Components

Optical communication systems

Components

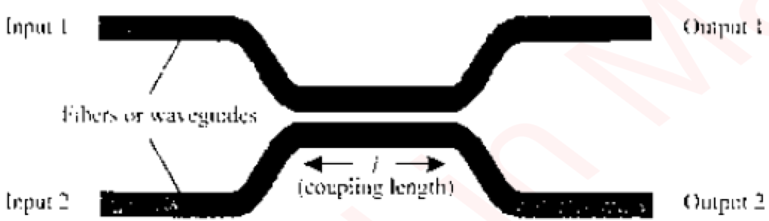
- Couplers
- Lasers
- Photodetectors
- Optical amplifiers
- Optical switches
- Filters
- Multiplexers

Couplers

Reciprocal device

Couplers

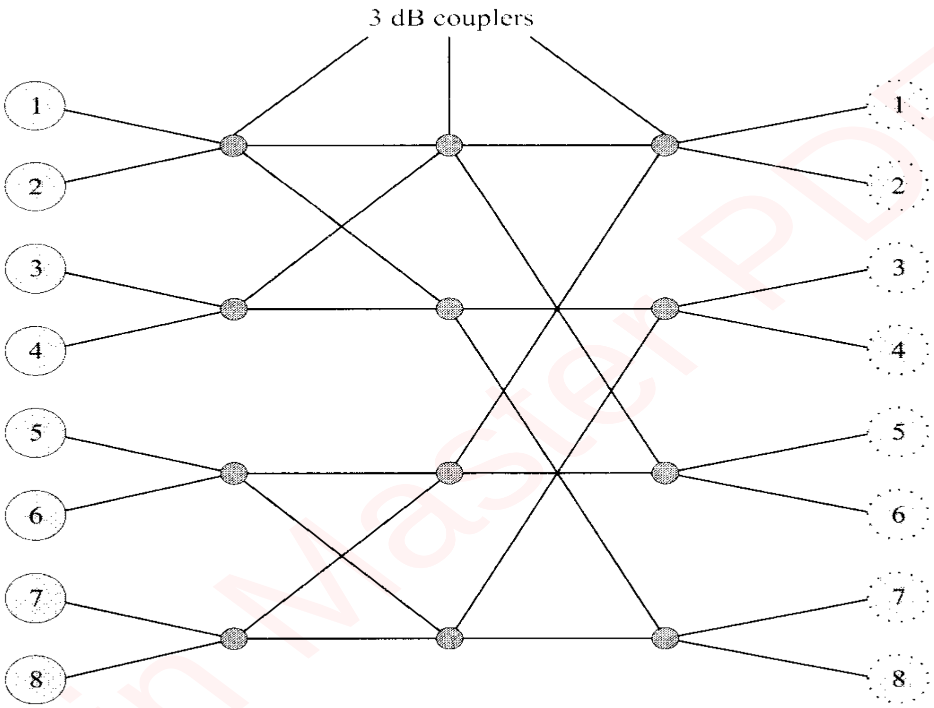
- Combine –split signals
- Categories
  - Wavelength selective
  - Wavelength independent
- α - coupling ratio
  - 2 x 2 coupler takes a fraction α of the power from input 1 and places it on output 1 and the remaining fraction 1-α on output 2.



A directional coupler.

- 3dB coupler
  - Distribute input signal equally among two output ports
- n x n star coupler
  - Generalization 3dB 2 x 2 coupler
  - Construction
    - Interconnection of 3 dB couplers
    - Integrated optics

Coupler-Applications



- A star coupler with eight inputs and eight outputs made by combining 3 dB couplers.
- The power from each input is split equally among all the inputs

Coupler-Applications

- Tap off a small portion of the light stream for monitoring purposes
  - α close to 1 (0.90-0.95)
- Building blocks
  - Modulator
  - Switches
  - Filters
  - Multiplexers/demultiplexers

Wavelength selective coupler

- Depend on the wavelength of the signal
- Combine signals at 1310nm and 1550nm without loss
- Separate the two signals in on a common fiber
- Combine 980nm or 1480nm pump signals along with a 1550nm signal into an EDFA

Principle of Operation

- Light "couples" from one wavelength to the other
  - The propagation mode of the combined waveguide
- Electric fields outputs (E_{o1} ,E_{o2}), inputs(E_{i1}, E_{i2})

- l :coupling length

$$\begin{pmatrix} E_{o1}(f) \\ E_{o2}(f) \end{pmatrix} = e^{-i\beta l} \begin{pmatrix} \cos(\kappa l) & i\sin(\kappa l) \\ i\sin(\kappa l) & \cos(\kappa l) \end{pmatrix} \begin{pmatrix} E_{i1}(f) \\ E_{i2}(f) \end{pmatrix}$$

- β:propagation constant in each of the two waveguides of the directional coupler
- k:coupling coefficient (function of the width of the waveguides)
- When used only one active input

$$\begin{pmatrix} T_{11}(f) \\ T_{12}(f) \end{pmatrix} = \begin{pmatrix} \cos^2(\kappa l) \\ \sin^2(\kappa l) \end{pmatrix} \qquad T_{ij}(f) = \left|E_{oj}\right|^2 / \left|E_{ii}\right|^2$$

Principle of Operation

- $T_{ij}(f)$:power transfer function from input i to output j
- For a 3dB coupler the coupling length must be chosen to satisfy

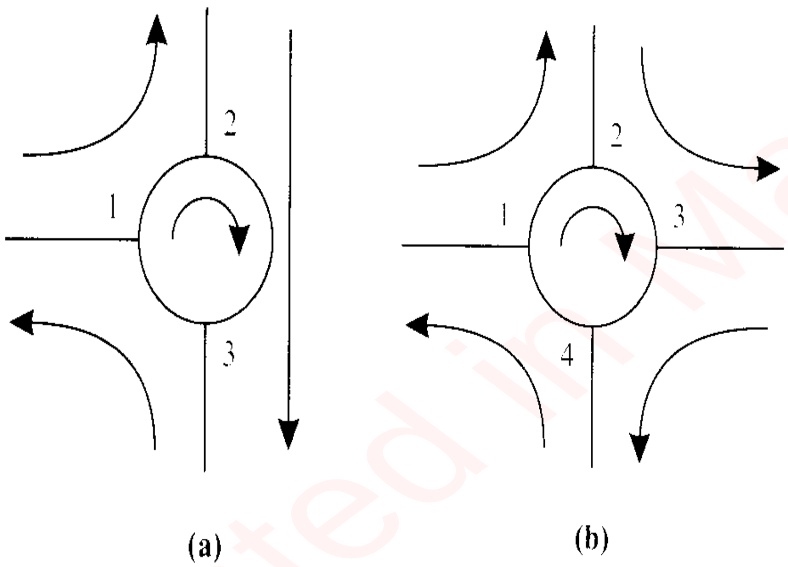
$$\kappa l = (2k+1)\pi / 4$$

- k:nonnegative integer

Isolators and Circulators

Circulator

- Similar to isolator
- Multiple ports (3-4)
- Useful to construct optical add/drop elements
- Operate the same principles as isolators

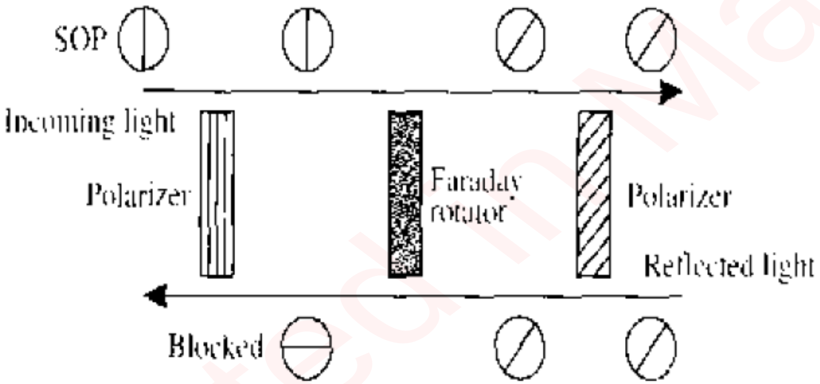


- Functional representation of circulators:
  - (a) three-port and
  - (b) four-port.

The arrows represent the direction of signal flow

Isolator

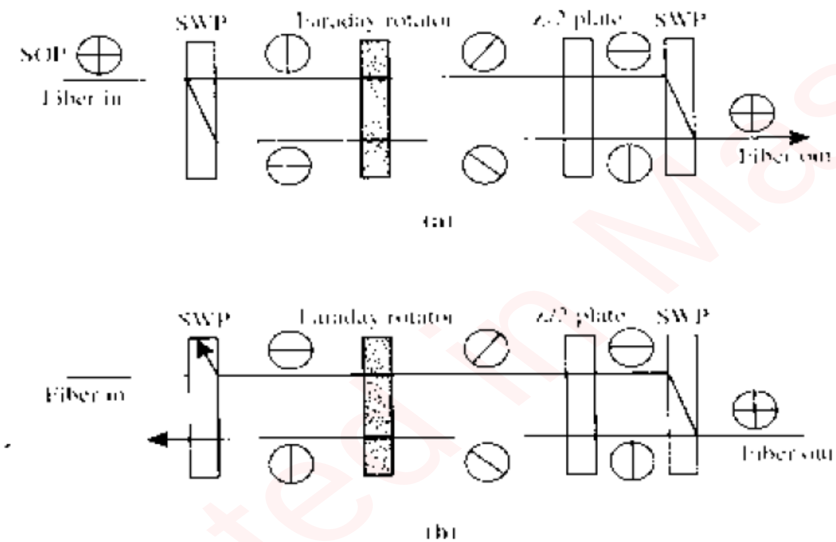
- Nonreciprocal device
- Allow transmission in one direction
- Use at the output of optical amplifiers and lasers
- Key parameters
  - Insertion loss (loss in forward direction - 1dB)
  - Isolation (loss in reserve direction – 40-50dB)



- Principle of operation of an isolator that works only for a particular state of polarization of the input signal

Principle of operation

- Vertical state of polarization (SOP)
- Polarizer – passes only vertical SOP and blocks horizontal SOP
- Faraday rotator – rotates the SOP clockwise 45°
- Polarizer – passes only SOPs with 45° orientation
- Light entering the device from the right due to a reflection is blocked



Polarization independent Isolator

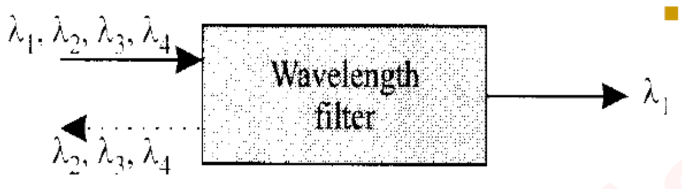
- This uses spatial walk-off polarizers at the input and outputs.
  - (a) Propagation from the left to right.
  - (b) Propagation from right to left.

