Optical communications

- Components and enabling technologies
- Optical networking
- Evolution of optical networking: road map

SDH = Synchronous Digital Hierarchy

SONET = Synchronous Optical Network

SDH	SONET	Bit rate
STM-1	OC-3	155 Mbit/s
STM-4	OC-12	622 Mbit/s
STM-16	OC-48	2.5 Gbit/s
STM-64	OC-192	10 Gbit/s
STM-256	OC-768	40 Gbit/s

40 Gbit/s corresponds to half a million simultaneous telephone conversations

References

S.V. Kartalopoulos, *Introduction to DWDM Technology -- Data in a Rainbow*, John Wiley & Sons, 2000.

R. Ramaswami and K.N. Sivarajan, *Optical Networks -- A Practical Perspective*, Morgan Kaufmann Publishers, 1998.

T. E. Stern and K. Bala, *Multiwavelengts Optical Networking -- A Layered Approach*, Addison-Wesley, 1999.

R.J. Bates, *Optical Switching and Networking Handbook*, McGraw-Hill, 2001.

Components and enabling technologies

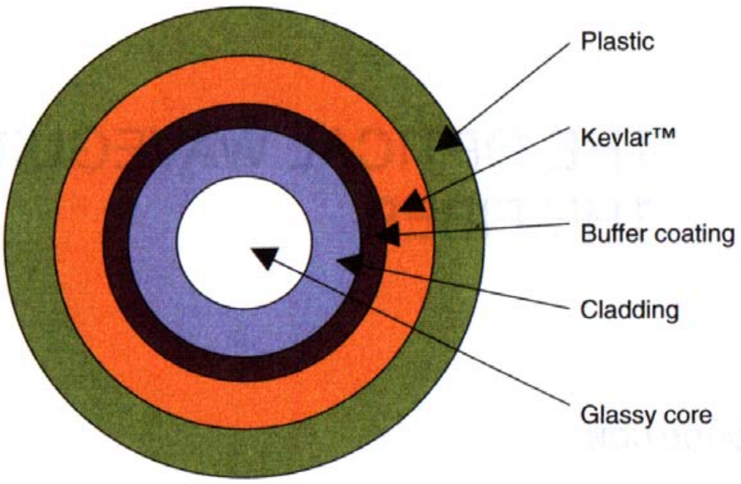
- Optical fiber
- Light sources, optical transmitters
- Photodetectors, optical receivers
- Optical amplifiers
- Wavelength converters
- Optical multiplexers and demultiplexers
- Optical add-drop multiplexers
- Optical cross connects
- WDM systems

Optical fiber

- Optical fiber is the most important transporting medium for high-speed communications in fixed networks.
- The optical fiber has many advantages:
  - immune to electromagnetic interference
  - does not corrode
  - huge bandwidth (25 Tbit/s)
- Some drawbacks:
  - connecting fibers requires special techniques (connectors, specialized personnel to splice and connect fibers)
  - does not allow tight bending

- An optical fiber consists of
  - ultrapure silica
  - mixed with dopants to adjust the refractive index

- A optical cable consists of several layers
  - silica core
  - cladding, a layer of silica with a different mix of dopants
  - buffer coating, which absorbs mechanical stresses
  - coating is covered by a strong material such as Kevlar
  - outermost there is a protective layer of plastic material



Cross section (not to scale)

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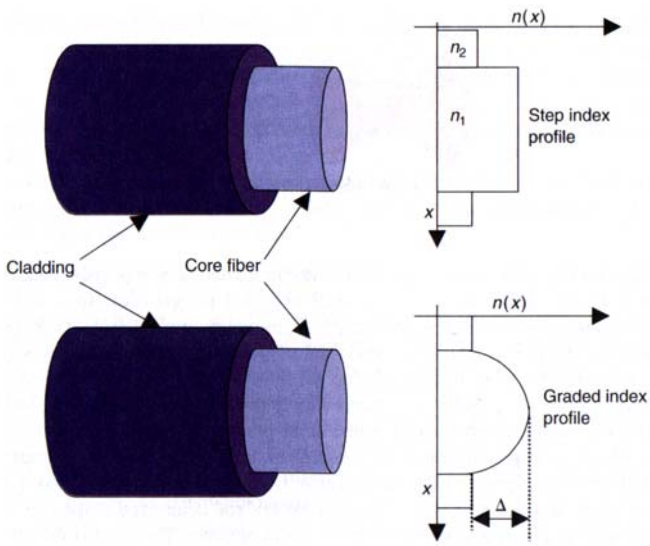
- Fiber cable consists of a bundle of optical fibers, up to 432 fibers.
- The refractive index profile of a fiber is carefully controlled during the manufacturing phase
- Typical refractive index profiles are
  - step index profile
  - graded index profile



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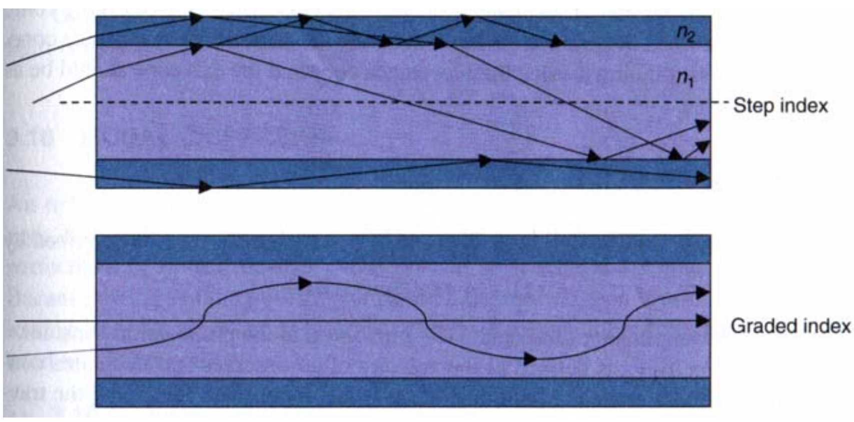
- The light rays are confined in the fiber by total reflection at the core.cladding interface in step-index fibers or by more gradual refraction in graded index fibers.



