Fiber Optic Switches
Definition

**Definition** of Optical Switch (Photonic Switches)

An all-optical fiber-optic switching device that maintains the signal as light from input to output, no matter what the line speed or protocol.

Optical switches may separate signals at different wavelengths and direct them to different ports.

Traditional switches that connected optical fiber lines were (are) electro-optic. They converted photons from the input side to electrons internally in order to do the switching and then converted back to photons on the output side.
Why do we see ever-increasing presence of photonic switches in optical networks?

1. **Evolution** from point to point WDM links to all optical networks

2. **Requirements** for new fiber optic networks
   - bit rate transparency
   - protocol transparency

3. **Challenge.** Optical networking today is hampered by the unavailability of high-performance low-cost optical components. Developing low-cost methods for fabricating large optical switches and tunable lasers is key to the realization of the all-optical networks.
Application

Application area of optical switches

1. Network protection and reconfiguration (required switching time ~5ms)
2. All optical networking - circuit switching (WDM networks, OADM’s, OXC’s)
3. All optical networking - packet switching (required switching time ~1ns)
Application example - OADM

Example details: 4 wavelength x 2.5 GB/s (STM-16), tunable Fabry–Perot filters, optomechanical switches and 3-R opto-electronic regenerators. All components commercially available.
Three nodes were interconnected in a unidirectional self-healing two-fiber ring network demonstrator. Nodes are separated by 90 km of standard single mode fiber.
Requirements

- Polarization independence,
- low crosstalk,
- low-insertion loss or even gain,
- wavelength independence (in the EDFA wavelength range);
- multiwavelength operation,
- bit-rate transparency (up to at least 10 (40?) Gb/s)
- fast switching,
- simple implementation,
- scalability.
Classification of optical switches

1. Thermooptic
2. MEMS
4. Bubble switch (including electrowetting)
3. Integrated optic, electrooptic
4. Acoustooptic
5. Semiconductor switches (with potential of monolithic integration)
MEMS switches

MEMS - Micro-electromechanical system
MEMS Switches

**Acronym.** MEMS - Micro-electromechanical system

**Technology.** MEMS are miniature devices fabricated with a process called micro machining. The structures range in dimensions from a few hundred microns to millimeters, and are mostly fabricated on silicon substrates, using standard semiconductor processing techniques.

MEMS offer the same potential **benefits** as large-scale electronic integrated circuits: low-cost and high-volume automated production.

MEMS offer their own **challenges:**
1. unlike electronic circuits, these are mechanical devices,
2. reliability for telecommunications applications is still to be proven.
Advantages of using silicon for micro-optical components

1. The silicon surface when treated properly can provide an optical surface of extremely high quality (flat and scatter-free).

2. The excellent mechanical properties of single-crystal silicon allow fabrication of fatigue-free devices. Since single-crystal silicon has no dislocations, it has virtually no fatigue and is a perfect elastic material — a property that is extremely desirable for precision mechanics applications.

3. The electrical properties of silicon allow for the integration of sensors and detectors with high precision.

4. Silicon is totally transparent at the wavelengths used in optical communication.

5. The lithographic batch-fabrication of these devices, driven and made possible by the existing IC technology, provides a relatively inexpensive fabrication method.
MEMS technologies

**Bulk micromachining.** Etching-subtraction process. It involves the removal of silicon from the bulk silicon substrate by etchants. Anisotropic etchants etch different silicon orientation planes at different rates. Isotropic etchants, on the other hand, etch the silicon evenly in all directions.

**Surface micromachining** - Thin-film materials are selectively added or removed from the wafer. The material deposited where a free-standing mechanical structure is needed is called a **sacrificial layer**, the material that is left after etching of the underlying sacrificial layer is called the **structural material**. Technologies: a combination of dry end wet etching, and thin film deposition.
MEMS Switch architectures

2D MEMS switches
Mirrors are arranged in a crossbar configuration. They can be in either the ON position to reflect light or the OFF position to let light pass uninterrupted. For an NxN-port switch, a total of $N^2$ mirrors is required for strictly nonblocking switching fabric.

3D MEMS switches
The switch has mirrors that can rotate about two axes. Light can be redirected in space to multiple angles. This approach results in $N$ or $2N$ mirrors ($2N$ mirrors offer lower insertion losses).
2D MEMS Switch

Mirrors are arranged in a crossbar configuration. Each mirror has only two positions and is placed at the intersections of light paths between the input and output ports. They can be in either the ON position to reflect light or the OFF position to let light pass uninterrupted.

