MIT 3.071
Amorphous Materials

13: Optical Fibers and Waveguides

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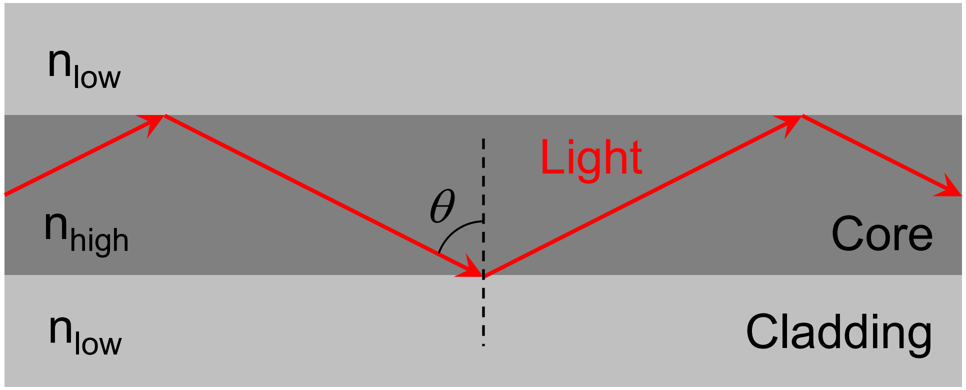
The masters of light

"*If we were to unravel all of the glass fibers that wind around the globe, we would get a single thread over one billion kilometers long – which is enough to encircle the globe more than 25 000 times – and is increasing by thousands of kilometers every hour.*"

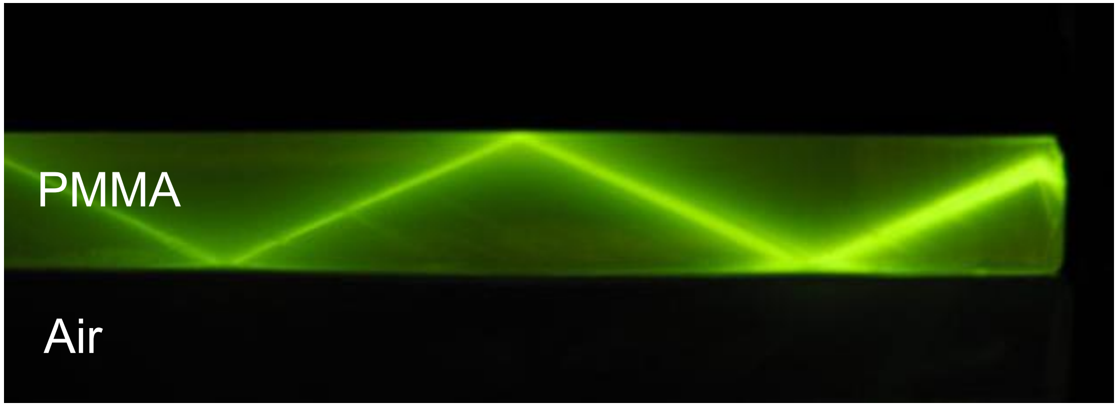
2009 Nobel Prize in Physics
Press Release

Light confinement via total internal reflection



Condition for TIR:

$$\sin\theta \geq n_{low} / n_{high}$$

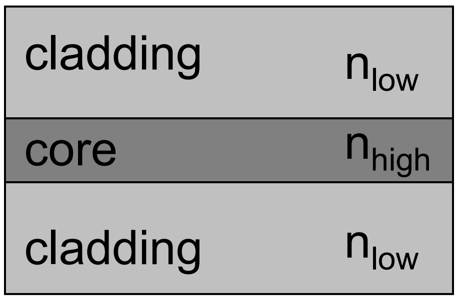


Snell is right
by Ulrich Lohmann

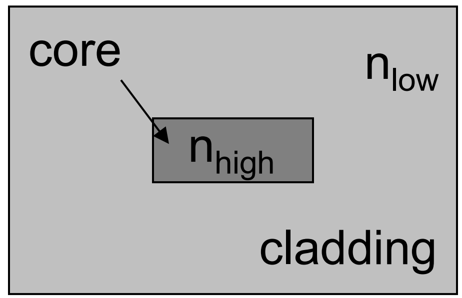
Waveguide cross-section geometries

1-d optical confinement

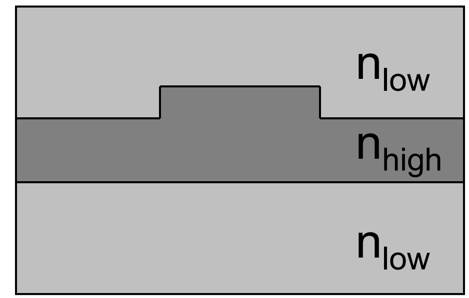
2-d optical confinement



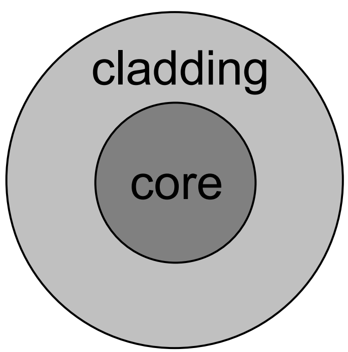
Slab waveguide



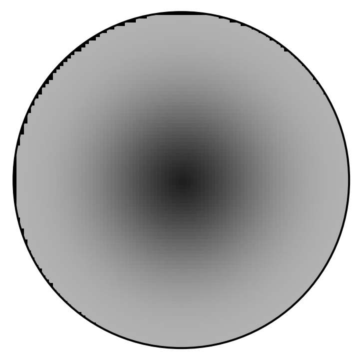
Channel/photonic wire waveguide



Rib/ridge waveguide



Step-index fiber



Graded-index (GRIN) fiber

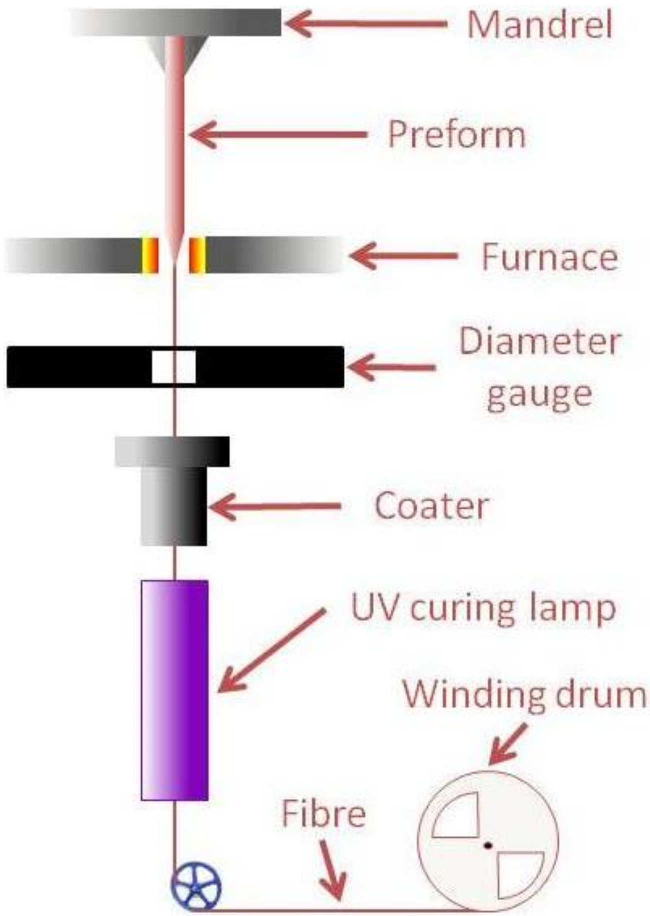
Optical fiber materials

- Glasses: silica and other oxides, chalcogenides, halides, polymers
- Metals, crystalline oxides and semiconductors, etc.
- Dopants in silica glass
  - Increase index: GeO_2, P_2O_5, TiO_2
  - Decrease index: B_2O_3
  - Luminescent centers: rare earth (e.g. Er)

Figure of Refractive index at λ = 0.5893 vs composition for GeO2–SiO2 glasses prepared and measured by various researchers removed due to copyright restrictions. See Figure 3: Fleming, J.W. "Dispersion in GeO2–SiO2 Glasses." *Appl. Opt.* 24 (2004): 4486-4493.

Appl. Opt. **24**, 4486 (2004)

