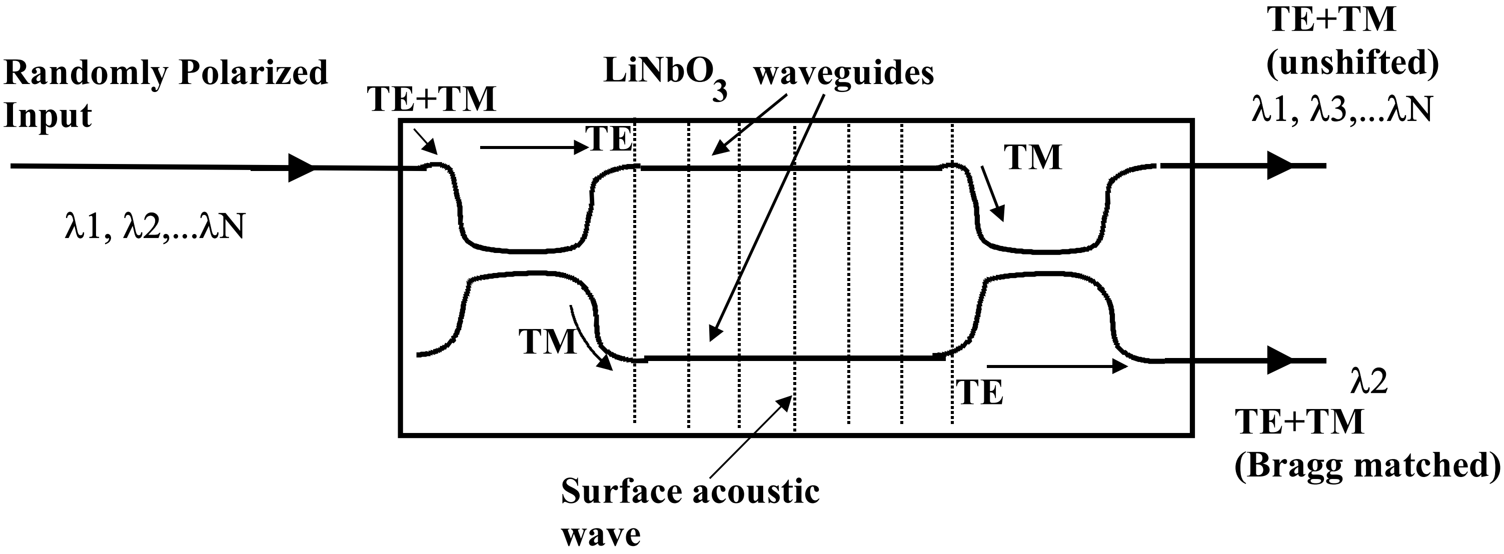
- *Basic Operation:* Assume that the input light is entirely TE polarized. At the output end of the device a polarizer is placed that selects only TM polarized light. The acousto optic (AO) device changes the polarization of a narrow spectral band of light from TE to TM. This light can then pass out of the device.

- An AO wave in an AO medium induces a periodic (period = $\Lambda_a$) change in the ordinary and extraordinary refractive indices ($n_o$, $n_e$) of the medium.

- If the refractive indices $n_{TM}$ and $n_{TE}$ of the TE and TM modes satisfy the *Bragg condition* then light couples from one polarization mode to the orthogonal state.

$$\frac{n_{TM}}{\lambda} = \frac{n_{TE}}{\lambda} \pm \frac{1}{\Lambda_a}$$

- An output polarizing BS can be used to filter out a narrow spectral band near λ that had its polarization changed.
    - If only one waveguide is used the device will be sensitive to the state of the input polarization.
    - However using two polarizing waveguide BSs in cascade as shown in the figure can be used to form a polarization insensitive device.



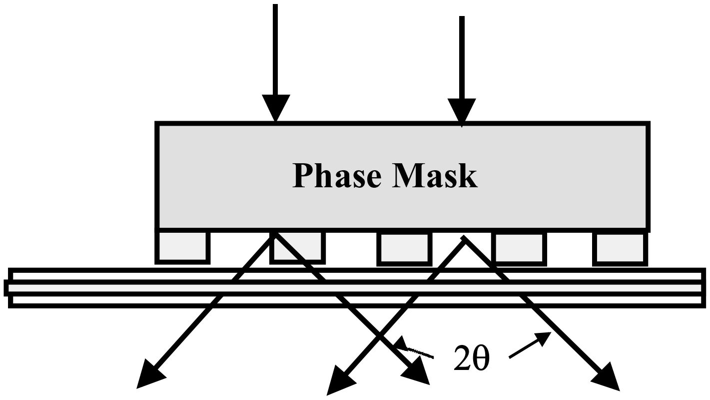
- Polarizations that are Bragg matched at $\lambda_2$ pass through one arm and non matched wavelengths pass through the other arm of the AOTF.

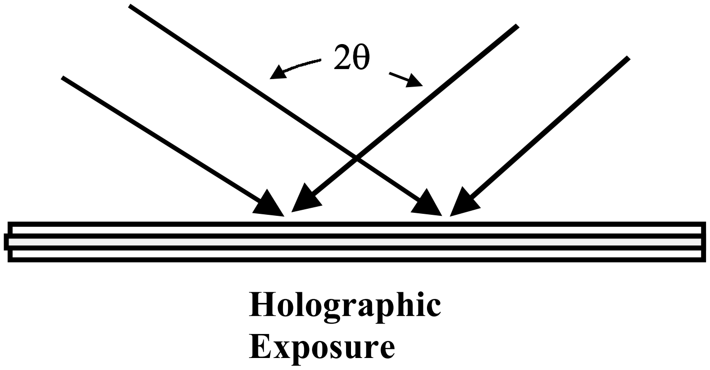
***Fiber Bragg Gratings:***

Gratings can be formed directly within the core of silica fibers either by using *holographic exposure* or by using a *phase mask* and patterning.

