UCL DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING
INTEGRATED GRADUATE DEVELOPMENT PROGRAMME
MSC TELECOMMUNICATIONS
MSC WIRELESS AND OPTICAL COMMUNICATIONS

Wavelength Division Multiplexing

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Topic Plan

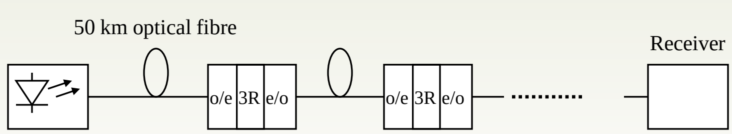
- WDM principles
- Limitations on number of wavelengths
- WDM classification
- WDM systems using optical amplifiers
- Limitations for amplified systems
- Multiwavelength optical networks
- Summary

Traffic Growth

- Historically, capacity growth rate of around 30% per year. The capacity increase per fibre has recently increased by 300% per year.
- IP traffic is 90 % of total traffic. New Internet services mean that bandwidth requirements may grow by 100 times in the next 10 years
- What current and future optical technologies will manage this growth?

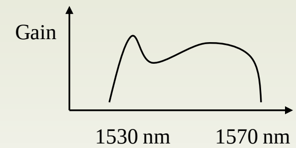
Requirement for WDM

- Early optical fibre communication systems used a single wavelength and electronic repeaters every 50 km.



- o/e – optical to electrical conversion
- e/o – electrical to optical conversion
- 3R regeneration – reamplification, reshaping, retiming
- The bit-rates of these systems increased from tens of Mbit/s up to around 1 Gbit/s

Erbium-doped fibre amplifier, EDFA, Gain Bandwidth



- EDFA introduced in early 1990's:
- Provides gain over a wide bandwidth, 1530 – 1570 nm ($\Delta\lambda$ = 40 nm) or to convert this to frequency bandwidth:

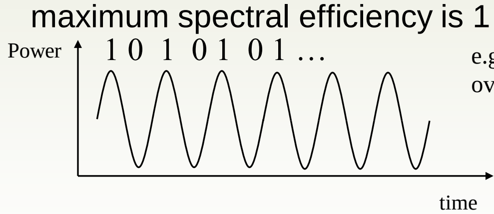
$$c = f\lambda \quad ; \quad \frac{df}{d\lambda} = \frac{-c}{\lambda^2} \quad \Rightarrow \quad \boxed{\Delta f = \frac{-c}{\lambda^2}\Delta\lambda}$$

- So at the operating wavelength of the EDFA (λ = 1.55 μm), 40 nm bandwidth $\equiv$ 5 THz (5×10^{12} Hz)
- How can this be used efficiently to transmit the most data?

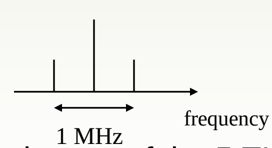
if the spacing is 25 GHz, there will be 201 channels, 5THz/25GHz just how many spaces, it need to be added 1.

Use of EDFA Gain Bandwidth

- In digital transmission, maximum bit-rate depends on the spectral efficiency that can be achieved (bit/s/Hz).
- In 2-level amplitude shift keying (ASK) coding, the maximum spectral efficiency is 1 bit/s/Hz



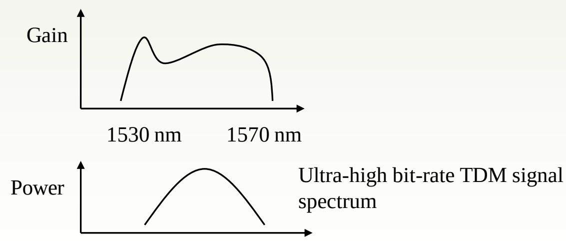
e.g. a 1 Mbit/s signal can be transmitted over a 1 MHz bandwidth channel



- The question was therefore, how to make use of the 5 THz bandwidth of the optical fibre and EDFAs?

Time division multiplexing (TDM)

- One suggested technique to make use of the EDFA bandwidth was to continue to use a single wavelength and keep increasing the bit-rate through TDM.
- Continue developing new generation of TDM systems, with 2.5, 10, 40, 80, 160, 640 … Gbit/s.



