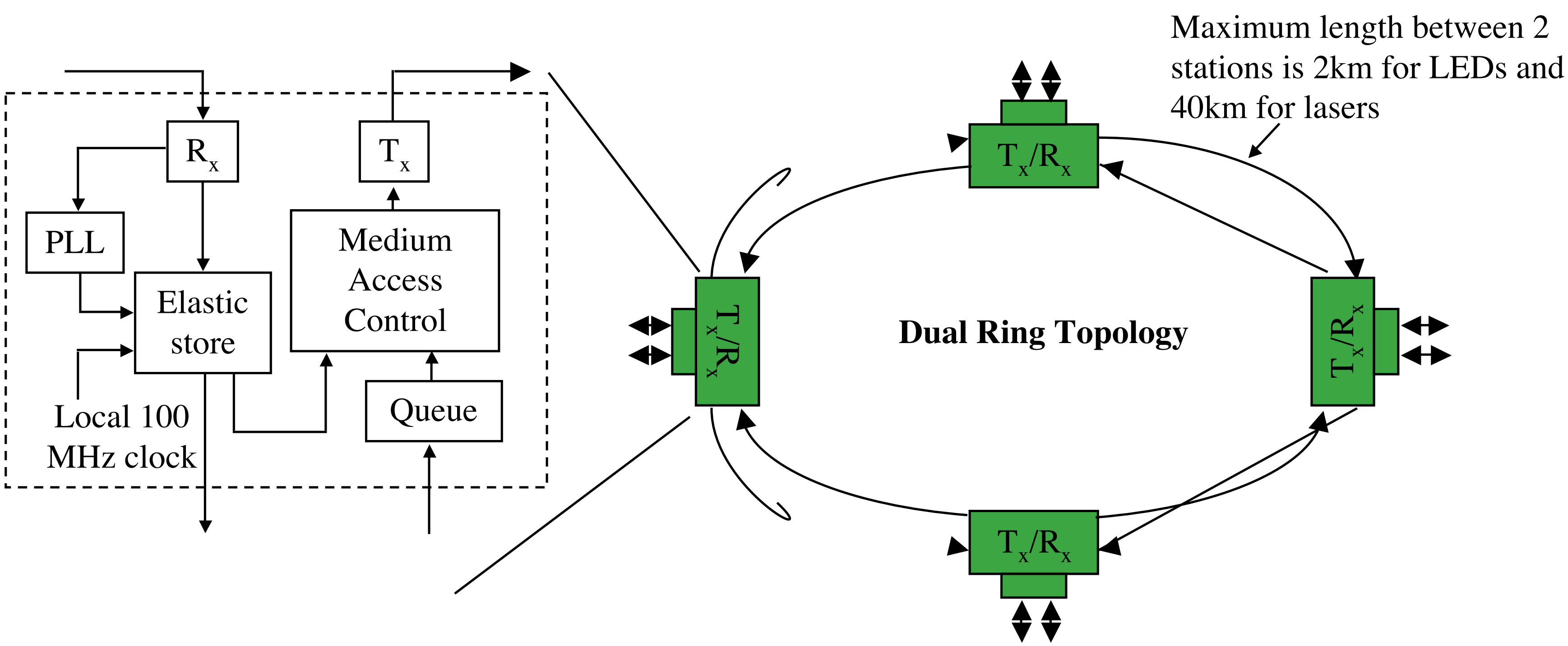
Lecture 3: First Generation Optic Networks and WDM Network Elements

IP+SONET vs. IP+ATM+SONET

- Bandwidth efficiency due to different protocol overheads
  - Under the assumption of
    - 576 byte IP packet
    - 155 Mbit/s SONET rate
  - the useful bandwidth is
    - 125.918 Mbit/s for IP+ATM+SONET (80% efficiency)
    - 147.150 Mbit/s for IP+SONET (95% efficiency)
- Bandwidth management and Quality of Service (QoS)
    - The use of ATM ensure a rich set of QoS parameters, that are not present in the PPP used for IP directly over SONET
- Addressing, Routing, Flow Control, Fault Tolerance
    - Again, most of these features are present in ATM, while they are not in PPP
- In conclusion, IP+SONET is to be preferred where the raw bandwidth is an issue, while IP+ATM+SONET is much more robust in terms of several others networking features
- Equipment cost may anyway override these considerations

Fiber Distributed Digital Interface (FDDI)

- Standard for Local Area Networks (LANs) and Metropolitan Area Networks (MANs)
- Extension of Token Ring to 100 Mbps optical fiber
- Connect up to 500 nodes
- Low cost implementation uses low power transmitters and graded index MMF



FDDI Frame Format

Data Frame	PA	SD	FC	DA	SA	Data	FCS	ED	FS

Token Frame	PA	SD	FC	ED

- PA: Preamble field: 16 symbols each coded with 4 5 bits to establish and maintain clock and synchronization
- SD: Starting delimiter field. Two unique symbol sequences to start processor on overhead sequence.
- FC: Frame control consisting of two symbols that define frame type and characteristics.
- DA: Destination address
- SA: Source address
- FCS: Frame checking sequence for error detection
- ED: End delimiter field.
- FS: Frame status field.

FDDI Flow Control

- Each node checks for the presence of tokens
- If a token is available, then the node may send data according to:
  - Synchronous: Time sensitive traffic with required upper bound on transmission delay
    - Transmission of data once a token has been received is for pre-assigned amount of time
  - Asynchronous: Time insensitive without guarantee of transmission delay
    - Transmission data may begin after a timer se to the token rotation time (TRT)
    - Transmission may last for a predetermined token holding time (THT)
- After transmission, the node replaces the token on the network.

Fibre Channel

⇨ A technology for transmitting data between computer devices at a data rate of up to 1 Gbps (A data rate of 4Gbps is proposed.)

⇨ Suited for connecting computer servers to shared storage devices and for interconnecting storage controllers and drives.

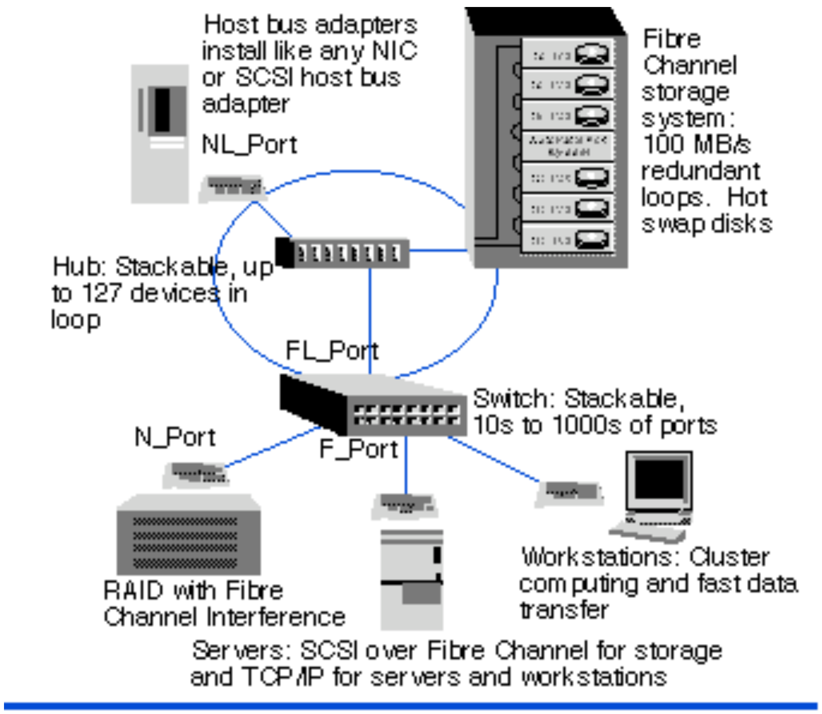
⇨ Fibre Channel Arbitrated Loop (FC-AL) supports copper media and loops containing up to 126 devices, or nodes.

⇨Three times as fast as the Small System Computer Interface (SCSI)

⇨ Devices can be as far as ten kilometers (about six miles) apart. Requires optical fiber for longer distances. Works with coaxial cable and twisted pair for shorter distances.

⇨ Offers point-to-point, switched, and loop interfaces. Interoperates with SCSI, the Internet Protocol (IP), and other protocols.

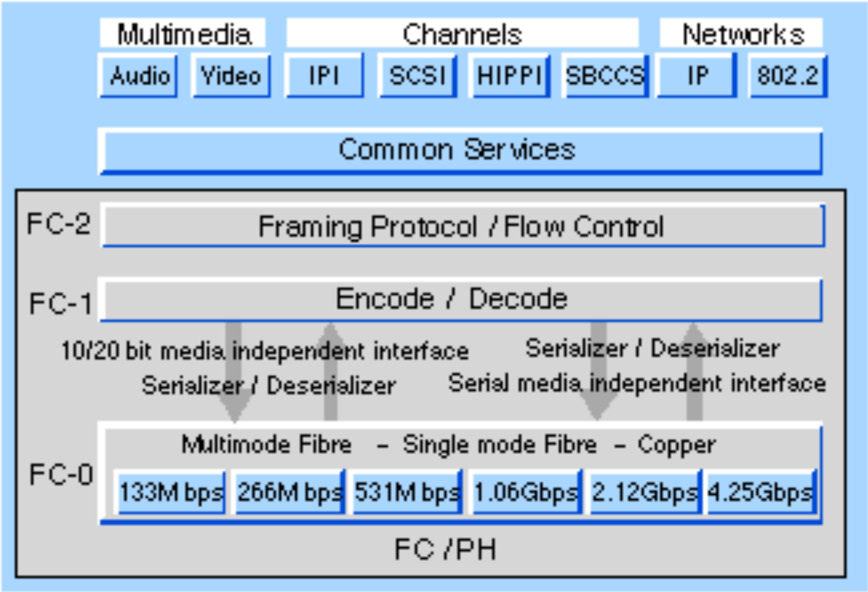
⇨ Specified by ANSI X3.230-1994 (ISO 14165-1).