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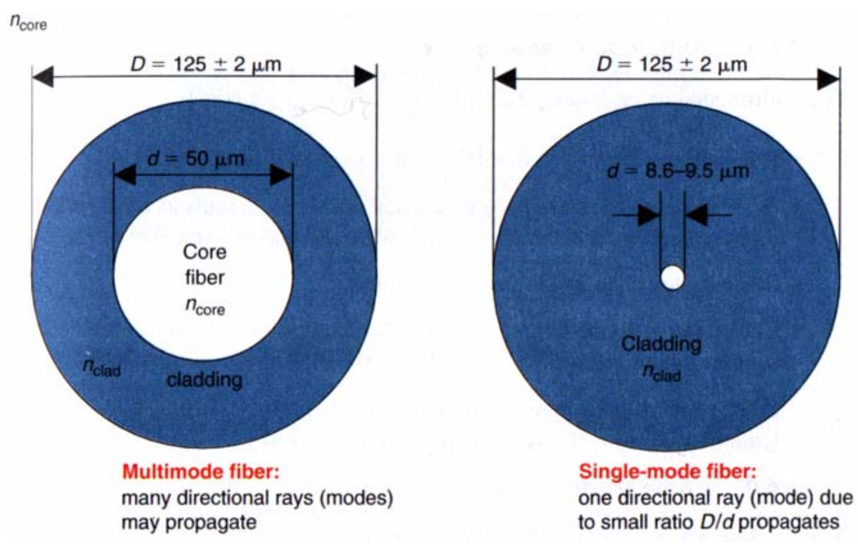
- The fiber can be designed to support
  - several propagation modes: multimode fiber
  - just a single propagation mode: single-mode fiber



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- Multimode graded index fiber
  - small delay spread
  - a 1% index difference between core and cladding amounts to a 1-5 ns/km delay spread
  - is easy to splice and to couple light into
  - bit rate is limited: up to 100 Mbit/s for lengths up to 40 km
  - fiber span without amplification is limited

- Single mode fiber
  - almost eliminates delay spread
  - is more difficult to splice and to exactly align two fibers together
  - is suitable for transmitting modulated signals at 40 Gbit/s or higher and up to 200 km without amplification

- Dispersion is an undesirable phenomenon in optical fibers
  - causes an initially narrow light pulse spread out as it propagates along the fiber

- There are different causes for dispersion
  - modal dispersion
  - chromatic dispersion

- Modal dispersion
  - occurs in multimode fibers
  - due to different (lengths of) propagation paths of different modes

- Chromatic dispersion
  - the material properties of the fiber, such as dielectric constant and propagation constant depend on the frequency of the light
  - each individual wavelength of a pulse travels at different speed and arrives at the end of the fiber at different time
  - dispersion is measured in ps/(nm*km), i.e. delay per wavelength variation and fiber length

- Dispersion depends on the wavelength
  - at some wavelength the dispersion may be zero
  - in conventional single mode fiber this typically occurs at 1.3 μm
  - below, dispersion is negative, above its positive

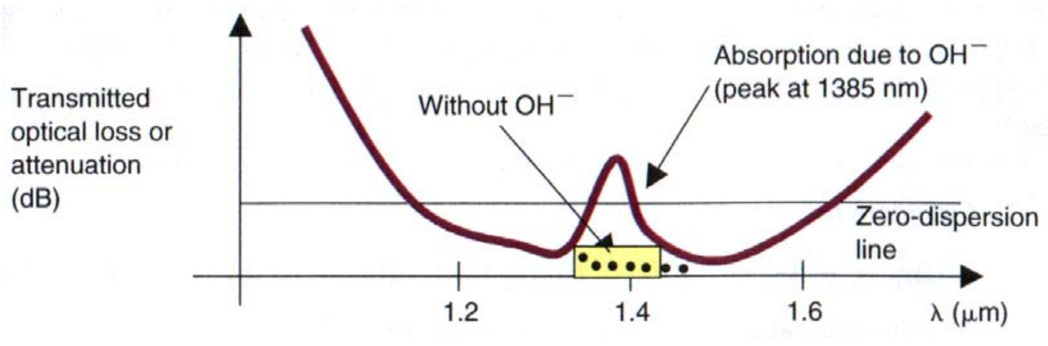
- For long-haul transmission, single mode fibers with specialized index of refraction profiles have been manufactured
  - dispersion-shifted fiber (DSF)
  - the zero-dispersion point is shifted at 1.55 μm

- Fiber attenuation is the most important transmission characteristic
  - limits the maximum span a light signal can be transmitted without amplification

- Fiber attenuation is due to light scattering on
  - fluctuations of the refractive index
  - imperfections of the fiber
  - impurites (metal ions and OH radicals have a particular effect)

- A conventional single-mode fiber has two low attenuation ranges
  - one at about 1.3 μm
  - another at about 1.55 μm

- Between these, there is a high attenuation range (1.35-1.45 μm), with a peak at 1.39 μm, due to OH radical
  - special fibers that are almost free of OH radicals have been manufactured
  - such fibers increase the usable bandwidth by 50%
  - the whole range from 1.335 μm to 1.625 μm is usable, allowing about 500 WDM channels at 100 GHz channel spacing



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- The attenuation is measured in dB/km; typical values are
  - 0.4 dB/km at 1.31 μm
  - 0.2 dB/km at 1.55 μm
  - for comparison, the attenuation in ordinary clear glass is about 1 dB/cm = 10^5 dB/km

Light sources, optical transmitters

- One of the key components in optical communications is the monochromatic (narrow band) light source.
- Desirable properties
  - compact
  - monochromatic
  - stable
  - long lasting
- Light source may be one of the following types:
  - continuous wave (CW); emits at a constant power; needs an external modulator to carry information
  - modulated light; no external modulator is necessary
- Two most popular light sources are
  - light emitting diode (LED)
  - semiconductor laser

Light emitting diode (LED)

- An LED is a monolithically integrated p-n semiconductor diode.
- Emits light when voltage is applied across its two terminals.
- In the active junction area electrons in the conduction band and holes in the valence band are injected.
- Recombination of the electron with holes releases energy in the form of light.
- Can be used either as a CW light source or modulated light source (modulated by the injection current).

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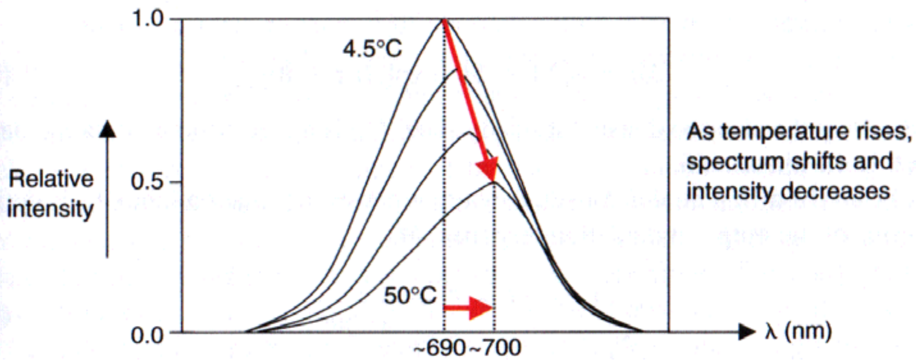


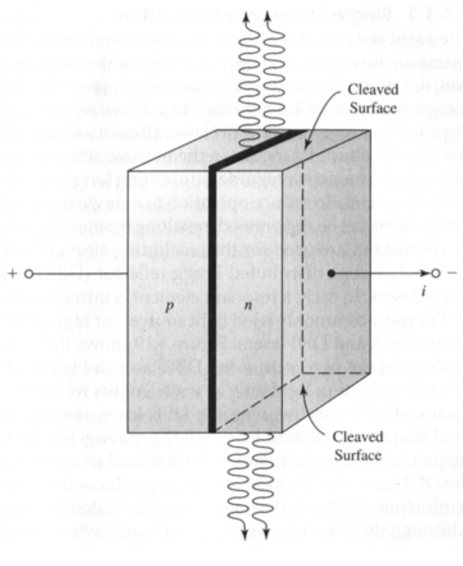
S.V. Kartalopoulos, Introduction to DWDM Technology -- Data in a Rainbow, John Wiley & Sons, 2000.

