



MIT 3.071

Amorphous Materials

13: Optical Fibers and Waveguides

Juejun (JJ) Hu

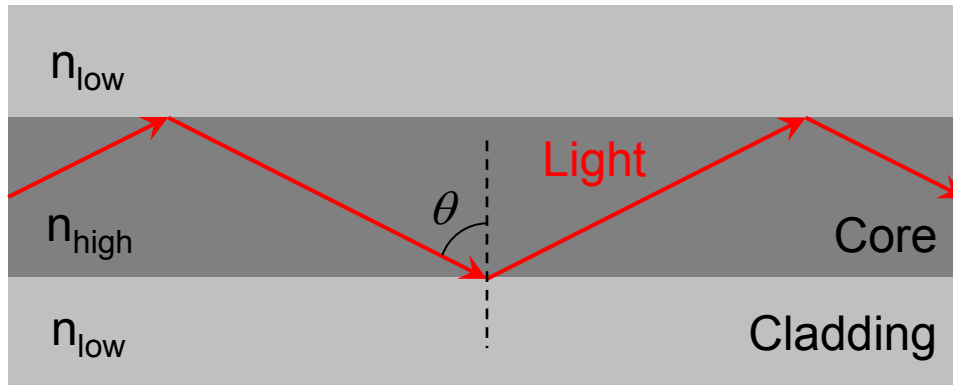


The masters of light

“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.”

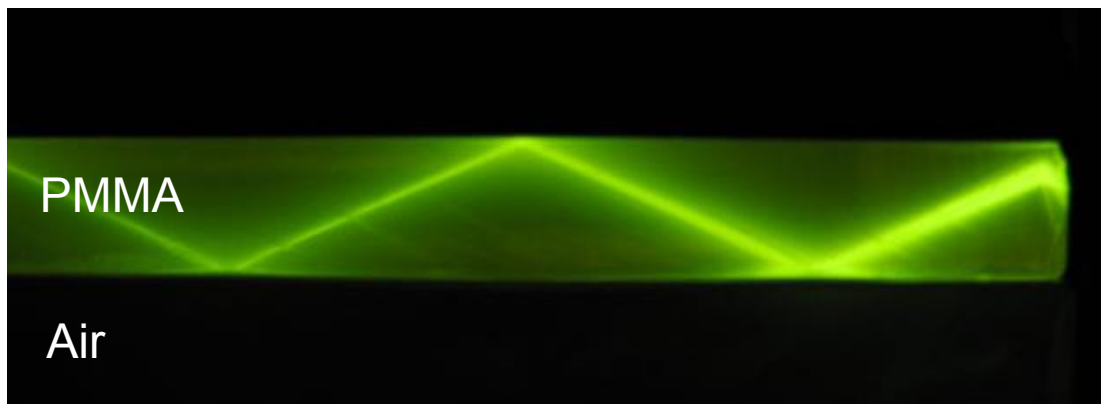
2009 Nobel Prize in Physics
Press Release

Light confinement via total internal reflection



Condition for TIR:

