Optical DWDM Networks

Raj Jain

Raj Jain is now at
Washington University in Saint Louis
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

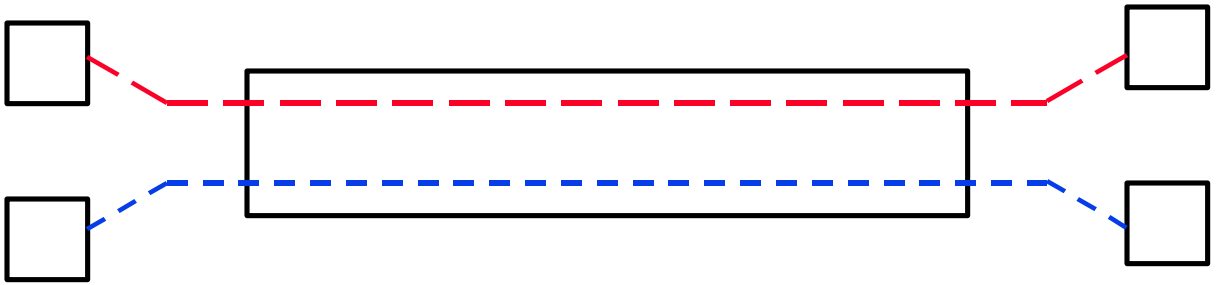
These slides are available at

http://www.cis.ohio-state.edu/~jain/talks/h_5opt.htm

Overview

- Sparse and Dense WDM
- Recent WDM Records
- WDM Applications and Sample Products
- Key Technologies
- Types of Fibers: Limiting factors to single wavelength
- Wavelength router and optical crossconnect
- Upcoming Technologies: Optic wireless, Soliton, Packet Switching, Optical CDMA, ...

Sparse and Dense WDM



- 10Mbps Ethernet (10Base-F) uses 850 nm
- 100 Mbps Ethernet (100Base-FX) + FDDI use 1310 nm
- Some telecommunication lines use 1550 nm
- WDM: 850nm + 1310nm or 1310nm + 1550nm
- Dense ⇒ Closely spaced ≈ 1nm separation

Recent WDM Records

- 1×40 G up to 65 km (Alcatel'98). PMD Limited.
- 32× 5 G to 9300 km (1998)
- 64× 5 G to 7200 km (Lucent'97)
- 100×10 G to 400 km (Lucent'97)
- 16×10 G to 6000 km (1998)
- 132×20 G to 120 km (NEC'96)
- 70×20 G to 600 km (NTT'97)
- 1022 Wavelengths on one fiber (Lucent 99)
- Ref: OFC'9x

WDM Applications

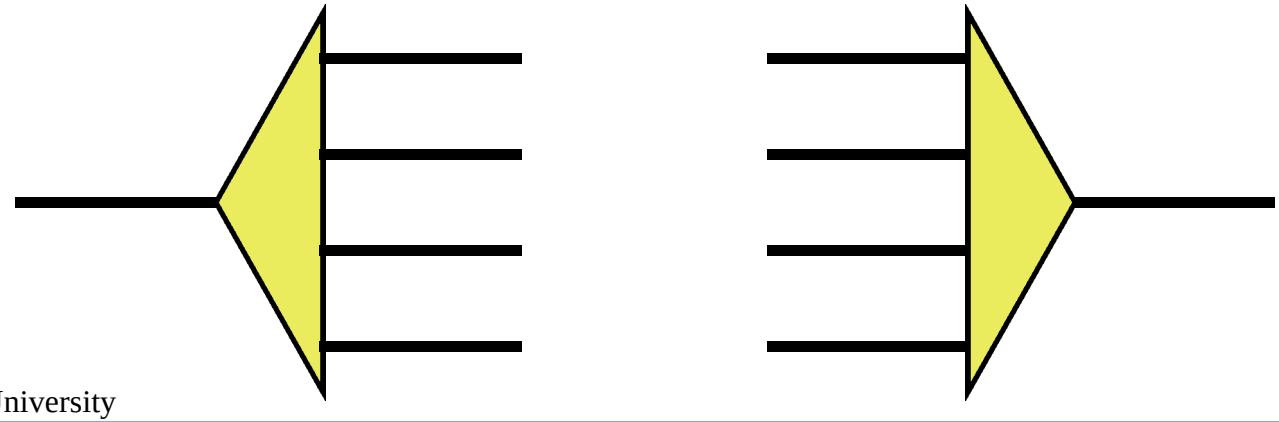
- WANs: Fiber links ⇒ WDM ⇒ DWDM Links
- Undersea Links: Amplifiers ⇒ High maintenance cost ⇒ Can't put too many fibers
- DWDM highly successful in long-haul market.
- Not yet cost-competitive in metro market.
  Bandwidth demand is low and more dynamic.
  Many new lower cost products for metro market.

Sample Products

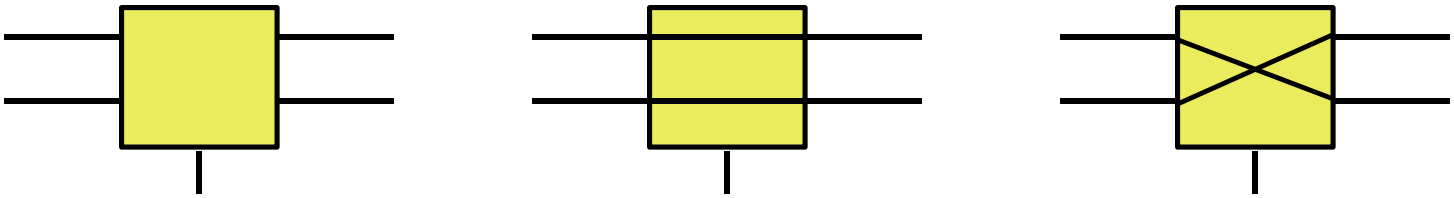
- **Nortel/Cambrian**: Optera Metro: 32 × 2.5G Optera LH: 2560×622Mbps, 1280×1.25Gbps (Gb Ethernet), 640×2.5Gbps, 160×10Gbps
- **Pirelli Optical Systems**: 128×10G TeraMuX
  WaveMux H-DWDM with Soliton
  OMDS 32λ WDM System
- **Monterey Networks**: Wavelength Router™
  256×256 OC-48 scalable to 160 Tbps
  Non-blocking any to any.
  Fully hot swappable w/o fiber swap
  1+1 or 1:N APS. Straight IP over DWDM.