Source: http://www.fibrechannel.com/technology

Fibre Channel

- High-speed serial data transfer interface that can be used to connect systems and storage in point-to-point or switched topologies.
- Supports bandwidths of 133 Mb/sec., 266 Mb/sec., 532 Mb/sec., 1.0625 Gb/sec., and 4 Gb/sec. (proposed) at distances of up to ten kilometers.
- The FC layered protocol architecture consists of five layers. The highest layer defines mappings from other communication protocols onto the FC fabric. Protocols supported include:
  - Small Computer System Interface (SCSI)
  - Internet Protocol (IP)
  - ATM Adaptation Layer (AAL5)
  - Link Encapsulation (FC-LE)
  - IEEE 802.2
- **FC-0:** Covers the physical characteristics of the interface and media, including the cables, connectors, drivers, transmitters, and receivers
- **FC-1:** Defines the 8B/10B encoding/decoding and transmission protocol used to integrate the data with the clock information required by serial transmission techniques
- **FC-2:** Defines the rules for the signaling protocol and describes transfer of the data frame, sequence, and exchanges



Source: http://www.fibrechannel.com/technology

Fibre Channel

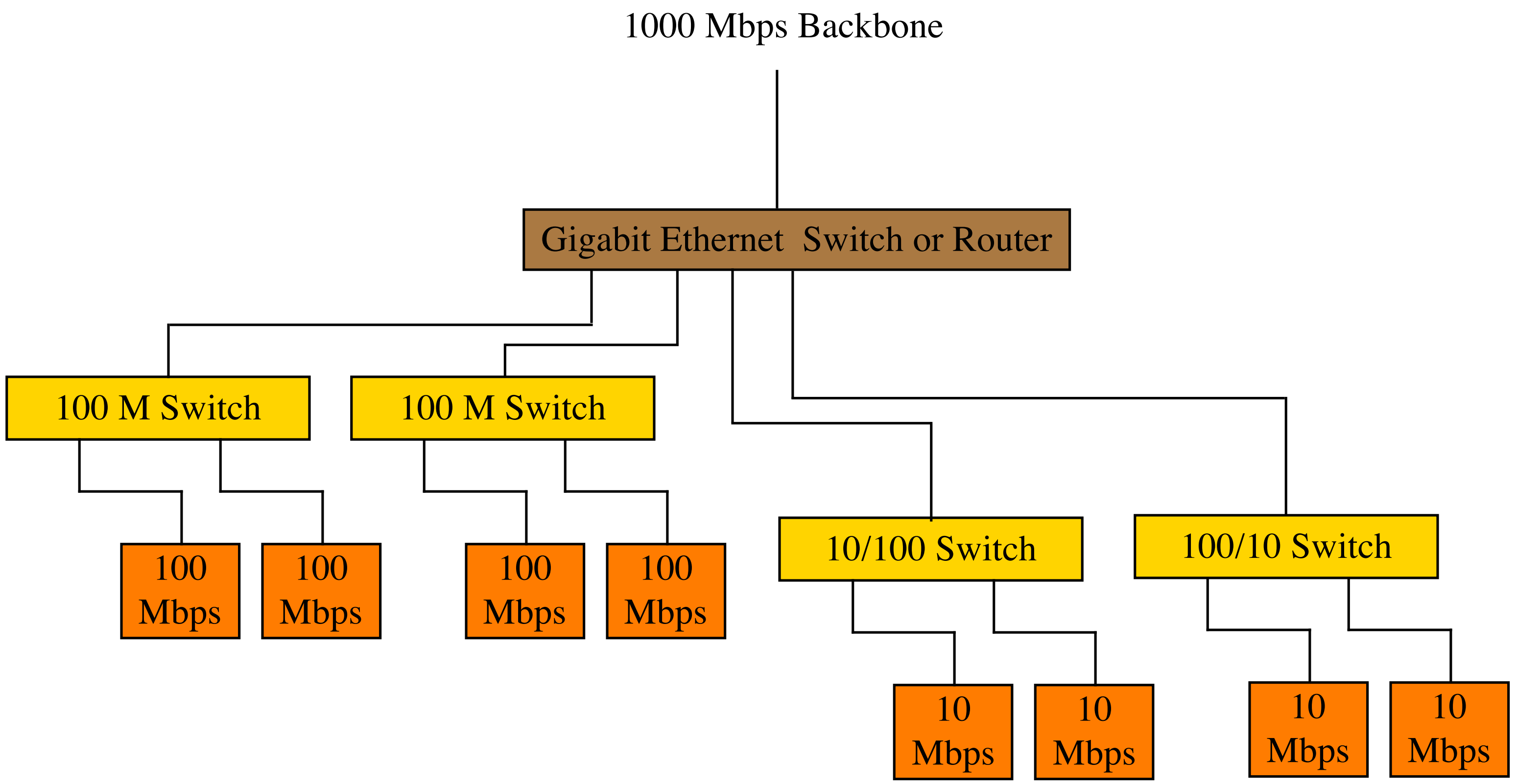
Frame size is up to 2,148 bytes:

Bytes	Function
4	Start of frame delimiter
24	Frame header, including 24-bit source and destination addresses and sequence numbers to support windowing and flow control
0 to 2,112	Higher-layer data (payload), may include a 64-byte optional header, reducing payload to 2,048 bytes
4	CRC
4	End of frame delimiter

8B/10B Channel Coding

- Eight data bits are sent in 10 bits to provide the following:
  - Error detection (called disparity control)
  - Frame delimiting with data transparency: Any bit pattern can be sent with a way to mark the beginning and end of a frame
  - Clock recovery: Signal transitions assist the receiver in finding the center of each bit, even if many contiguous ones (or zeros) are sent and the sender has a slightly different transmission rate
  - D.C. voltage balance (on average, the signal spends an equal time positive and negative; this is required if the signal is AC coupled at the receiver

Gigabit Ethernet



Gigabit Ethernet

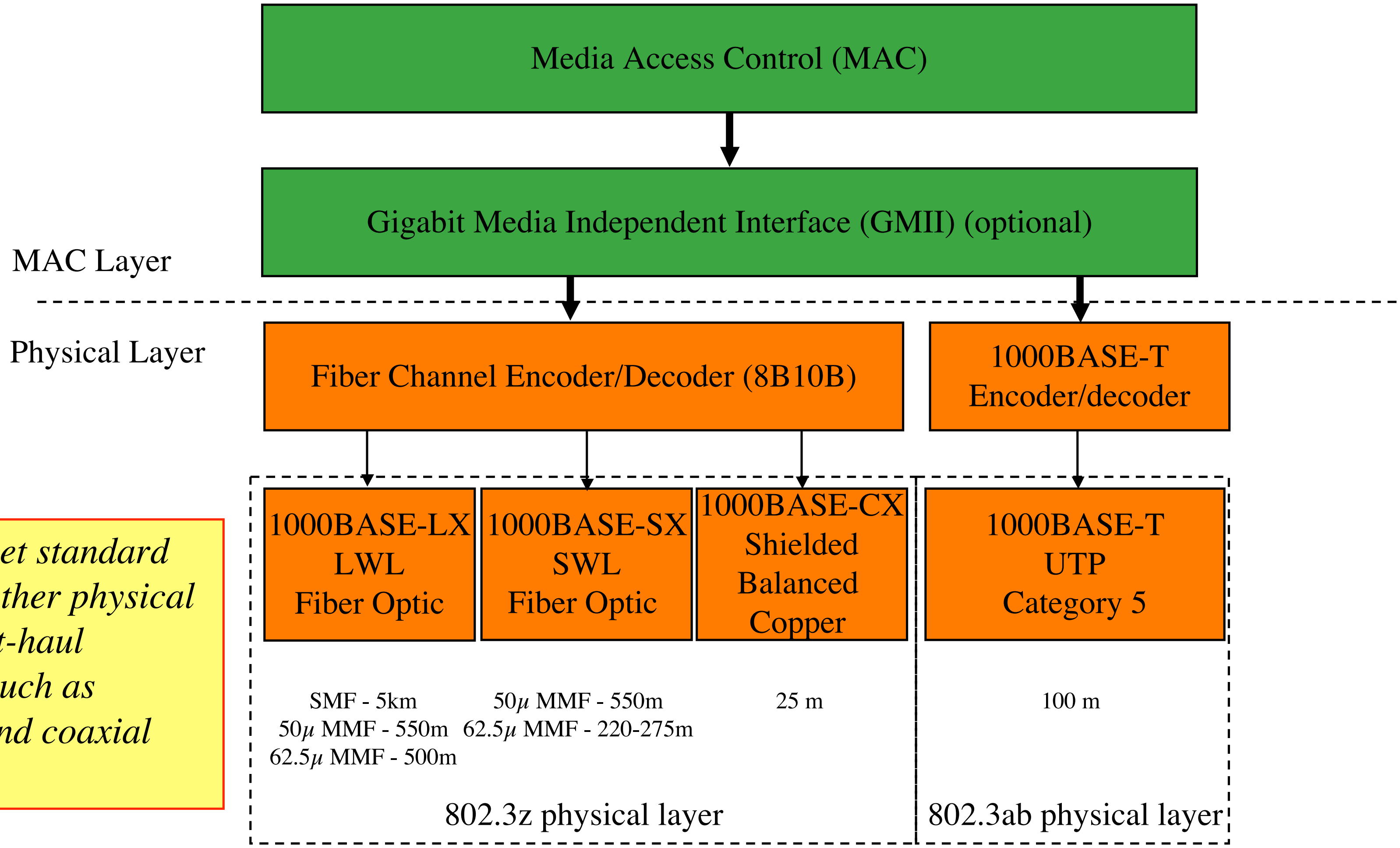
- Allows half- and full-duplex operation at speeds of 1000 Mbps
- Full-duplex is by far the most used approach
  - For full duplex, CSMA/CD is not used, since the system works on point to point connections only
- Uses the 802.3 Ethernet frame format
- Addresses backward compatibility with 10BASE-T and 100BASE-T technologies
- Utilizes Fiber Channel physical layer technology, with the following options:

SX stands for the **short-wavelemgth** option (850 nm)

LX stands for the **long-wavelemgth** option (1300 nm)

