MSc in Photonics & Europhotonics

Laser Systems and Applications 2018/2019

Applications of low power lasers

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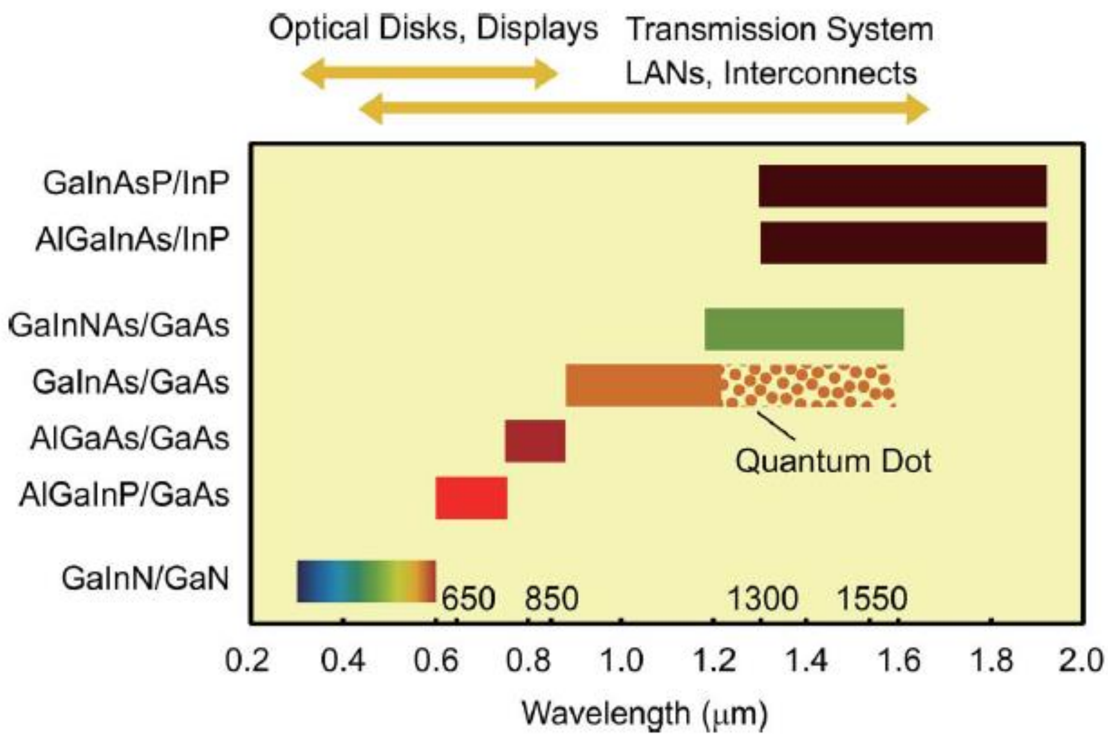
Semiconductor lasers: types and applications

- **Low-power visible**: displays, projectors, imaging, pointers, data storage, etc.

- **Low-power near-infrared**: telecom, datacom, sensors, etc.

- **High-power near-infrared**:
  - Pumping (fiber lasers, solid-state lasers, amplifiers)
  - Material processing (cutting, soldering)

Wavelengths and applications



- The use of CDs, DVDs and Blu-rays is **decreasing** due to Flash drives, streaming video, the Cloud, smart phones, etc.
- But the **opposite scenario** holds for diode lasers used in datacenters and telecommunications.

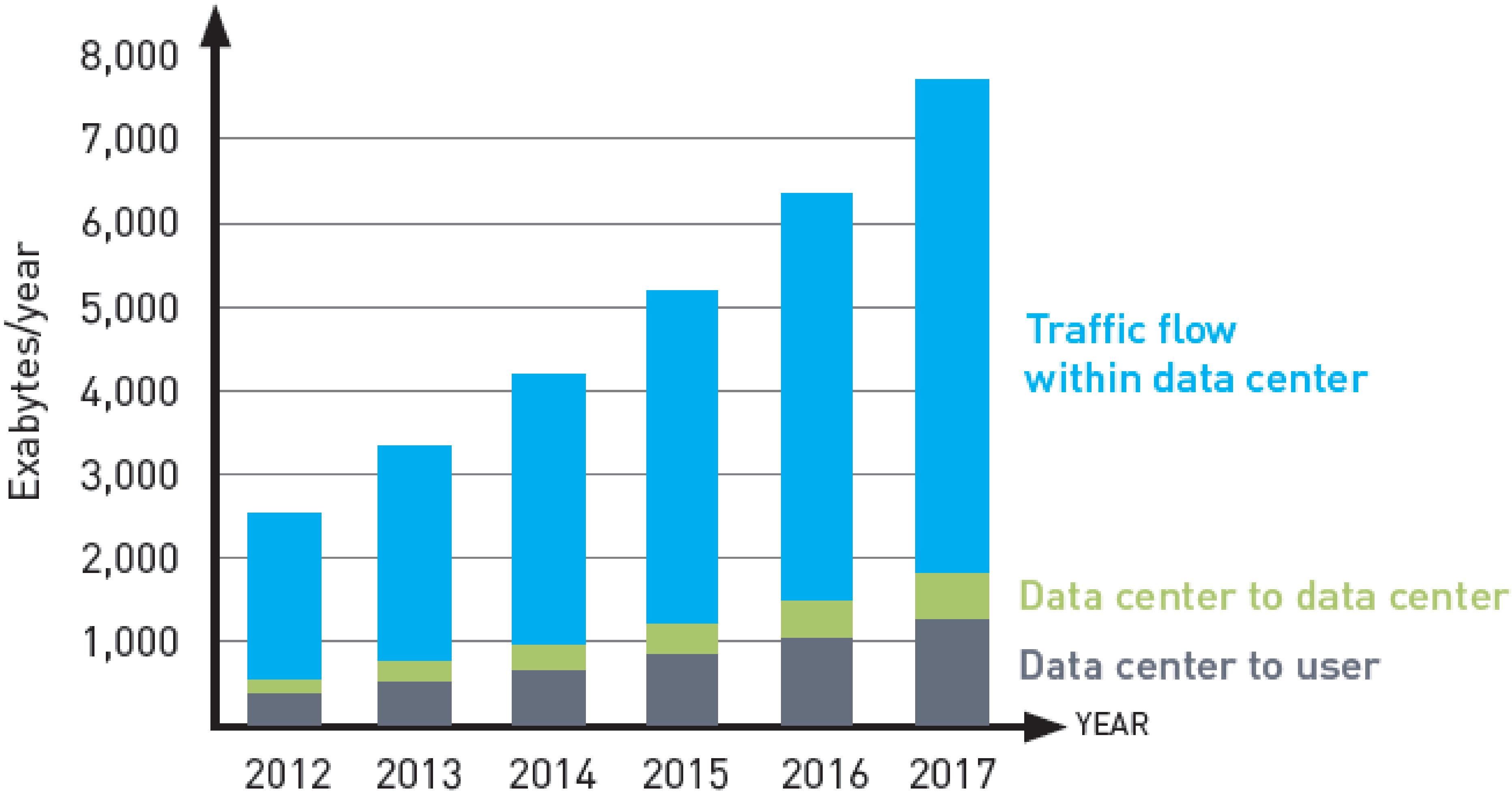
Source: SUEMATSU & IGA: SEMICONDUCTOR LASERS IN PHOTONICS, JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, 1132, 2008

Optical data transport

- Today, every phone, every text message, every downloaded movie, every Internet-based application and service: the information, at some point, is converted to photons that travel down a **huge network of optical fibers**.
- The network: more than two billion kilometers of optical fibers, a string of glass that could be wrapped around the globe more than 50,000 times.
- Optical fibers not only connect homes to Internet, but also link up the cell towers, where the **radio frequency photons** picked up from billions of mobiles are **converted to infrared photons** and transmitted by optical cables.
- Huge traffic within data centers.