Time division multiplexing (TDM)

- The current generation of systems is now operating at 10 Gbit/s with 40 Gbit/s in development. However, a number of physical reasons will limit the growth of TDM data-rates:
- Electronic devices become difficult to implement and expensive.
- The short pulses used to encode high data-rates suffer large distortion during transmission.

Time division multiplexing (TDM)

- One limiting effect in transmission is chromatic dispersion. A measure of this effect is the dispersion length, L_D, the length of fibre over which the pulses broad by a factor of $\sqrt{2}$.
- For Gaussian pulses, this is given by:

$$L_D = \frac{T_0^2}{|\beta_2|}$$

- where T_0 is the pulse half-width (at 1/*e*-intensity point) and β_2 is the fibre dispersion

Time division multiplexing (TDM)

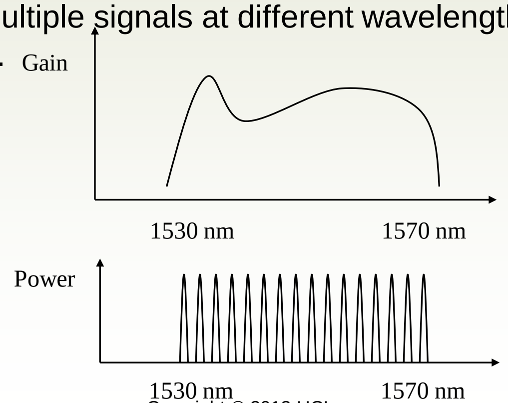
- The accumulated dispersion of the link must be $<L_D$ to avoid intersymbol interference.
  For standard single-mode fibre (β_2 = -21.7 ps^2/km), with:
- 10 Gbit/s, using T_0 = 20 ps, L_D = 18 km
- 40 Gbit/s, using T_0 = 5 ps, L_D = 1.2 km
- 160 Gbit/s, using T_0 = 1.25 ps, L_D = 72 metres
- Matching the dispersion compensation of long-haul system to within ±72 metres is not practical. Other effects (fibre nonlinearity, polarisation mode dispersion) also impact 160 Gbit/s transmission.

advantages of WDM: Besides multiplication of the data rate in a single fiber, WDM systems have an advantage in that the number of channels can be adapted according to actual demand.

Problem of WDM :The first problem is signal attenuation. The second problem is that of optical amplification.Widely used erbium-doped fibe amplifiers (EDFAs) operate efficiently in only a portion of the 1280- to 1650nm window.

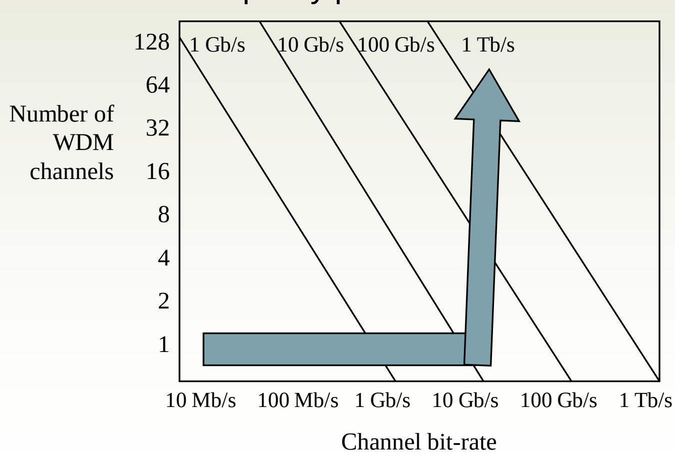
Wavelength division multiplexing (WDM)

- The most efficient approach is to combine TDM with wavelength division multiplexing to fully use the EDFA bandwidth.
- Transmit multiple signals at different wavelengths over a single fibre.