Fiber drawing process



Drawing tower

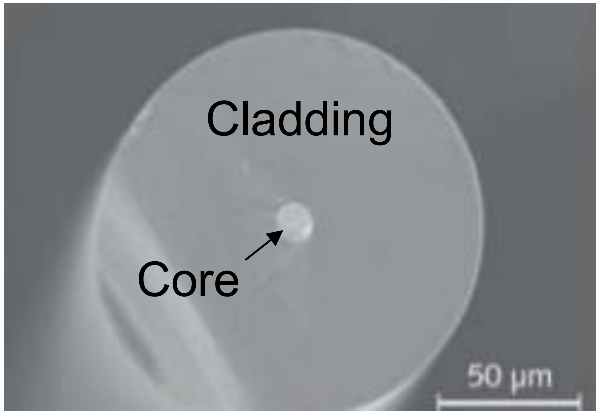
Fiber preforms

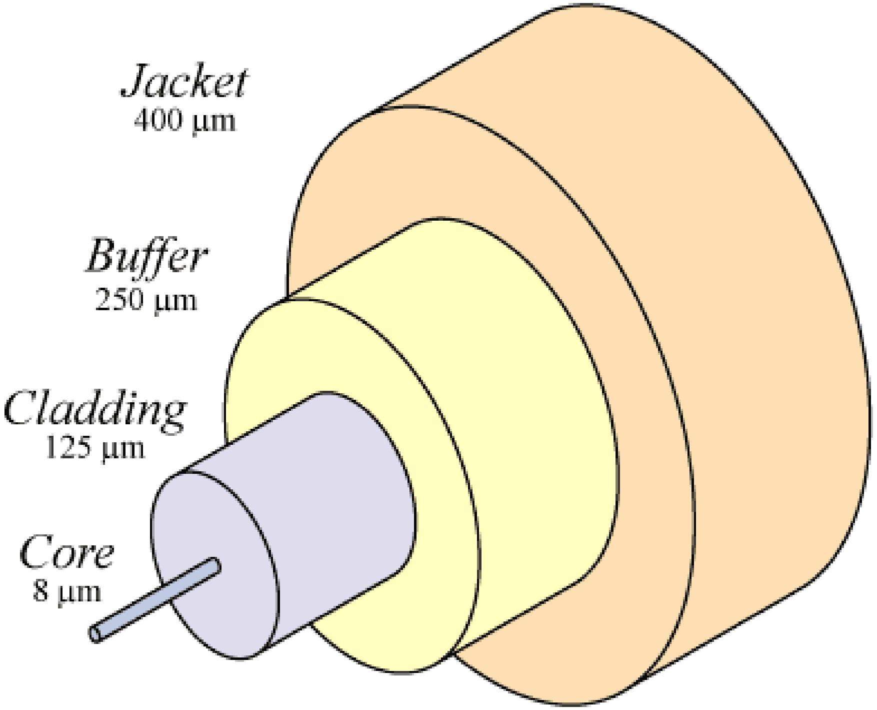
Viscosity window for fiber drawing:
10^4 to 10^6 Pa·s

Fiber spool

Standard single-mode silica optical fiber structure

- Core/cladding: low loss light propagation
- Buffer/jacket: protection against mechanical damage and the environment (UV radiation, humidity, etc.)





Fiber drawing: diameter control

Figure removed due to copyright restrictions.
See Figure 0: Mawardi, A. "Optical Fiber Drawing Process Model Using an Analytical Neck-Down Profile." IEEE Photonics Journal 2, no. 4 (2010): 620-629.

- Drawing tension:

$$F = 3\eta A \cdot \frac{\partial v_z}{z}$$

- Fiber diameter is determined by the drawing speed
- Fiber diameter is feedback loop controlled in real time during drawing
- Candy fiber drawing

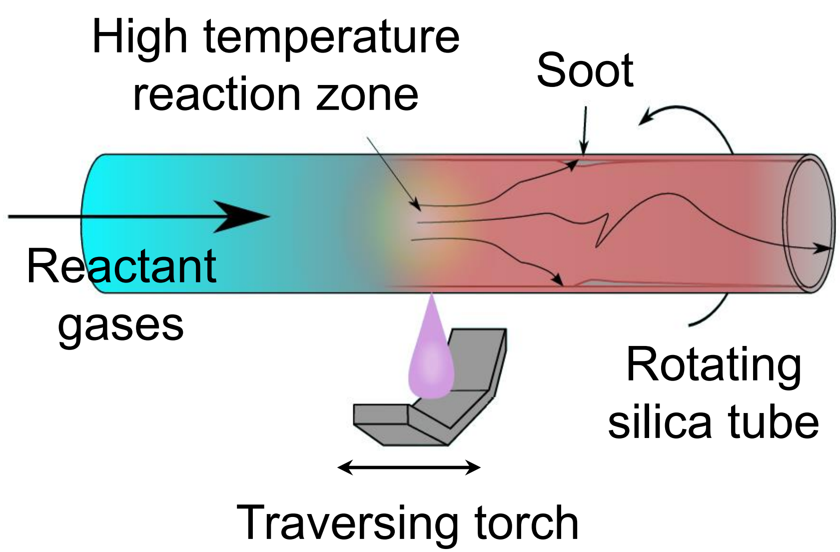
IEEE Photon. J. **2**, 620 (2010)
J. Appl. Phys. **49**, 4417 (1978)

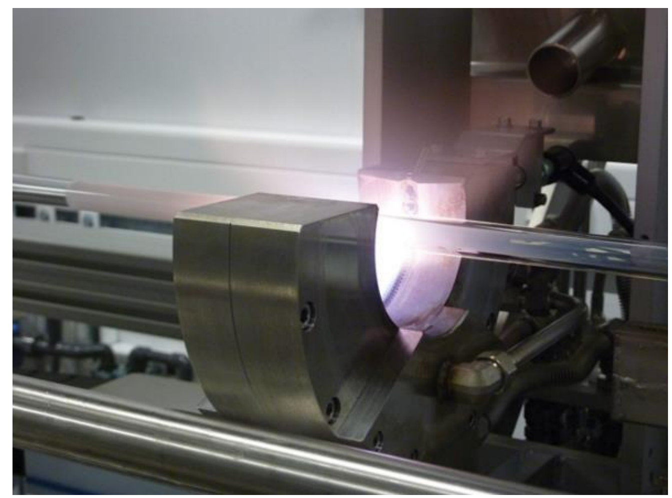
Standard silica fiber preform fabrication