- The fiber is typically sensitized (doped with $GeO_2$ or by H loading of the silica) to enhance changes to the refractive index when exposed in the UV (~244 nm).
- Refractive index changes from $10^{-4}$ to $10^{-2}$ are readily obtainable.

The two most common exposure methods are shown below:



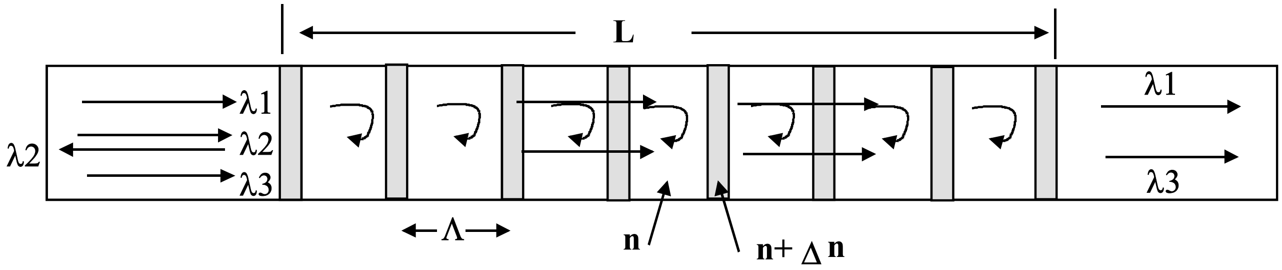


- The inter beam angle between the exposing beams determines the grating period and the wavelength that is selected by the filter.

- If the angles of the exposing beams relative to the surface normal are equal (i.e. both = θ) then the grating period set within the core is equal to

$$\Lambda = \frac{\lambda}{2 n_{core} \sin\theta} .$$

The grating formed within the core sets up a reflection grating as indicated below:



- The wavelength $\lambda_2$ selected in this case is the Bragg wavelength where

$$\lambda_B = 2n\Lambda$$

- The diffraction efficiency of a reflection grating is given by

$$\eta_{refl} = \tanh^2\left(\kappa L\right),$$

with κ the grating coupling coefficient given by $\kappa = \frac{\pi\,\Delta n}{\lambda_o}$.

- Since ***Δn*** is approximately proportional to *exposure* the efficiency of the grating *saturates* with increasing exposure.

- The spectral bandwidth (Δλ) of the grating is determined in part by the strength of the modulation produced in the refractive index (Δn).

**Two Cases can be distinguished:**

**Case A:** When $\Delta n << \frac{\lambda_B}{L}$ (i.e. Δn is small)

$$\frac{\Delta\lambda}{\lambda_B} = \frac{\lambda_B}{nL}.$$

- The spectral bandwidth is inversely proportional to the length of interaction of the field with the grating ( ***L*** ).

**Case B:** When $\Delta n >> \frac{\lambda_B}{L}$ (i.e. Δn is large)

$$\frac{\Delta\lambda}{\lambda_B} = \frac{\Delta n}{n} .$$

- In this case the grating is already saturated.

- Increasing the index modulation of the grating increases the spectral width of the grating.

- The spectral dependence does not depend on the interaction length.

A typical form for the diffraction efficiency of fiber Bragg gratings with different coupling strengths are shown below.

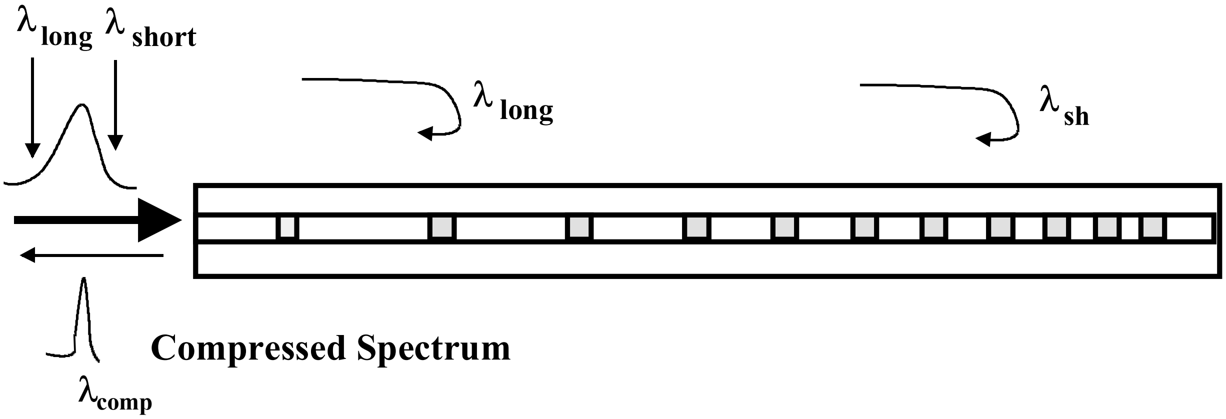
- *(from James M. Battiato PhD. Dissertation)*

The fiber format of *fiber Bragg gratings* (FBGs) make them extremely useful for a variety of applications in fiber optic communications systems.

- For instance they can be used in the design of fiber amplifiers and lasers, for *add-drop applications*, and for *dispersion compensators*.

- A ***Dispersion Compensator*** can also be made by ***chirping*** (*varying the period of*) the grating.

This is schematically shown in the figure below.



- A broad pulse enters the fiber.