Key Components

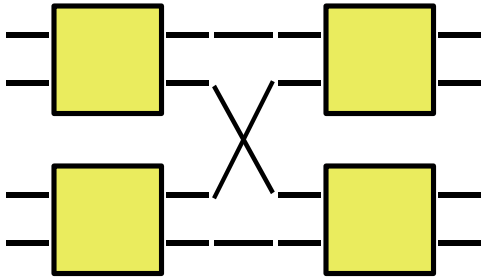
- Tunable Lasers
- Fast tuning receivers
- Frequency converters
- Amplifiers: Erbium Doped Fiber Amplifiers (EDFA)'s
- Splitters, Combiners



Directional Couplers

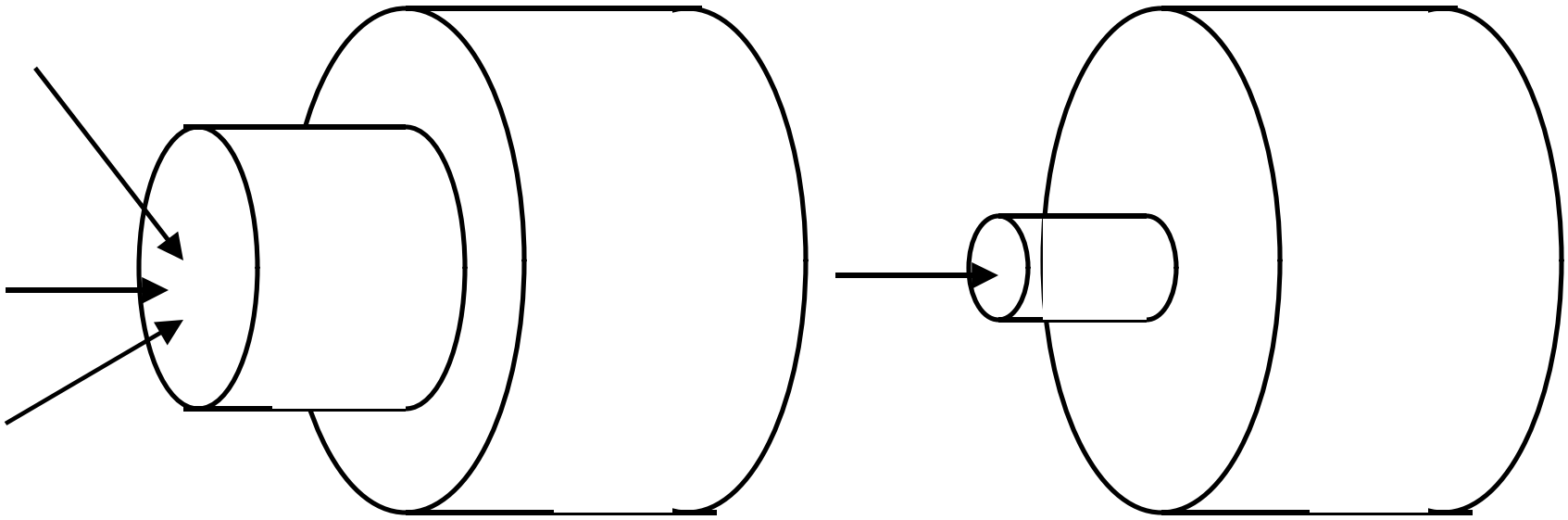


- Larger switches can be built out of 2×2 switches



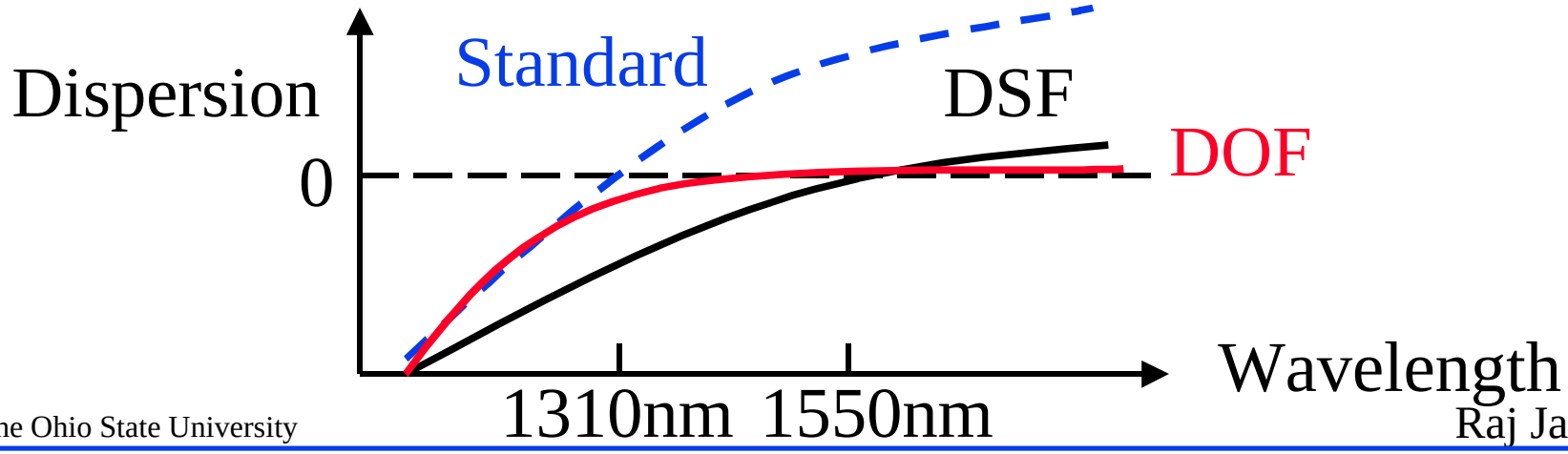
Types of Fibers I

- Multimode Fiber: Core Diameter 50 or 62.5 μm
  Wide core ⇒ Several rays (mode) enter the fiber
  Each mode travels a different distance
- Single Mode Fiber: 10-μm core. Lower dispersion.

