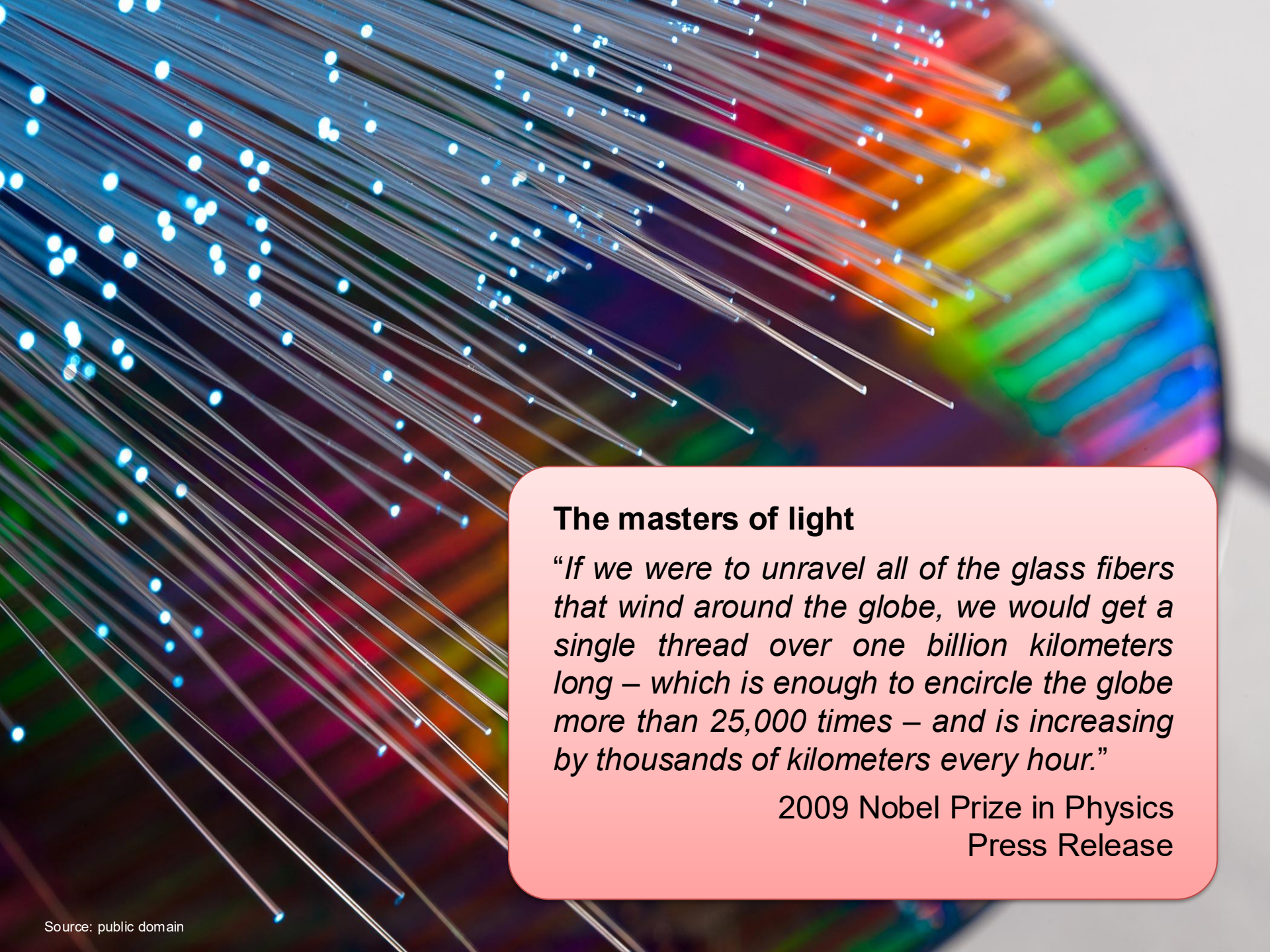
# MIT 3.071
# Amorphous Materials

## 14: Optical Fibers and Waveguides

Juejun (JJ) Hu



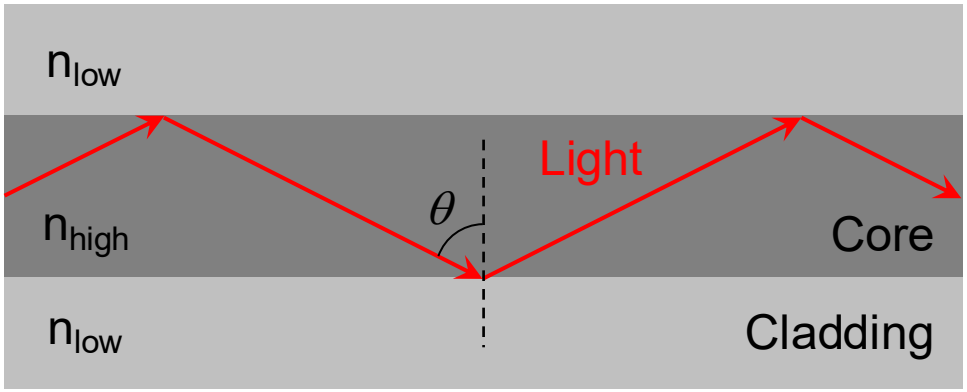
**The masters of light**

"*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

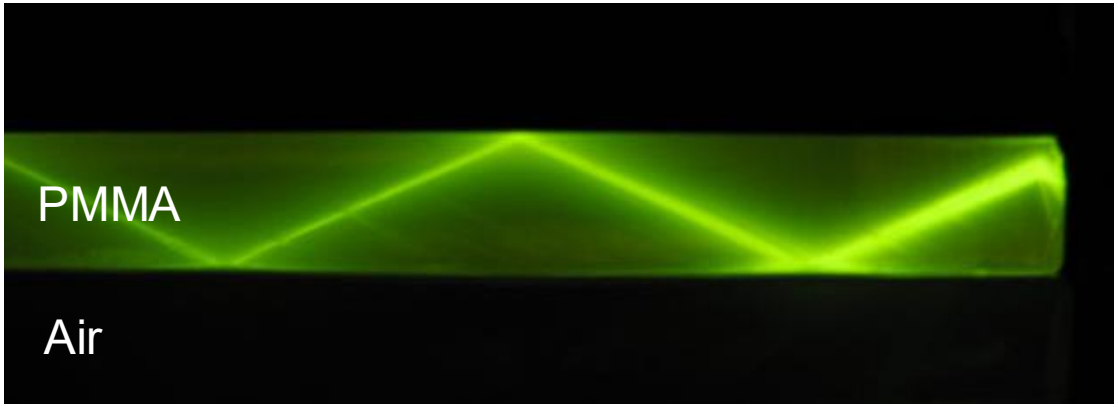
Source: public domain

# Light confinement via total internal reflection




Condition for TIR:

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



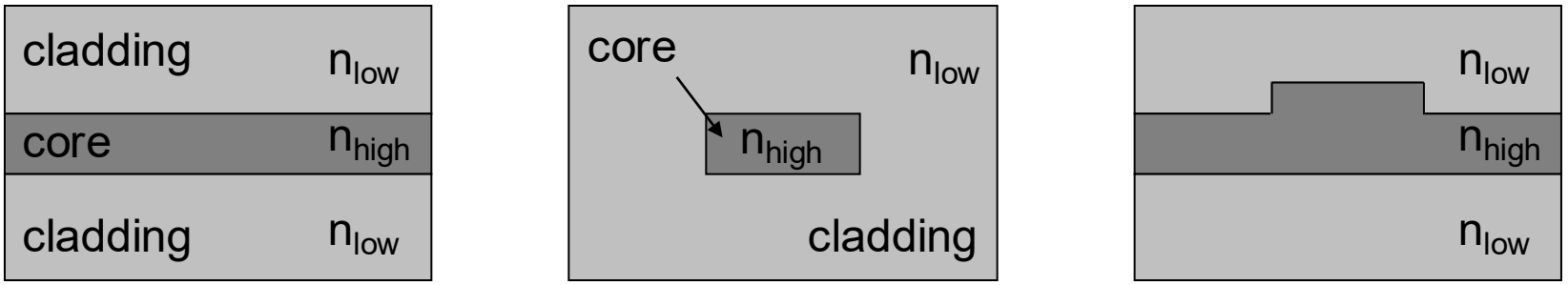

[Snell is right](#)
by Ulrich Lohmann

© Ulrich Lohmann. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Waveguide cross-section geometries

