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HUT Communications Laboratory

S-72.3340 Optical Networks Course

Lecture 11: Future Directions in Optical Networking

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Lecture Outline

- Introduction
- Past and present predictions
- Non-optical technologies
- Optical switching evolution
- Alternative optical multiplexing schemes
- Novel optical device technologies
- Conclusions

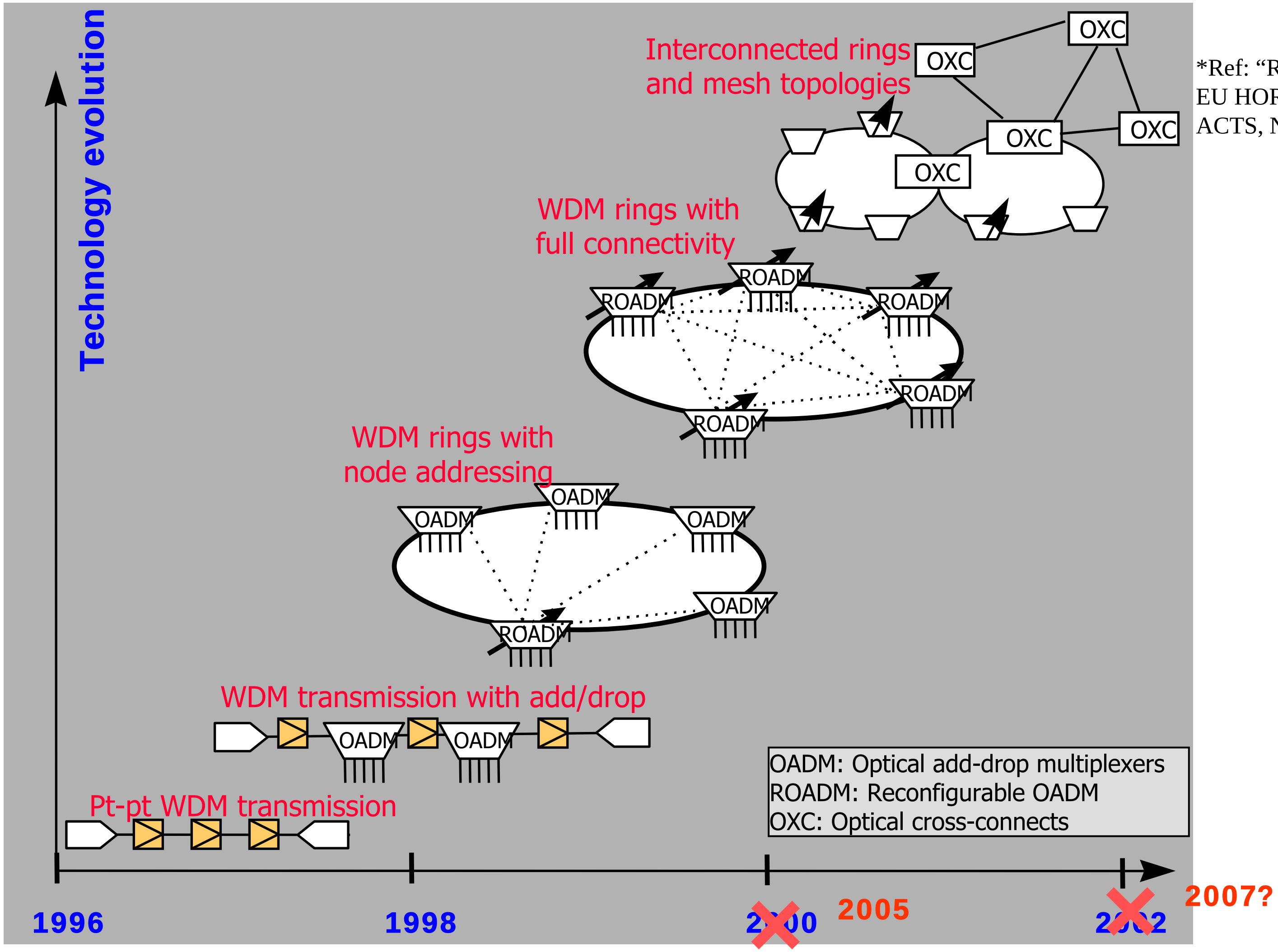
1. Introduction

- The field of optical networking has had some up and downs
  - Boom time characterized by bold predictions and huge injection of funds for R&D
  - Followed by downturn, pessimism and reduced funding
  - Current gradual upturn, more realistic predictions and targets
  - Prolonged recovery will inevitably bring back the bold predictions
- This lecture highlights some of optical technological activities in those recent boom-bust cycles

2. Past and Present Predictions

- Some predictions on optical networking where made in the 1990s during the telecomm/dot-com boom
  - Some were accurate, albeit delayed in realization
  - Some were a too optimistic
- Example predictions from the European Union project HORIZON (Horizontal Action on Optical Networks)
  - Summarized in a report titled "Roadmap towards the Optical Communication Age: A European view by the HORIZON project and the ACTS Photonic Domain" November 1999.

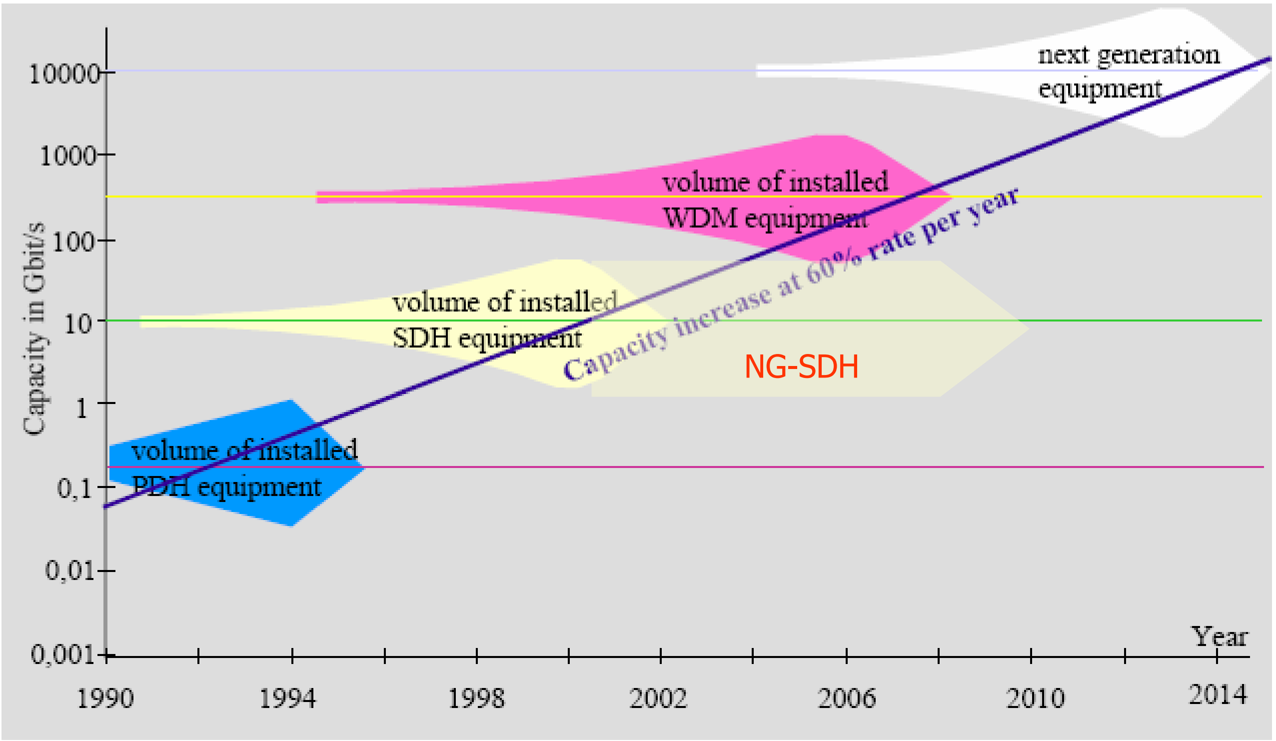
2. Past and Present Predictions



*Ref: "Roadmap towards…," EU HORIZON project and ACTS, Nov. 1999.

2. Past and Present Predictions

- WDM-based networks were expected to be dominant by now
- Timetable distorted by the emergence of next-generation SDH solutions and post-bubble reduced investment

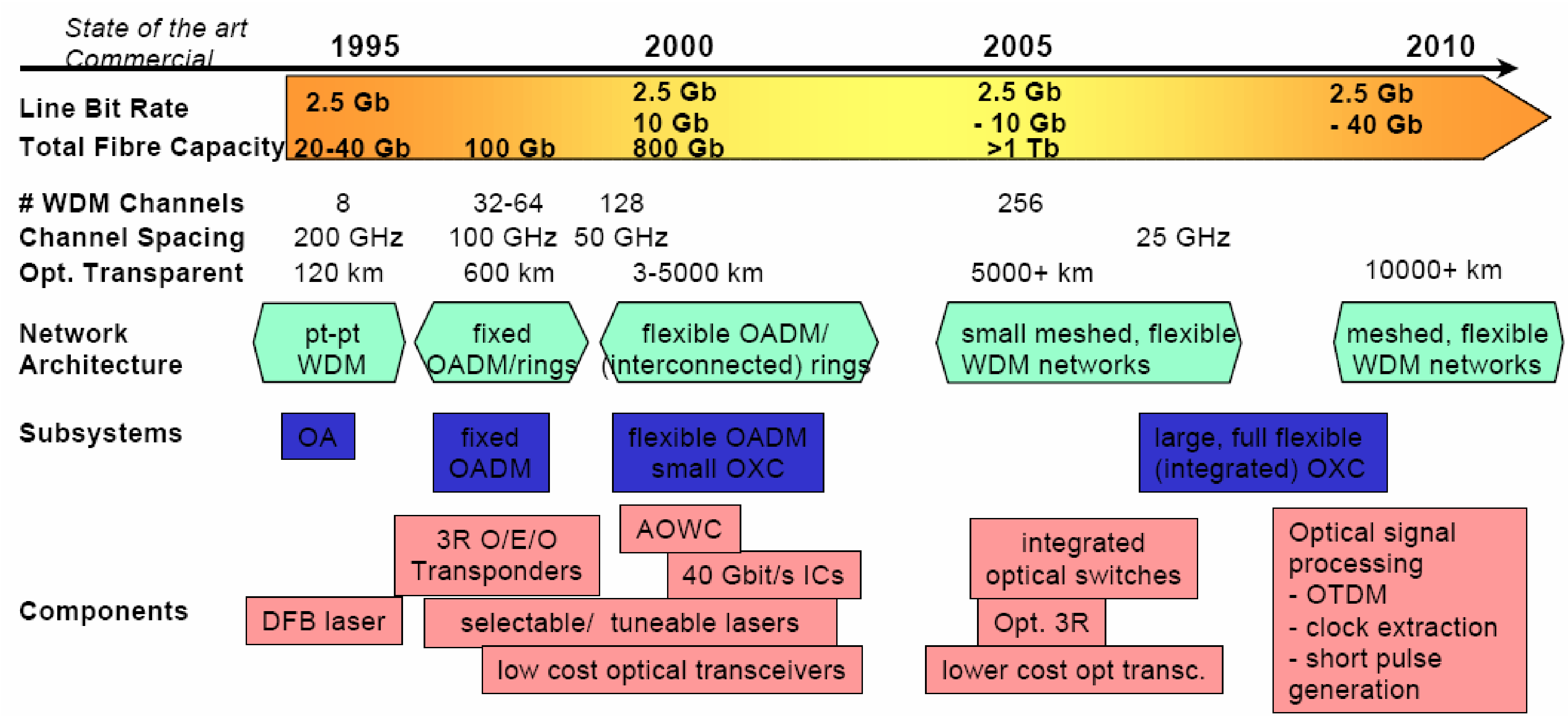


Evolution of the introduction of transport equipment against capcity increase

*Ref: "Roadmap towards…," EU HORIZON project and ACTS, Nov. 1999.