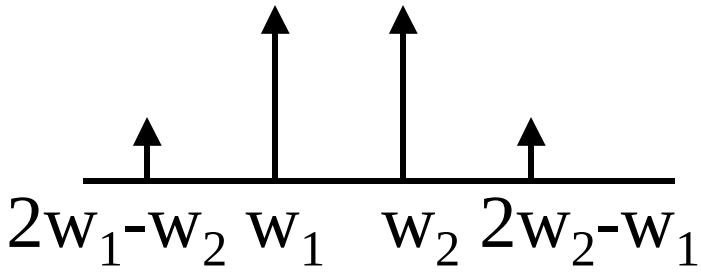


Types of Fibers II

- **Dispersion-Shifted Fiber:** Zero dispersion at 1310nm
  EDFAs/DWDM systems operate at 1550 nm
  Special core profile ⇒ zero dispersion at 1550 nm
- **Dispersion Optimized Fiber:** 3 ps/nm/km 1300-1700nm
  Use 1300 nm now and 1550 in future
  Low dispersion causes four-wave mixing
  ⇒ DSF/DFF not used in DWDM systems

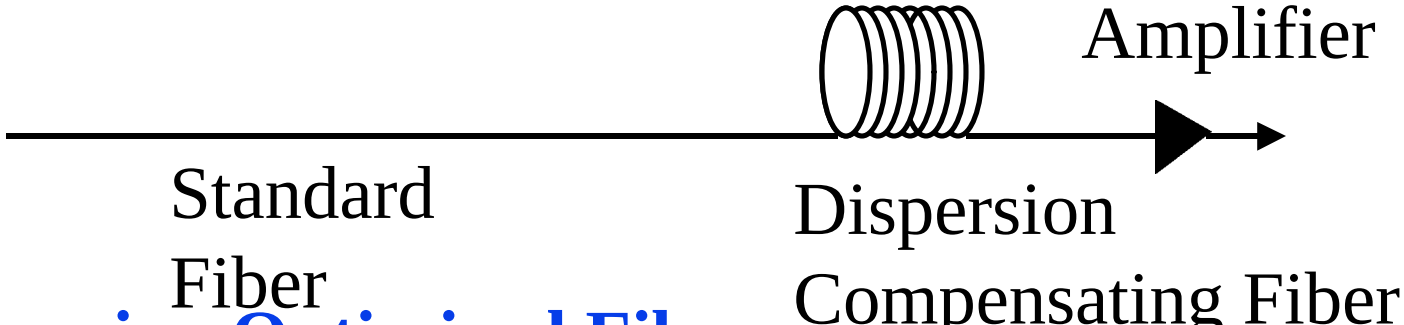


Four-way Mixing (FWM)



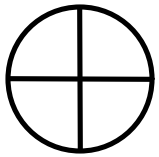
- Caused when multiple wavelengths travel in the same phase for long time
- New signals are generated at the same frequency spacing as original: $w_1, w_2 \Rightarrow 2w_2-w_1, 2w_1-w_2$
- Closer channels $\Rightarrow$ More FWM
- More power $\Rightarrow$ More FWM
- Less dispersion $\Rightarrow$ More time same phase $\Rightarrow$ More FWM

Types of Fibers III



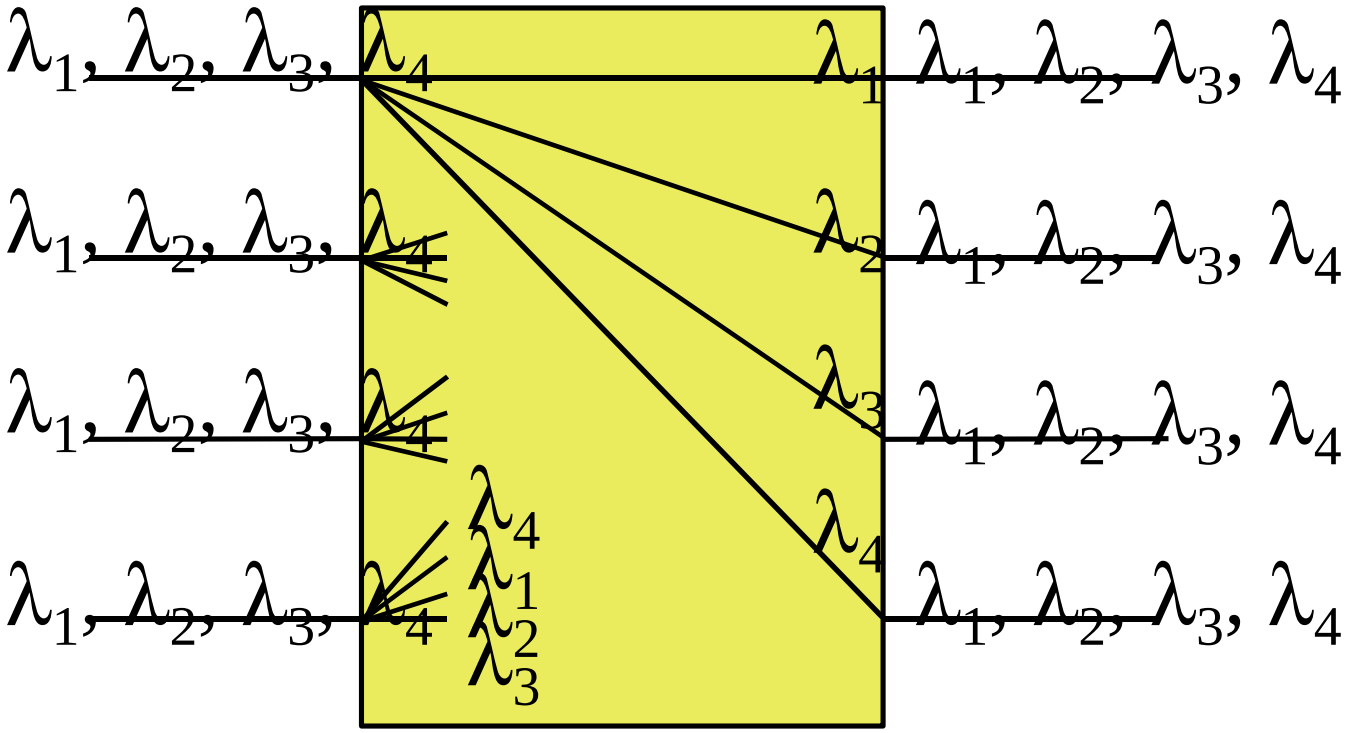
- **Dispersion Optimized Fiber:**
  - Non-zero dispersion shifted fiber (NZ-DSF)
    $\Rightarrow$ 4 ps/nm/km near 1530-1570nm band
  - Avoids four-way mixing
- **Dispersion Compensating Fiber:**
  - Standard fiber has 17 ps/nm/km. DCF -100 ps/nm/km
  - 100 km of standard fiber followed by 17 km of DCF
    $\Rightarrow$ zero dispersion