1-d optical confinement

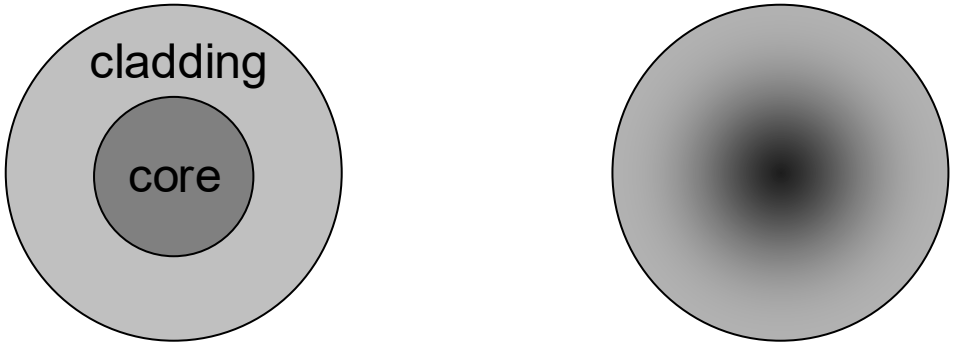
2-d optical confinement




Slab waveguide

Channel/photonic wire waveguide

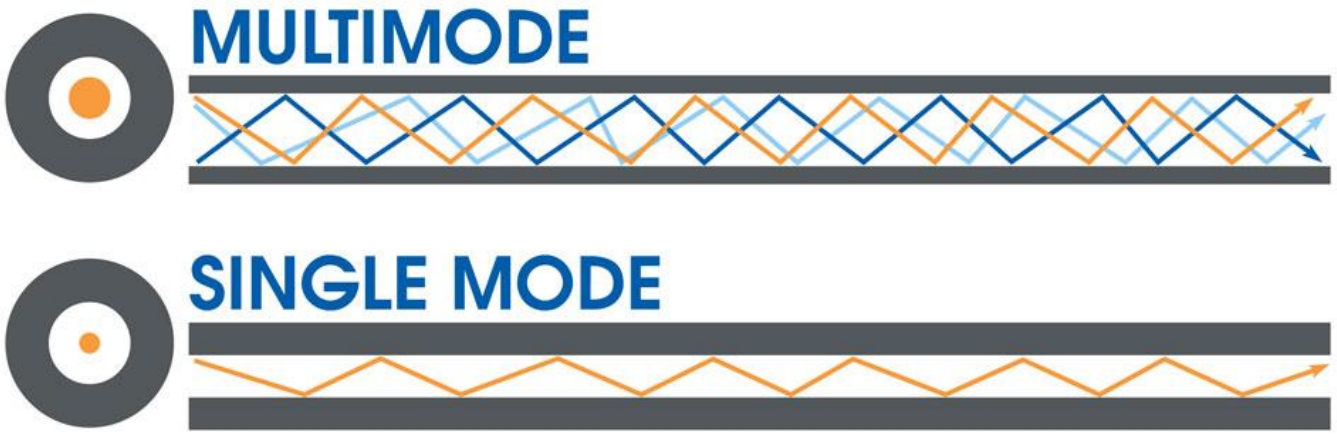
Rib/ridge waveguide

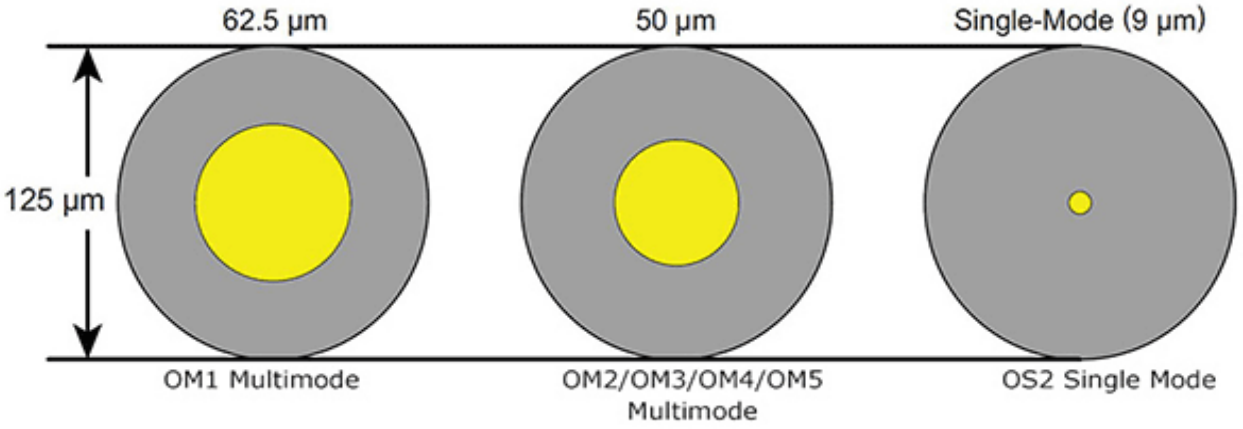



Step-index fiber

Graded-index (GRIN) fiber

# Single-mode vs. multi-mode light guiding

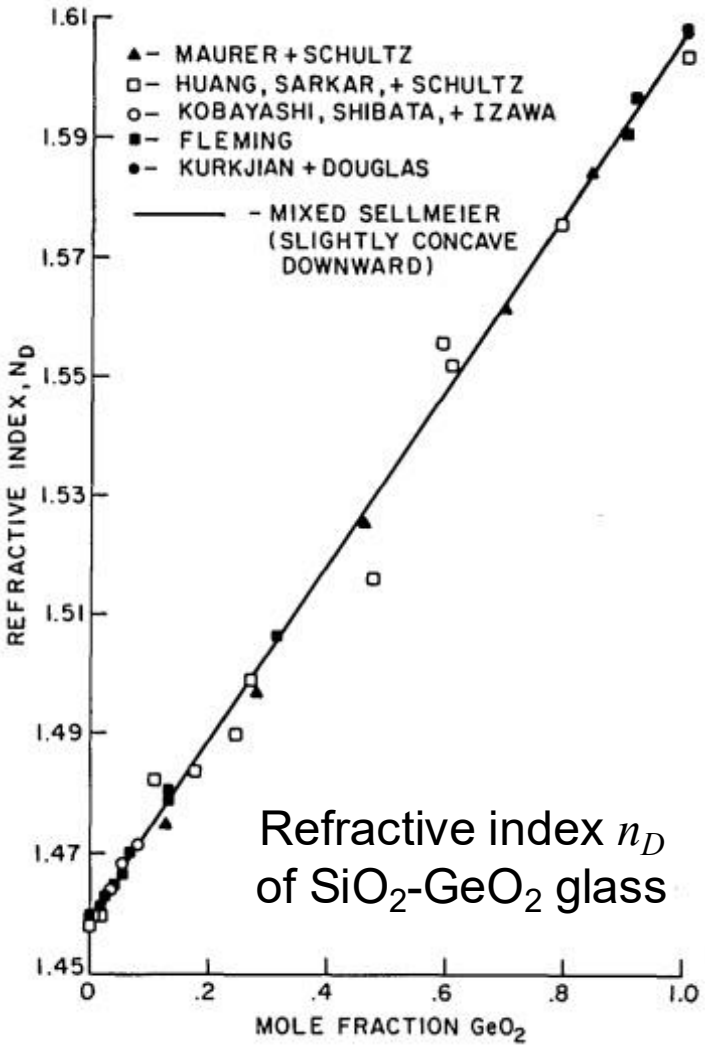



© TC Communications, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# 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)



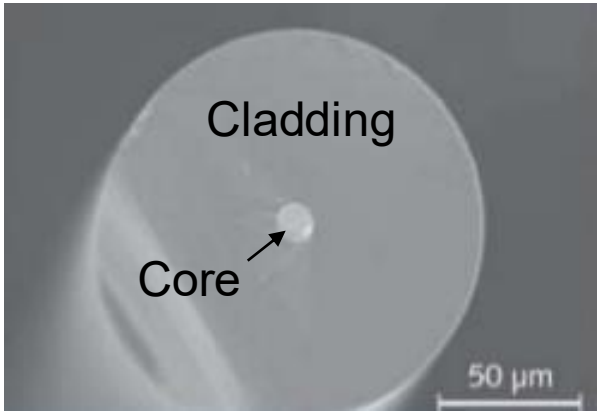

*Appl. Opt.* **24**, 4486 (2004)

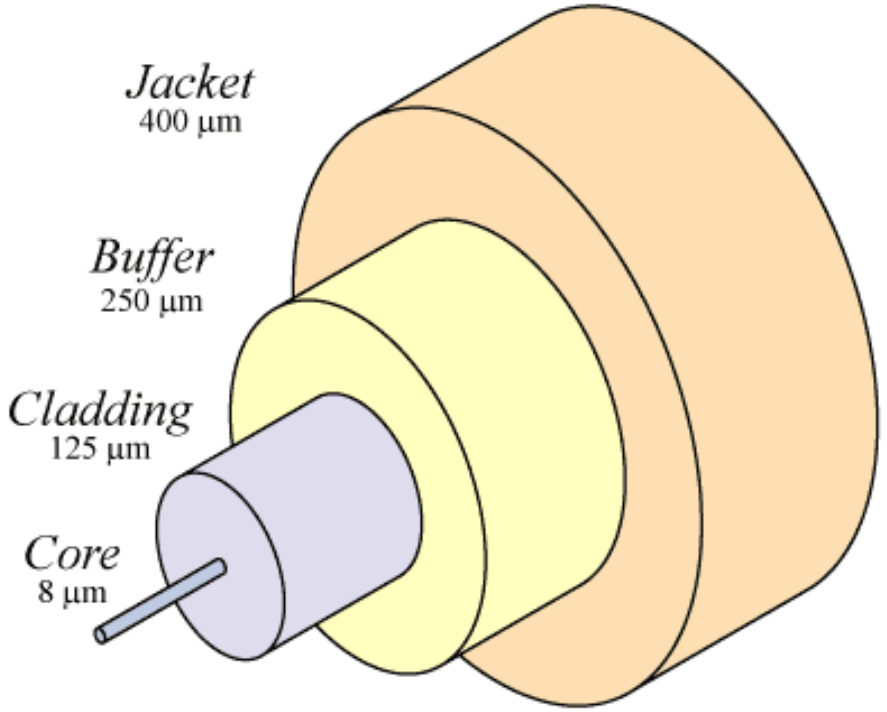


© Optical Society of America. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

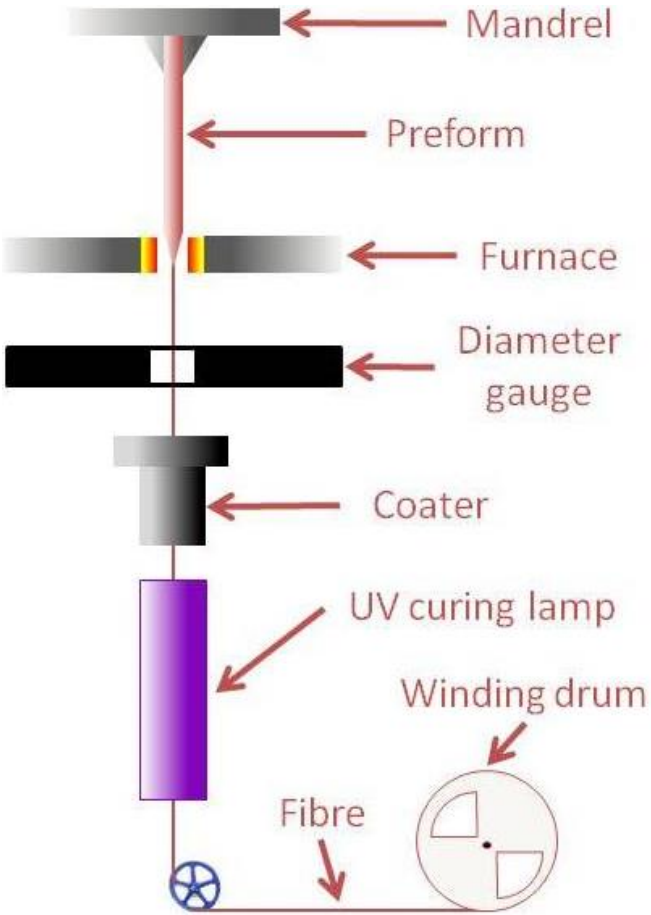
# Standard single-mode silica optical fiber structure