2. Past and Present Predictions

- Optical 3R, optical signal processing yet to mature

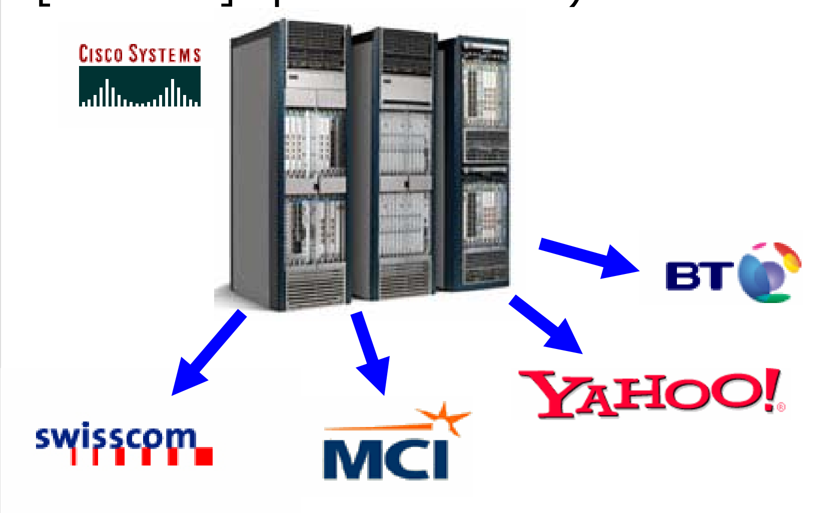


*Ref: "Roadmap towards…," EU HORIZON project and ACTS, Nov. 1999.

2. Past and Present Predictions

- Cautious but gradual migration from 10 to 40 Gb/s

Cisco's CRS1- routers (with 40 Gb/s [STM-256] optical interfaces)



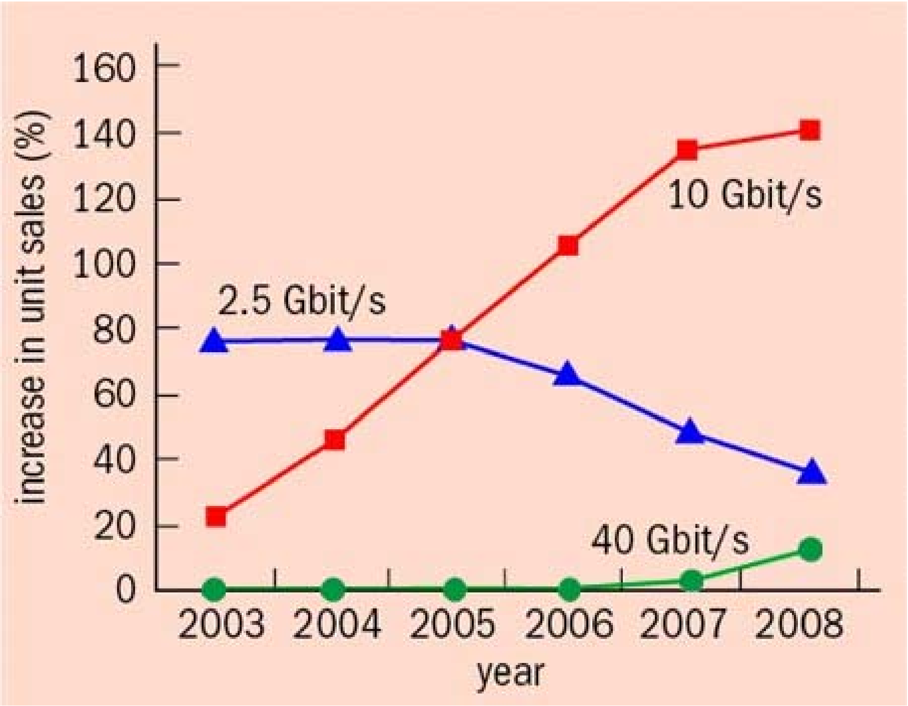


Figure: Unit sales of long-haul transceivers, shown as a percentage of the total number of transceiver sales in 2003. The 40 Gbit/s values quoted include short-reach transponders. Source: *Strategies Unlimited/FiberSystems Europe*.

2. Past and Present Predictions

- Evolutions of the Ethernet standard

Ethernet Line Rate	**10 Mb/s**	**100 Mb/s**	**1 GbE**	**10 GbE**	**100 GbE**
Year Launched	**1983**	**1994**	**1996**	**2002**	**Standard being developed**

- 2.5 Gb/s ⇒ Gb/s 10 ⇒ Gb/s ⇒ 40 Gb/s ⇒ 160 Gb/s
  - Activities in 160 Gb/s development have actually started!

UCSB: 160 Gb/s ADM, clock recovery.

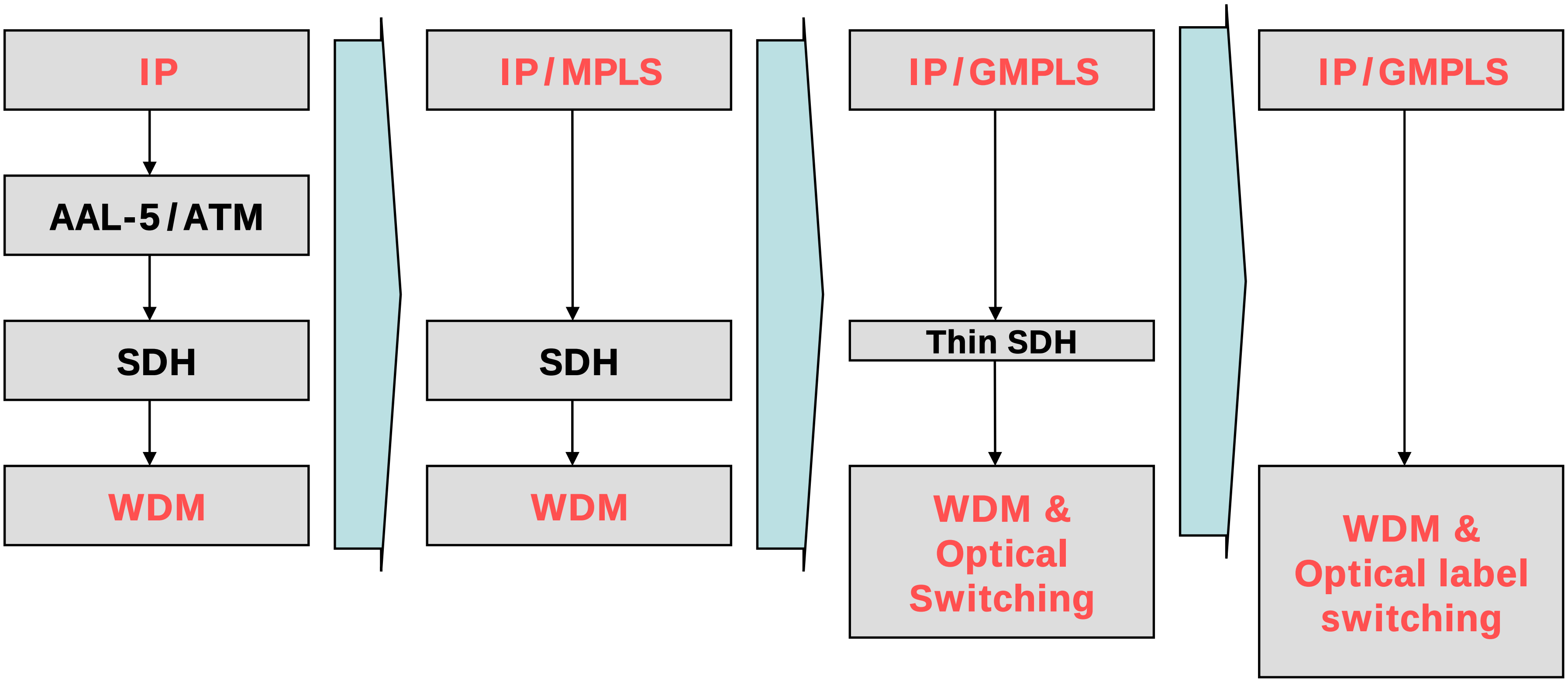
OKI: 160Gb/s x 640km

TU berlin: 160 Gb/s serial transmission

FASHION – Information Society Technologies – European Commission: 160Gb/s x 350km, techno-economics, demultiplexing

2. Past and Present Predictions

- Evolution trend of protocol stacks for IP-over-WDM



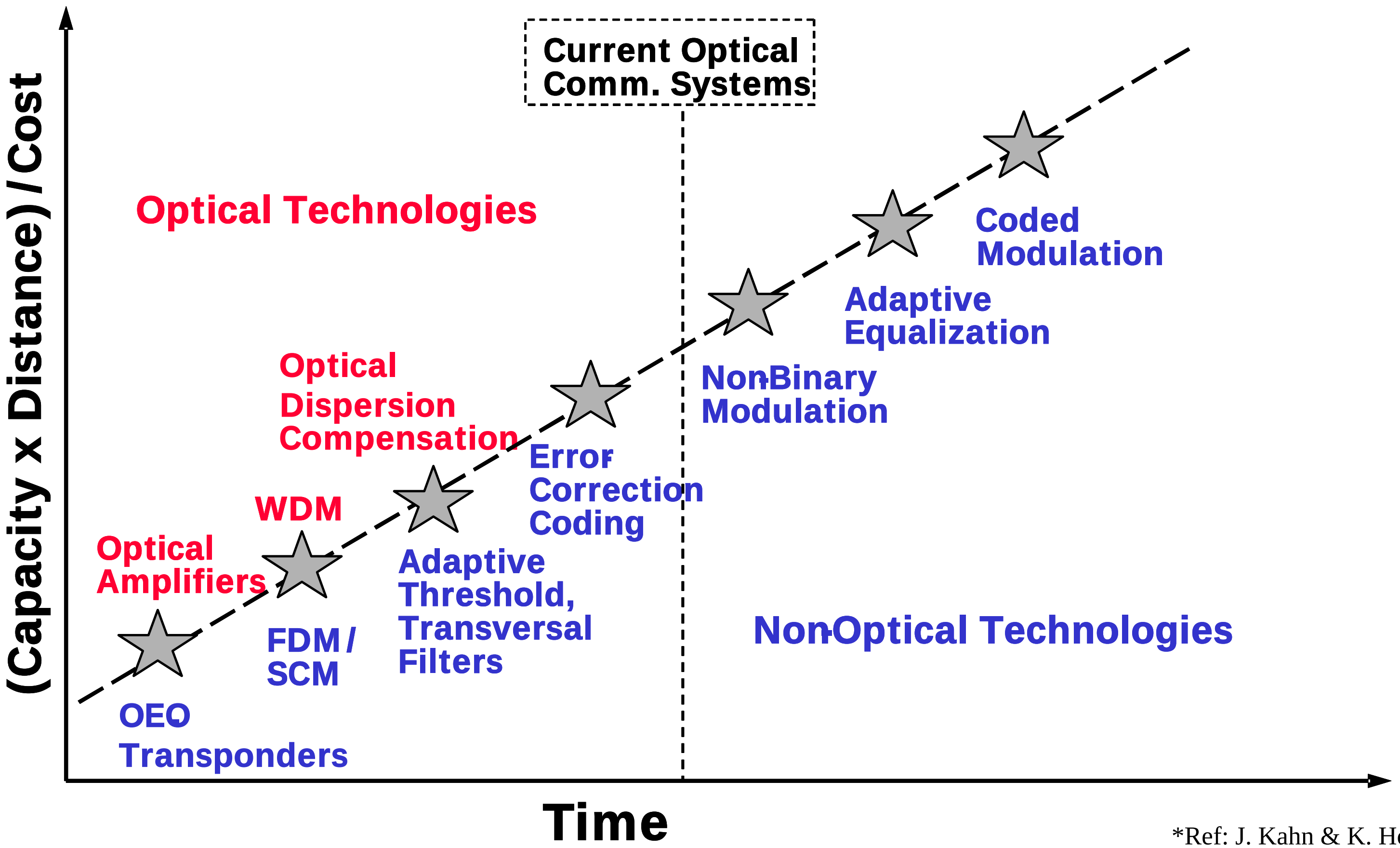
Adapted from article by S. Yoo, J. Lightwave Tech., Dec. 2006.