Polarization Mode Dispersion



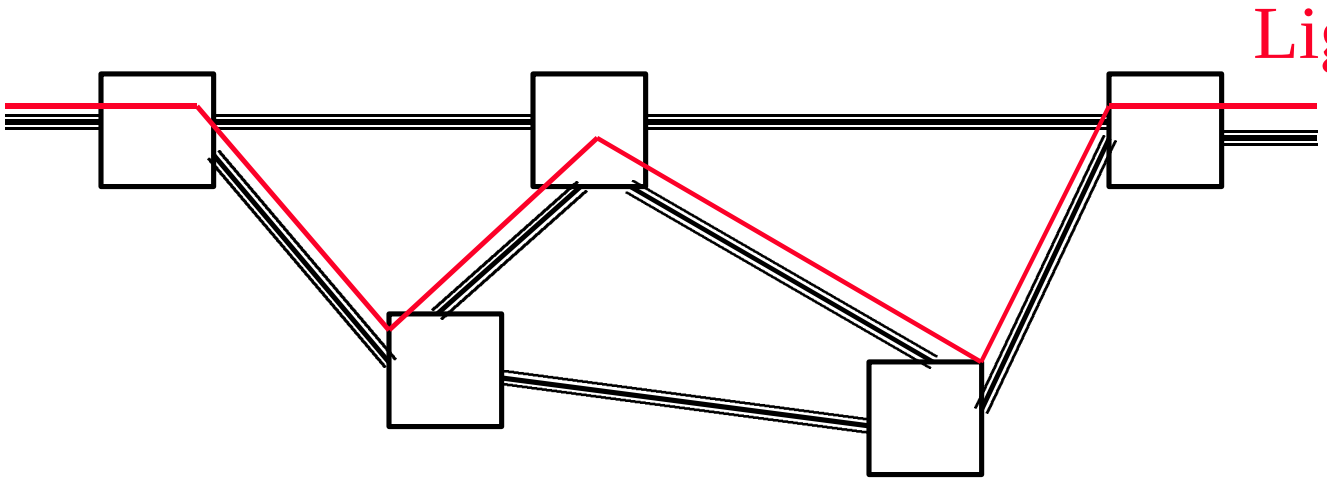
- Each light pulse consists of two orthogonally polarized pulses.
- These polarizations experience different delays through the fiber.
- Polarization Mode Dispersion (PMD) limits distances to square of the bit rate
  $\Rightarrow$ OC-192 to 1/16th of OC-48, OC-768 to 1/256th.
- Need Regenerators to compensate for PMD
  $\Rightarrow$ Expensive
  $\Rightarrow$ Most DWDM systems operate at OC-48

Wavelength Grafting Router



- Wavelength k on port i is route to output port $i+k$ mod M, $k \in [0,M]$
- Passive ⇒ Reliable

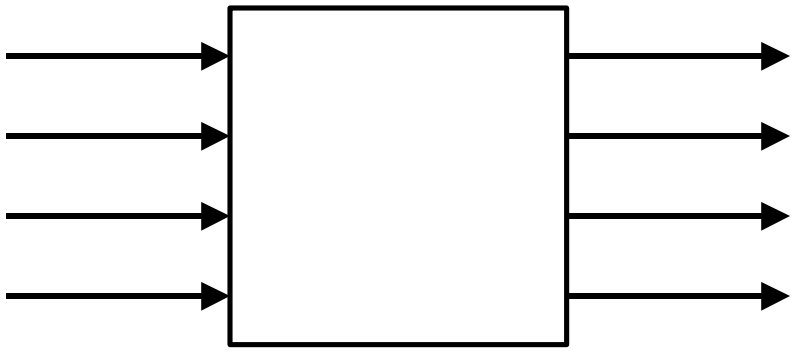
Wavelength Routed Networks



- Light path through a WGR network
- Routing ⇒ Wavelength assignment problem
- Two wavelengths from different fibers should not be mixed ⇒ Need wavelength conversion

Optical (Wavelength) Cross Connect

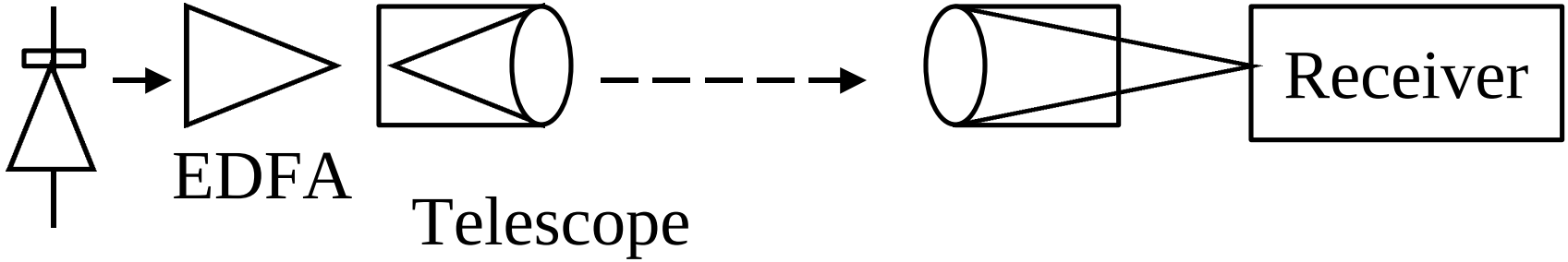
- Slow switching nodes.
- Configuration changed by management.
- May allow any wavelength on any fiber to go to any fiber.
- Programmable.
- Control channel could be electronic or optical.