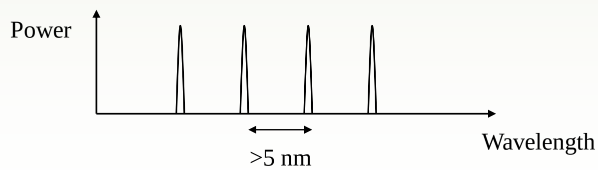
Wavelength division multiplexing (WDM)

- This schematic shows the route taken in reaching Tbit/s transmission capacity per fibre:



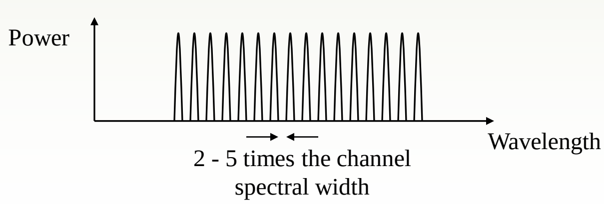
Coarse WDM

- For low cost, short distance links (e.g. 10 Gb/s Ethernet standard)
- Wide channel spacing, can tolerate large wavelength drift, low capacity.



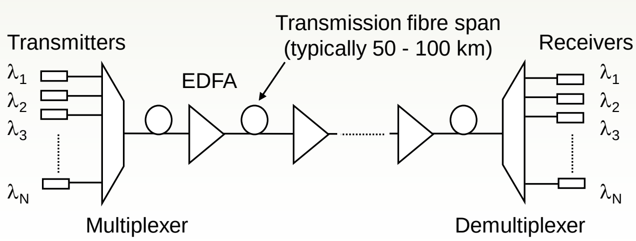
Dense WDM

- For long distance, high capacity (wide area networks)
- Narrow channel spacing, temperature control of transmitter lasers required to maintain good wavelength stability.



WDM Link

- Transmitters send independent signals on different wavelengths.
- Multiplexer combines all the signals onto one fibre.
- Cascaded fibre spans and EDFAs transmit the signals.
- Demultiplexer separates the signals before receiving.



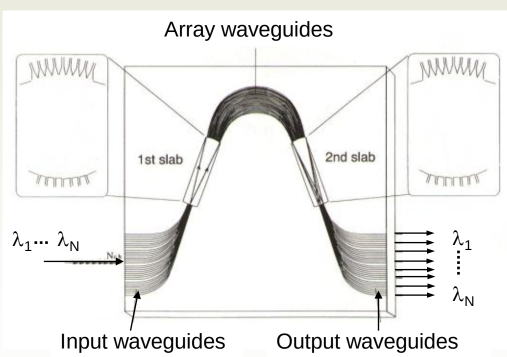
WDM Multiplexers and Demultiplexers

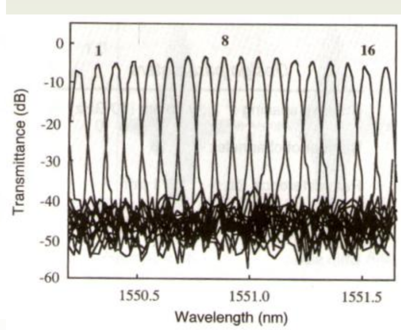
- Wavelengths are combined and separated using optical gratings which spatially disperse the wavelengths.
- One type of grating is the free space grating – grooves ruled or holographically written on metal, and aligned with the optical fibre.

WDM Multiplexers and Demultiplexers

- An alternative is the arrayed waveguide grating (AWG), based on a silica slab waveguide (shown below). The constructive interference of the light which has been split and propagated through waveguides of different lengths is recombined, giving constructive interference (and hence transmission bands) at well defined wavelengths.