Multiplexers and filters

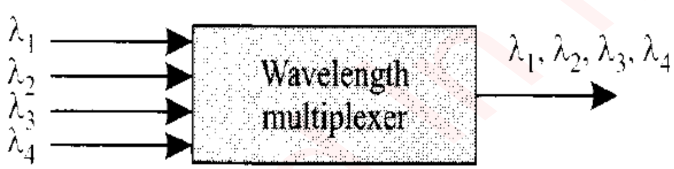
Wavelength selection technologies

Optical Filters

- Essential components in transmission systems
  - Multiplex and demultiplex wavelengths in WDM systems
  - Provide equalization of the gain and filtering of noise in optical amplifiers



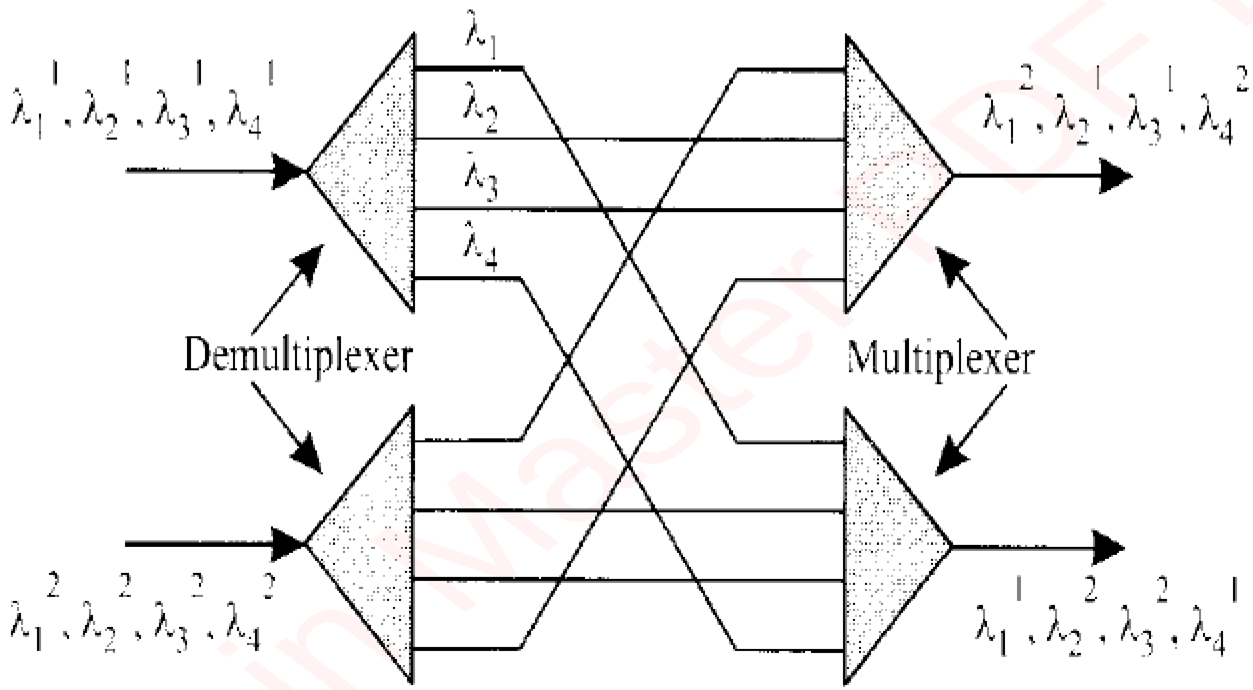
(a)



(b)

- Different applications for optical filters in optical networks.
  - (a) A simple filter, which selects one wavelength and blocks the remaining wavelengths or makes them available on a third port.
  - (b) A multiplexer, which combines, multiple wavelengths into a single fiber.
  - In the reverse direction, the same device acts as a demultiplexer to separate the different wavelengths.

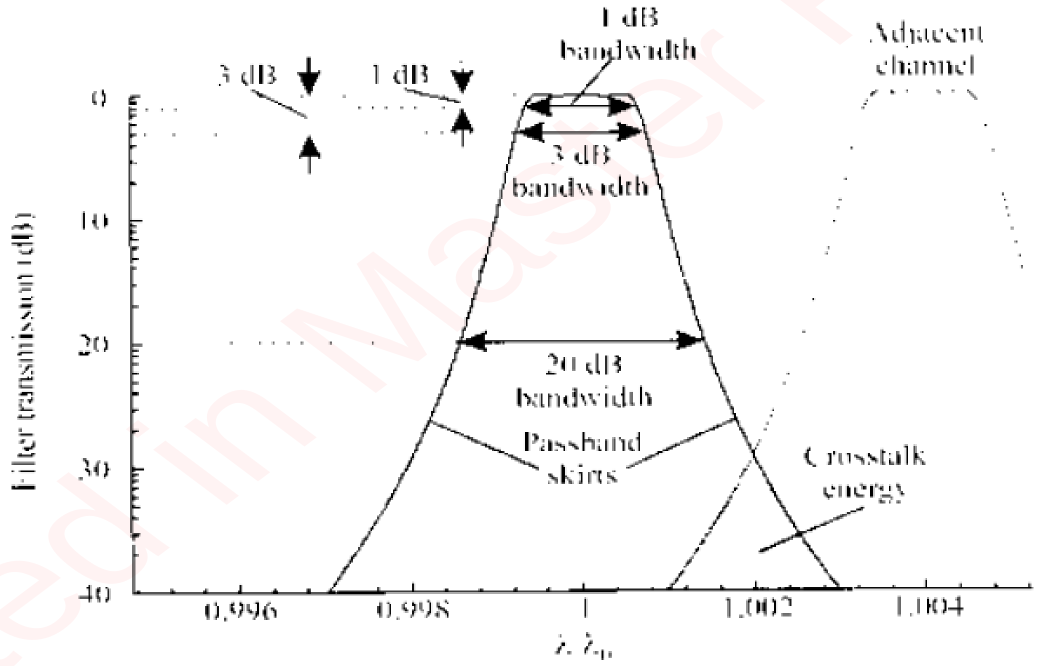
Static WXC



- A static wavelength crossconnect. The device routes signals from an input port, to an output port based on the wavelength.

Optical filters-key characteristics

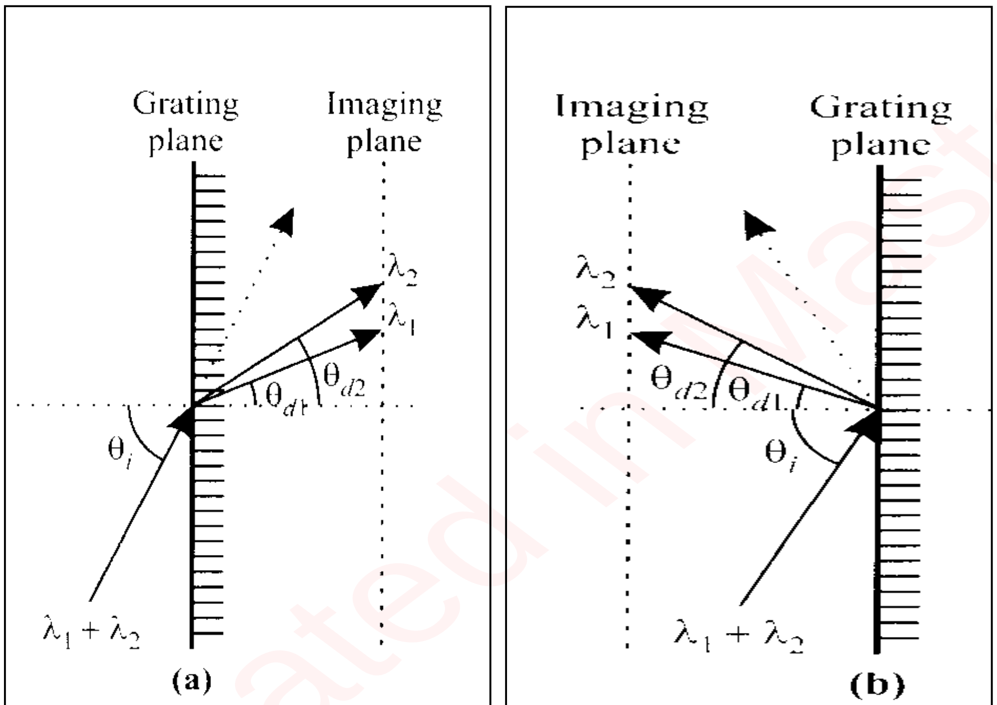
- Low *insertion losses,* Loss independent of the SOP of the input signal
- Passband of a filter should be insensitive to variations in ambient temperature
- Flat passband. Passband skirts should be sharp to reduce the amount of energy passed through the adjacent channels



λ_0 is the center wavelength of the filter and λ is the input signal wavelength.

Gratings

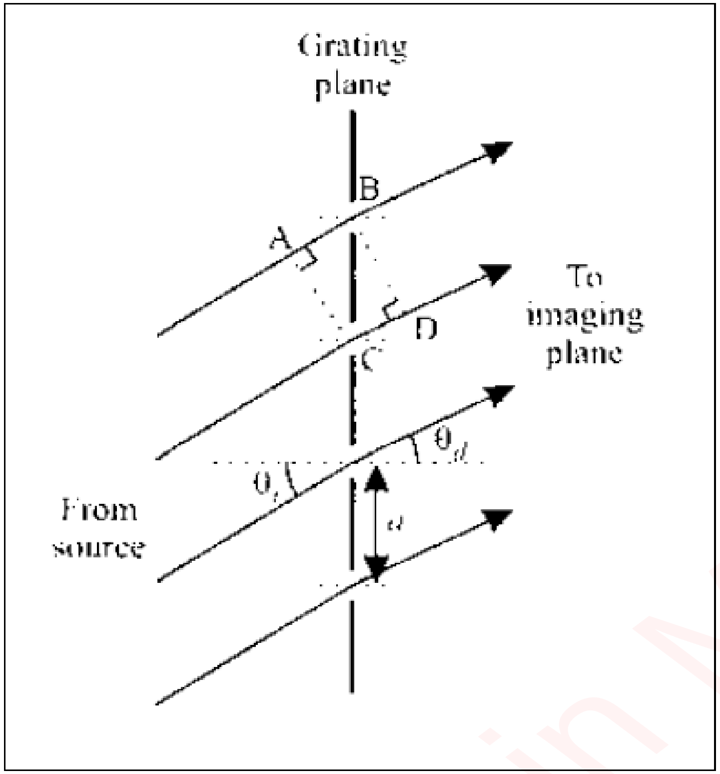
- Grating –any device whose operation involves interference among multiple optical signals originated from the same source but with different relative *phase shifts*
- *Gratings- separate light into its constituent wavelengths*
- In WDM systems gratings are used as demultiplexers



- (a) A transmission grating
- (b) A reflective grating.

