PART A- Optical waveguides

LESSON A3-

Optical interconnect

Lesson A3

- What an “optical interconnect” is?
- Physical limits of electrical interconnect
- Levels of optical interconnect and requested technology
- Advantages (and disadvantages) of optical interconnect

Optical interconnect

Linking with Light

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Contributing Editor

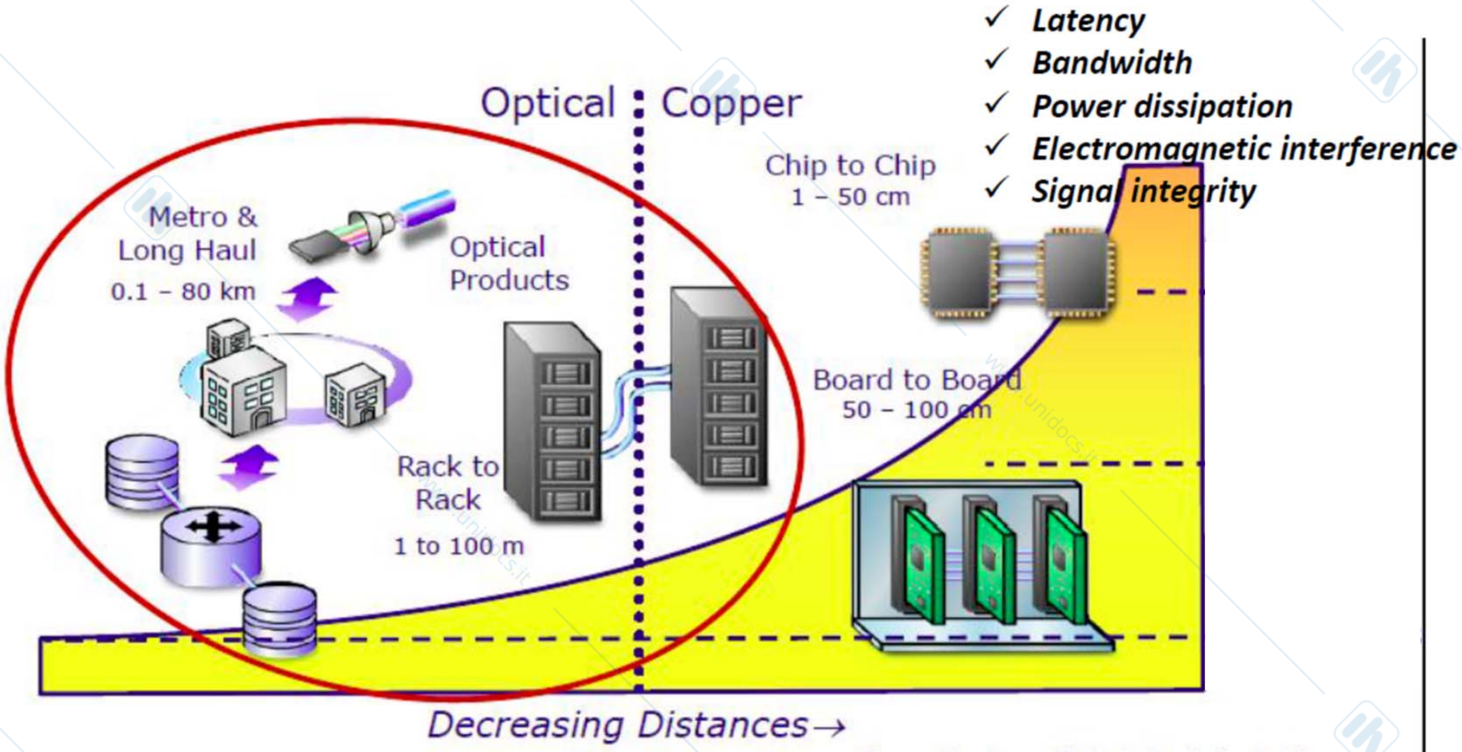
Having proven their worth in long-distance communications, photons will soon take over inside the computer

Optical interconnect

Some researchers say that, within just a few years, many of the copper connections in computers will be replaced with high-speed optical interconnects, in which photons, rather than electrons, will pass signals from board to board, or chip to chip, or even from one part of a chip to another.

The idea is simple in principle and it parallels what has already happened in telecommunication systems. An electrical signal from the processor would modulate a miniature laser, which would shine through the air or a waveguide to a photodetector, which would in turn pass the signal on to the electronics.

Battle between optics and copper



- ✓ ***Latency***
- ✓ ***Bandwidth***
- ✓ ***Power dissipation***
- ✓ ***Electromagnetic interference***
- ✓ ***Signal integrity***

Figure Courtesy of Mario Paniccia, Intel

Optics has progressively eliminated copper in the metro and long haul network in the last 20 years and will continue its migration all the way to chip to chip application in the next 20 years

Physical reasons for optical interconnect

- Limits of electrical interconnects
- Can optic solve these problems?

Exercise

Electrical

1) CK frequency: 1GHz-10GHz

- $\lambda=c/f$; With c=3e8m/s we have λ=3-30 cm

2) CK Propagates over the transmission line, CK signal is a voltage high or low => no frequency carrier

4) Loss of the transmission line increases with frequency

5a) Each signal requires a separate line => cross-talk due to coupling of the lines

5b) Increasing number of lines, it increases the physical space requested for the interconnection

Optical

1) λ=1.55 μm ***f***=193.5 THz

2) Information propagates along the optical waveguide; ***f*** is the frequency of the carrier. Information is sent turning light ON (=>1) and OFF (=>0)

4) No frequency dependent loss => Huge bandwidth is available for carrying the information

5a) same optical waveguide can carry more carriers (WDM) with very limited cross-talk

5b) WDM: each signal has a different carrier **(λ1,λ2,λ3) but it is transmitted within the same optical waveguide**