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



# Fiber drawing process






Drawing tower



Fiber preforms

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



Fiber spool

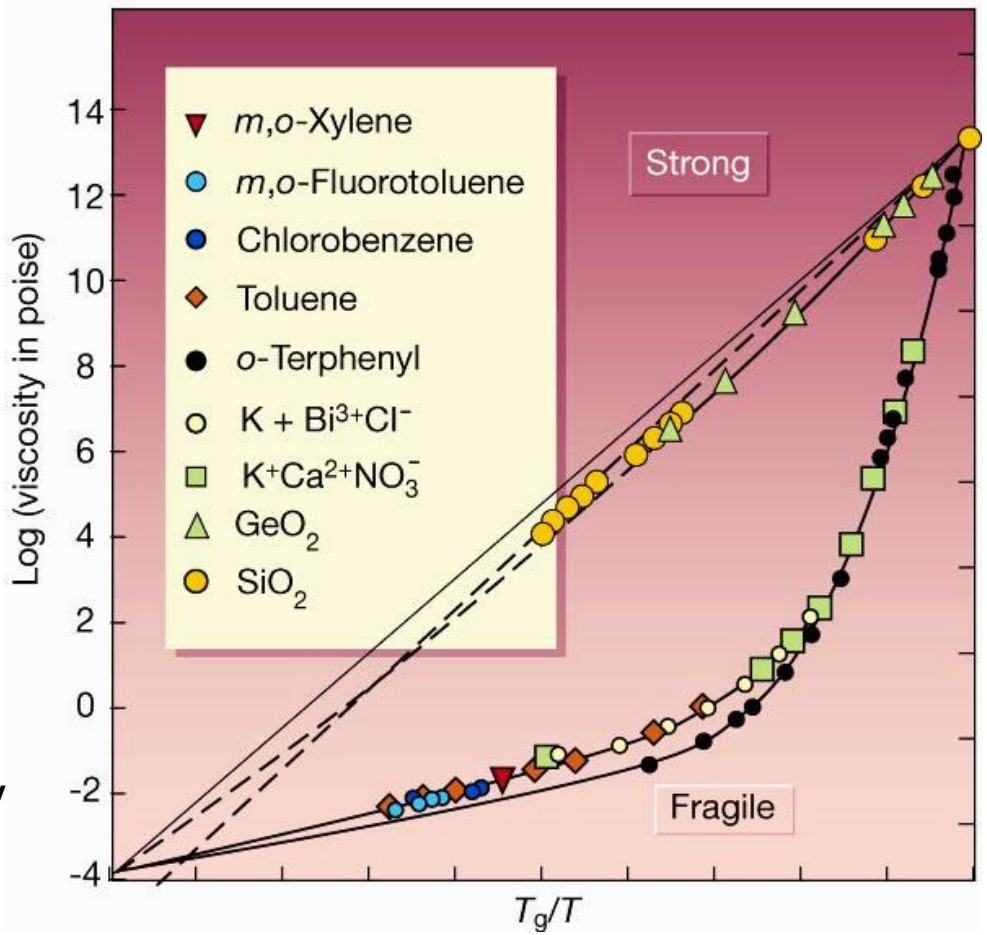
© MIT Technology Review. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Glass properties impact fiber processing

- Glass forming ability
  - $\Delta T = T_x - T_g$
  - Processing window
- Liquid fragility
  - Fragility parameter

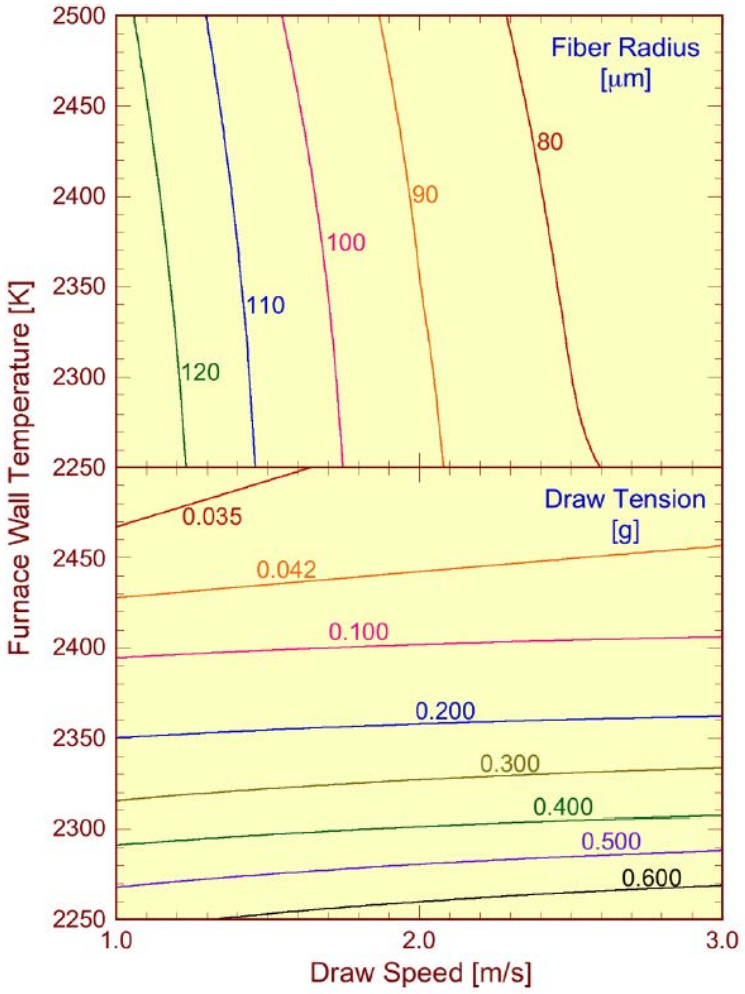
$$m \equiv \left. \frac{\partial \log_{10} \eta}{\partial \left( T_g / T \right)} \right|_{T=T_g}$$

  - Temperature sensitivity




© Informa UK Limited. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Fiber drawing: diameter control







- Drawing tension:

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

- 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)

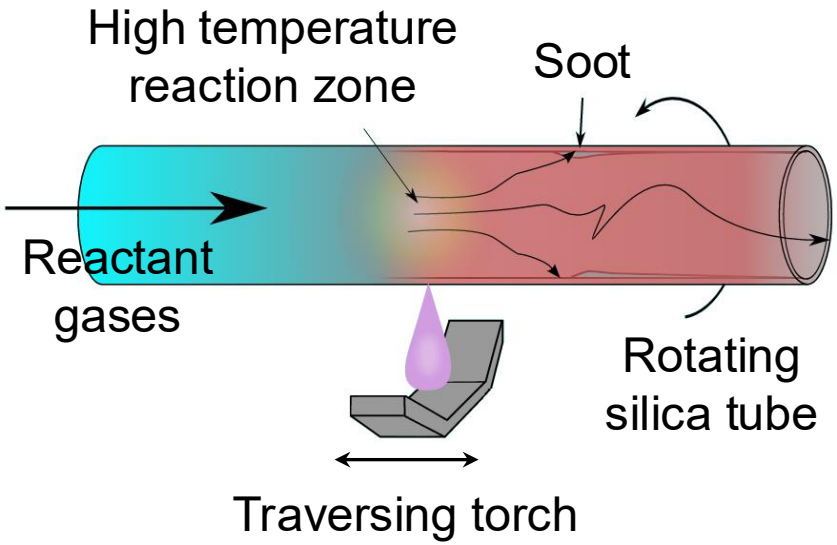
Courtesy of A. Mawardi and R. Pitchumani. Used with permission.

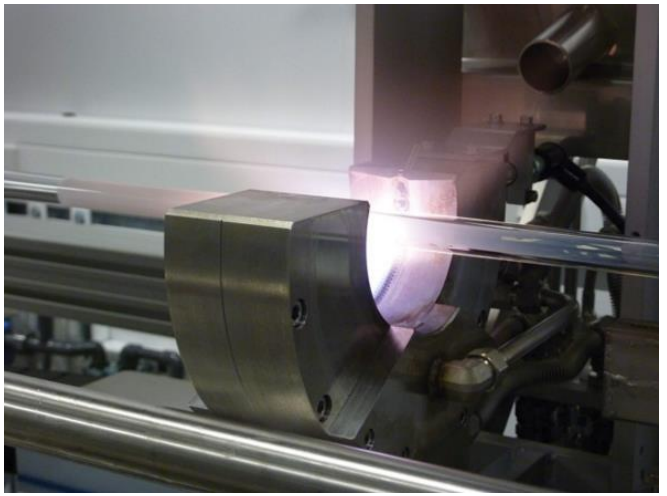
# Standard silica fiber preform fabrication

- 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

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/

# Optical fiber manufacturing and testing



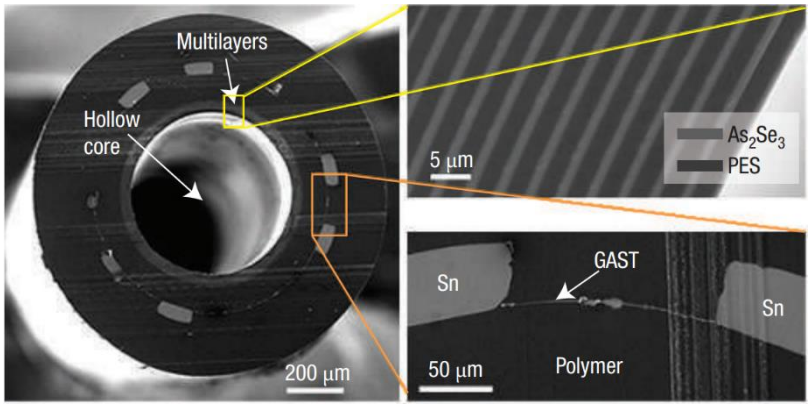
© phillip7833 on YouTube. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# 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



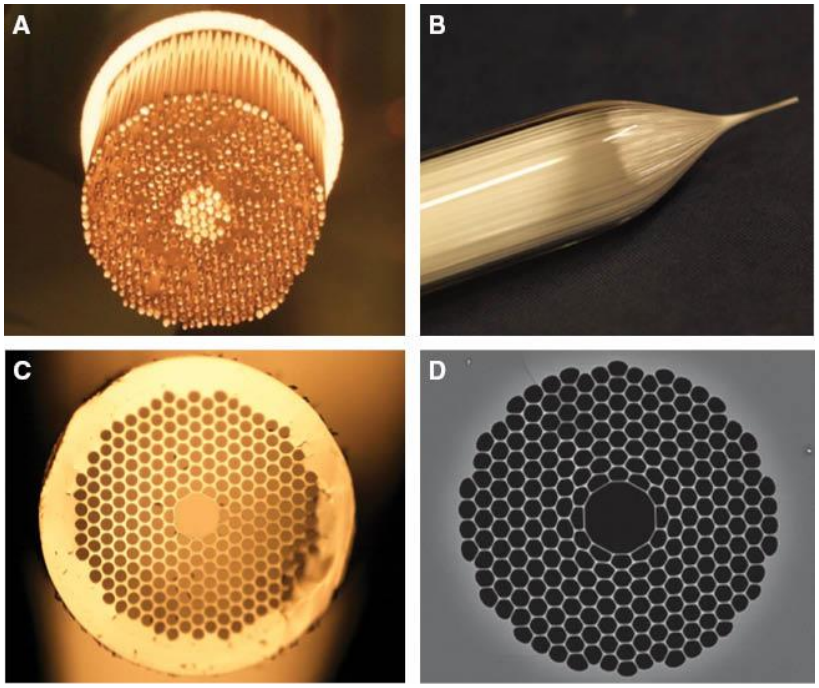

*Nat. Mater.* **6**, 336, (2007)

© Springer Nature Limited. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/help/faq-fair-use/