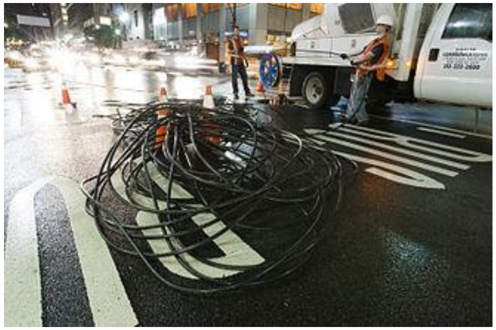
Source: OPN march 2015

“Big data”



Source: OPN set. 2014

The optical transport network (OTN)



- Internet demand is growing at about 40% per year. This growth is driven mainly by increasing video traffic
  - Netflix takes up to 30% of the internet’s bandwidth at peak hours.
  - Over 100 million people enjoy fiber optic connections directly to their homes (March 2015)
- Advances in telecom lasers and in signal processing allow internet providers to upgrade to a new technology: 100 Gbit/s.
- The challenge: scale the OTN while lowering the Gbit/s cost.

Optical communications: a along way from the beginning

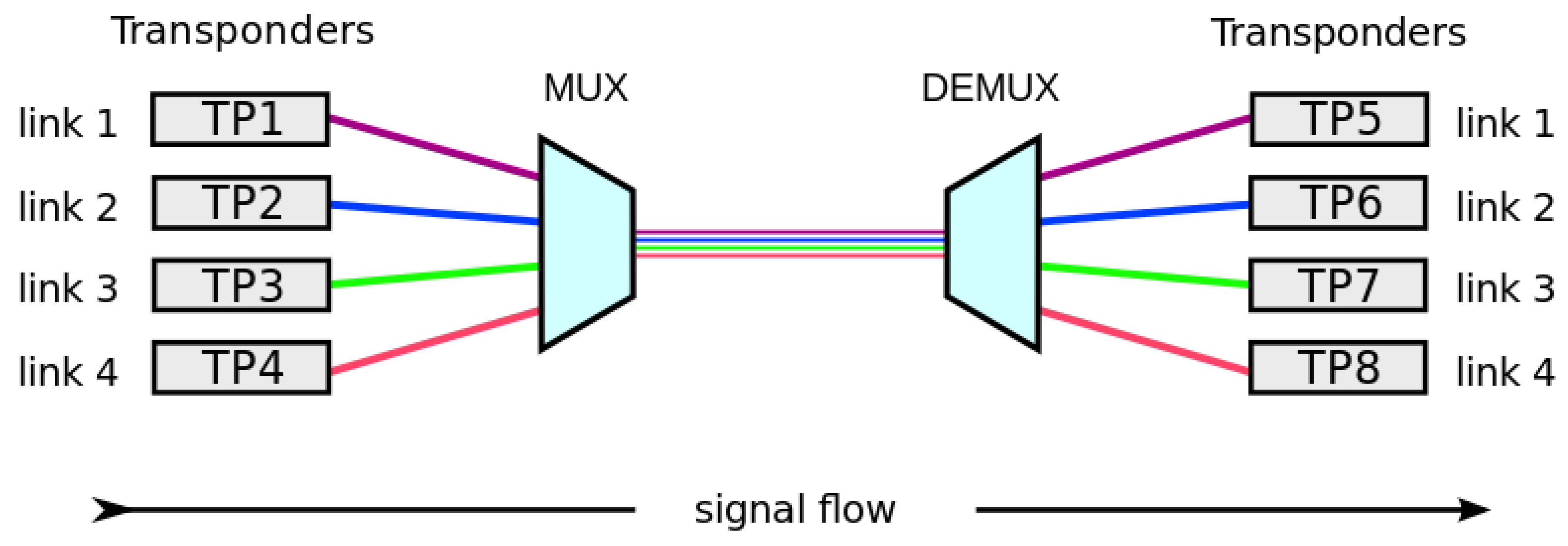
- In the **1960s**, **Charles Kao** and co-workers did pioneering work in the realisation of fibre optics as a telecommunications medium, by demonstrating that the high-loss of existing fibre optics arose from impurities in the glass, rather than from an underlying problem of the technology itself.
- Known as "*Godfather of Broadband*" and "*Father of Fibre Optics*".
2009 Physics Nobel Prize for "*groundbreaking achievements concerning the transmission of light in fibers for optical communication*."

- The first optical transmission system operated **over 11 km of fiber at 45 Mbit/s**: in May 1977 optical fibers were used to connect three telephone central offices in downtown Chicago.

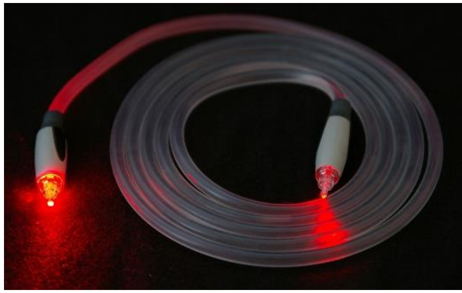
- In the late **1970s**, InGaAsP lasers operating at longer wavelengths were demonstrated, enabling systems to transmit data at higher speeds and over longer distances.

Wavelength-division multiplexing (WDM)

- Developed in the **1980s**: a multiplexer at the transmitter is used to join signals together, and a demultiplexer at the receiver, to split them apart.
- The first WDM systems combined only two signals. Modern systems can handle 160 signals and can thus expand a basic 100 Gbit/s system over a single fiber to over 16 Tbit/s.