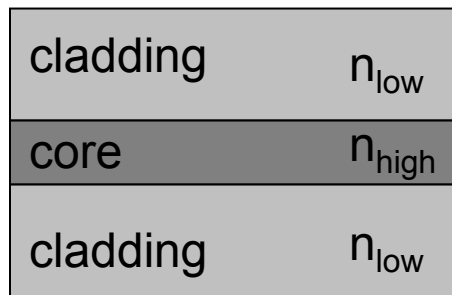
$$\sin \theta \geq n_{low} / n_{high}$$



[Snell is right](#)
by Ulrich Lohmann

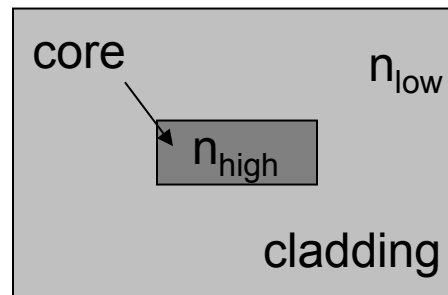
Waveguide cross-section geometries

1-d optical confinement

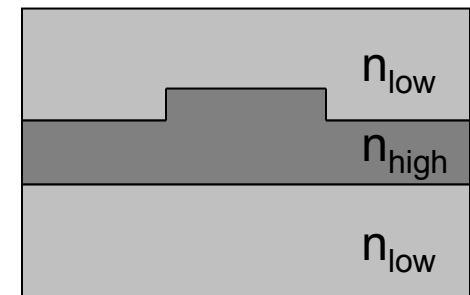


Slab waveguide

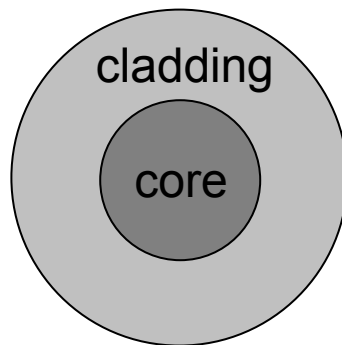
2-d optical confinement



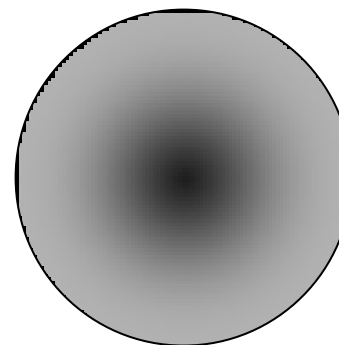
Channel/photonic wire waveguide



Rib/ridge waveguide



Step-index fiber



Graded-index (GRIN) fiber

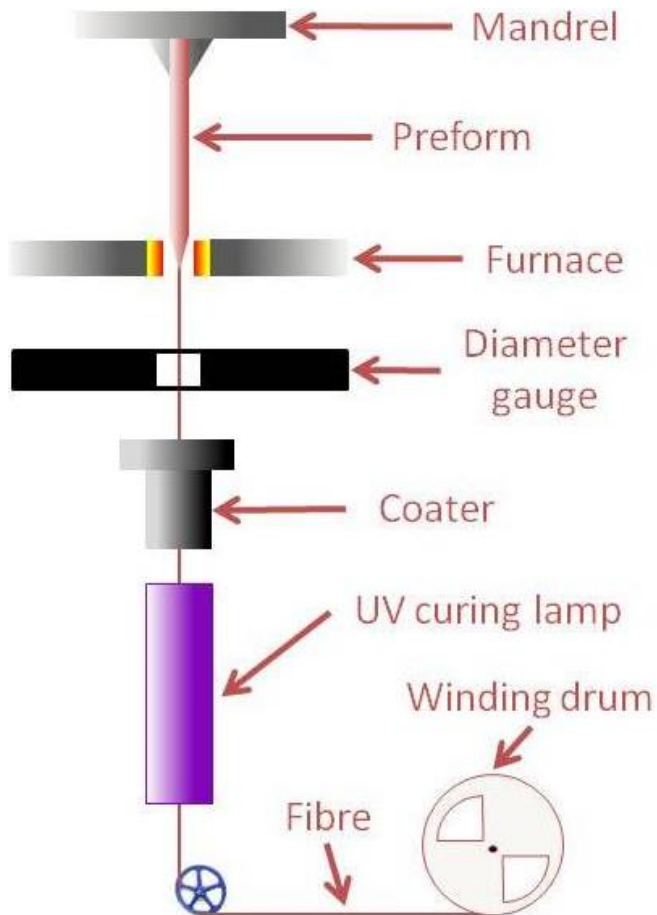
Optical fiber materials

- 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 $\lambda = 0.5893$ vs composition for GeO_2 - SiO_2 glasses prepared and measured by various researchers removed due to copyright restrictions. See Figure 3: Fleming, J.W. "Dispersion in GeO_2 - SiO_2 Glasses." *Appl. Opt.* 24 (2004): 4486-4493.

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

Fiber drawing process



Courtesy of Silvio Abrate, Roberto Gaudino and Guido Perrone. License: CC BY.
Source: *Current Developments in Optical Fiber Technology*. Chapter 7: Step-index PMMA Fibers and Their Applications. Harun, S.W. and Arof, H. (eds.). InTech, 2013.