3. Non-Optical Technologies

- Major strides in digital signal processing (DSP) for non-optical communications systems
- Pressure to squeeze out ever better performance from very bandwidth limited systems
  - Multipath RF wireless channels
  - High-speed DSL and cable modems
  - Audio echo cancellation
  - etc.
- Same technologies can reduce cost and improve performance of optical systems

3. Non-Optical Technologies

- The immediate future is not “all-optical”



*Ref: J. Kahn & K. Ho, Proceedings of SPIE, Vol. 4872, July 2005

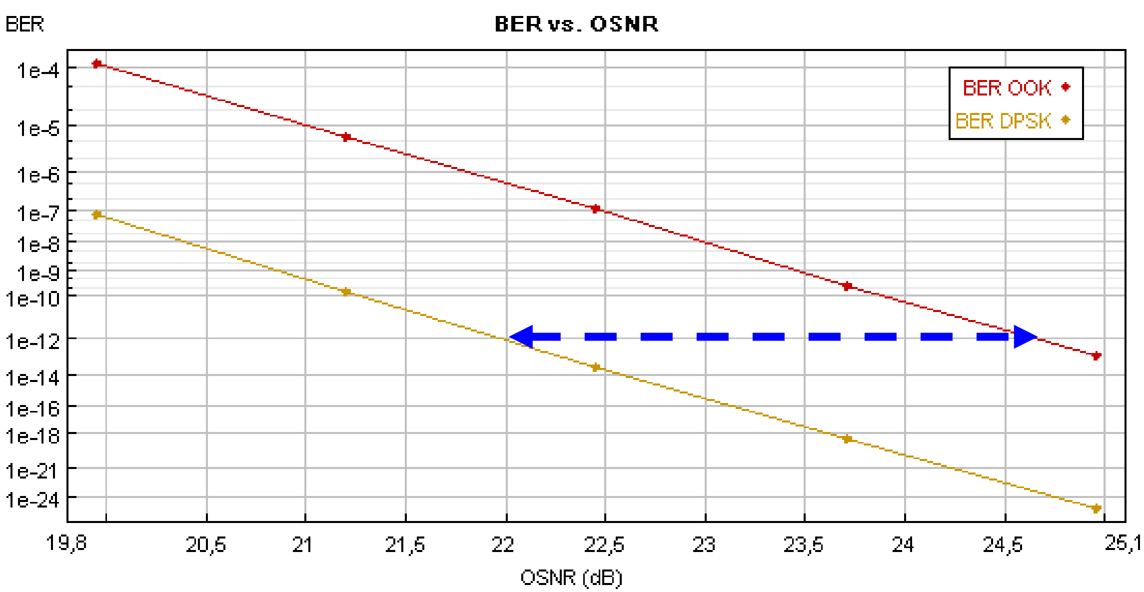
3.1 Non-Binary Modulation

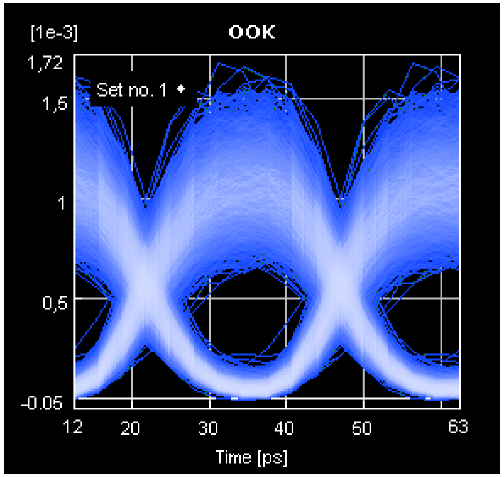
- Conventional binary NRZ or RZ on-off keying (OOK)
  - 0 bit ⇒ No light in bit interval
  - 1 bit ⇒ Light in bit interval
  - Simple and good performance for ≤10 Gbit/s line rates

- Interest in phase-shift keying (PSK) schemes such as differential PSK (DPSK) for ≥40 Gbit/s line rates
  - Increased tolerance to fiber nonlinearities
  - Information carried in optical phase changes
  - Light always present for 0 and 1 bits
  - 0 bit ⇒ Apply π phase change whenever you see 0 bit
  - 1 bit ⇒ Do not change phase if you see 1 bit

3.1 Non-Binary Modulation

- DPSK has the advantage of requiring about 3 dB lower OSNR than OOK to achieve given BER
  - Doubles the reach of a DPSK link compared to OOK
  - Reduce transmit power requirements





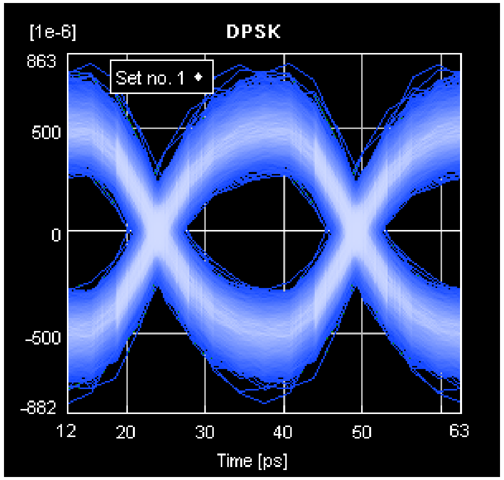


Figure: BER vs OSNR comparison of the two modulation schemes for a 40 Gb/s system.

3.1 Non-Binary Modulation

- Differential Quadrature PSK (DQPSK) is even better but more complex ⇒ enabler for 160 Gbit/s line rates

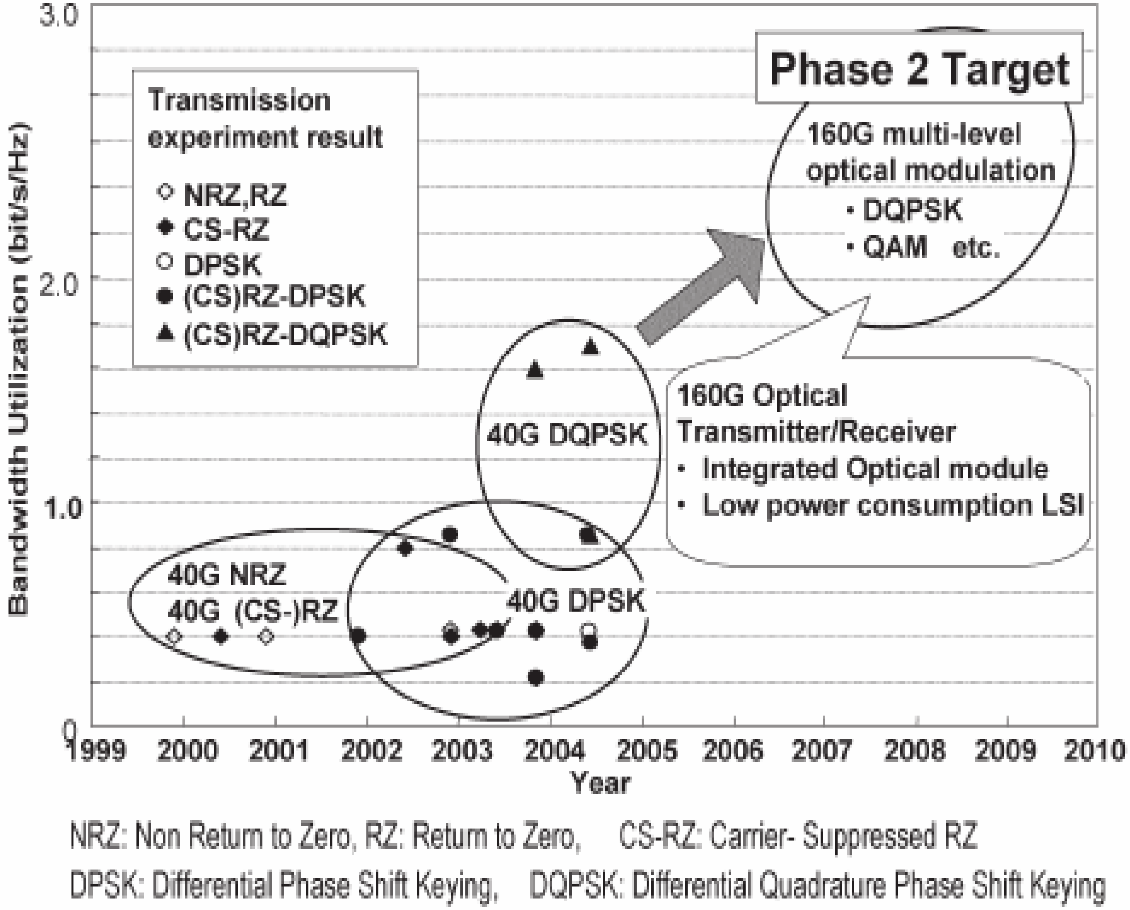


Figure: Research trends in optical modulation formats

*Ref: K. Kitayama, J. Lightwave Tech, October 2005.

3.2 Adaptive Equalization

- Plenty of R&D in adaptive equalizers to combat dispersion (electronic dispersion compensators) and nonlinearity
  - Linear or Feed-forward equalizers (FFE)
  - Decision-feedback equalizers (DFE)
  - Maximum likelihood sequence estimation (MLSE) equalizers

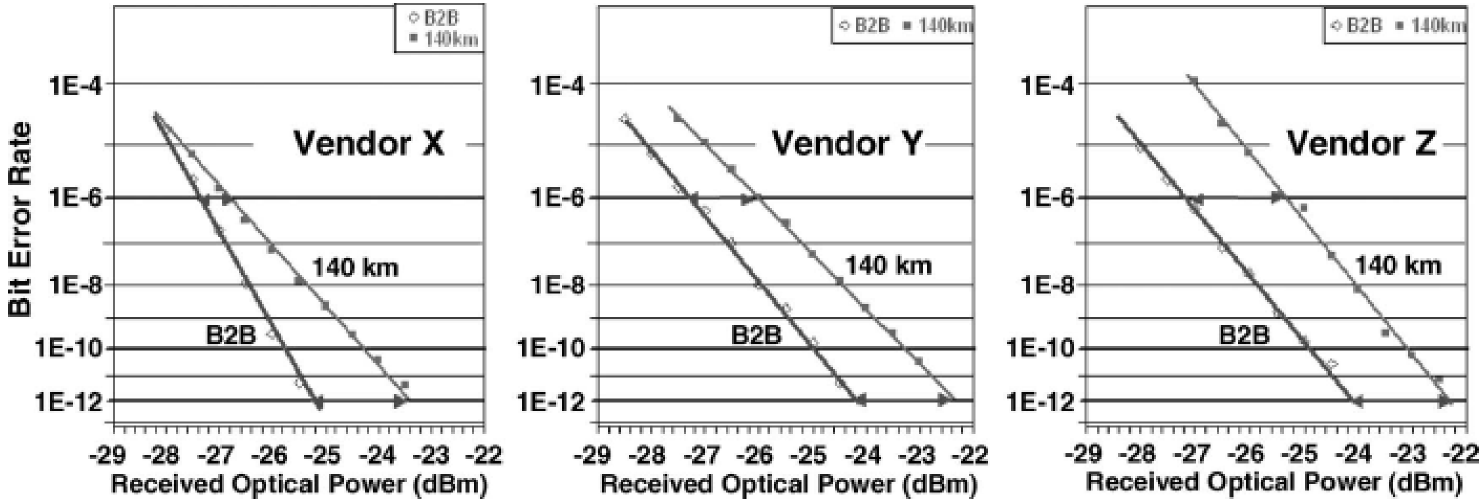


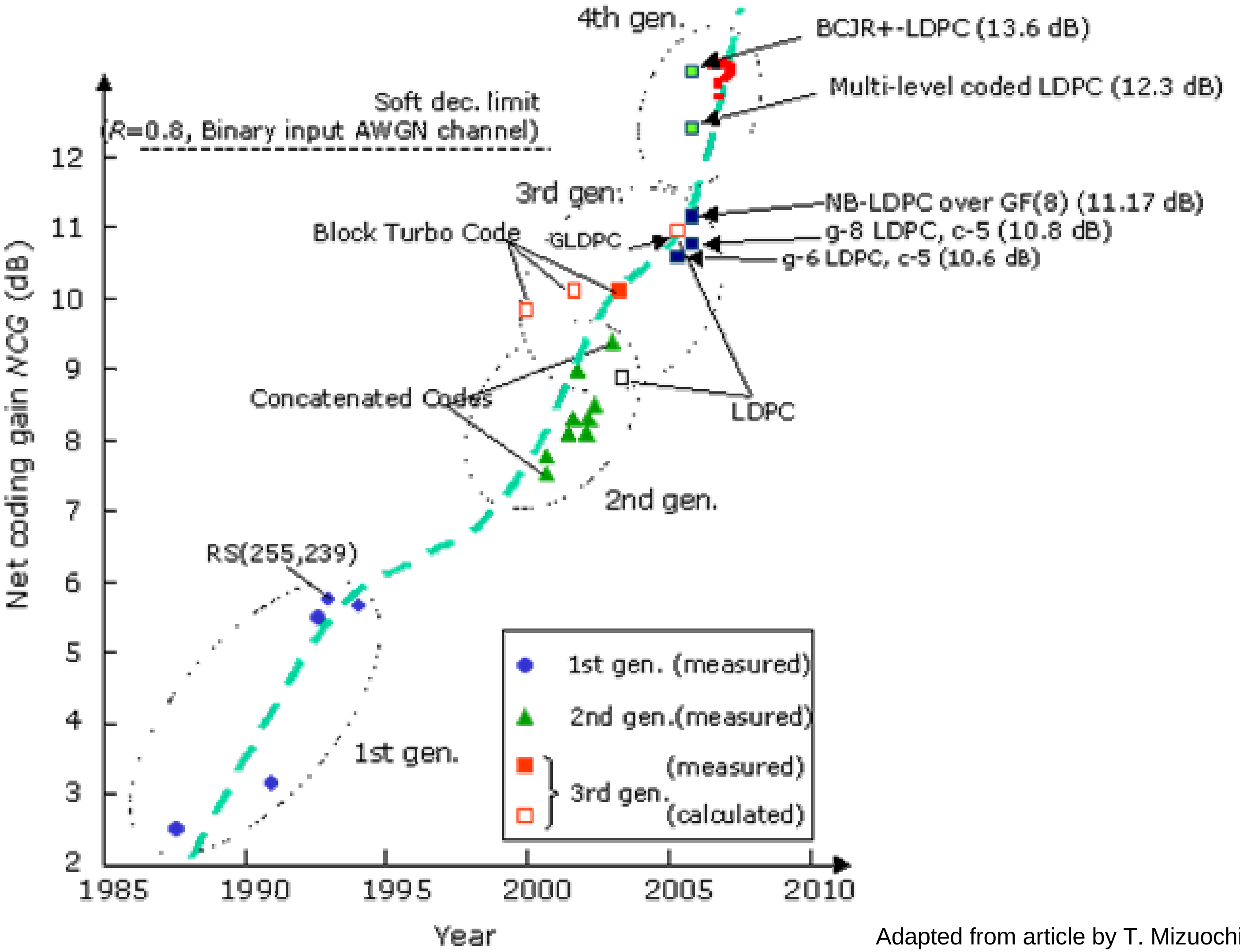
Fig. 10. Receiver sensitivity for back-to-back and 140-km SMF using an X-cut chirped MZ modulator at 10.709 Gb/s and 11-dBm launch power. Results are shown for three different vendors' EDCs (courtesy of [55]).