Applications: switches with small port counts

Disadvantages:
- large mirror-count required
- free space propagation distances are different, which results in different insertion losses for different paths (>5dB).
3D MEMS Switch

3D MEMS switches
3D MEMS switch has mirrors that can rotate about two axes. Light can be redirected precisely in space to multiple angles. This approach results in only N or 2N mirrors.
Actuating mechanisms requirements

Actuating mechanism = method to move the mirror

1. Small
2. Easy to fabricate
3. Accurate
4. Predictable
5. Low power consumption
Actuating mechanisms

1. **Electrostatic** - attraction forces of two oppositely charged plates. Advantages: well understood, good repeatability. Disadvantages: nonlinearity in force-voltage relationship, high driving voltages

2. **Electromagnetic** - attraction between electromagnets with different polarity. Advantages: large forces with high linearity, low driving voltages. Disadvantages: shielding required to prevent crosstalk, reliability not proved yet

3. **Scratch drive actuator (SDA)**: movement controlled by balance of friction and pulsed electrostatic interaction between planes. Advantages: no holdup voltage required, movement in small steps (10 nm)
Scratch-Drive Actuator - movement Principle

To drive the SDA:
1. A step voltage load is applied between the substrate and the plate.
2. This results in the unsupported end of the plate snapping to the insulators, pushing the bushing outwards.
3. When the voltage is released, the SDA is moved forward by the bushing.

http://www.intellisense.com/contentfiles/intellisuitepapers/CADModelingofScratchDriveActuation.pdf
Scratch Drive Actuator (SDA) Switch
Semiconductor switches - basic types

1. Interferometric Mach-Zehnder switch

2. Directional couplers

3. Mode transformers (digital optical switch, DOS)

4. Semiconductor optical amplifiers (active space switches)
Semiconductor switches - basic structure

Double heterostructure waveguides

• Ridge, embedded or strip loaded waveguides

• InGaAsP/InP or GaAs/AlGaAs heterostructures

• Attenuation of free waveguides $\sim 0.2$ dB/cm, waveguide/contacting layer/electrode structure $< 1$ dB/cm

• Modulators are usually anisotropic - special design required for polarization independent performance
Directional coupler

Simple direction coupler. Very high accuracy of technology required.

Double segment, reversed $\Delta \beta$ coupler. Moderate accuracy of technology required.

Layout of electrodes in integrated-optics directional coupler.
## Semiconductor directional coupler - examples

<table>
<thead>
<tr>
<th>Matrix type</th>
<th>Switch points</th>
<th>Material</th>
<th>Results</th>
<th>year [ref]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4x4</td>
<td>6 CIDC</td>
<td>InGaAsP</td>
<td>TE, crosstalk &lt;-10dB, insertion loss &lt;15dB, switching &gt;10mA, size 6..5mm</td>
<td>1992 [1]</td>
</tr>
<tr>
<td>4x4</td>
<td>6 CIDC</td>
<td>InGaAsP</td>
<td>TE, crosstalk &lt;-15dB, chip loss 15dB, switching ~10mA, size 35mm</td>
<td>1991 [2]</td>
</tr>
<tr>
<td>4x4</td>
<td>16 EODC</td>
<td>InGaAsP</td>
<td>TE, crosstalk &lt;-10dB, prop. loss 3dB, switching &lt;30V, size 35-40mm</td>
<td>1991 [3]</td>
</tr>
<tr>
<td>4x4</td>
<td>6 QCSE Benes DC</td>
<td>InGaAlAs MQW</td>
<td>TE, crosstalk &lt;-15dB, chip loss 18dB, switching &lt;6V, size 9mm</td>
<td>1993 [4]</td>
</tr>
<tr>
<td>8x8</td>
<td>64 EODC</td>
<td>GaAs/Al GaAs</td>
<td>TE, crosstalk &lt;-21dB, chip loss 8.7dB, switching &lt;26V, size 26.5mm</td>
<td>1992 [5]</td>
</tr>
</tbody>
</table>


M-Z interferometric switches - structures

Mach-Zehnder interferometer - principle of operation

M.-Z switch with 3dB couplers

M.-Z switch with MMI segments
### Semiconductor M-Z interferometric switches - examples