Drawing tower



Fiber preforms

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

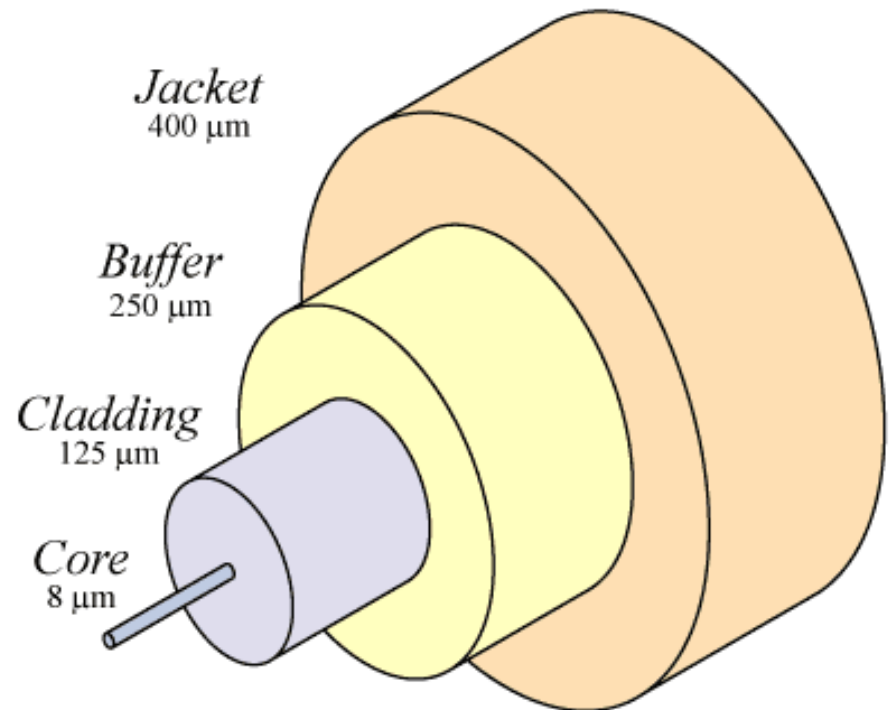
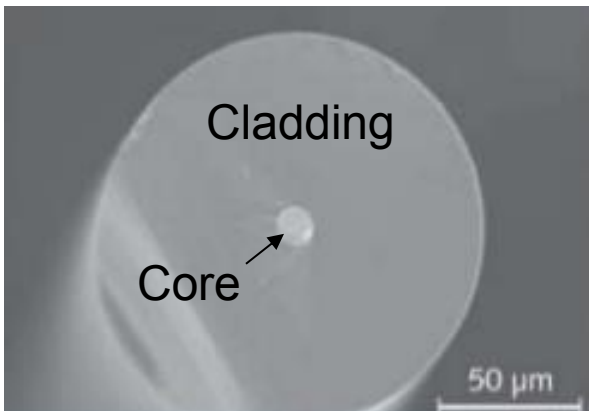


Fiber spool

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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:

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

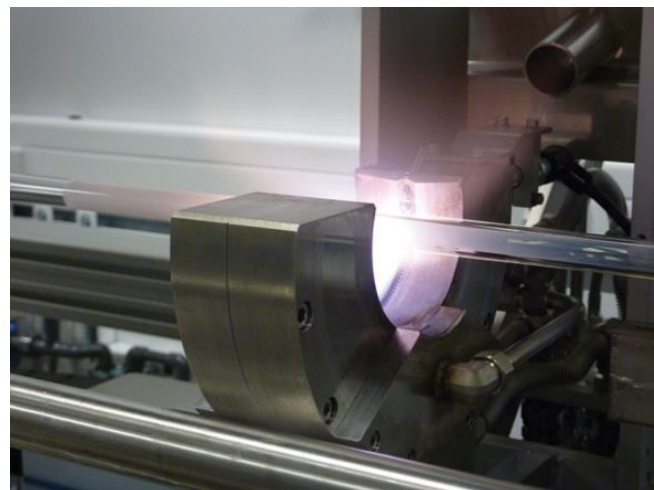
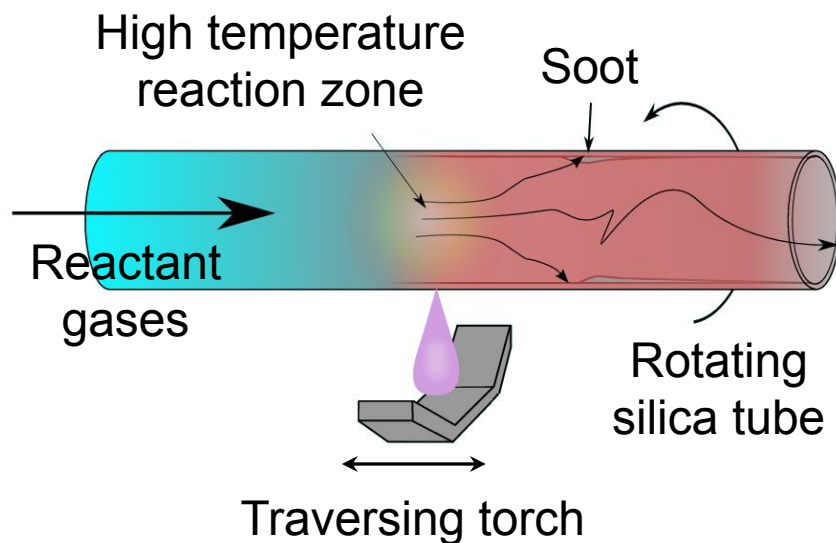
- Fiber diameter is determined by the drawing speed
- Fiber diameter is feedback loop controlled in real time during drawing
- Candy fiber drawing