Characteristics of LEDs:

- Relatively slow: modulation rate < 1 Gbit/s
- Bandwidth depends on the material; relatively wide spectrum
- Amplitude and spectrum depend on temperature
- Inexpensive
- Transmits light in wide cone; suitable for multimode fibers

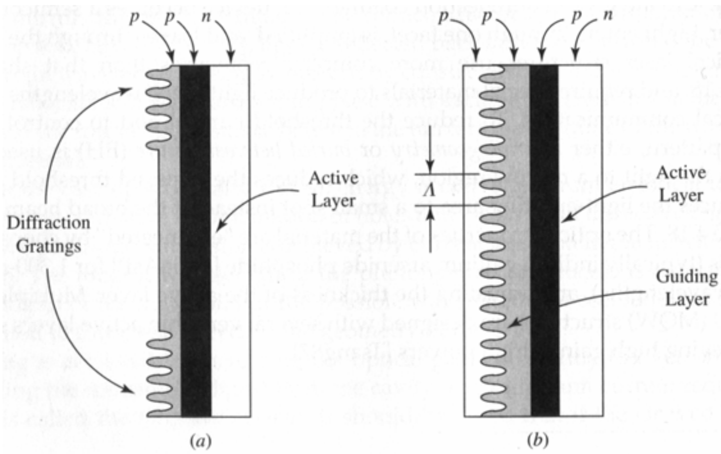
Semiconductor laser

- LASER (Light amplification by stimulated emission of radiation)
- Semiconductor laser is also known as
  - laser diode
  - injection laser
- Operation of a laser is the same as for any other oscillator: gain (amplification) and feedback.
- As a device semiconductor laser is similar to an LED: a p-n semiconductor diode.
- A difference is that the ends of the active junction area are carefully cleaved and act as partially reflecting mirrors
  - this provides feedback.
- The junction area acts as a resonating cavity for certain frequencies (those for which the roundtrip distance is a multiple of the wavelength in the material; constructive interference).
- The light fed back by the mirrors is amplified by stimulated emission.
- Lasing is achieved above a threshold current where the optical gain is sufficient to overcome losses (including the transmitted light) from the cavity.



T. E. Stern and K. Bala, Multiwavelengts Optical Networking -- A Layered Approach, Addison-Wesley, 1999.

- A Fabry-Perot laser the cavity can support many modes of oscillation; it is a multimode laser.
- In single frequency operation all but a single longitudinal mode must be suppressed. This can be achieved by different approaches:
  - cleaved-coupled cavity (C^3) lasers
  - external cavity lasers
  - distributed Bragg reflector (DBR) lasers
  - distributed feedback (DFB) lasers
- The most common light sources for high-bitrate, long-distance transmission are the DBR and DFB lasers.



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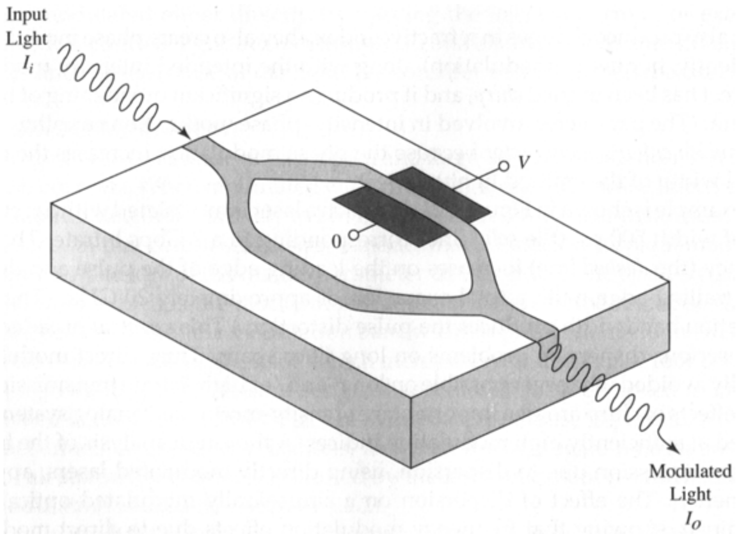
Laser tunability is important for multiwavelength network applications.

- Slow tunability (on a ms time scale) is required for setting up connections in wavelength or waveband routed networks
  - achieved over a range of 1 nm via temperature control.
- Rapid tunability (on a ns-μs time scale) is required for TDM-WDM multiple access applications
  - achieved in DBR and DFB lasers by changing the refractive index, e.g. by changing the injected current in grating area.
- Another approach to rapid tunability is to use multiwavelength laser arrays
  - one or more lasers in the array can be activated at a time

- Lasers are modulated either directly or externally
  - direct modulation by varying the injection current
  - external modulation by an external device, e.g. Mach-Zehnder interferometer



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Photodetectors, optical receivers

- A photodetector converts the optical signal to a photocurrent that is then electronically amplified (front-end amplifier).
- In a direct detection receiver, only the intensity of the incoming signal is detected
  - in contrast to coherent detection, where the phase of the optical signal is also relevant
  - coherent systems are still in research phase
- Photodetectors used in optical transmission systems are semiconductor photodiodes.
- The operation is essentially the reverse of a semiconductor optical amplifier:
  - the junction is reverse biased
  - in absence of optical signal only a small, minority carrier current, the <u>dark current</u> flows
  - a photon impinging on the surface of the device can be absorbed by an electron in the valence band, transferring the electron to the conduction band
  - each excited electron contributes to the photocurrent

- PIN photodiodes (p-type, intrinsic, n-type)
- An extra layer of intrinsic semiconductor material is sandwiched between the p and n regions
- Improves the responsivity of the device
  - captures most of the light in the depletion region

- Avalanche photodiodes (APD)
- In a photodiode only one electron-hole pair is produced by an absorbed photon.
- This may not be sufficient when the optical power is very low.
- The APD resembles a PIN
  - an extra gain layer is inserted between the i and n layers
  - a large voltage is applied across the gain layer
  - photoelectrons are accelerated to sufficient speeds
  - produce additional electrons by collisions: avalanche effect
  - largely improved responsivity

Optical amplifiers

- Optical signal travelling in a fiber suffers attenuation.
- The optical power level of the signal must be periodically conditioned.
- Optical amplifiers are key components in long haul optical systems.