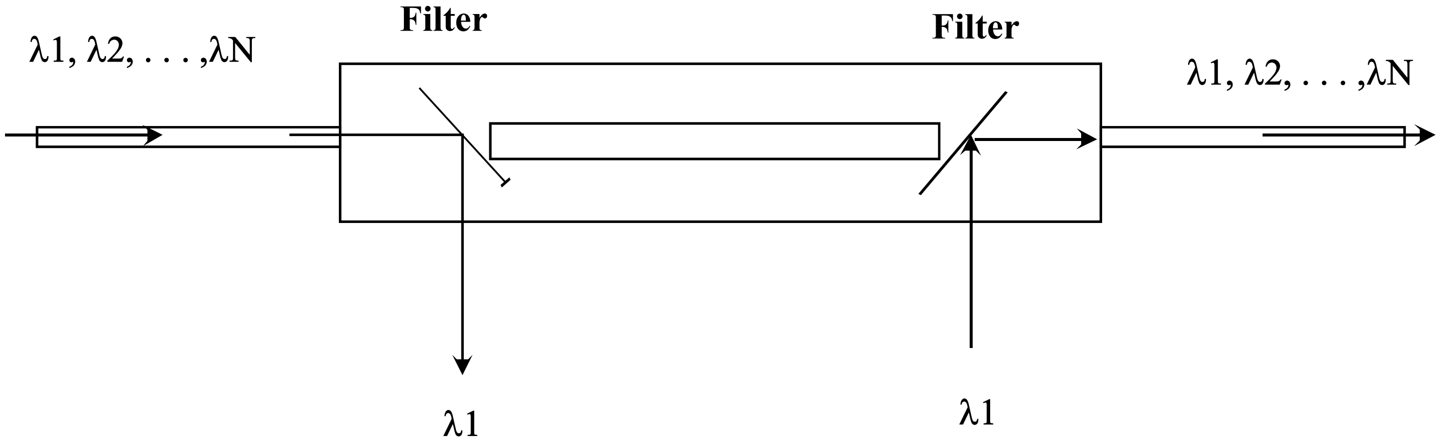
- Longer wavelength components are reflected earlier into the FBG than shorter components and equalizes the time delay of different spectral components.

- This effectively compresses the spectrum of the pulse emerging from the fiber.

## ***Optical ADD-DROP Filters***

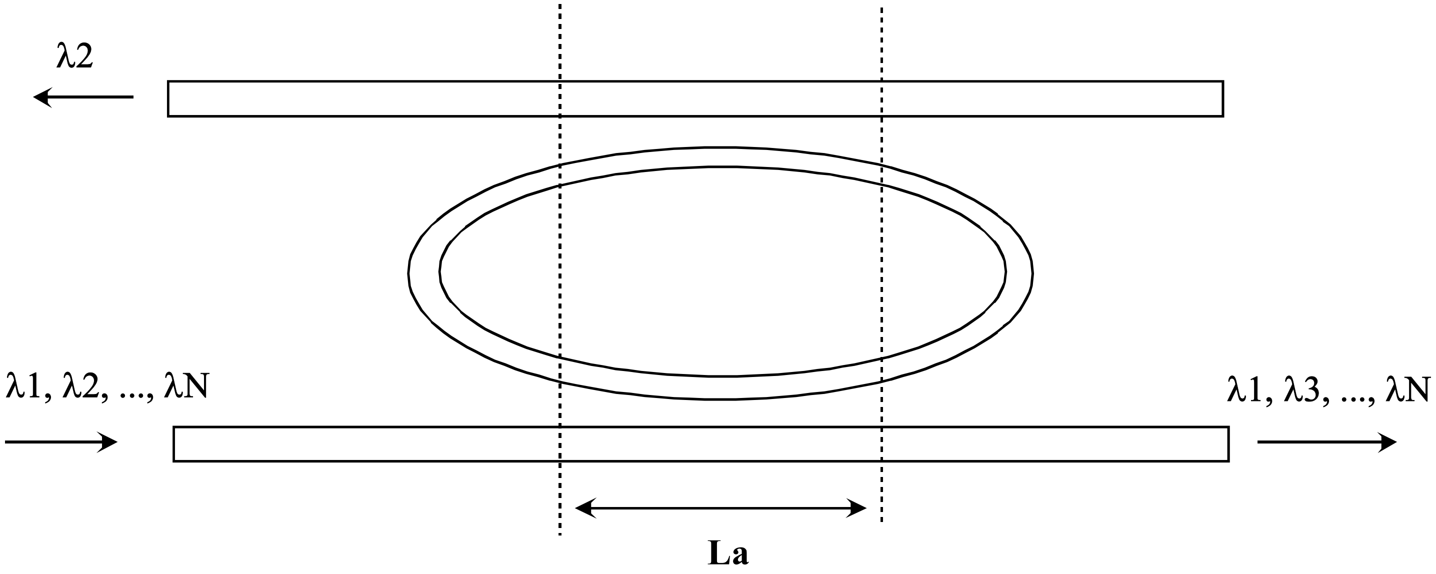
- Required for loading and downloading wavelengths from the network.

- Add-Drop Multiplexer is used to extract information from one of the wavelengths in the data stream. New data is then loaded onto this wavelength channel and it is re-sent on the fiber network.