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

Standard silica fiber preform fabrication

- Modified chemical vapor deposition (MCVD)
 - $\text{SiCl}_4 + \text{O}_2 \rightarrow \text{SiO}_2 \text{ (soot)} + \text{Cl}_2$
 - $\text{GeCl}_4 + \text{O}_2 \rightarrow \text{GeO}_2 + \text{Cl}_2$
- Layer composition and thickness controlled in each torch sweep

Water-free reaction:
minimal -OH contamination



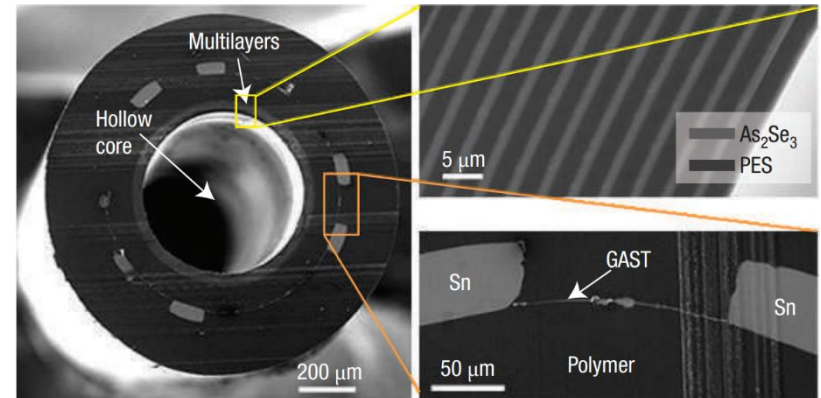
MCVD lathe, University of Southampton

Image of MCVD lathe © unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see <http://ocw.mit.edu/help/faq-fair-use/>.

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



Courtesy of Macmillan Publishers Limited. Used with permission.
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

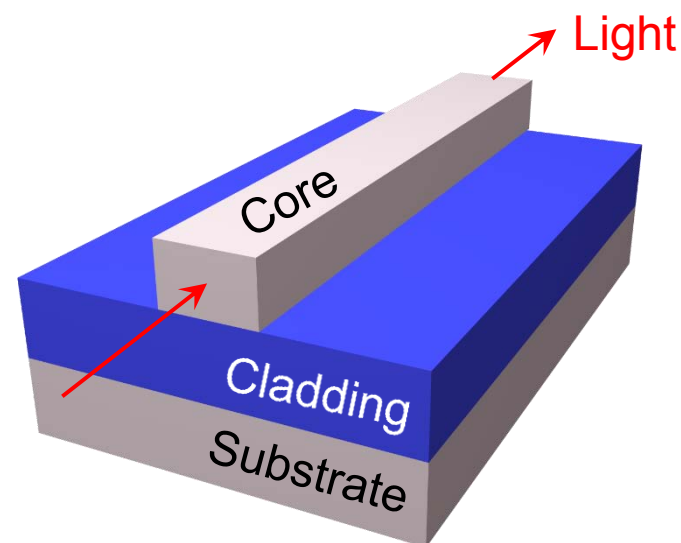
Rod-in-tube, extrusion, and stack-and-draw fabrication diagram removed due to copyright restrictions. See Figure 3: Tao, G., et al. "Multimaterial Fibers." *Int. J. Appl. Glass Sci.* 3 (2012): 349–368.