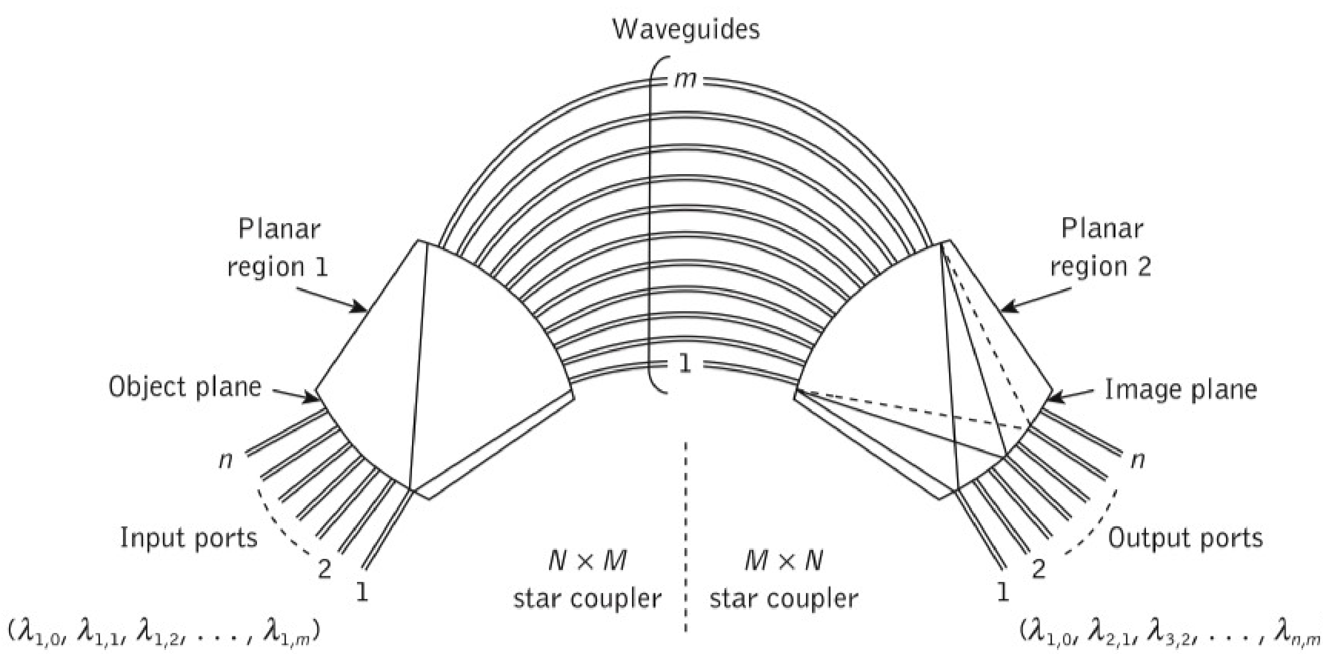
WDM multiplexers and demultiplexers





The AWG-based coupler demultiplexes an incoming WDM signal comprising a number of wavelengths M (i.e. λ 1 to λm) on each input port in the planar region 1. Each of the M wavelength demultiplexed channels after traveling separately through different lengths of the curved waveguides are then multiplexed in the planar region 2. A specific wavelength channel from an input port is directed into the reconstructed WDM signal which appears at precisely one output port of the second planar region. The reconstituted spectrum of the WDM signal at any output port contains a different set of wavelength channels with at least one wavelength channel from each input port and therefore when the number of WDM channels M is present at N input ports then the output port 1 always produces a WDM signal containing a wavelength signal from each of the input ports.

For example, the input port 1 contains a WDM signal with a number of wavelengths M (i.e. $\lambda_{1,0}$, $\lambda_{1,1}$, $\lambda_{1,2}$, . . . , $\lambda_{1,m}$) and similarly the rest of the input ports from 2 to N contain ($\lambda_{2,0}$, $\lambda_{2,1}$, $\lambda_{2,2}$, . . . , $\lambda_{2,m}$), . . . , ($\lambda_{n,0}$, $\lambda_{n,1}$, $\lambda_{n,2}$, . . . , $\lambda_{n,m}$). In this case the output port 1 always produces a WDM signal containing $\lambda_{1,0}$, $\lambda_{2,1}$, $\lambda_{3,2}$, . . . , $\lambda_{n,m}$. The remaining output ports produce different WDM signals comprising one wavelength channel from each input port following the same pattern. It should be noted that the number of output ports is dependent on the number of channels and also the separation between the channels.



(b)

difference between waveguide and optical fiber
1. the thin of waveguide is 5 micron which is single mode

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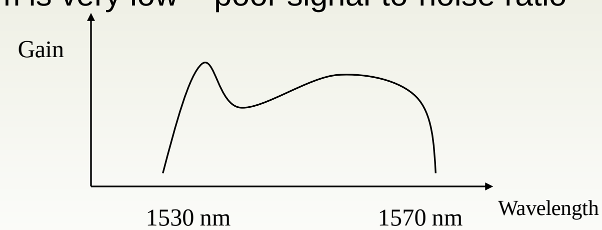
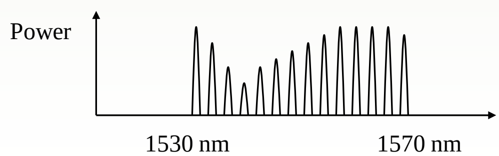
Gain-flattened EDFA