<table>
<thead>
<tr>
<th>Matrix type</th>
<th>Switch points</th>
<th>Material</th>
<th>Results</th>
<th>year [ref]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2</td>
<td>QCSE</td>
<td>InGaAs MQW</td>
<td>TE, TM, crosstalk &lt;-10dB, insertion loss 20dB, switching 4.5V, electrode 675um, size 1.84mm</td>
<td>1992 [1]</td>
</tr>
<tr>
<td>2x2</td>
<td>EO MZI</td>
<td>InGaAsP</td>
<td>TE, TM, crosstalk &lt;-16dB, on-chip loss &lt;3.2dB, switching 6V, electrode 3mm, size 7mm</td>
<td>1993 [2]</td>
</tr>
<tr>
<td>2x2</td>
<td>EO MZI</td>
<td>InGaAs</td>
<td>TE, crosstalk &lt;-12dB, loss 1.5dB/cm, switching 6V, electrode 3mm, bandwidth 35GHz</td>
<td>1995 [3]</td>
</tr>
<tr>
<td>2x2</td>
<td>QCSE MZI</td>
<td>InGaAsP MQW</td>
<td>TE, crosstalk &lt;-15dB, insertion loss 22dB, switching 6.8V, electrode 0.5mm, bandwidth 10GHz</td>
<td>1995 [4]</td>
</tr>
<tr>
<td>2x2</td>
<td>QCSE MZI</td>
<td>InGaAlAs MQW</td>
<td>TE, TM, crosstalk &lt;-20dB, insertion loss 14dB, switching 4.5V, electrode 1.5mm, size 4mm</td>
<td>1996 [5]</td>
</tr>
<tr>
<td>2x4 module</td>
<td>4 EO MZI</td>
<td>InGaAsP</td>
<td>TE TM ±0.5dB, crosstalk &lt;-10dB, insertion loss 12dB, switching 5.5V, electrode 6mm, switch time 200ps</td>
<td>1994 [6]</td>
</tr>
<tr>
<td>4x4 module</td>
<td>4 EO MZI</td>
<td>InGaAsP</td>
<td>TE TM ±0.5dB, crosstalk &lt;-15dB, insertion loss 5dB, switching 4.5V, electrode 6mm, switch time 200ps, optical bandwidth &gt;30nm</td>
<td>1996 [7]</td>
</tr>
</tbody>
</table>

# Semiconductor digital optical switches (DOS) - examples

<table>
<thead>
<tr>
<th>Matrix type</th>
<th>Switch points</th>
<th>Material</th>
<th>Results</th>
<th>year</th>
<th>[ref]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x2</td>
<td>CD DOS</td>
<td>InGaAsP</td>
<td>TE TM, crosstalk &lt;-14dB, switching 12V, optical band. &gt;50nm, length 5mm, att. &lt;2dB/cm</td>
<td>1991</td>
<td>[1]</td>
</tr>
<tr>
<td>4x4</td>
<td>24 CI DOS</td>
<td>InGaAsP</td>
<td>TE TM, crosstalk &lt;-16dB, switching &lt;10mA, optical bandwidth &gt;50nm, size 40mm, 25dB fiber to fiber loss</td>
<td>1992</td>
<td>[2]</td>
</tr>
<tr>
<td>4x4</td>
<td>24 CI DOS</td>
<td>InGaAsP</td>
<td>TE TM, crosstalk &lt;-13dB, switching &lt;30mA, optical bandwidth &gt;50nm, size 20mm, 15dB fiber to fiber loss</td>
<td>1993</td>
<td>[3]</td>
</tr>
<tr>
<td>1x2</td>
<td>CI DOS</td>
<td>InGaAsP</td>
<td>TE TM, crosstalk &lt;-20dB, switching 50/100mAfor 1.3/1.5µm, optical bandwidth 200nm, electrode 3mm, att. 2dB/cm</td>
<td>1994</td>
<td>[4]</td>
</tr>
<tr>
<td>1x2</td>
<td>QCSE DOS</td>
<td>InGaAsP</td>
<td>TE, crosstalk &lt;-7dB, switching 4V, size 0.9mm, 1.25 chip loss, 10GHz 3dB bandwidth</td>
<td>1995</td>
<td>[5]</td>
</tr>
<tr>
<td>1x2</td>
<td>CI DOS</td>
<td>InGaAsP</td>
<td>TE TM, crosstalk &lt;18dB, switching 30mA, electrode 1,5mm, 10dB f to f loss for 2x2 matrix</td>
<td>1995</td>
<td>[6]</td>
</tr>
</tbody>
</table>

DOS digital optical switch, CD carrier depletion, CE carrier injection, QCSE quantum-confined Stark effect

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Photonic switches
Active space switches

Current injection into semiconductor pn-junctions generates free carriers. This carrier modulation varies the loss and/or gain characteristics. Employing these characteristics, switchable semiconductor optical amplifiers (SOA’s) can be realized.