Standard	Fiber Type	Diameter (µm)	Modal BW (MHz*km)	Minimum Range (m)
1000BASE-SX (850 nm)	MM	62.5	160	**2 to 220**
	MM	62.5	200	**2 to 275**
	MM	50	400	**2 to 500**
	MM	50	500	**2 to 550**
1000BASE-LX (1300 nm)	MM	62.5	500	**2 to 550**
	MM	50	400	**2 to 550**
	MM	50	500	**2 to 550**
	SM	9	NA	**2 to 5000**

Gigabit Ethernet Layers



Gigabit Ethernet standard specifies also other physical media for short-haul transmission, such as twisted pairs and coaxial cables

Gigabit Ethernet Standards

Worst-Case 1000BASE-SX Link Power Budget and Penalties

Parameter	62.5-μ 2 Multimode		50-μ Multimode		Units
Modal bandwidth as measured at 850 nm (minimum, overfilled launch)	160	200	400	500	MHz*km
Link power budget	7.5	7.5	7.5	7.5	dB
Operating distance	220	275	500	550	meters
Channel insertion loss (@ 830 nm)	2.38	2.60	3.37	3.56	dB
Link power penalties	4.27	4.29	4.07	3.57	dB
Unallocated margin in link power budget	0.84	0.60	0.05	0.37	dB

Worst-Case 1000BASE-LX Link Power Budget and Penalties

Parameter	62.5-μ 2 Multimode	50-μ Multimode		10-μ Single-Mode	Units
Modal bandwidth as measured at 1300 nm (minimum, overfilled launch)	500	400	500	NA	MHz*km
Link power budget	7.5	7.5	7.5	8.0	dB
Operating distance	550	550	550	5000	meters
Channel insertion loss (@ 1270 nm)	2.35	2.35	2.35	4.57	dB
Link power penalties	3.48	5.08	3.96	3.27	dB
Unallocated margin in link power budget	1.67	0.07	1.19	0.16	dB

Worst-Case Long Haul Link Power Budget and Penalties

Parameter	10-μ 2 Single-Mode	Units
Link power budget	10.5	dB
Operating distance	10,000	meters
Channel insertion loss (@1280 nm)	7.8	dB
Link power penalties	2.5	dB
Unallocated margin in link power budget	0.2	dB

Gigabit Ethernet Fiber Cable Standards

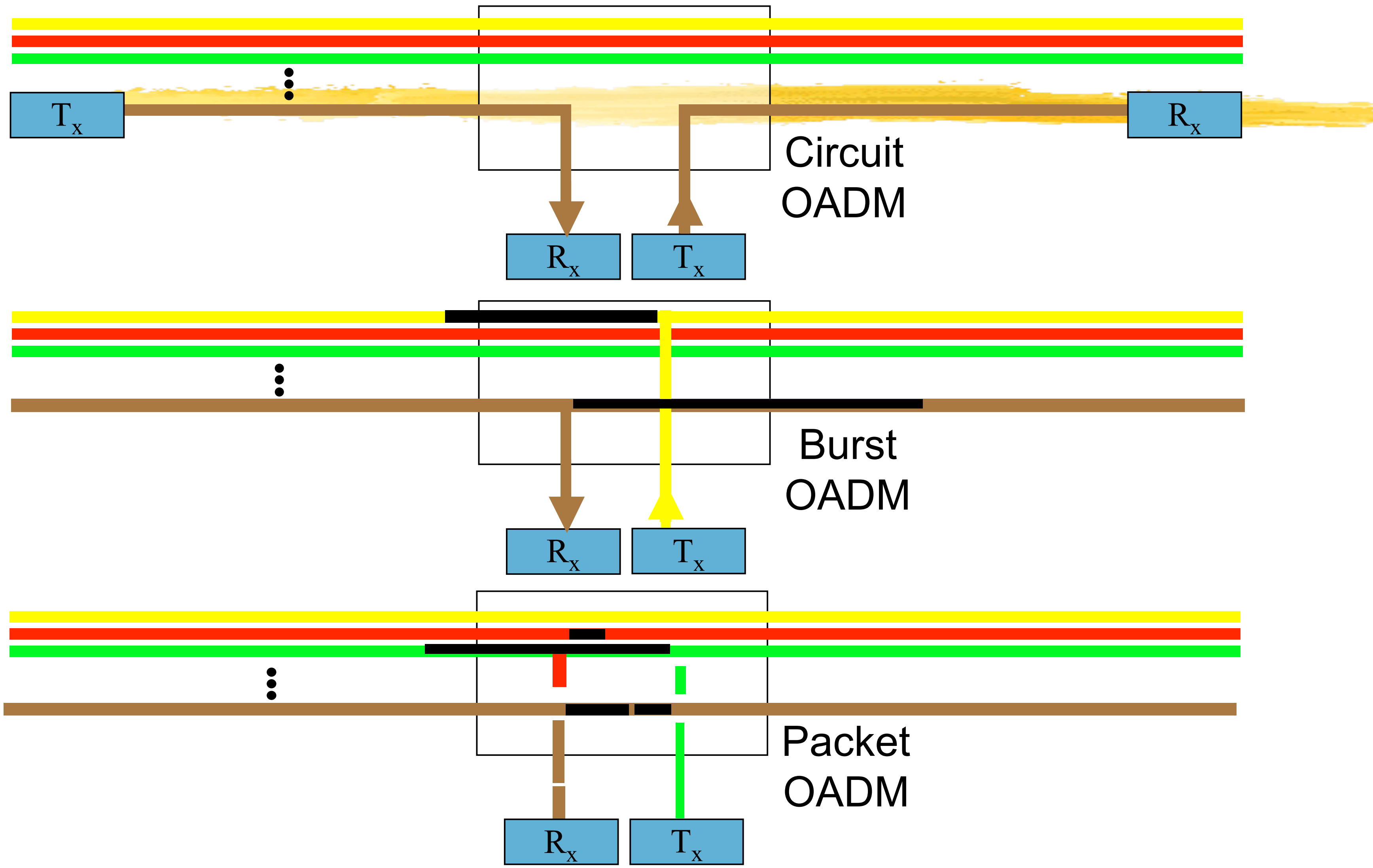
Description	62.5-μm 1 Multimode		50-μm Multimode		10-μm Single-Mode	Units
Nominal Wavelength	850	1300	850	1300	1300	nm
Fiber cable attenuation (maximum)	3.75	1.5	3.5	1.5	0.5	dB/km
Modal bandwidth	160	500	400	400	NA	MHz*km
(minimum, overfilled Launch)	200	500	500	500	NA	MHz*km
Zero dispersion wavelength	1320–1365		1295–1320		1300–1324	nm

2^{nd} Generation Optical Networks

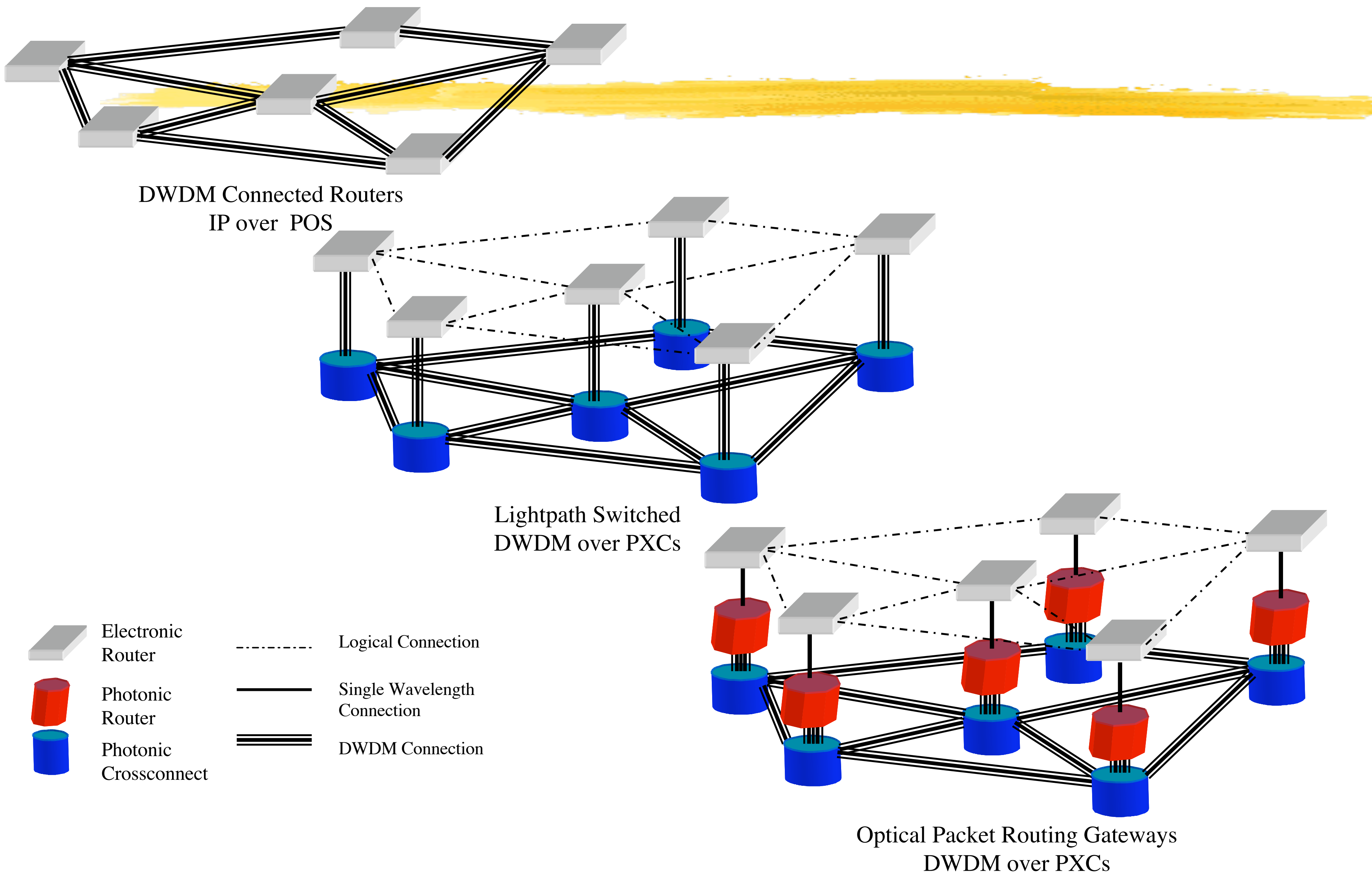
- Current evolution of 1st Generation Optical Networks
  - WDM and DWDM to increase link capacity
  - Multichannel optical amplification for long haul distance
  - OEO regenerators can be greatly eliminated

- 2nd Generation Optical Networks
  - Perform routing and switching functions optically
  - Map protocols directly to optical layer via WDM
  - Allows some level of Bit-rate and Format transparency

Example OADM



Network Evolution



Optical Circuit & Packet Switching

- Optical Circuit Switching, also called:
    - OTN: Optical Transport Networks (by ITU)
    - ASON: Automatically Switched Optical Network (by ITU)
    - All-Optical Network
    - Truly Optical Network
    - …
  - is (nearly) ready for commercial deployment
  - Year 2001 is probably the "Year Zero" for All-Optical (circuit switched) Networks
- Optical Packet Switching is still at the R&D level
  - Some testbeds have been implemented
  - No one has ever been truly engineered
  - We will see anyway a lot of development in this area in the next 4-5 years

Why "True" Optical networking?

