



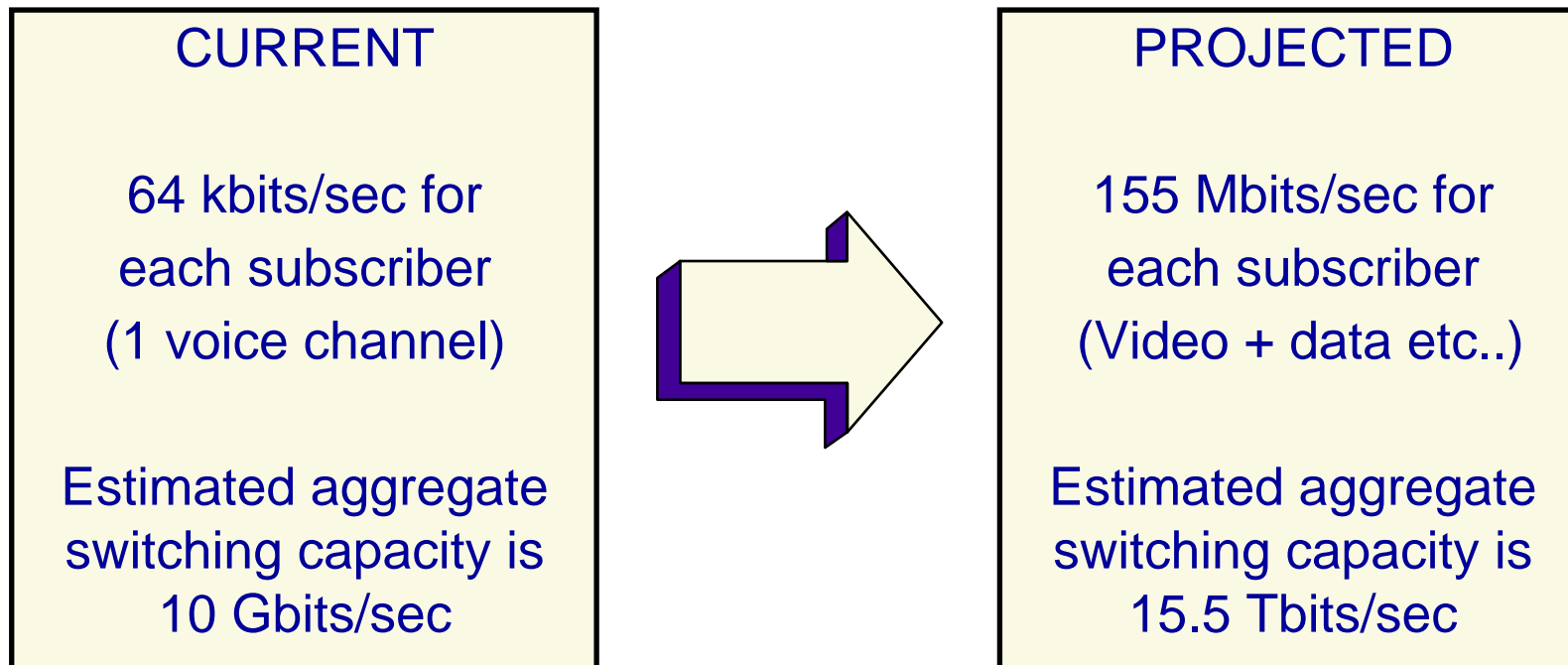
Optical Switching



The need for Optical Switching

- High bit rate transmission must be matched by switching capacity
 - Optical or Photonic switching can provide such capacity
-

Example: 100,000 subscriber digital exchange



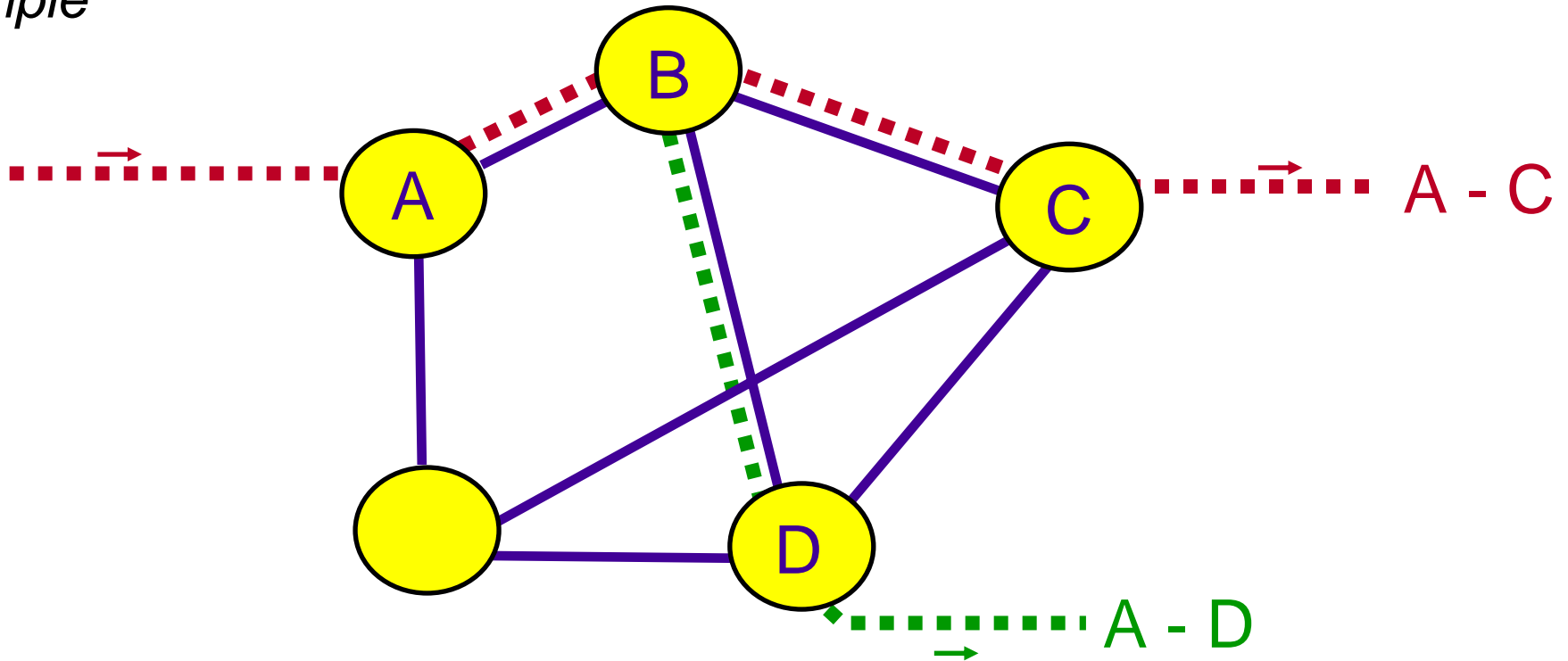


What is Optical Switching?

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Switching is the process by which the destination of a individual optical information signal is controlled

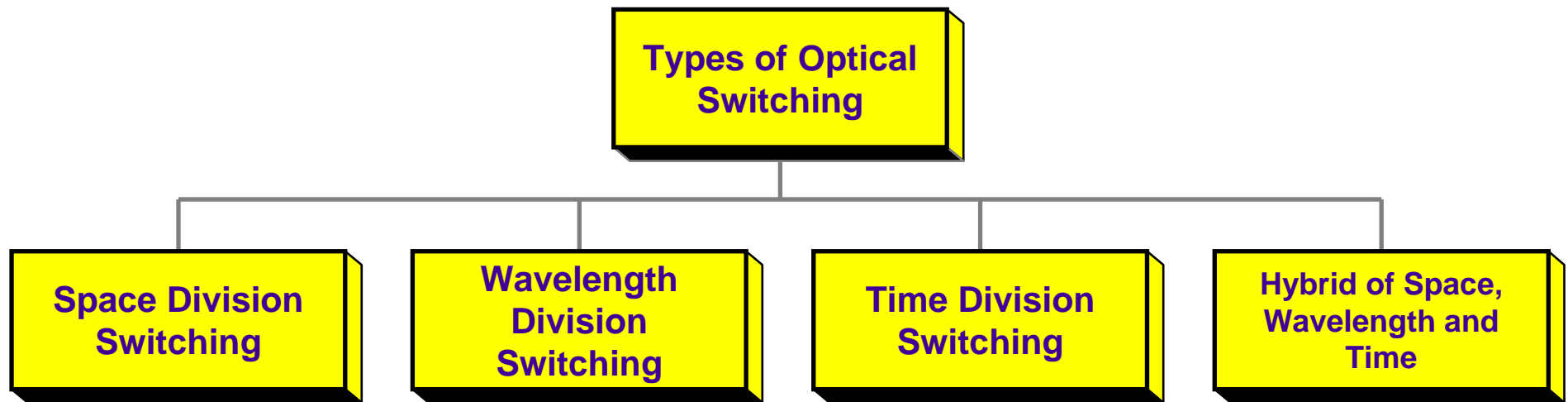
Example





Optical Switching Overview

Switching is the process by which the destination of a individual optical information signal is controlled



Switch control may be:

- Purely electronic (present situation)
- Hybrid of optical and electronic (in development)
- Purely optical (awaits development of optical logic, memory etc.)



Switching In Optical Networks.

Electronic switching

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- ▶ **Most current networks employ electronic processing and use the optical fibre only as a transmission medium. Switching and processing of data are performed by converting an optical signal back to electronic form.**
- ▶ **Electronic switches provide a high degree of flexibility in terms of switching and routing functions.**
- ▶ **The speed of electronics, however, is unable to match the high bandwidth of an optical fiber (Given that fibre has a potential bandwidth of approximately 50 Tb/s – nearly four orders of magnitude higher than peak electronic data rates).**
- ▶ **An electronic conversion at an intermediate node in the network introduces extra delay.**
- ▶ **Electronic equipment is strongly dependent on the data rate and protocol (any system upgrade results in the addition/replacement of electronic switching equipment).**



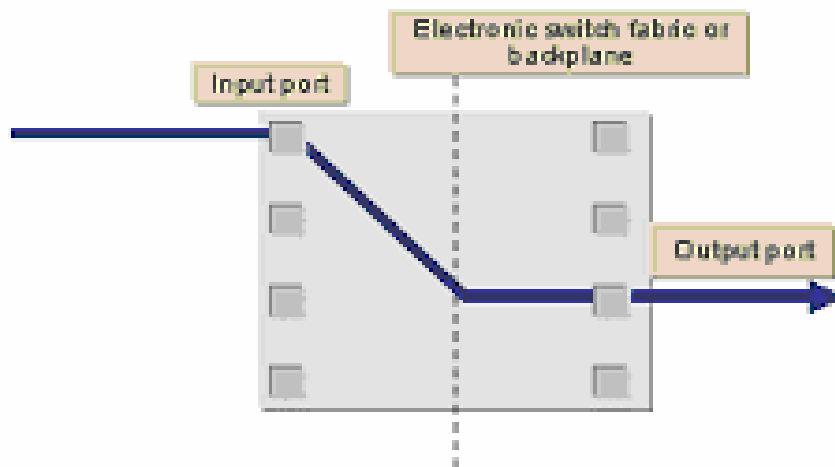
Switching In Optical Networks.

All-Optical switching

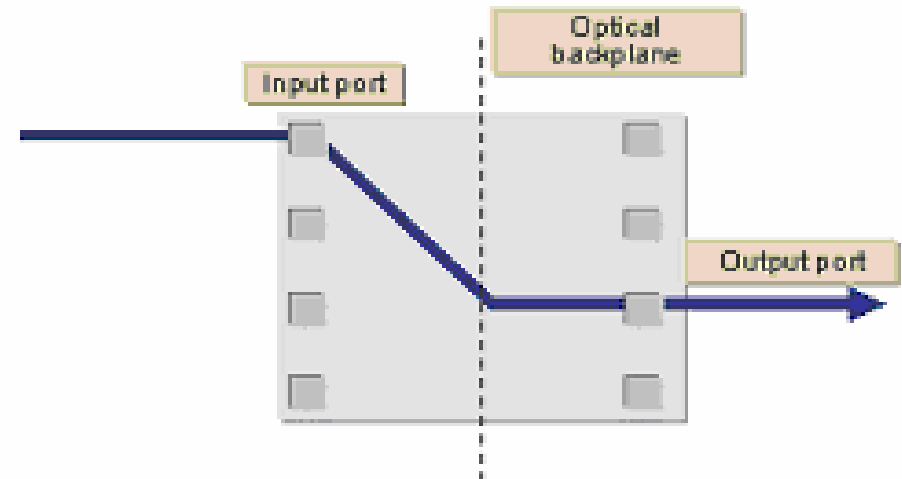
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- ▶ All-optical switches get their name from being able to carry light from their input to their output ports in its native state – as pulses of light rather than changes in electrical voltage.
- ▶ All-optical switching is independent on data rate and data protocol.
- ▶ Results in a reduction in the network equipment, an increase in the switching speed, a decrease in the operating power.