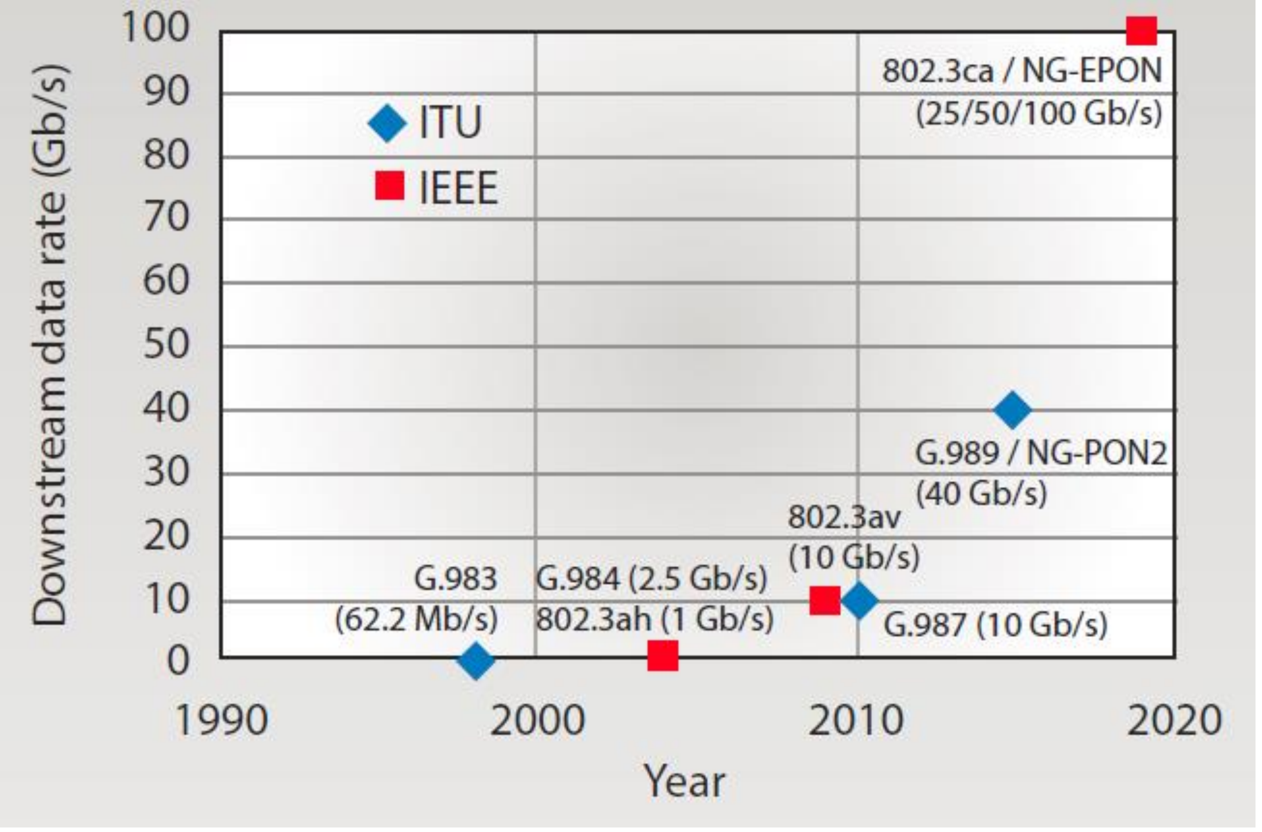
Evolution of optical communications



- In the **1990s** the development of Erbium-doped fiber amplifiers (**EDFAs)** enabled long transmission distances.
- Diode lasers are efficient pump sources for EDFAs.
- EDFAs cover the C-band between 1,530 nm and 1,565 nm.
- In **1996: 5 Gbit/s transoceanic** systems spanning more than 6,000 km without the need for optical-to-electronic conversion.
- **Dense wavelength division multiplexing** (DWDM) uses the C-Band window with dense channel spacing. Channel plans vary, but a typical DWDM system uses 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing.
- By **2010**: *standardization* of 100 Gbit/s (100GbE).

Terabit Ethernet (TbE)

200 Gbit/s & 400 Gbit/s standards were approved on Dec. 2017

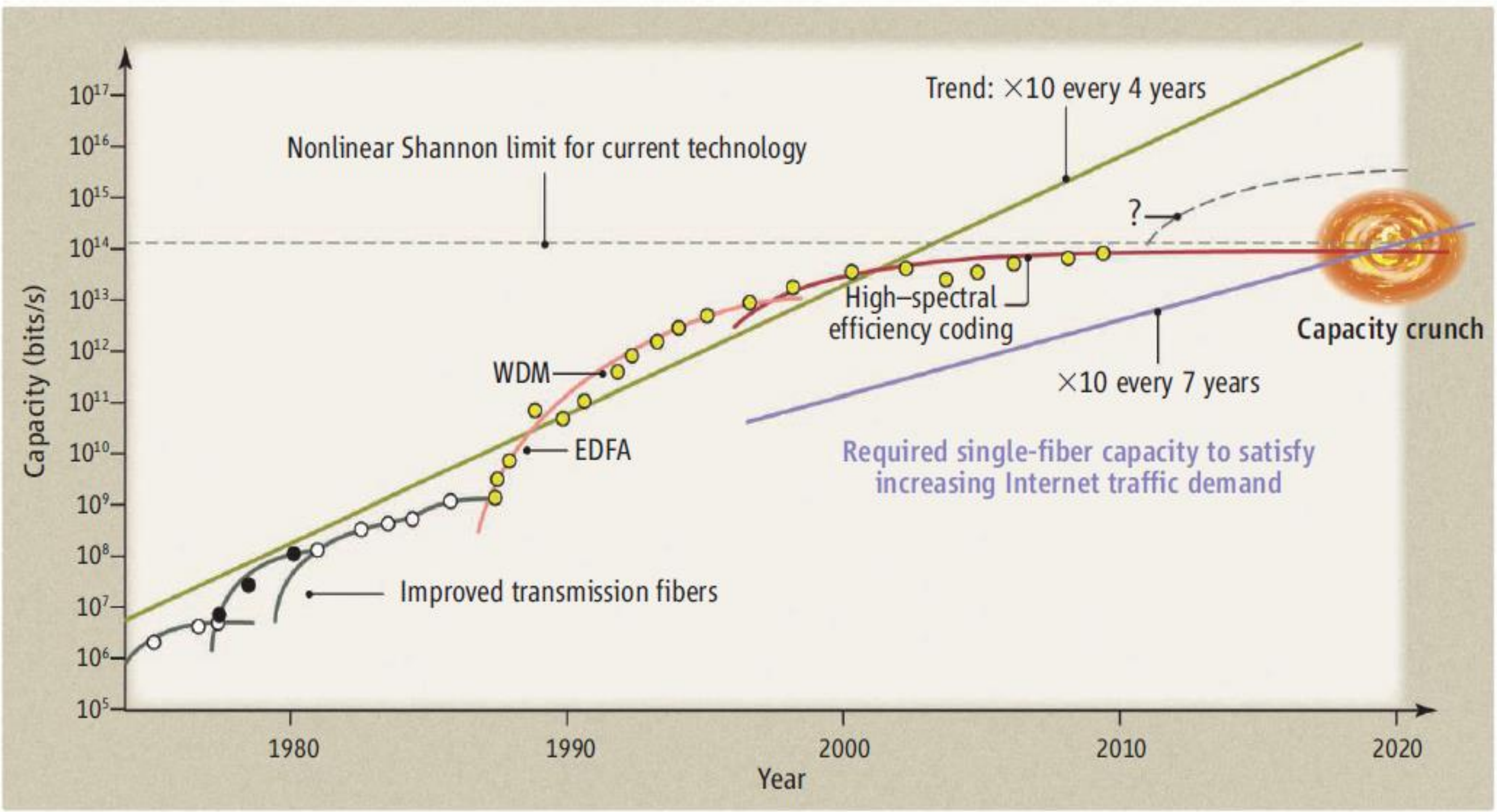


International Telecommunication Union (ITU)
Institute of Electrical and Electronics Engineers (IEEE)

Source: OPN march 2016

Problem

Shannon limit: for any given degree of noise contamination of a communication channel, it is possible to communicate discrete data (digital information) through the channel, nearly error-free up, to a computable maximum rate.

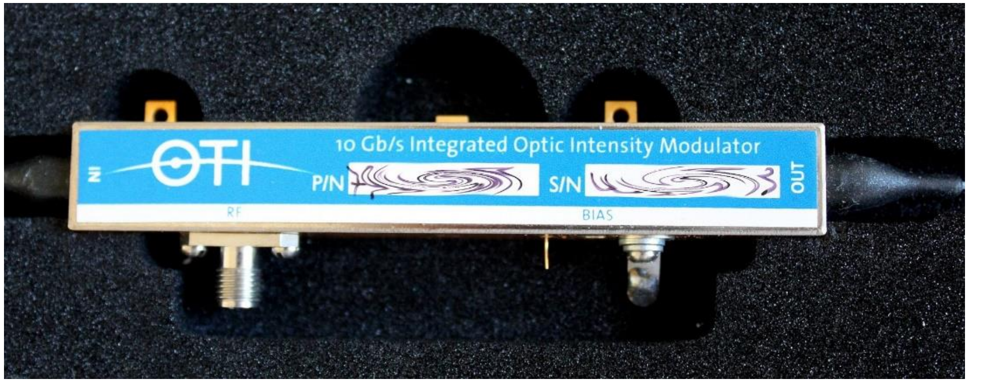


Reaching the limit

- The information capacity of optical fibers is rapidly becoming fully utilized.
- The increase of speed in the last decade **would not have been possible** just by increasing modulation speeds from 10 Gbit/s to 40 Gbit/s to 100 Gbit/s.
- Why not?
- While direct modulation of a semiconductor laser's current enables fiber-optic communications at 2.5 Gbit/s, higher-speed operation using direct modulation has been limited by **frequency chirp**.

Limit of direct modulation: Frequency chirp

- Side effect of modulating the laser intensity: the carrier density in the laser active region changes, and this leads to phase (and frequency) changes. The effect is not detected in the intensity vs time (oscilloscope) but
- is a Big Problem for data transmission through a **long** optical fiber. Because the **chromatic** dispersion of the fiber, there is frequency-dependent time delay.
- This has forced commercial 10 Gbit/s systems to use **external electro-optic modulators**.