- θi is the angle of incidence of the light signal.
- The angle at which the signal is diffracted depends on the wavelength θ_{d1} for wavelength λ_1 and θ_{d2} for wavelength λ_2)

Principle of operation



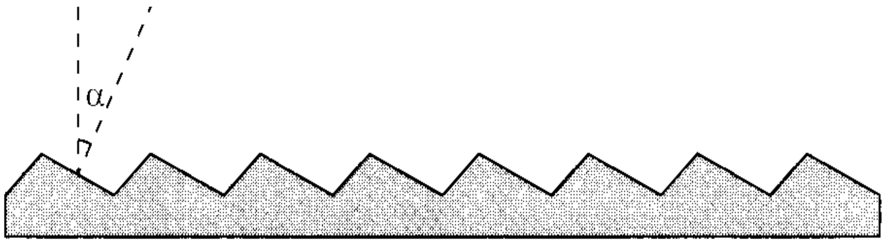
- ***a*** – the distance between adjacent slits (the pitch of the grating)
- The light rays diffracted at an angle $\boldsymbol{\theta_d}$ to the grating plane.
- Grating equation: The path length difference between rays diffracted at angle θ_d for adjacent slits is

AB – CD = $a[\sin(\theta_i) - \sin(\theta_d)] = m\lambda$

m – integer (order of the grating)

- The grating equation is satisfied at different points in the imaging plane for different wavelengths
- When the grating is used as a demultiplexer in a WDM, light is collected from only one of these angles

Blazed Grating



- Blazed reflection grating with blaze angle a.
- The energy in the interference maximum corresponding to the blaze angle is maximized.

Bragg Gratings

- Any periodic perturbation in the propagation medium serves as Bragg grating
- Lasers use Bragg gratings to achieve single frequency operation
- Bragg gratings to written in fibers can be used to make a variety of devices such as filters, add/drop multiplexers, and dispersion compensators

Bragg Gratings - Principle of operation

- Two waves propagating in opposite directions with propagation constants $\boldsymbol{\beta_0}$, $\boldsymbol{\beta_1}$
- Energy is coupled from one wave to the other if they satisfy the Bragg phase-matching condition

$$|\beta_0 - \beta_1| = \frac{2\pi}{\Lambda}$$

- **Λ** – period of the grating

- In a Bragg grating, energy from the forward propagating mode of a wave at the right wavelength is coupled into a backward propagating mode
- Consider a light wave with propagation constant β1 propagating from left to right
- The energy from this wave is coupled onto a scattered wave traveling in the opposite direction at the same wavelength provided

Bragg Gratings - Principle of operation

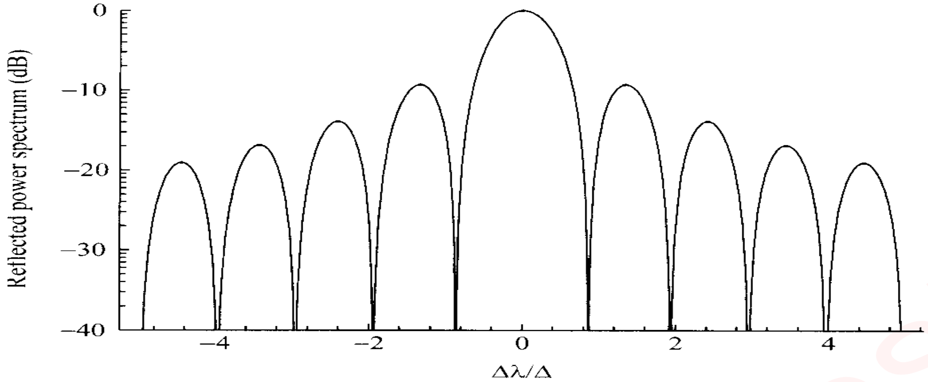
$$\left|\beta_0 - (-\beta_0)\right| = 2\beta_0 = \frac{2\pi}{\Lambda}, \beta_0 = 2\pi n_{eff} / \lambda_0$$

- λ_0 – wavelength of the incident wave
- n_{eff} – effective refractive index of the waveguide or fiber
- The wave is reflected provided

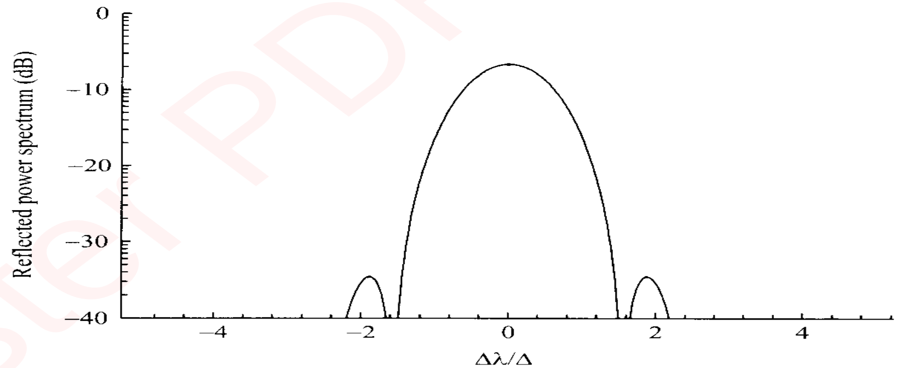
$$\lambda_0 = 2 n_{eff} \Lambda$$

- λ_0 – the Bragg wavelength

Bragg Gratings - Principle of operation



(a)



(b)

- Reflection spectra of Bragg gratings with
  - (a) uniform index profile and (b) apodized index profile.
- Δ is a measure of the bandwidth of the grating and is the wavelength separation between the peak wavelength and the first reflection minimum, in the uniform index profile case.
- Δ is inversely proportional to the length of the grating.
- Δλ is the detuning from the phase-matching wavelength.

Fiber Gratings

- Used for a variety of applications
  - Filtering
  - Add/drop functions
  - Compensating for accumulated dispersion of the system

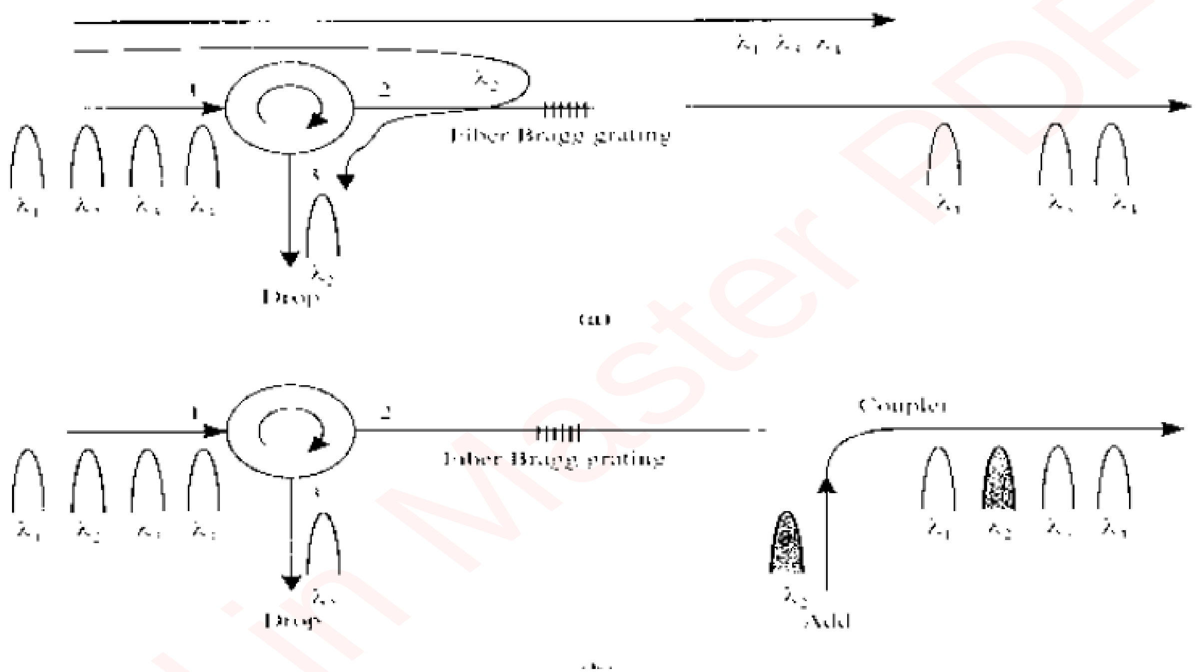
- Advantages
  - Low loss
  - Ease of coupling (with other fibers)
  - Polarization insensitivity
  - Low temperature coefficient
  - Simple packaging
  - low-cost devices

Fiber Gratings

- Gratings are "written" in fibers by making use of *photosensitivity* of certain types of optical fibers
- Phase masks used to produce gratings
  - Phase mask is a diffractive optical element
- Classification based on the period of grating
  - Short-period
  - Long-period

- Short-period
  - Called Bragg gratings
  - Periods comparable to the wavelength (0.5 μm)
- Long-period
  - Periods much greater than the wavelength (hundred micrometers -few millimeters)
  - Used as filters inside EDFA's to compensate for their nonflat gain spectrum.

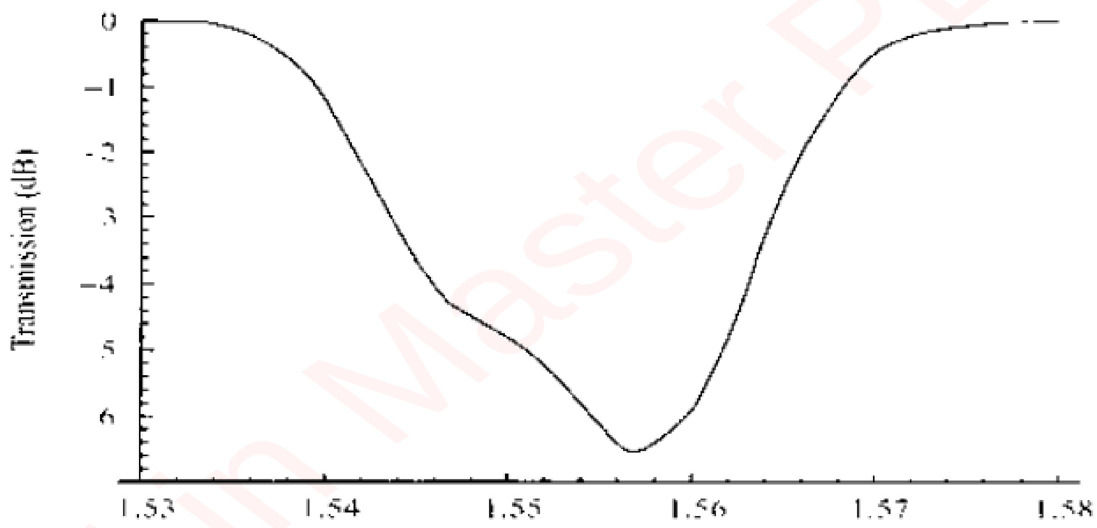
Fiber Gratings



- Optical add/drop elements based on fiber bragg gratings.
  - (a) A drop element.
  - (b) A combined add/drop/element

Fiber Gratings-principle of operation

- Retain all attractive properties of fiber gratings



- Transmission spectrum of a long-period fiber Bragg grating used as a gain equalizer for erbium-doped fiber amplifier.