Figures removed due to copyright restrictions. See Figure 1: A) Fabrication steps for the fiber preform; 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

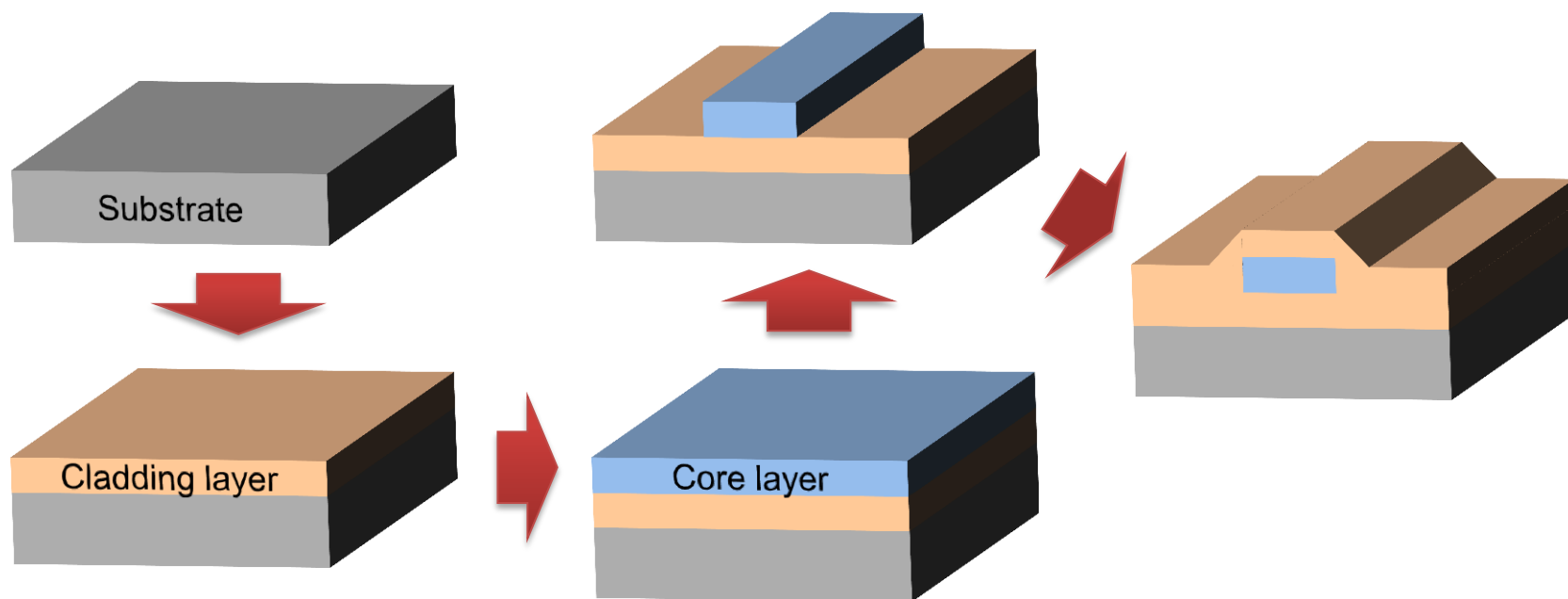


[IMEC photonic chip & Tyndall fiber array packaging](#)

Integrated planar waveguide

- ✓ Substrate platforms: Si, III-V semiconductors, glass, LiNbO₃, polymer
- ✓ Core material: c-Si, III-V, a-Si, SiO₂, 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

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

- 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

Figure removed due to copyright restrictions.
See Figure 1: Barwicz, T. and H. Haus. "Three-dimensional Analysis of Scattering Losses Due to Sidewall Roughness in Microphotonic Waveguides." *J. Lightwave Technol.* 23, (2005): 2719-2732.