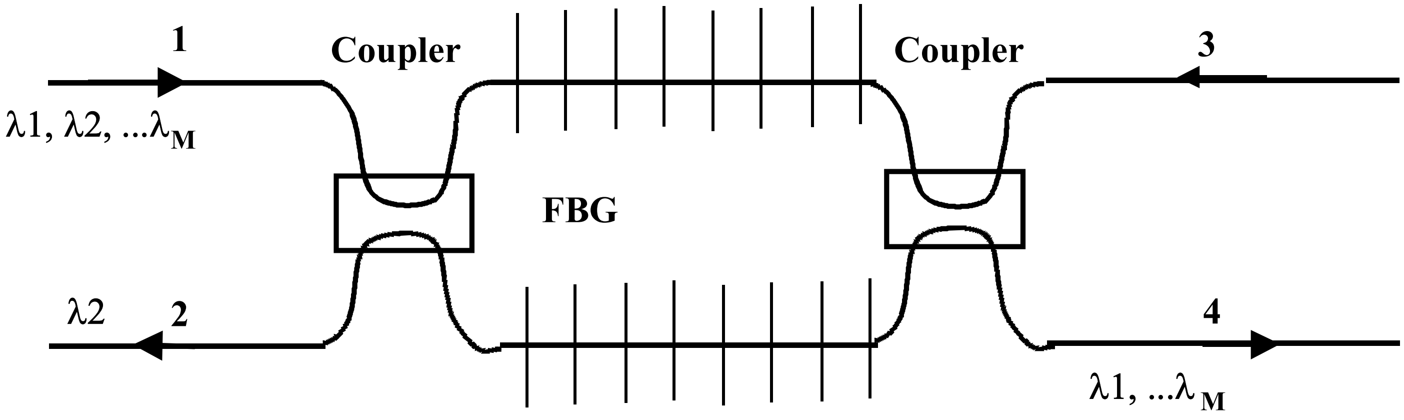


### Micro-Ring Resonators

- Small diameter resonant structures can be used to act as wavelength selective filters.
- Devices can be fabricated in GaAs-AlGaAs or Si-$SiO_2$ (fused silica) substrates.



The system below shows an *add/drop filter* based on FBGs and a MZI:



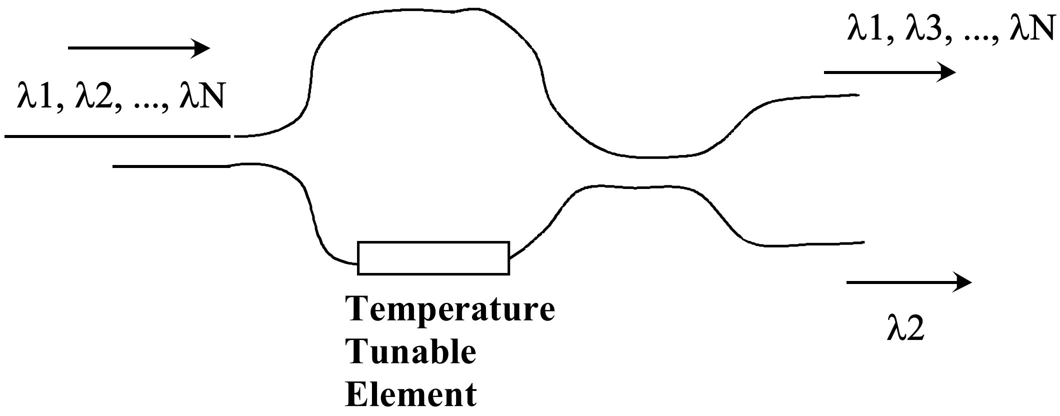
- FBGs are formed on two arms of a MZI and multiple wavelength signals enter the system through *Port1*.

- A single channel with $\lambda_{ch1}$ is within the stop band of the FBG will be totally reflected from the FBG and comes out of the coupler through *Port 2*.

- The remaining wavelengths that are not within the stop band will pass out of the device at *Port 4*.

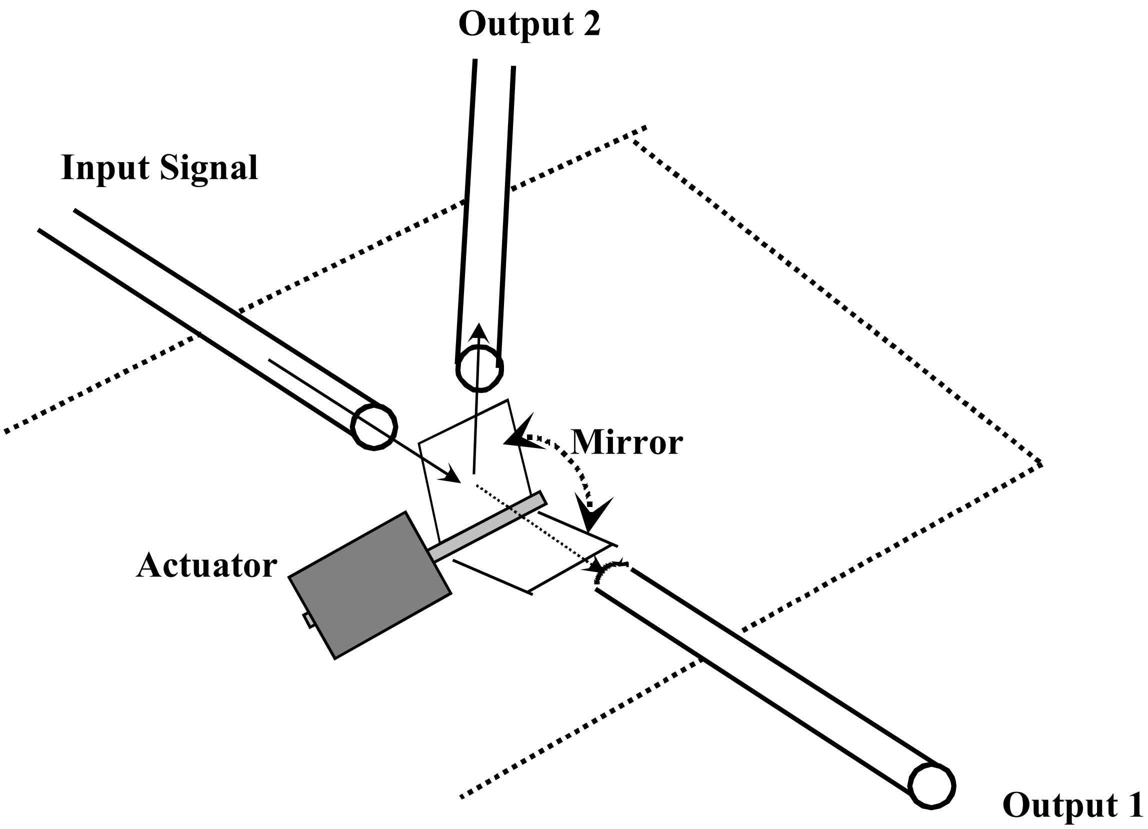
- Additional wavelengths within the stop band can be added by entering the coupler through *Port 3*.