- Enabling technologies
  - New potential offered by long-haul, not-repeatered optical transmission
  - New devices for optical handling of WDM channels
- Motivations & Drivers
  - Wavelength reuse
  - Avoid OEO conversion of "Passing-Through" traffic
  - Allow efficient fault-protection

Long-Haul Transmission

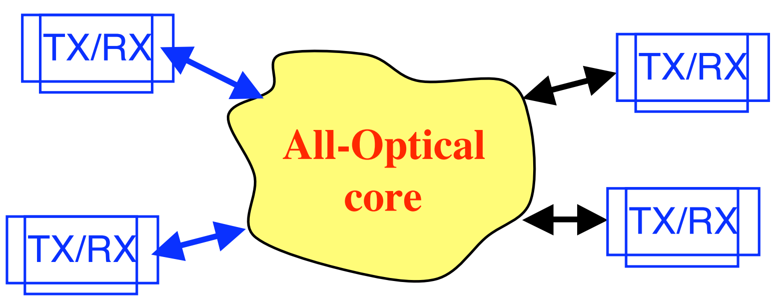
- Optical WDM technology has reached a very good maturity
  - WDM transmission on 40-100 channels on 400-500 Km using optical amplification (without OEO conversion) is commercially available from most major vendors
  - An extension to much higher distances (>1000 Km up to transoceanic distances) is ready at the R&D level, and (nearly?) ready at the commercial level
- Consequences
  - OEO conversion, from a pure transmission point of view, is less and less required
    - The need to place an OEO along a link will be more and more related to networking (switching, routing) requirements, and not to transmission
  - It may be envisioned to cover extremely large areas (Europe, United States and more) with all-optical transmission, based on EDFA amplification and without OEO conversion

DXC "Passing-Through" Traffic

- In a digital cross connect (DXC) in a complex mesh network, most of the traffic has just to pass through the node, since it must simply be forwarded to next nodes
  - Only a fraction of the total traffic has to be added or dropped locally
  - The local add/drop traffic is naturally handled by OEO conversions
- On the passing-through traffic, OEO conversion is not strictly required
  - If possible, the signal can be kept in the photonic domain
- Nowadays, OEO SONET systems satisfying long-haul WDM standards are extremely expensive
  - A huge number of SONET OE and EO cards are required on a DXC, given by the input number of fibers times the number of wavelength per fiber

The ITU G.872 standard

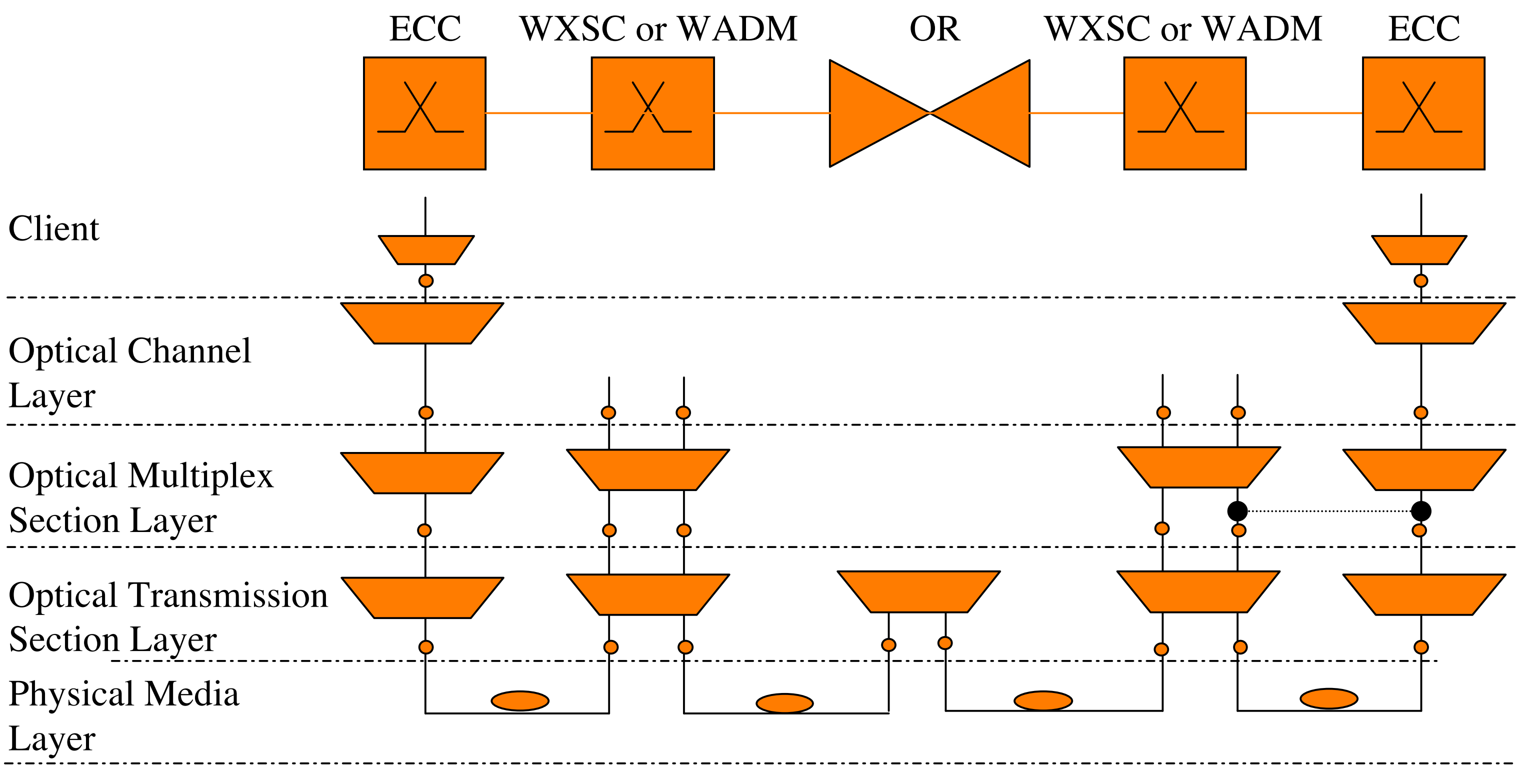
- Title: Architecture of Optical Transport Networks (OTN)
- This recommendation is at the basis of the current vision on OTN, i.e., on WDM reconfigurable networks
  - Though the current network visions of vendors and carriers vary a lot, still most architecture are based on the ITU vision
- The bottom line
  - Create an "Optical Layer" that resides below any "electrical" layer, being SONET, SDH, Gigabit Ethernet, etc
  - The "electrical" layers have access to Optical Channels going through the network on a wavelength basis