Principle of operation

- In fiber Bragg gratings, energy from the forward propagating mode in the fiber core at the right wavelength is coupled into a backward propagating mode
- β – propagation constant of the mode in the core (single mode)
- β_{cl}^{p} – pth-order cladding mode
- Phase-matching condition $\beta - \beta_{cl}^{p} = \frac{2\pi}{\Lambda}$
- Λ – pitch of the grating
- n_{eff} and n_{eff}^{p} – effective refractive indices of the core and p^{th}-order cladding modes
- The wavelength at which energy is coupled from the core to the cladding mode can be obtained as

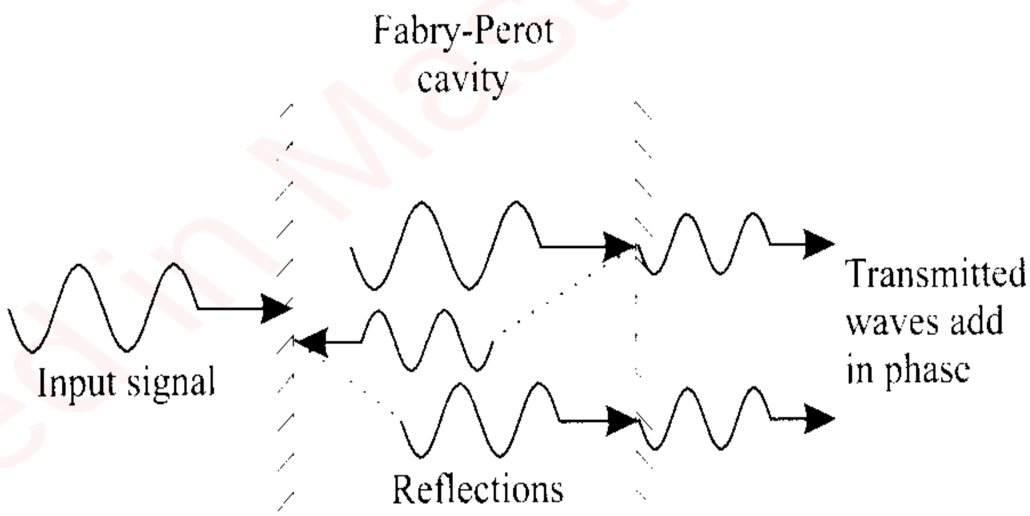
$$\lambda = \Lambda(n_{eff} - n_{eff}^{p})$$

Where we have used the relation $\beta = 2\pi n_{eff} / \lambda$

Fabry-Perot Filters (etalon)

- Consists of the cavity formed by two highly reflective mirrors placed parallel to each other
- Used in lasers
- They can be tuned to select different channels in WDM systems (change the cavity length)

- Principle of operation of a Fabry-Perot filter:



Principle of operation

- The input signal is incident on the left surface of the cavity
- After one pass the cavity, a part of the light leaves the cavity through the right facet and a part is reflected
- A part of the reflected waves is again reflected by the left facet to the right facet

- For those wavelengths for which the cavity length is an integral multiple of half the wavelength of the cavity
  - A round trip through the cavity is an integral multiple of the wavelength
- All the light waves transmitted through the right facet add in phase
  - Resonant wavelengths of the cavity

Principle of operation

- Transfer function of a filter is the fraction of input light power that is transmitted by the filter as a function of optical frequency *f*, or wavelength

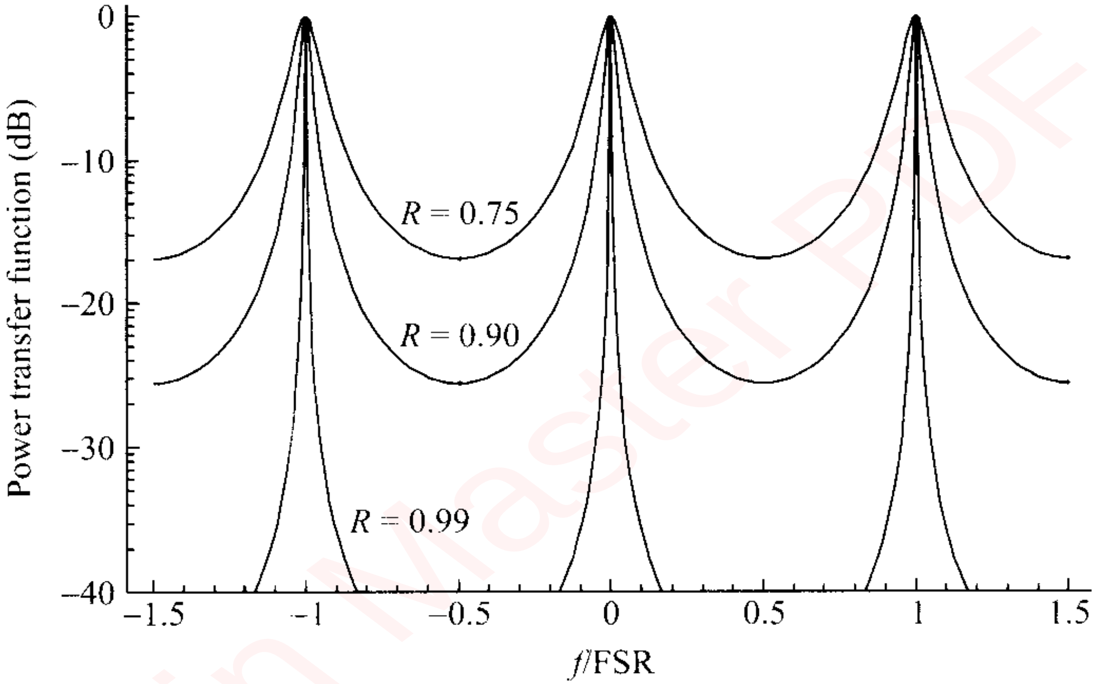
$$T_{FP}(f) = \frac{\left(1 - \frac{A}{1-R}\right)^2}{\left(1 + \left(\frac{2\sqrt{R}}{1-R}\sin(2\pi f \tau)\right)^2\right)}$$

- Or in terms of optical free-space wavelength λ

$$T_{FP}(\lambda) = \frac{\left(1 - \frac{A}{1-R}\right)^2}{\left(1 + \left(\frac{2\sqrt{R}}{1-R}\sin(2\pi nl / \lambda)\right)^2\right)}$$

- A – absorption loss of each mirror
- R – reflectivity of each mirror
- τ – one way propagation delay across the cavity
- n – refractive index of the cavity
- l – length of the cavity
- τ=nl/c , c: velocity of light vacuum

Principle of operation



- **Transfer function –** periodic in *f* and the peaks or passbands occur at frequencies *f* that satisfy $f\tau = k/2$
- **FSR** – free spectral range (spectral range between two successive passbands
- **FWHM** – *full width* at the point where the transfer function is *half* of its *maximum* (measure of width)

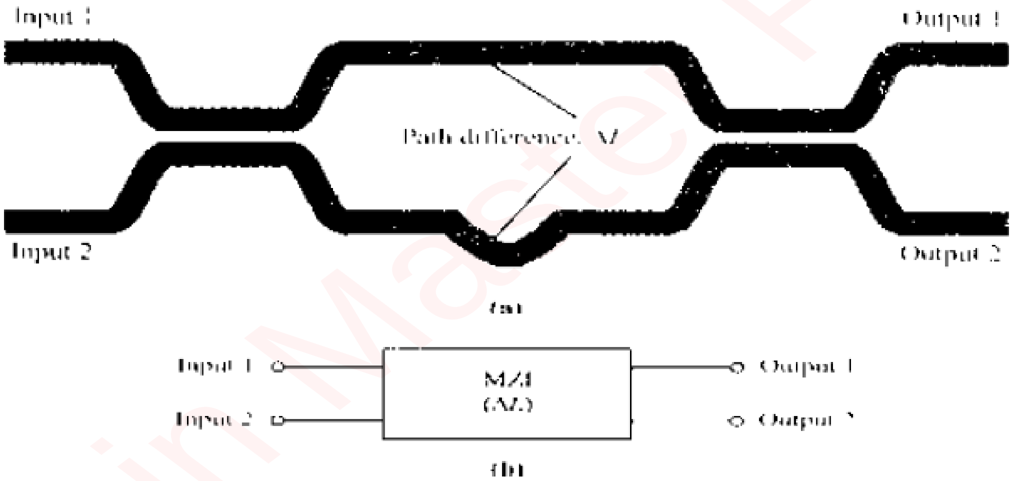
Principle of operation

- In WDM, the separation between two adjacent wavelengths must be separated by a FWHM + an integral multiple of FSR in order to minimize crosstalk
- Ratio FSR/FWHM – number wavelengths that can be accommodated by the system (finesse F)

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

Mach-Zehnder Interferometers

- MZI is an interferometric device that makes use of two interfering paths of different lengths to resolve different wavelengths
- Constructed in integrated optics and consists of two 3 dB couplers interconnected through two paths of differing lengths.

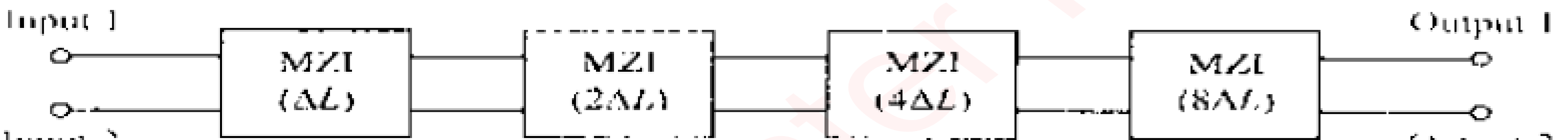


- (a) An MZI constructed by interconnecting two 3dB directional couplres.
- (b) A block diagram representation of the MZI in (a).

ΔL denotes the path difference between the two arms.

Mach-Zehnder Interferometers

- (c) A block diagram of a four-stage Mach-Zehnder interferometer, which uses different path length differences in each stage.