Source: Q. Yu, J. Lightwave Tech., Dec. 2006.

3.3 Forward Error Correction (FEC)

- 1st/2nd generation FEC codes
  - Reed–Solomon codes , concatenated RS codes
- Future 3rd generation FEC codes
  - Turbo codes, low-density parity-check (LDPC) codes
- 4th generation FEC codes ?

3.3 Forward Error Correction (FEC)



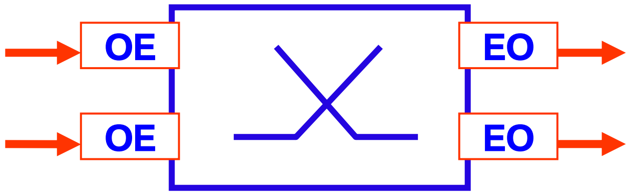
Adapted from article by T. Mizuochi, IEEE JSTQE May/June 2006

3.4 Limitations of Electronics

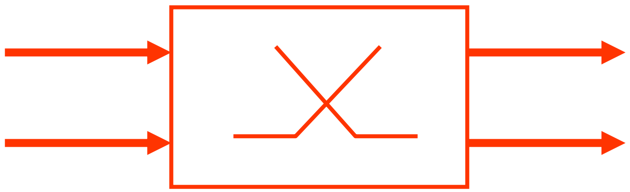
- Difficulties in implementing high-speed (≥ 40 GHz) analog, digital or mixed-signal integrated circuits
- Current 40 Gbit/s linecards usually employ slower electronics operating in parallel
  - Complicated architectures
  - Larger dimensions or footprint
  - Large power consumption
- Optical signal processing still necessary for future

4. Future Optical Switching

- Optical switching enables switching of optical signal without the need of OE or EO conversions



2x2 electrical switch

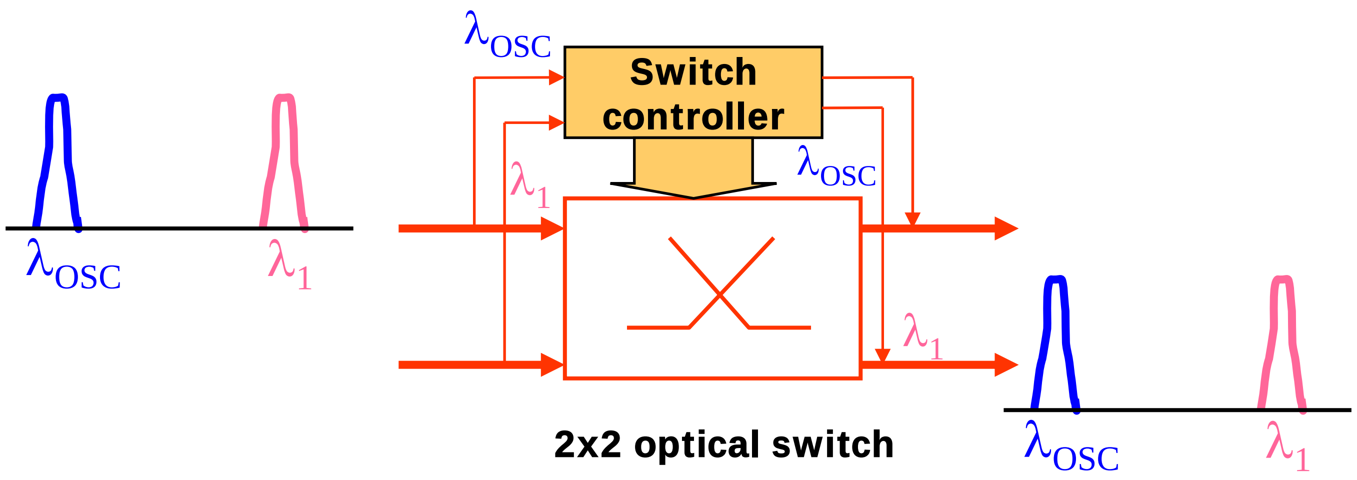


2x2 optical switch

- Types of optical switching
  - Optical Circuit Switching
  - Optical Packet Switching
  - Optical Burst Switching

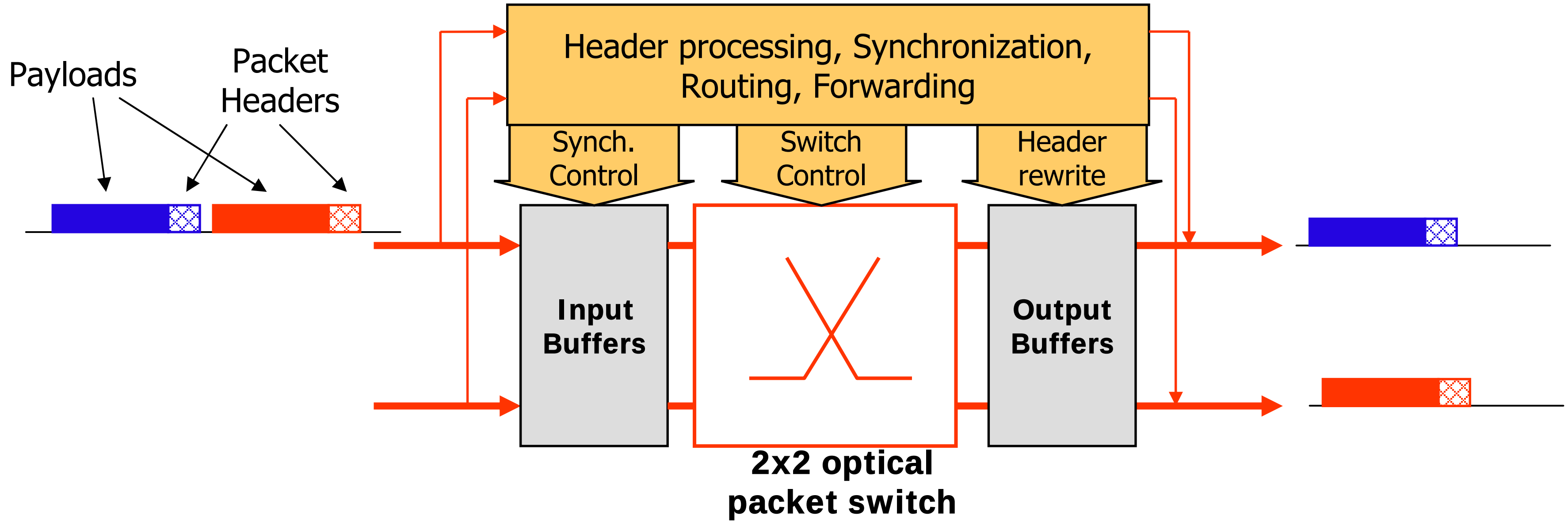
4.1 Optical Circuit Switching (OCS)

- Current optical systems mostly use OCS
  - Switching of all traffic (usually gigabytes) on a wavelength channel or multiple wavelength channels
  - Out-of-band switch control using optical supervisory channel (OSC) on a different wavelength
  - Required switching speed in millisecond range
  - Inefficient utilization of large wavelength channel capacities



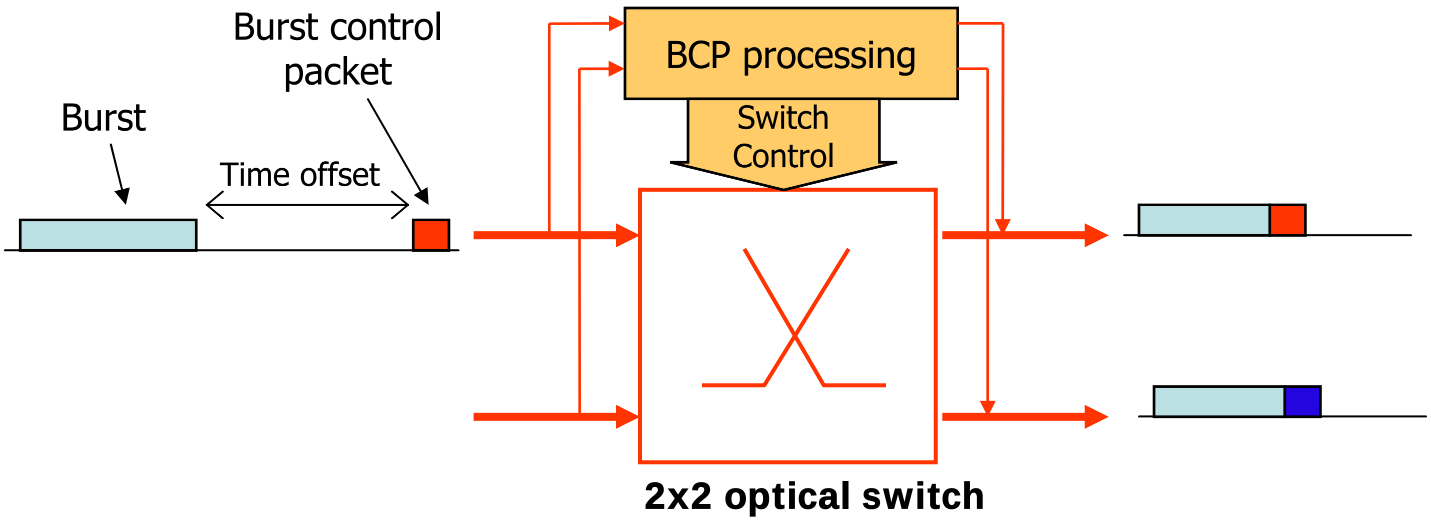
4.2 Optical Packet Switching (OPS)

- OPS introduces statistical multiplexing in the optical layer
  - Switching of optical packets (40 to 1500 bytes long)
  - In-band (same wavelength) switch control using optical packet headers
  - Required switching speed in nanosecond range
  - Optical buffering techniques still limited, bulky, lossy and expensive
  - OEO conversions required for electronic header processing



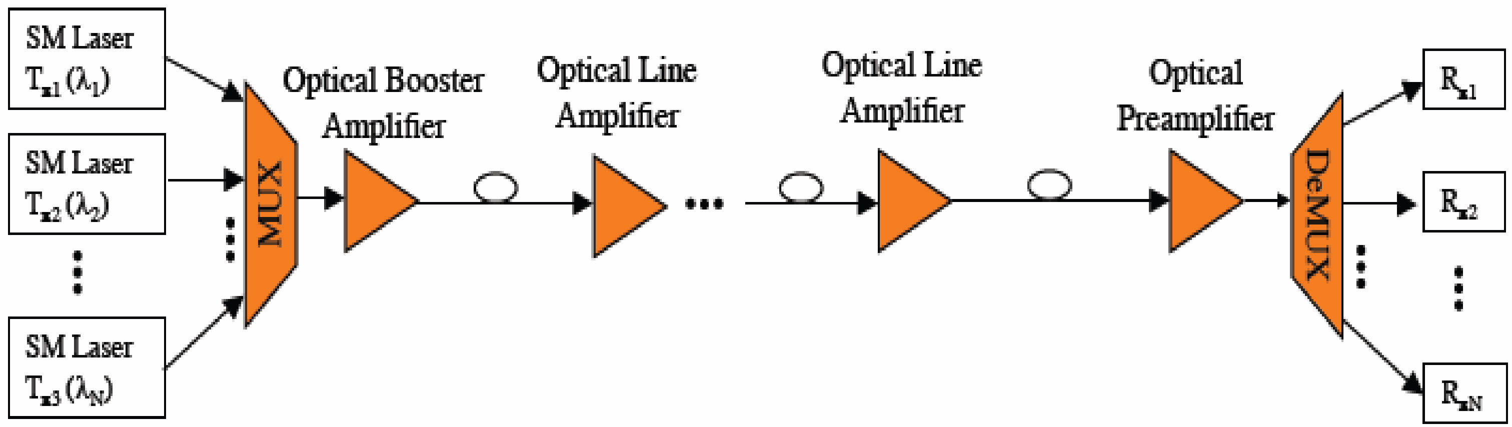
4.3 Optical Burst Switching (OBS)