WDM optical interconnect

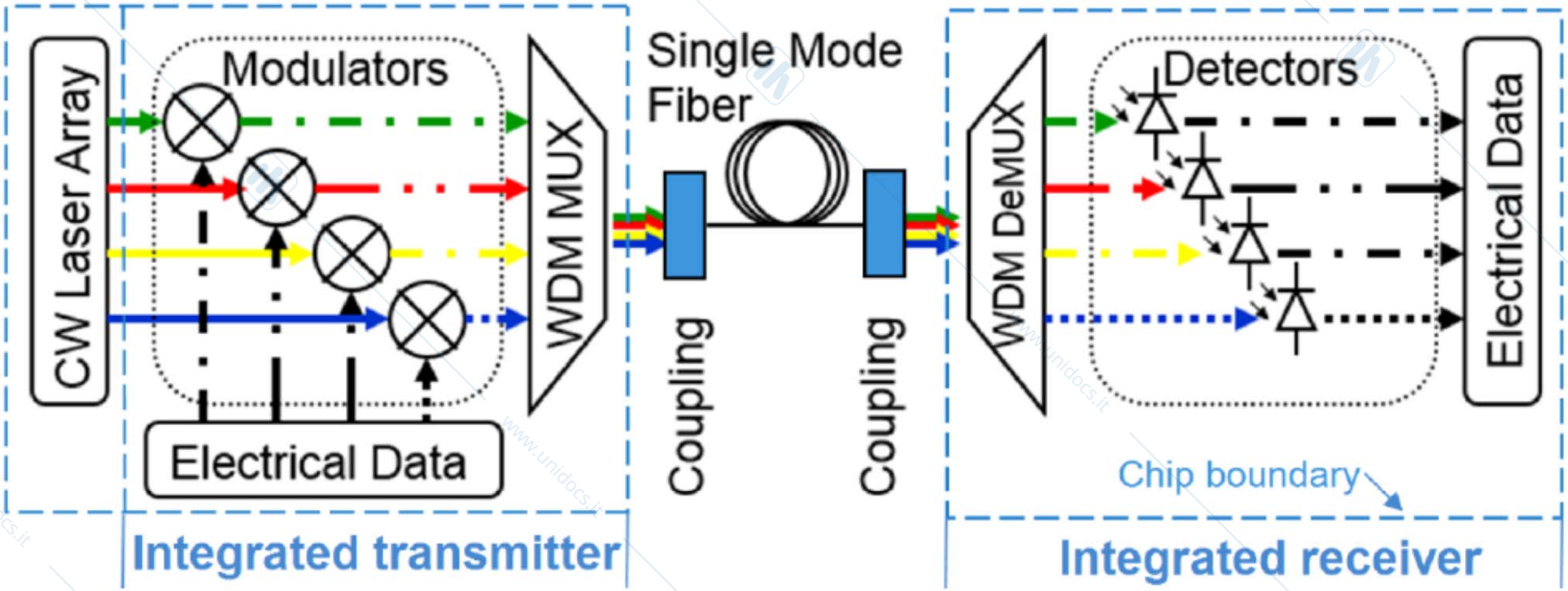
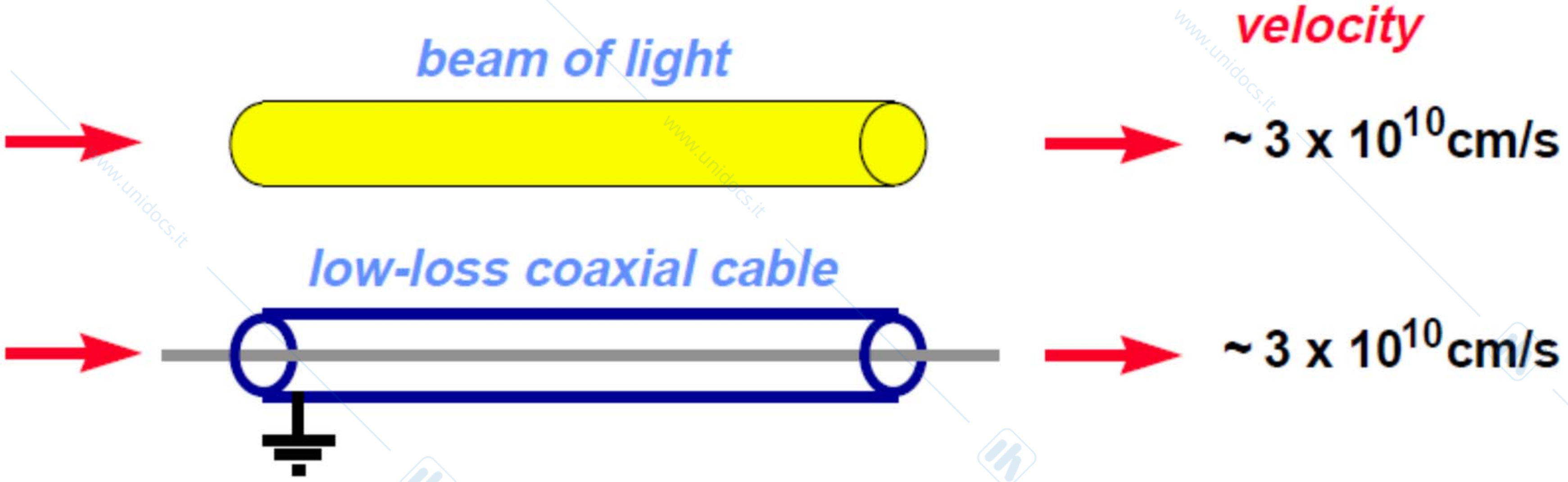


Fig. 6. Generic schematic of a Si photonics link consisting of a multi-wavelength laser source, an integrated transmitter, a fiber-based interconnect, and an integrated receiver.

Electrical and optical signals

- All optical signals are electromagnetic waves, and the same electromagnetic physics underlies electrical systems. In practice, in both the electrical and optical cases, it is electromagnetic waves that carry the signals. The signals move essentially at the velocity of light (actually somewhat smaller if the cables are filled with a dielectric; the same for optical waveguides). (Hence it is not in general correct to say that signals propagate faster in optics because they move at the speed of light - a point that is relatively obvious physically, but often mis-stated.



Phase velocity:
$v_{ph}=c/n_{eff}$

Group velocity
$v_g=c/n_g$

Limits of high speed interconnects

- Skin-effect
- Dispersion => distortion
- Cross-talk

Skin effect

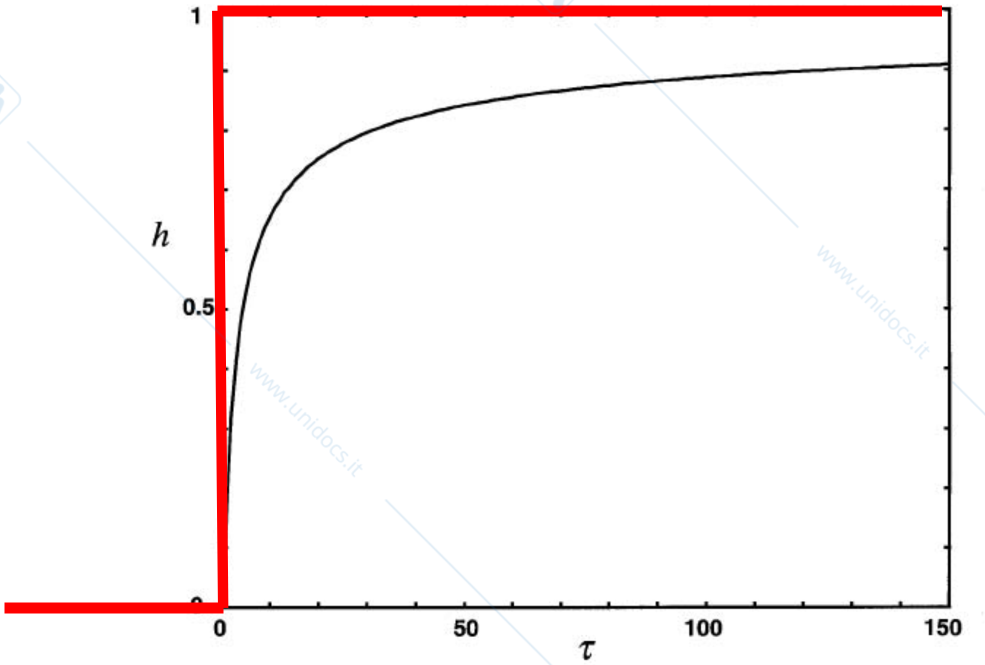
Skin-effect: The skin effect is a well-known consequence of Maxwell’s equations for the case of wave propagation in the presence of conductors. All of the conduction tends to occur within about a “skin depth,” ,of the surface of the conductor. It is given by:

$$\delta = \frac{1}{\sqrt{\pi f \mu_r \mu_o \sigma}},$$

=> Increase of resistance R => transmission line with loss

Consequence of R

When skin-effect-limited resistance loss dominates (e.g., neglecting radiation loss and dielectric loss), the response, h(τ), at the (properly terminated) end of an LC line to a unit step function input is:



Red: voltage step at driver

Black: voltage at line end (match load termination)

FIG. 1. Rise of a voltage at the end of a terminated, skin-effect-limited transmission line when driven by a unit step function (in dimensionless units of time).

Consequence on Eye diagram

The long total rise time of the skin-effect-limited line leads to substantial “pattern-dependent” effects, as can be seen in Fig. 2. For a bit period of 5 time units, making the digital decision as to whether a given bit is a “zero” or a “one” is not quite impossible (the eye is still “open”), but a relatively sophisticated “decision” circuit would be required to do so, and the immunity to noise is clearly significantly degraded.