Optical parallelism

The increase to 100 Gbit/s possible thanks to optical parallelism that exploits other physical dimensions.

- independently modulating the real and imaginary parts of the optical field (the so-called in-phase and quadrature components)
- modulating two orthogonal polarizations (polarization division multiplexing, PDM).

$\Rightarrow$ Transition from direct detection of the optical pulse intensity to **coherent detection** of the optical field.

Most 100 Gbit/s systems modulate four parallel electrical signals at around 30 Gbit/s (25 Gbit/s, plus overhead for error correction).

Coherent detection

- Heavily researched in the 1980s
- It was abandoned in the early 1990s with the advent of EDFAs.
- Rebirth of coherent detection in the 2000s was technologically enabled by the capabilities of **digital electronic signal processing** (DSP), including the necessary
  - digital-to-analog converters (DACs) and
  - analog-to-digital converters (ADCs)

Modulator limitations

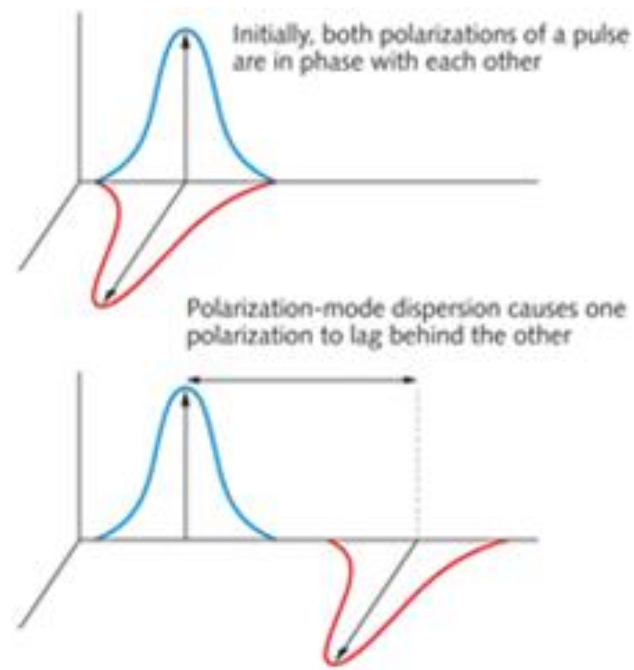
- **Coherent** systems also use external electro-optic modulators to deliver complex modulation formats.

- High-speed in-phase-quadrature (IQ) **modulation formats** (such as quadrature amplitude modulation, or QAM) are modulated on an optical carrier using **expensive, bulky, and difficult-to-integrate** lithium niobate ($LiNbO_3$) IQ modulators.

- While indium phosphide (InP), silicon (Si), and gallium arsenide (GaAs) modulators are being researched, their performance is poor compared to $LiNbO_3$.

The problem: dispersion

- **Modal dispersion:** differences in propagation times between different modes; it can be avoided by using single-mode fibers.
- **Chromatic dispersion** arises from refractive-index variation as a function of wavelength. A fiber's refractive-index profile can be specially tailored to fabricate **dispersion-compensating fibers** to offset those of standard transmission fibers.
- **Polarization-mode dispersion** (PMD) arises from fiber birefringence, which delays one polarization mode with respect to the other. Birefringence in standard transmission fibers is small, so PMD went unnoticed until data rates reached gigabits per second.



Dispersion management

- Optical dispersion has been managed by assembling transmission systems from two or more types of fibers with different characteristic dispersion to keep total dispersion low and uniform across the operating wavelengths.

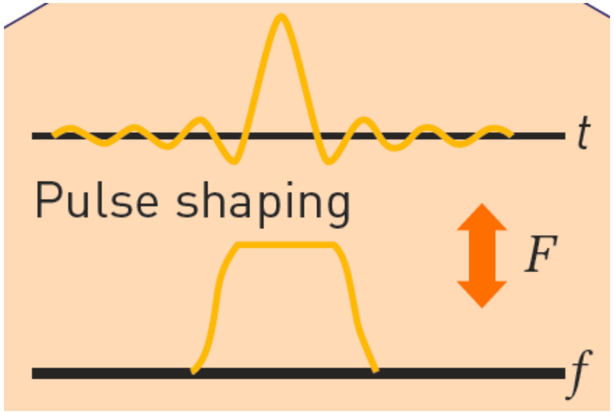
- That delicate balancing act could manage chromatic dispersion for WDM systems using **narrow-linewidth lasers** at channel rates of 2.5 or 10 Gbit/s.

- However, transmitting at higher rates requires much tighter control of chromatic dispersion + management of PMD.

Electronic dispersion compensation

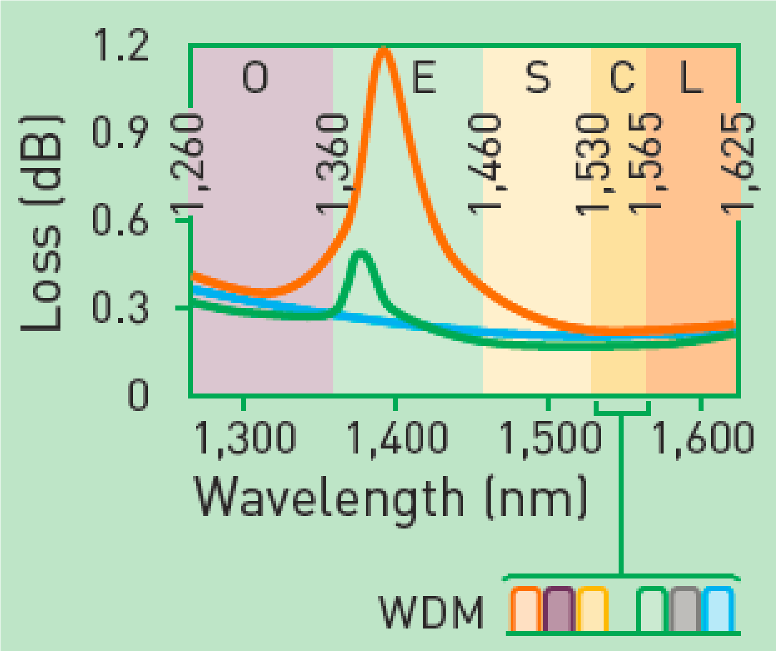
- **Electronic digital signal processing has replaced optics in dispersion management**: the replacement of in-line optical dispersion compensation with **digital signal processing (DSP)** in special-purpose chips has been key to the success of coherent fiber-optic transmission at 100 Gbit/s and up.
- Electronic dispersion compensation was first demonstrated in the early 1990s. The compensators used the Viterbi algorithm—a standard signal-reconstruction technique—and application-specific integrated circuits (ASICs) to regenerate the original signal.
- **Electronic pre-compensation at the transmitter and post-compensation at the receiver** replace optical compensation for rates higher than 10 Gbit/s.

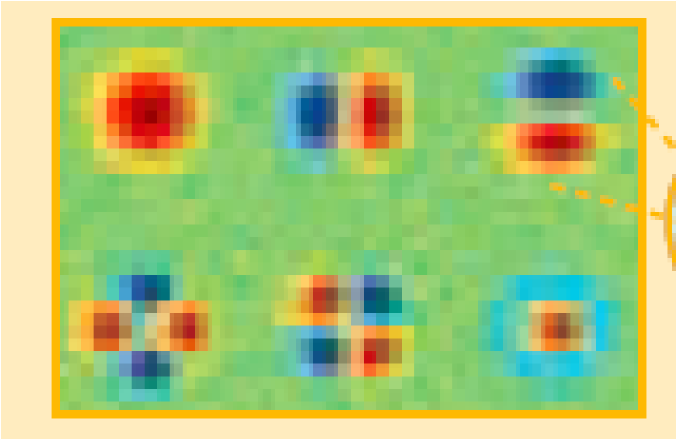
Digital-to-analog and analog-to digital convertors



- Nowadays the use of digital-to-analog converters (DACs) at the **transmitter** enables the generation of Nyquist-shaped and magnitude/phase **predistorted** optical pulses.
- Analog-to-digital converters (ADCs) at the **receiver** allow the faithful conversion of the full optical field of high-speed signals into the digital electronic domain for further digital processing.
- In research experiments (march 2015), rates are approaching 1 Tbit/s per optical wavelength, with symbol rates of about 100 Gbaud (Baud: symbols or pulses per second), carrying higher-level quadrature amplitude modulation (QAM) formats with bit rates of up to **864 Gbit/s**.