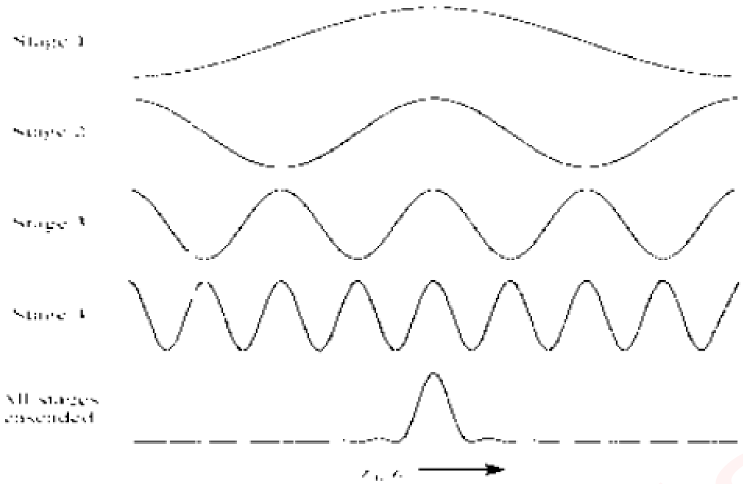
(c)

- Power transfer function

$$\begin{pmatrix} T_{11}(f) \\ T_{12}(f) \end{pmatrix} = \begin{pmatrix} \sin^2(\beta\Delta L/2) \\ \cos^2(\beta\Delta L/2) \end{pmatrix}$$

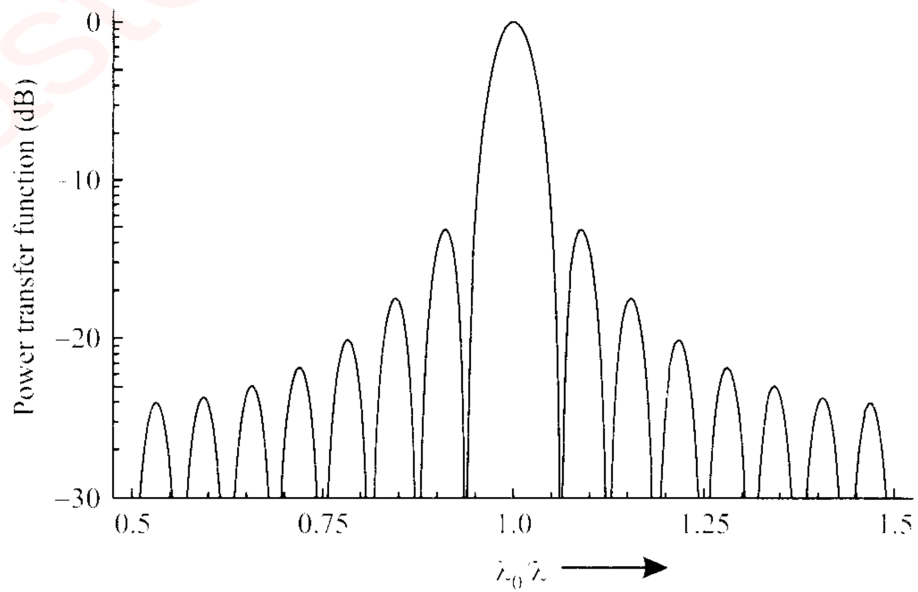
- ΔL – path difference between the two arms

Principle of operation



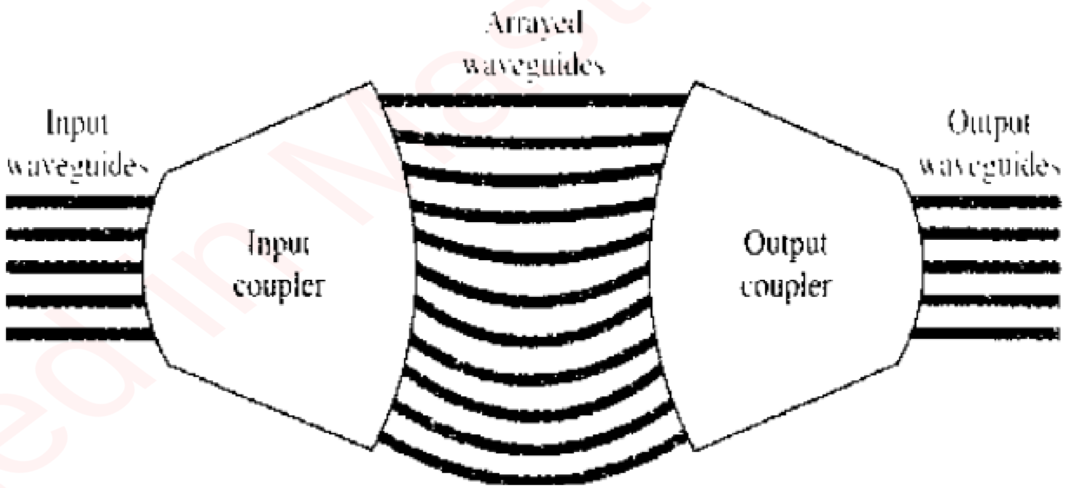
- Transfer function of each case of a multistage MZI.

- Overall transfer function of the multistage MZI.



Arrayed Waveguide Grating

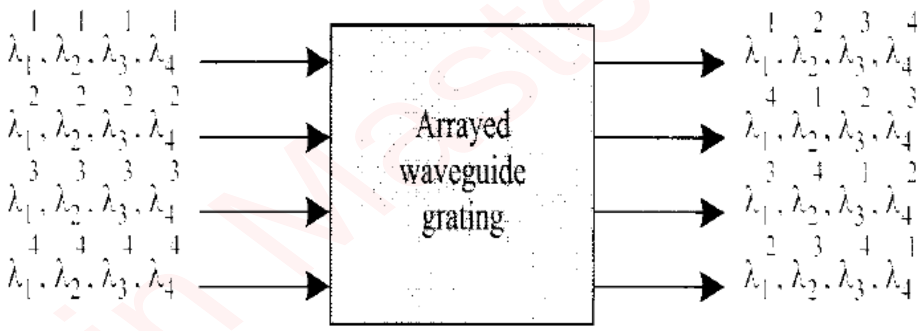
- AWG is a generalization of the Mach-Zehnder interferometer
- It consists of two multiport interconnected by an array of waveguides
- MZI-device where two copies of he same signal but shifted in phase by different amounts, are added together
- AWG-device where several copies of the same signal, but shifted in phase by different amounts, are added together



An Array Waveguide Grating

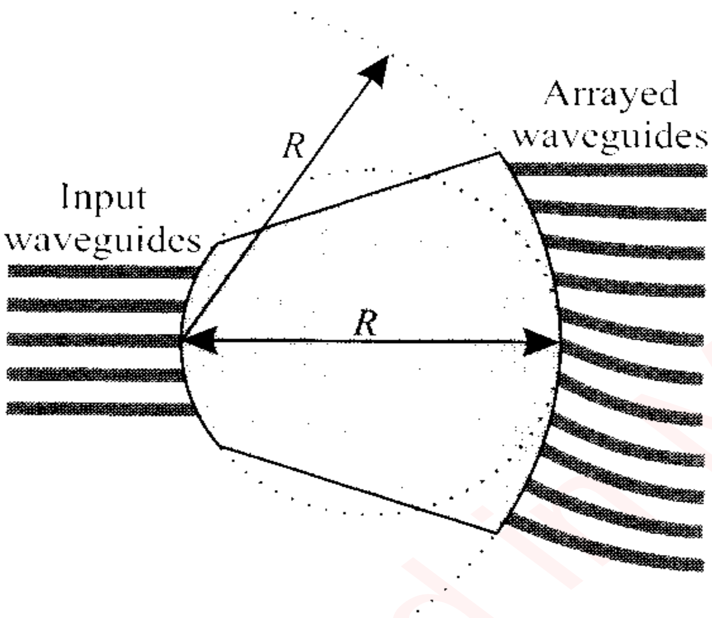
Arrayed Waveguide Grating

- AWG uses
  - N x 1 wavelength multiplexer and 1 x N wavelength demultiplexer
  - Static wavelength crossconnect
- Relative to an MZI chain, an AWG has lower loss, flatter passband, and is easier to realize on an integrated-optic substrate



- The crossconnect pattern of a static wavelngth crossconnect constructed from an arrayed waveguide grating. The device routes signal from an input to an output based on their wavelength

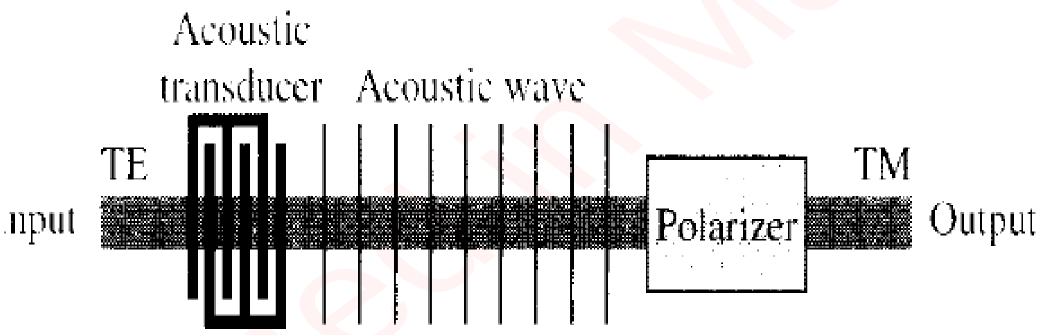
Arrayed Waveguide Grating



- The Rowland circle construction for the couplers used in the AWG.
- The arrayed waveguides are located on the arc of a circle called the *grating circle*, whose center is at the end of the central input (output) waveguide.
- Let the *radius* of this circle be denoted by *R*. The other input (output) waveguides are located on the arc of a circle whose diameter is equal to *R*; this circle is called the *Rowland circle.*
- The vertical spacing between the arrayed waveguides is chosen to be constant.

Acousto-Optic Tunable Filter

- AOTF are versatile devices
- The only tunable filter that is capable of selecting several wavelengths simultaneously.
- Can be used to construct wavelength crossconnect
- Integration of sound and light
- AOTF is dependent on the state polarization of the filter.
- **A simple AOTF:**



- An acoustic wave introduces a grating whose pitch depends on the frequency of the acoustic wave.
- The grating couples energy from one polarization mode to another at a wavelength that satisfies the Bragg condition.

Principle of operation

- TE modes: the electric field is approximately traverse
- ME modes: the magnetic field is approximately traverse
- If the refractive indices nTE and nTM of the TE and TM modes satisfy the Bragg condition

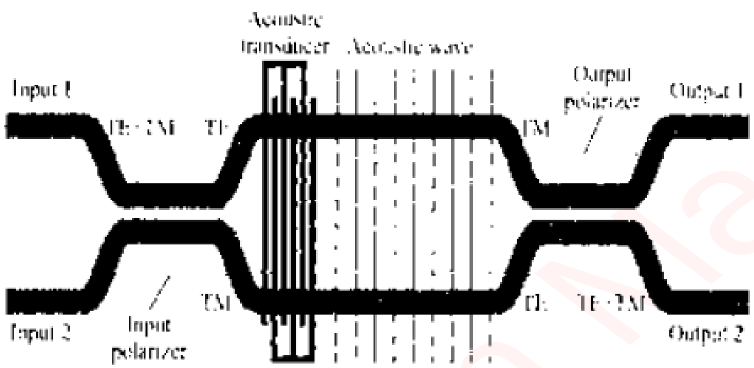
$$\frac{n_{TM}}{\lambda} = \frac{n_{TE}}{\lambda} \pm \frac{1}{\Lambda}$$

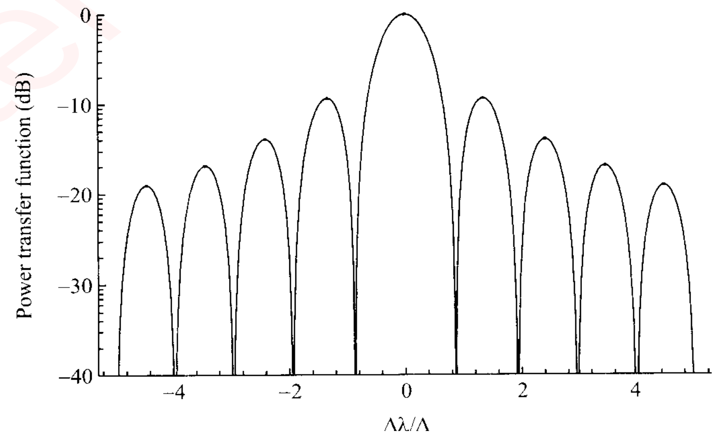
<u>the light couples from one mode to the other</u>

- The light energy is a narrow spectral range around the wavelength λ that satisfies the previous equation undergoes TE to TM mode conversion
- The device acts as a narrow bandwidth filter when only light energy in the TE mode is input and only the light energy in the TM mode is selected at the output

Acousto-Optic Tunable Filter

- A polarization-independent integrated-optics AOTF. A polarizer splits the input signal into its constituent polarization modes and each mode is converted in two separate arms, before being recombined at the output.