# Temperature Tunable Mach Zehnder



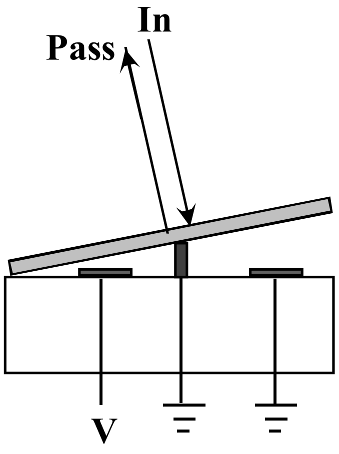
***<u>Switches:</u>***

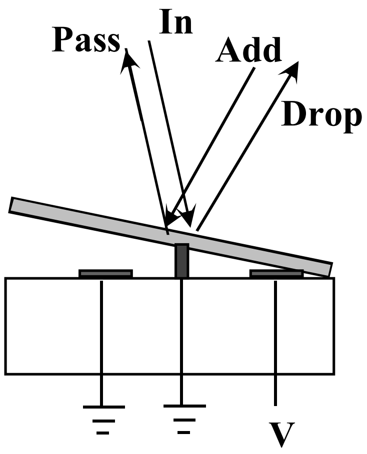
**Micro-Electro-Mechanical Systems (MEMS):**



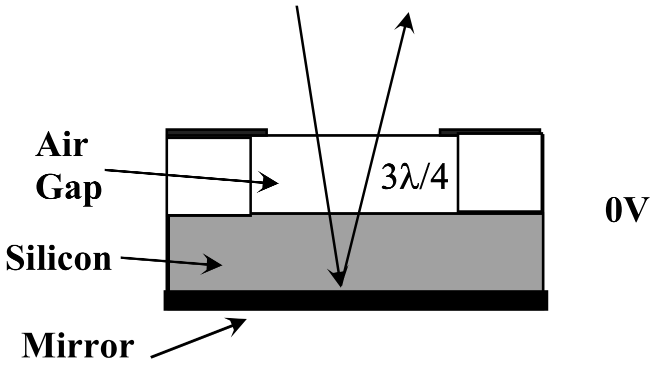
- **Simple MEMS switch for routing a signal from a fiber.**
- **Pop-Up Mirror allows signal to switch from fiber #1 to fiber #2.**

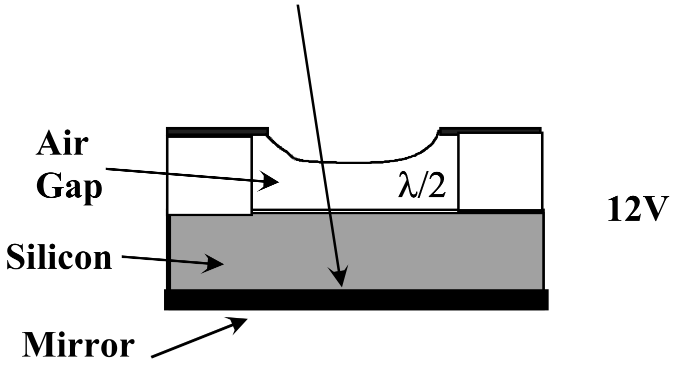
- ***Lucent* MEMS ADD-Drop Filter Switch**.