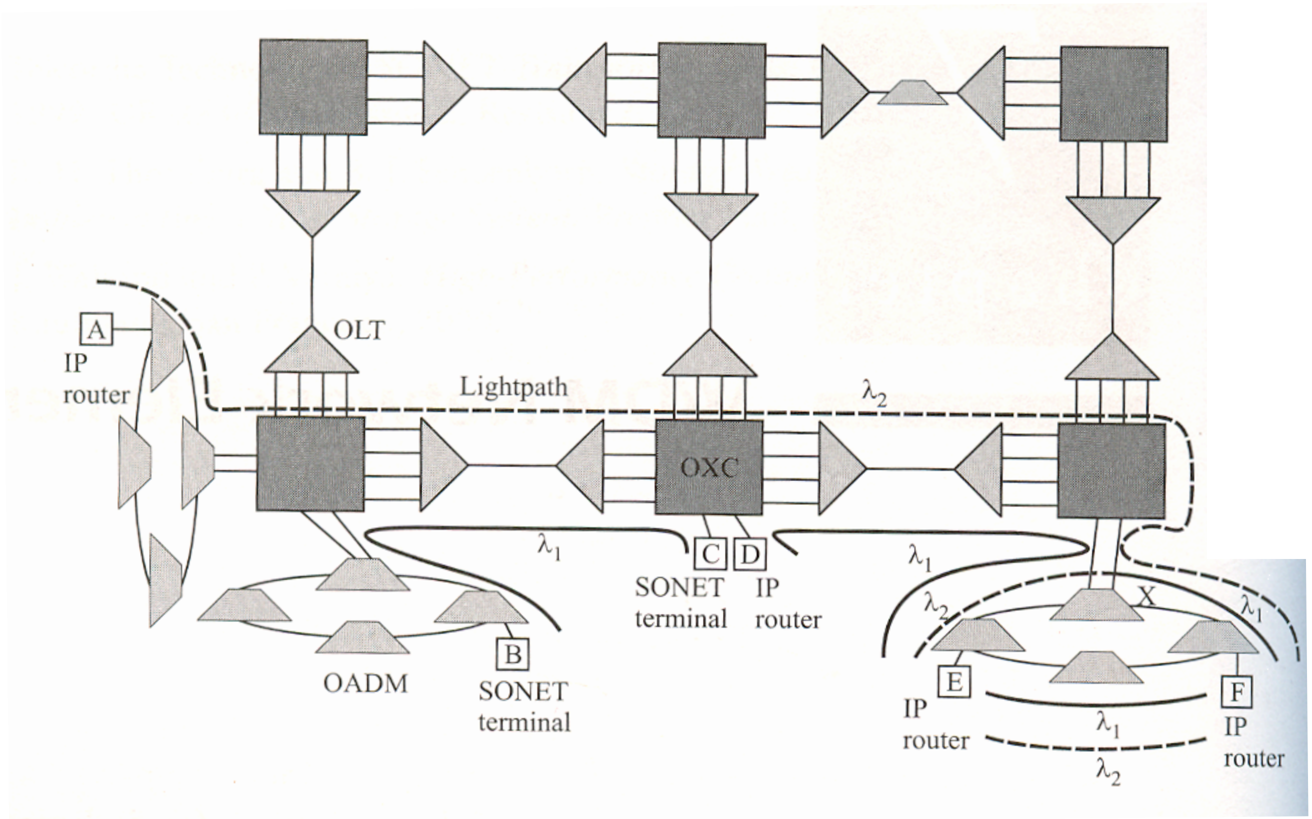
ITU G.872 layering

- Four layers are proposed by the Recommendation
  - Optical Channel Layer (OCh layer)
  - Optical Multiplex Section Layer
  - Optical Transmission Section Layer
  - Physical Media Layer
- The four layers basically maps on the lower three layers of the OSI model
- The Recommendation does not give technological details on the implementation, but rather gives general rules for the development of OTN

ITU G.872 layering



Wavelength Routed Mesh Network

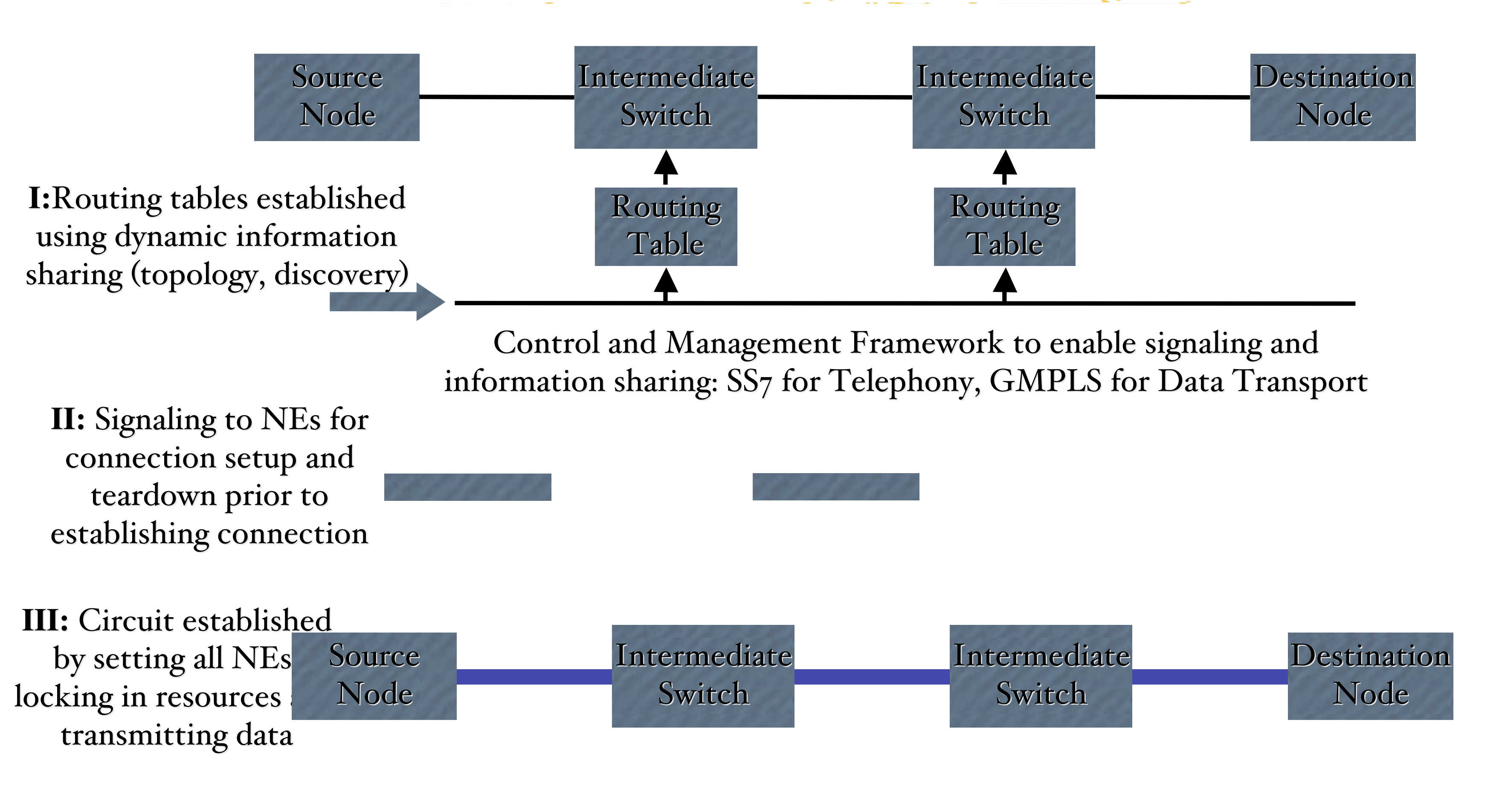


Ramaswami and Sivarajan, Optical Networks

Architectural Features

- Wavelength Reuse
- Wavelength Conversion
- Transparency
- Circuit Swicthing
- Survivability
- Lightpath Topology Engineering

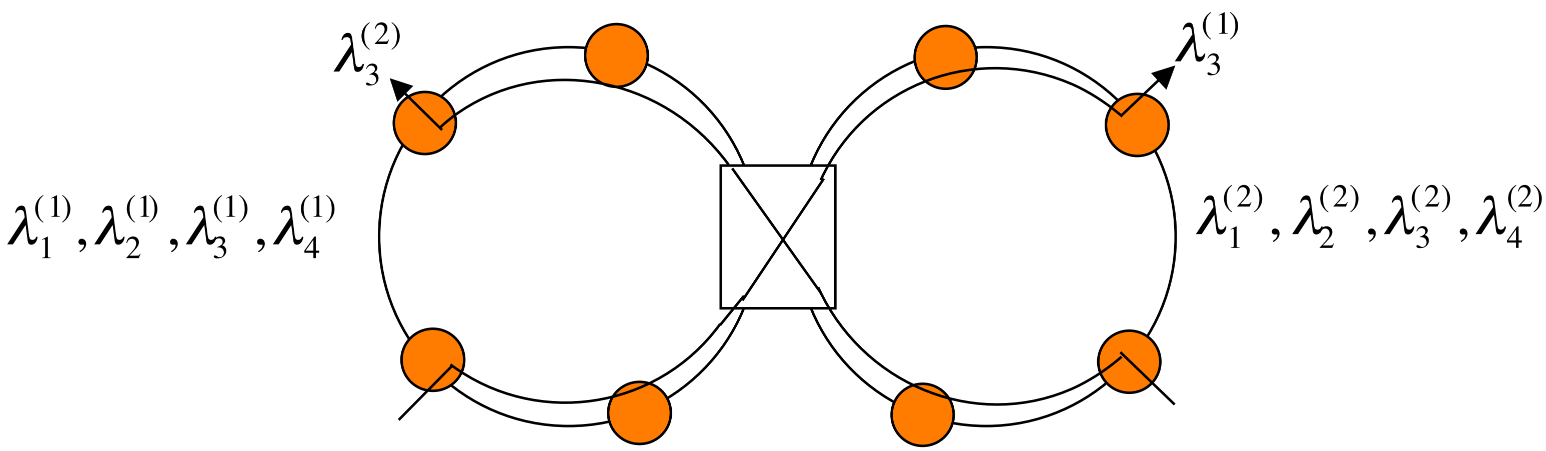
Optical Circuit Switching (OCS)



Wavelength Reuse

- The number of wavelength currently available are on the order of 40 and will most likely reach 128 for high performance systems over the next several years.
  - If we want to design networks that can support 1000's of nodes, we have to use architectures that don't rely on one wavelength per node.
  - Similar to frequency reuse in wireless networks, wavelength reuse in optical networks can support a large number of users on a limited number of wavelengths

Example: Interconnected WDM rings: 8 nodes with 4 discrete wavelengths



Fault-Protection

- The issue of fault protection in WDM network is a fundamental issue
  - A fiber cut may be easily interrupt hundreds of gigabit of transmission
  - Fiber cut are actually mostly “bundle” cut, meaning that hundred of fiber may go out of service
- The restoration mechanisms on such bandwidth-massive networks, may become extremely complex
- The implementation of an optical layer can give a new “layer” in protection mechanism

Optical Reconfigurability

- A degree of optical reconfigurability may be useful to cope with:
  - Changes in Connection Patterns
  - Changes in Traffic Characteristics
  - Provisioning and load balancing
  - Network Operations and Management
  - Topological updating, provisioning
  - Network element maintenance
  - Link/Node Failure and Restoration
  - Dynamic changes in number of wavelengths on the fiber
  - Transmitter, link, node and overhead (OH) channel failure

Optical Channel Layer (Och)

- Provides end-to-end networking of optical channels
  - The channels are totally transparent, i.e., they can carry on a wavelength any kind of client formats (SONET/SDH at different bit rates, Gigabit Ethernet, ATM cell based formats, etc)
- Processes optical channel overhead information, to ensure the integrity of the optical channel
- Processes optical channel Operation and Maintenance (OAM) functions, such as
  - Connection provisioning, Network survivability, QoS parameters, etc
- It is similar to OSI layer 3

Interfaces OCh/Client

- The interface (adaptation) between Och and the Client should implement the following functions:
  - Independently of the Client characteristics, the SOURCE interface must generate a continuous data stream suitable for optical modulation, of defined bit rate and coding scheme (note that burst transmission is not available)
  - The SINK interface must decode the received continuous data stream , and convert it in a format suitable for the Client
  - Generation and termination of the overhead signals required by this layer