Basic electronic switch

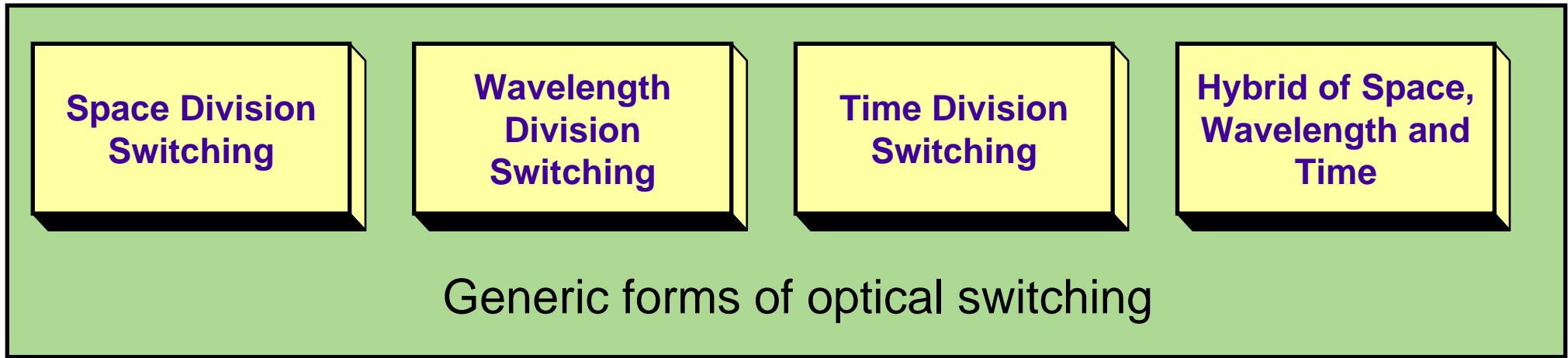


Basic optical switch





Generic forms of Optical Switching



- The forms above represent the domains in which switching takes place
- Net result is to provide routing, regardless of form
- Switch control may be:
 - Purely electronic (present situation)
 - Hybrid of optical and electronic (in development)
 - Purely optical (awaits development of optical logic, memory etc.)



Network Applications

- Protection switching
- Optical Cross-Connect (OXC)
- Optical Add/Drop Multiplexing (OADM)
- Optical Spectral Monitoring (OSM)

Switching applications and the system level functions

System level functions	Applications			
	Protection	OADM	OSM	OXC matrix
DWDM (metro, long-haul)	X	X	X	
SONET, SDH transport (point-to-point links, optical rings)	X	X		
Crossconnect (optical or electrical cores)	X		X	X (optical core based systems only)
Routing (meshes, edges of networks)	X	X		



Protection Switching

- ▶ **Protection switching allows the completion of traffic transmission in the event of system or network-level errors.**
- ▶ **Usually requires optical switches with smaller port counts of 1X2 or 2X2.**
- ▶ **Protection switching requires switches to be extremely reliable.**
- ▶ **Switch speed for DWDM, SONET, SDH transport and cross connect protection is important, but not critical, as other processes in the protection scheme take longer than the optical switch.**
- ▶ **It is desirable in the protection applications to optically verify that the switching has been made (optical taps that direct a small portion of the optical signal to a separate monitoring port can be placed at each output port of the switch).**



Optical Cross Connect

- ▶ **Cross connects groom and optimize transmission data paths.**
- ▶ **Optical switch requirements for OXCs include**
 - ▶ **Scalability**
 - ▶ **High-port-count switches**
 - ▶ **The ability to switch with high reliability, low loss, good uniformity of optical signals independent on path length**
 - ▶ **The ability to switch to a specific optical path without disrupting the other optical paths**
- ▶ **The difficulty in displacing the electrical with the optical lies in the necessity of performance monitoring and high port counts afforded by electric matrices.**

Optical Add/Drop Multiplexing

- ▶ **An OADM extracts optical wavelengths from the optical transmission stream as well as inserts optical wavelengths into the optical transmission stream at the processing node before the processed transmission stream exits the same node.**
- ▶ **Within a long-haul WDM-based network, OADM may require the added optical signal to resemble the dropped optical signal in optical power level to prevent the amplifier profiles from being altered. This power stability requirement between the add and drop channels drives the need for good optical switch uniformity across a wavelength range.**
- ▶ **Low insertion loss and small physical size of the OADM optical switch are important.**
- ▶ **Wavelength selective switches!**



Optical Spectral Monitoring

- ▶ **Optical spectral monitoring receives a small optically tapped portion of the aggregated WDM signal, separates the tapped signal into its individual wavelengths, and monitors each channel's optical spectra for wavelength accuracy, optical power levels, and optical crosstalk.**
- ▶ **OSM usually wraps software processing around optical switches, optical filters and optical-to-electrical converters.**
- ▶ **The optical switch size depends on the system wavelength density and desired monitoring thoroughness. Usually ranges from a series of small port count optical switches to a medium size optical switch.**
- ▶ **It is important in the OSM application, because the tapped optical signal is very low in optical signal power, that the optical switch has a high extinction ratio (low interference between paths), low insertion loss, and good uniformity.**



Optical Functions Required

- Ultra-fast and ultra-short optical pulse generation
- High speed modulation and detection
- High capacity multiplexing
 - Wavelength division multiplexing
 - Optical time division multiplexing
- Wideband optical amplification
- Optical switching and routing
- Optical clock extraction and regeneration
- Ultra-low dispersion and low non-linearity fibre



Parameters of an Optical Switch

- ▶ **Switching time**
- ▶ **Insertion loss:** the fraction of signal power that is lost because of the switch. Usually measured in decibels and must be as small as possible. The insertion loss of a switch should be about the same for all input-output connections (loss uniformity).
- ▶ **Crosstalk:** the ratio of the power at a specific output from the desired input to the power from all other inputs.
- ▶ **Extinction ratio:** the ratio of the output power in the on-state to the output power in the off-state. This ratio should be as large as possible.
- ▶ **Polarization-dependent loss (PDL):** if the loss of the switch is not equal for both states of polarization of the optical signal, the switch is said to have polarization-dependent loss. It is desirable that optical switches have low PDL.
- ▶ Other parameters: **reliability, energy usage, scalability** (ability to build switches with large port counts that perform adequately), and **temperature resistance**.



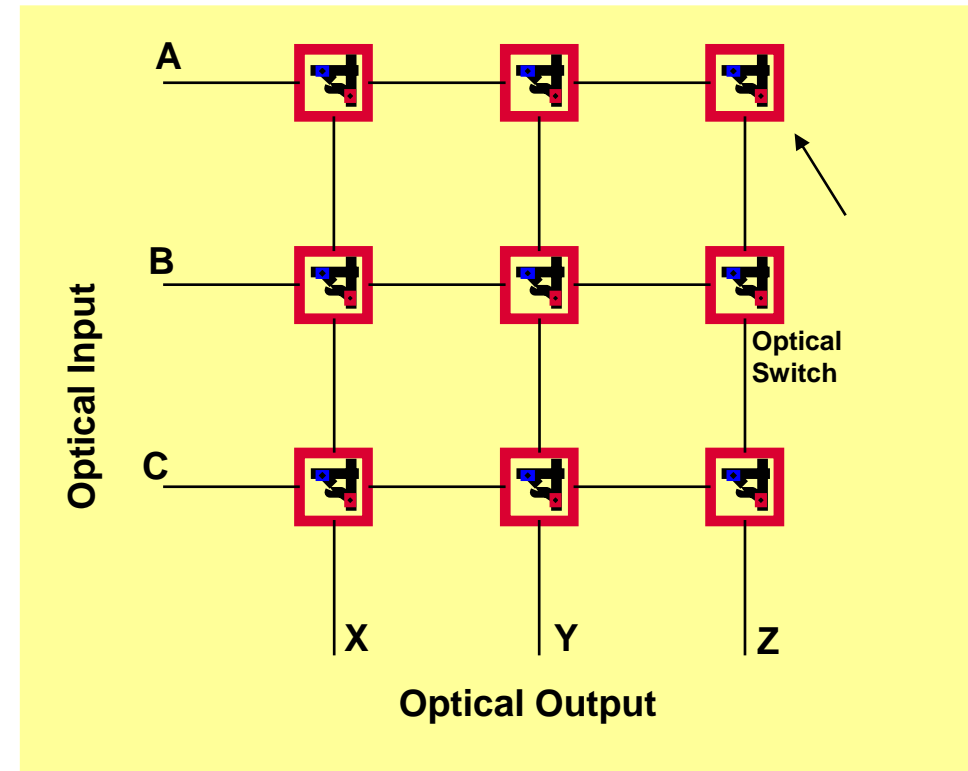
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Space Division Optical Switching



Space Division Switching

- Simplest form of optical switching, typically a matrix
- Well developed by comparison to WDS and TDS
- Variety of switch elements developed
- Can form the core of an OXC
- Features include
 - Transparent to bit rate
 - Switching speeds less than 1 ns
 - Very high bandwidth
 - Low insertion loss or even gain



SPACE DIVISION SWITCHING
3 x 3 matrix



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Optical Switching Element Technologies

Not Scalable
Polarization Dependent

High Loss

Poor Reliability

Optical Switching Element Technologies

★ LiNbO_3

★ Gel/oil based

★ Liquid Crystal

★ Mechanical

★ SOA

★ Micro-Optic (MEMS)

★ Bubble

★ Thermo-optic

★ Fibre (acousto-optic)

★ SiO_2/Si

★ Indium Phosphide

★ Waveguide
★ Free Space

Can be configured in two or three dimensional architectures



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Opto-mechanical Inc. MEMS

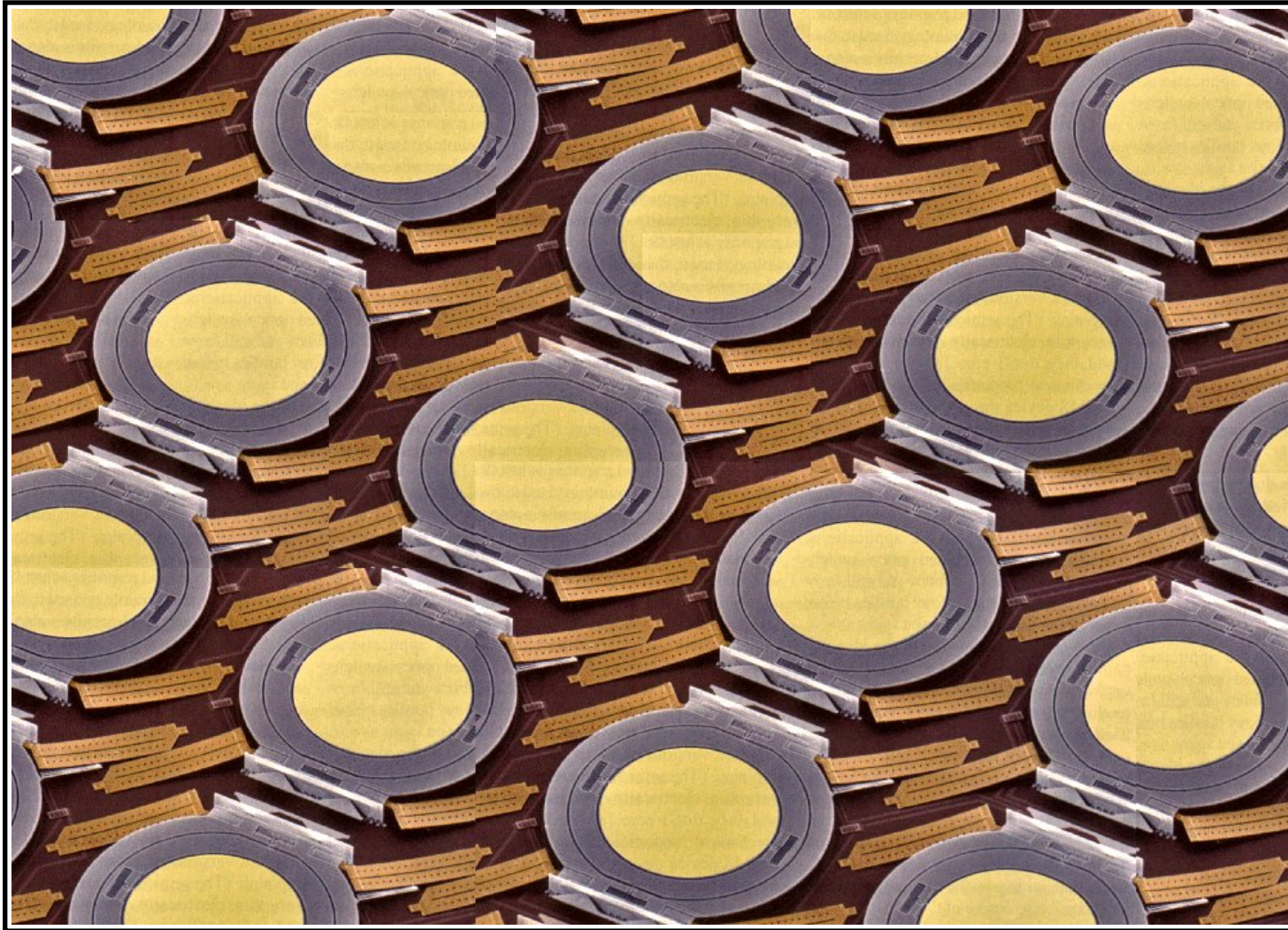


Optomechanical

- ▶ **Optomechanical technology was the first commercially available for optical switching.**
- ▶ **The switching function is performed by some mechanical means. These mechanical means include prisms, mirrors, and directional couplers.**
- ▶ **Mechanical switches exhibit low insertion losses, low polarization-dependent loss, low crosstalk, and low fabrication cost.**
- ▶ **Their switching speeds are in the order of a few milliseconds (may not be acceptable for some types of applications).**
- ▶ **Lack of scalability (limited to 1X2 and 2X2 ports sizes).**
- ▶ **Moving parts – low reliability.**
- ▶ **Mainly used in fibre protection and very-low-port-count wavelength add/drop applications.**