- OBS is a combines the advantages of OCS and OPS
  - Switching of aggregated bursts or megapackets (tens of kB long)
  - In-band or out-of-band switch control using a burst control packet (BCP) transmitted ahead of the burst
  - BCP alerts switching nodes of size and destination of coming burst
  - Burst sent without requiring confirmation after time offset period
  - Eliminates need for optical buffering
  - Required switching speed in microsecond range



5. Alternative Optical Multiplexing

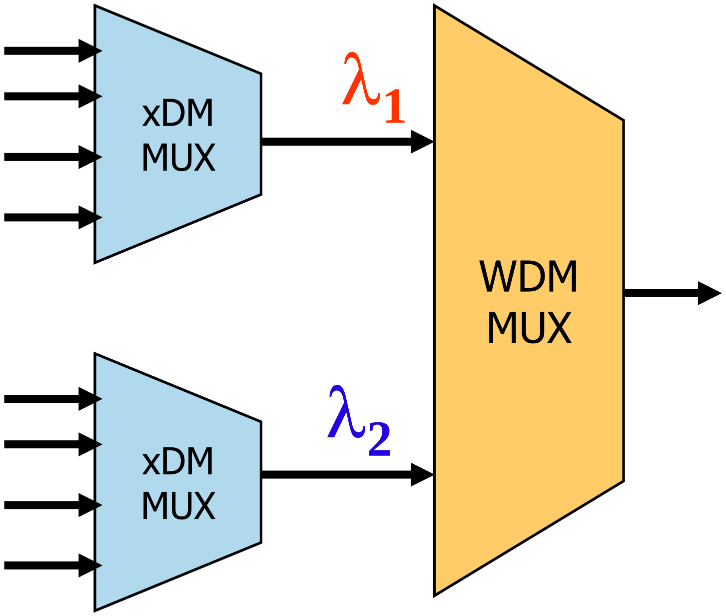
- Wavelength division multiplexing (WDM)



- If wavelength channel number insufficient add more wavelengths by reducing channel spacing
  - Deploy more stable lasers with negligible wavelength drifting
  - Use filters with sharper skirts (high selectivity) to retriever channels

5. Alternative Optical Multiplexing

- Otherwise increase reuse of existing wavelength channels
- Use alternative optical multiplexing schemes to share a single wavelength channel



5.1 Optical TDM (OTDM)

- OTDM combines slow optical data streams in to higher speed streams
  - Either by optical bit-interleaving or optical packet-interleaving
  - Electrical TDM line rates limited by speed of electronic circuits
  - OTDM would be necessary for line rates beyond 40 Gb/s
    - e.g. four 40Gb/s streams multiplexed into single 160 Gb/s

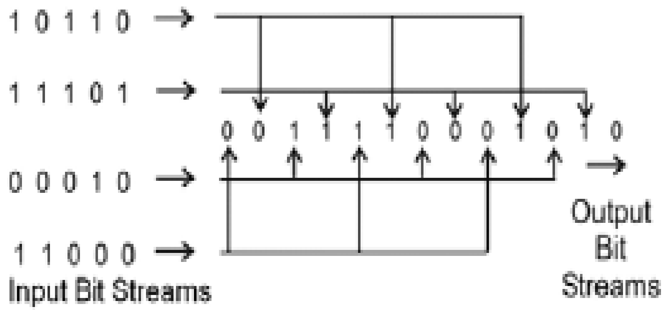
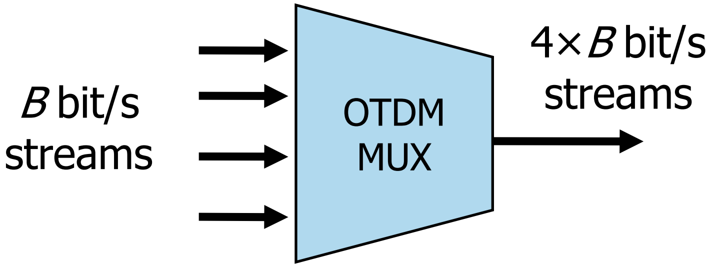


Figure: Example TDM by bit interleaving

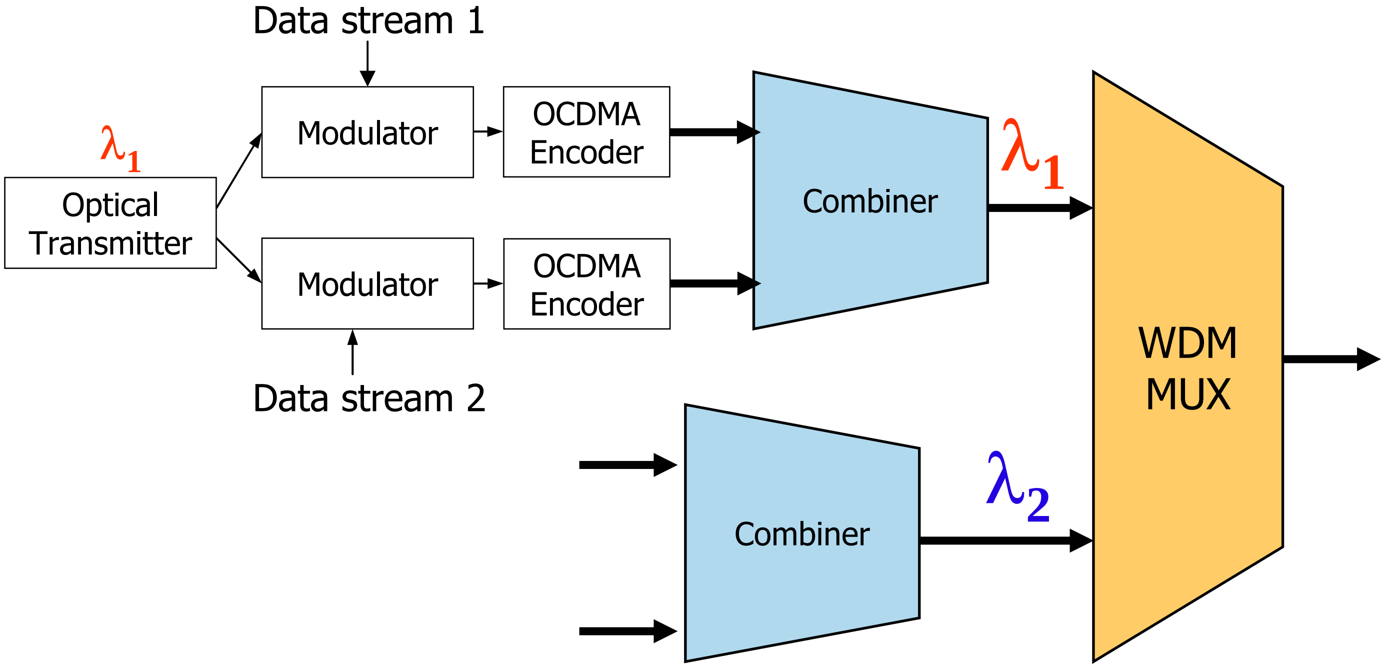


5.1 Optical TDM (OTDM)

- Challenges in implementing high-speed OTDM
  - Need for ultrashort optical pulse sources
  - Synchronization between the receiver and input signal is difficult
  - Fiber impairments at OTDM signal rates will be very significant $\Rightarrow$ optical 3R necessary

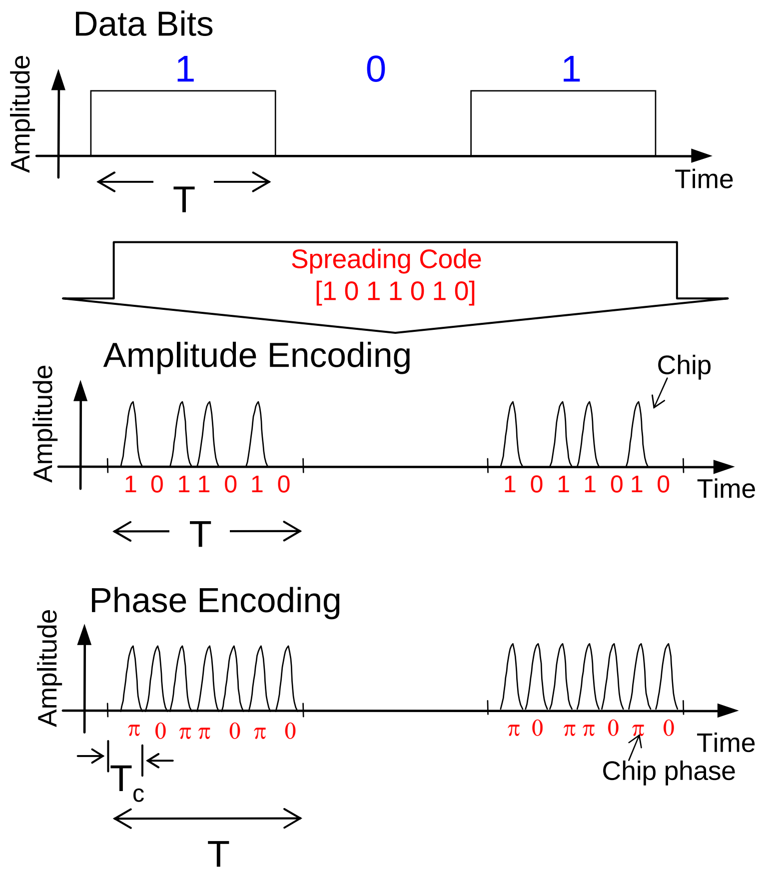
5.2 Optical Code Division Multiplexing

- Similar to conventional CDMA for RF systems, but now applied to optical signals
- Different streams share a wavelength channel by being assigned distinct signature codes
- Corresponding decoder used to recover data at receiver



5.2 Optical Code Division Multiplexing

- Optical CDMA or OCDM
- Mostly direct-spreading
  - Amplitude encoding
  - Phase encoding
- Longer code lengths (i.e. larger code weight)
  - More distinct codes possible
  - Reduced limitations due to multiple access interference
  - Higher chip rate ($1/T_c$) $\Rightarrow$ increased dispersion penalties



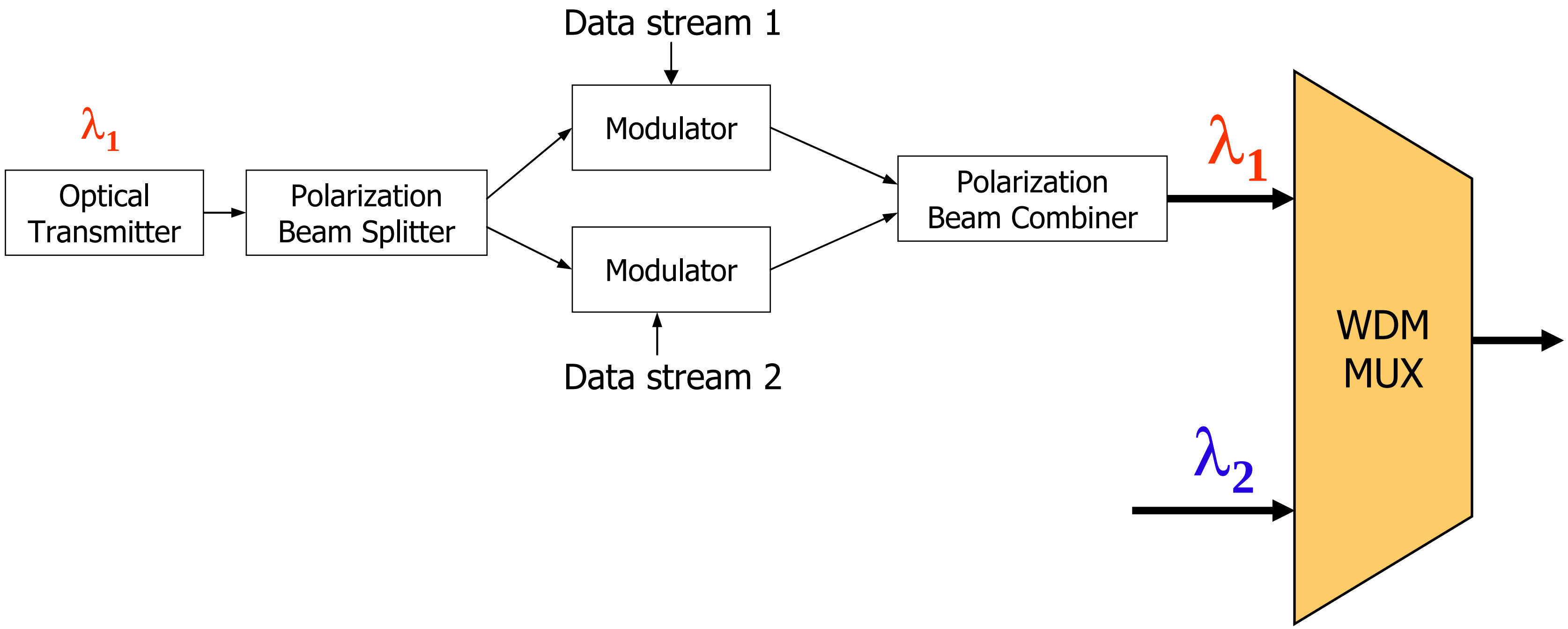
5.2 Optical Code Division Multiplexing

- Comparison between RF/Wireless and Optical CDMA

Attributes	Wireless CDMA	Optical CDMA
Medium	Air	Fiber waveguides
Processing	Mature VLSI Chips	Underdeveloped, bulky
Bit Rate	Low (in Mbps)	High (in Gbps)
Impairments	Multipath Near-far effect Severe attenuation	Dispersion Fiber nonlinearities

