Components of Optical Networks

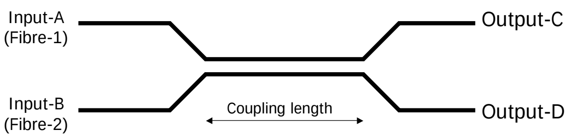
Based on:
Rajiv Ramaswami, Kumar N. Sivarajan, "*Optical Networks – A Practical Perspective 2nd Edition*," 2001 October, Morgan Kaufman Publishers

Optical Components

- Couplers
- Isolators/Circulators
- Multiplexers/Filters
- Optical Amplifiers
- Transmitters (lasers,LEDs)
- Detectors (receivers)
- Switches
- Wavelength Converters

Couplers

- Directional coupler is used to combine and split optical signals.



- $C=\alpha A+(1-\alpha)B \quad D=\alpha B+(1-\alpha)A$
- α is called the coupling ratio

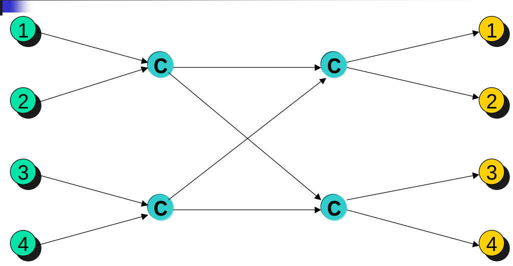
Couplers

- Can be:
  - Wavelength independent (α is independent of the wavelengths)
  - Wavelength selective (α is wavelength dependent)

Wavelength Independent Couplers

- 3dB coupler ($\alpha=0.5$) can be used to build n×n couplers (e.g., n×n star coupler)
- Can also be used used to tap off a small portion of light ($\alpha=0.9–0.95$), e.g., for monitoring purposes.

4×4 Star Coupler



Power is split equally among the outputs...

Wavelength Dependent Coupler

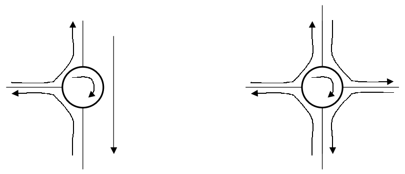
- Used to combine signals at 1310nm and 1550nm (two different bands) together without loss. It may only have one output.
- Can be used to separate optical signals of different bands.
- Also used for mixing the pumping signal for EDFA.

Isolators

- Allows “light-flow” in one direction but blocks it in the other (nonreciprocal device).
- Used after EDFA and lasers to improve performance.
- Insertion loss: loss in forward direction (~1dB)
- Isolation: loss in reverse direction (~40-50dB)

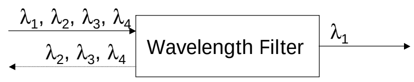
Circulators

- Isolator with multiple ports (e.g., 3, 4).
- Helpful in constructing optical add/drop elements.



Filters

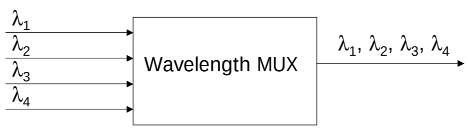
- Essential to selecting (dropping) wavelengths from the fibre (demultiplexing).



- Filters can be tuneable

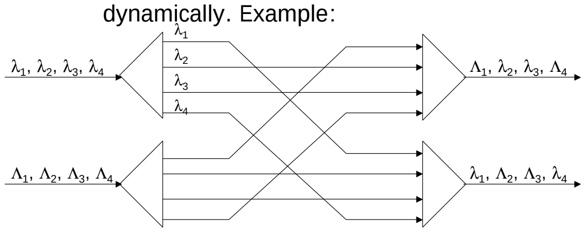
Multiplexers

- Essential to combine wavelengths onto one fibre.



Static Wavelength Crossconnects

- The crossconnect pattern is established at manufacturing and cannot be changed dynamically. Example:



Optical Amplifiers

- Since optical signals are attenuated by fibre and insertion losses of other components, signals may become too week to be detected.
- It is possible to do 1R regeneration optically (with all its benefits and drawbacks).
- Furthermore optical amplifiers have large gain bandwidths (one regenerator is enough for the entire band).
- But, they introduce additional noise (noise that accumulates). (Gain should be also flat over the entire band and insensitive to the input signal).