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

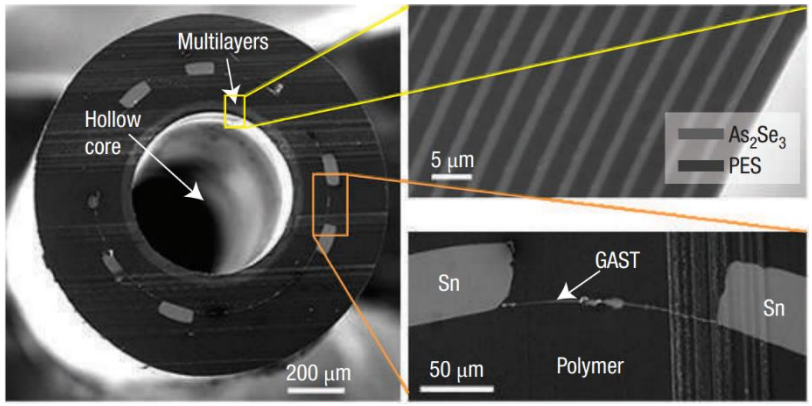
© Optica.. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Multi-material, microstructured optical fibers




Hollow-core photonic crystal fiber fabrication process flow using the stack-and-draw technique

*Nanophotonics* **2**, 315-340 (2013)



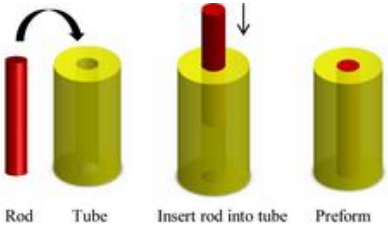

*Nat. Mater.* **6**, 336, (2007)

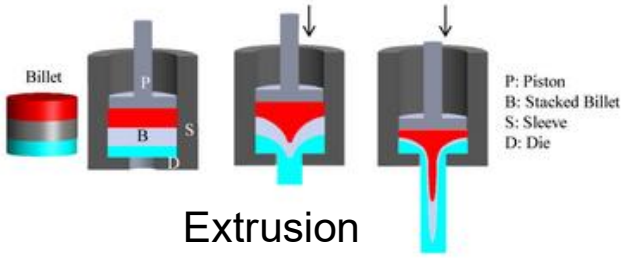
- Optical mode shaping
- Dispersion engineering
- Broadband transmission
- Multi-functional sensing

Courtesy of Poletti, F, Petrovich, M.N, and Richardson, D.J. Used with permission.

# Multi-material, microstructured optical fibers

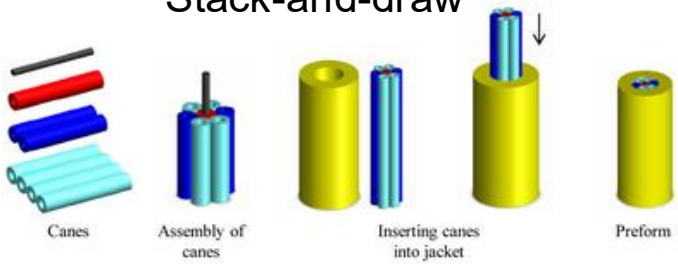
Rod-in-tube

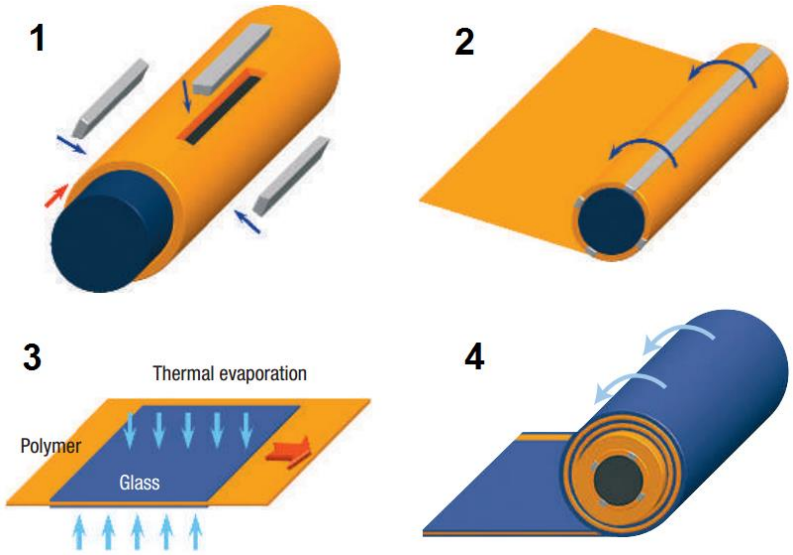


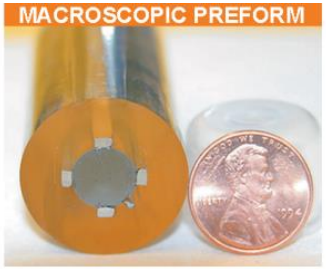



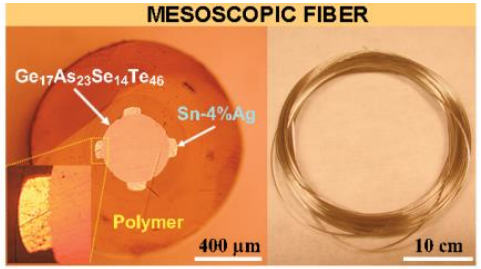

Extrusion

Stack-and-draw



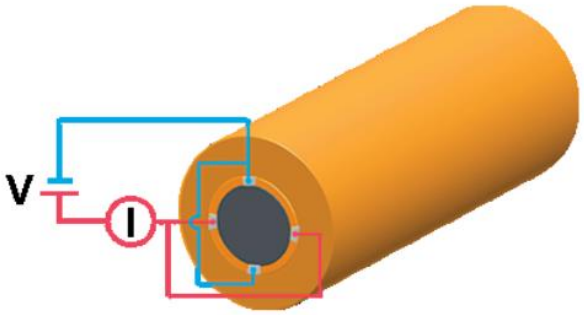

*Int. J. Appl. Glass Sci.* **3**, 349 (2012)

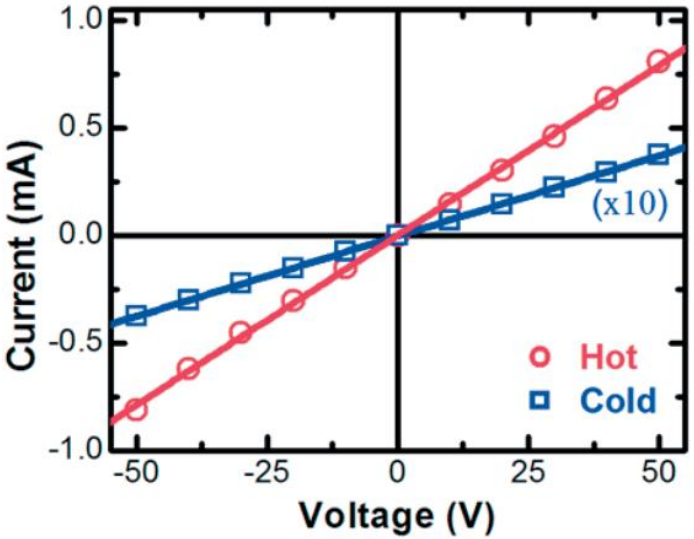
*Adv. Mater.* **18**, 845 (2006)

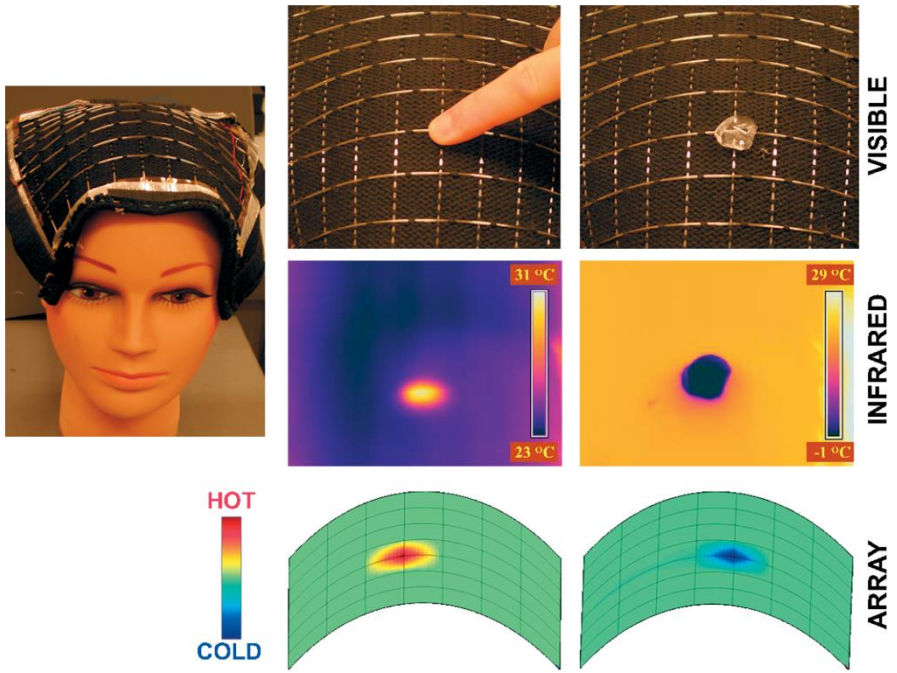
© John Wiley & Sons, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

© John Wiley & Sons, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Multi-material, microstructured optical fibers