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

Optical communication system



0 = peace

1 = invasion

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Optical communication system

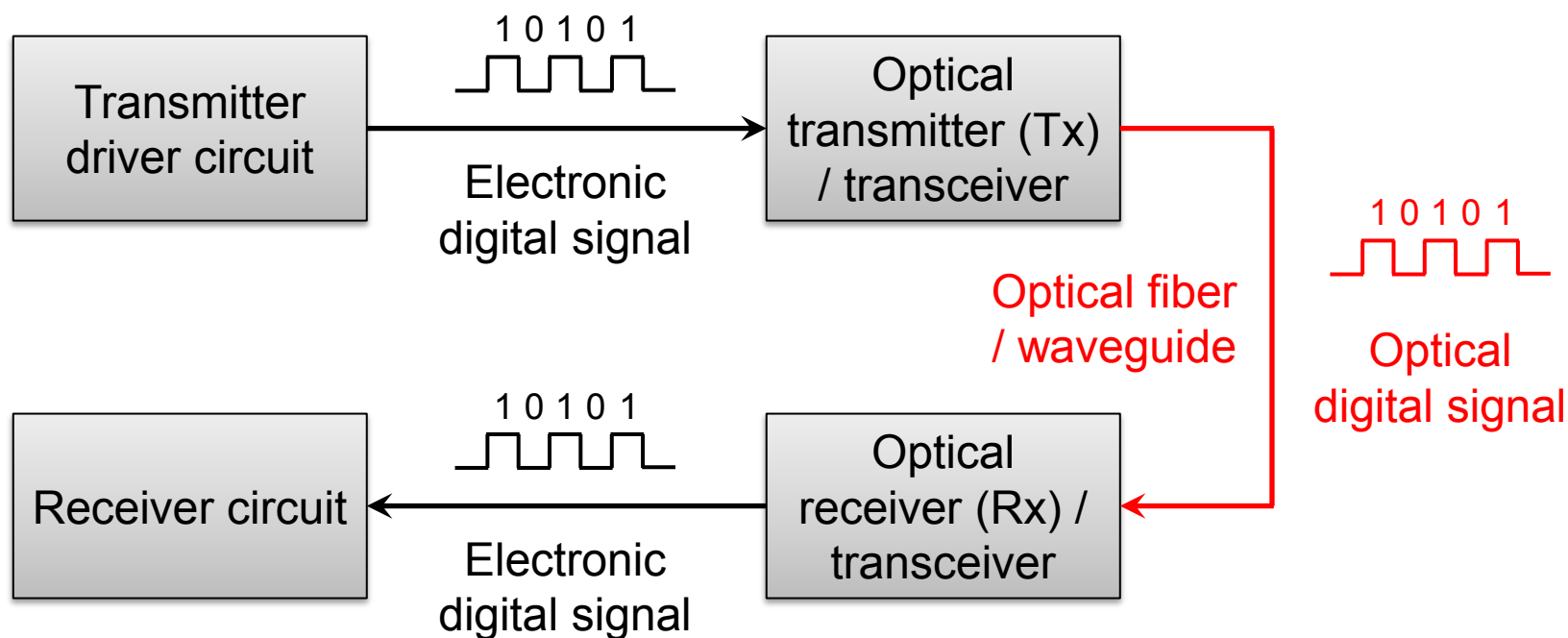
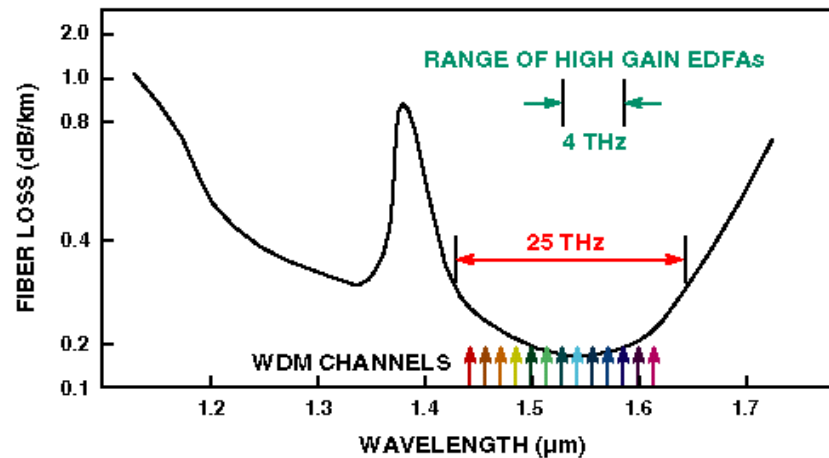
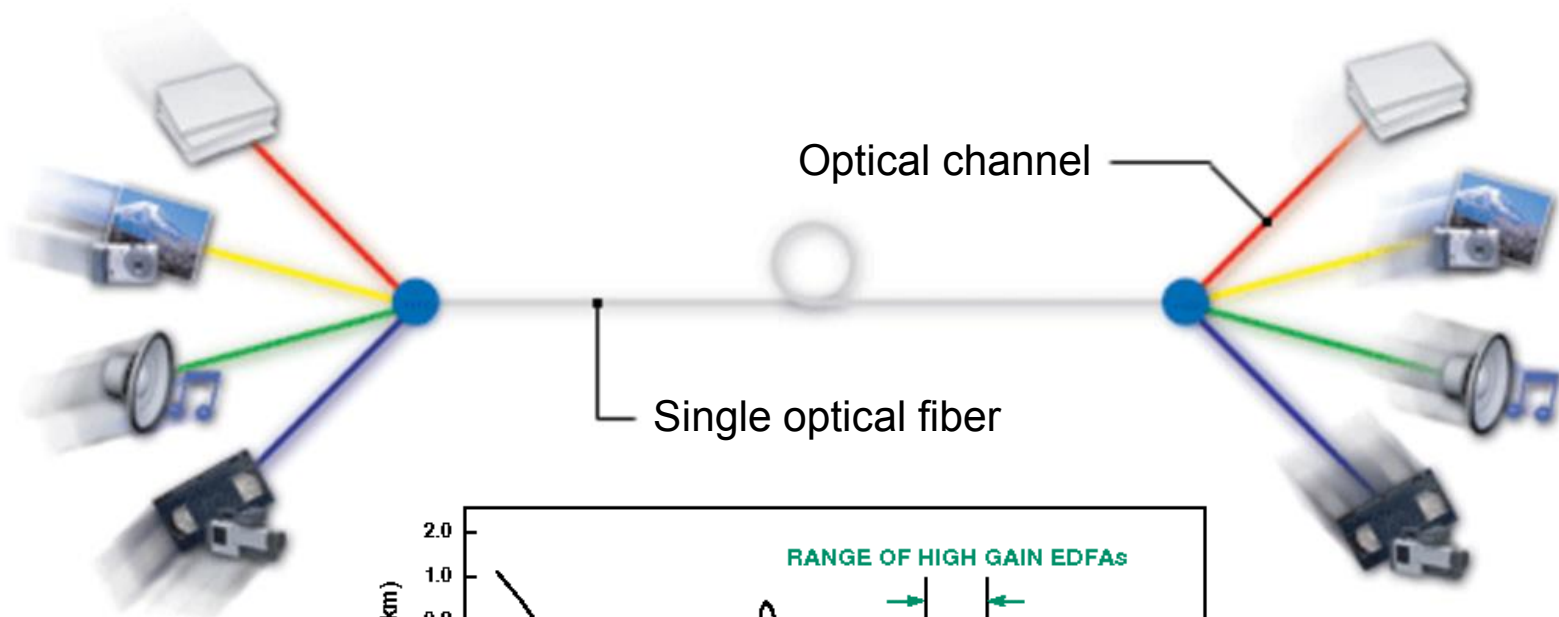