- Modified chemical vapor deposition (MCVD)
  - $SiCl_4 + O_2 \rightarrow SiO_2$ (soot) $+ Cl_2$
  - $GeCl_4 + O_2 \rightarrow GeO_2 + Cl_2$

Water-free reaction:
minimal -OH contamination

- Layer composition and thickness controlled in each torch sweep



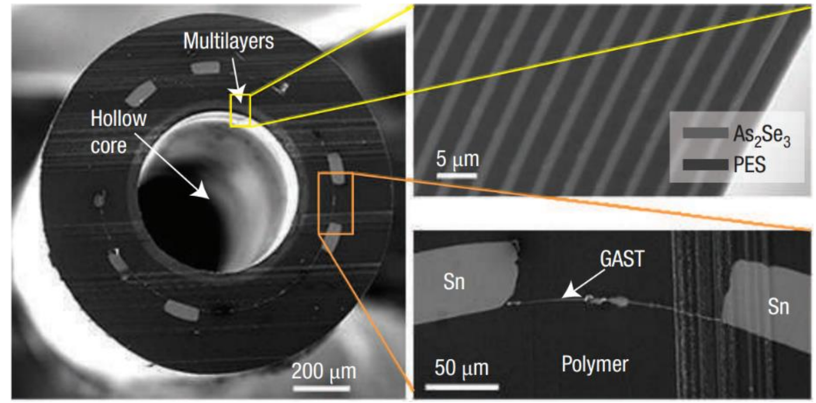


MCVD lathe, University of Southampton

Multi-material, microstructured optical fibers

Microstructured optical fibers: photonic bandgaps and various sizes of the rings give rise to the different colors

A. Argyros, the University of Sydney



Source: Abouraddy, A. F., et al. "Towards Multimaterial Multifunctional Fibres that See, Hear, Sense and Communicate." *Nature Materials* 6 (2007): 336-347.

Nat. Mater. **6**, 336, (2007)

- ✓ Optical mode shaping
- ✓ Dispersion engineering
- ✓ Broadband transmission
- ✓ Multi-functional sensing

Multi-material, microstructured optical fibers

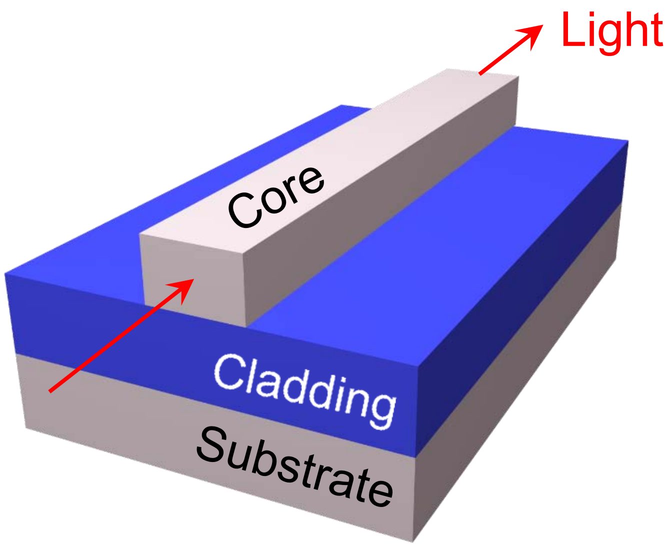
Rod-in-tube, extrusion, and stack-and-draw fabrication diagram removed due to copyright restrictions. See Figure 3: Tao, G., et al. "Multimaterial Fibers." *Int. J. Appl. Glass Sci.* 3 (2012): 349–368.

Figures removed due to copyright restrictions. See Figure 1: A) Fabrication steps for the fiber perform; C) Images of the preform and fiber cross section: Bayindir, M., et al. "Thermal-Sensing Fiber Devices by Multimaterial Codrawing." *Adv. Mater.* 18 (2006): 845-849.

Int. J. Appl. Glass Sci. **3**, 349 (2012)

Adv. Mater. **18**, 845 (2006)