- One important feature of EDFAs for WDM systems is that their gain uniform over the bandwidth of the WDM signal.
- After cascaded EDFAs, power of channels around 1535 – 1540 nm is very low – poor signal-to-noise ratio





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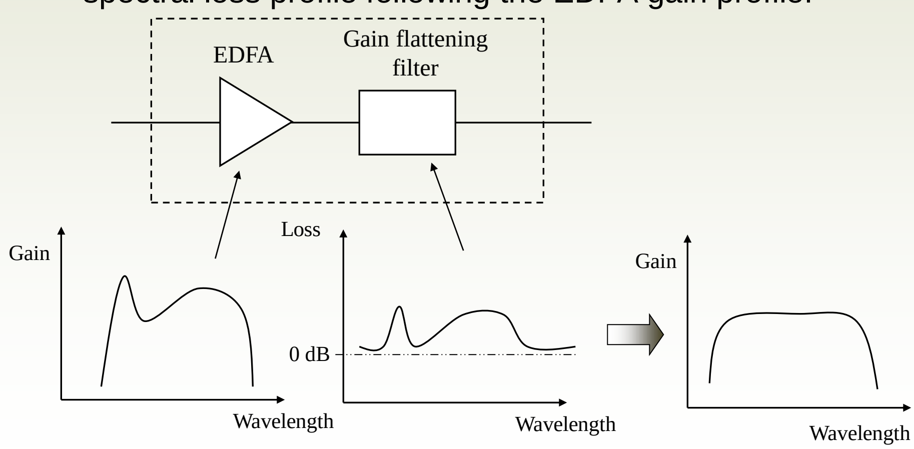
Gain-flattened EDFA (cont.)

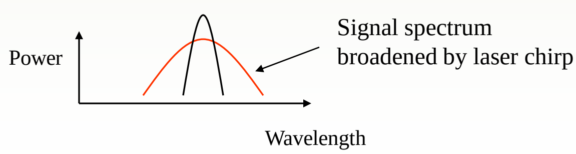
- Gain flattening in achieved using optical filters with spectral loss profile following the EDFA gain profile:



isolator, equalizer, narrowband filter are important components in optical fiber communica tion systems

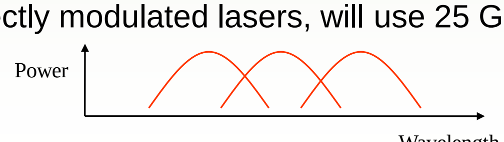
Minimum channel wavelength spacing

- Channel spectrum is broadened by the modulation e.g. a 10 Gbit/s optical signal spectral minimum width is around 10-20 GHz (0.08 – 0.16 nm wavelength width).
- In practice, the laser 'chirp' increases the spectral width (laser wavelength varies with output power).



Minimum channel wavelength spacing

- If the WDM channels are too close, spectral overlap occurs → interferometric crosstalk and eye closure, leading to high bit error rate.
- Hence, ITU standards specify a 50 GHz (0.4 nm) spaced grid of wavelengths for 10 Gbit/s per channel WDM.
- This gives a spectral efficiency of 0.2 bit/s/Hz.
- 5 THz EDFA bandwidth gives ~1 Tbit/s.
- Future systems, using external modulators with lower chirp than directly modulated lasers, will use 25 GHz spacing.



Minimum channel wavelength spacing (cont.)

- Fibre nonlinear effects also limit channel spacing. These are caused by the dependence of the fibre refractive index on the optical power in the fibre.
- Four-wave mixing – beating of two channels results in the modulation of the refractive index $\rightarrow$ this in turn modulates the channels, and transfers signal power to new optical frequencies.
- Cross-phase modulation – the modulated power of one channel affects the optical phase of another.