Optical Amplifiers

- Types of optical amplifiers:
  - Erbium-doped fibre amplifiers (silica fibre doped with Erbium ions. Laser pumps are needed)
  - Raman amplifiers (using the Raman scattering non-linear effect. Needs laser pump source but it can be used al all bands).
  - Semiconductor optical amplifiers (earlier technology, using p-n junctions of semiconductors to amplify light. No pump source is needed).

Transmitters - LEDs

- Light Emitting Diodes are inexpensive but have a wide spectrum and work only in the ~800nm range.
- LEDs cannot be directly modulated at high data rates.

Transmitters - Lasers

- Lasers are used as transmitters and pump sources for EDFA and Raman amplification (higher power is required).
- Semiconductor lasers are the most commonly used, essentially they are semiconductor optical amplifiers with positive feedback (very effective and efficient).
- Erbium lasers are EDFAs positively fed back but need pumping source (semiconductor laser)

Transmitters - Lasers

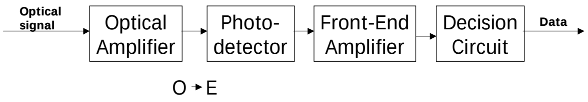
- Need to produce high output (0-10dBm)
- Have to have narrow spectral bandwidth (for WDM)
- Have to be stabile in the transmitting wavelength (lifetime drifting needs to be small)
- Need to be easily modulated.

Transmitters – Tunable Lasers

- Highly desirable components:
  - For a 100-channel WDM system 100 types of conventional lasers have to be stocked (extensive inventory)
  - Key elements of reconfigurable optical networks (less lasers than wavelengths; switching times:~ms)
  - Also essential for for efficient optical packet switched networks (switching times: ~ns)
- Still in research labs but soon to be available.

Detectors - Receivers

- For O-E conversion.



- Tunable receivers are available.

Wavelength Converters

- Converts data on optical signal for incoming wavelength to an other outgoing wavelength.
- Can be used:
  - between legacy and WDM systems (transponder).
  - Within the network to improve on utilization.
  - Between boundaries of networks belonging to different carriers, who do not coordinate assignment of wavelengths.

Wavelength Converters

- Can be classified:
  - Fixed-input, fixed-output
  - Variable-input, fixed-output
  - Fixed-input, variable-output
  - Variable-input, variable-output
- Can be:
  - Optoelectronic (2R/3R OEO conversion, usually VIFO)
  - Optical grating (VIFO or VIVO)
  - Interferometric (Optical 2R)
  - Wave mixing (truly transparent, λ–s have to be close)

Switches

Switches

- Applications:
  - Provisioning
  - Protection switching
  - Packet switching
  - External modulation

Provisioning Switching

- Provisioning of lightpaths.
- Switches are used inside wavelength crossconnects to reconfigure them to support new lightpaths.
- These switches replace manual patch-panels, thus requiring additional control software but enable easy and fast reconfiguration.
- Switching times of a couple of ms are acceptable.
- Challenge is to realize large switches.

Protection Switching

- Switch the entire traffic of a primary fibre to another fibre in case the primary fibre fails.
- Switching time is in order of couple of ms. (The entire protection operation should be done in a couple 10ms).
- Switch sizes may vary from 2 ports up to several thousand ports (when used in wavelength crossconnects)

Packet Switching

- High-speed optical packet switching switches, switching on a packet-by-packet basis.
- Switching times should be as small as couple of ns. (at 10Gbps 53bytes correspond to 42ns).
- This is the switching technology of the future...

External Modulator Switches

- To turn off and on the laser beam after the laser transmitter (to reduce laser's spectral bandwidth, thus to reduce chromatic dispersion).
- Switching time is around 10ps (rise and fall time) for a 10Gbps signal (1bit time = 100ps, switching time has to be at least an order of magnitude less).

Switches - comparison

Application	Switching time	Number of ports
Provisioning	1-10ms	>1000
Protection	1-10ms	2-1000
Packet switching	1ns	>100
External modulation	10ps	1

Parameters of Switches

- Extinction ratio: output power on state/output power off state (40-50dB for mechanical switches, 10-25dB for high-speed modulators).
- Insertion loss: loss should be uniform over all paths (determined by the architecture mainly not the technology).
- Crosstalk: calculated by the output power of all input ports not switched to that output port.