Integrated photonics

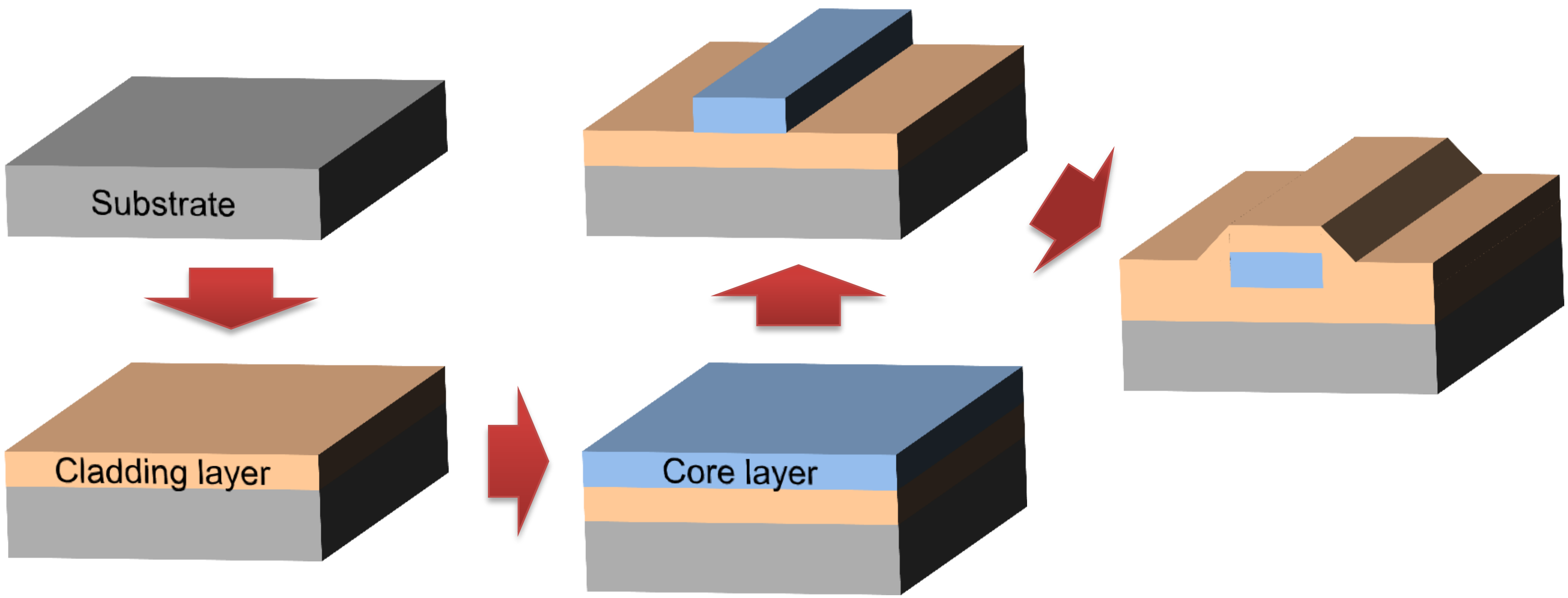


IMEC photonic chip & Tyndall fiber array packaging

Integrated planar waveguide

- ✓ Substrate platforms: Si, III-V semiconductors, glass, $LiNbO_3$, polymer
- ✓ Core material: c-Si, III-V, a-Si, SiO_2, SiN, ion exchange glass, polymer

Planar waveguide fabrication



- ✓ Amorphous waveguide material: ease of deposition, low optical loss
- ✓ Planar waveguide platform: massively parallel low-cost fabrication, geometry/material diversity, interfacing with other on-chip components

Optical loss in fibers and waveguides

- Material attenuation
- Surface roughness scattering

$$\alpha_s \propto \left(n_{core}{}^2 - n_{clad}{}^2\right)\cdot\sigma^2 \qquad \sigma\text{: RMS roughness}$$

  - Optical fiber
    - Frozen surface capillary waves due to energy equipartition
    - Usually small in optical fibers
  - Planar waveguide
    - Surface roughness resulting from imperfect patterning
    - A major loss mechanism