Upcoming Technologies

- Optic Wireless
- Optical Time Domain Multiplexing (OTDM)
- Soliton
- Optical Packet Switching

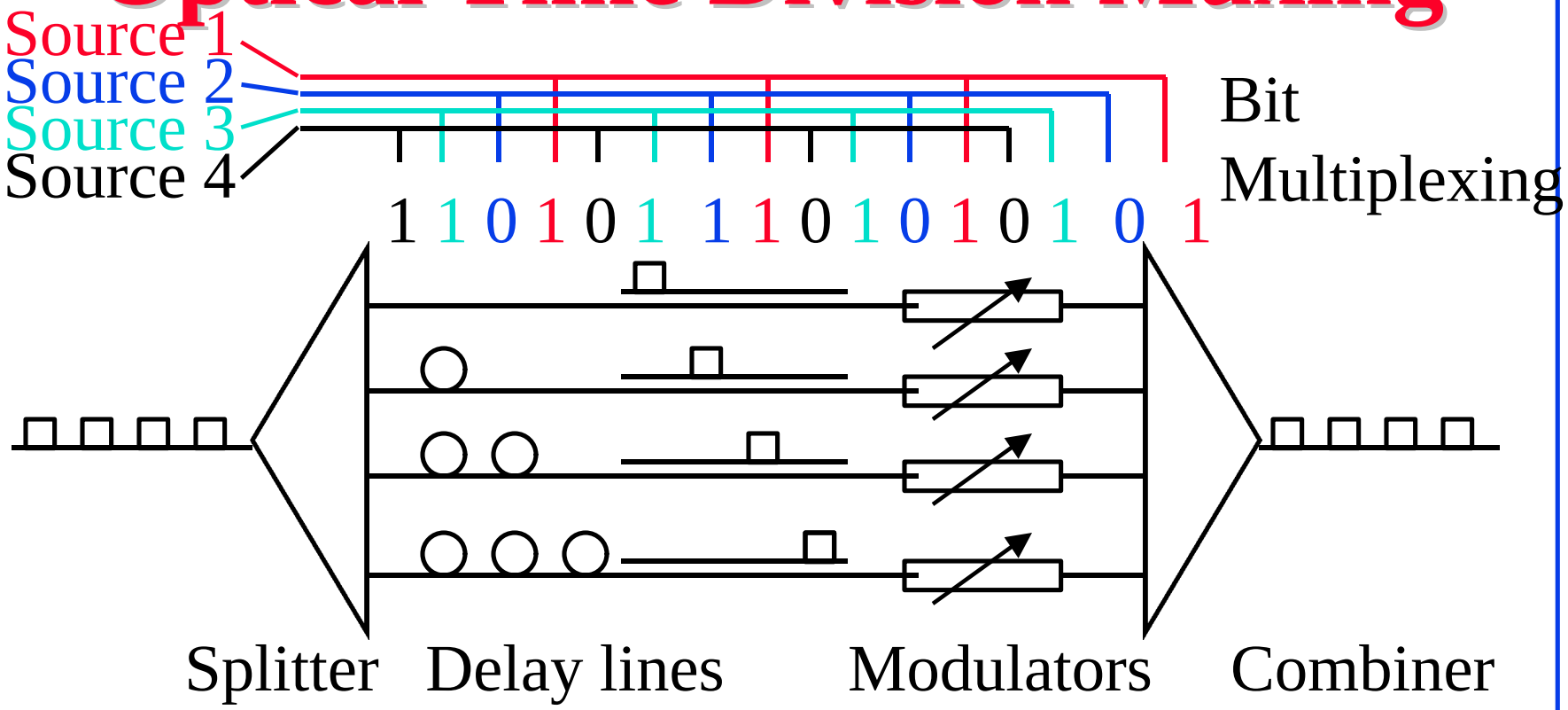
Optical Wireless



Laser Source

- Uses WDM in open air
- Sample Product:
  Lucent WaveStar OpticAir: 4×2.5Gbps to 5 km
  Available March'00.

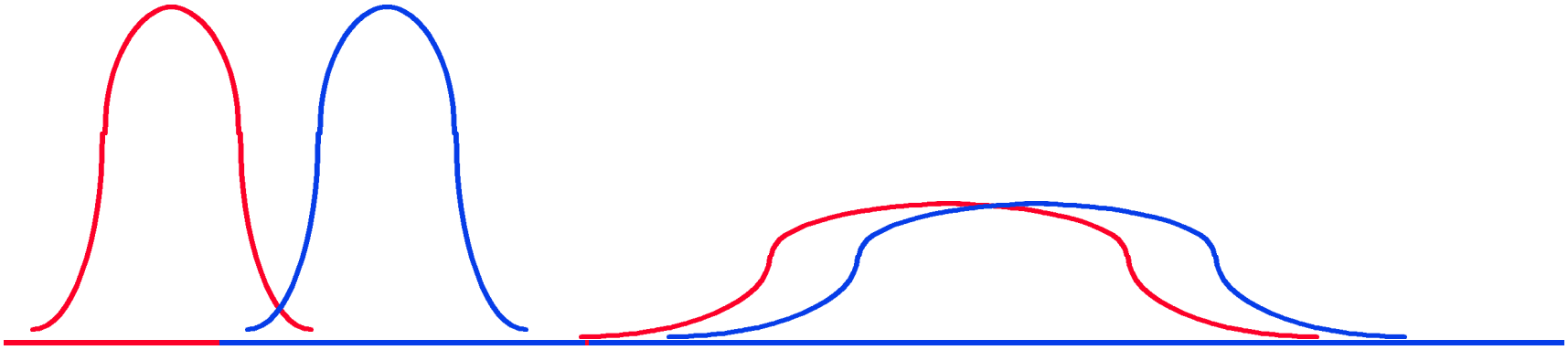
Optical Time Division Muxing



- A laser produces short pulses.
  Pulse stream divided in to 4 substreams
  Each substream modulated by different source.
  Combined.