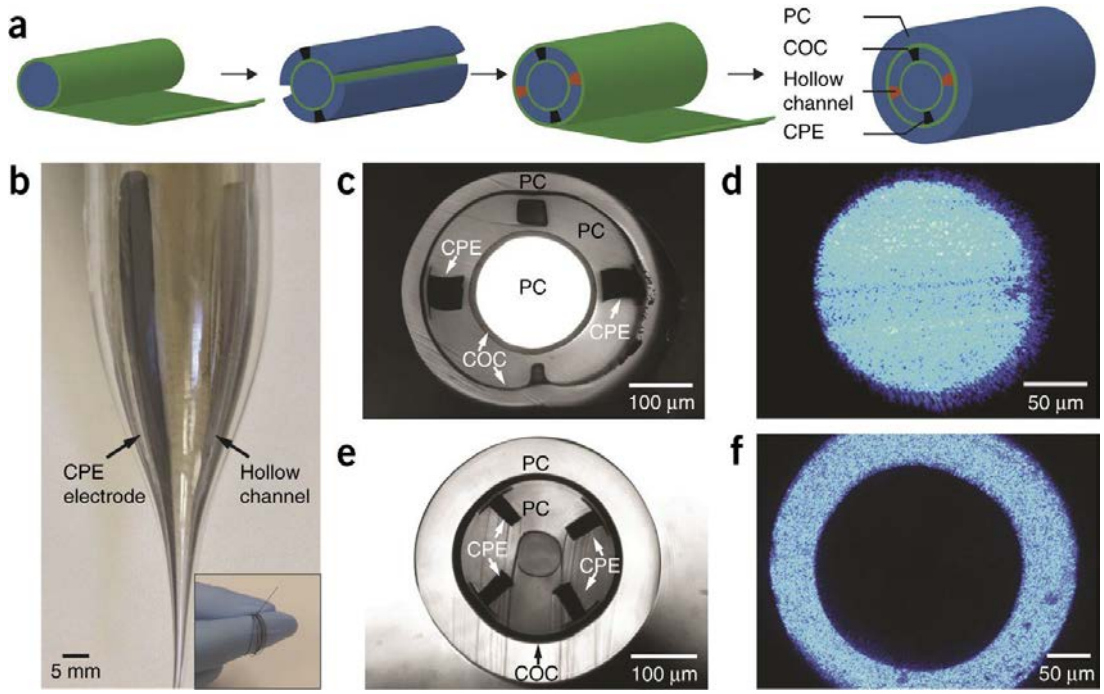



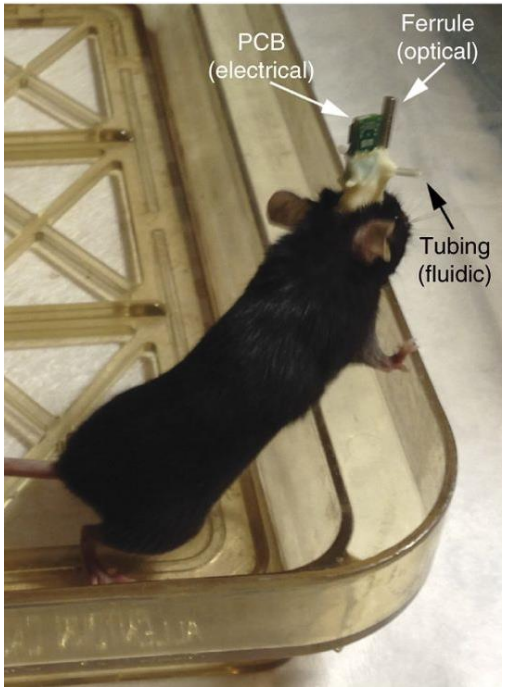

**Thermal sensing fibers**

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

© John Wiley & Sons, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Multi-material, microstructured optical fibers



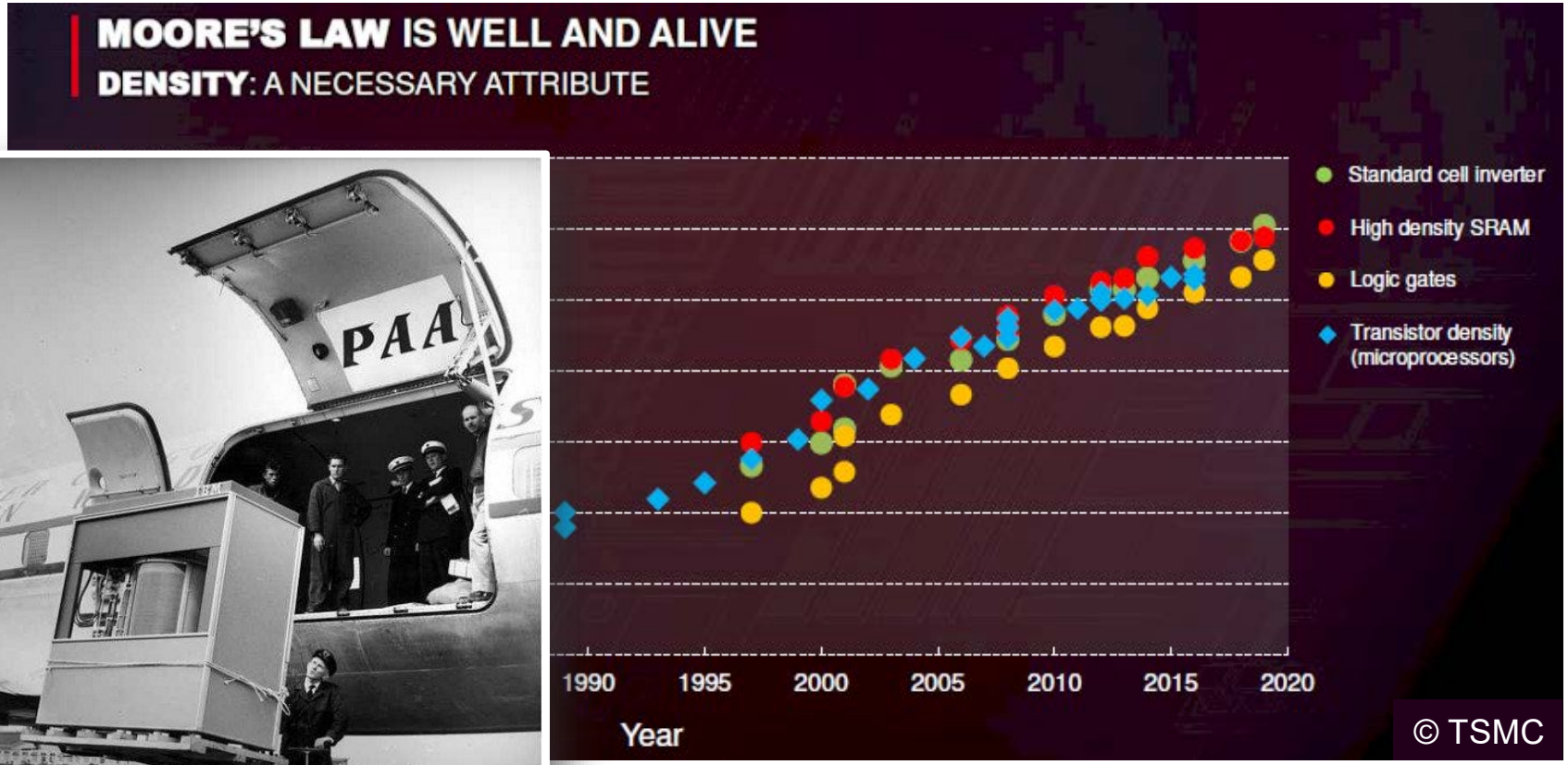

**Multifunctional (optical, electrical and chemical) neural probes**

*Nat. Biotechnol.* **33**, 277 (2015)



© Springer Nature Limited. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

"*Exponential growth is the most powerful force in the universe.*"





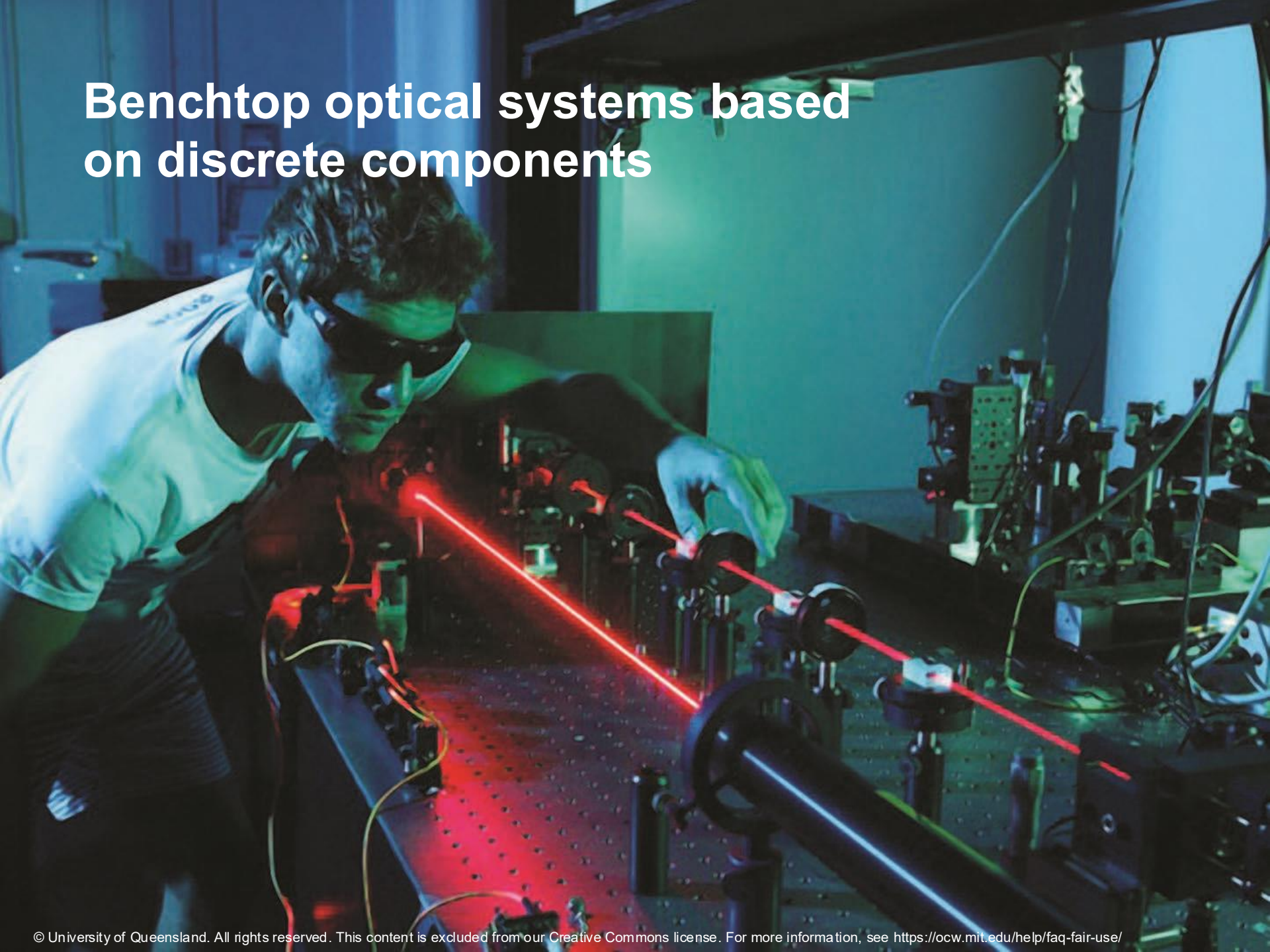


**A 5 MB hard disk (1956)**

© Stephen Shankland/CNET. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

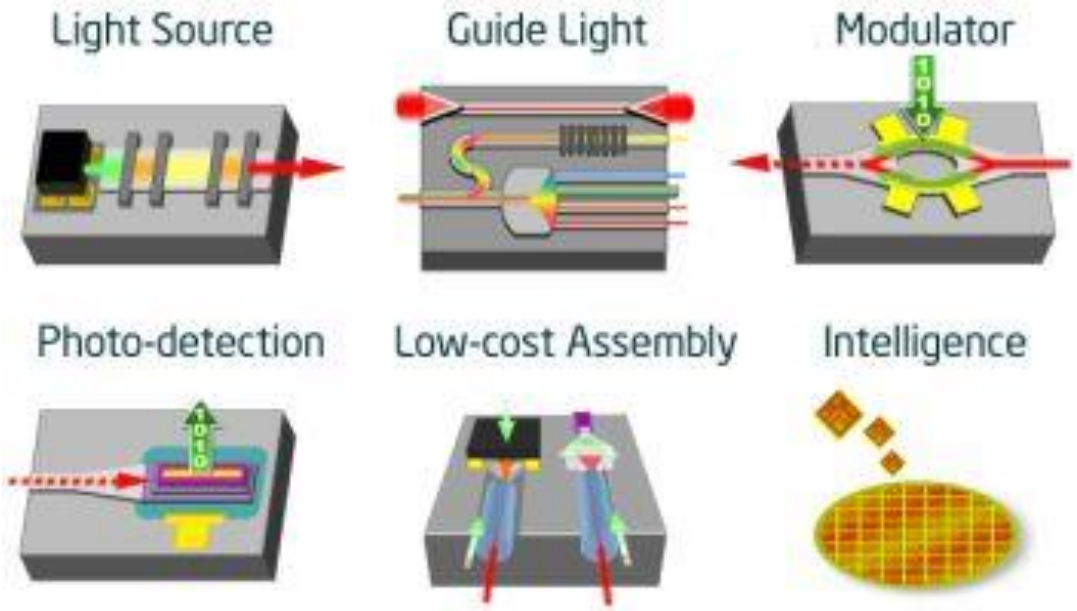
© source unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Benchtop optical systems based on discrete components