5.3 Polarization Division Multiplexing

- A light signal has two orthorgonal polarization components
- Polarization division multiplexing (PolDM) ⇒ different data streams carried on each polarization component



5.3 Polarization Division Multiplexing

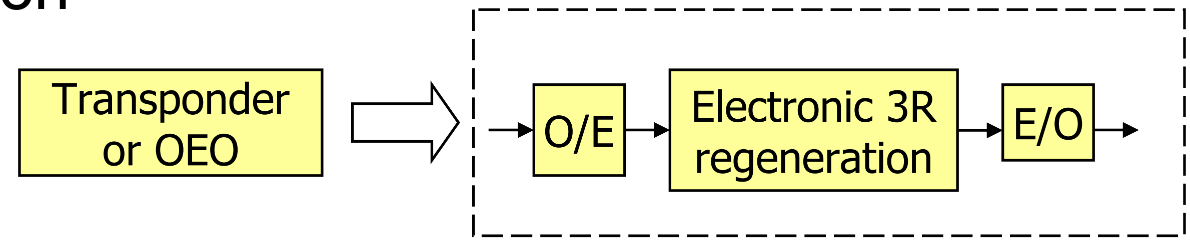
- PolDM challenges and limitations
  - Only two data streams can share single wavelength channel
  - State of polarization of a light not preserved in fiber ⇒ dynamic polarization control required at demultiplexer
  - Polarization dependent losses

6. Novel Optical Device Technologies

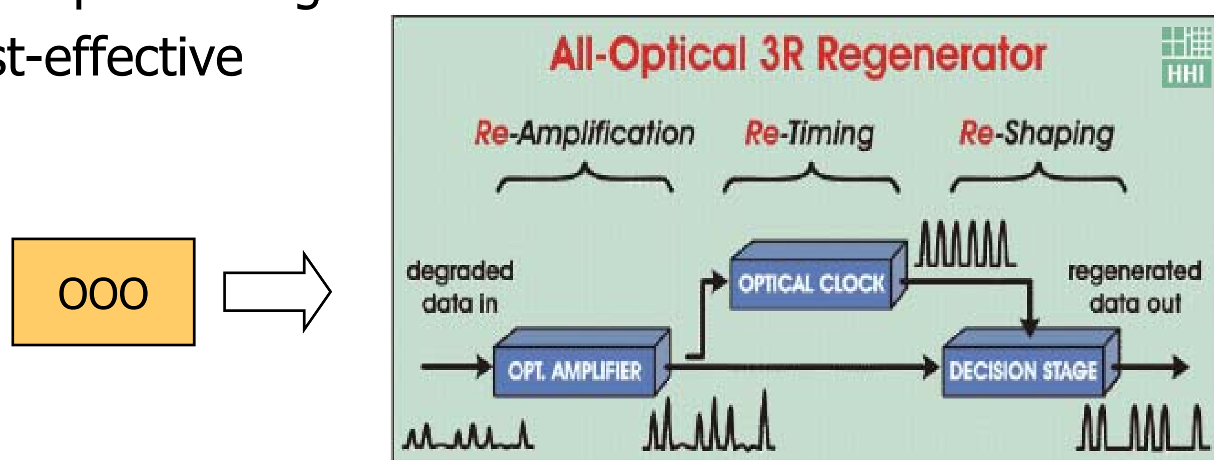
- The need to process signal optically still remains for future systems
  - Ultra fast line rates beyond electronic processing speed limits
  - Tighter wavelength channel spacing
- Applications include:
  - Monitoring signal quality (e.g. BER, Q-factor) optically
  - Optical header or control packet processing
  - All-optical wavelength conversion
  - All-Optical 3R (re-amplify, reshape, retime) regeneration

6. Novel Optical Device Technologies

- Example: currently electronic 3R transponders only feasible option



- All-optical (OOO) 3R regenerators
  - Simplify designs
  - Eliminate electronic processing bottlenecks
  - Might also be cost-effective



6. Novel Optical Device Technologies

- Optical 3R would significantly increase line rates and/or distance without performance degradations

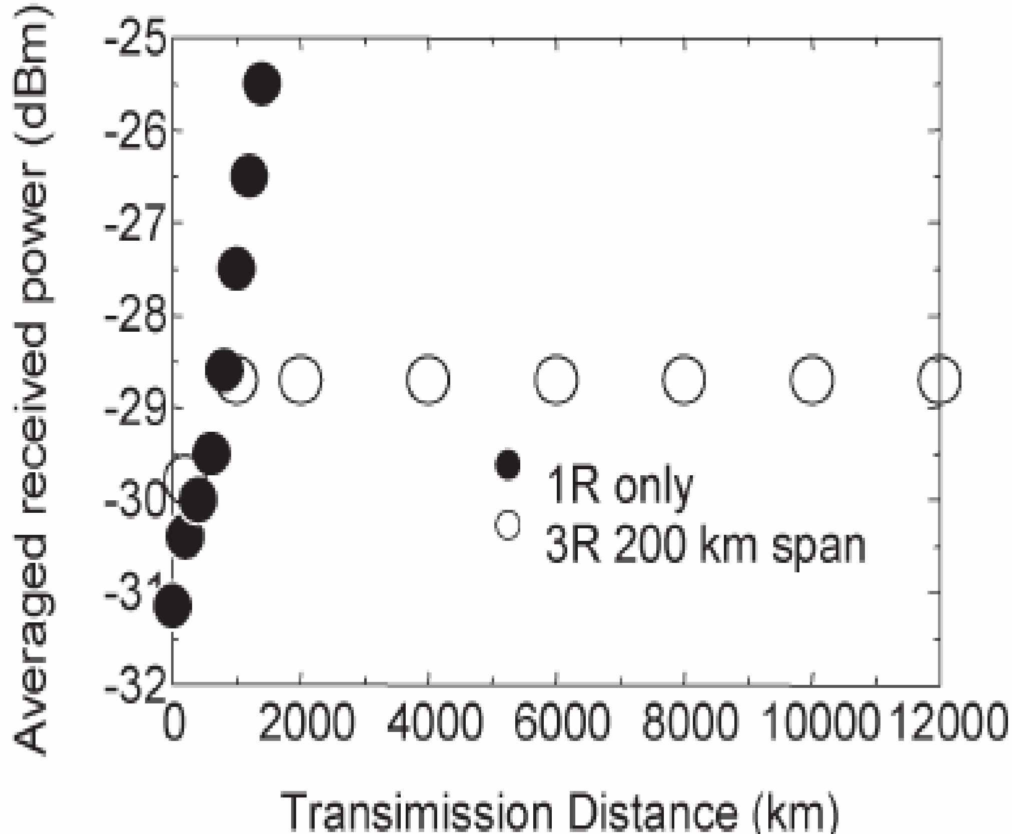


Figure: Comparison of receiver sensitivities for 40 Gb/s transmission over 12000 km with 1R and 3R regeneration.

*Ref: K. Kitayama, J. Lightwave Tech, October 2005.

6.3 Photonic Integrated Circuits

- Most of current optical devices compared to electronic ICs
  - Bulky, costly, difficult to scale, low volume production and relatively low reliability
  - Limited to mostly small or medium scale integration

Figure: A compact mini EDFA module. Single function: amplify WDM signal.

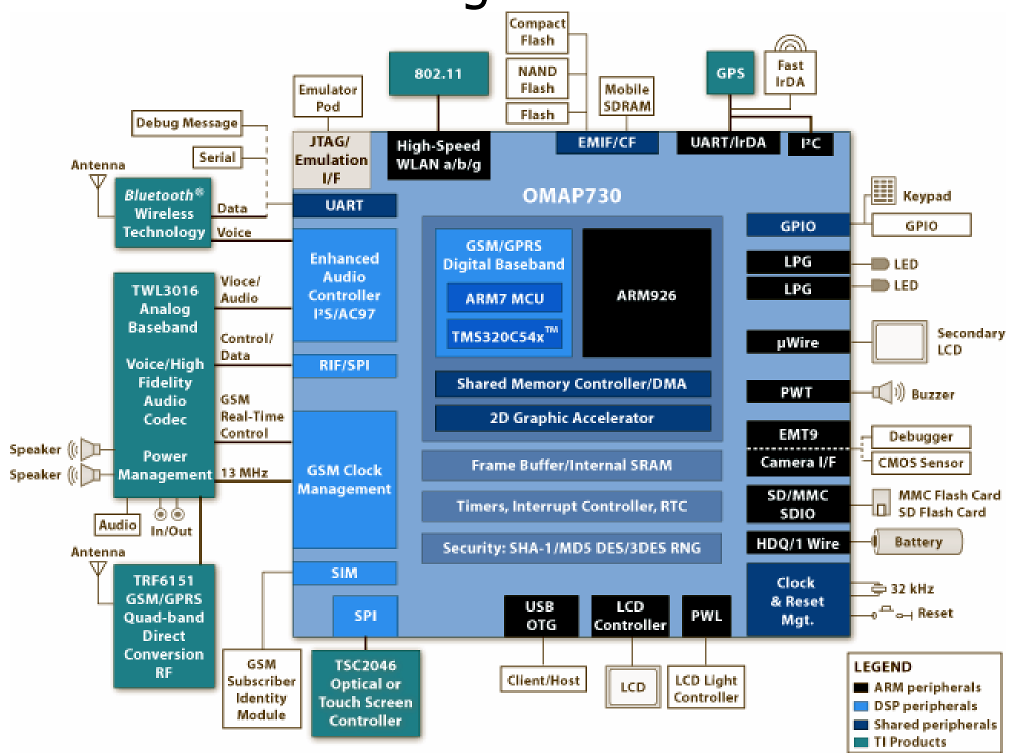


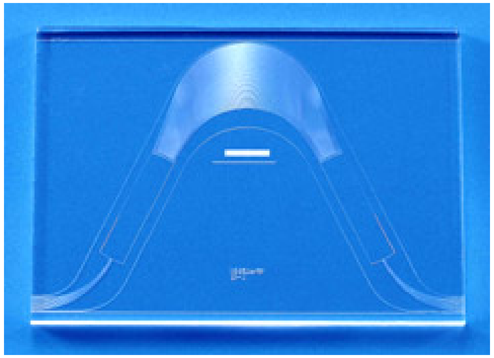
Figure: TI's OMAP730 single-chip GSM/GPRS baseband processor