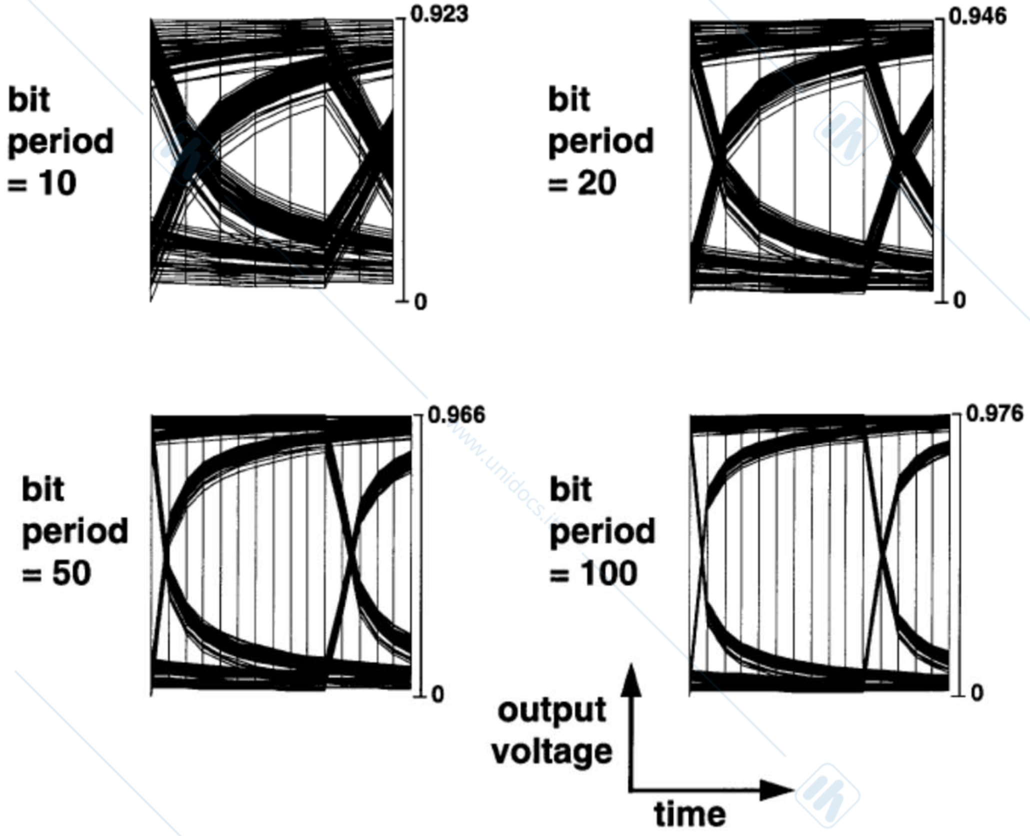
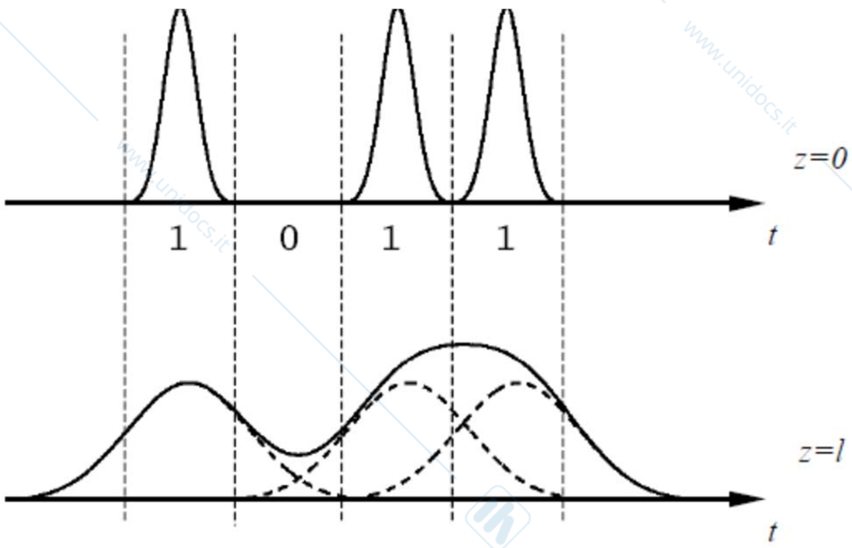


FIG. 2. Eye diagrams for bit periods corresponding to 10, 20, 50, and 100 normalized time units, calculated for a random 256-bit pattern.

Signal distortion due to attenuation and dispersion

- Attenuation and dispersion of the transmission line causes ISI => limits the bit rate . ISI makes impossible the simple discrimination of the current bit being transmitted.



Limits of electrical interconnect (many wires…)

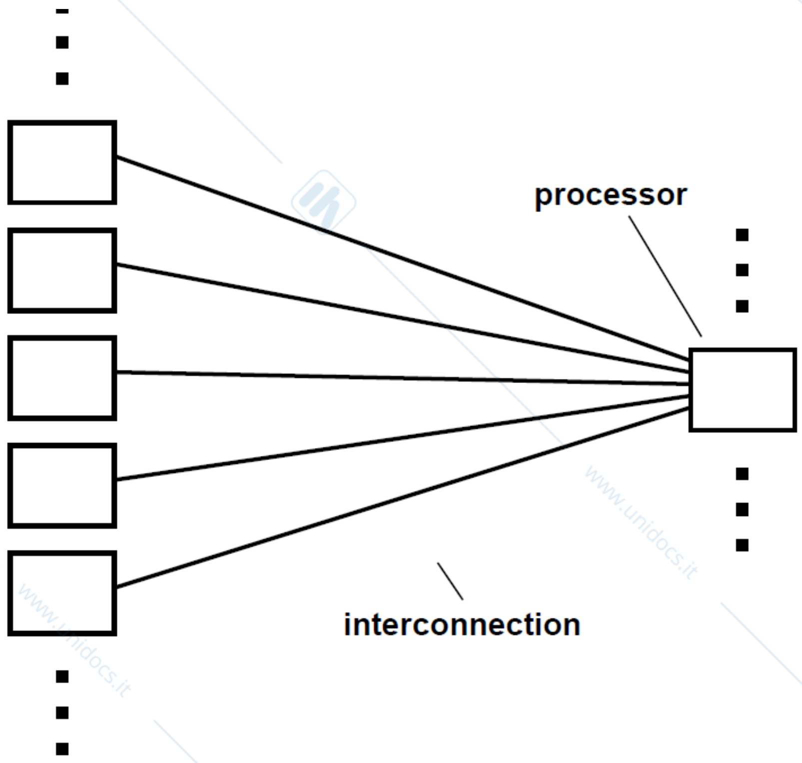


Fig. 4. Illustration of one kind of high-aspect-ratio architecture, in which one processor needs to communicate directly with many others, hence requiring long, thin interconnections (i.e., high aspect ratio interconnects).