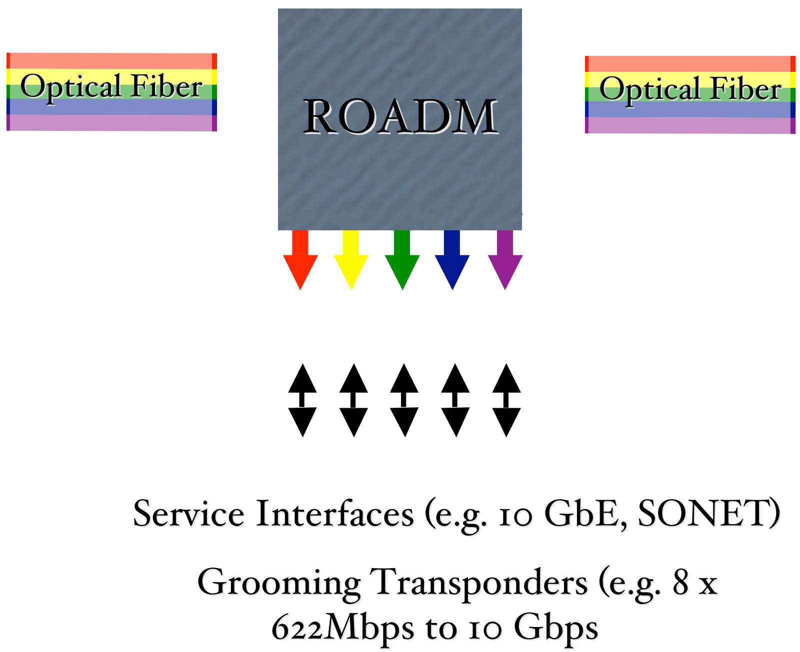
Optical Multiplex Section Layer (OMS)

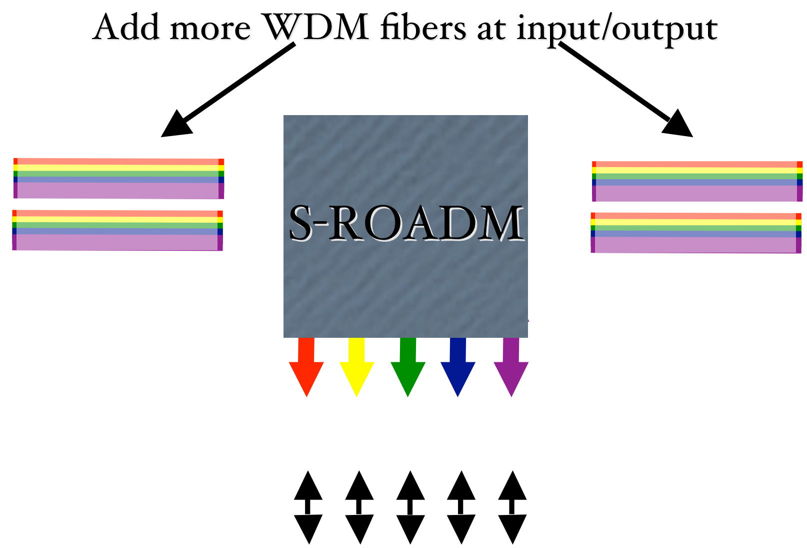
- Provides the functionality required for networking a multi-channel (WDM) optical signal
  - Multiplexing and Demultiplexing of the WDM signal
- Processes multiplex section overhead information, to ensure the integrity of the multiplex section
  - Monitoring of the integrity of the WDM signal as a single entity
  - OAM function of the WDM signal as a single entity
- It is similar to OSI layer 2
- Interface OMS/OCh
  - SOURCE:
    - modulation of *N* optical carriers
    - Wavelength multiplexing
    - Generation and termination of the overhead signals required by this layer
  - SINK
    - Wavelength demultiplexing
    - Detection of each of the *N* optical signals

Optical Transmission and Physical Layer

- Optical Transmission Section layer
  - Monitoring of the integrity of the optical transmission between
  - OAM overhead functions at the transmission level
- Physical media layer
  - It is concerned with the physical details of the transmission (fiber types, length, amplifiers, etc.)
  - The specification of the physical layer are outside the scope of the Recommendation

ROADMs and S-ROADMs (Scalable ROADM)

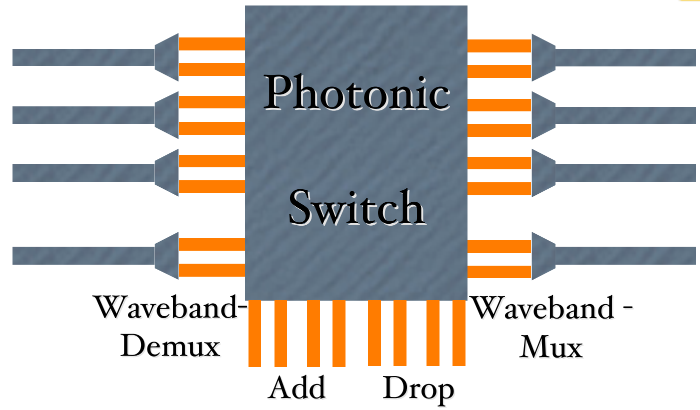




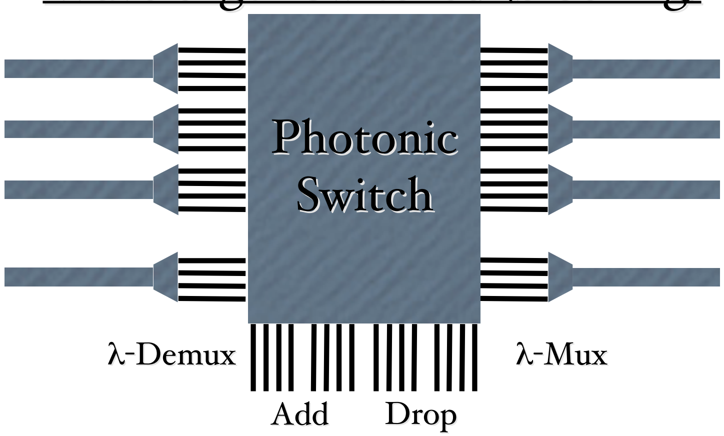
Photonic Crossconnects

Fiber Bundled/Switched

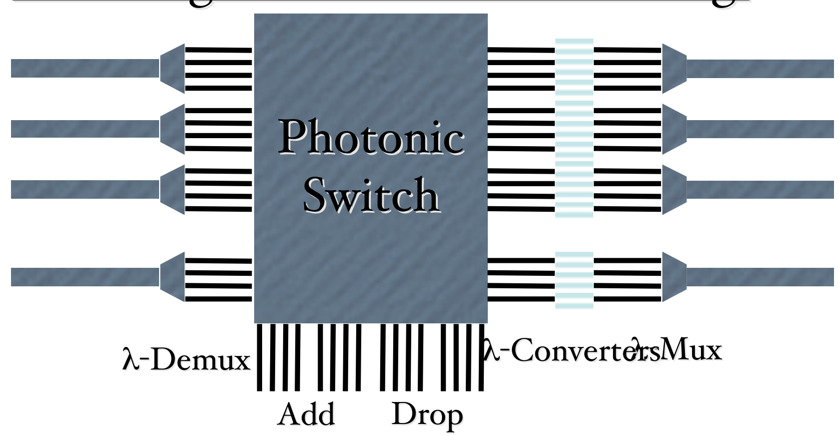
Waveband Bundled/Switched



Wavelength Switched (blocking)



Wavelength Switched (nonblocking)

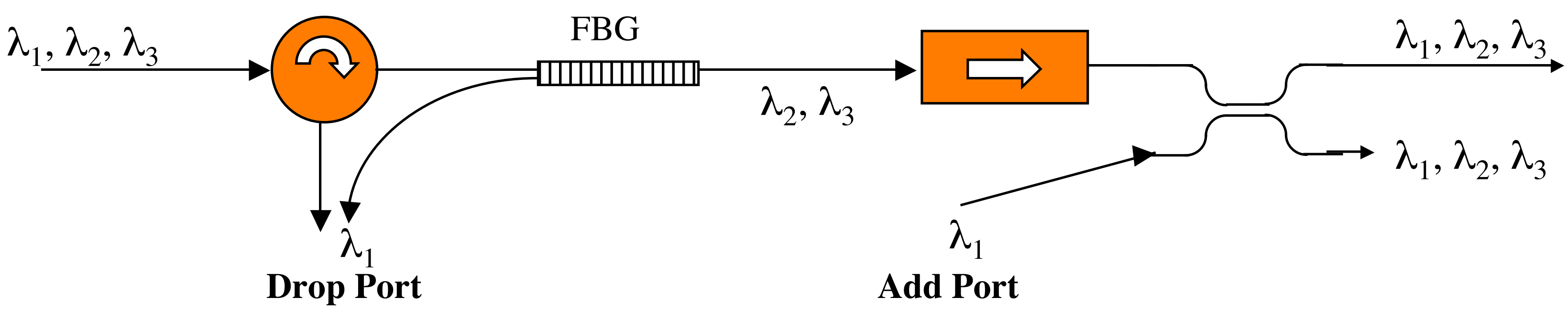


ROADM Technologies

- Arrayed Waveguide Gratings (AWG)
- Tunable Optical Filters (Fiber Bragg gratings, thin film filters)
- Thermo-optic (Glass or silicon)
- Liquid Crystal
- Electro-optic
  - LiNbO3, InGaAsP, GaAs, Liquid Crystal
  - Mach-Zehnder, Fabry-Perot, Michelson Interferometers
- Acousto-optic filters and switches (AOTF)
- Gain (splitter with gain on each arm)
  - Er:SiO2, InGaAsP
- MEMS (MicroElectroMechanical Systems)