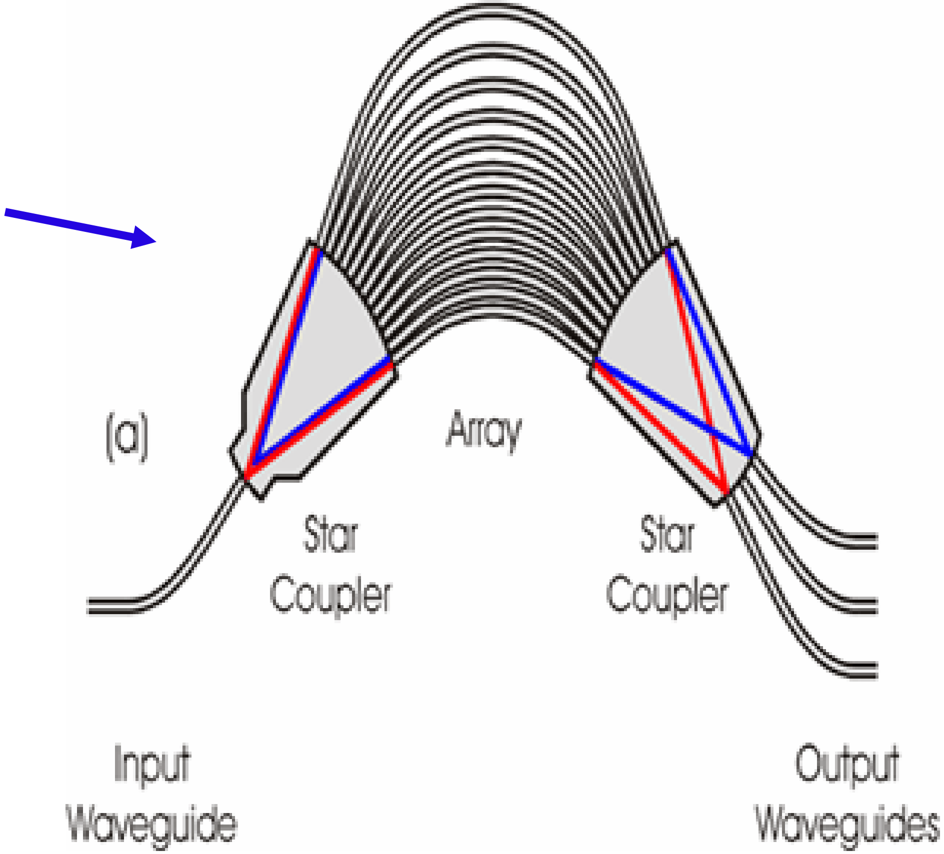
6.3 Photonic Integrated Circuits

- Extensive optical DSP will be possible with fully fledged photonic integrated circuits (PICs)
  - Processing digital optical bits instead of analog optical signals
- Photonic integration criteria includes:
  - Low coupling and absorption losses
  - Polarization insensitivity
  - Diverse operating wavelengths and temperatures
  - Interaction between optical active and passive devices
  - Package mechanically stable
  - Reproducibility on a manufacturing scale

6.3 Photonic Integrated Circuits

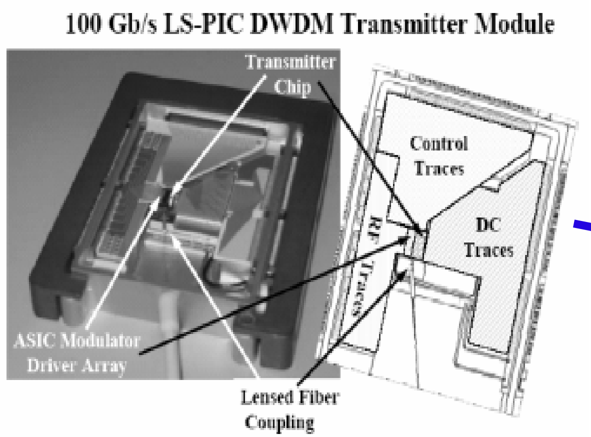
- Example: planar arrayed-waveguide grating (AWG)
  - A dual function (demultiplexing or multiplexing) PIC

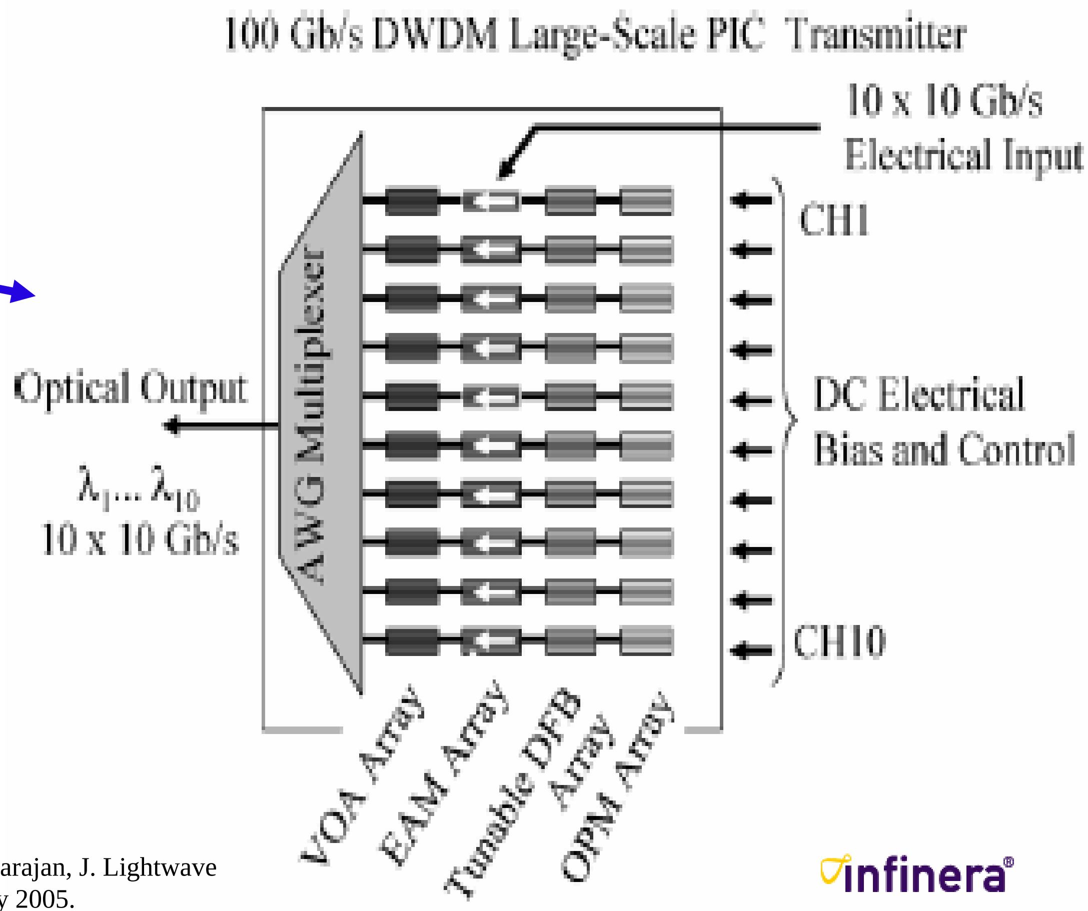




6.3 Photonic Integrated Circuits

- Example: 10 wavelength (@10 Gb/s) DWDM transmitter
  - A 50 function large scale PIC





VOA: Variable optical attenuator

EAM: Electro-absorption modulator

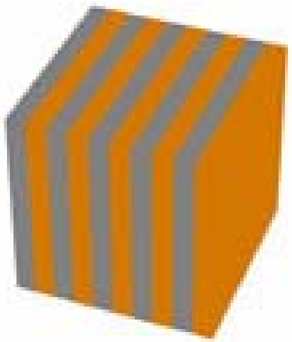
DFB: Distributed feedback laser

OPM: Optical performance monitors

*Ref: R. Nagarajan, J. Lightwave Tech, January 2005.

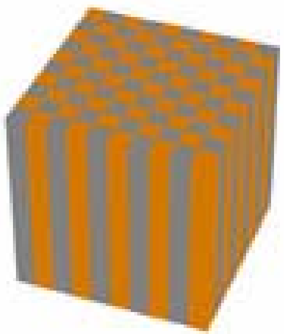
6.4 Photonic Crystals

- Candidate technology future optical signal processing devices (inventors: E. Yablonovitch & S. John 1987)
- Manipulate and control light using photonic band-gap effect created by periodic refractive index variations
  - Like semiconductor devices controlling flow of electrons using energy band-gap



1D photonic crystal

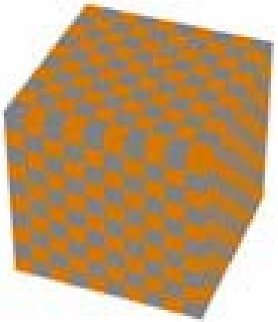
•1D periodicity like a fiber Bragg grating



2D photonic crystal

•2D planar periodicity

•Relatively easy to fabricate



3D photonic crystal

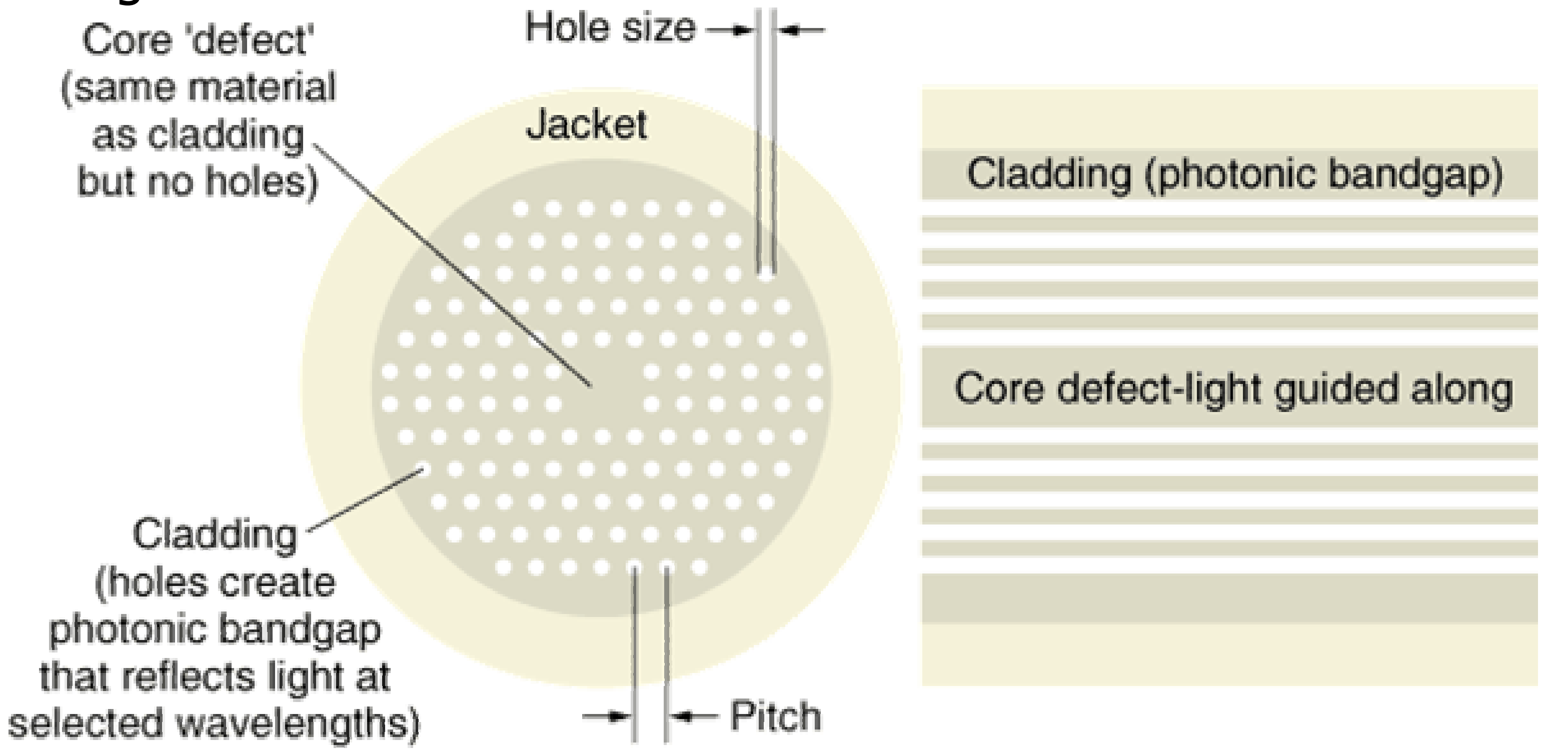
•3D planar periodicity

•Difficult to fabricate

•Potentially many functions

6.4 Photonic Crystals

- Photonic crystal fibers (holey fibers)
  - Transparent solid material (e.g., glass) and air contained in holes
  - Diameter (size) and spacing (pitch) of holes determines blocked wavelengths



6.4 Photonic Crystals

- Photonic crystal fibers have some distinct and easily tailorable optical properties compared to conventional fibers
  - Could be custom-made for ultrafast rate and/or long distance links
  - Useful for making various fiber-based devices e.g. fiber amplifiers

Dispersion Regimes

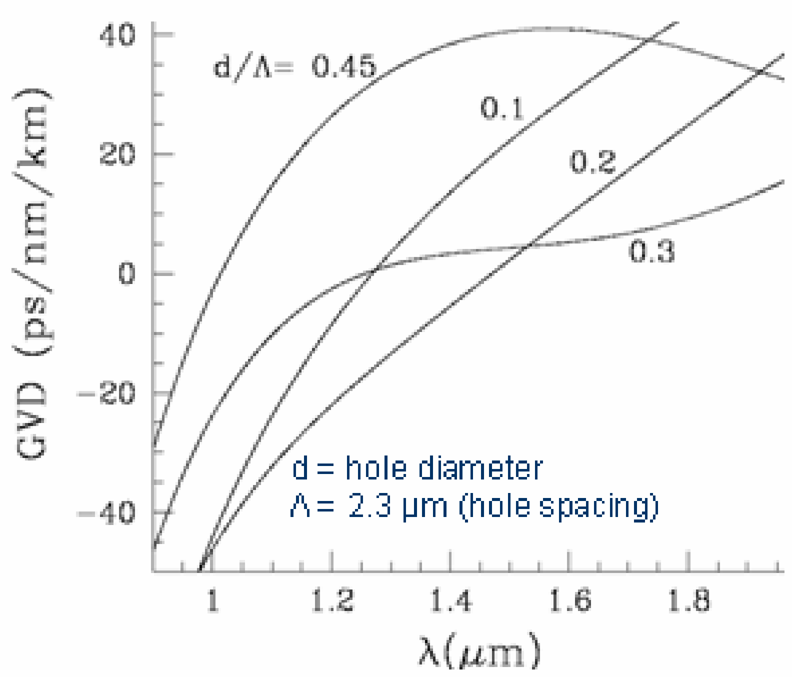


Figure: Various dispersion regimes possible in holey fibers, dependent upon the hole diameter/spacing ratio.