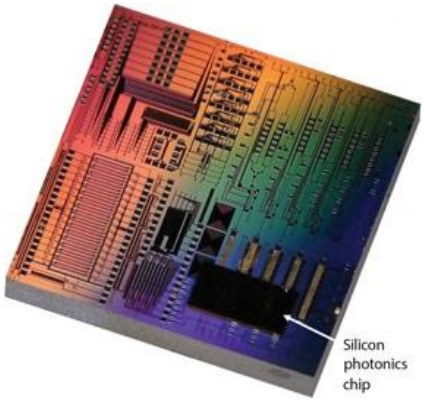


© University of Queensland. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Photonic integrated circuits (PICs)




© Intel. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/




Courtesy of Optica. Used with permission.

**Photonic integration enables rugged and low-cost miniature optical systems**

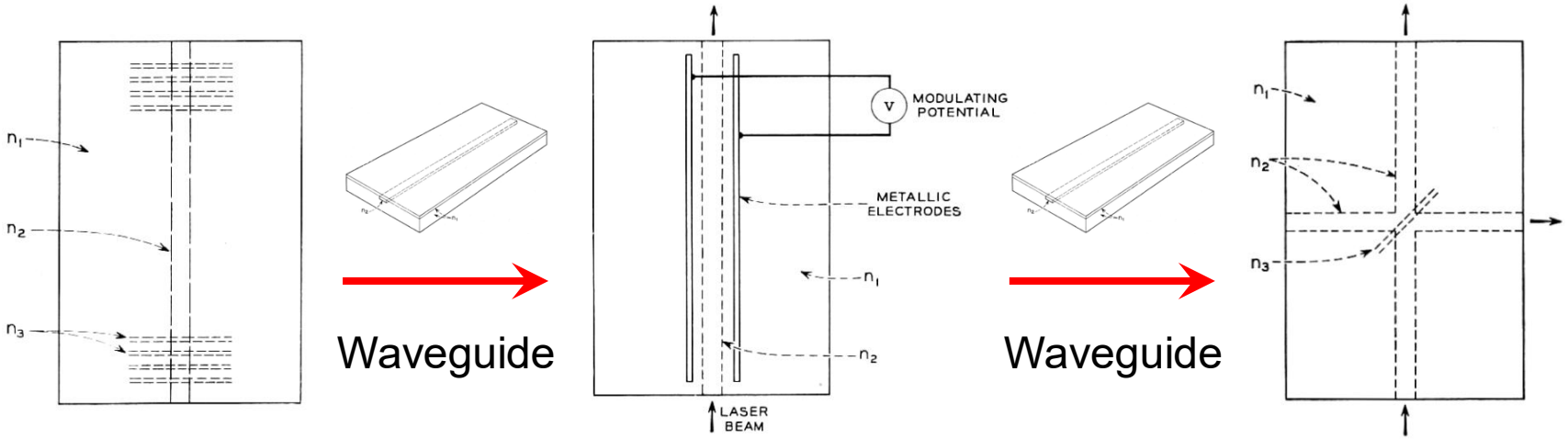
# Value proposition for integrated photonics



# Integrated Optics: An Introduction

By STEWART E. MILLER

(Manuscript received January 29, 1969)

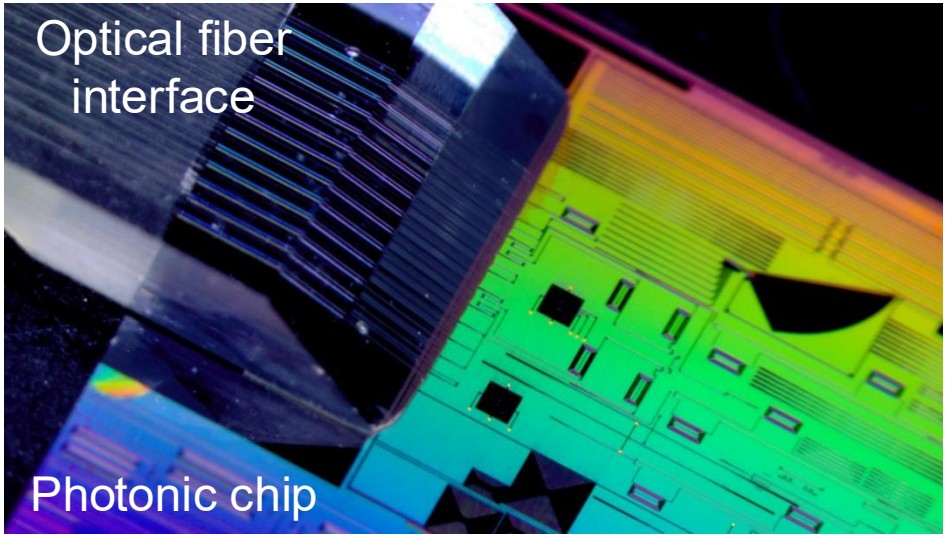



Laser cavity | Optical switch | Photodetector

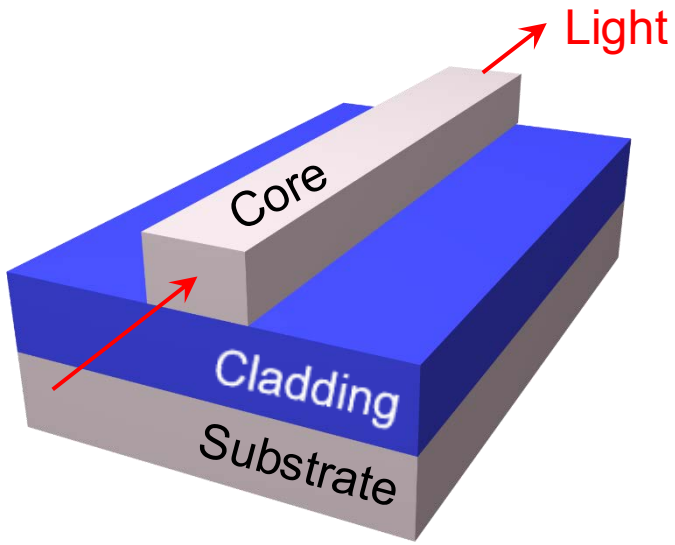
All optical components integrated on a **glass** substrate

© John Wiley & Sons, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# State-of-the-art integrated photonics