J. Lightwave Technol. **23**, 2719 (2005)

Optical communication system

0 = peace

1 = invasion

Optical communication system

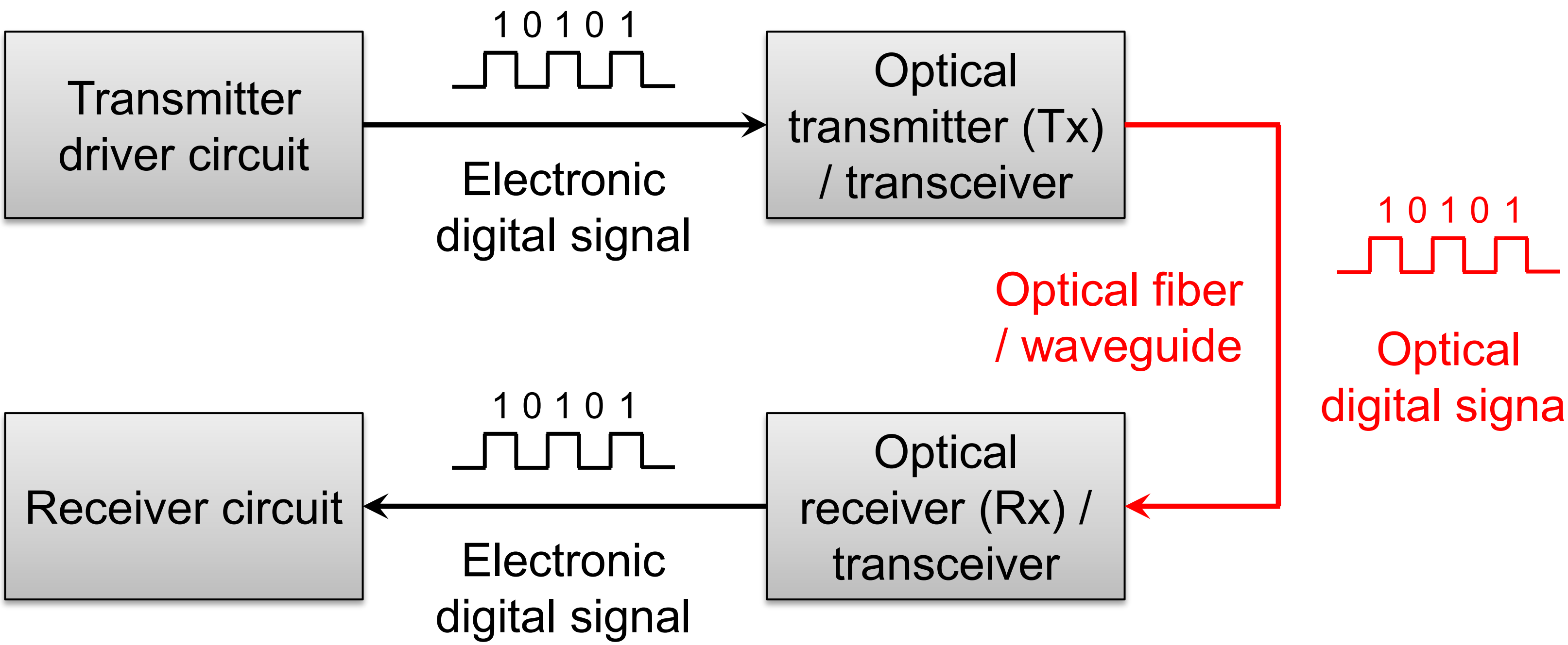
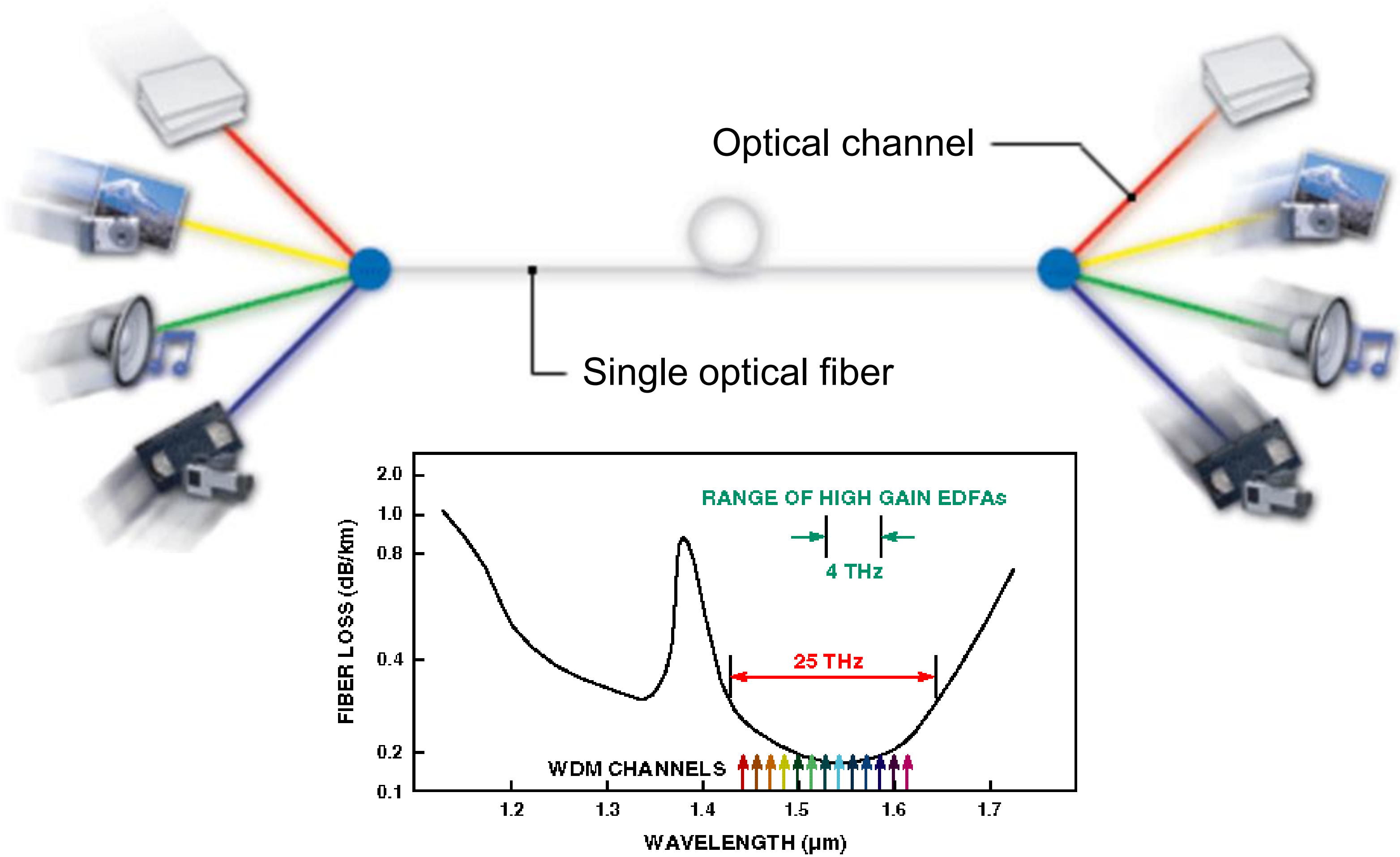