6.4 Photonic Crystals

- 2D/3D photonic crystal slabs
  - For future realization of photonic integrated circuits (PIC)

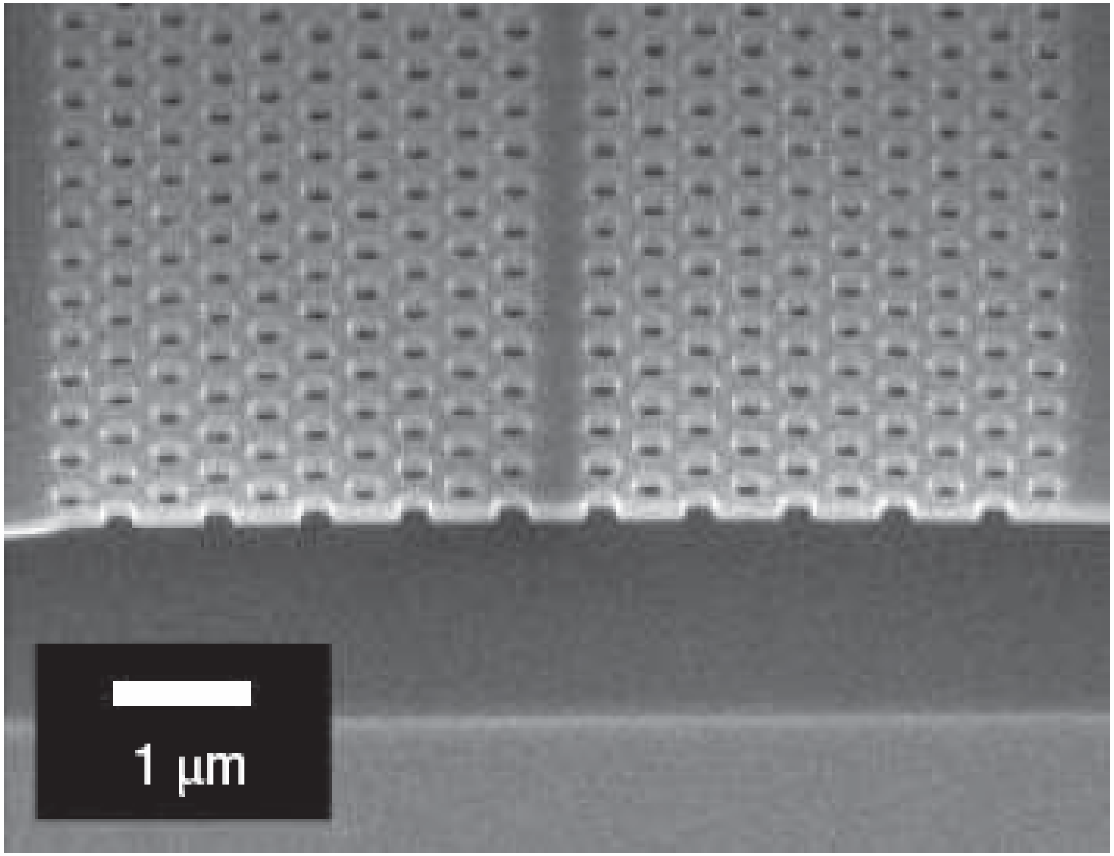


Figure: Photonic crystal waveguide (source: Nature Photonics, pp. 11, Jan 2007).

6.4 Photonic Crystals

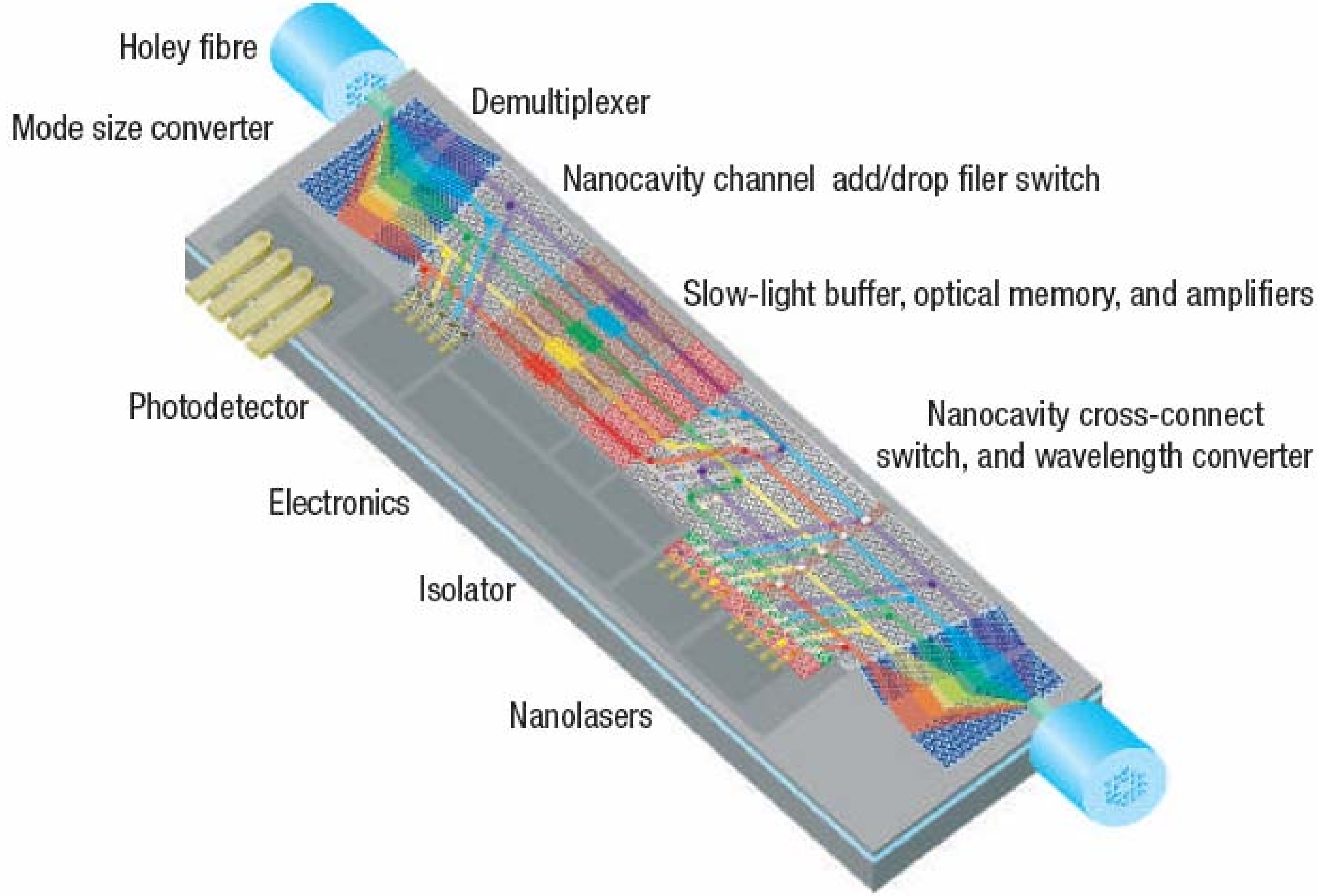
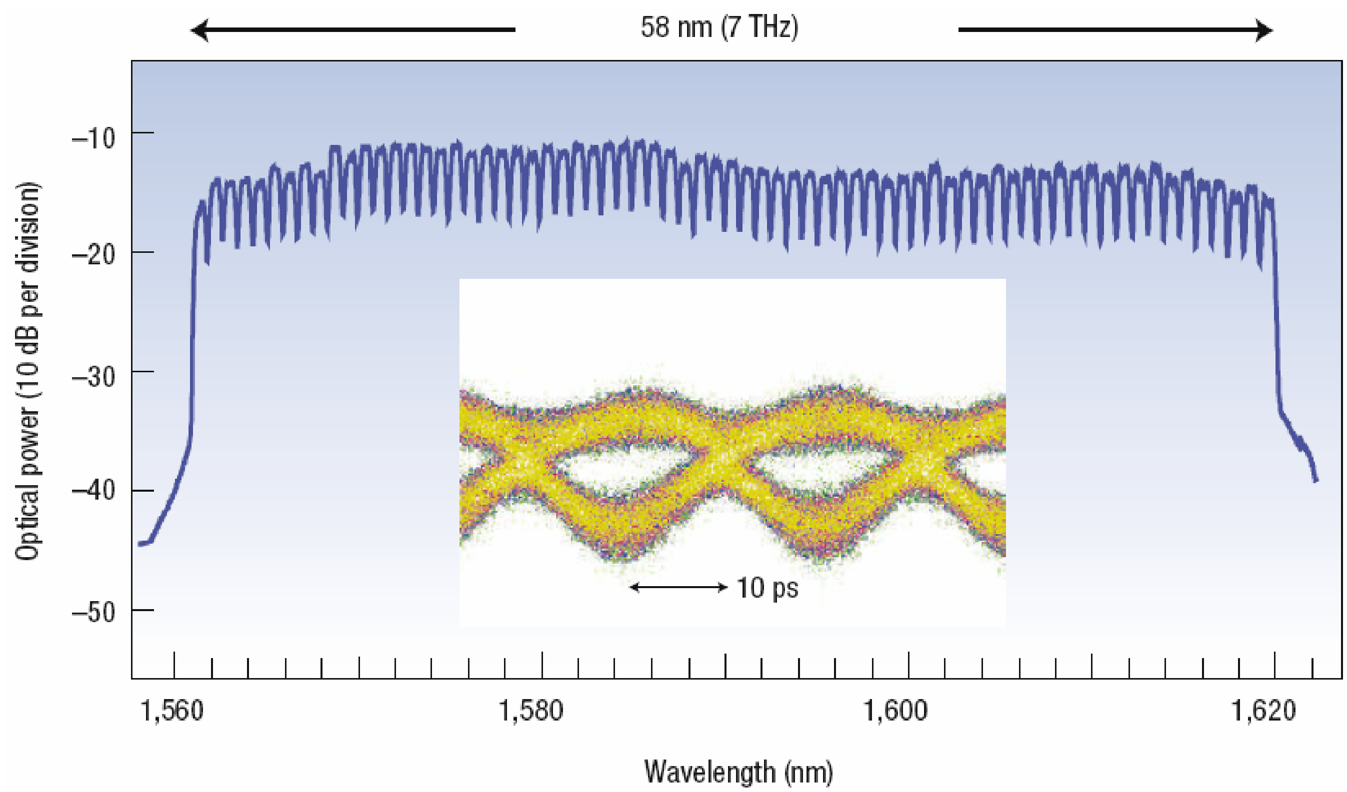


Figure: A typical photonic crystal PIC envisioned for the future (source: Nature Photonics, pp. 11, Jan 2007).

7. A Glimpse Further Into the Future

- Ref: M. Jinno, Y. Miyamoto, Y. Hibino, "Optical Transport Networks in 2015," Nature Photonics, March 2007.



Sept 2006 record by NTT (Japan) 14 Tbit/s over 160 km fiber (140 WDM/PolDM channels, each a 111 Gbit/s DQPSK signal with FEC)

Thank You!

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