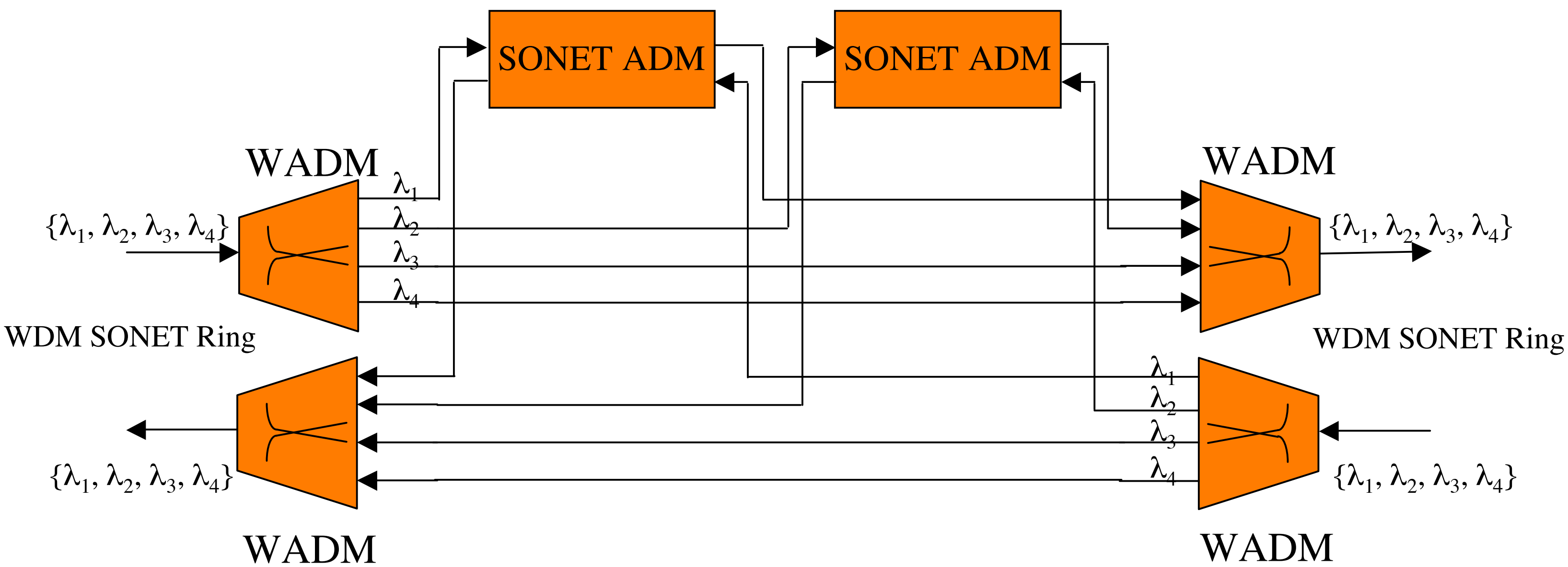
Fixed Single Wavelength Add/Drop

- The simplest architectures is based on nodes equipped with a fixed add-drop on a single wavelength
  - It can be used on a single-fiber ring
- Such an optical devices is totally available nowadays at the commercial level, on any wavelength of the ITU grid
- Most common solutions are based on gratings, together with recirculators, isolators and couplers



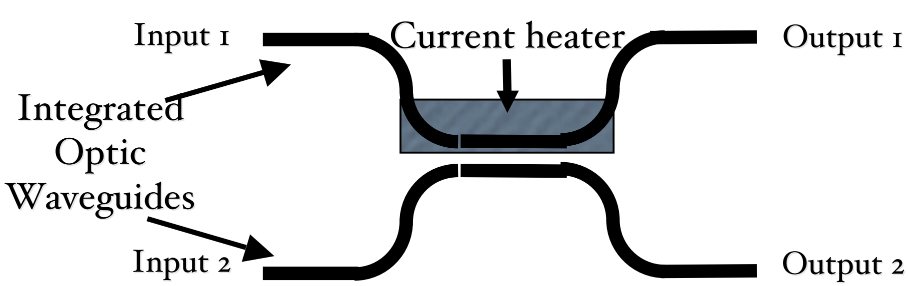
Static Multiwavelength Add/Drop

- This solution reduces the number of SONET ADMs over dropping every wavelength at a SONET ADM
- It allows to add/drop more than one wavelength per node
- It can be used on a bi-directional ring
- It is manually reconfigurable, by changing optical connections on a patch panel



Thermo-Optic Switches

- 2D so small switches are best (<32 ports)
- Power consumption (0.5 W per switch)
- Speed (typically 6-8 ms)
- Loss (1 dB/cm typical)
- Size: 4” wafer for 16x16 switch

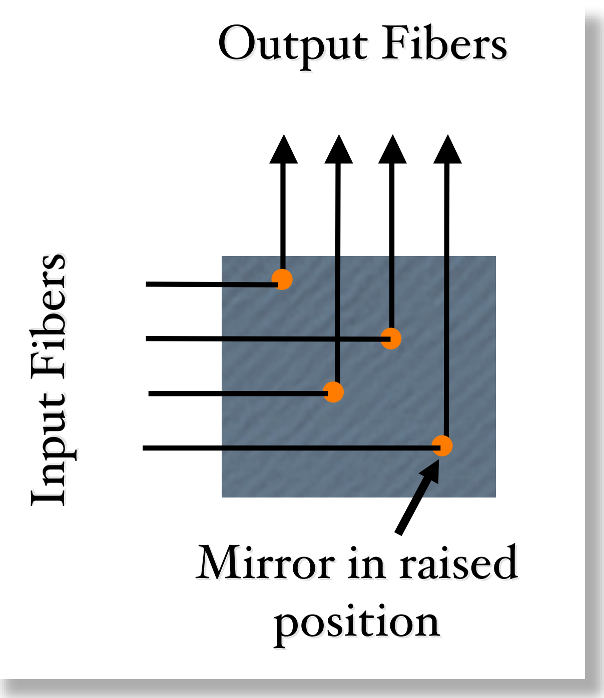


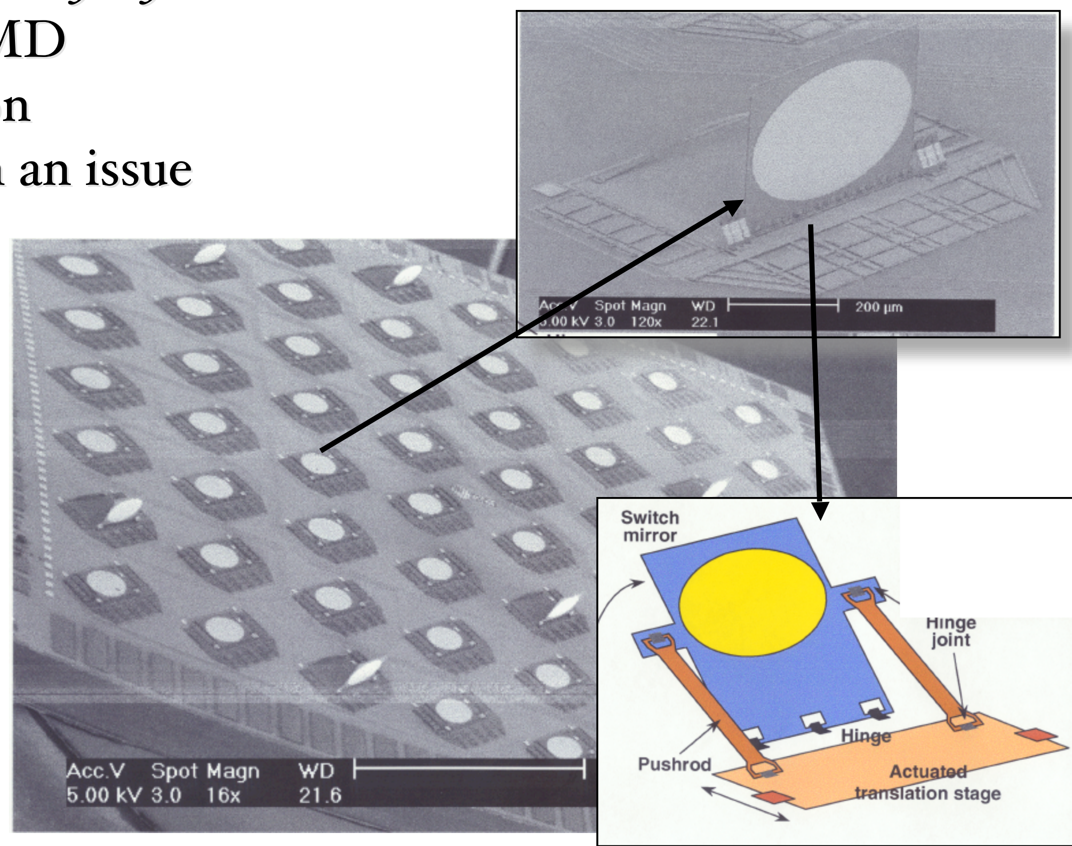
(Mach-Zehnder with thermal phase shift)