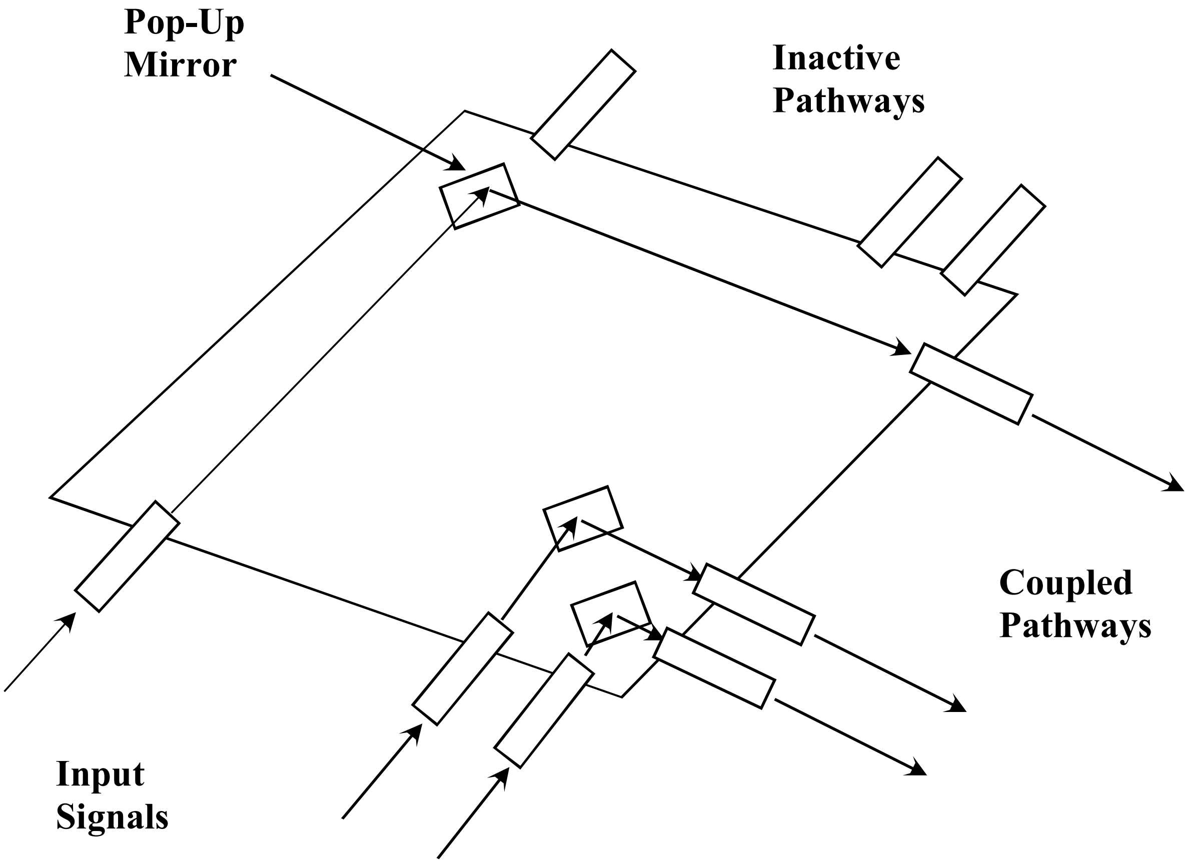


- **Tunable MEMS Cavity**





- ***AT&T Labs MEMS Cross Connect***

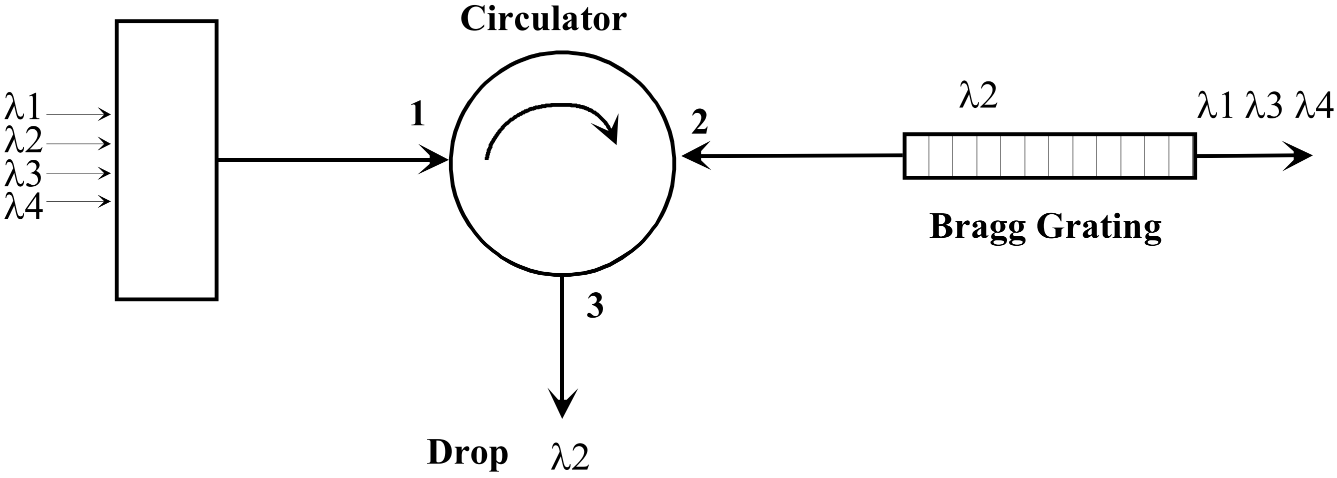


# <u>MEMS Cross – Connect</u>

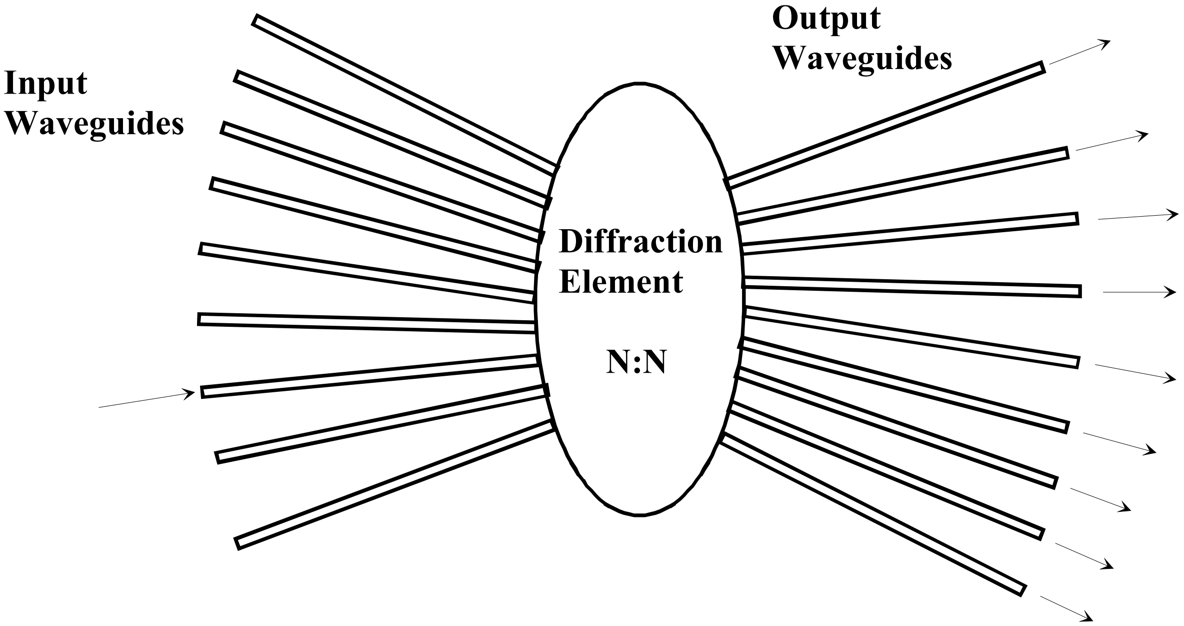
(L-Y Lin, et.al. JOLT, Vol. 18, 482-489, 2000)