Many closely spaced wires cause cross-talk

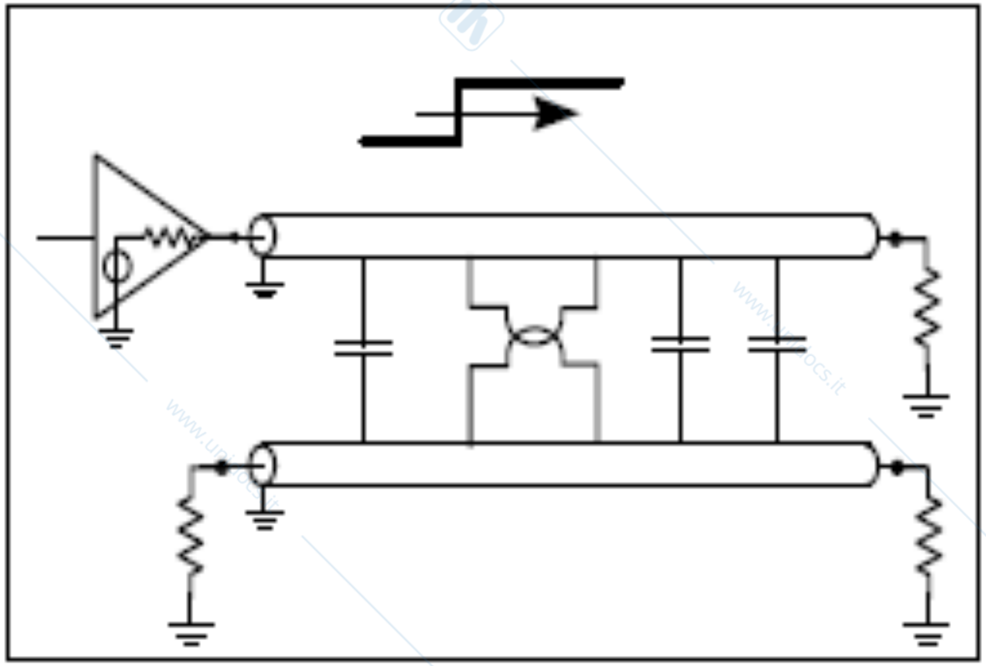


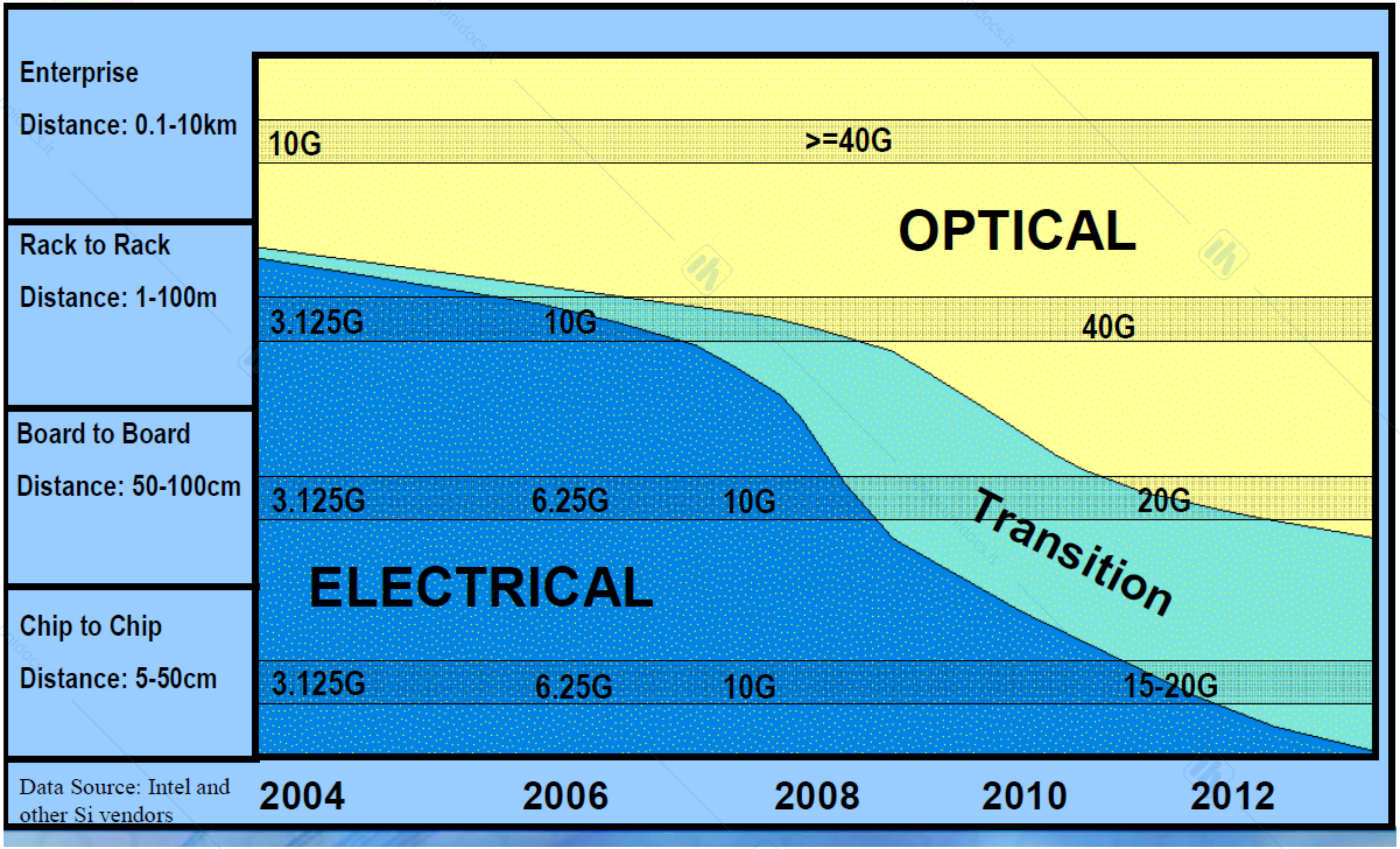
Fig 1.4 Transmission line model for crosstalk analysis.

Advantages of optical interconnect

- **No frequency dependent loss**. For example changing the modulation frequency of an optical signal from 10MHz to 10GHz does not change (significantly!!) the loss experienced by the signal
- **The loss in optical fibers (or other low loss optical waveguides) can be extremely low in absolute magnitude**, e.g., 0.2 dB/km in fiber used for long distance communications, leading to negligible distance dependent loss over the scale of interconnect distances.
- **Dispersion**, though it does exist in optical fiber, i**s relatively weak compared to metallic cable**, and can be compensated anyway. Optical fiber dispersion is not relevant in short distance links.
- **We can use WDM**: more than one channel on the same physical cable
- **No EMI**
- **Optical interconnects give us perfect electrical isolation** between two circuits, and make the absolute voltage levels in the different circuits irrelevant.

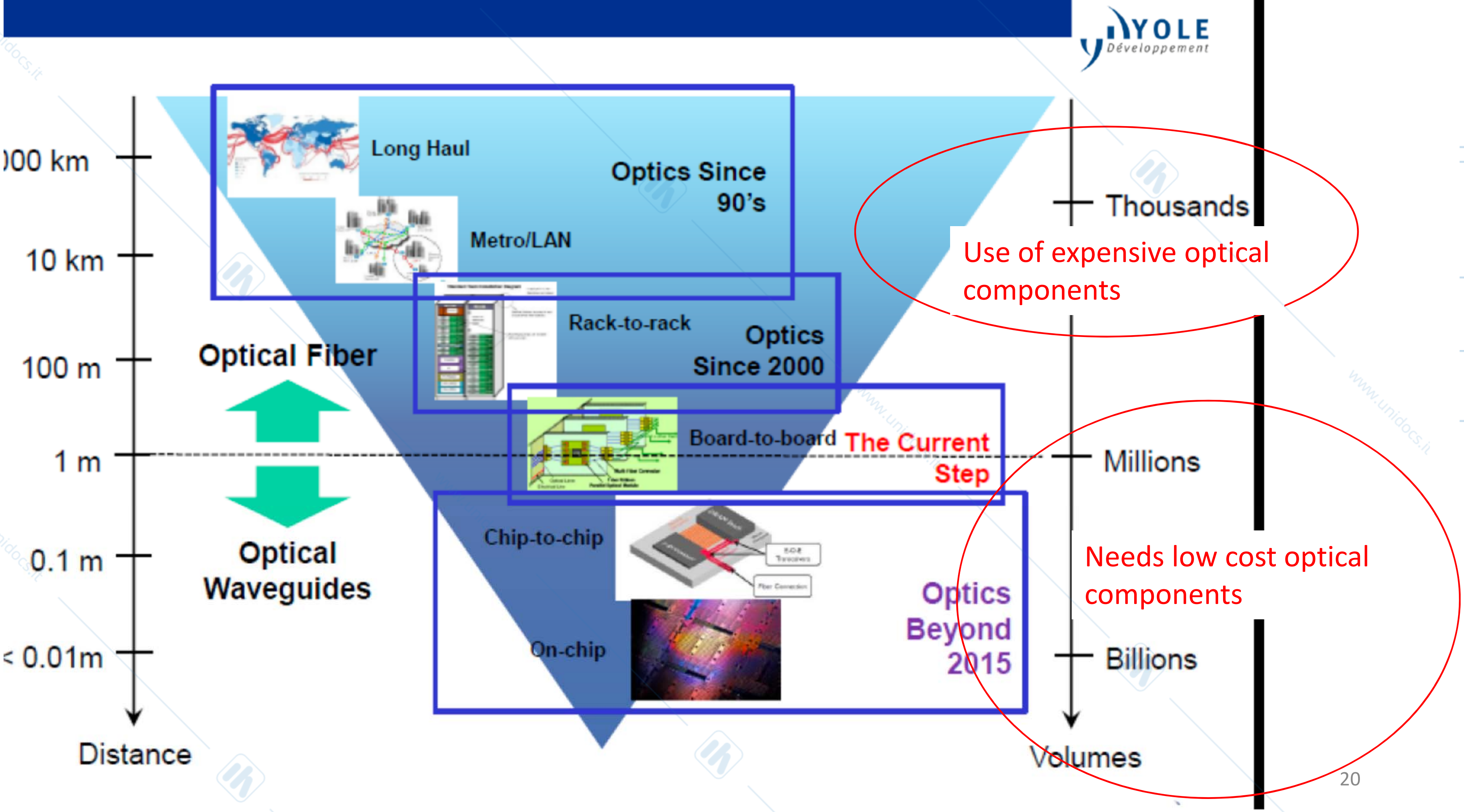
Levels of optical interconnect

- Connect racks=> use fibers, distance 1-100 m
- Connect boards => A use fibers, distance 50-100 cm
- Connection on the board, chip to chip => use fibers or other dielectric waveguides, distance <50 cm
- Inside the chip: is optics a good solution??