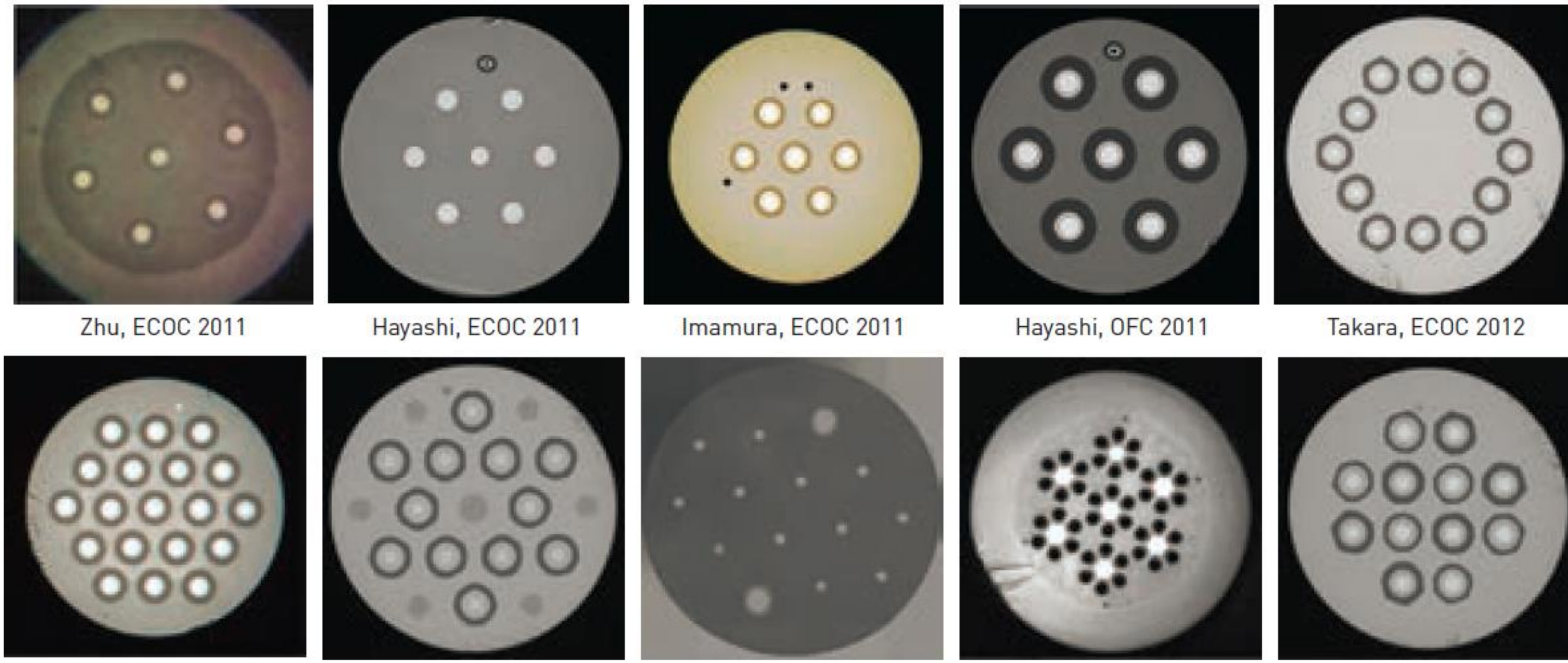
Wavelength vs spatial/space division multiplexing





Spatial multiplexing or space division multiplexing (SDM)

- Some fibers for SDM transmission



Zhu, ECOC 2011 | Hayashi, ECOC 2011 | Imamura, ECOC 2011 | Hayashi, OFC 2011 | Takara, ECOC 2012

Sakaguchi, OFC 2012 | Kobayashi, ECOC 2013 | Qian, FiO 2012 | Cia, IPS SumTop 2012 | Mizuno, OFC 2014

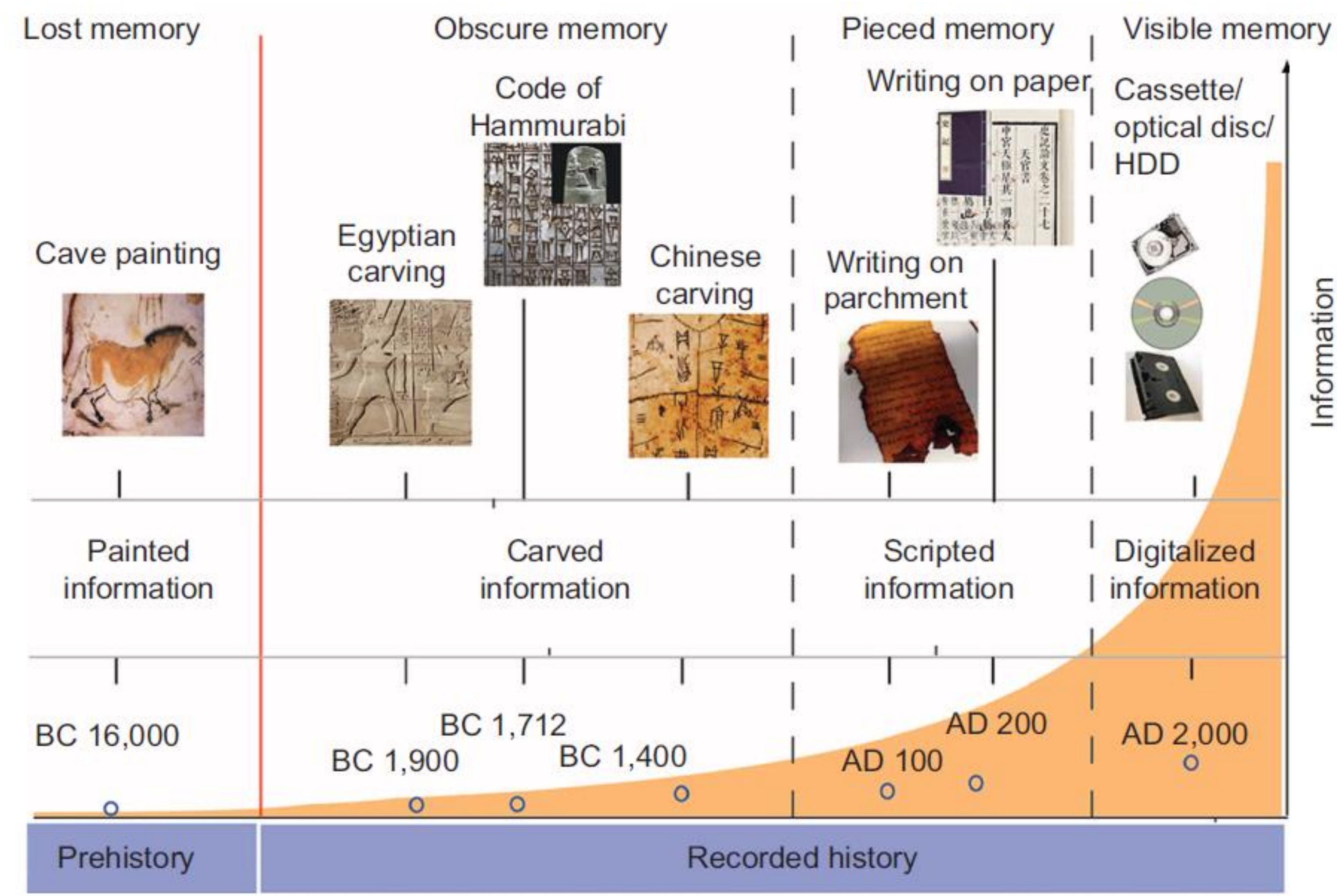
Source: OPN march 2015

Problems

- Huge investment: the new waveguide technology will require the deployment of new transmission fibers.
- How to ensure a smooth upgrade path from existing fiber optic networks?
- For now, such waveguides belong to the realm of fiction.
- Space division multiplexing systems must reuse the existing fiber infrastructure and available optical system components to the maximum possible extent.