## Passive Optical Network (PON) Components:

- ***Circulators*- transmits an incoming signal from Port 1 to 2 while transmitting another signal from Port 2 to 3. Typically implemented with active and passive polarization components.**

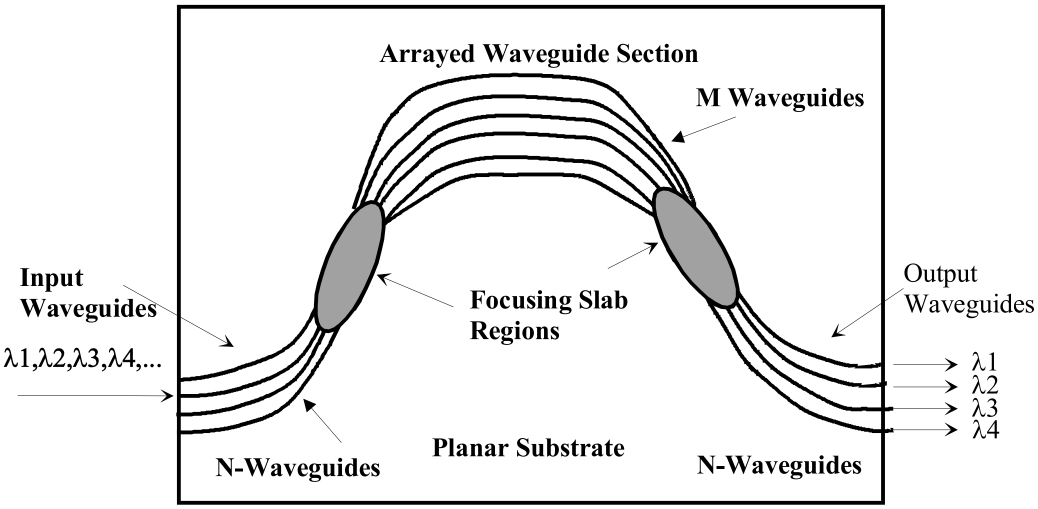


- ***Star Coupler* – A planar optic device consisting of an array of input and output waveguides connected by a slab diffraction region. Goal is to equally divide power from every input waveguide to all of the output waveguides. The splitting is independent of wavelength.**



***<u>Arrayed Waveguide Grating</u>*** **– A planar optic device for separating multiple wavelengths on an input waveguide to individual output waveguides. Commonly used as a DWDM multiplexer and demultiplexer.**

## <u>Principle of Operation of AWG:</u>



- Assume that there are N input waveguides and N output waveguides.
- The coupler connects N (I/O) waveguides to M waveguides in the arrayed section.
- The lengths of the arrayed waveguides are chosen so that the difference in length between consecutive waveguides is a constant given by ΔL.
- The first coupler splits the signal into M parts going to each of the waveguides in the arrayed section. The relative phases of these fields are determined by the distances traveled in the coupler from the input waveguides to the entrance position to an arrayed waveguide.

- The difference in distance from an input waveguide (i) to an arrayed waveguide (k) is $d_{ik}^{in}$. Similarly the distance difference from the arrayed waveguide (AW) output to the output wavguide entrance is $d_{ik}^{out}$.
- The difference in path length between arrayed waveguide k and k-1 is ΔL.
- Relative phase from input I to output j is:

$$\phi_{ijk} = \frac{2\pi}{\lambda}\left(n_1 d_{ik}^{in} + n_2 k\Delta L + n_1 d_{ik}^{out}\right); \quad k = 1,\ldots,M$$

$n_1$ is the index of the input and output couplers and $n_2$ is the index of the Aws.

  - λs such that $\phi_{ijk}, k = 1,\ldots,M$ differ by 2π add in phase at output *j*. This is the selection mechanism.
  - To determine what type of coupler/AW structure satisfies this condition let $\begin{aligned} d_{ik}^{in} &= d_i^{in} + k\delta_i^{in} \\ d_{kj}^{out} &= d_j^{out} + k\delta_j^{out} \end{aligned}$
  - The phase difference then becomes