Figure of optical tranceiver removed due to copyright restrictions. See Figure 5: Takemoto, T., et al. "100-Gbps CMOS Transceiver for Multilane Optical Backplane System with a 1.3 cm2 Footprint." *Opt. Express* 19 (2011): B777-B783.

Opt. Express **19**, B777 (2011)

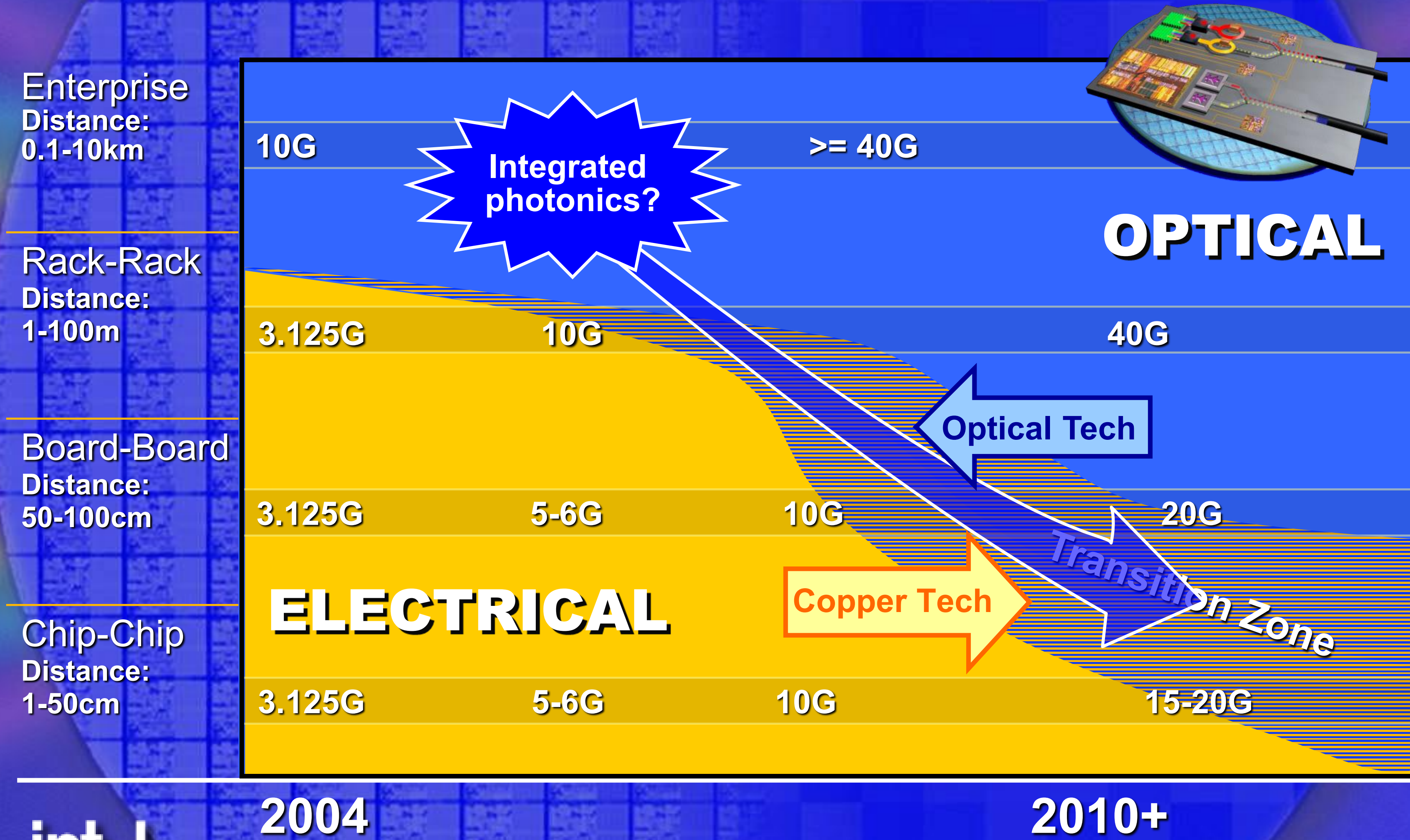
Wavelength division multiplexing (WDM)



Verizon PON Architecture diagram removed due to copyright restrictions. See Slide 5: O'Byrne, V. "FTTP (Fiber-to-the-Premises) Next Generation Broadband." Verizon, 2004.