INFORMATION STORAGE

Evolution of information storage



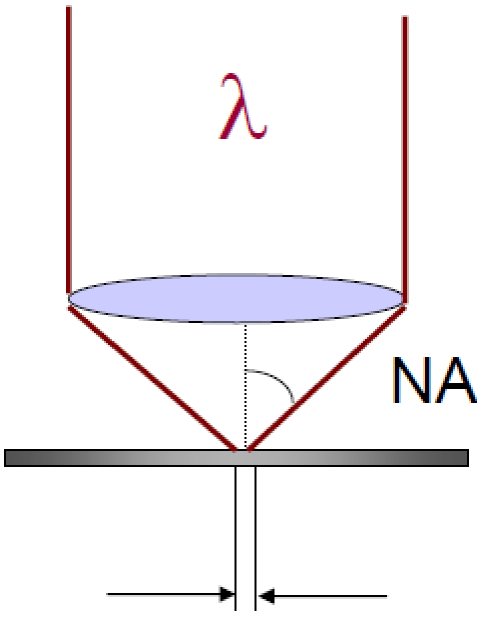
Light: Science & Applications (2014) 3, e177; doi:10.1038/lsa.2014.58

Evolution of optical data storage systems

First demonstration: Phillips 1979

First generation (1980s): CDs

- The information is in a 2D surface of a recording medium and occupies less than **0.01 %** of the volume.
- λ =780 nm (GaAlAs)
- Due to the limitation of the recording wavelength and the numerical aperture (NA) of the recording lens, the storage capacity was **650-750 MB**.



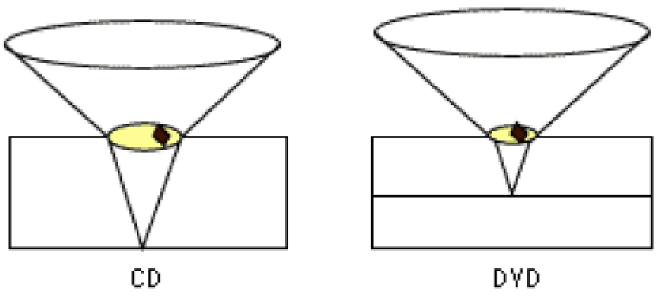
D=1.22λ/(NA)

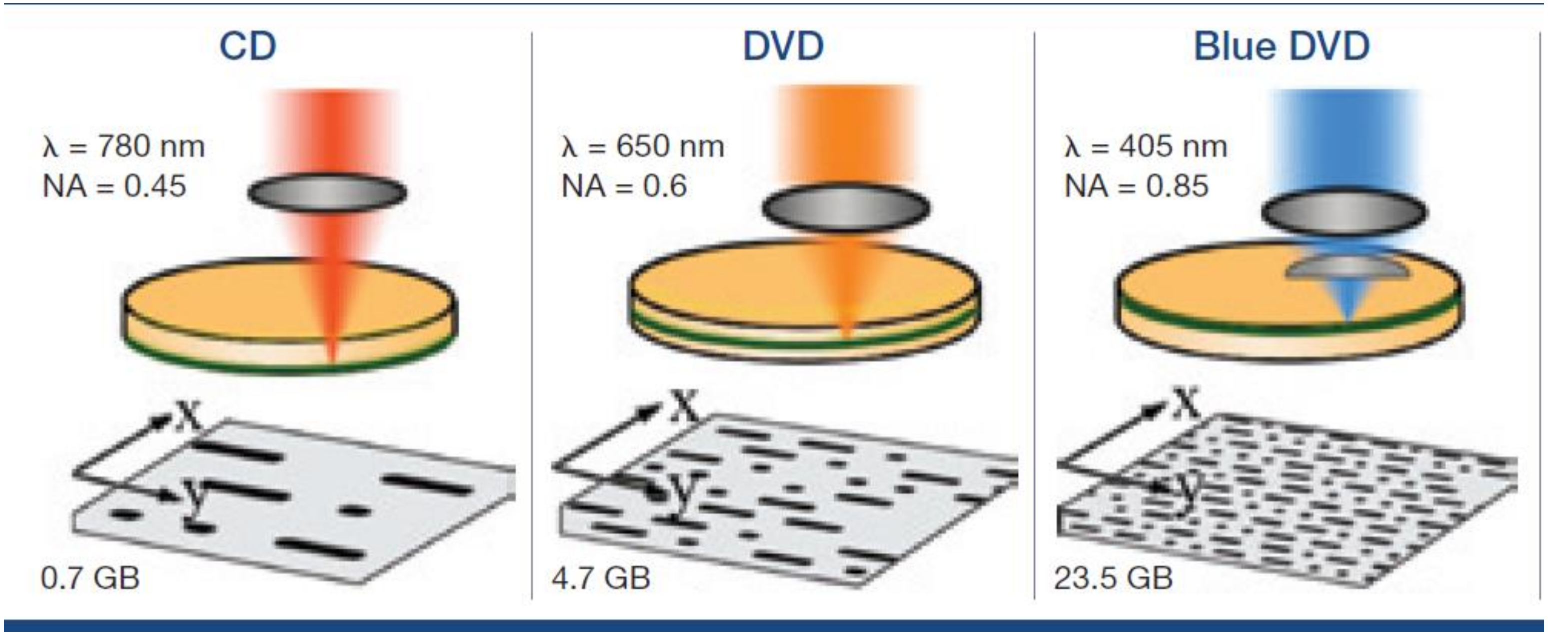
Diffraction-limited Focused Spot

Source: Optics and Photonics News July/August 2010

The following generations

- Digital versatile disks (DVDs, 1995)
- Blue DVDs (Blu-rays, 2000)





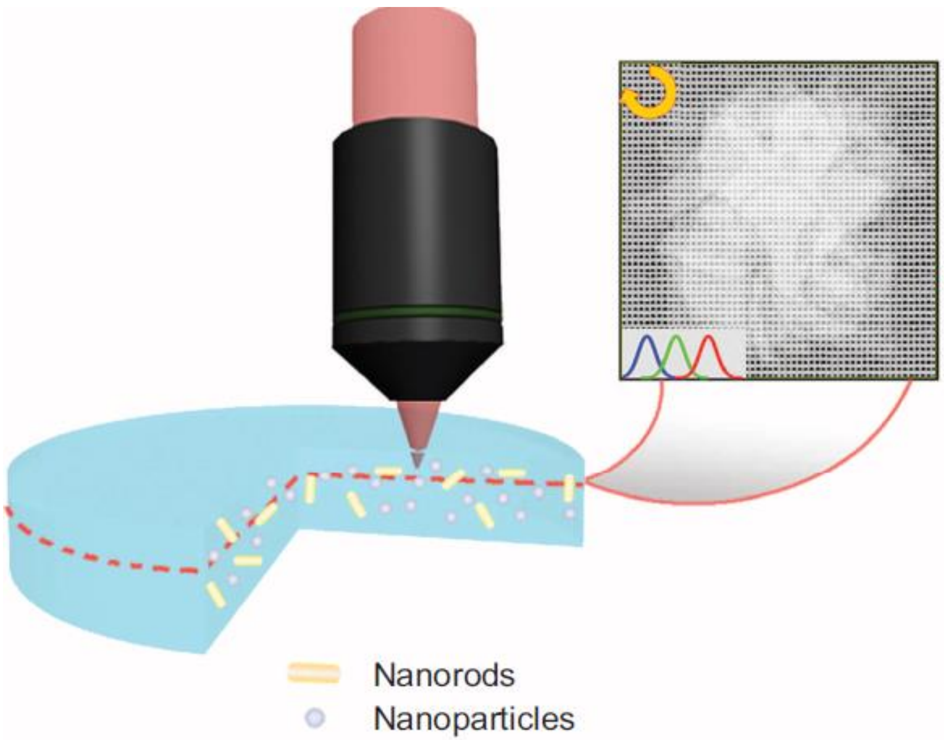
Blue light allowed to fit a full high-definition film onto a 12 cm disk