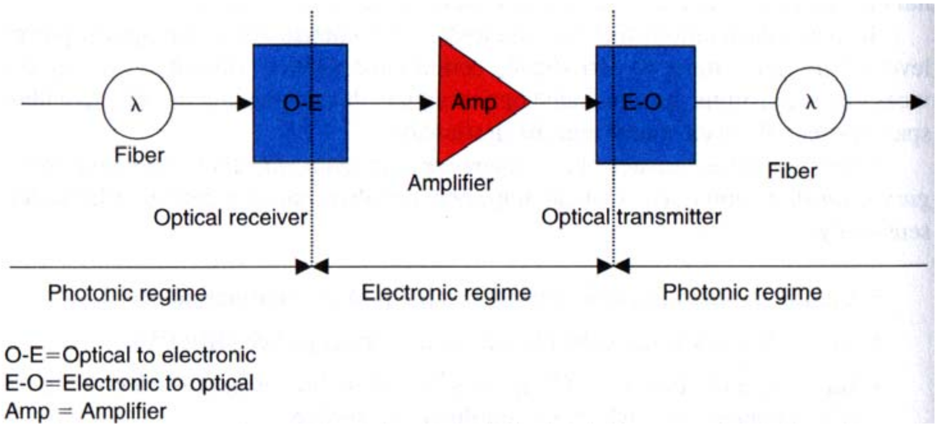
- An optical amplifier is characterized by
  - gain: ratio of output power to input power (in dB)
  - gain efficiency: gain as a function of input power (dB/mW)
  - gain bandwidth: range of frequencies over which the amplifier is effective
  - gain saturation: maximum output power, beyond which no amplification is reached
  - noise: undesired signal due to physical processes in the amplifier

Types of amplifiers

- Electro-optic regenerators
- Semiconductor optical amplifiers (SOA)
- Erbium-doped fiber amplifiers (EDFA)

Electro-optic regenerators

- Optical signal is
  - received and transformed to an electronic signal
  - amplified electronically
  - converted back to optical signal at the same wavelength



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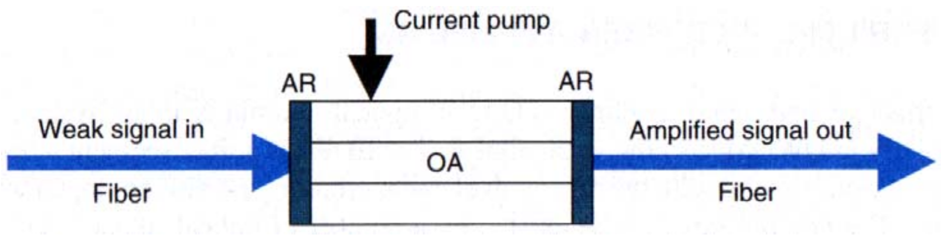
Semiconductor optical amplifiers (SOA)

- The structure of an SOA is similar to that of a semiconductor laser.
- It consists of an active medium (p-n junction) in the form of waveguide; usually made from InGaAsP.
- Energy is provided by injecting electric current over the junction.



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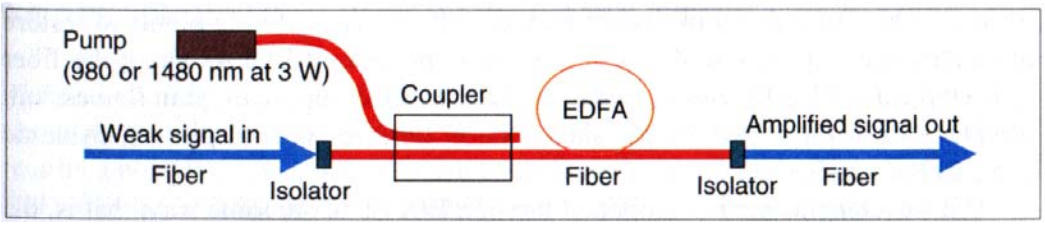
- SOAs are small, compact and able to be integrated with other semiconductor and optical components.
- They have large bandwidth and relatively high gain (20 dB).
- Saturation power in the range of 5-10 dBm.
- SOAs are polarization dependent and thus require a polarization-maintaining fiber.
- Because of nonlinear phenomena SOAs have a high noise figure and high cross-talk level.

Erbium-doped fiber amplifiers (EDFA)

- EDFA is a very attractive amplifier type in optical communications systems.
- EDFA is a fiber segment, a few meters long, heavily doped with erbium (a rare earth metal).
- Energy is provided by a pump laser beam.



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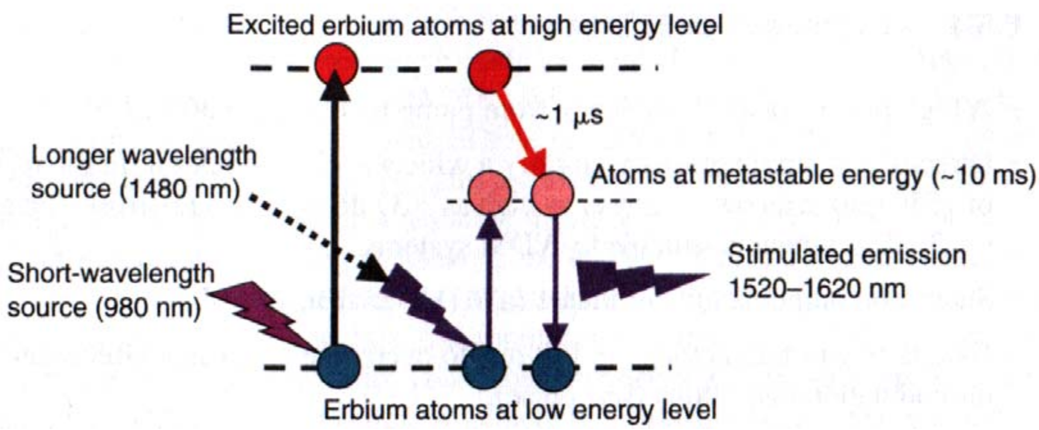
- Amplification is achieved by quantum mechanical phenomenon of stimulated emission
  - erbium atoms are excited to a high energy level by pump laser signal
  - they fall to a lower metastable (long-lived, 10 ms) state
  - an arriving photon triggers (stimulates) a transition to the ground level and another photon of the same wavelength is emitted



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- EDFAs have a high pump power utilization (> 50 %).
- Directly and simultaneously amplify a wide wavelength band (> 80 nm in the region 1550 nm) with a relatively flat gain.
- Flatness of the gain can be improved with gain-flattening optical filters.
- Gain in excess of 50 dB
- Saturation power is as high as 37 dBm
- Low noise figure
- Transparent to optical modulation format
- Polarization independent
- Suitable for long-haul applications
- EDFAs are not small and cannot easily be integrated with other semiconductor devices.