SOA-based NxN space switch in a tree arrangement.
### Active space switches - examples

<table>
<thead>
<tr>
<th>Size</th>
<th>Configuration</th>
<th>Material</th>
<th>Wavelength</th>
<th>Gain</th>
<th>Current</th>
<th>Off-on</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x2</td>
<td>6 SOA in 2 stages</td>
<td>InGaAsP</td>
<td>$\lambda=1.28\mu m$, f to f gain &gt;0 dB, current 75+60 mA</td>
<td>1995</td>
<td>[68]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2x2</td>
<td>4 SOA</td>
<td>InGaAsP</td>
<td>$\lambda=1.58\mu m$, TE TM ±3dB, f to f gain 7dB, current 160mA, on/off 25dB</td>
<td>1996</td>
<td>[69]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2x2</td>
<td>4 SOA + 8 TIR</td>
<td>InGaAsP</td>
<td>$\lambda=1.3\mu m$, f to f gain 1dB, current 80+250mA, on/off &gt;45dB</td>
<td>1993</td>
<td>[76]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1x4</td>
<td>4 SOA</td>
<td>InGaAsP</td>
<td>$\lambda=1.57\mu m$, TE, f to f gain &gt;0dB, current 58mA, on/off 38dB</td>
<td>1996</td>
<td>[70]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4x4</td>
<td>SOA</td>
<td>InGaAs/ GaAs QW</td>
<td>$\lambda=0.99\mu m$, f to f gain &gt;0dB, current 16mA, on/off &gt;30dB, switch time &lt;1ns</td>
<td>1992</td>
<td>[75]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4x4</td>
<td>16 SOA + 32 TIR</td>
<td>InGaAsP</td>
<td>$\lambda=1.3\mu m$, TE TM ±1dB, f to f gain 5dB, current 250+120mA, on/off 54dB</td>
<td>1994</td>
<td>[77]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4x4</td>
<td>24 SOA (3 stages)</td>
<td>InGaAsP</td>
<td>$\lambda=1.55\mu m$, TE, f to f gain 6dB, current 50+50+100mA, on/off 40dB</td>
<td>1992</td>
<td>[71]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4x4</td>
<td>24 SOA (3 stages)</td>
<td>InGaAsP</td>
<td>$\lambda=1.55\mu m$, TE TM ±0.5dB, f to f gain 0dB, current 20+20+50mA, on/off 40dB</td>
<td>1995</td>
<td>[72]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4x4</td>
<td>4 SOA</td>
<td>InGaAsP</td>
<td>$\lambda=1.31\mu m$, TE TM ±0.5dB, chip gain 20dB, current 100mA</td>
<td>1994</td>
<td>[79]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4x4</td>
<td>module hybrid 2x8 array SOA</td>
<td>InGaAsP</td>
<td>SiO$_2$/TiO$_2$</td>
<td>$\lambda=1.3\mu m$, insertion loss &gt;26dB, current 80mA, on/off 30dB</td>
<td>1992</td>
<td>[78]</td>
<td></td>
</tr>
<tr>
<td>4-array</td>
<td>module 4 SOA</td>
<td>InGaAsP</td>
<td>$\lambda=1.55\mu m$, TE TM ±1dB, f to f gain 14dB, current 80mA</td>
<td>1995</td>
<td>[80,81]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-array</td>
<td>module 4 SOA</td>
<td>InGaAsP</td>
<td>$\lambda=1.55\mu m$, f to f gain 17dB, current 150mA</td>
<td>1996</td>
<td>[82]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Nonlinear optical switches
(optically controllable switches)

1. Nonlinear optical loop mirror (NOLM)
2. Non-Linear Amplifying Optical Loop Mirror (NALM)
3. Nonlinear directional coupler
4. Nonlinear Mach-Zehnder interferometer
Nonlinear optical loop mirror (NOLM)

The device consists of a fused fiber coupler (splitter) with two of its arms connected to an unbroken loop of fiber. The device makes use of the phenomenon of “Nonlinear Kerr Effect”. The two counter propagating light beams are nonlinearly phase-shifted by different amount. The phase shift is power-dependent.

Applications: noise limiter, optical gate, optical signal processing (digital)

Coupler ≠ 50%, ⇒ complete coupling not possible
The Non-Linear Amplifying Optical Loop Mirror (NALM)

Coupler = 50%, ⇒ complete coupling is possible
The NOLM as a Logic Gate

Demultiplexing of a TDM Data Stream. A control pulse is used to select a channel from an incoming high-speed TDM data stream.

NOLM Configured as an AND Logic Gate