MEMS Microscopic Mirror Optical Switch Array



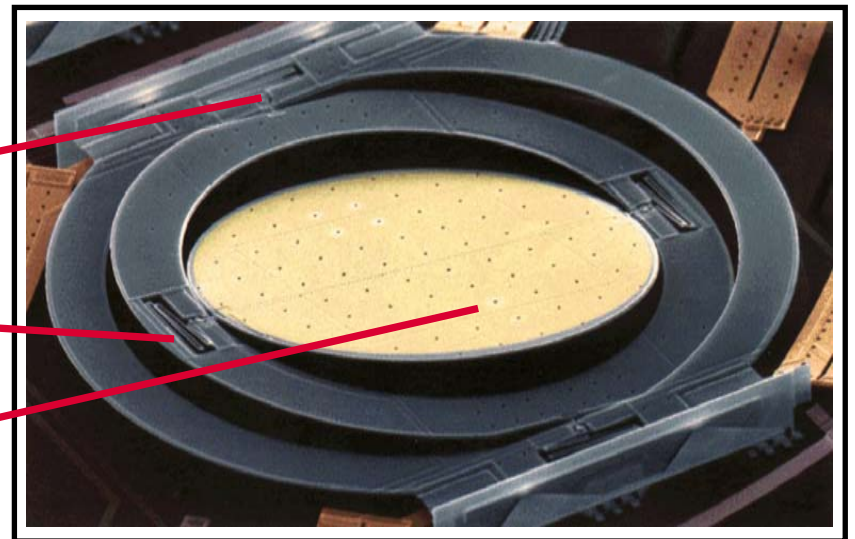


MEMS based Optical Switch

- MEMS stands for "Micro-ElectroMechanical System"
- Systems are mechanical but very small
- Fabricated in silicon using established semiconductor processes
- MEMS first used in automotive, sensing and other applications
- Optical MEMS switch uses a movable micro mirror
- Fundamentally a space division switching element

Two axis motion

Micro mirror



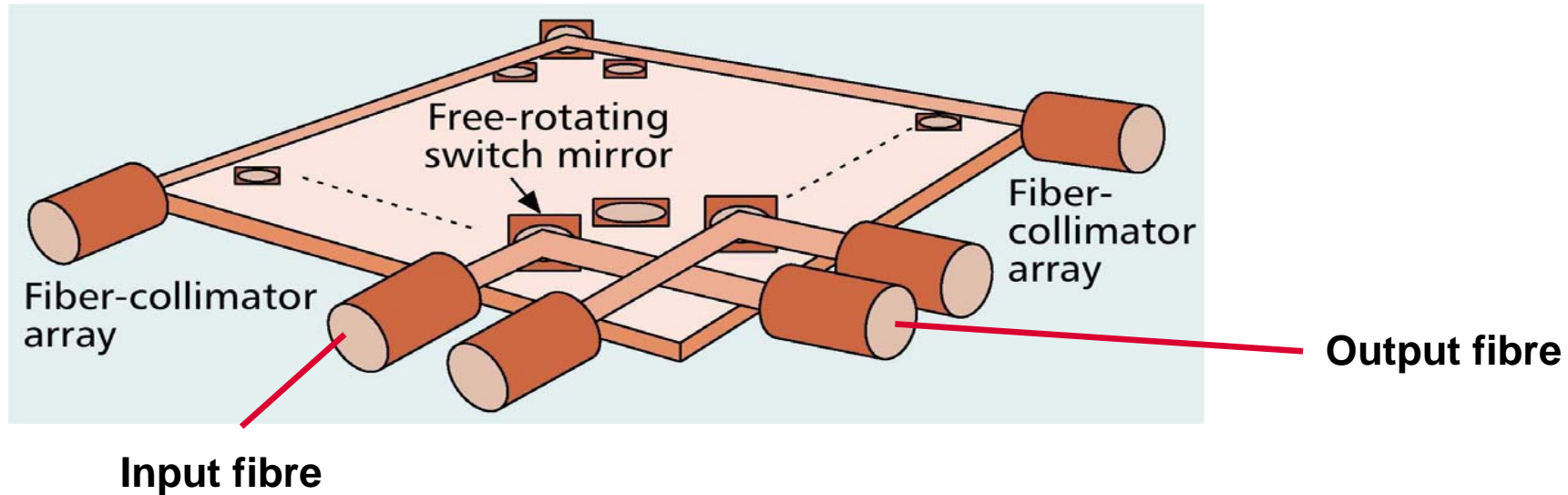


Micro-Electro-Mechanical System (MEMS)

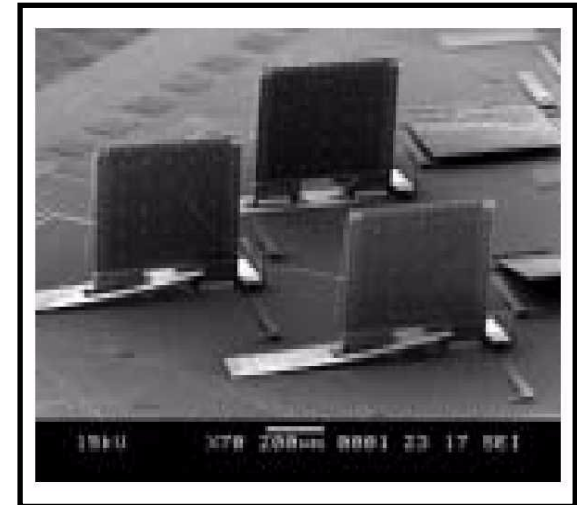
- ▶ **MEMS can be considered a subcategory of optomechanical switches, however, because of the fabrication process and miniature natures, they have different characteristics, performance and reliability concerns.**
- ▶ **MEMS use tiny reflective surfaces to redirect the light beams to a desired port by either ricocheting the light off of neighboring reflective surfaces to a port, or by steering the light beam directly to a port.**
- ▶ **Analog-type, or 3D, MEMS mirror arrays have reflecting surfaces that pivot about axes to guide the light.**
- ▶ **Digital-type, or 2D, MEMS have reflective surfaces that “pop up” and “lay down” to redirect the light beam propagating parallel to the surface of substrate.**
- ▶ **The reflective surfaces’ actuators may be electrostatically-driven or electromagnetically-driven with hinges or torsion bars that bend and straighten the miniature mirrors.**



2D MEMS based Optical Switch Matrix



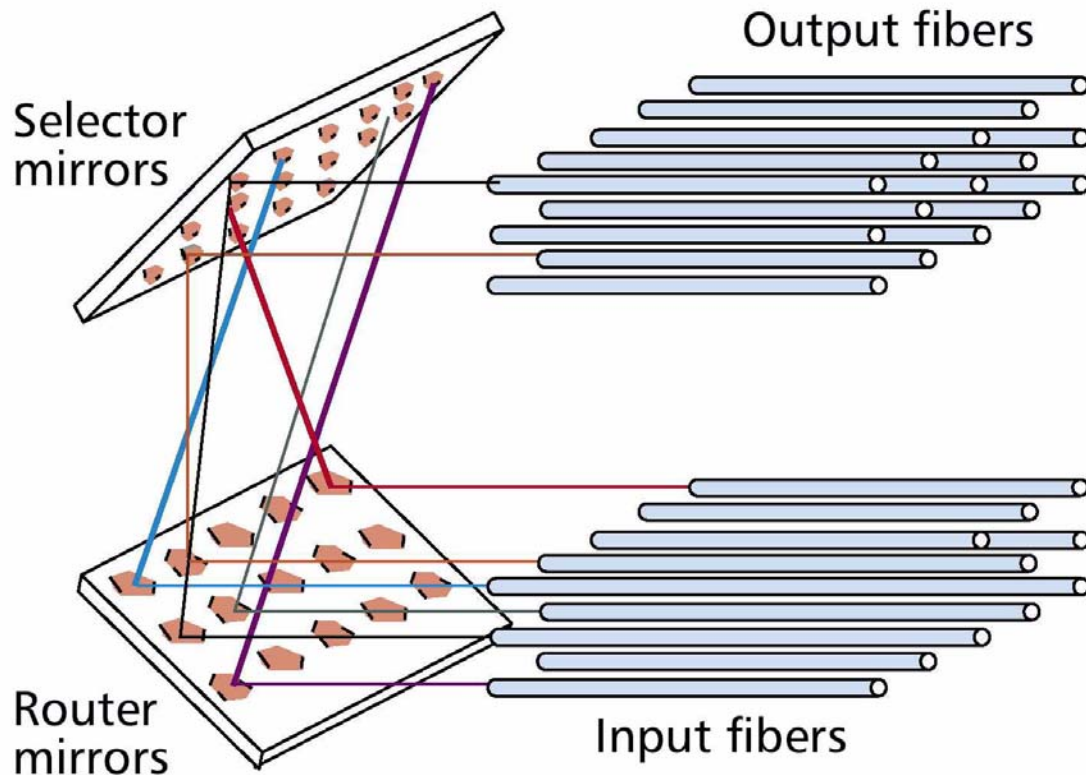
- Mirrors have only two possible positions
- Light is routed in a 2D plane
- For N inputs and N outputs we need N^2 mirrors
- Loss increases rapidly with N



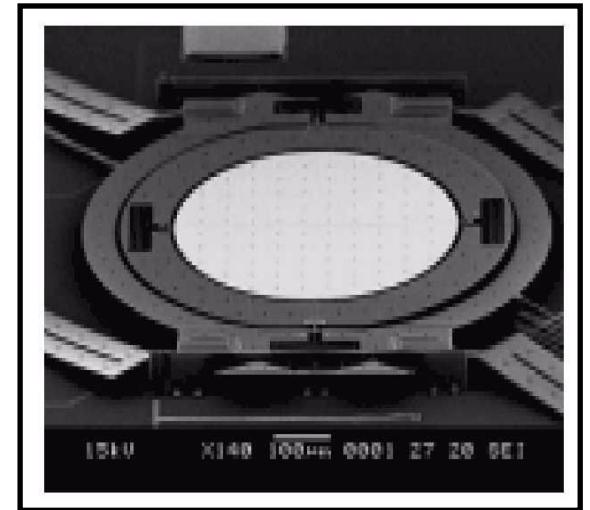
SEM photo of 2D MEMS mirrors



3D MEMS based Optical Switch Matrix



- Mirrors require complex closed-loop analog control
- But loss increases only as a function of $N^{1/2}$
- Higher port counts possible