Parameters of Switches

- Polarization dependence should be negligible.
- Latching: switching remains intact even if power supply is turned off.
- Monitoring: switching state should be monitorable.
- Reliability: long-term history is desired. Short term reliability is tested by switching through states a couple million times. In provisioning although it is important that the switch remains capable of switching even after spending years at a given state.

Large Optical Switches

- Number of ports: n*100-n*1000 (couple of fibres carrying several tens to hundreds of wavelengths).
- Properties of large optical switches:
  - Number of switching elements required.
  - Loss uniformity.
  - Number of crossovers.
  - Blocking characteristics.

Number of Switching Elements

- Large switches are built up by multiple small switch elements (e.g. 2*2 or 1*n elements).
- Cost and complexity depend on the number of switching elements.

Loss Uniformity

- The problem of loss uniformity (as mentioned before) is exacerbated for large switches.
- Can be measured, e.g., by counting the minimum and maximum number of switch elements in the optical path for different inputs/outputs.

Number of Crossovers

- Some switches are manufactured on a single substrate on a single(!) layer. If paths of waveguides cross it will introduce two undesirable effects:
  - Power Loss and
  - Crosstalk.
- Thus crossovers have to be minimized (eliminated).
- It is not an issue with free space propagation, i.e., with MEMS.

Switch Blocking Characteristics

- Switches can be of two types:
  - Non-blocking: an unused input can be connected to any unused output, thus every (possible) interconnection pattern can be realized.
  - Blocking: some interconnection patterns cannot be realized (e.g., there is no way of connecting input fibre one to output fibre 6 on wavelength 3).

Non-blocking Switches

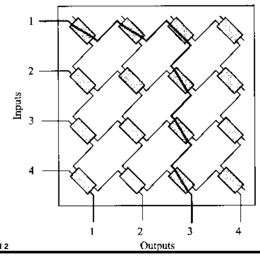
- Can be further characterized into:
  - Wide-sense non-blocking: every input can be connected to every output without rerouting any ongoing connections but employing some kind of sophistication for establishing connections to begin with.
  - Strict-sense non-blocking: any input can be connected to any output without rerouting and without added sophistication.
  - Rearrangeably non-blocking: ongoing connections may be interrupted and rerouted which may not be acceptable but uses fewer switching elements and more sophisticated control is needed).

Basic Switch Architectures

	Non-block. type	Number Switches	Max. Loss	Min. Loss
Crossbar **2x2**	Wide	n^2	2n-1	1
Clos **2x2**	Strict	$4\sqrt{2}n^{1.5}$	$5\sqrt{2n}-5$	3
Spanke **1xn**	Strict	2n	2	2
Beneš **2x2**	Rearr.	$n(2\log_2 n-1)/2$	$2\log_2 n-1$	$2\log_2 n-1$
Spanke-Beneš **2x2**	Rearr.	n(n-1)/2	n	n/2

Crossbar Switch

- No crossovers but not loss uniform
- Used in Clos switches

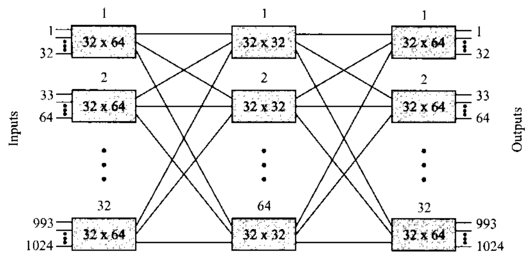


Clos Switch

- Used in practice for large switches.
- 3 parameters: m,k, and p.
- 1st and 3rd stage have k (m*k) switches, 2nd stage has p (k*k) switches.
- If p>=2m-1 then switch is strictly non-b, thus usually p=2m-1.
- Individual switches are usually designed by crossbar switches.
- Loss uniformity is better than with crossbar.
- Number of switching elements is less than that of a crossbar.