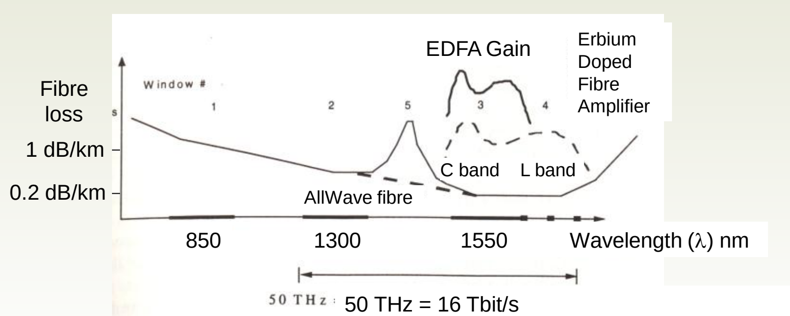
Maximum number of channels

- So the bandwidth of the EDFA, and the limit on channel spacing, limit the WDM data-rate to 1-2 Tbit/s.
- Another technique to increase data-rates is to extend the bandwidth of the optical amplifier.
- A number of techniques can achieve this:
- L-band (long wavelength band) EDFA – by reducing the pump power, the gain of the EDFA moves to longer wavelengths, 1600-1700 nm.

Maximum number of channels

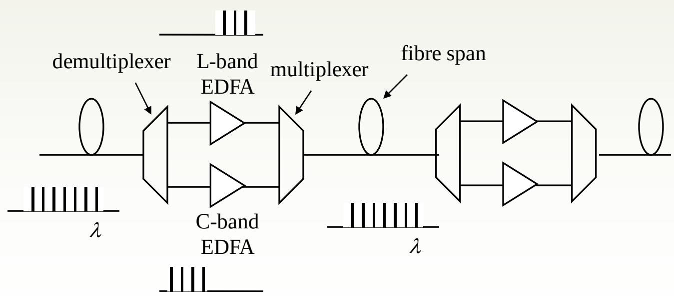
- Other rare-earth dopants (eg Nd for gain at 1300 nm)
- Use of Raman amplification, which can access any wavelength, using pump wavelength at 13 THz above the signal frequency (will be covered in a later lecture).
- Semiconductor optical amplifiers (SOA) (similar to laser diodes, but with no optical feedback). However, the nonlinearity of the SOA (cross-gain modulation) makes it difficult to use for WDM, due to cross-talk.

Maximum number of channels (cont.)



Maximum number of channels (cont.)

- The use of different types of optical amplifiers along the same fibre require broadband demultiplexing at each amplifier:

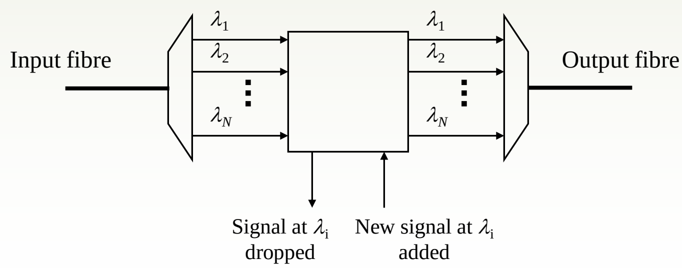


Limitations of amplified systems

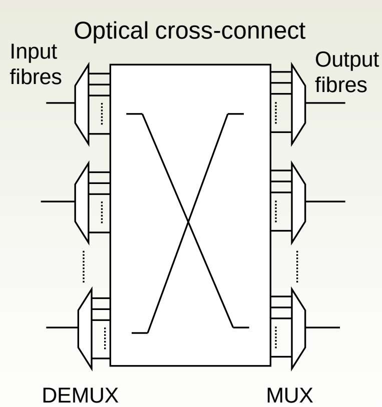
	Single channel	Multiple WDM channels
Linear effects:	Chromatic dispersion Polarisation mode dispersion	Dispersion slope Amplifier gain slope
Nonlinear effects:	Self-phase modulation Intrachannel four-wave-mixing Intrachannel cross-phase modulation Gordon-Haus jitter	Four wave mixing Cross-phase modulation Raman scattering

Wavelength routing: optical add-drop multiplexer

- Optical add-drop multiplexing, based on signal wavelength.
- Carried out at high data-rates (for example, adding and dropping a 10 Gb/s WDM channel)