SEM photo of 3D MEMS mirrors



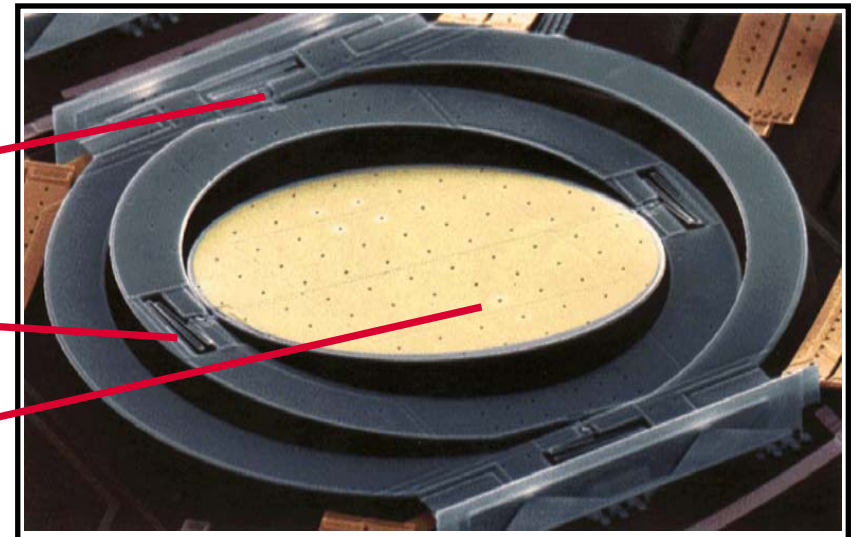
Lucent LambdaRouter Optical Switch

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- Based on microscopic mirrors (see photo)
- Uses MEMS (Micro-ElectroMechanical Systems) technology
- Routes signals from fibre-to-fibre in a space division switching matrix
- Matrix with up to 256 mirrors is currently possible
- 256 mirror matrix occupies less than 7 sq. cm of space
- Does not include DWDM Mux/Demux, this is carried out elsewhere
- Supports bit rates up to 40 Gb/s and beyond

Two axis motion

Micro mirror





Liquid Crystal Switching

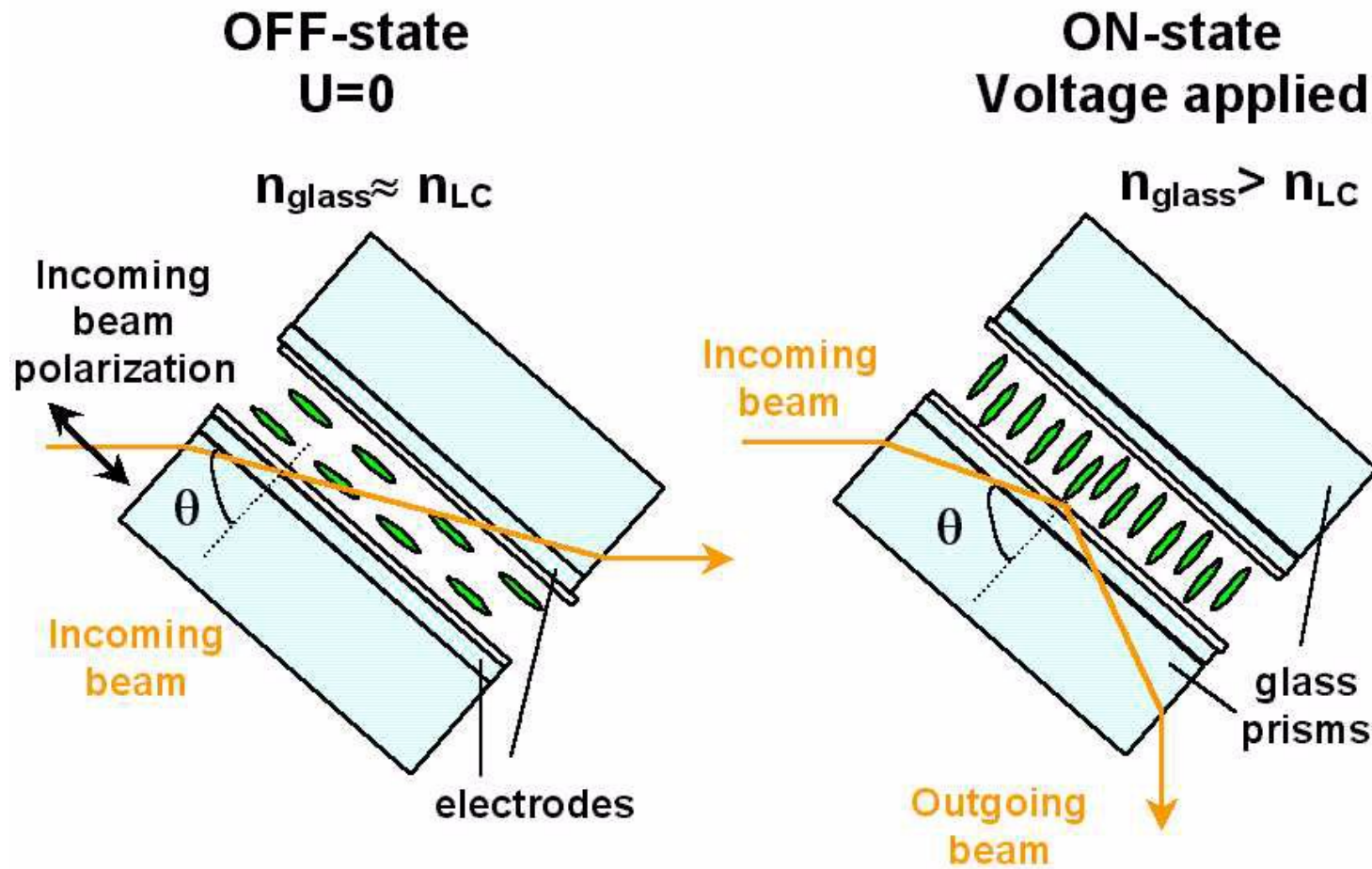
- LC based switching is a promising contender - offers good optical performance and speed, plus ease of manufacture.
- Different physical mechanisms for LC switches:
 - LC switch based on light beam diffraction
 - LC switch based dynamic holograms
 - Deflection LC switching
 - LC switching based on selective reflection
 - LC switching based on total reflection
- Total reflection and selective reflection based switches possess the smallest insertion loss
- D.I.T. research project has investigated:
 - A selective reflection cholesteric mirror switch
 - A total reflection LC switch



DIT Group LC SDS Switch (Nematic)



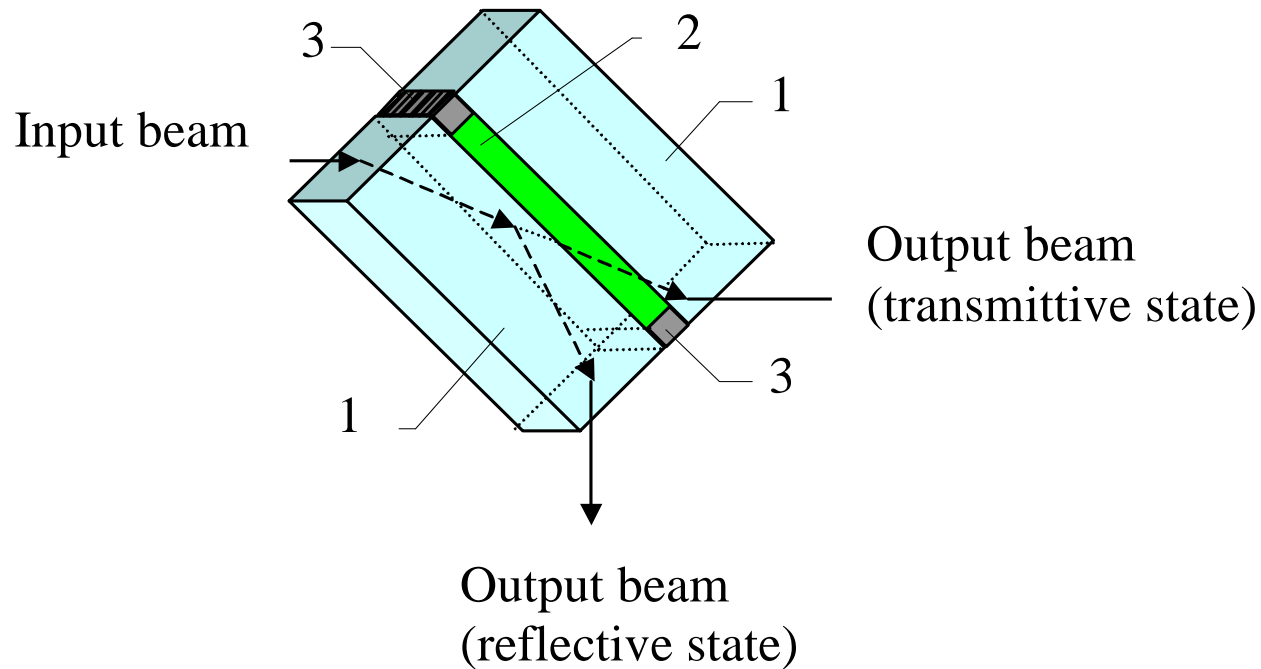
Total Internal Reflection LC Switch





Liquid crystal (Total internal Reflection)

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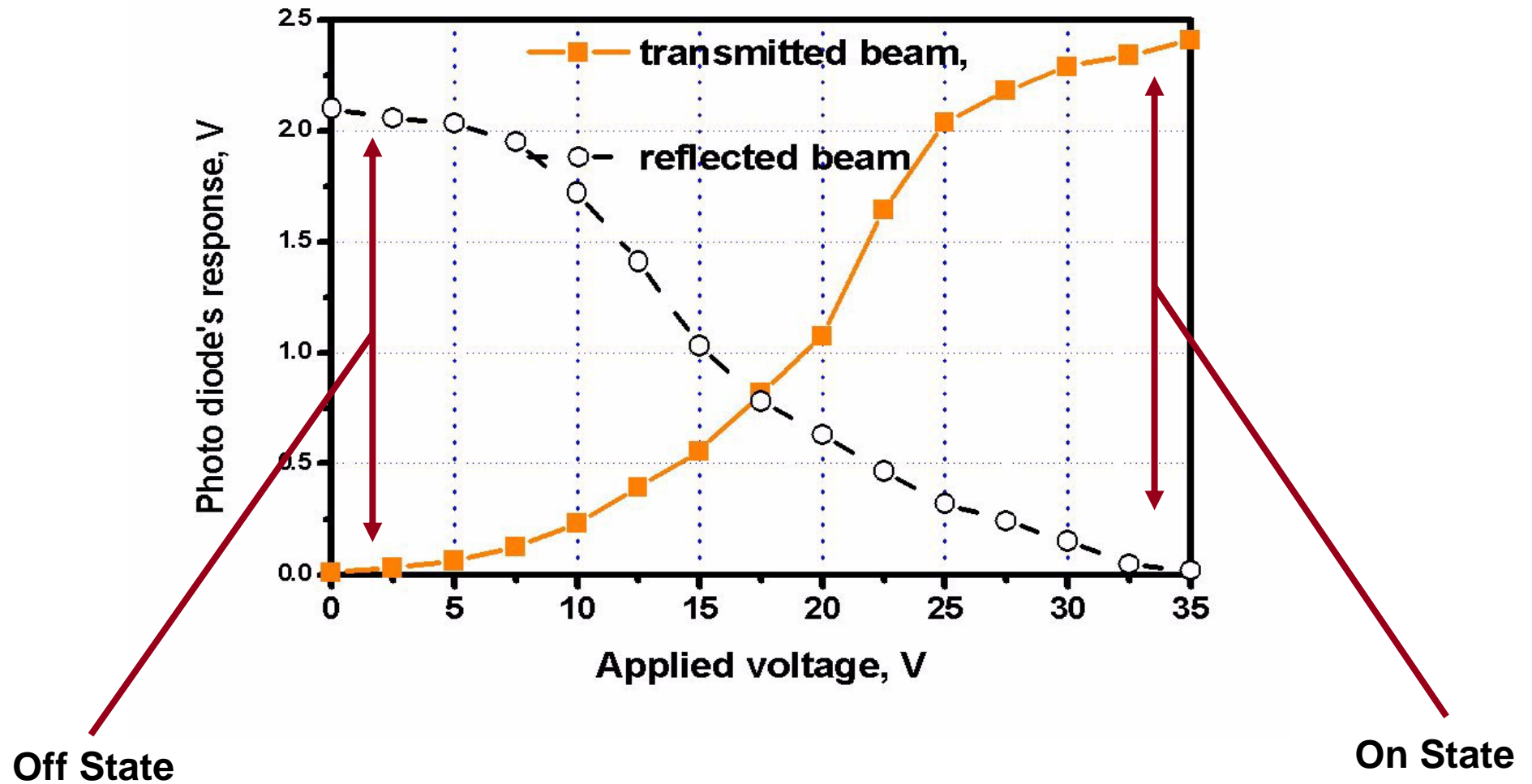
Schematic diagram of the total reflection switch: 1- glass prisms; 2- liquid crystal layer; 3-spacers

The glass and nematic liquid crystal refractive indices are chosen to be equal in the transmittive state and to satisfy the total reflection condition in the reflective state