Wavelength converters

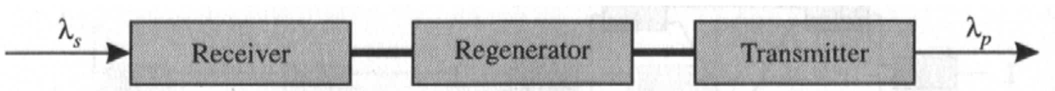
- Enable optical channels to be relocated
- Achieved in optical domain by employing nonlinear phenomena

Types of wavelength converters

- Optoelectronic approach
- Optical gating: cross-gain modulation
- Four-wave mixing

Optoelectronic approach

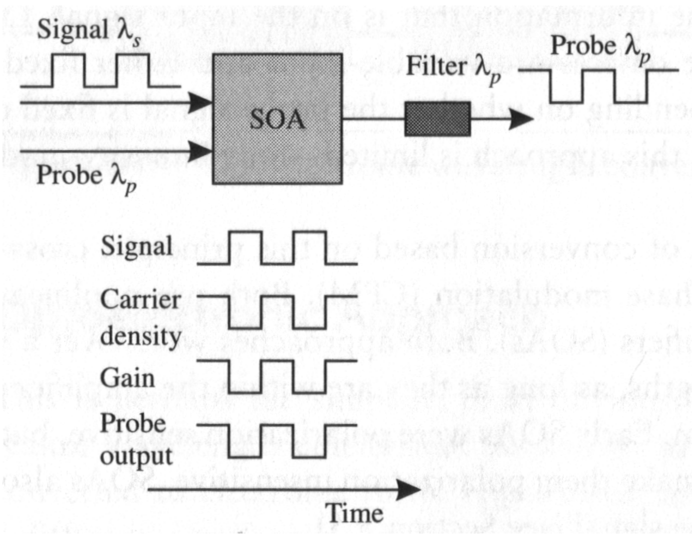
- Simplest approach
- Input signal is
  - received
  - converted to electronic form
  - regenerated
  - transmitted using a laser at a different wavelength



R. Ramaswami and K.N. Sivarajan, Optical Networks -- A Practical Perspective, Morgan Kaufmann Publishers, 1998.

Optical gating: cross-gain modulation

- Makes use of the dependence of the gain of an SOA (semiconductor optical amplifier) on its input power.
- Gain saturation occurs when high optical power is injected
  - carrier concentration is depleted
  - gain is reduced
- Fast
  - can handle rates 10 Gbit/s

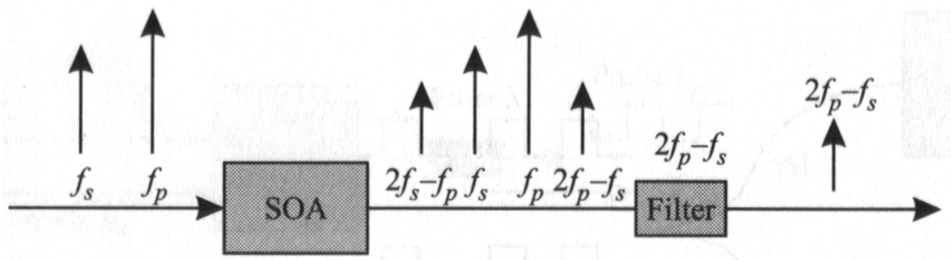


R. Ramaswami and K.N. Sivarajan, Optical Networks -- A Practical Perspective, Morgan Kaufmann Publishers, 1998.

Four-wave mixing

- Four-wave mixing is usually an undesirable phenomenon in fibers
- Can be exploited to achieve wavelength conversion
- In four-wave mixing, three waves at frequencies f_1, f_2 and f_3 produce a wave at the frequency $f_1+f_2-f_3$
- When
  - $f_1 = f_s$ (signal)
  - $f_2 = f_3 = f_p$ (pump)

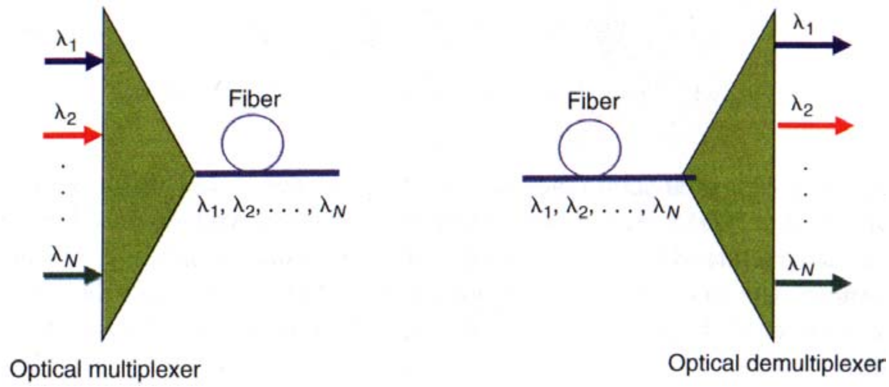
  a new wave is produces at $2f_p-f_s$
- Four-wave mixing can be enhanced by using SOA to increase the power levels.
- Other wavelengths are filtered out.



R. Ramaswami and K.N. Sivarajan, Optical Networks -- A Practical Perspective, Morgan Kaufmann Publishers, 1998.

Optical multiplexers and demultiplexers

- An optical multiplexers receives many wavelengths from many fibers and converges them into one beam that is coupled into a single fiber.
- An optical demultiplexer receives from a fiber a beam consisting of multiple optical frequencies and separates it into its frequency components, which are coupled in individual fibers (as many as there are frequencies).



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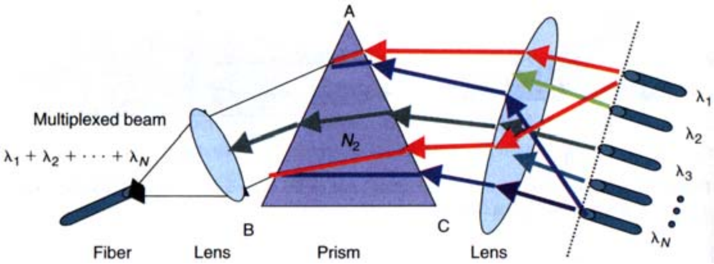
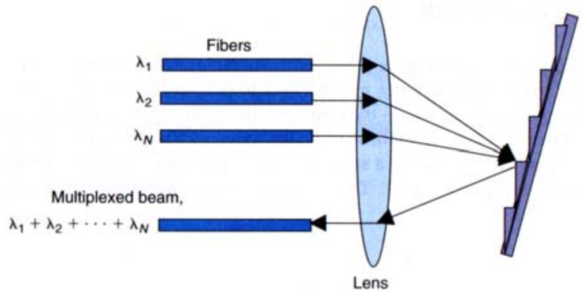
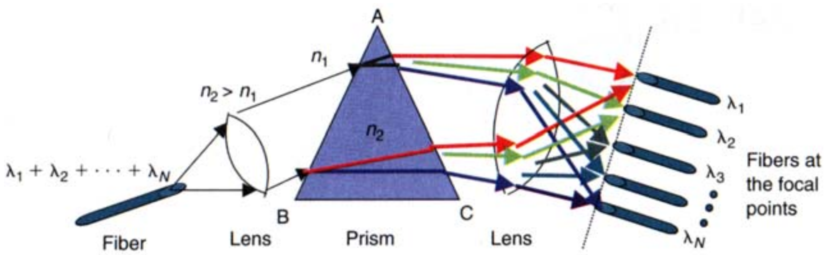
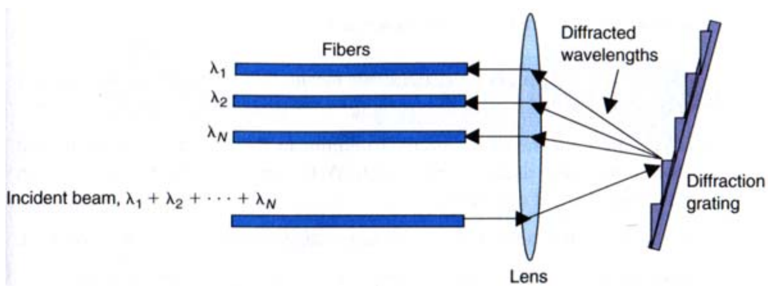
Prisms and diffraction gratings

- Prisms and diffraction gratings can be used to achieve these functions in either direction (reciprocity)
  - in both of these devices a polychromatic parallel beam impinging on the surface is separated into frequency components leaving the device at different angles
  - based on different refraction (prism) or diffraction (diffraction grating) of different wavelengths.