Wavelength routing: optical cross-connect



Future devices required in wavelength-routed networks

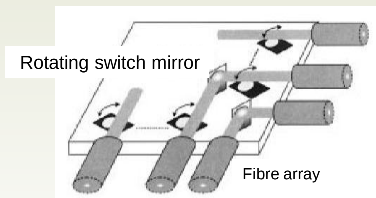
1. Wavelength cross-connect/router – uses WDM MUX/DEMUX and optical switches.
2. Wavelength tuneable lasers – used in transmitter to select correct light path through the network.
3. Wavelength converters – to avoid light paths blocking each other at routing nodes.
4. Amplifier gain control – to control signal powers as light paths are switched.
5. Network signalling – identification of the light path transmitted with the signal

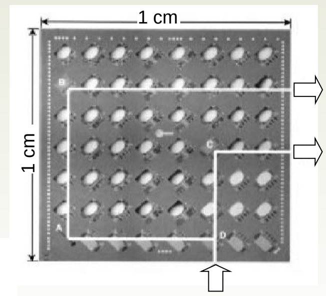
Microelectromechanical systems MEMS

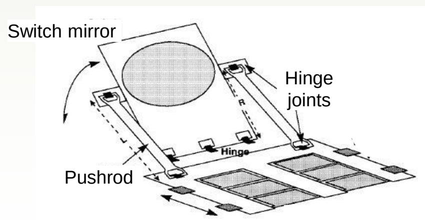
- Device technology using lithographic fabrication techniques developed for silicon electronics to create miniature mechanical components.
- High yield and reliability means that 1000 × 1000 switch-fabric is possible

Microelectromechanical systems MEMS

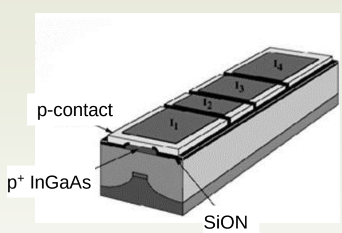
After L. Y. Lin et al, IEEE J. of Selected Topics in Quantum Electron. 5, pp. 4-9, 1999







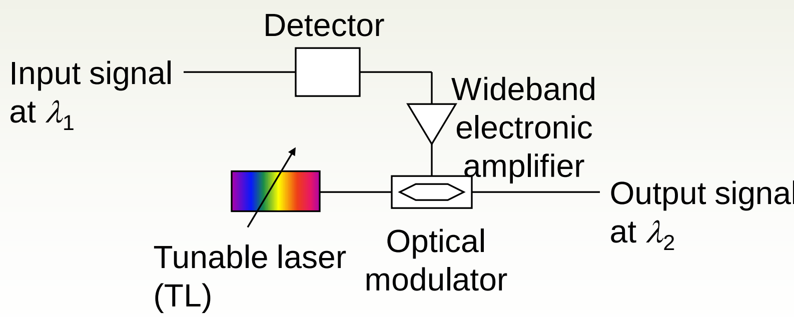
Wavelength tuneable lasers



- Widely tuneable lasers
- Multi-section monolithic semiconductor lasers are compact and offer the possibility of fast, continuous tuning over the range of the EDFA bandwidth

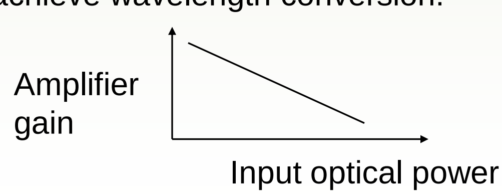
Wavelength converter

- Wavelength conversion can be carried out using a transponder (receiver and transmitter at a new wavelength).



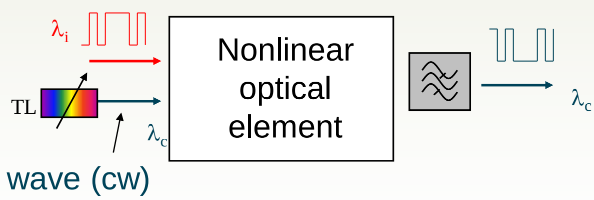
Wavelength converter

- Wavelength conversion can be carried out using a transponder (receiver and transmitter at a new wavelength) – however, requires expensive broadband electronics.
- Potentially cheaper option – use nonlinear optical element, such as a semiconductor optical amplifier. As the input power increases, the gain reduces – this effect can be used to achieve wavelength conversion:



Wavelength converter

- Based on cross-gain modulation in semiconductor optical amplifiers



Optical cross-connect using tuneable lasers