Data Source: Intel and other Si vendors

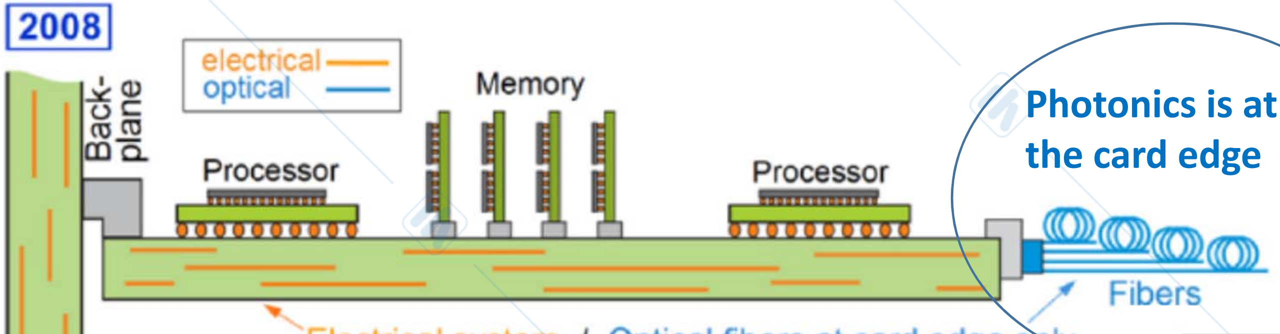
Optical Interconnects



Use of expensive optical components

Needs low cost optical components

Rack to Rack

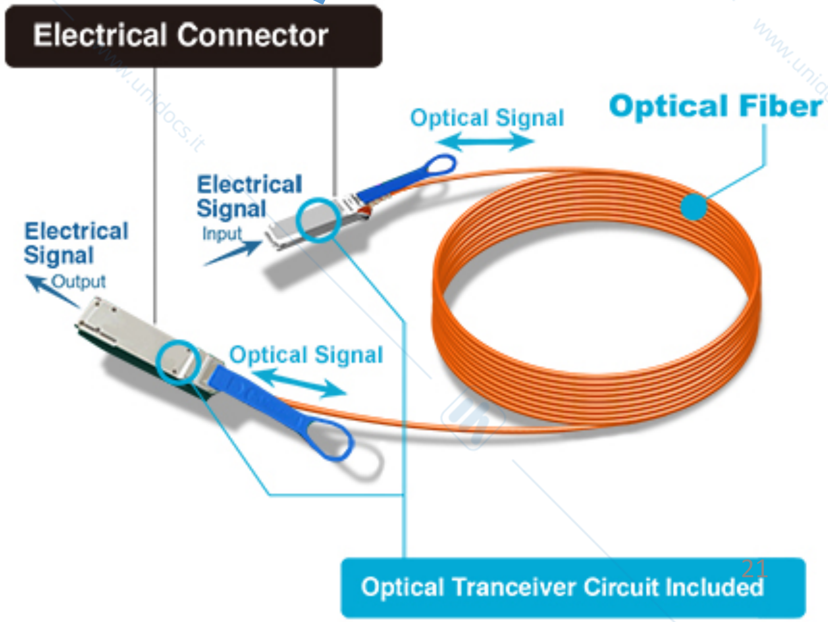


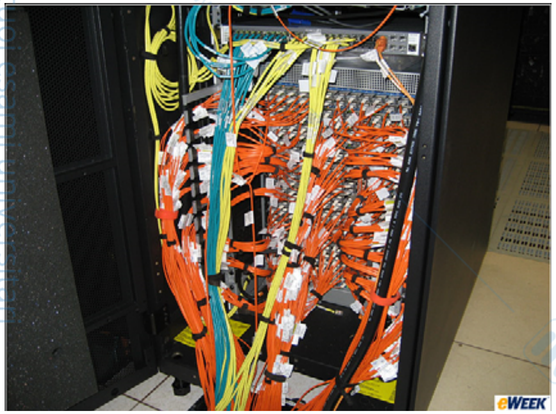
Electrical system / Optical fibers at card edge only

(a)

Photonics is at the card edge

Today
Optical connections between individual computers are commercially available.

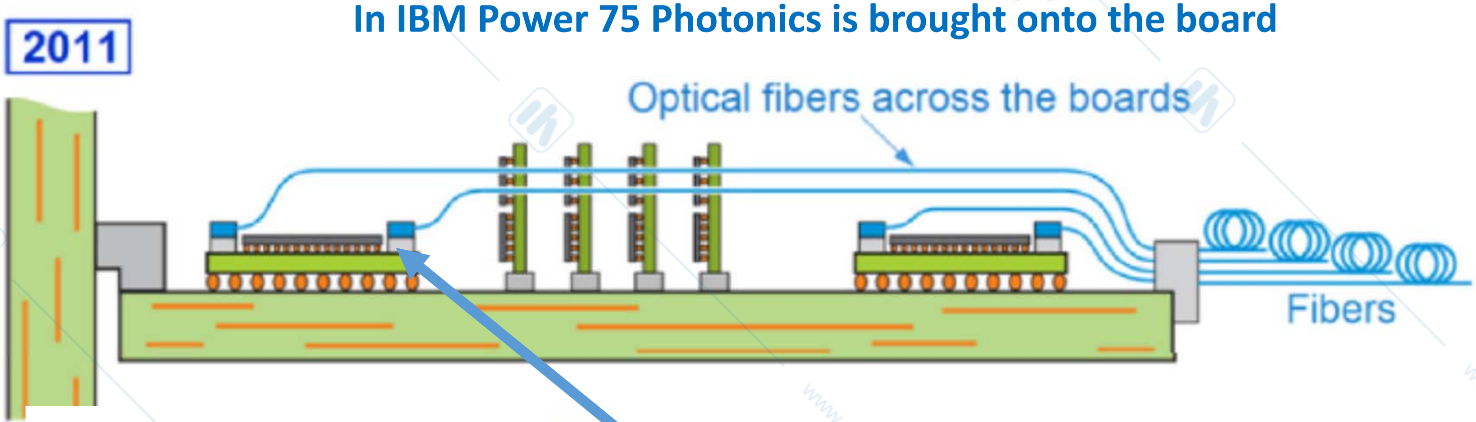




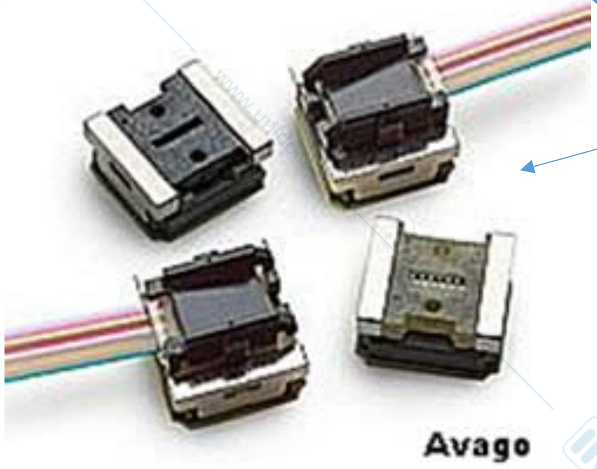
In putting together Roadrunner, IBM engineers needed to run miles and miles of fiber-optic cabling to connect the various pieces into one supercomputer.