Figure of optical transceiver removed due to copyright restrictions. See Figure 5: Takemoto, T., et al. "100-Gbps CMOS Transceiver for Multilane Optical Backplane System with a 1.3 cm² Footprint." *Opt. Express* 19 (2011): B777-B783.

Opt. Express 19, B777 (2011)

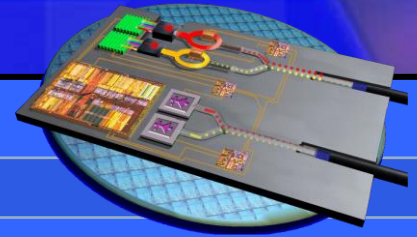
Wavelength division multiplexing (WDM)



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



Enterprise
Distance:
0.1-10km

10G

Integrated
photonics?

$\geq 40G$

OPTICAL

Rack-Rack
Distance:
1-100m

3.125G

10G

40G

Board-Board
Distance:
50-100cm

3.125G

5-6G

10G

20G

Chip-Chip
Distance:
1-50cm

3.125G

5-6G

10G

15-20G

ELECTRICAL

Copper Tech

Optical Tech

Transition Zone

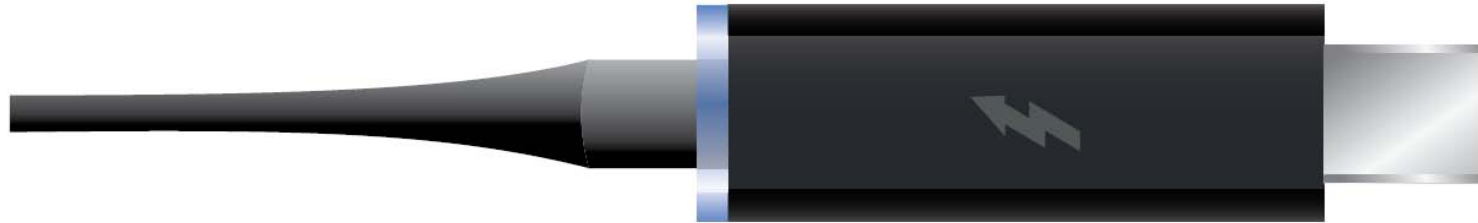
2004

2010+

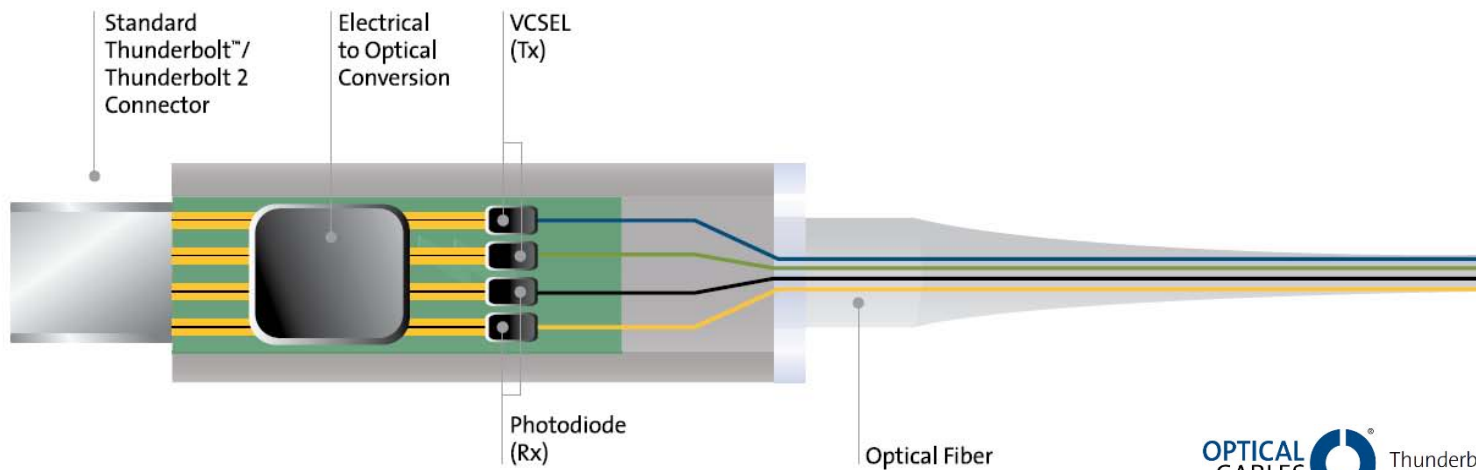
intel.

Active optical cable (AOC)

Exterior



Interior



OPTICAL CABLES  Thunderbolt™ Optical Cables

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Summary

Device fabrication

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

Optical loss in fibers and waveguides

- Material attenuation
- Surface roughness scattering

Optical communications

- Digital communication systems & WDM

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