Clos Switch

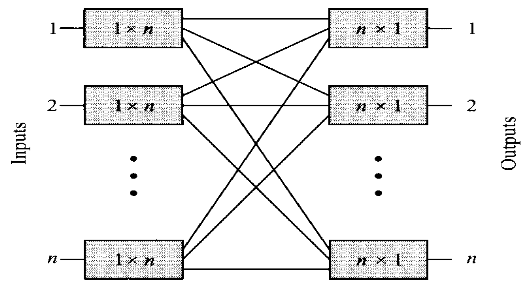
- A three stage 1024 port switch:



Spanke Switch

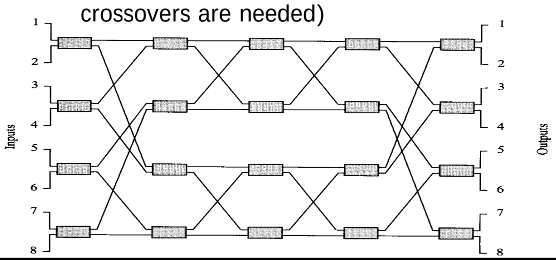
- Becoming more and more popular.
- n*n switch is established by n (1*n) switches and n (n*1) switches.
- These elements can be built (e.g., using MEMS technology).
- Only 2n switches are needed (linear!) and all paths cross through only 2 elements.
- Loss uniformity can be achieved and insertion loss is small.

Spanke Switch



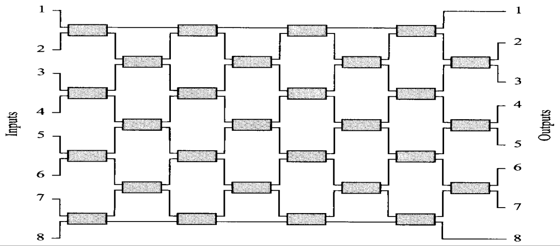
Beneš

- Rearrangeably non-blocking and very efficient in the number of 2*2 switches (waveguide crossovers are needed)



Spanke-Beneš

- Rearrangeably non-blocking, efficient in the number of 2*2 switches (no waveguide crossovers – n-stage planar architecture). Not loss uniform.



Optical Switching Technologies

- Bulk Mechanical Switches
- Micro-Electro-Mechanical System (MEMS)
- Bubble-Based Waveguide Switch
- Liquid Crystal Switches
- Electro-Optic Switches
- Thermo-Optic Switches
- Semiconductor Optical Amplifier Switches
- Electro-Holographic Switches

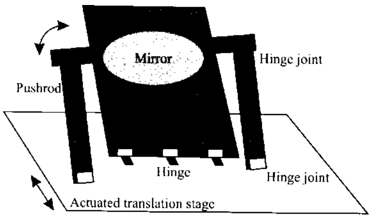
Mechanical Switches

- Examples include:
  - Moving mirrors in and out of the optical path
  - Bending or stretching fibre in a coupler changing the α value of coupling.
- Low insertion loss, low crosstalk and relatively inexpensive and well suited for crossbars. Switching times of few ms and little port counts (small crossconnects, protection, provisioning). Long term reliability? Can be cascaded but there are better ways...

MEMS Switches

- Small mechanical devices on silicon substrates. In optical networking MEMS refers to small mirrors of a few hundred micrometers. Several of these mirrors can be put on one substrate with common semiconductor manufacturing techniques.
- Mirrors can be digital (only two positions – for crossbar architectures) or analogue (several positions – for 1*n switches) controlled.

Pop-up (Digital) MEMS



Pop-up (Digital) MEMS

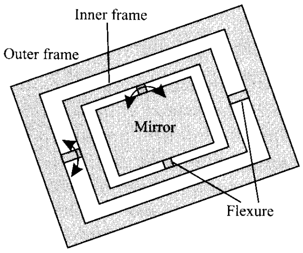
- Practical size: 32x32

A.S. Morris, "In Search of Transparent Networks," IEEE Spectrum, October 2001

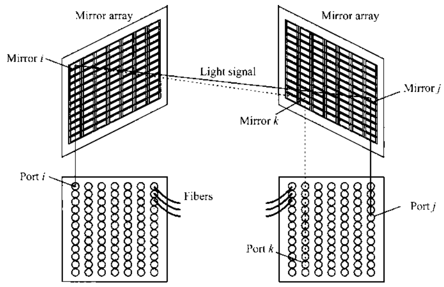
Analogue Beam Steering Mirror

- Also called a Gimbel mirror or 3D mirror.
- Control is difficult sophisticated servo control is needed (high voltages with mV scales).
- Suited to realize Spanke architectures with hundreds to thousands of ports.
- Challenges: control, reliability, stability to temperature, humidity and vibration