IMEC photonic chip & Tyndall fiber array packaging

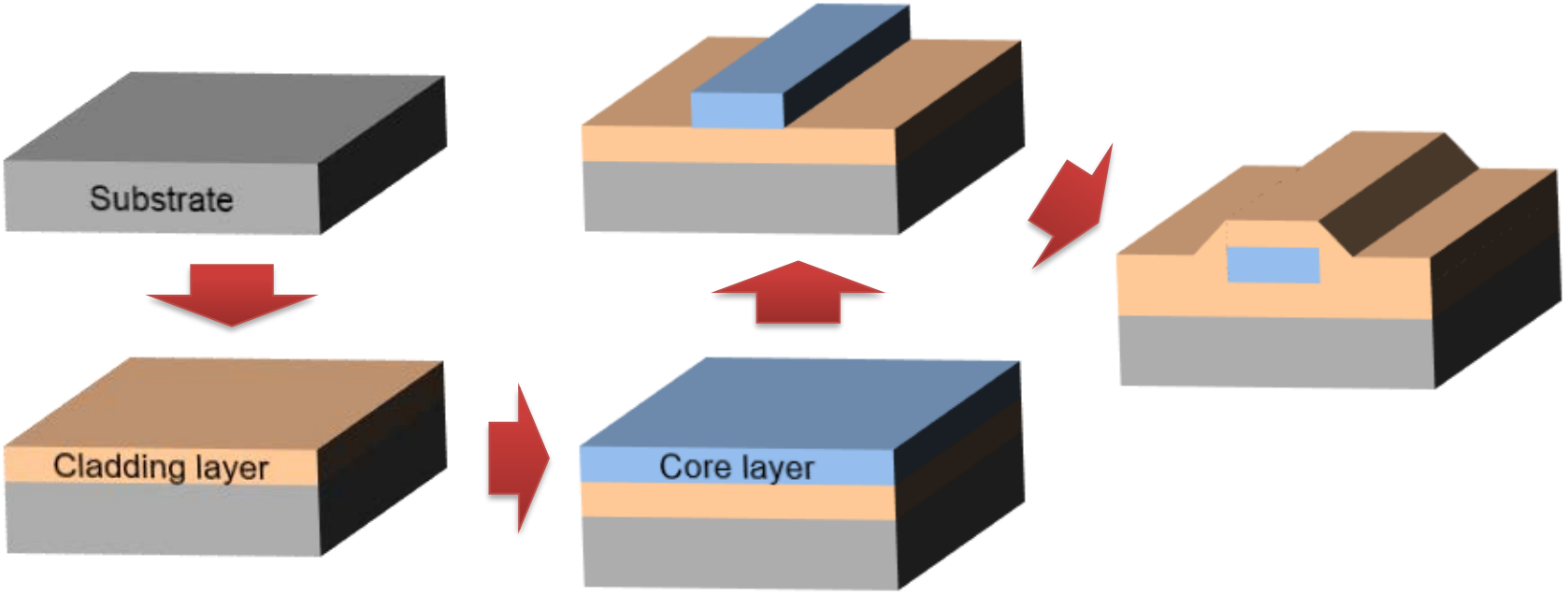



Integrated planar waveguide

- 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

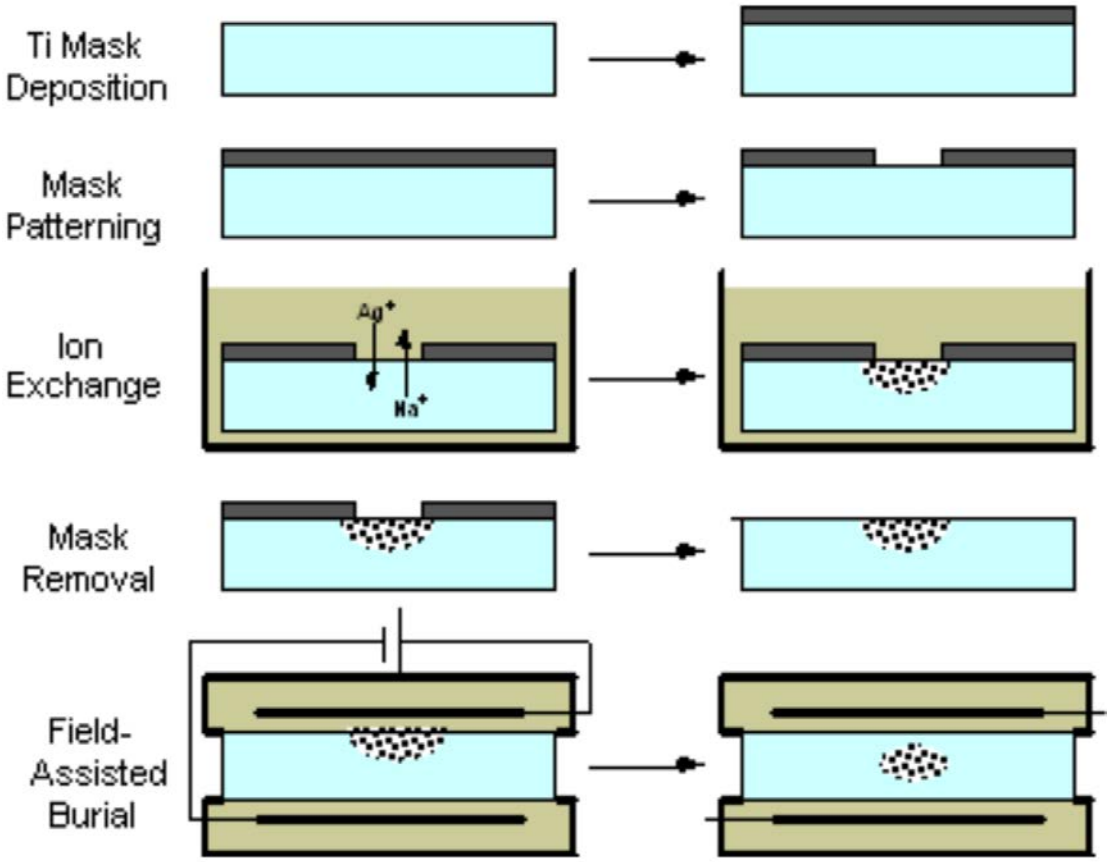
© imec and Tyndall National institute. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Planar waveguide fabrication: lithography




- 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

# Planar waveguide fabrication: ion exchange

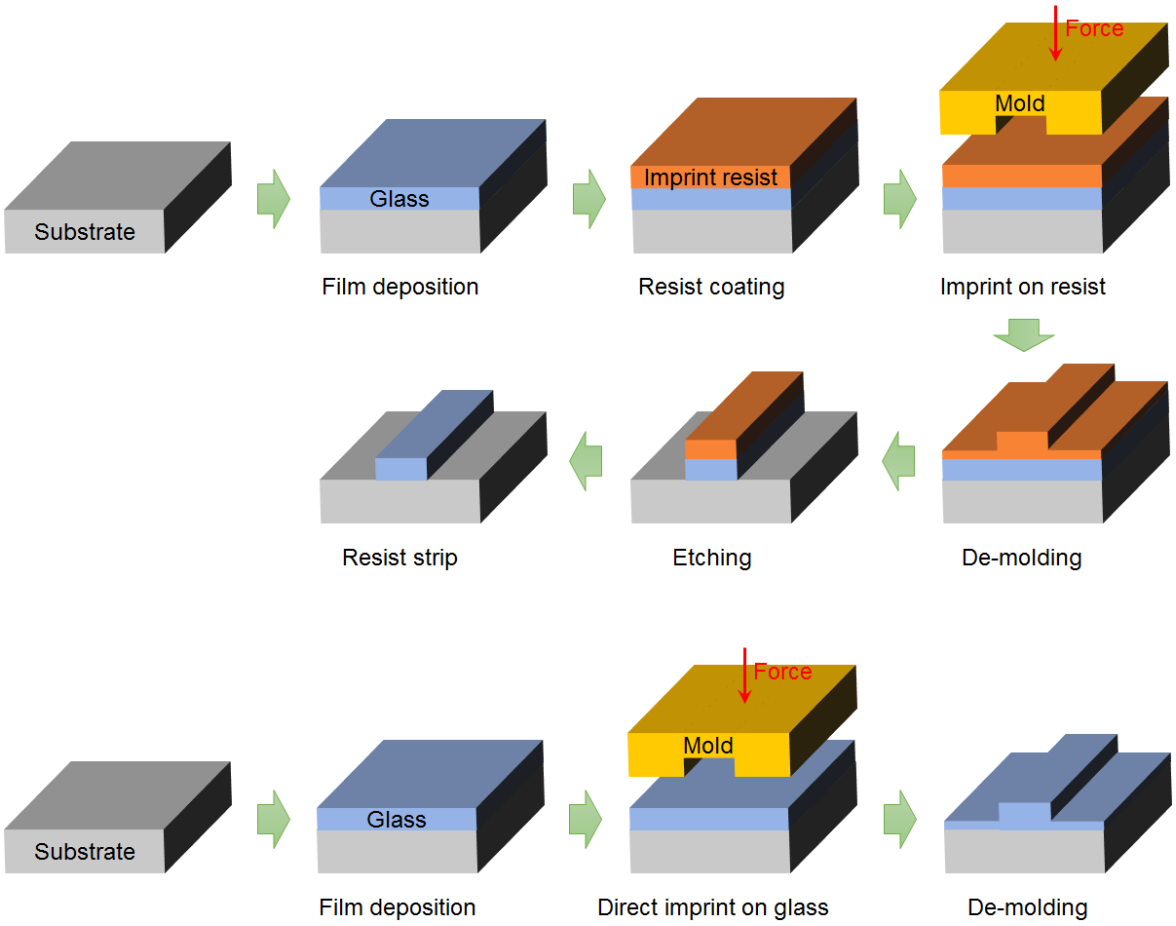


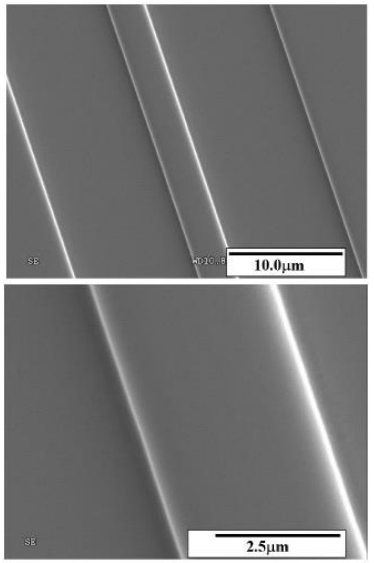

- Scalable, simple lithographic processing
- Low optical loss
- Potential for adjustments with post-annealing

© Seppo Honkanen, University of Arizona

© S. Honkanen, B. West, and S. Yliniemi. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Planar waveguide fabrication: nanoimprint



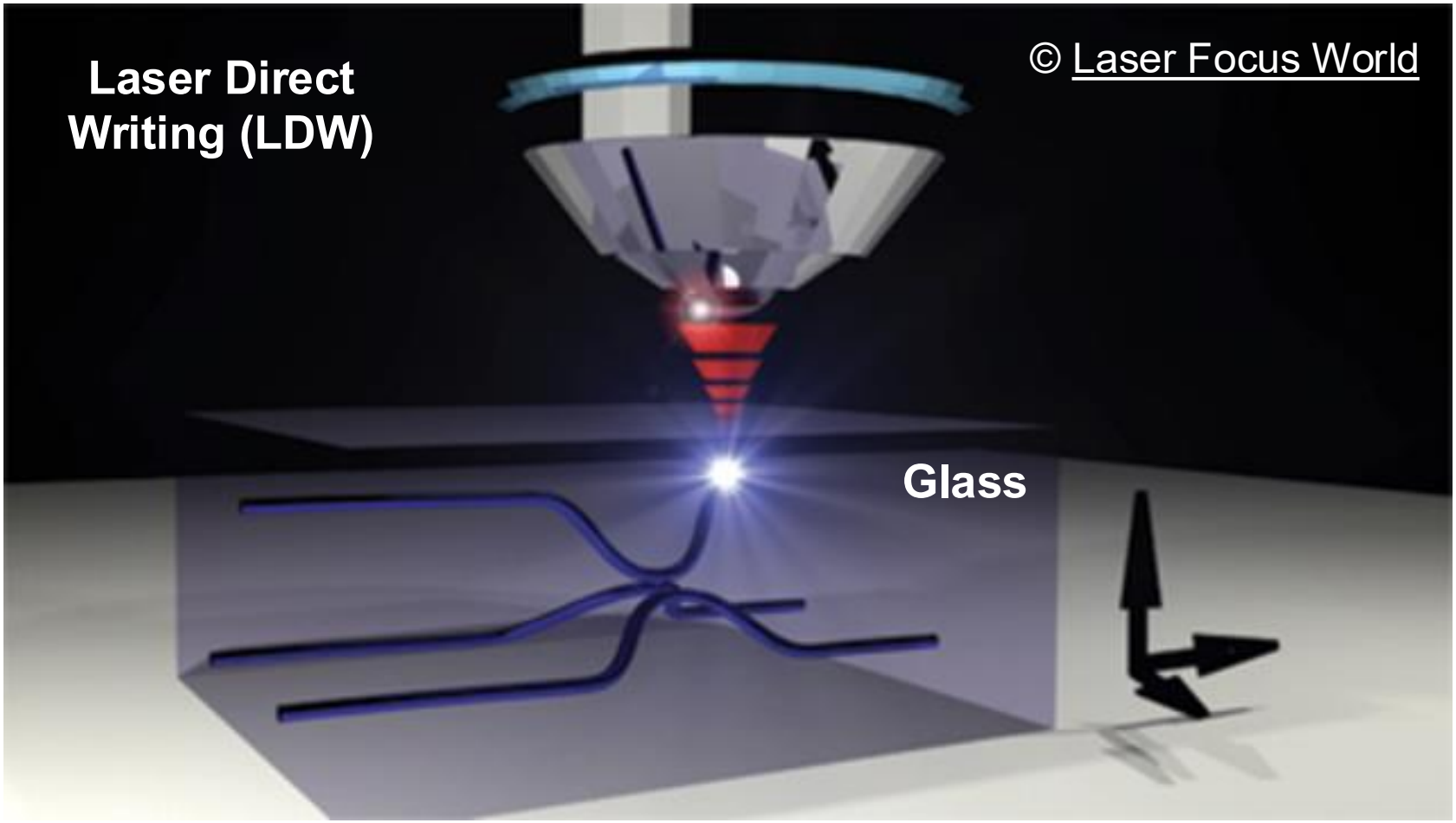




$As_2S_3$ waveguide patterned using direct nanoimprint

*Opt. Express* **18**, 19286 (2010)