Board to board: IBM+ Avago Micropod

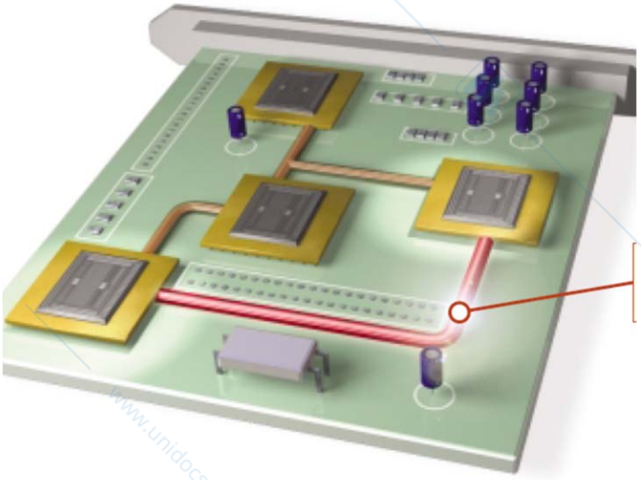
In IBM Power 75 Photonics is brought onto the board



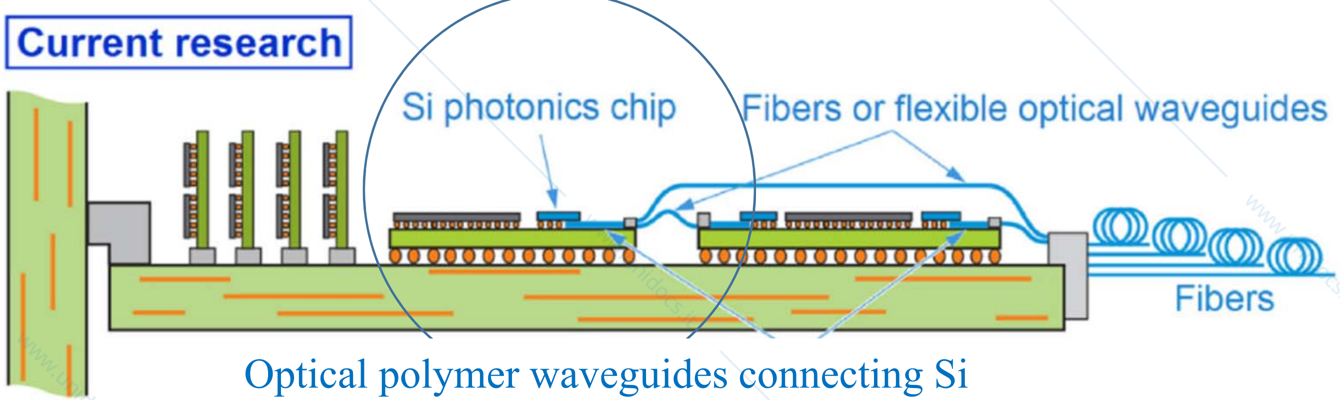
Avago MicroPOD transceiver or Avago optical FPGA



On board: chip to chip (IBM)



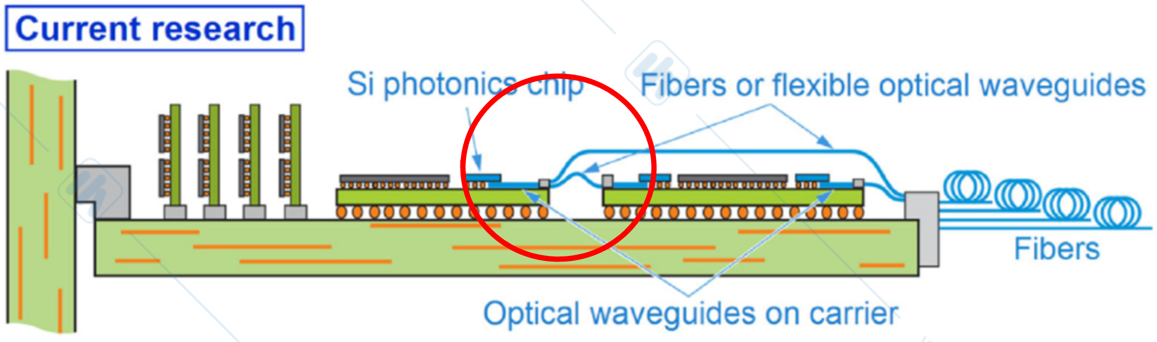
Integration of electronic chip
with silicon photonic chip



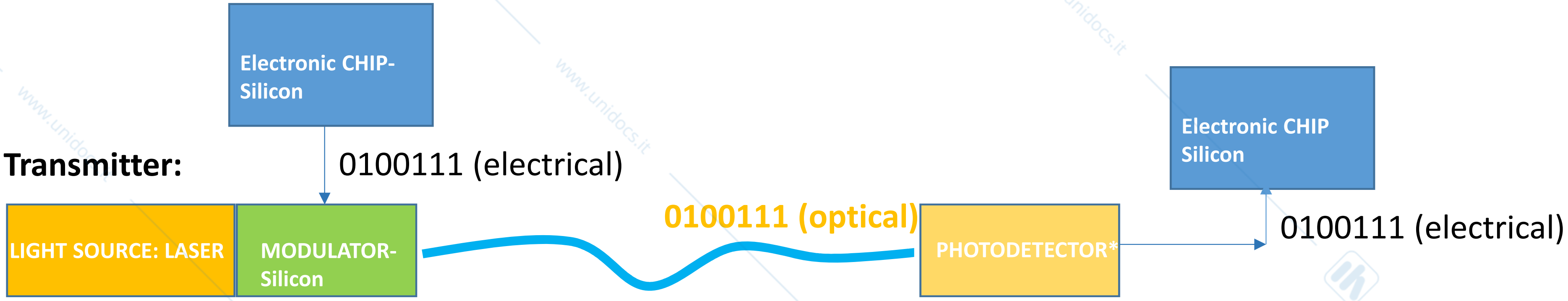
Optical polymer waveguides connecting Si photonics chips assembled on carriers with the carrier edge, other carriers, and board edge.

Inside the chip?

Optical interconnect building blocks



(c)



Transmitter:

LIGHT SOURCE: LASER

MODULATOR-Silicon

Electronic CHIP-Silicon

0100111 (electrical)

0100111 (optical)

PHOTODETECTOR*

Electronic CHIP Silicon

0100111 (electrical)

Laser sources do not exist in Silicon!!

Fiber or flexible optical waveguide

Receiver:

* Ge Photodetector can be integrated in silicon

Building blocks of optical interconnect

Optical link: Optical waveguides or optical fiber

Optical transmitter:

- Light source (lasers)=> generate light signal (carrier)
- Modulation (optical modulator): add the information (0100111…)
- Signal processing blocks (MUX, filter, ….): they are passive optical or electrical controlled components and can be realized in silicon chip (silicon waveguides)

Optical receiver:

- Signal processing blocks (DEMUX, filter, …):they are passive or electrically controlled optical components and can be realized in silicon chip (silicon waveguides)
- Photodetector => generate electrical signal (0100111…)

Silicon for Photonics components: the good and the not so good!!

- Transparent in 1.3-1.6 μm region
- CMOS compatibility
- Low cost
- High-index contrast – small footprint
- – High index contrast –waveguide loss
- – No detection in 1.3-1.6 μm region (in bulk Si) → Use Germanium photodetectors
- – No linear electro-optic effect → Need of plasma effect for realizing intensity modulators
- – No efficient light emission → Lasers can not be realized in Silicon! Need "strategies" to integrated III-V materials with silicon

Challenge (I): optical waveguide integrated in with PCB carrier

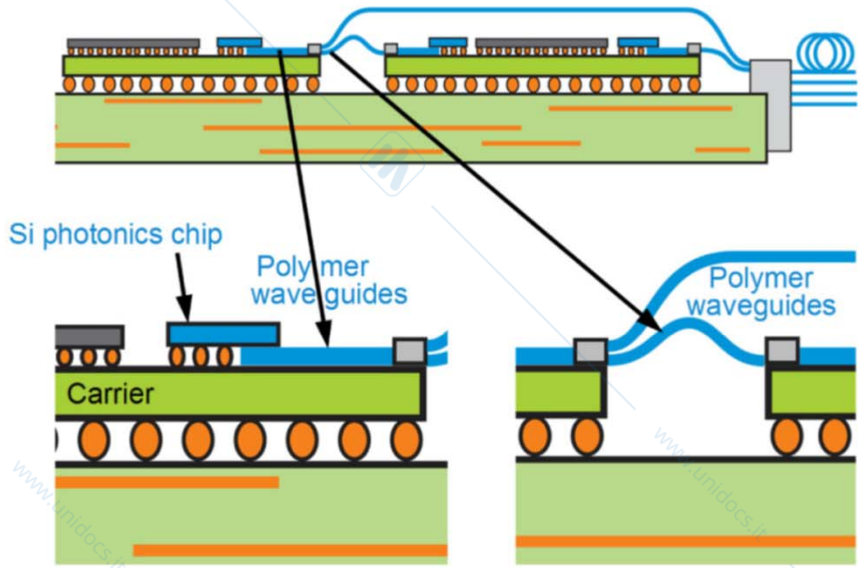


Fig. 5. Schematic illustrating current research work, i.e., the use of SM polymer waveguides to connect Si photonics chips with the system.