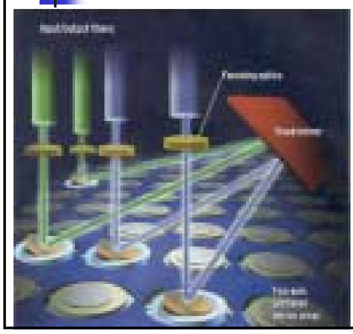
Analogue Beam Steering Mirror



Analogue Beam Steering Mirror



Analogue Beam Steering Mirror

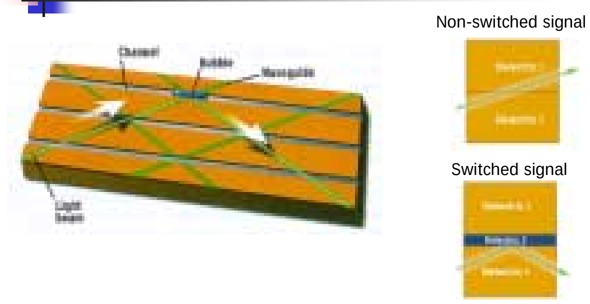


A.S. Morris, "In Search of Transparent Networks," IEEE Spectrum, October 2001

Bubble-Based Waveguide Switch

- Technology is similar to what is used in inkjet printers!
- Trenches are filled with index matching fluid (that can be vaporized or moved).
- Small crossbar switches (32x32) can be built efficiently with switching times of >10ms.

Bubble-Based Waveguide Switch



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Liquid Crystal Switches

- Make use of polarization effects. LC cells can be used to rotate polarization (or not). Different polarizations of the same signal then can be used to cancel each other out.
- Can be produced. in volume with low cost (32x32 size)

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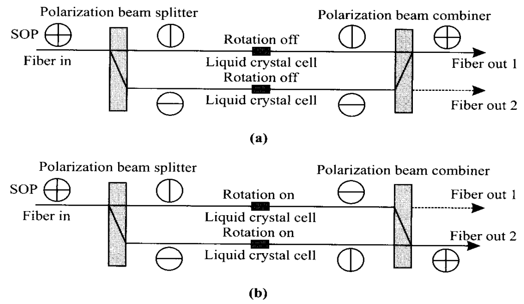
Liquid Crystal Switches



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Electro-Optic Switches

- Based on directional couplers with varying coupling ratio (α) using a voltage.
- Made with lithium niobate (usually)
- Capable of rapid changes (<1ns).
- High loss, high complexity and high polarization dependent loss.

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Electroholographic Switches

- A switch matrix is created by ferroelectric crystals (e.g., lithium niobate)(basically electro-optic switches).
- Rows correspond to fibers, while columns correspond to wavelengths(!)
- They claim it is going to be fast enough for photonic packet switching.
- Do not scale well, PDL, sophisticated focusing is needed, etc.

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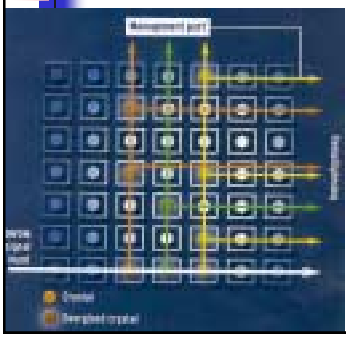
Electroholographic Switches



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Large Electronic Switches

- Today most practical crossconnects still use OEO switching elements.
- Clos architecture is preferred (strict non-blocking).
- Cost is mainly determined by the number of OEO conversions not the switching fabric.
- High data rate streams may be spliced into lower rate parallel streams. But today 64*64 crossbar ICs operating at 2.5Gbps are available (dissipates 25W !!).

Large Electronic Switches

- A 1024x1024 switch needs about 100 such ICs => power dissipation is around 25kW (cooling is needed)(with 3D MEMS it would be ~3kW and would be significantly more compact).
- Connections between boards and racks at these high speeds becomes a problem => not scalable. (Can be done optically with less dissipation and interference while at a longer range.)