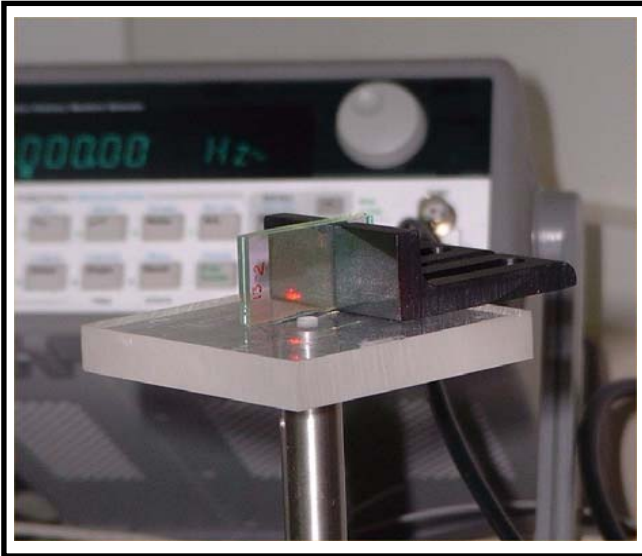
Electro-optic Response of TIR Switch

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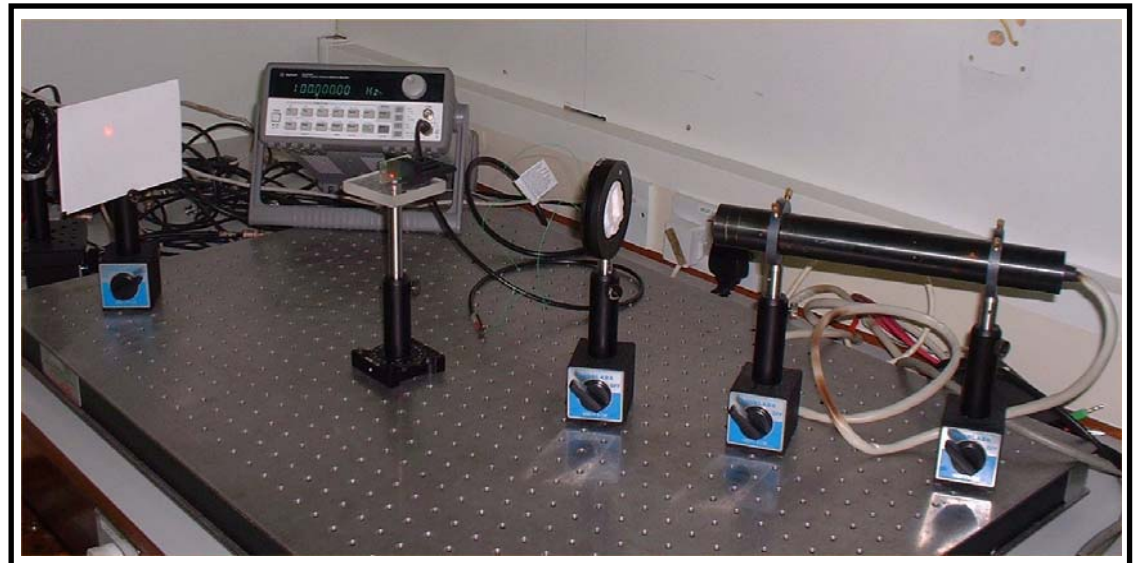


Some Photos of the TIR LC Switch



Switching element
close-up

Early visible light
demonstration





DIT Group LC SDS Switch (Ferroelectric)



Ferroelectric Switch

- **Previous work used nematic liquid crystals to control total internal reflection at a glass prism – liquid crystal interface.**
- **Nematic switches:**
 - Low loss,
 - Low crosstalk level,
 - Relatively slow , switching time is in the ms range
- **Latest work investigates an all-optical switch using ferroelectric liquid crystal.**
- **The central element of the switch is a ferroelectric liquid crystal controllable half-waveplate.**

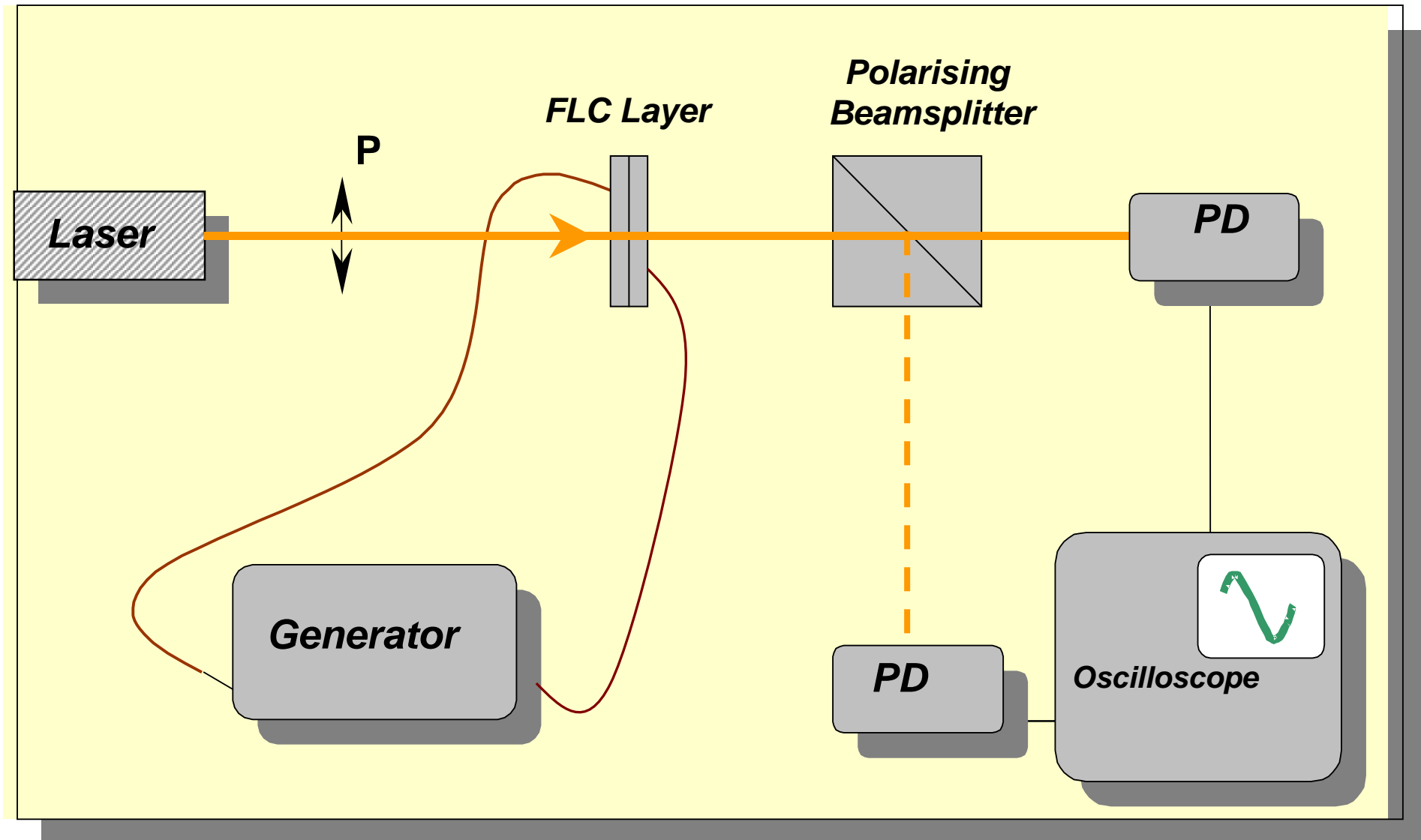


Operating Principle

- The switching element consists of two Beam Displacing (BD) Calcite Crystals and FLC cell that acts as a polarisation control element.
- Two incoming signals A and B are set to be linearly polarised in orthogonal directions.
- Both signals enter the calcite crystal with polarisation directions aligned with the crystal's orientation.
- Both signals emerge as one ray with two orthogonal polarisations, representing signals A and B.
- For the through state (a) the light beam is passing through the FLC layer without changing polarization direction. Two signals A and B will continue propagate in the same course as they entered the switch.
- If the controllable FLC is activated (b), the two orthogonal signals will undergo a 90 degree rotation, meaning the signals A and B will interchange.