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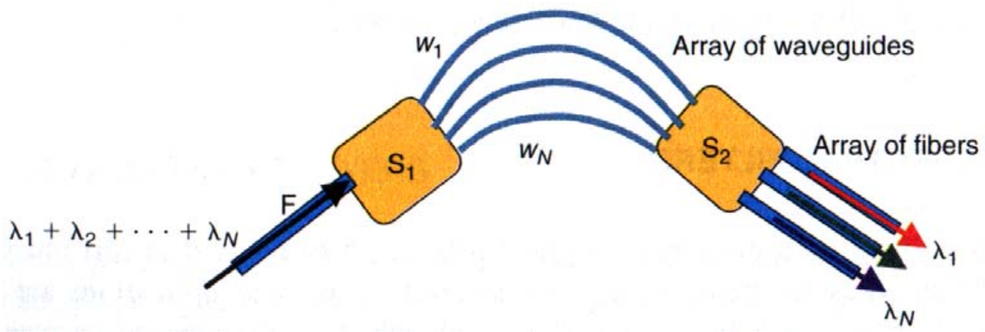
Arrayed waveguide grating (AWG)

- AWGs are integrated devices based on the principle of interferometry
  - a multiplicity of wavelengths are coupled to an array of waveguides with different lengths
  - produces wavelength dependent phase shifts
  - in a second cavity the phase difference of each wavelengths interferes in such a manner that each wavelength contributes maximally at one of the output fibers
- Reported systems
  - SiO_2 AWG for 128 channels with 250 GHz channel spacing
  - InP AWG for 64 channels with 50 GHz channel spacing



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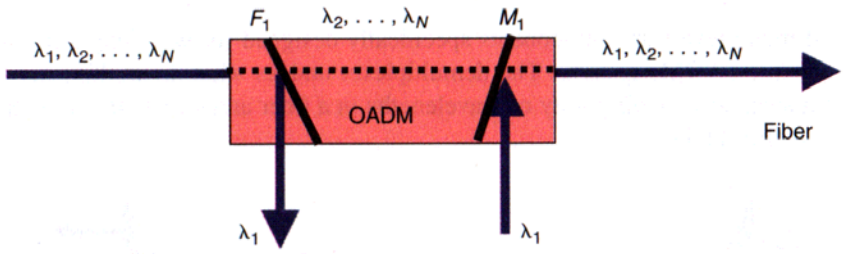
Optical add-drop multiplexers (OADM)

- Optical multiplexers and demultiplexers are components designed for wavelength division (WDM) systems
  - multiplexer combines several optical signals at different wavelengths into a single fiber
  - demultiplexer separates a multiplicity of wavelengths in a fiber and directs them to many fibers

- The optical add-drop multiplexer
  - selectively removes (drops) a wavelength from the multiplex
  - then adds the same wavelength, but with different data



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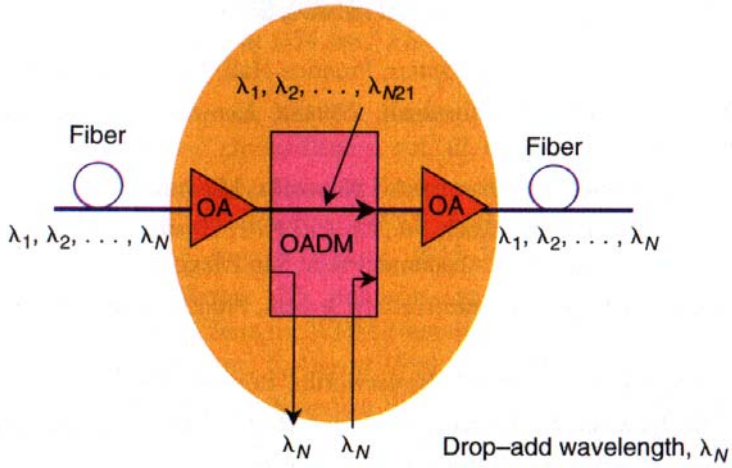
- An OADM may be realized by doing full demultiplexing and multiplexing of the wavelengths
  - a demultiplexed wavelength path can be terminated and a new one created



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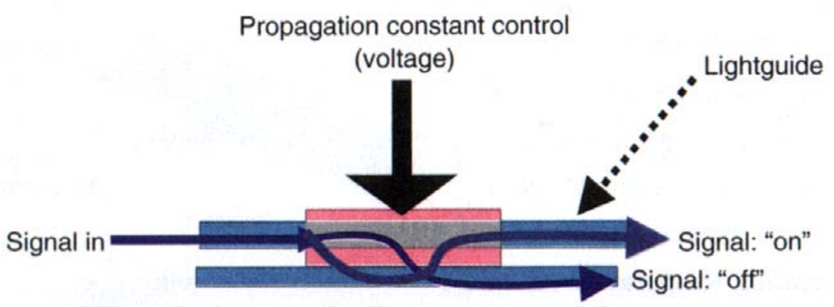
Optical cross connects

- Channel cross-connecting is a key function in communication systems.
- Optical cross-connection may be accomplished by
  - hybrid approach: converting optical signal to electronical domain, using electronic cross connects, and converting back to optical domain
  - all-optical switching: cross-connecting directly in the photonic domain
- Hybrid approach is currently more popular because the all-optical switching technology is not fully developed
  - all optical NxN cross-connects are feasible for N = 2…32
  - large cross-connects, N up to 1000, are in experimental or planning phase
- All-optical cross-connecting can be achieved by
  - optical solid-state devices (couplers)
  - electromechanical mirror-based free space optical switching devices

Solid-state cross-connects

- Based on semiconductor directional couplers
- Directional coupler can change optical property of the path
  - polarization
  - propagation constant
  - absorption index
  - refraction