NTT 8X8 thermo-optic switch

2D MicroElectroMechanical Systems (MEMS) Mirrors

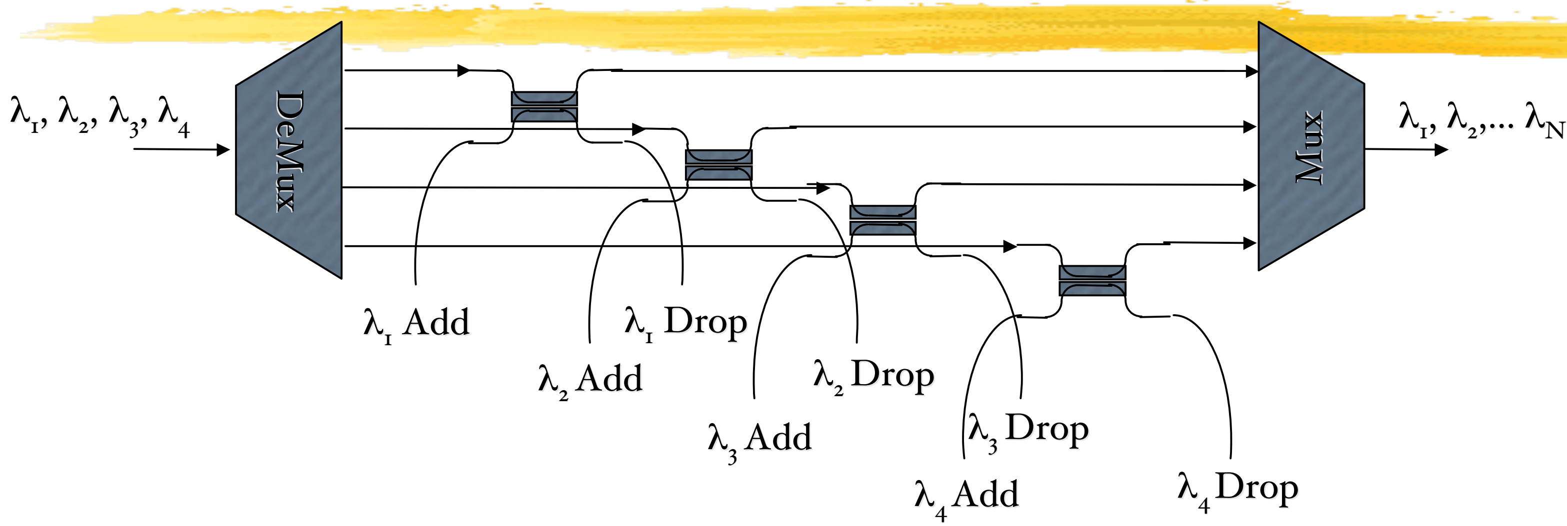
- Low loss for small sizes (< 32x32)
- Low PDL and PMD
- Digital operation
- Sticking due to friction an issue

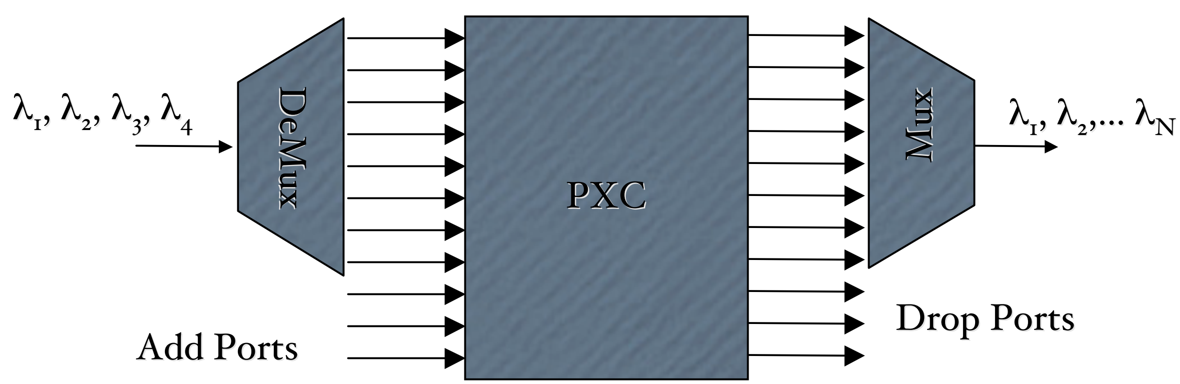




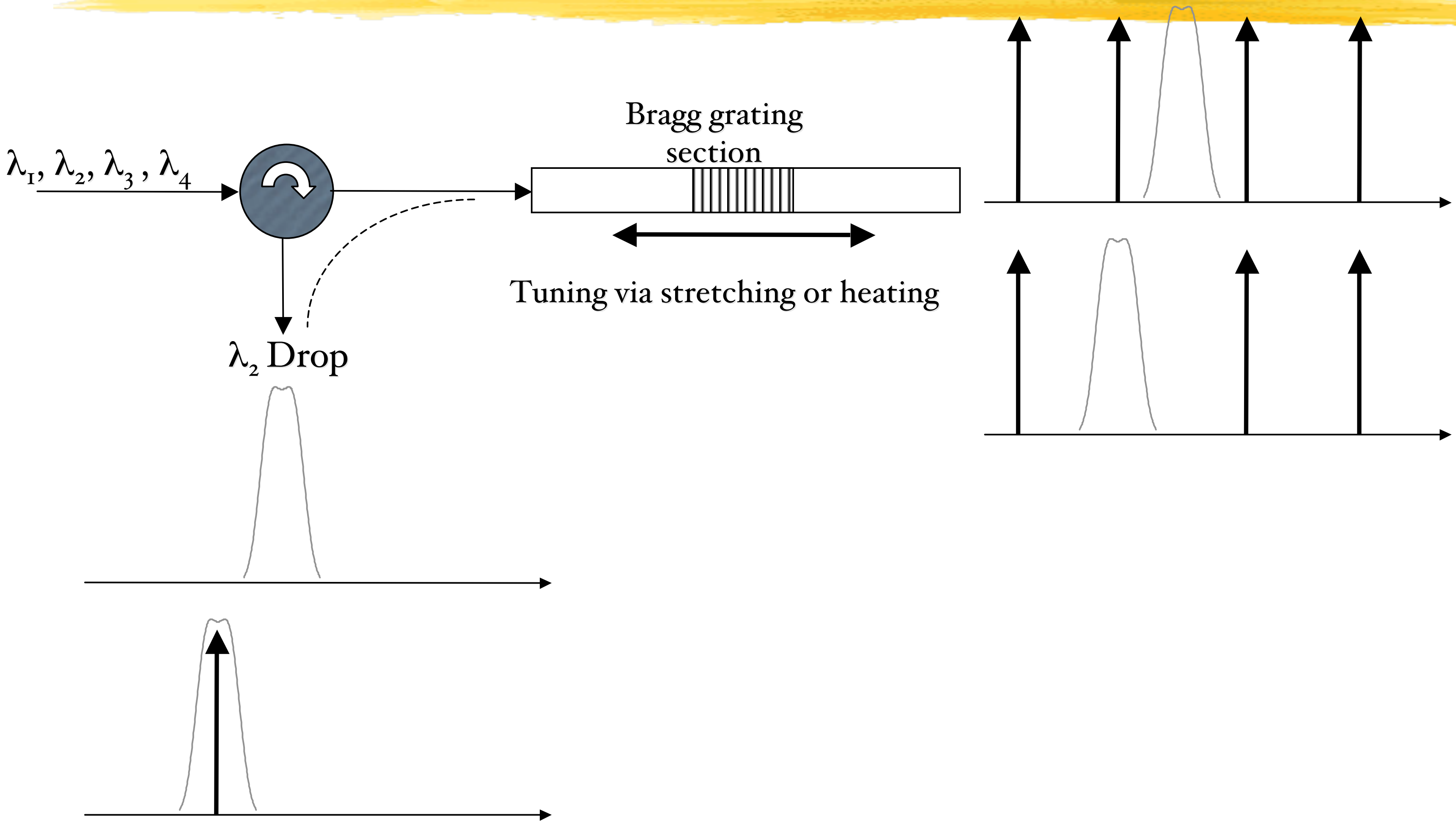
L. Lin, "Free-Space Micromachined Optical-Switching Technologies and Architectures," Topical Meeting on Photonics in Switching, Santa Barbara, CA (1999)

Reconfigurable OADMs (ROADM)



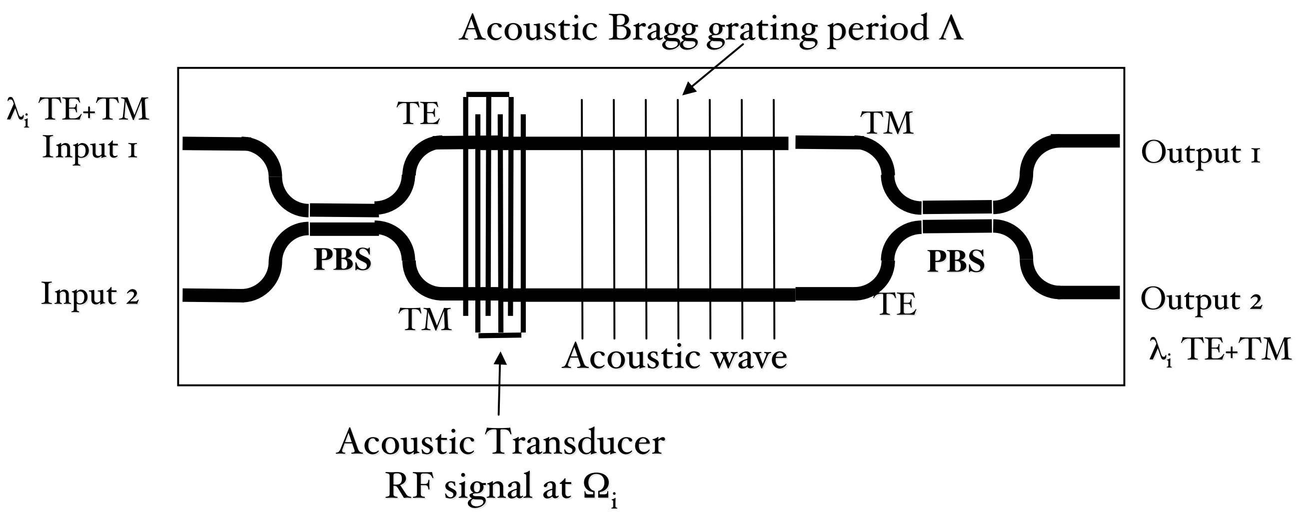


Tunable FBGs for ROADM



Acoustooptic Tunable Filters

- Medium loss (greater than 6 dB)
- High PMD and PDL, polarization diverse architectures necessary
- Multichannel crosstalk issues



TE to TM conversion for λ_i
TM to TE conversion for λ_i

$$\frac{\eta_{TM}}{\lambda} = \frac{\eta_{TE}}{\lambda} \pm \frac{1}{\Lambda}$$

Homework #1, Due April 24th

- Problem 6.1 Ramaswami
- Problem 6.3 Ramaswami
- Problem 6.4 Ramaswami
- Problem 7.1 Ramaswami
- Problem 7.2 Ramaswami
- Problem 7.4 Ramaswami
- Problem 7.5 Ramaswami