FLC Experimental Setup

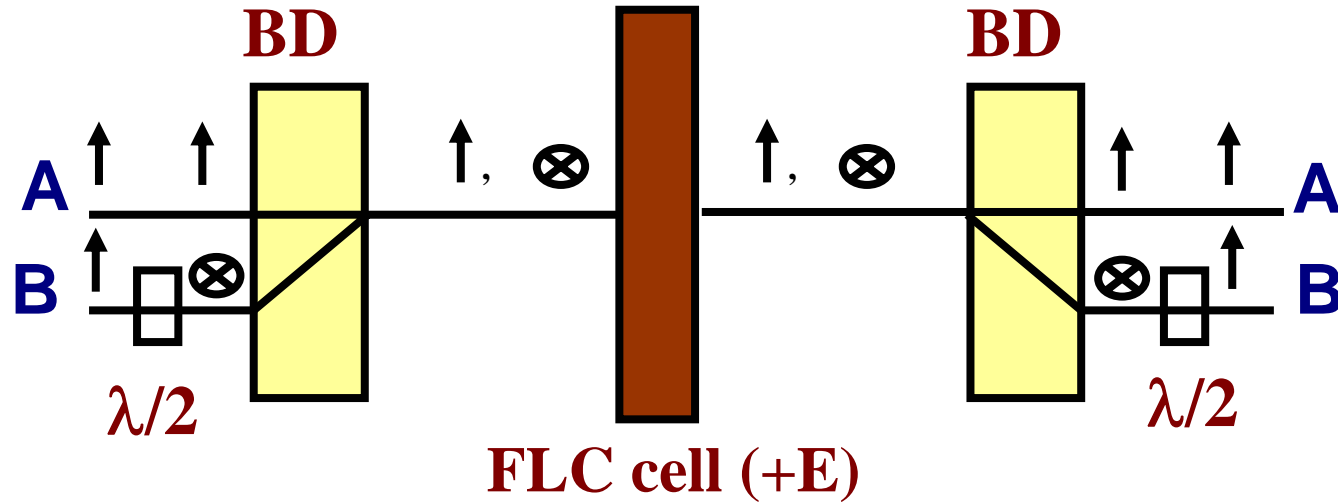




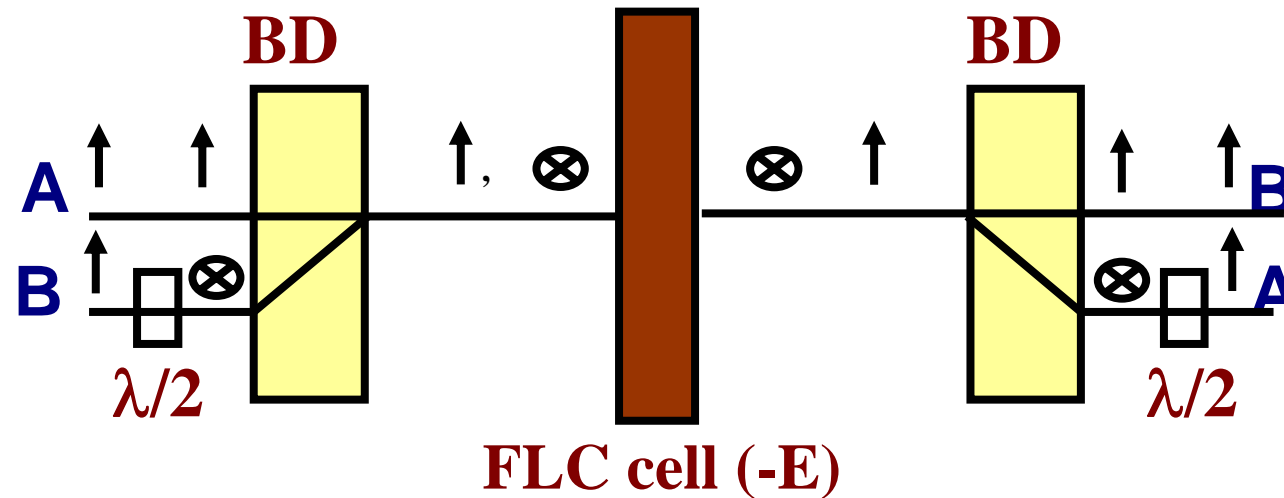
Basic Structure of the Switch

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(a)
Through
State

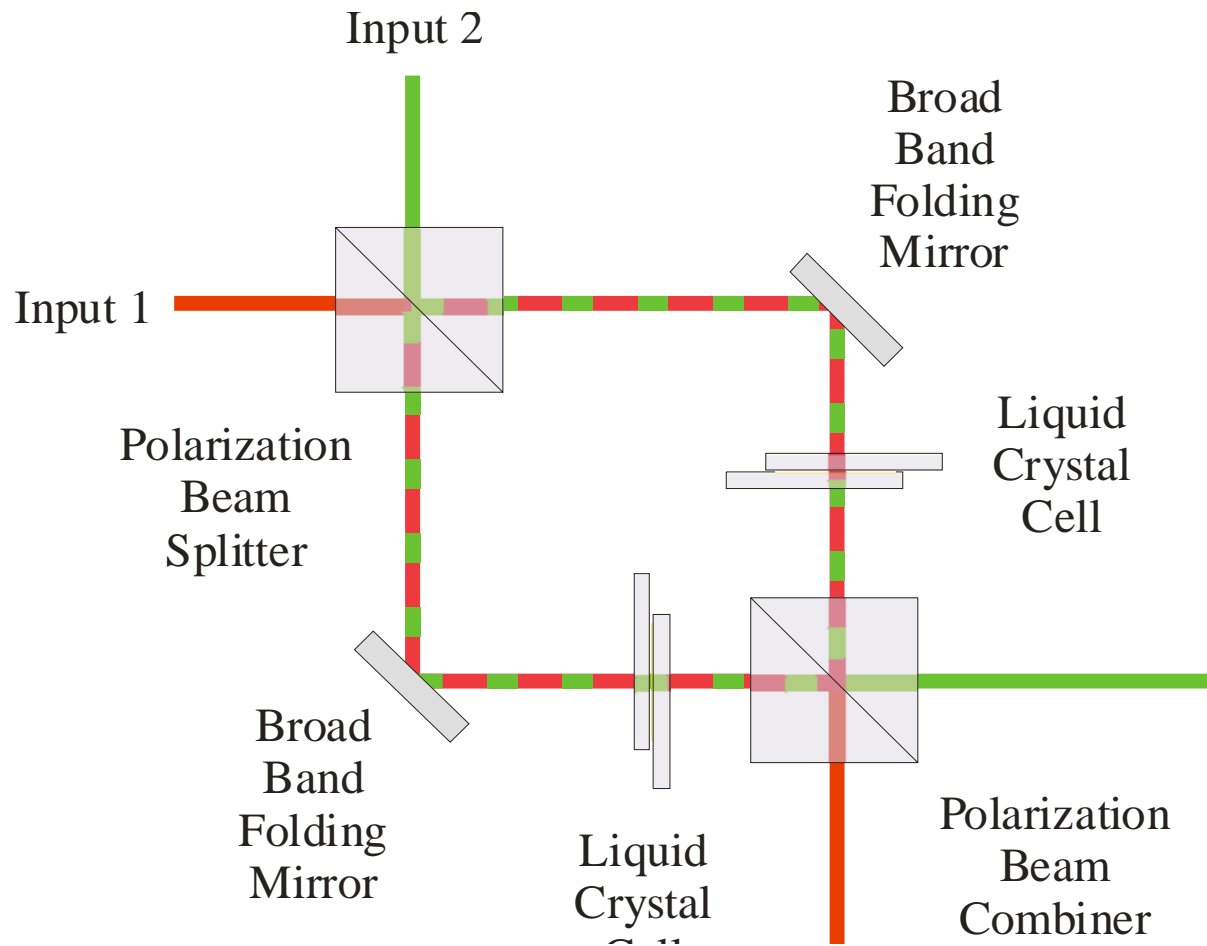


(b)
Switched
State





Liquid Crystal



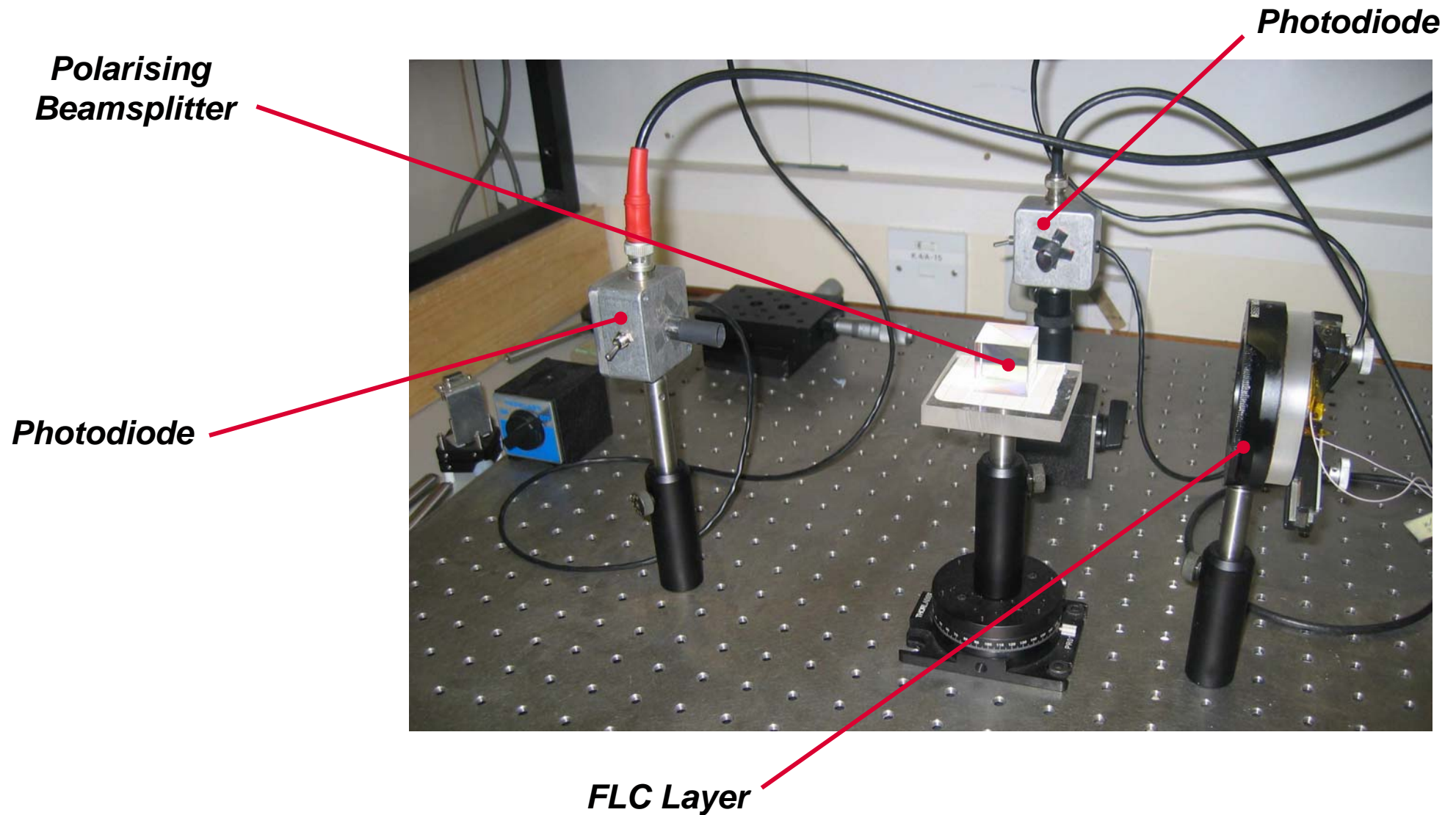
► Liquid crystal switches work by processing polarisation state of the light. Apply a voltage and the liquid crystal element allows one polarization state to pass through. Apply no voltage and the liquid crystal element passes through the orthogonal polarization state.

► These polarization states are steered to the desired port, are processed, and are recombined to recover the original signal's properties.

► With no moving parts, liquid crystal is highly reliable and has good optical performance, but can be affected by extreme temperatures.



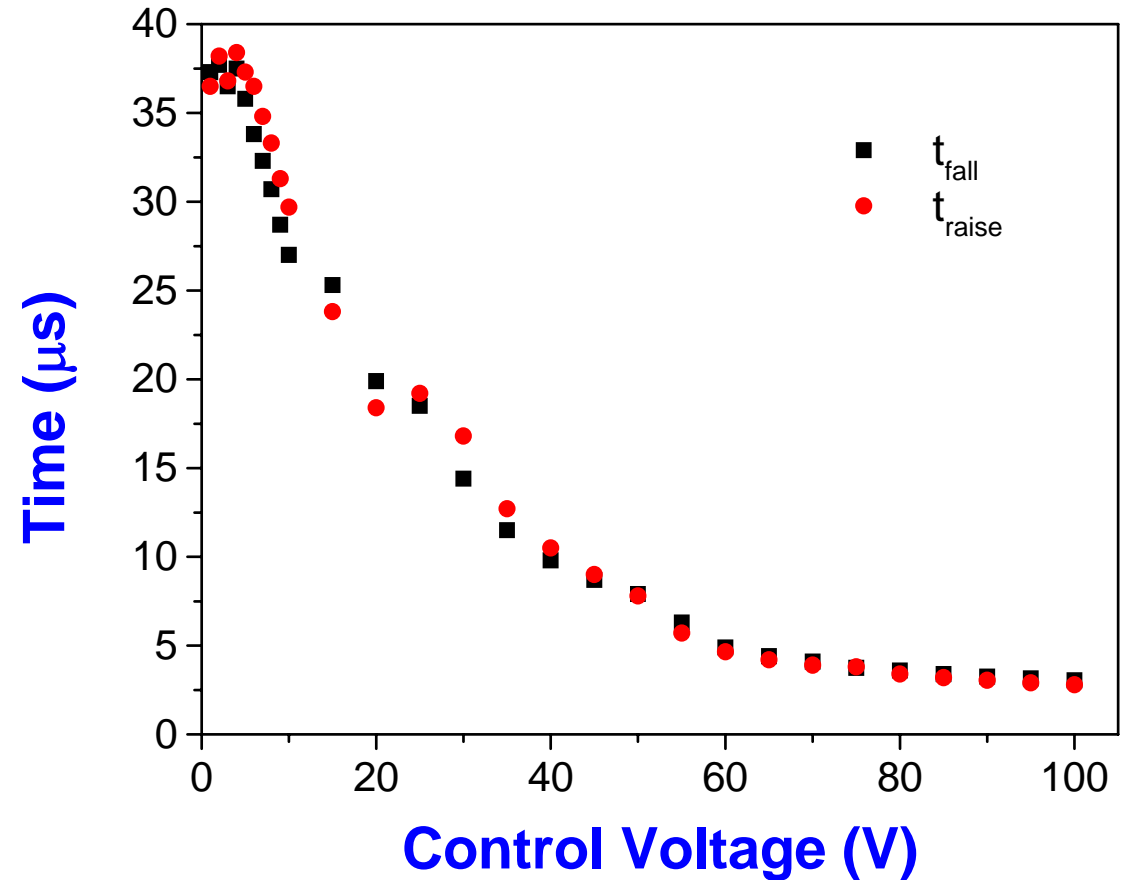
Output Side of Experimental Setup





Switching Speed Experimental Results

- Switching time is strongly dependent on control voltage
- Rise and fall times are approximately the same
- Order of magnitude better than Nematic LC
- For a drive voltage of 30 V FLC speed is 16 μs .
- Equivalent Nematic speed is much higher at 340 μs .





Performance Comparison of LC Switches

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	Contrast ratio, dB		Insertion loss, dB	Switching time, ms	Relaxation time, ms	Drive, V
	Transmitted light	Reflected light				
Total reflection	42	20.5*	2.89	0.34**	80	30 p-p
Cholesteric mirror	38.5	17.8*	2.39	60	150	3.55

* This parameter can be improved by using of anti-reflection coatings

**Switching time for the Total Reflection switch can be improved by using FLCs

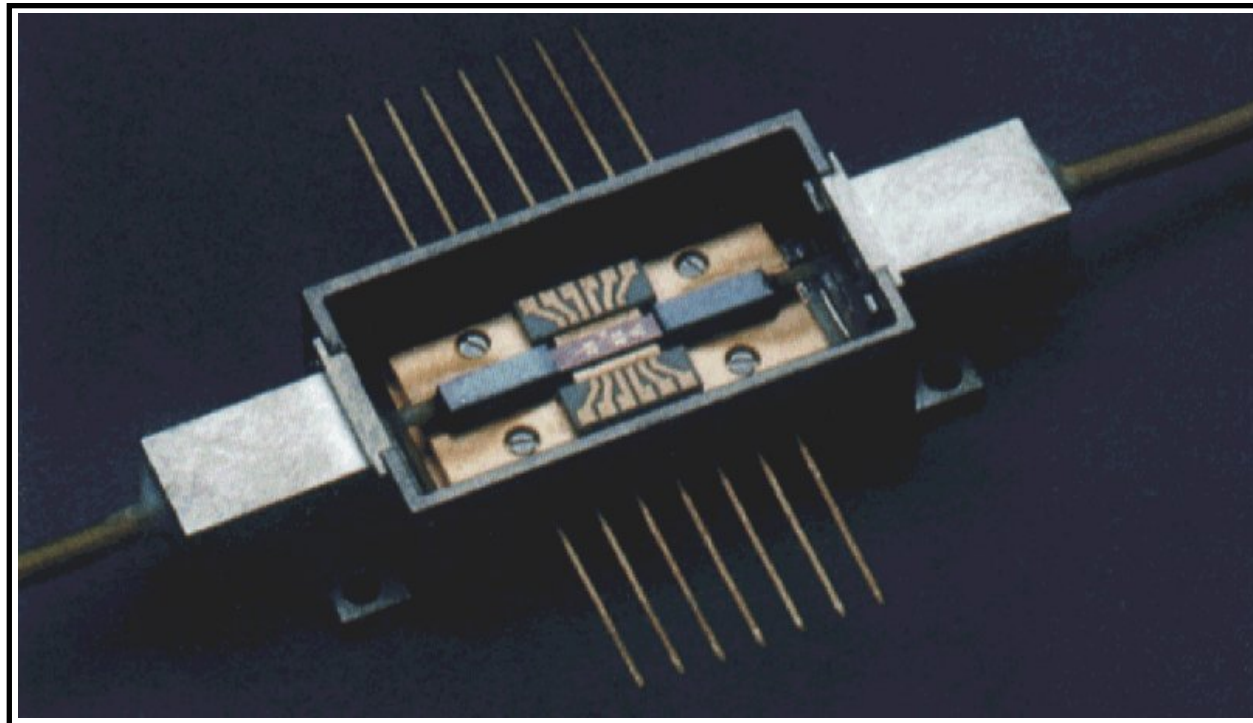


Other SDS Switches



Indium Phosphide Switch

- Integrated Indium Phosphide matrix switch
- 4 x 4 architecture
- Transparent to bit rates up to 2.5 Gbits/s