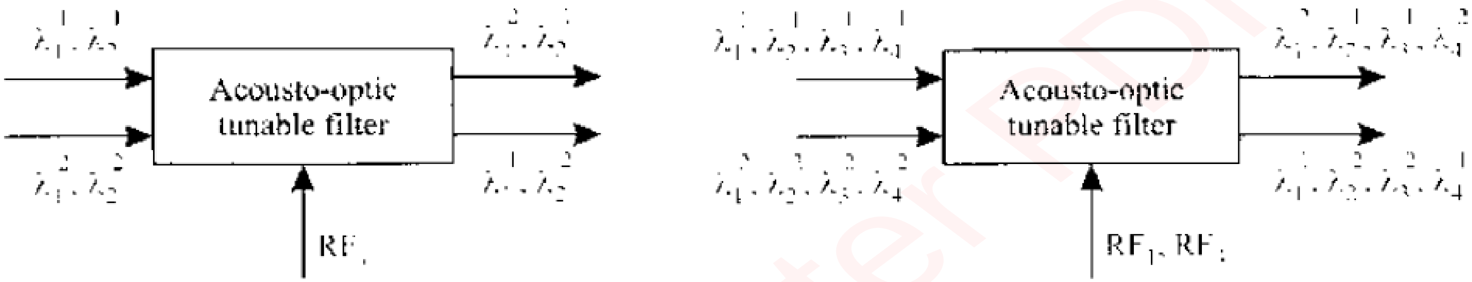




- Transfer function

$$T(\lambda) = \frac{\sin^2\left((\pi/2)\sqrt{1+(2\Delta\lambda/\Delta)^2}\right)}{1+(2\Delta\lambda/\Delta)^2}$$

AOTF as a Wavelength Crossconnect



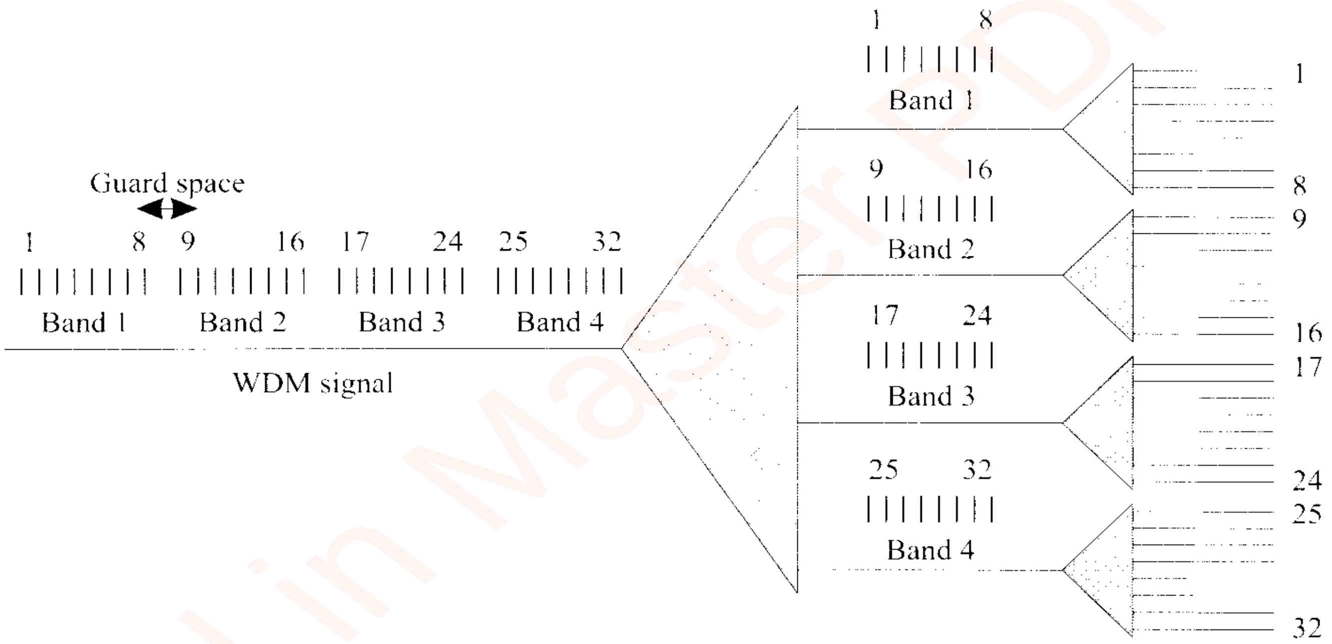
(a) (b)

- Wavelength crossconnects constructed from acousto-optic tunable filters,
  - (a) The wavelength λ1 is exchanged between the two ports.
  - (b) The wavelengths λ1 and λ4 are simultaneously exchanged between the two ports by the simultaneous launching of two appropriate acoustic waves.

High Channel Count Multiplexer Architectures

- **Serial Architectures**
  - Demultiplexing is done one wavelength at a time
  - W filter stages in series, one for each of the W wavelengths
  - Pay as you grow approach-the filter stages can potentially be added one at a time, as more wavelengths are added
  - Work for small number of channels
- **Single stage**
  - Lower losses, better loss uniformity (serial approach)
  - The number of channels that can be demultiplexed is limited by the maximum number of channels that can be handled by a single device
- **Multistage Banding**
  - Larger channels – use of multiple demultiplexing stages
  - Popular approach – divide the wavelengths into bands
  - Drawback – we need to leave a “guard” space between bands

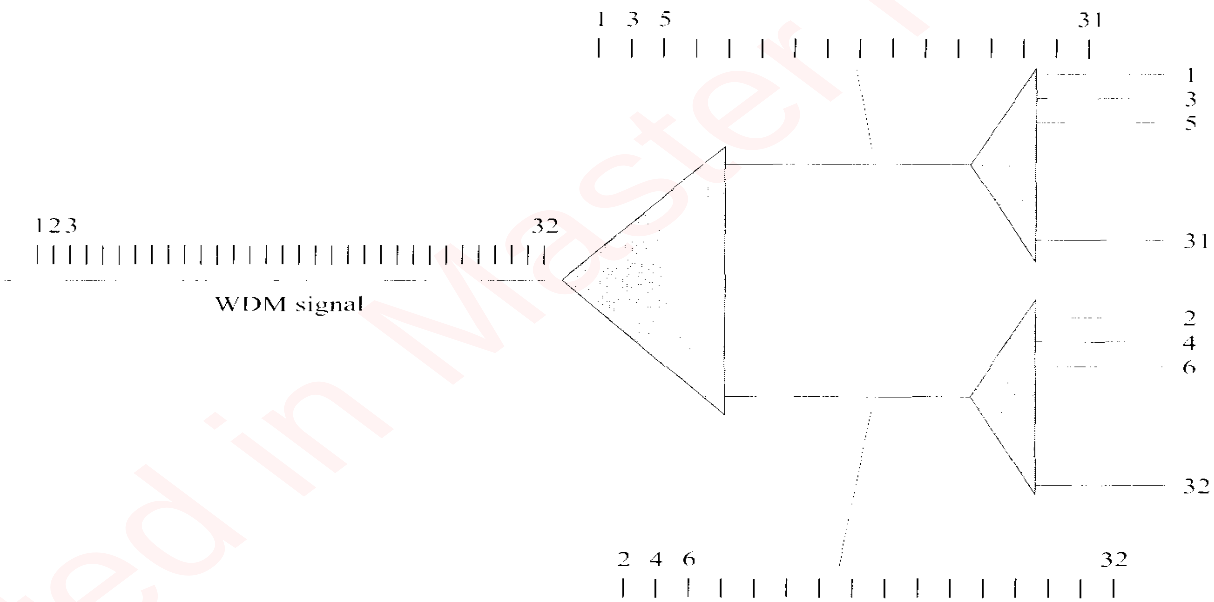
High Channel Count Multiplexer Architectures



- A two – stage demultiplexing approach using bands.
- A 32-channel demultiplexer is realized using four bands of 8 channels each

High Channel Count Multiplexer Architectures

- Multistage Interleaving
  - Large channel count demultiplexers with no "guard" bands required
  - Filters in the last stage can be much wider than the channel width



- A 32-channel demultiplexer, the first stage picks out every alternate wavelength and the second stage extracts the individual wavelength.

Transmitters

Light sources

Laser as a light source

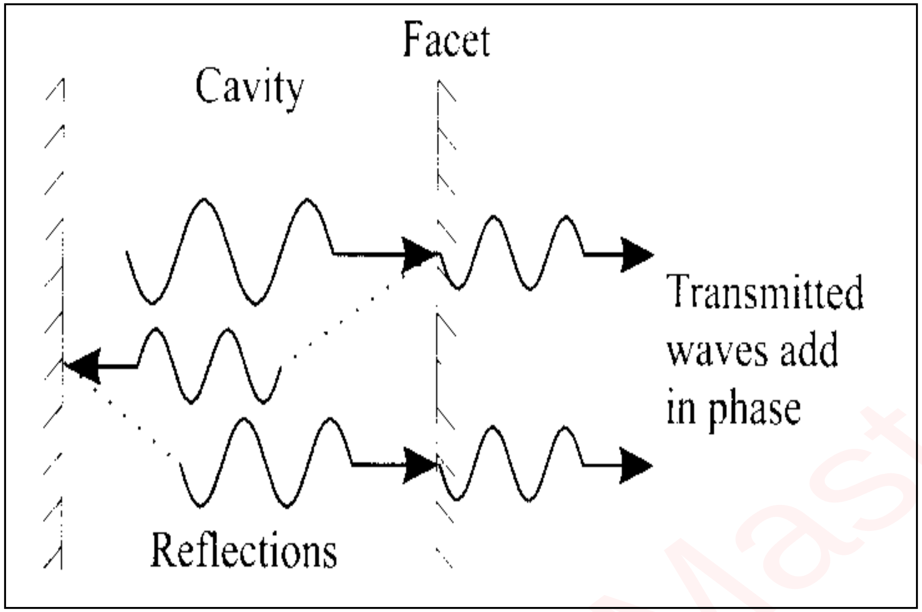
- Reasonably high output power (0-10 dBm range)
- Threshold current – drive current at which the laser starts to emit optical power
- Slope efficiency – ratio of output optical power to drive current
- Narrow spectral width at a specified operating wavelength- the signal can pass through intermediate filters and multiple channels can be placed together