Solitons

- Light velocity is a function of amplitude
  $\Rightarrow$ Index of dispersion is non-linear:
  - $n=n_0 + n_2E^2$, Where, E=field strength
  - No dispersion if the pulse is sech(t)
- Need high amplitude pulses (100 mW) and high non-linearity

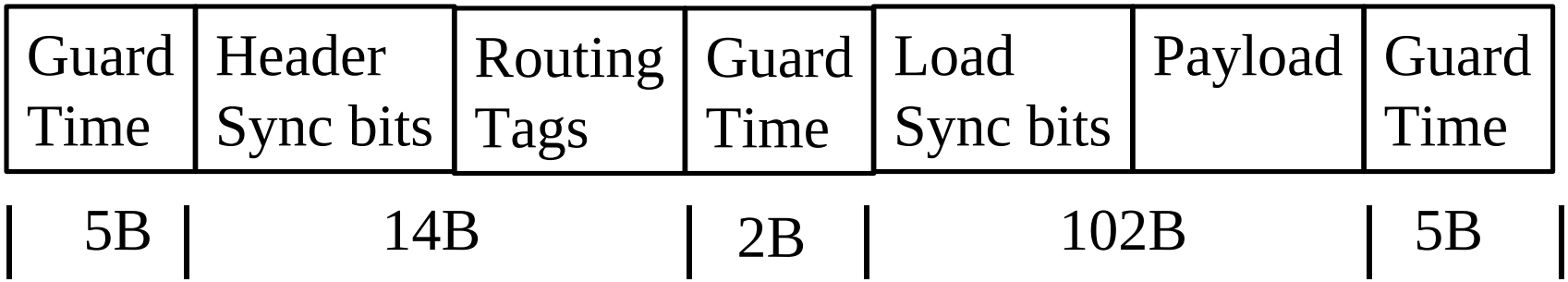


Solitons (Cont)

- Solitons have no distortion but must be amplified periodically. Erbium doped fiber amplifiers are used
- Can be very short duration 10 ps ⇒ High bit rate 20 Gb/s×8λ over 10,000 km using solitons
- Sample Product: Pirelli Optical Systems
- Soliton (nonlinear) systems are superior for ultra long distance and 10+ Gbps. Linear systems are superior for short-medium-long distances and lower rates.
- Problem: Closely packed solitons can attract or repulse ⇒ Errors ⇒ Bit rate $\leq$ 10 × soliton width
- 10 ps pulses ⇒ 100 ps spacing ⇒ 10 Gbps

Optical Packet Switching

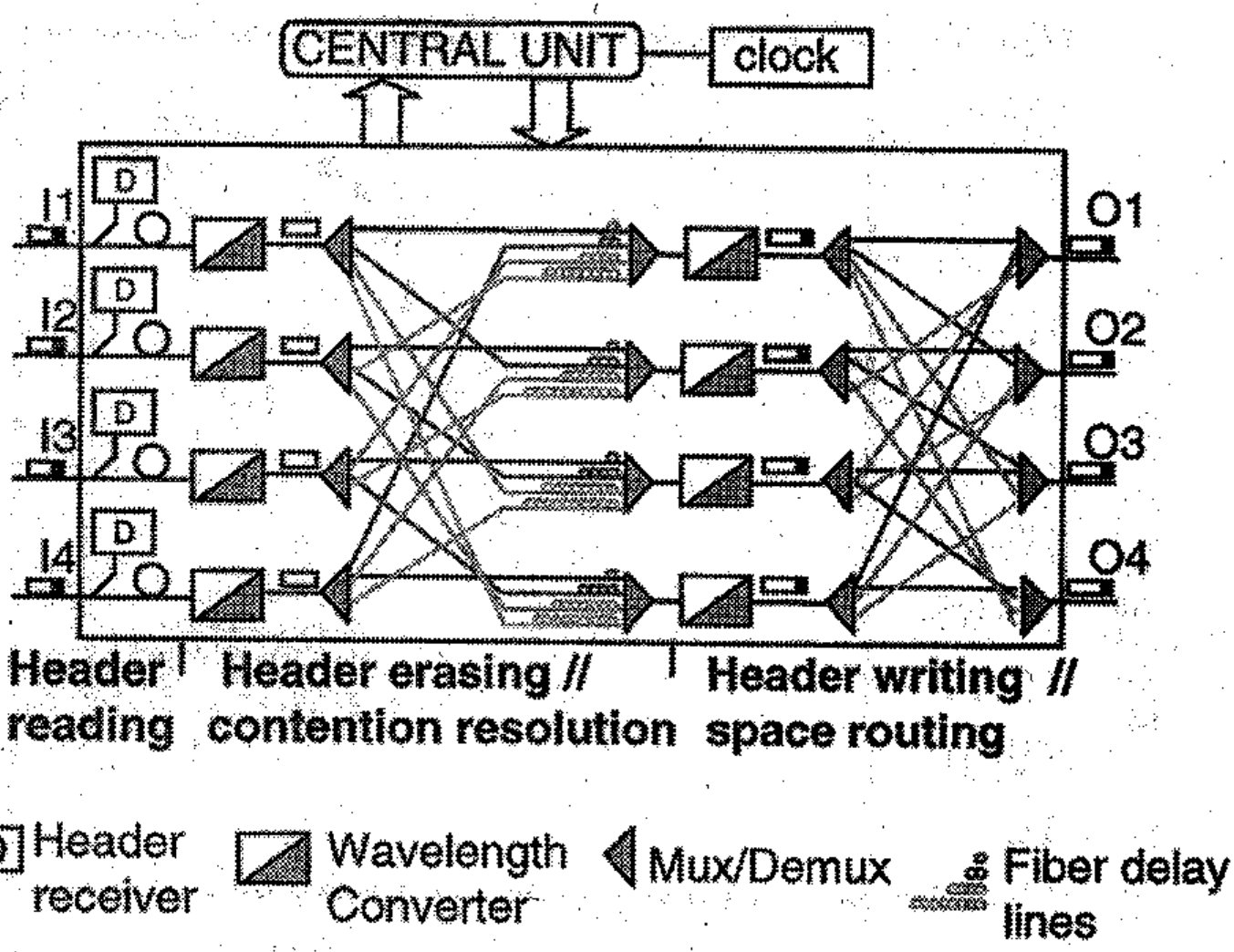
- Example: Keys to Optical Packet Switching (KEOPS) Project in Europe
- 1.646μs slots (1500B at 10G = 1.2 ms)
- 14B 622 Mb/s header processed electronically
- Fixed-duration payload at variable rate ⇒ Transparant
- 64 packet optical buffering feasible now
  ⇒ 10^{-10} loss up to 80% load