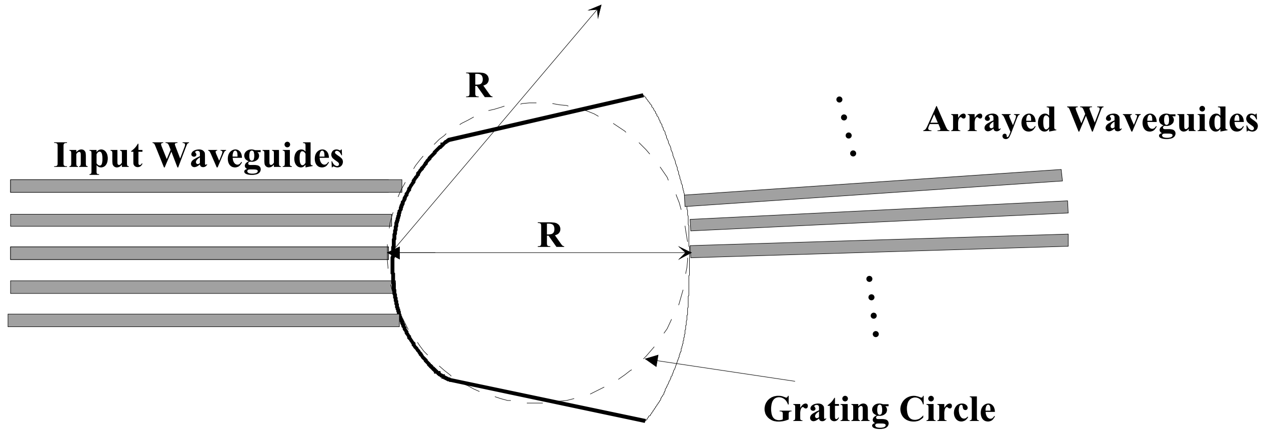
$$\phi_{ijk} = \frac{2\pi}{\lambda}\left(n_1 d_i^{in} + n_1 d_j^{out}\right) + \frac{2\pi k}{\lambda}\left(n_1\delta_i^{in} + n_2\Delta L + n_1\delta_j^{out}\right)$$

Wavelengths that satisfy the condition:

$$p\lambda = n_1\delta_i^{in} + n_2\Delta L + n_1\delta_j^{out} \quad p = 0,1,2,\ldots$$

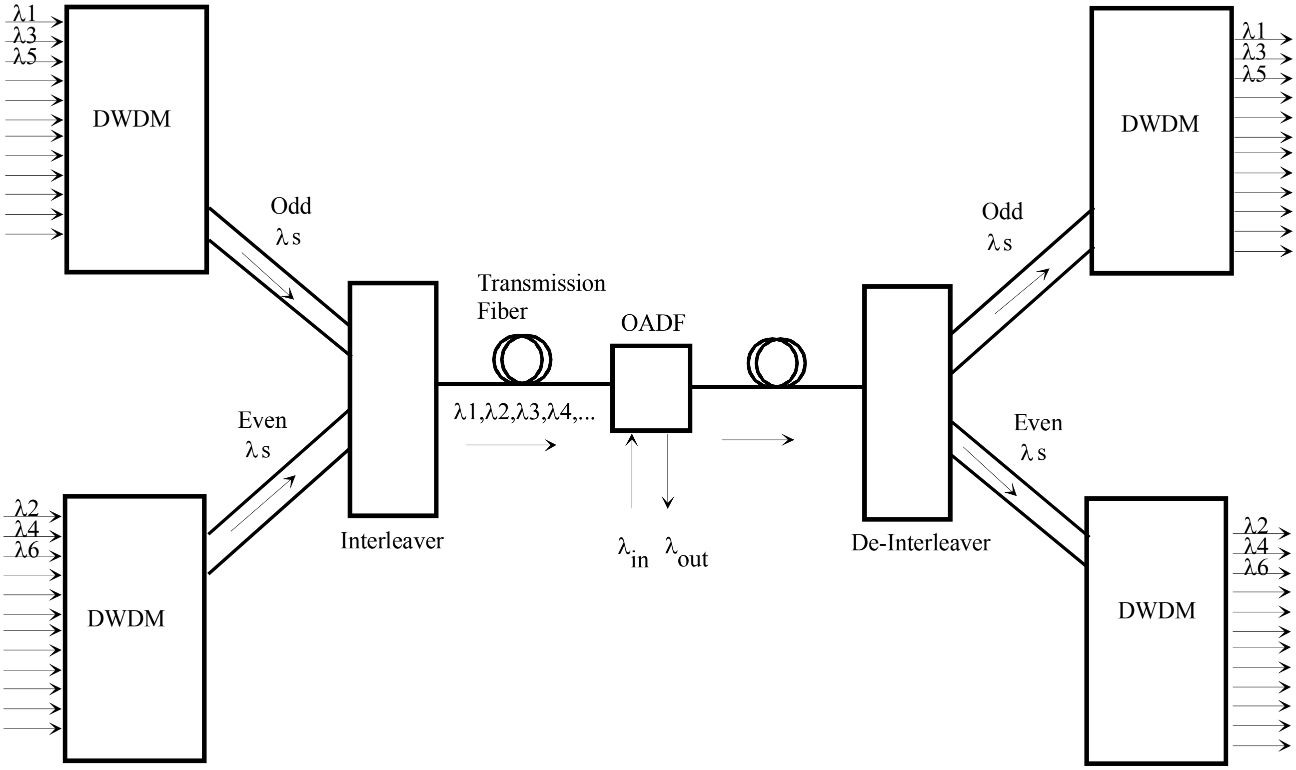
will add in phase at the output positions *j*.

- This phase requirement can be met using a Rowland Circle construction for the design of the I/O coupler.



- The radius of the arrayed waveguides lie along a circle of *radius R*. The input waveguides lie along a circle of *diameter R.*
- R is the *Rowland Circle*.
- Note that after the phase reaches 2π another set of wavelengths satisfies the matching conditions. Therefore there will be a FSR for the AWG as well.

# High Performance DWDM System



- ***Interleaver- Interleaves wavelengths from different DWDM combiners allowing larger effective spectral separation through the transmission fiber.***

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