- Wavelength stability – the wavelength drift over the life of the laser needs to be small relative to the wavelength spacing between adjacent channels
- Chromatic dispersion (limiting factor)
- Pump lasers are required to produce much higher power levels than levels used as WDM sources

LASER - **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

- Laser is an optical amplifier enclosed within a reflective cavity that causes it to oscillate via feedback
- Semiconductor lasers
  - Semiconductors as the gain medium
  - Most popular light sources
  - Compact (few hundred micrometres in size)
  - pn-junctions
  - No need of optical pumping
  - High efficient in converting input electrical energy into output optical energy
- Fiber lasers
  - Erbium-doped fiber as the gain medium
  - Uses a semiconductor laser as a pump
  - Used mostly to generate trains of very short pulses

LASER



Reflection and transmission at the facets of a Fabry-Perot cavity

- Laser (light amplification by stimulated emission of radiation)
- If the combination of the amplifier gain and the facet reflectivity is sufficiently large, the amplifier will start to "oscillate"
- The point at which this happens is called its lasing threshold
- Beyond this threshold, the device is no longer an amplifier but an oscillator or laser

Longitudinal modes

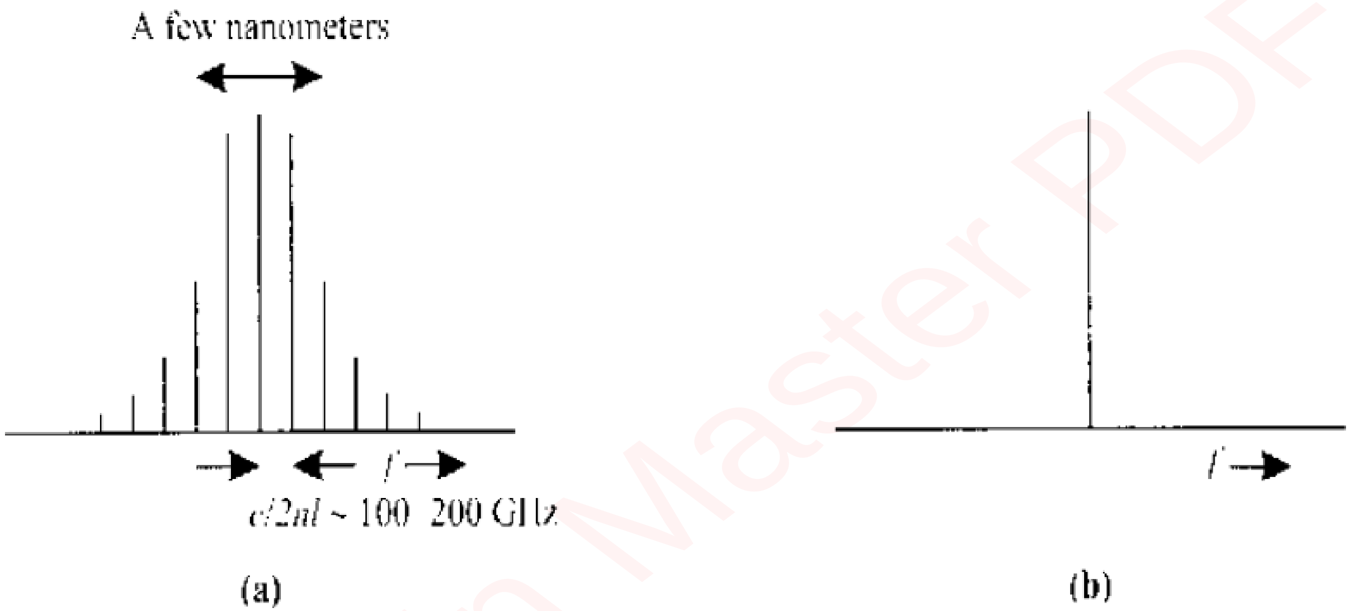


Figure 3.43 The spectrum of the output of (a) an MLM laser and (b) an SLM laser. The laser cavity length is denoted by l, and its refractive index by n. The frequency spacing between the modes of an MLM laser is then $c/2nl$.

Distributed-Feedback Lasers

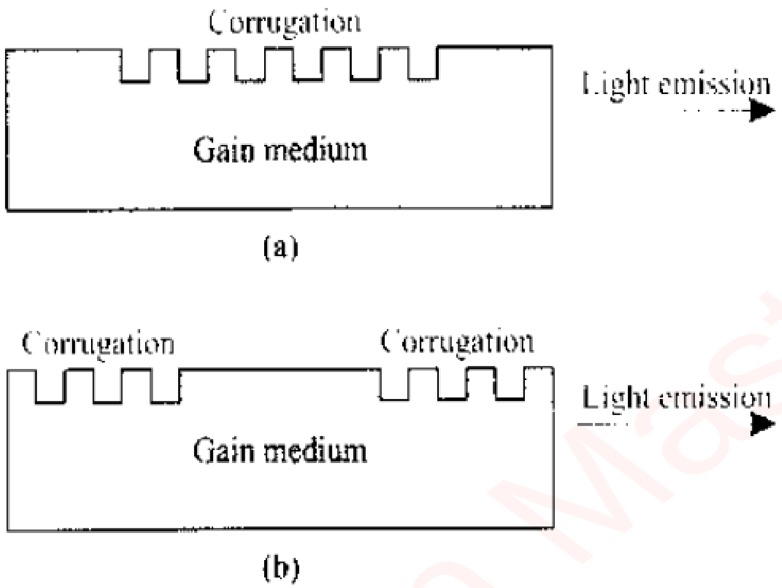


Figure 3.44 The structure of (a) a DFB laser and (b) a DBR laser. In a DFB laser, the gain and wavelength selection are obtained in the same region, whereas in a DBR laser, the wavelength selection region is outside the gain region.

Vertical Cavity Surface-Emitting lasers

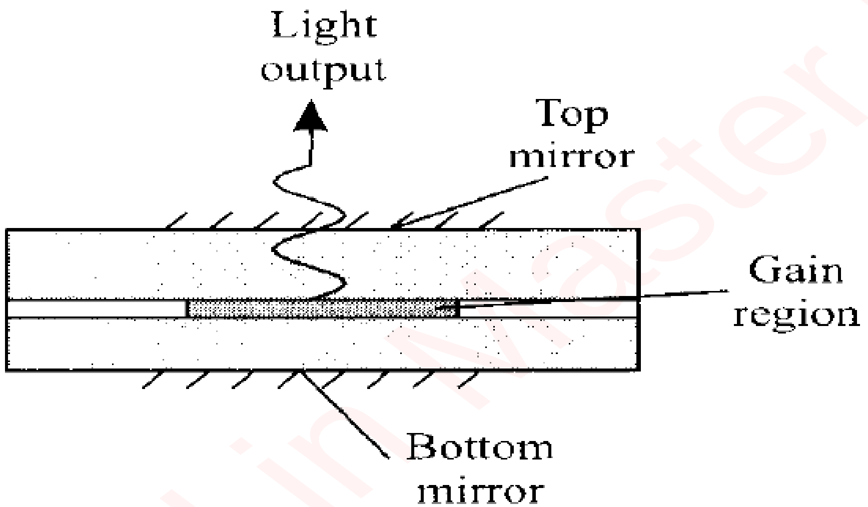
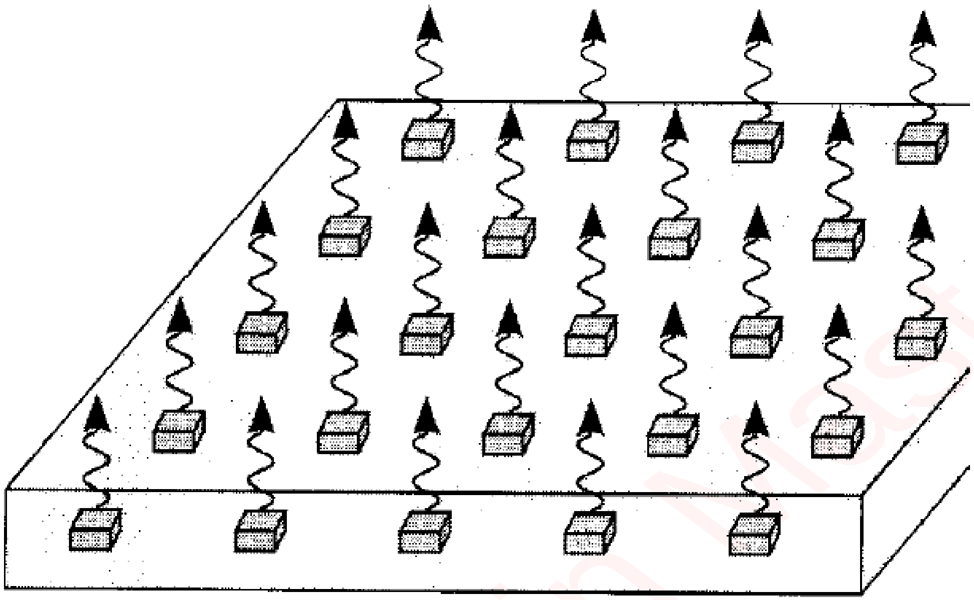


Figure 3.47 The structure of a VCSEL.

Vertical Cavity Surface-Emitting lasers



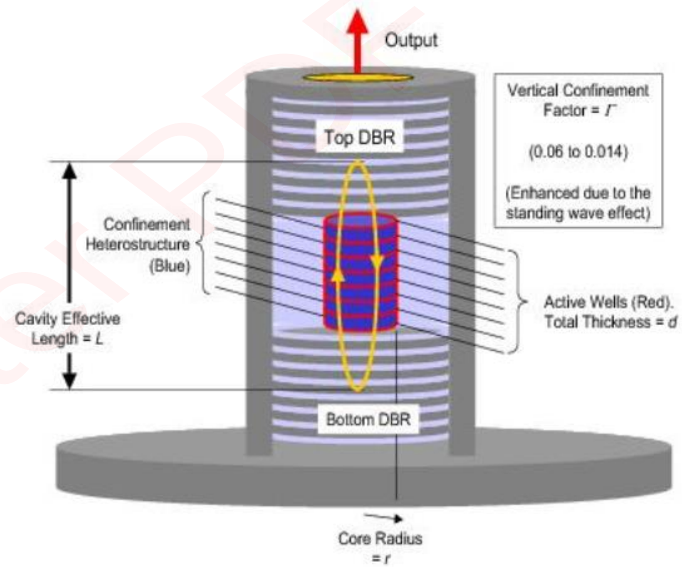


Figure 3.48 A two-dimensional array of vertical cavity surface-emitting lasers.