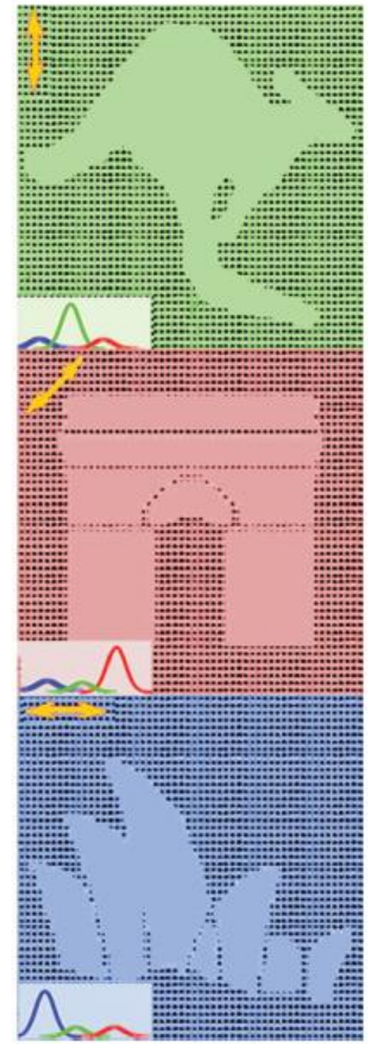
Source: Optics and Photonics News July/August 2010

What is next in optical data storage?

- Multi-dimensional systems (via two-photon absorption to decrease depth of field for more layers, or via the polarization of the laser beam),
- shorter wavelengths (via nonlinear optics: frequency doubling),
- super-resolution (stimulated emission depletion STED),
- holographic data storage.

5D data storage





The multiplexed information can be individually addressed by using the appropriate polarization state and wavelength.

Light: Science & Applications (2014) 3, e177; doi:10.1038/lsa.2014.58

INTEGRATED PHOTONICS: FROM ELECTRONS TO PHOTONS

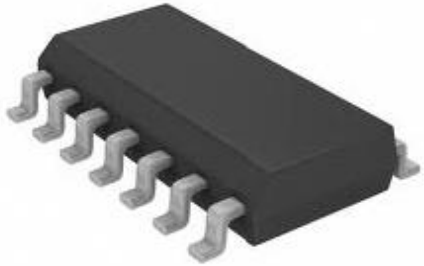
Moving **photons,** rather than **electrons,** requires less power

In electronics:

Vacuum tubes

Transistor

Integrated circuit

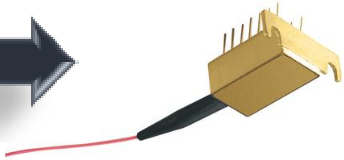


In photonics:

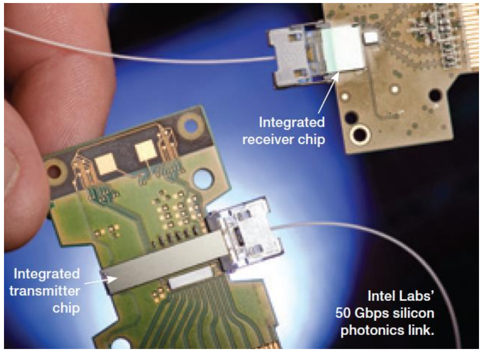
First diode lasers

Close-up of an early diode laser at Lincoln Laboratory

Diode laser



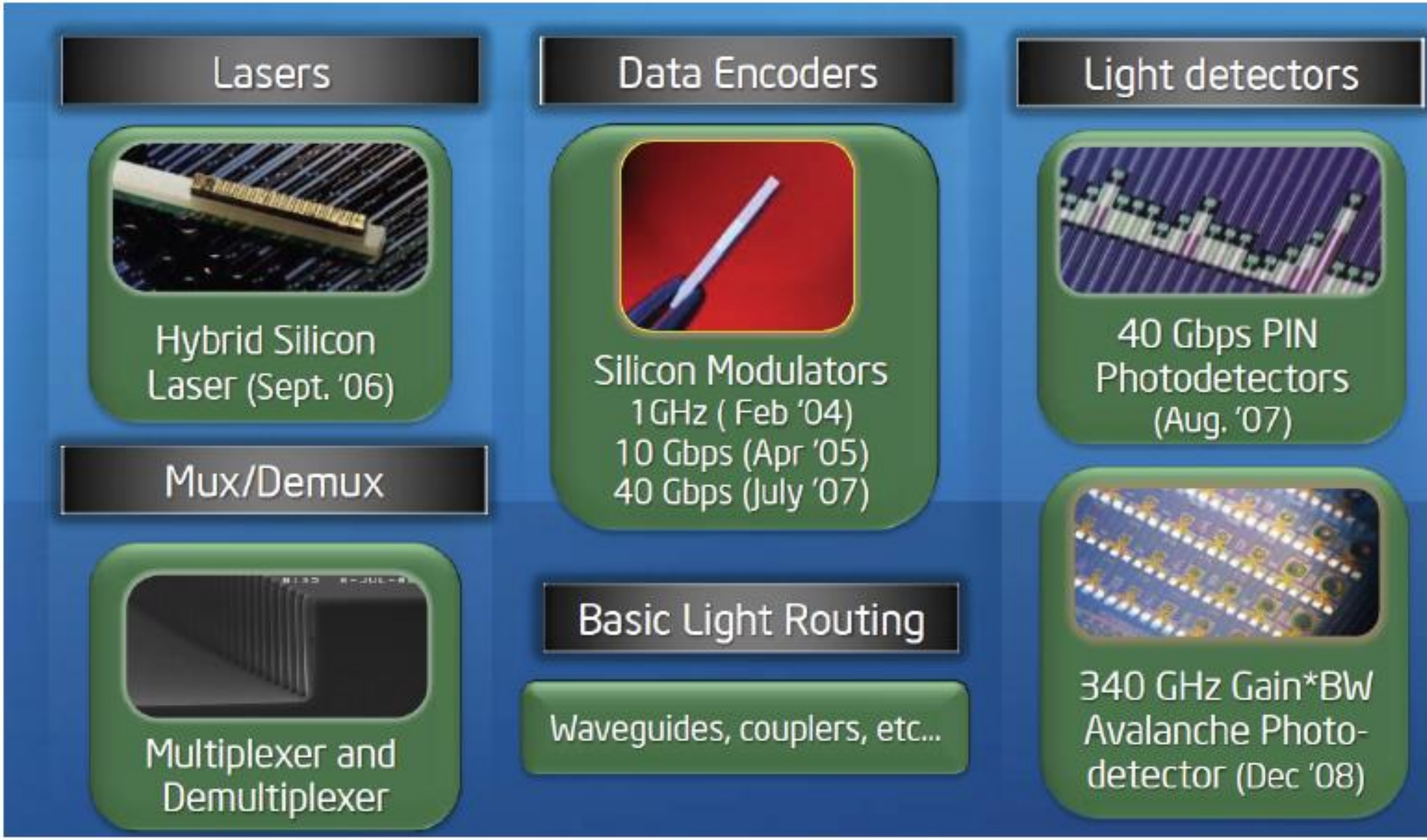
Photonic Integrated Circuit (PIC)



Silicon photonics

- Silicon is optically transparent at telecom wavelengths (1,310 and 1,550 nm), so it can be used to create waveguides.
- But silicon lacks the necessary physical properties for active devices:
  - the direct bandgap needed for light emission and
  - the electro-optic effect used for modulation of light.
- The temperatures at which high-quality GaAs layers grow are so high (700 C) that they damage conventional complementary-metal-oxide-semiconductor (CMOS) chips.