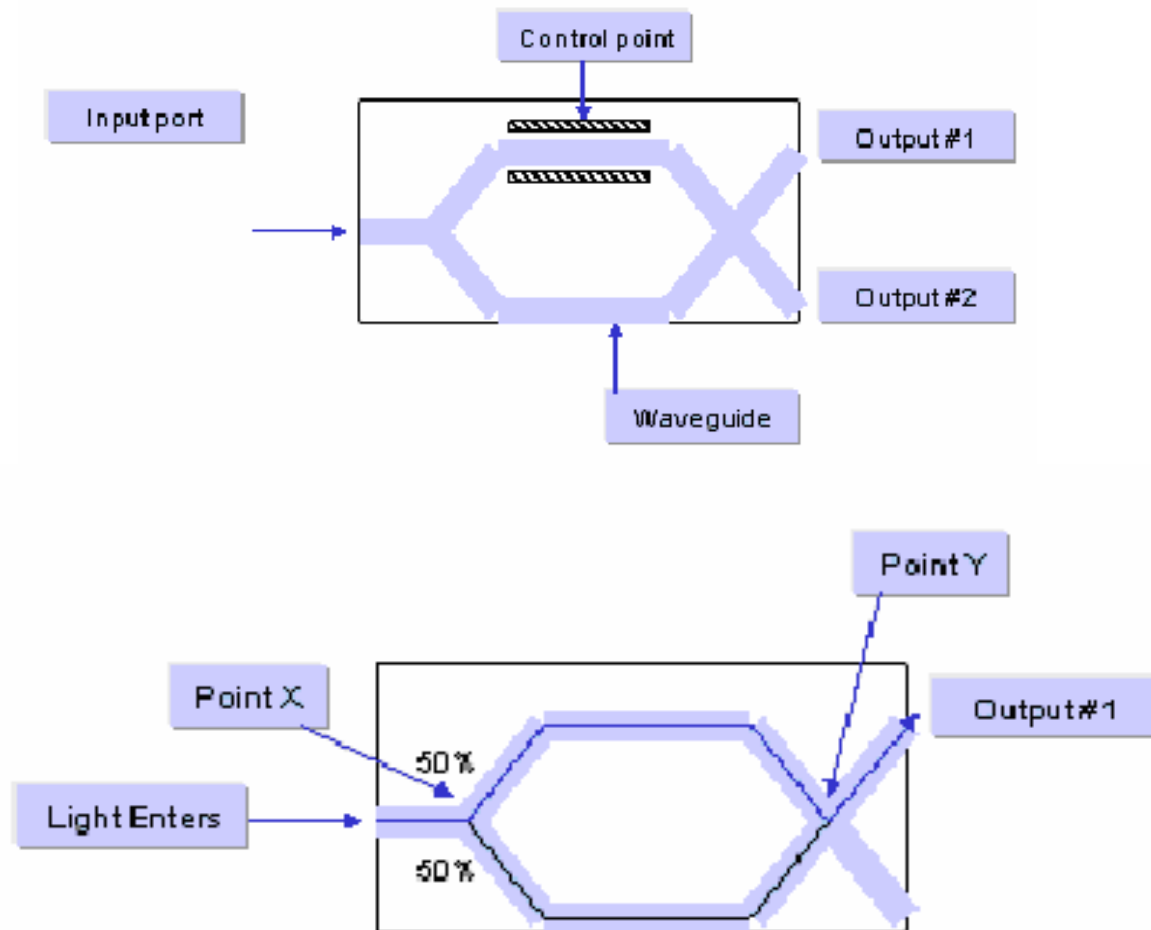


Thermo-Optical

- ▶ **Planar lightwave circuit thermo-optical switches are usually polymer-based or silica on silicon substrates. Electronic switches provide a high degree of flexibility in terms of switching and routing functions.**
- ▶ **The operation of these devices is based on thermo optic effect. It consists in the variation of the refractive index of a dielectric material, due to temperature variation of the material itself.**
- ▶ **Thermo-optical switches are small in size but have a drawback of having high driving-power characteristics and issues of optical performance.**
- ▶ **There are two categories of thermo-optic switches:**
 - ▶ **Interferometric**
 - ▶ **Digital optical switches**



Thermo-Optical Switch. Interferometric



The device is based on Mach-Zender interferometer. Consists of a 3-dB coupler that splits the signal into two beams, which then travel through two distinct arms of the same length, and a second 3-dB coupler, which merges and finally splits the signal again.

Heating one arm of the interferometer causes its refractive index to change. A variation of the optical path of that arm is experienced. It is thus possible to vary the phase difference between the light beams. As interference is constructive or destructive, the power on alternate outputs is minimized or maximized.



Gel/Oil Based

- ▶ Index-matching gel- and oil-based optical switches can be classified as a subset of thermo-optical technology, as the switch substrate needs to heat and cool to operate.
- ▶ The switch is made up of two layers: a silica bottom layer, through which optical signals travel, and a silicon top level, containing the ink-jet technology.
- ▶ In the bottom level, two series of waveguides intersect each other at an angle of about 120° . At each cross-point between the two guides, a tiny hollow is filled in with a liquid that exhibits the same refractive index of silica, in order to allow propagation of signals in normal conditions. When a portion of the switch is heated, a refractive index change is caused at the waveguide junctions. This effect results in the generation of tiny bubbles. In this case, the light is deflected into a new guide, crossing the path of the previous one.
- ▶ Good modular scalability, drawbacks: low reliability, thermal management, optical insertion losses.

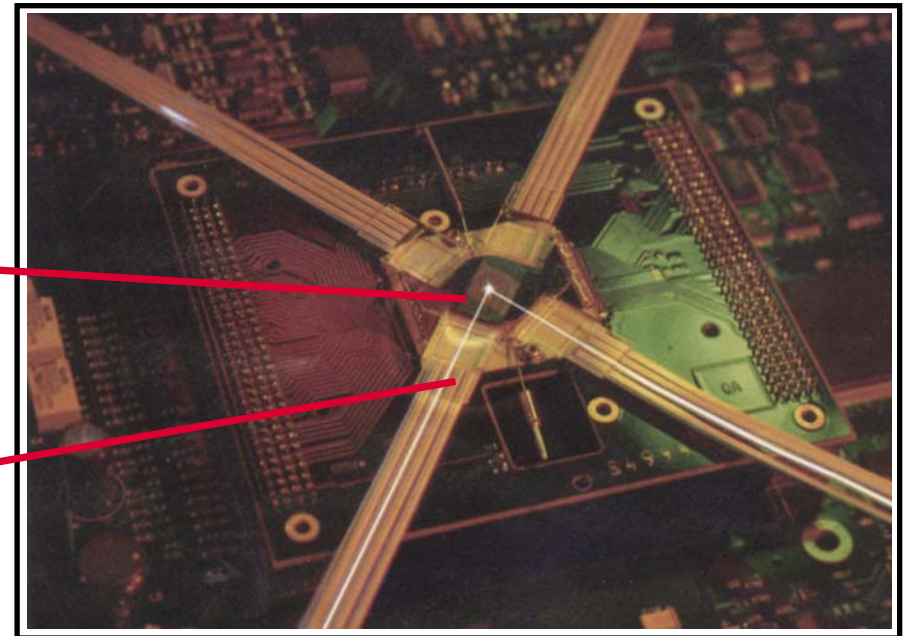


Agilent Bubble Switch

- Based on a combination of Planar Lightwave Circuit (PLC) and inkjet technology
- Switch fabric demonstrations have reached 32 x 32 by early 2001
- Uses well established high volume production technology

Bubble switch

Planar lightguides





Electro-Optical

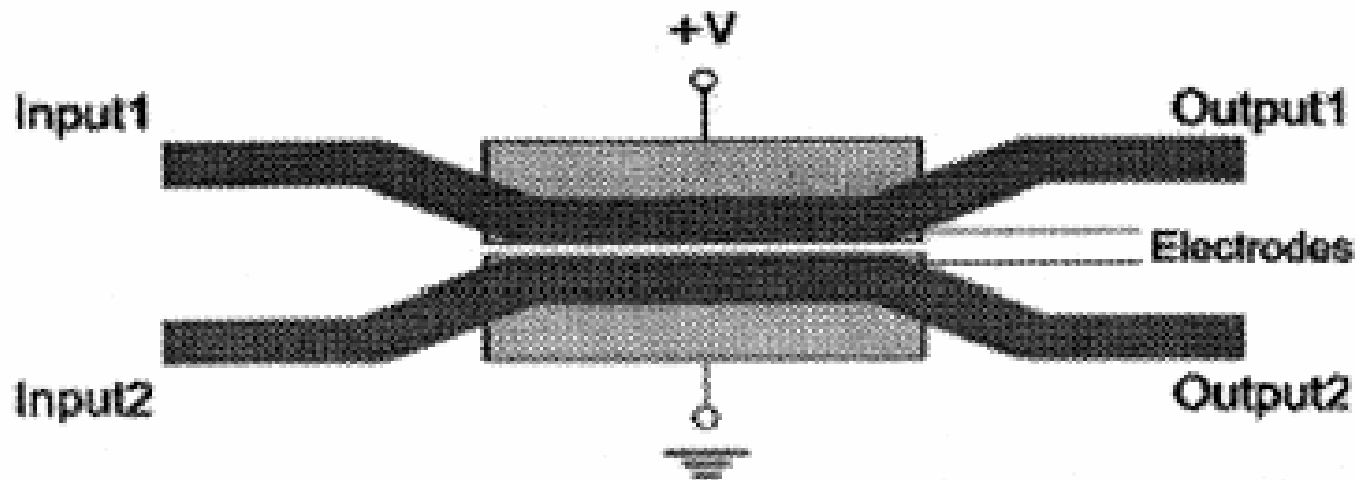
- ▶ **Electro-optical switches use highly birefringent substrate material and electrical fields to redirect light from one port to another.**
- ▶ **A popular material to use is Lithium Niobate.**
- ▶ **Fast switches (typically in less than a nanosecond). This switching time limit is determined by the capacitance of the electrode configuration.**
- ▶ **Electrooptic switches are also reliable, but they pay the price of high insertion loss and possible polarization dependence.**



Lithium Niobate Waveguide Switch

► The switch below constructed on a lithium niobate waveguide. An electrical voltage applied to the electrodes changes the substrate's index of refraction. The change in the index of refraction manipulates the light through the appropriate waveguide path to the desired port.