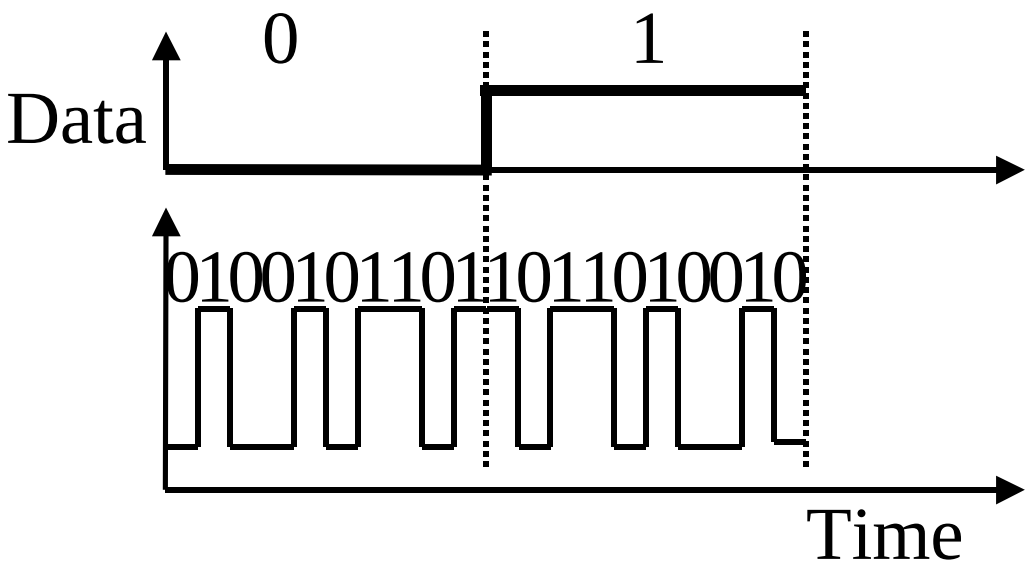
KEOPS (Cont)

- High dispersion fiber for fine synchronization
- Delay lines for coarse synchronization
- Multicast using optical components $1 \rightarrow N$ λ
- Input Interface: Header detection, payload alignment, header erasure
- Switching Matrix: Payload routing using Wavelength router, contention resolution using buffering (delay lines)
- Output Interface: Wavelength reallocation, header re-writing

Architecture of KEOPS Switch



Optical CDMA



- Allows Time, Frequency, and Space Overlap
- Spreading factor = Code bits/data bit, 10-100 commercial (Min 10 by FCC), 10,000 for military
- Signal bandwidth >10 × data bandwidth
- Correlation between codes ⇒ Interference ⇒Orthogonal

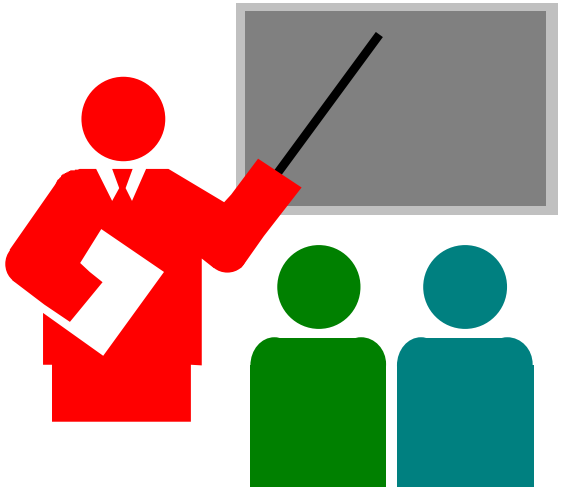
Optical CDMA (Cont)

- Coherent phase-shifted: More complex, higher SNR
- Incoherent intensity modulated
- 4 Codes/$\lambda \Rightarrow$ Hybrid OCDMA/WDM allows
  150×10 Gb/s using 38 wavelengths
  at 100 GHz spacing. 25 GHz with WDM.
- Orthogonal codes on each link
  $\Rightarrow$ Need code conversion
- Currently code conversion done electronically.
  Optical code conversion possible in future
- Broad WDM (1300nm-1600nm) possible in future

Other Research Topics

- Dark Solitons: A Gap in a high-powered beam
- Light Guiding Light: A high-powered beam in a dispersive substance alters its refrection index and forms a waveguide. Other light waves will follow this waveguide.
- ZBLAN Fiber: Zirconium, barium, lanthanum, aluminium, and sodium (Na) fiber. 10^{-2} or 10^{-3} dB/km attenuation. Cross oceans without amplification. Need 2.55 micron wavelength $\Rightarrow$ Larger core.

Summary



- DWDM allows 32- to 128- channels per fiber
- Several types of fibers with different dispersion characteristics
- Wavelength routers/switches ⇒ all-optical networks
- Solitons allow high-datarate over very long distances
- Optical Packet switching is around the corner.

References:

- See references in http://www.cis.ohio-state.edu/~jain/refs/opt_refs.htm
- Recommended books on optical networking, http://www.cis.ohio-state.edu/~jain/refs/opt_book.htm
- Optical networking and DWDM, http://www.cis.ohio-state.edu/~jain/cis788-99/dwdm/index.html
- IP over DWDM, http://www.cis.ohio-state.edu/~jain/cis788-99/ip_dwdm/index.html
- Newsgroup: sci.optics.fiber

Standards Organization

- ITU:
  - **G.681** Functional characteristics of interoffice and long-haul line systems using optical amplifiers including optical multiplexing
  - **G.692** Optical Interfaces for multichannel systems with optical amplifiers (Oct 98): 50 and 100 GHz spacing centered at 193.1 THz (1553.5 nm)
  - **G.872** Architecture for Optical Transport Networks, 1999
  - Several others in preparation

Standards (Cont)

- ANSI T1X1.5: http://www.t1.org/t1x1/_x1-grid.htm
- IETF: MPLS over DWDM
- Optical Interoperability Forum (OIF): www.oiforum.com
  - Started April 1998 by CISCO, Ciena, ...Now over 128 members
  - Working groups on Architecture, Physical and Link Layer, OAM&P
  - Signaling protocols for rapid provisioning and restoration