- Polymer waveguides are envisioned to distribute the optical signals, similar to the role played by copper traces in established high-density electrical laminates.

- Furthermore, they form the interface between the Si photonics chip and the fiber cable.

- This approach has several advantages:

a) Direct soldering of Si photonics chips reduces the overall assembly effort.

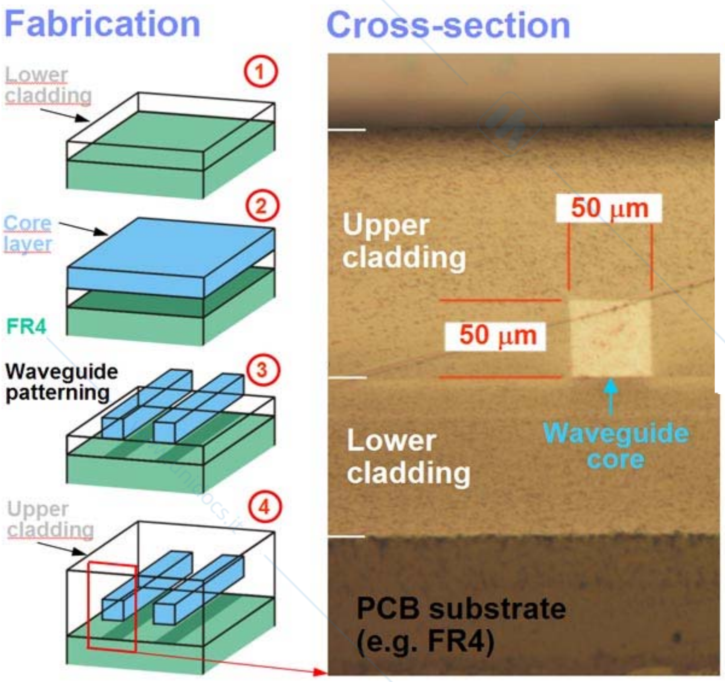
b) Smaller footprint

c) Improved electrical signaling due to shorter electrical interconnects with fewer interfaces.

d) Additional functionalities available in integrated Si photonics, such as wavelength division multiplexing (WDM).

Polymer optical waveguides (IBM)

On PCB carrier



Waveguide characteristics

Table 1. Comparison between MM polymer, SM polymer, and SOI waveguides (WGs)

Properties	MM polymer WGs	SM polymer WGs	SOI waveguides
WG dimensions [width × height]	35–50 µm × 35–50 µm	6–8 µm × 6–8 µm	300–500 nm × 140–250 nm
Operation wavelength	850 nm	1.31 and 1.55 µm	1.31 and 1.55 µm
Typical propagation loss	0.05 dB/cm @ 850 nm	0.5 dB/cm @ 1.31 µm 1 dB/cm @ 1.55 µm	3 dB/cm @ 1.31 µm 3 dB/cm @ 1.55 µm

Index contrast:
Δn=0.02

Index contrast:
Δn=0.008

Index contrast:
Δn=3.5-1.45

Assembling with Silicon photonic chip

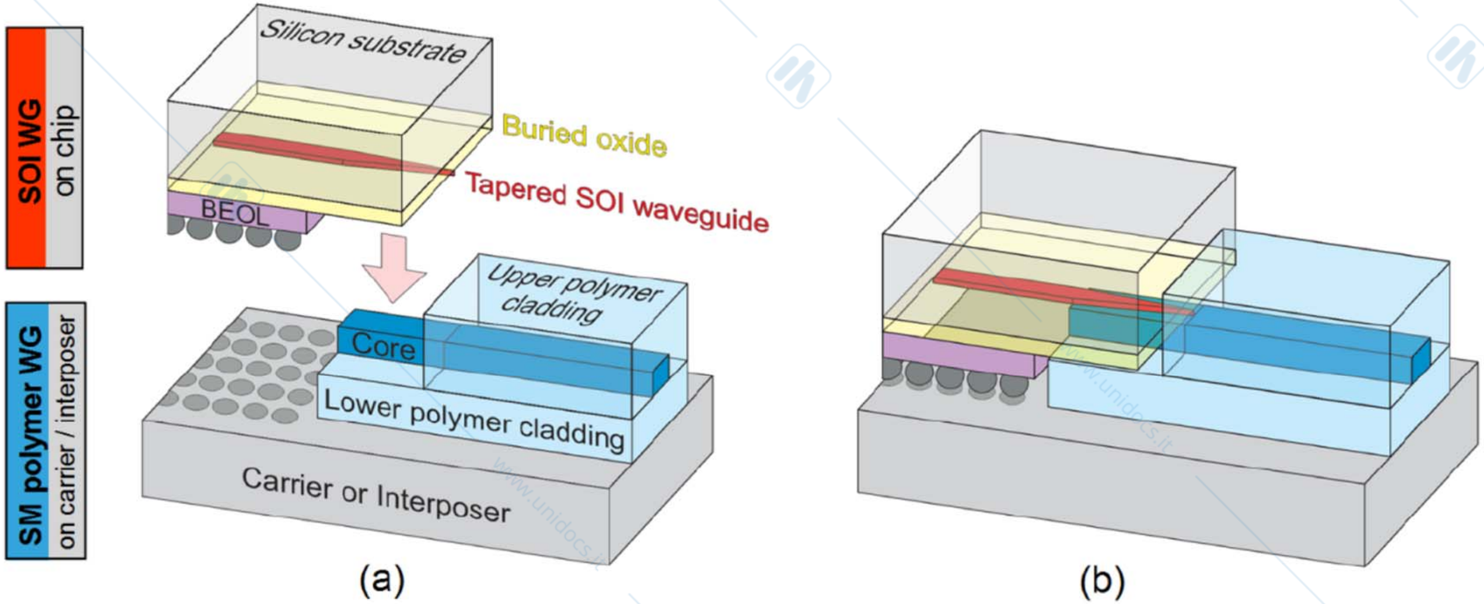


Fig. 13. Assembly for adiabatic optical coupling between Si photonics chip and SM polymer waveguide. (a) Locally tapered and un-cladded SOI waveguide on Si chip is brought into physical contact with locally un-cladded SM polymer waveguide on a carrier or interposer. (b) Situation after assembly.