Optical amplifiers

Optical Amplifiers

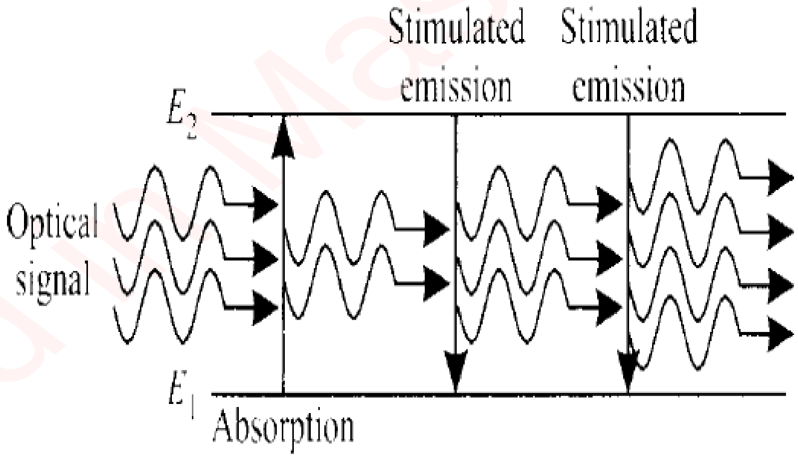
- Signals attenuated by the optical fiber
- Optical components (multiplexers, couplers) add loss
- The signal strength has to be restored
- Prior the advent of optical amplifiers the only option was to regenerate the signal (*regenerators*)
- Regenerator converts the optical signal to an electrical signal, cleans it up, and converts it back into an optical signal for onward transmission

- Introduce additional noise
- The noise accumulates as the signal passes through multiple amplifiers along its path due to analog nature of the amplifier
- Spectral shape of the gain, output power, and the transient behavior of the amplifier are important considerations for system applications

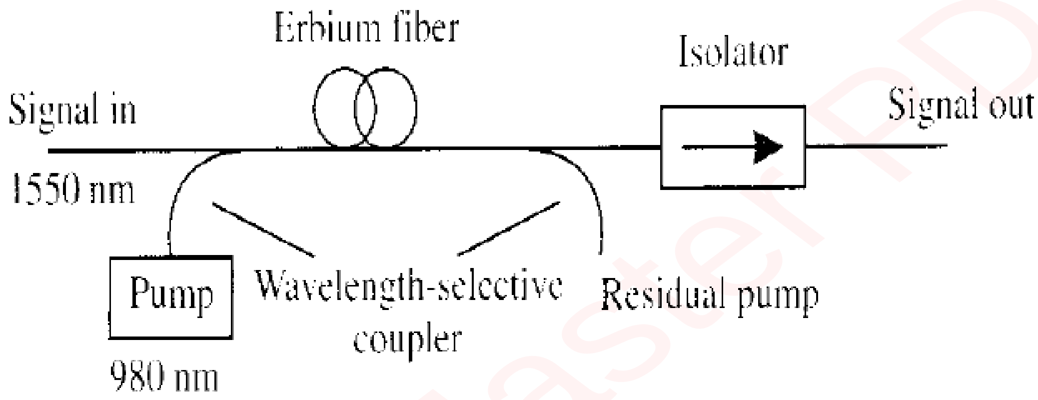
Stimulated emission

- Key physical phenomenon behind signal amplification is stimulated emission of radiation by atoms in the presence of an electromagnetic field
- This field is an optical signal in the case of OA.

- Stimulated emission and absorption in an atomic system with two energy levels:



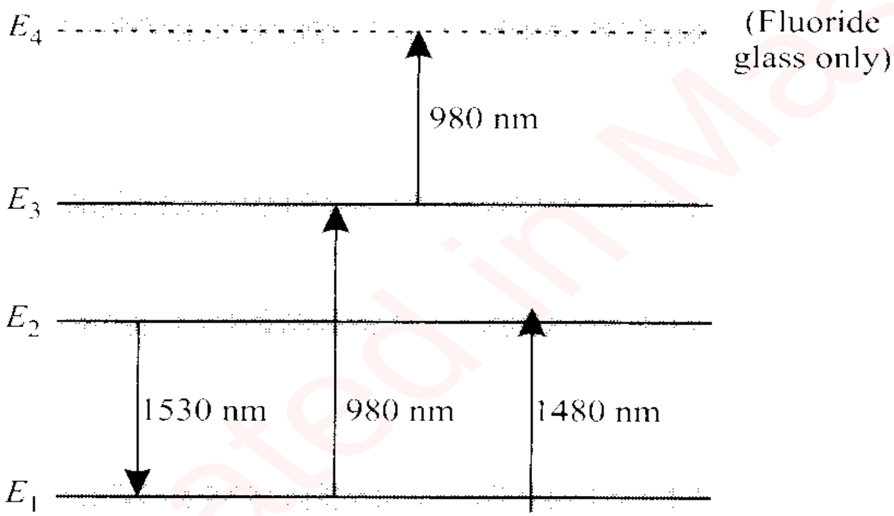
Erbium-Doped Fiber Amplifiers



- Compact and reliable high-power semiconductor pump lasers are available.
- It is in all-fiber device, making it polarization independent and easy to couple light in and out of it
- Simplicity of the device design
- It introduces no crosstalk when amplifying WDM signals

Principle of operation

- Three energy levels E_1, E_2 and E_3 of Er^{3+} ions in silica glass. The fourth energy level, E4, is present in fluoride glass but not in silica glass.
- The energy levels are spread into bands by the Start splitting process. The difference between the energy levels is labeled with the wavelength in nm of the photon corresponding to it.
- The upward arrows indicate wavelengths at which the amplifier can be pumped to excite the ions into the higher energy level.



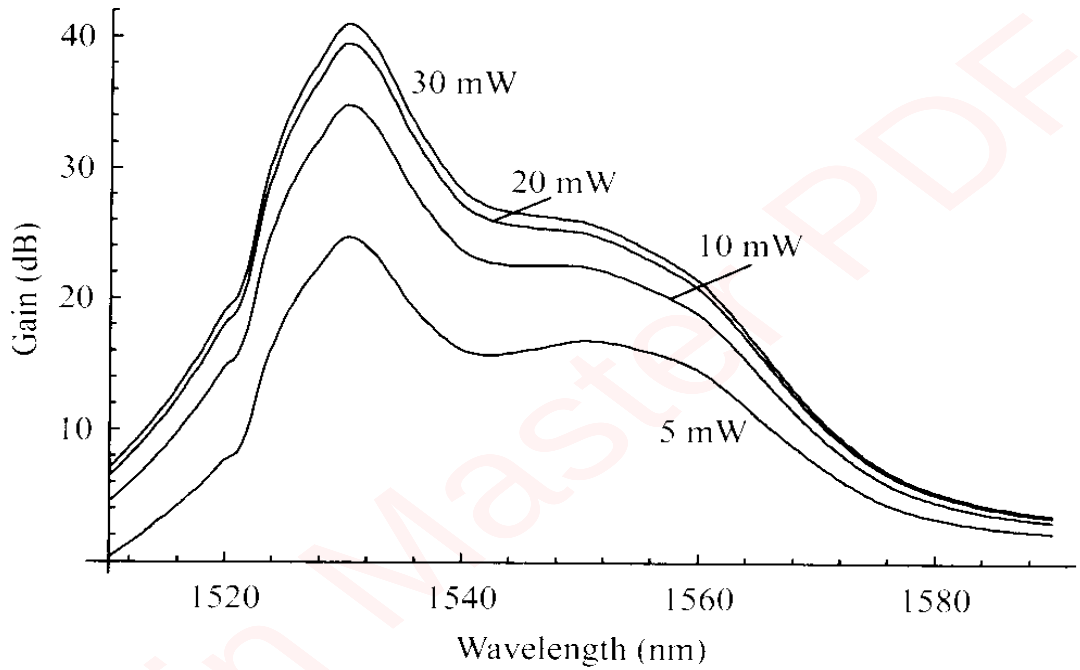
- The 980nm transition corresponds to the band gap between the E1 and E3 levels.
- The 1480nm transition corresponds to the gap between the bottom of the E1 band to the top of the E2 band.
- The downward transition represents the wavelength of photons emitted due to spontaneous and stimulated emission.

Principle of operation

E_2

- Stark Splitting – Each energy level that appears as a discrete line in an isolated ion of erbium is split into multiple energy levels when these ions are introduced into silica glass
- Thermalization – Within each energy band, the erbium ions are distributed in the various levels within the band in a nonuniform manner
- Only an optical signal at the frequency f_c satisfying $hf_c = E_2 - E_1$ could be amplified
- If these levels are spread into bands, all frequencies that correspond to the energy difference between some energy in the E_2 band and some energy in the E_1 band can be amplified.
- The set of frequencies that can be amplified by stimulated emissions from the E_2 band to the E_1 band corresponds to the wavelength range 1525-1570nm (bandwidth 50nm) with a peak around 1532nm

Optical Gain



- The gain of a typical EDFA as a function of the wavelength for four different values of the pump power, obtained through simulations. The length of the doped fiber is taken to be 15m and 980nm pumping is assumed.

Stimulated Emission

- Any physical system (atom) is found in one of a discrete number of energy levels
- Consider an atom and two of its energy levels E_1 and E_2, with $E_2 > E_1$.
- An electromagnetic field whose frequency f_c satisfies $hf_c = E_2 - E_1$ introduces transitions of atoms between the energy levels E_1 and E_2.

- $E_1 \rightarrow E_2$ transitions are accompanied by absorption of photons from the incident electromagnetic field.
- $E_2 \rightarrow E_1$ transitions are accompanied by the emission of photons of energy hf_c, the same energy as the incident photons.
- The emission process is termed stimulated emission.

Stimulated Emission

- If stimulated emission were to dominate over absorption, we would have a net increase in the number of photons of energy hf_c and an amplification of the signal
- From theory of quantum mechanics the *rate (r)* of the $E_1 \rightarrow E_2$ transitions per atom equals the rate of the $E_2 \rightarrow E_1$ transitions per atom
- If the population (number of atoms) in the energy levels E_1 and E_2 are N_1 and N_2 we have a net increase in power (energy per unit time) of

$$(N_2 - N_1) r h f_c$$

Stimulated Emission

- For amplification it is : $N_2 > N_1$
- Population inversion
  - At thermal equilibrium, lower energy levels are more highly populated, that is $N_2 < N_1$
  - Therefore, at thermal equilibrium, we have only absorption of the input signal
  - So, we have to invert the relationship between the populations of levels E_1 and E_2
- Population inversion can be achieved by supplying additional energy in a suitable form to pump the electrons to the higher energy level.

Spontaneous Emission

- Independent of any external radiation, atoms in energy level E_2 transit to the lower energy level E_1 emitting a photon of energy hf_c
- The spontaneous emission rate per atom from level E_2 to the level E_1 is a characteristic of the system, and its reciprocal, denoted by τ_{21} is called the spontaneous emission lifetime.

- If there are N_2 atoms in level E_2, the rate of spontaneous emission is N_2 / τ_{21} and the spontaneous emission power is $hf_c N_2 / \tau_{21}$
- The spontaneous emission power does not contribute to the gain of the amplifier (to first order)
- Although the emitted photons have the same energy hf_c as the incident optical signal, they are emitted in random directions, polarizations, and phase

Spontaneous Emission

- Stimulated emission process is coherent, whereas the spontaneous emission process is incoherent
- The OA treats spontaneous emission radiation as another electromagnetic field at the frequency hf_c , and the spontaneous emission also gets amplified
- Amplified spontaneous emission appears as noise at the output of the amplifier.