An electrooptic directional coupler switch





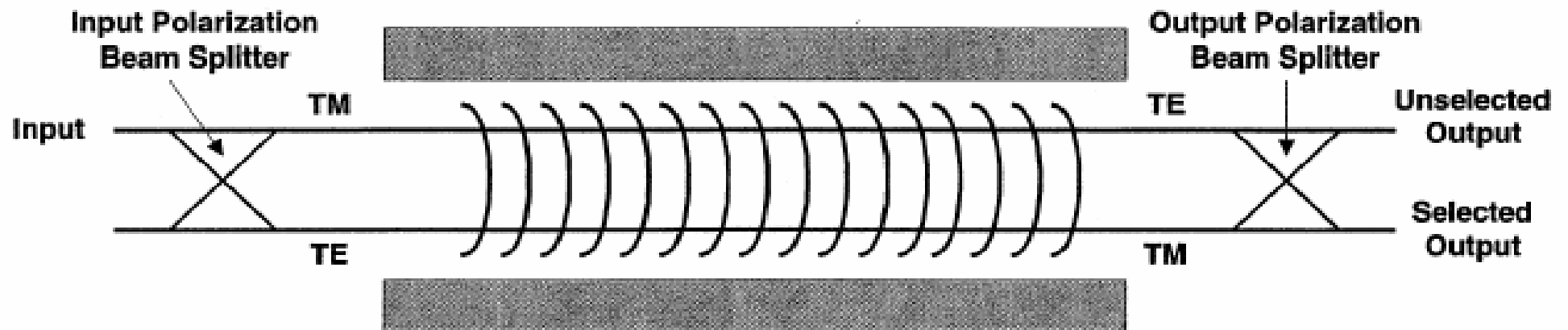
Acousto-Optic

- The operation of acousto-optic switches is based on the acousto-optic effect, i.e., the interaction between sound and light.
- The principle of operation of a polarization-insensitive acousto-optic switch is as follows. First, the input signal is split into its two polarized components (TE and TM) by a polarization beam splitter. Then, these two components are directed to two distinct parallel waveguides. A surface acoustic wave is subsequently created. This wave travels in the same direction as the lightwaves. Through an acousto-optic effect in the material, this forms the equivalent of a moving grating, which can be phase-matched to an optical wave at a selected wavelength. A signal that is phase-matched is “flipped” from the TM to the TE mode (and vice versa), so that the polarization beam splitter that resides at the output directs it to the lower output. A signal that was not phase-matched exits on the upper output.



Acousto-Optic Switch

Schematic of a polarization independent acousto-optic switch.



If the incoming signal is multiwavelength, it is even possible to switch several different wavelengths simultaneously, as it is possible to have several acoustic waves in the material with different frequencies at the same time. The switching speed of acoustooptic switches is limited by the speed of sound and is in the order of microseconds.

Semiconductor Optical Amplifiers (SOA)

- ▶ An SOA can be used as an ON–OFF switch by varying the bias voltage.
- ▶ If the bias voltage is reduced, no population inversion is achieved, and the device absorbs input signals. If the bias voltage is present, it amplifies the input signals. The combination of amplification in the on-state and absorption in the off-state makes this device capable of achieving very high extinction ratios.
- ▶ Larger switches can be fabricated by integrating SOAs with passive couplers. However, this is an expensive component, and it is difficult to make it polarization independent.



Comparison of Optical Switching Technologies

Platform	Scheme	Strengths	Weaknesses	Potential applications
Opto-mechanical	Employ electromechanical actuators to redirect a light beam	Optical performance, “old” technology	Speed, bulky, scalability	Protection switching, OADM, OSM
MEMS	Use tiny reflective surfaces	Size, scalability	Packaging, reliability	OXC, OADM, OSM
Thermo-optical	Temper. control to change index of refraction	Integration wafer-level manufacturability	Optical performance, power consumption, speed, scalability	OXC, OADM



Comparison of Optical Switching Technologies (Contd)

APPLIED OPTOELECTRONICS CENTRE

Platform	Scheme	Strengths	Weaknesses	Potential applications
Liquid Crystal	Processing of polarisation states of light	Reliability, optical performance	Scalability, temperature dependency	Protection switching, OADM, OSM
Gel/oil based	A subset of thermo-optical technology	Modular scalability	Unclear reliability, high insertion loss	OXC, OADM
Magneto-optics	Faraday	Speed	Optical performance	Protection switching, OADM, OSM, packet switching



Comparison of Optical Switching Technologies (Contd)

APPLIED OPTOELECTRONICS CENTRE

Platform	Scheme	Strengths	Weaknesses	Potential applications
Acousto-optic	Acousto-optic effect, RF signal tuning	Size, speed	Optical performance	OXC, OADM
Electro-optic	Dielectric	Speed	High insertion loss, polarisation, scalability, expensive	OXC, OADM, OSM
	SOA-based	Speed, loss compensation	Noise, scalability	OXC

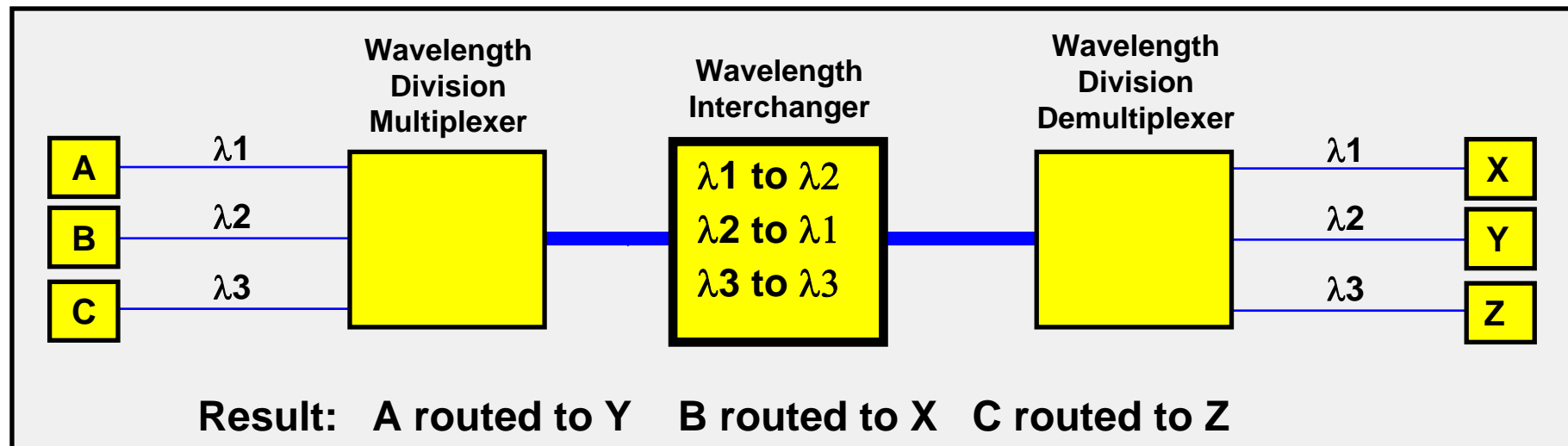
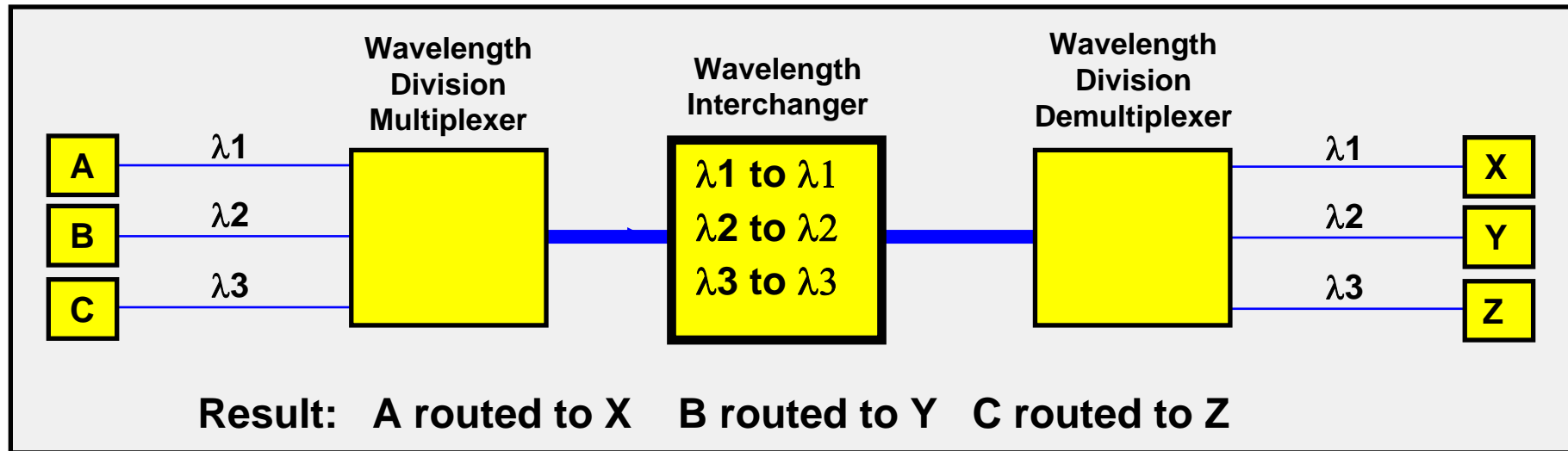


Wavelength Division Optical Switching



Wavelength Division Switching

APPLIED OPTOELECTRONICS CENTRE





Wavelength Division Switching

- Very attractive form of optical switching for DWDM networks
- Complex signal processing involved:
 - Fibre splitters and combiners
 - Optical amplifiers
 - Tunable optical filters
 - Space division switches
- Current sizes:
 - European Multi-wavelength Transport network is a good example
 - Three input/output fibres and four wavelengths switched (12 x 12)
- Problems exist with:
 - Limited capacity
 - Loss
 - Noise and Crosstalk

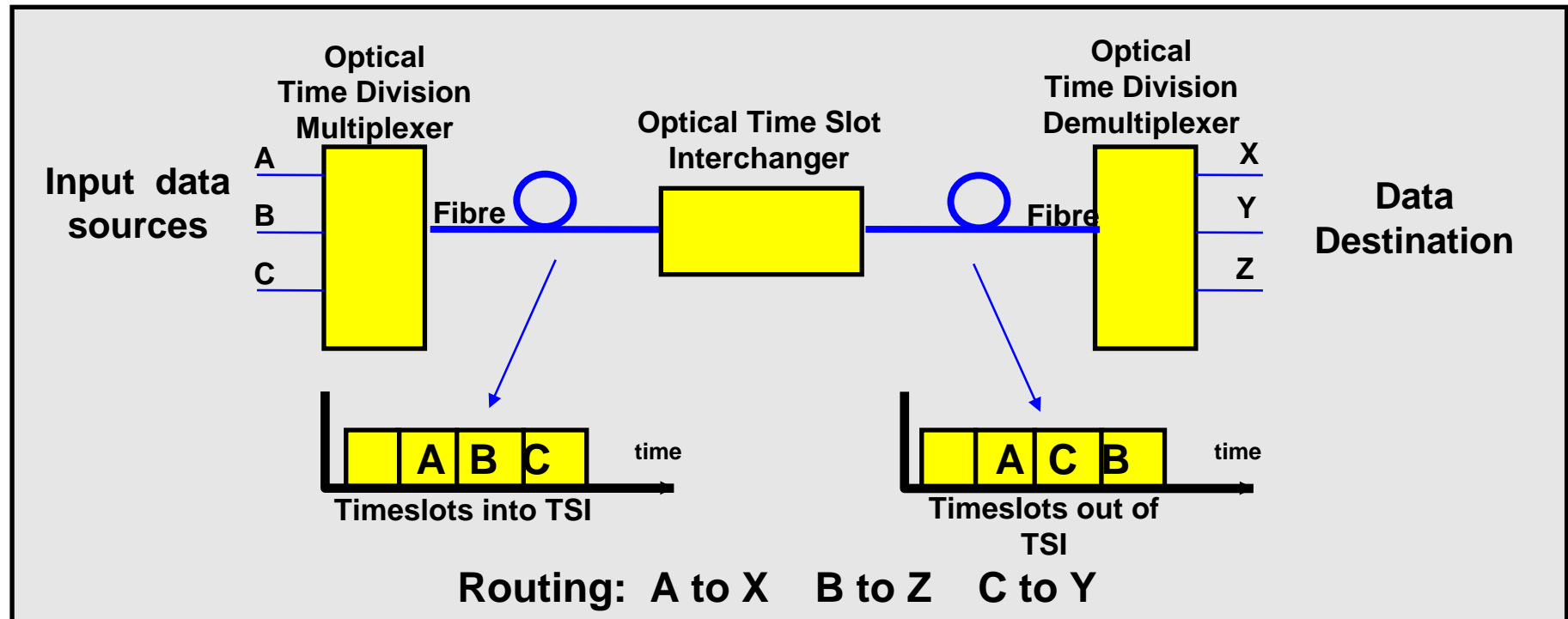


Time Division Optical Switching



Time Division Switching

- Used in an Optical Time Division Multiplex (OTDM) environment
- Basic element is an optical time slot interchanger
- TSI can rearrange physical channel locations within OTDM frame, providing simple routing.





Time Division Switching Issues

APPLIED OPTOELECTRONICS CENTRE

- Control system works at speeds comparable to frame rate
 - Electronic control is the only option at present
 - Totally Optical TDS must await developments in optical logic, memory etc.
- Use of Optical TDS could emerge if OTDM becomes widely acceptable.
 - Historically Telecoms operators have favoured electronic TDM solutions.
- OTDM and Optical TDS are more bandwidth efficient:
 - Bandwidth of 40 Gbits/sec WDM is >6 nm (16 Chs, 0.4 nm spacing)
 - Bandwidth of equivalent OTDM signal is only 1 nm
 - But dispersion is a problem for high bit rate OTDM