Light coupling

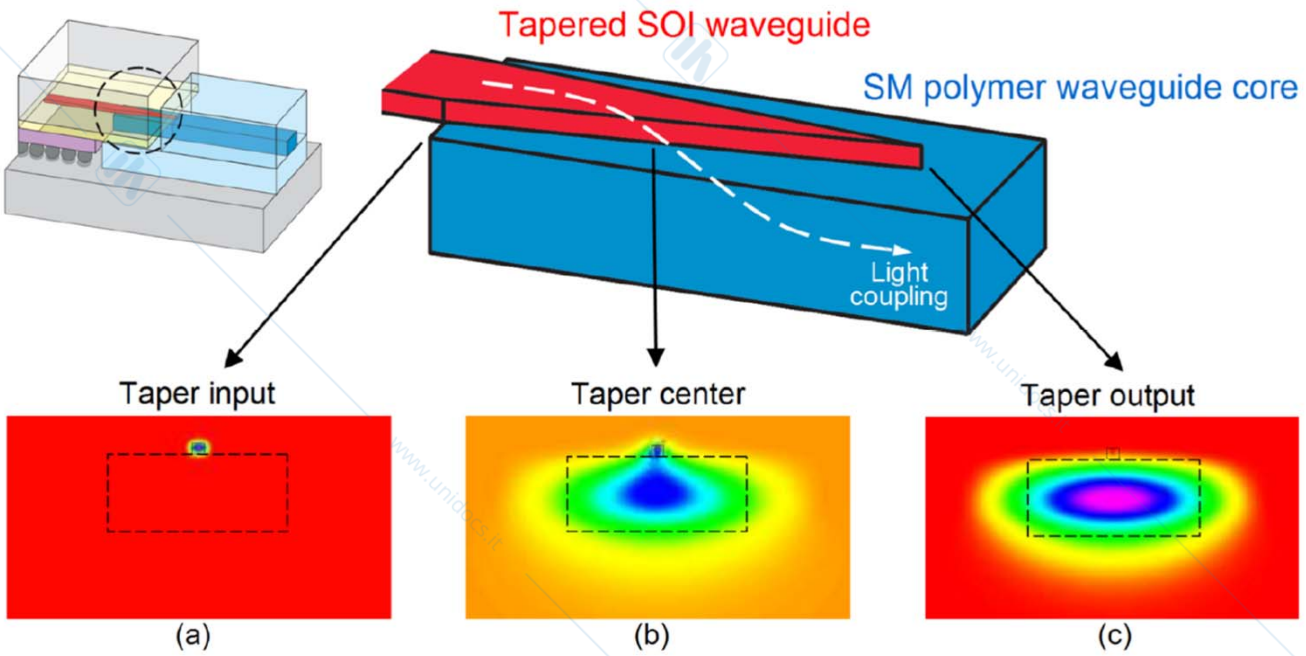
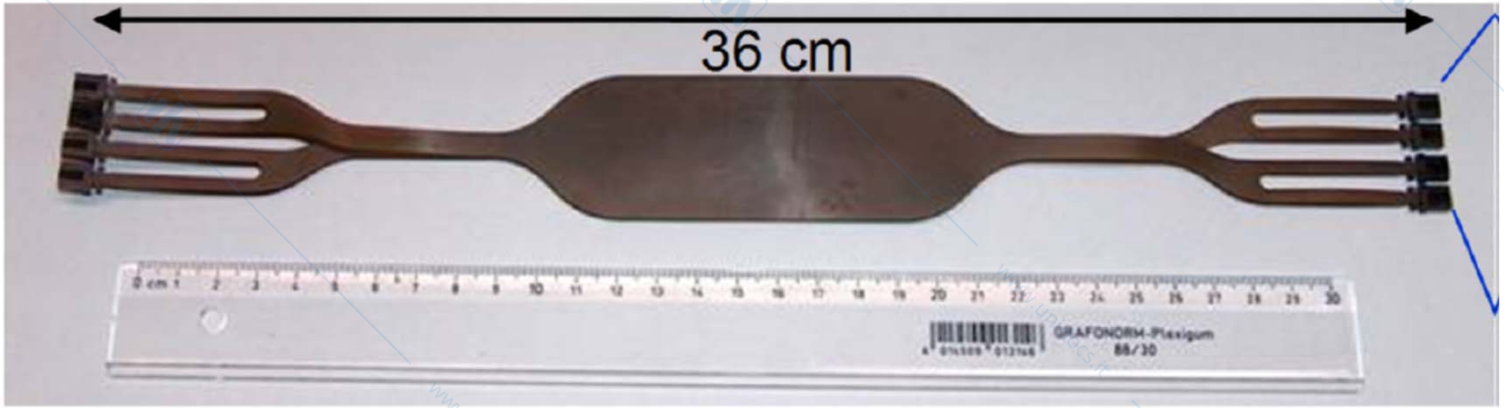


Fig. 14. Theoretical simulation results for adiabatic optical coupling at $\lambda = 1550$ nm: (a) light is completely confined in SOI waveguide, (b) light is confined in both waveguides, and (c) light is completely confined in SM polymer waveguide.

Flexible polymer waveguides



(c)

Challenge (II): Silicon photonics integrated circuit, devices compatible with CMOS technology

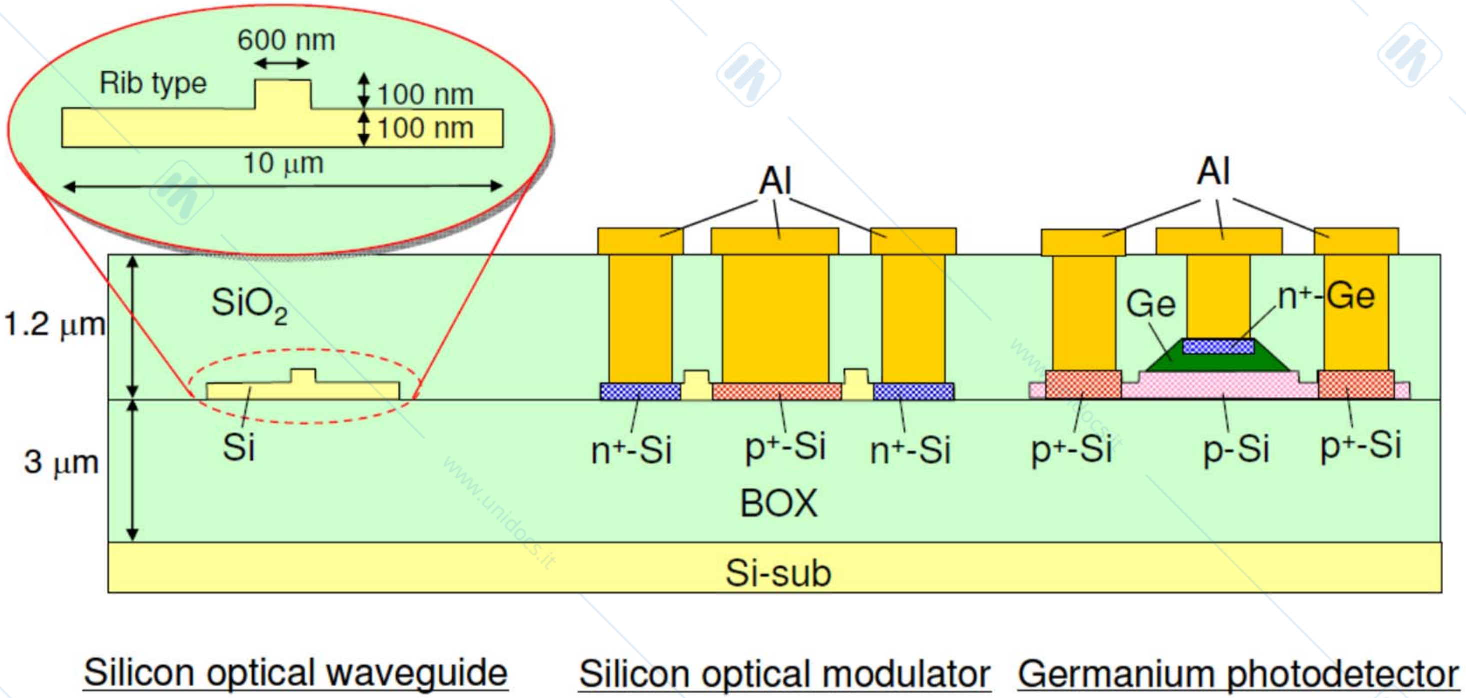


Fig. 2. Cross section diagrams of optical components.

Challenge (III): laser integration

- ☹ Lasers are not available in silicon.
- ☹ We need integrating the lasers realized with other semiconductor materials with the silicon platform

Summary slide

- Optical interconnects may overcome limitations of copper interconnect and may have success also in short distance link

- We have various levels of optical interconnects:
- Rack to rack => active optical cable
- Board to board => optical fibers
- On board => optical fibers, polymer waveguides and silicon photonic integrated circuits

- The development of optical interconnect requires production of hich volume and low cost optical components

- The low cost can be achieved if the optical components are realized in Silicon and compatible with CMOS technology.