Products

- **Ciena** MultiWave Family: 16, 40, 96-channel systems with SONET/ATM/IP to DWDM
  - CoreDirector: 256× OC-48 or 64× OC192 (640G total) Switch, Optical signaling and routing protocol
  - EdgeDirector: ATM VP ring with 50ms APS, DS1 to OC3, 10-100Base-T interfaces, RIP and OSPF
  - CoreStream: 2.5G or 10G (to 2 Tbps total) DWDM Long Haul transport
  - Metro: 24×2.5G duplex ADM nodes on a 2 fiber ring

Products (Cont)

- Sentry: 40×2.5G long haul 800 km
- Optical Line Amplifier: EDFA, 1540-1560nm
- Sentry ADM: OC-48 ADM at any amplifier site
- Firefly: 24×2.5G Short haul, point-to-point, 1310nm
- WaveWatcher SNMP & TMN Fault Management System
- WaveWatcher SNMP & TMN Element Management System

Products (Cont)

- **Sycamore**:
  - SN 6000 Intelligent Optical Transport Node
  - OC-192 DWDM
  - Allows OC-48 IP/ATM/SONET inputs
  - Private line applications
  - 28 OC-48 inputs per rack
  - SILVX Optical Network Management System
- **Corvis**: CorWave supports OC-192 SONET/ATM/IP streams to 3200 km

Products (Cont)

- **Optical Networks Inc**: ONLINE 9000 Metro Nodes, OPTX Metro Network Operating System (design, configuration, operation), OLMP Optical link management
- **NEC**: Submarine WDM System 16×10G up to 300 km expandable to 32×10G
- **Monterey Networks**:
  - Teraseed: Single chip. Clustered to create switch matrix.
  - Wavelength Routing Protocol™ (WaRP™)

Products (Cont)

- **Tellium**:
  - Aurora 32: Carrier Class Optical Switch
  - Aurora 512: Bidirectional carrier class 1.2 Tbps nonblocking optical switch
- **Alidian Networks**:
  - Optical Service Networks (OSN): Metro and Access Rings with
  - ATM/FR/TDM/SONET Services with QoS

Products (Cont)

- **CISCO**:
  - 12000 Gigabit Switch Router with OC-48c line card
  - Dynamic Packet Transport (DPT)
    - Uses SONET framing
    - Dual Ring
    - Both rings used simultaneously
  - Spatial Reuse Protocol (SRP)
  - SRP fairness algorithm

Products (Cont)

- Intelligent Protection Switching (IPS): Handles events at layer 1, 2, and 3 (APS handles only layer 1). Can provide reduced capacity during failures.

- **Canoga Perkins Corp**: Converter MMF/SMF 8M-1.25G to 1310/1550nm
- **Integral Access**: PurePacket Node DSL Access Mux (DSLAM), Voice, Data to DWDM/MPLS

Products (Cont)

- **Lucent WaveStar Family**:
  - OLS 400G/80G/40G/10G/2.5G: 80×OC-48 or 40×OC-192 (point-to-point)
  - Bandwidth Manager: 1152 STS-1/384 STM-1 Switch Fabric with electrical and optical interfaces
- **Lucent OpticGate Family**: Allows connecting ATM Switches and IP routers to 400G.
  - MetroPoint: 16×2.5G to 60 km
  - AllMetro: 40×2.5G with add/drop
  - OpticAir: 4×2.5Gbps to 5 km
  - FT-2000: STS-1 to OC-48 SONET

Products (Cont)

- **Lucent OptiStar Family**: OC48/OC12/1G: non-DWDM Network adapters for NT/2000/Linux
- **OSICOM**: 32×2.5G Gigamux (point-to-point)
- More Vendors: ADC, Bosch, DSC, Ericsson, Fujitsu, Hitachi, NEC, Scientific-Atlanta, and Tellabs

Acronyms

- ADM Add-Drop Multiplexer
- PANDA Polarization maintaining AND Absorption reducing
- ANSI American National Standards Institute
- APS Automatic Protection Switching
- ATM Asynchronous Transfer Mode
- CDMA Code Division Multiple Access
- DARPA Defense Advanced Research Project Agency
- DCF Dispersion Compensating Fiber
- DPT Dynamic Packet Transport
- DSF Dispersion Shifted Fiber

- DFF Dispersion Flattened Fiber
- DSL Digital Subscriber Lines
- DWDM Digital Wavelength Division Multiplexing
- EDFAs Erbium-Doped Fiber Amplifiers
- FCC Federal Communications Commission
- FWM Four-Wave Mixing
- GHz Giga Hertz
- IEEE Institution of Electrical and Electronic Engineers
- IETF Internet Engineering Taskforce
- IPS Intelligent Protection Switching

- ITU International Telecommunications Union
- KEOPS Keys to Optical Packet Switching
- LAN Local Area Network
- LED Light Emitting Diode
- MMF Multimode Fiber
- NRZ Non-return to zero
- NTONC National Transparent Optical Network Consortium
- OAM Operation Administration and Maintenance
- OC Optical Carrier
- OCh Optical Channel Layer

- OFC Optical Fiber Conference
- OIF Optical Interoperability Forum
- OMS Optical Multiplex Section
- OPP Optical Packet Path
- SPP Secondary Packet Paths
- OSC Optical Supervisory Channel
- OSN Optical Service Networks
- OSPF Open Shortest Path First
- OTDM Optical Time Domain Multiplexing
- OTS Optical Tranmission Section
- OXC Opical cross connect
- PMD Polarization Mode Dispersion

- PMF Polarization Maintening Fiber
- PMMA PolyMethylMethyelAcrylate
- RI Refrective Index
- RIP Routing Information Protocol
- SNMP Simple Network Management Protocol
- SNR Signal to Noise Ratio
- SONET Synchronous Optical Network
- SRP Spatial Reuse Protoco
- TDM Time Division Multiplexing
- WAN Wide Area Network
- WC Wavelength converter

- WDM Wavelength Division Multiplexing
- WGR Wavelength Grafting Router
- WIXC Wavelength Interchanging Crossconnect
- WSXC Wavelength Selective Crossconnect
- ZBLAN Zirconium, barium, lanthanum, aluminium, and sodium