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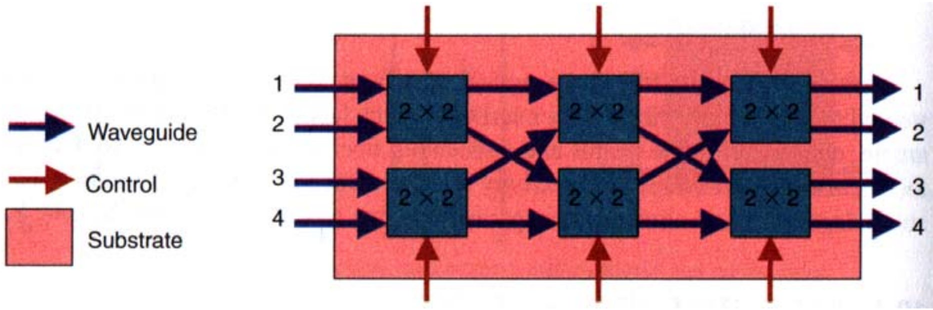
- The optical property may be change upon application of
  - heat
  - light
  - mechanical pressure
  - current injection
  - electric field
- The technology determines the switching speed, for instance
  - $LiNbO_3$ crystals: order of ns
  - SiO_2 crystals: order of ms

- A multiport switch, also called star coupler, is constructed by employing several 2x2 directional couplers
- For instance, a 4x4 switch can be constructed from six 2x2 directional couplers



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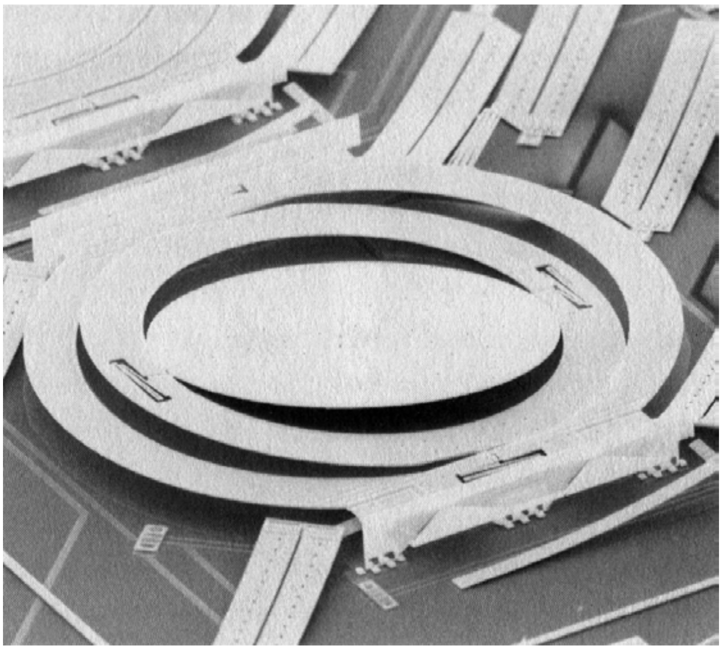
- Because losses are cumulative, the number of couplers in the path is limited and, therefore, also the number of ports is limited, perhaps to 32x32.

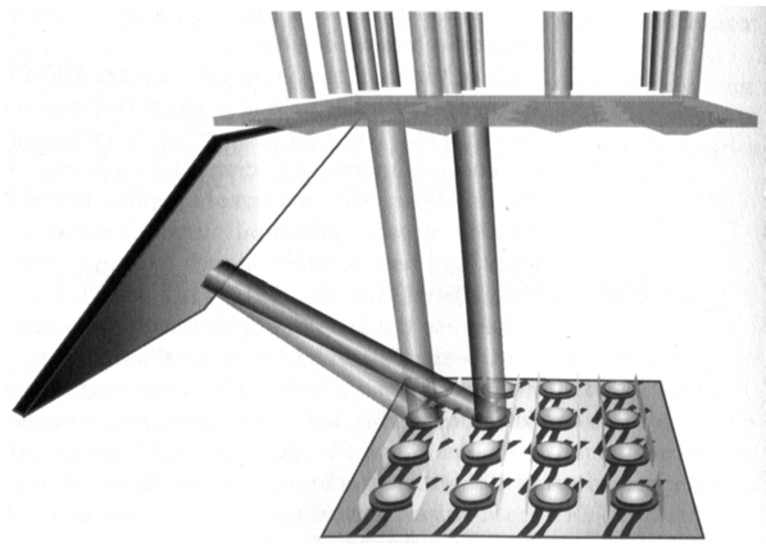
Microelectromechanical switches (MEMS)

- Tiny mirrors micromachined on a substrate
  - outgrowth of semiconductor processing technologies: deposition, etching, lithography
  - a highly polished flat plate (mirror) is connected with an electrical actuator
  - cab be tilted in different directions by applied voltage



R.J. Bates, *Optical switching and networking handbook*, McGraw-Hill, 2001.

- MEMS technology is still complex and expensive.
- Many MEMS devices may be manufactured on the same wafer
  - reduces cost per system
- Many mirrors can be integrated on the same chip
  - arranged in an array
  - experimental systems with 16x16=256 mirrors have been built
  - each mirror may be independently tilted
- Based on mirror arrays an all-optical space switch can be constructed.

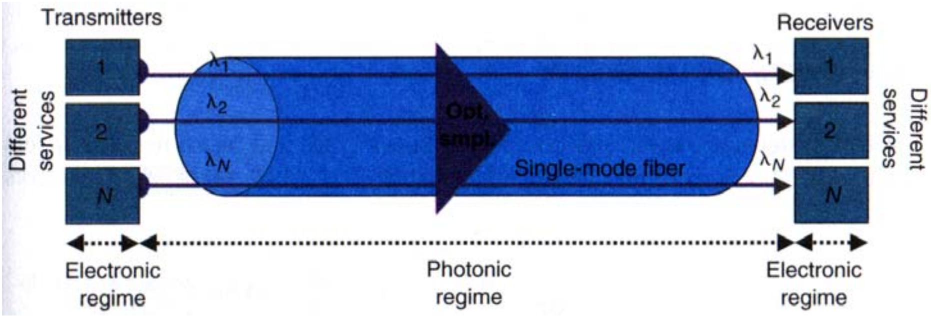


R.J. Bates, *Optical switching and networking handbook*, McGraw-Hill, 2001.