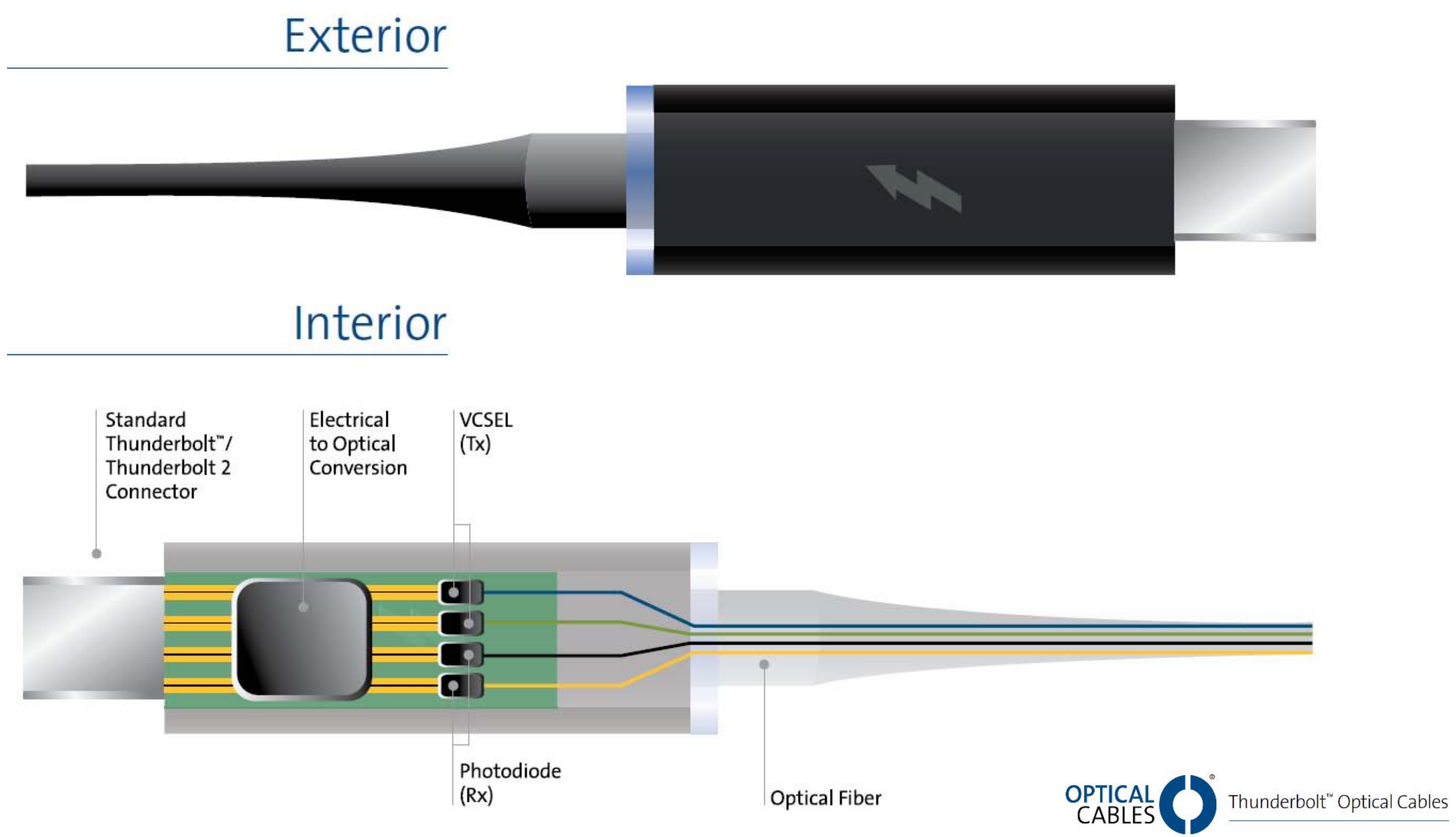
See what the "FiOS boy" says about WDM!

Electrical to optical interconnect



intel

Active optical cable (AOC)



Summary

<u>Device fabrication</u>

- Fiber drawing
  - Preform fabrication: MCVD process
  - Drawing parameter control: fiber diameter & draw tension
  - Multi-material fiber and microstructured fiber processing
- Planar waveguide fabrication

<u>Optical loss in fibers and waveguides</u>

- Material attenuation
- Surface roughness scattering

<u>Optical communications</u>

- Digital communication systems & WDM

3.071 Amorphous Materials
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