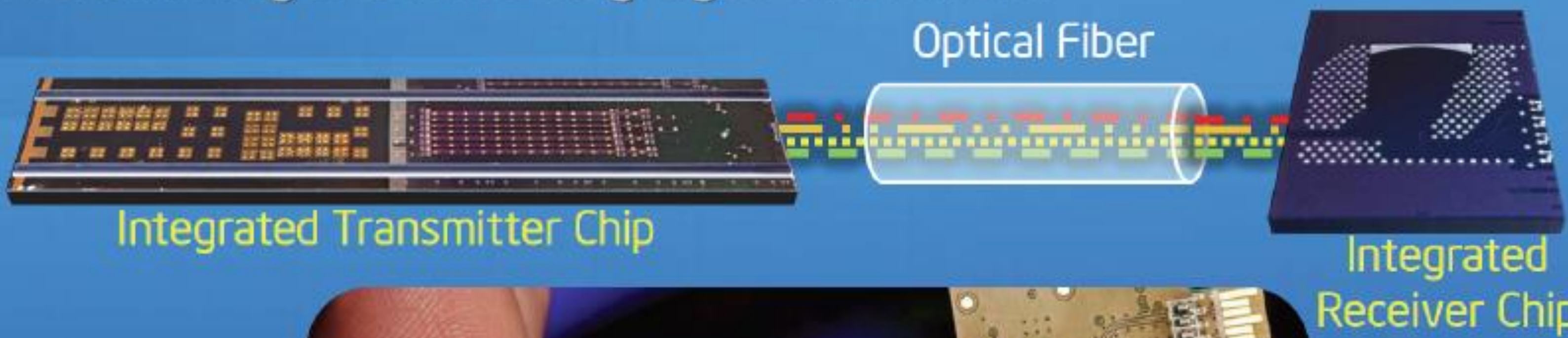
Silicon Photonics Building Blocks

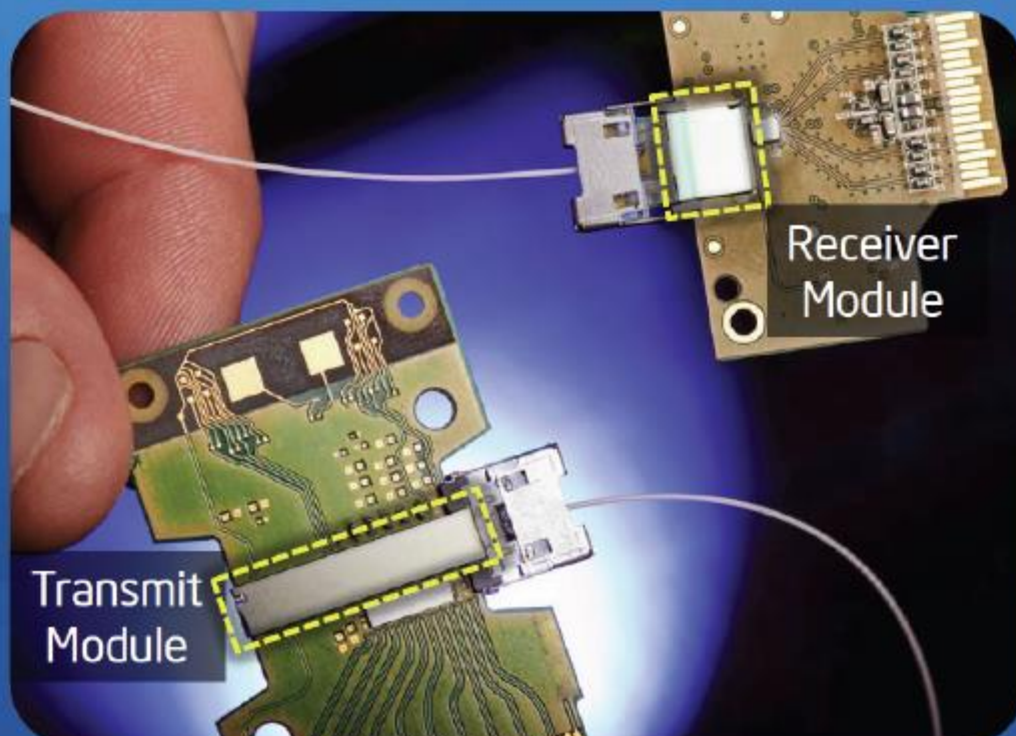


Source: Intel

The 50Gbps Silicon Photonics Link

Transmitting and Receiving Light with Silicon



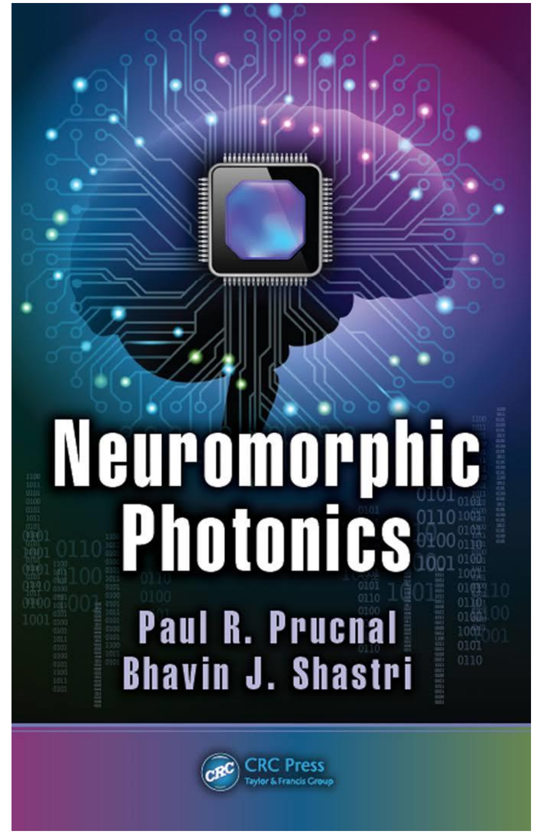


Recent advances in optical computing (or doing neural networks with photons)

- A programmable silicon nanophotonic processor was built with waveguides and interferometers.
- The team then trained the **simple neural net** implemented on the chip to recognize four vowel sounds, at an accuracy level of 77 percent.
- Compared to electronic chips, the nanophotonic chip can carry out computationally intensive operations using less than one thousand energy per operation.
- It can be scaled up to much bigger neural nets through techniques based in 3D photonic integration.

Shen et al, "Deep learning with coherent nanophotonic circuits", Nat. Phot. 11, 441 (2017)
Optics and Photonics News June 2017

New research field on neuromorphic photonics



- Excitable lasers could be the building blocks of ultra-fast, energy-efficient information processing systems.
- Inexpensive laser diodes (perturbed by optical feedback).

Summary

- Novel semiconductor lasers are nowadays actively being developed to meet the requirements of faster, and more energy-efficient optical communications.
- A lot of efforts are focused in developing silicon-compatible lasers.
- Integration is essential.
- With PICs, microprocessor chips use light, rather than electrons, to move data. This can result in much faster and energy-efficient datacenters and super-computes.

TF

- Long-wavelength VCSELs are used for short and medium distance optical communication links.
- Erbium-doped fiber amplifiers (EDFAs) are routinely used in datacenters and interconnect networks.
- Narrow-linewidth single-mode lasers allow optical dispersion compensation in transmission channels at rates of 2.5 or 10 Gbit/s.
- Electronic digital signal processing has replaced optical dispersion compensation in high-rate fiber-optic transmission systems.
- Increasing the diode laser wavelength increases the capacity of optical storage systems.
- The high-temperature required to grow III-V semiconductor materials is the main problem for integrating lasers into silicon chips.

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