WDM systems

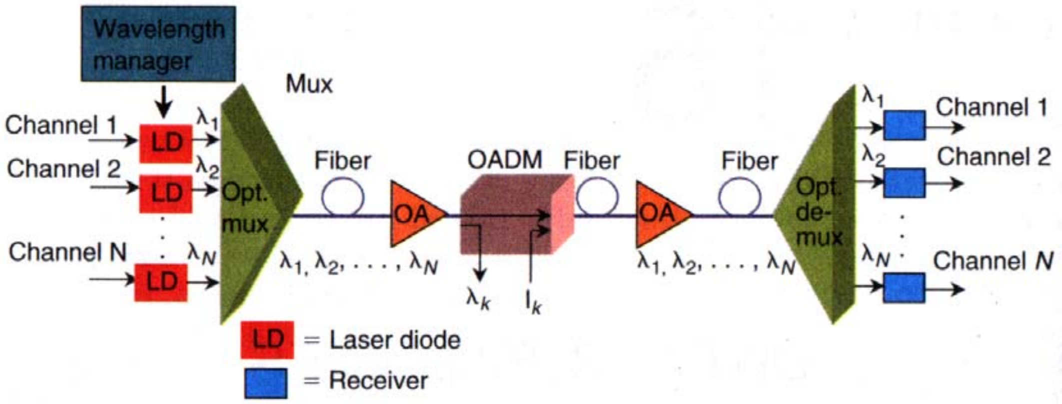
- WDM = Wavelength Division Multiplexing
  - equivalent of frequency division multiplexing in the optical domain.
- In WDM systems several optical signals at different wavelengths are carried on a single fiber
  - each wavelength may carry traffic at STM-4, STM-16 or STM-64 rate (622 Mbit/s, 2.5 Gbit/s or 10 Gbit/s).
- Increases the capacity of a fiber by the number of wavelengths carried.
- Depending on the channel (wavelength) separation one speaks about
  - WDM
  - DWDM (Dense WDM)
  - CWDM (Coarse WDM)
- ITU-T recommendation G.692 defines
  - 43 wavelength channels from 1530 to 1565 nm
  - with a spacing of 100 GHz
  - each channel carrying an STM-64 signal at 10 Gbit/s
  - total capacity 430 Gbit/s (enough to transmit 10000 volumes of an encyclopedia in 1 second)
- Commercial systems with 16, 40, 80 and 128 channels per fiber have been announced
  - 40 channels with a channel spacing of 100 GHz
  - 80 channels with a channel spacing of 50 GHz
- Theoretically more than 1000 channels may be multiplexed in a fiber
  - aggregate bandwidths of 8 Tbit/s per fiber are feasible (corresponding to 100 million simultaneous telephone conversations)
  - maybe even 40 Tbit/s per fiber can be achieved
  - in an optical cable of 432 fibers with 50% utilization this amounts to the total aggregate bandwidth of 8000 Tbit/s

- Initially, WDM and DWDM systems are used in point-ti-point configuration
  - to create a "big fat pipe" for long-haul transport



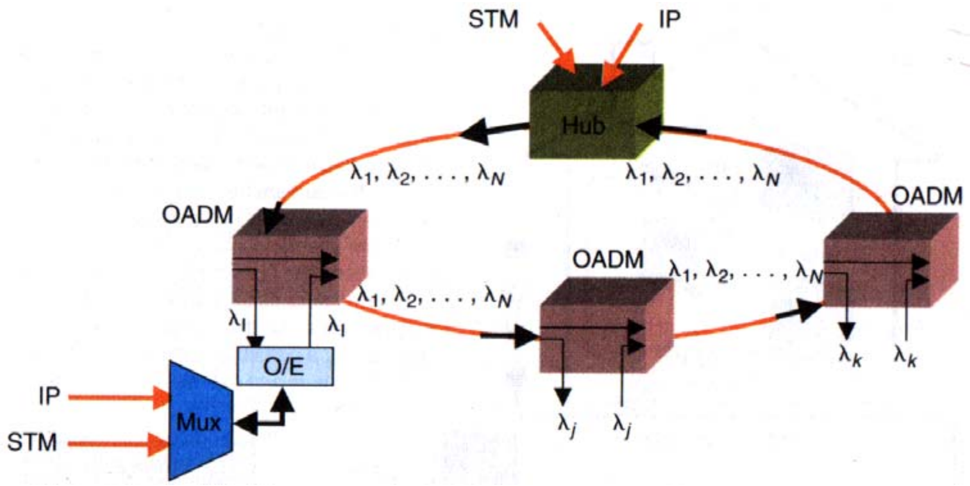
S.V. Kartalopoulos, Introduction to DWDM Technology -- Data in a Rainbow, John Wiley & Sons, 2000.

- OADM multiplexers may be added enabling the system to drop and add channels along its path.



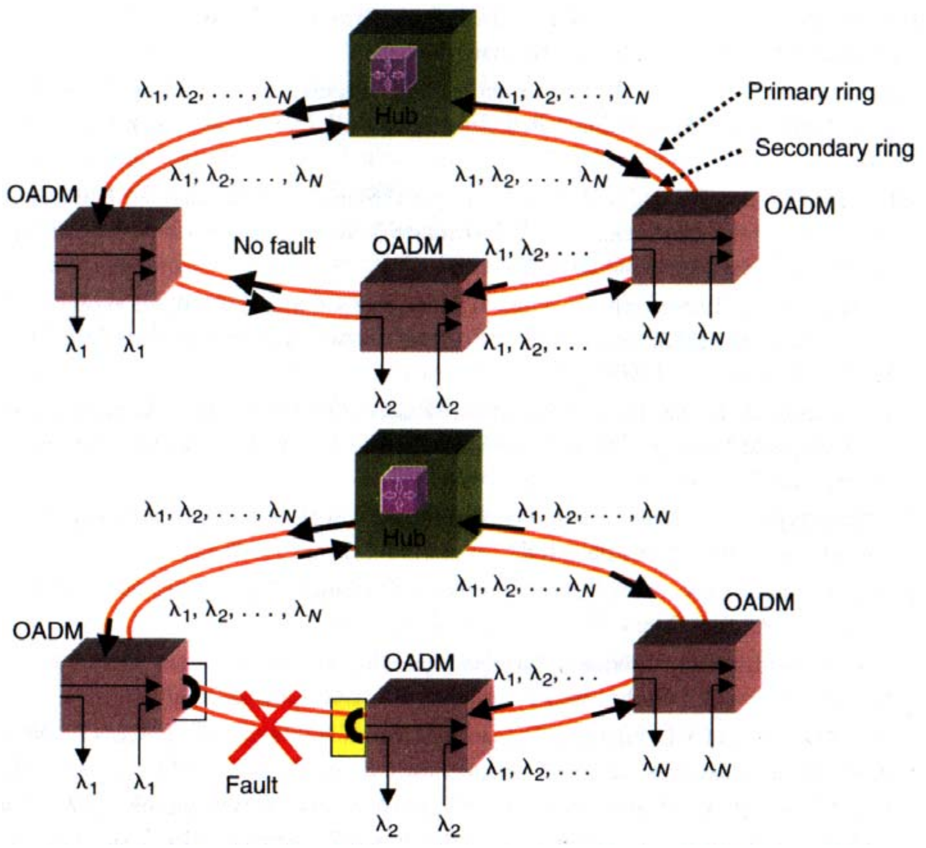
S.V. Kartalopoulos, Introduction to DWDM Technology -- Data in a Rainbow, John Wiley & Sons, 2000.

- DWDM networks with ring topology may also be created
  - covers a local or metropolitan area
  - spans a few tens of kilometers
  - one node serves as a hub where all wavelengths are sourced and terminated
  - each node has an OADM to drop off or add one or more wavelength channels
  - number of nodes is typically less than the number of wavelengths



S.V. Kartalopoulos, Introduction to DWDM Technology -- Data in a Rainbow, John Wiley & Sons, 2000.

- Fault protection may be accomplished with dual counterrotating rings
  - when a fault is detected, the neighboring nodes reroute the traffic via a U-turn optical cross-connect
  - requires additional optical cross-connect devices that put an additional burden on the power and cost budget of the ring network



S.V. Kartalopoulos, Introduction to DWDM Technology -- Data in a Rainbow, John Wiley & Sons, 2000.