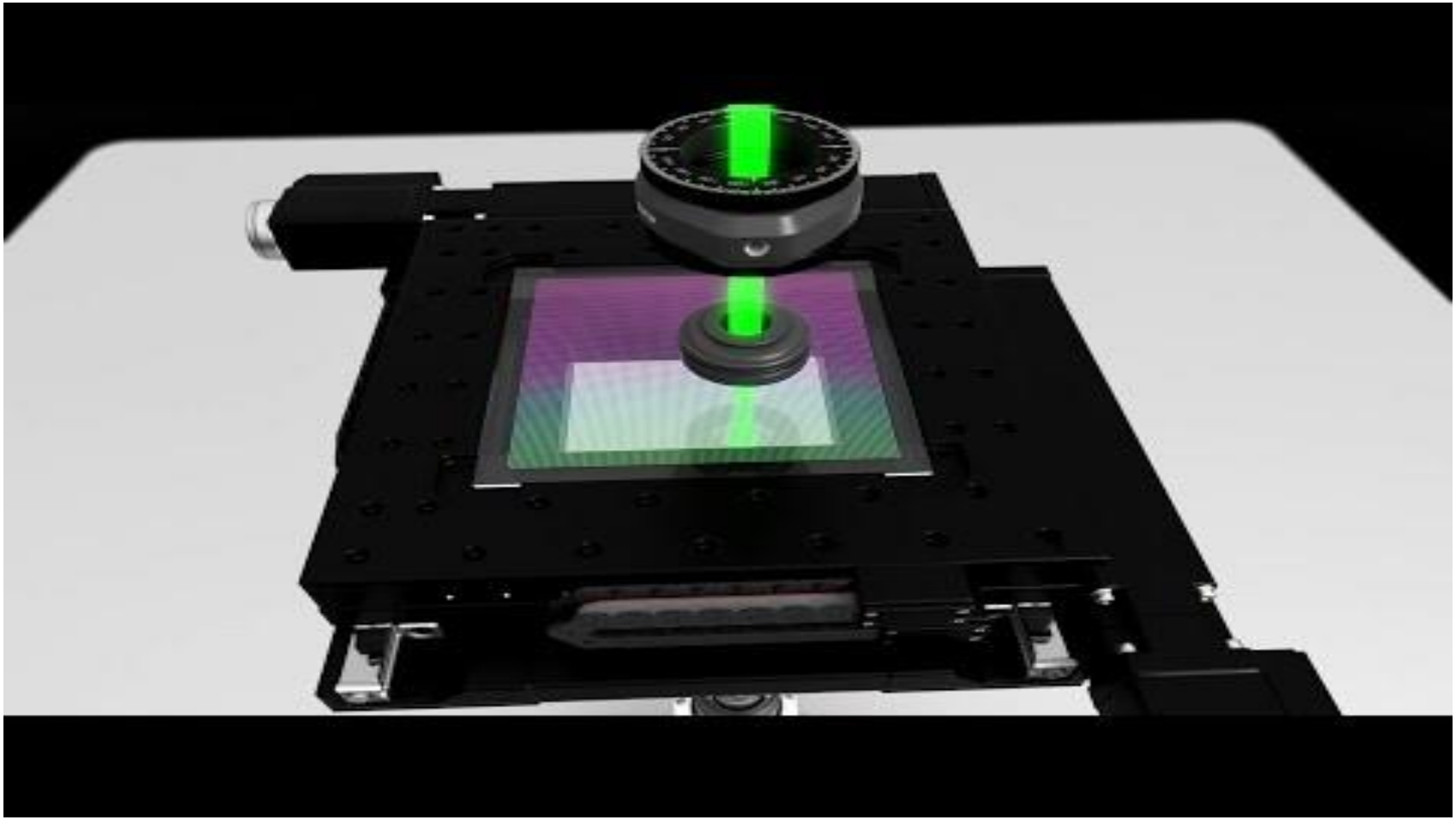
Courtesy of T. Han, S. Madden, D. Bulla, and B. Luther-Davies. Used with permission.

# Planar waveguide fabrication: laser writing




© Laser Focus World. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Beyond waveguide fabrication: LDW for data storage



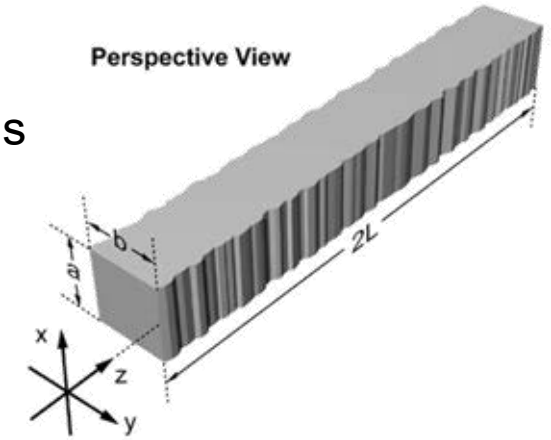
© Microsoft Research. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

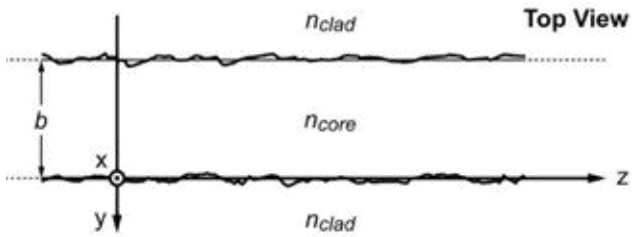
# Optical loss in fibers and waveguides

- 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)

© IEEE. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

Communications

Augmented reality

**Applications of integrated optics and photonics**

LIDAR

Sensing

# Optical communication system

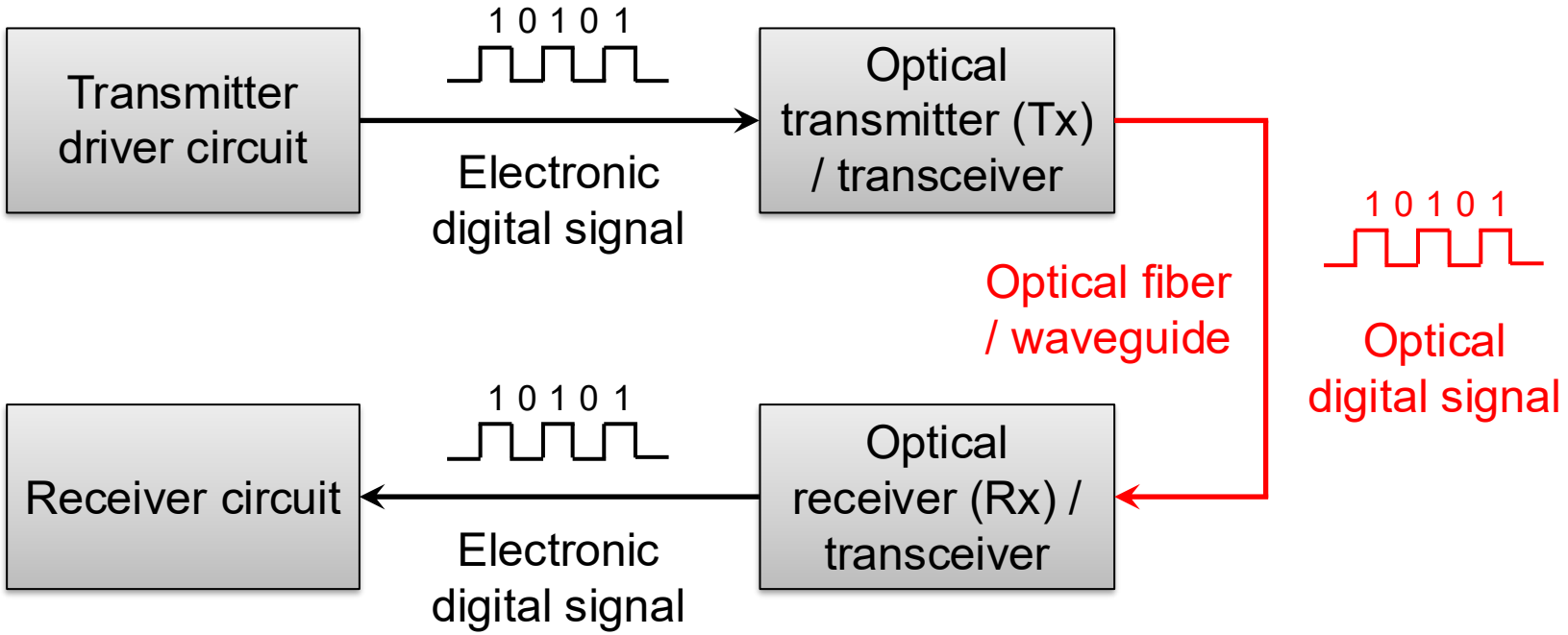


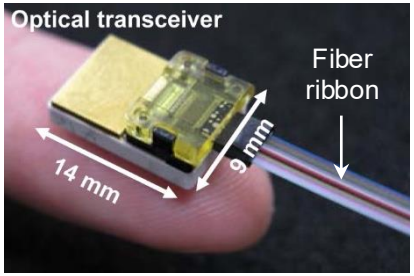
0 = peace

1 = invasion

Image of Great Wall of China © 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/

# Optical communication system

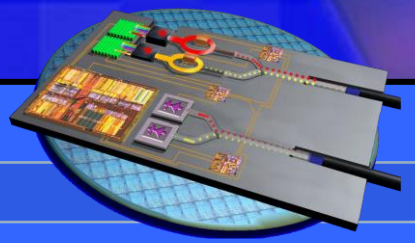



*Opt. Express* **19**, B777 (2011)

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.

# Electrical to optical interconnect



Enterprise
**Distance:**
**0.1-10km**

Rack-Rack
**Distance:**
**1-100m**

Board-Board
**Distance:**
**50-100cm**

Chip-Chip
**Distance:**
**1-50cm**

10G

Integrated photonics?

>= 40G

OPTICAL

3.125G 10G 40G

Optical Tech

3.125G 5-6G 10G 20G

ELECTRICAL

Copper Tech

Transition Zone

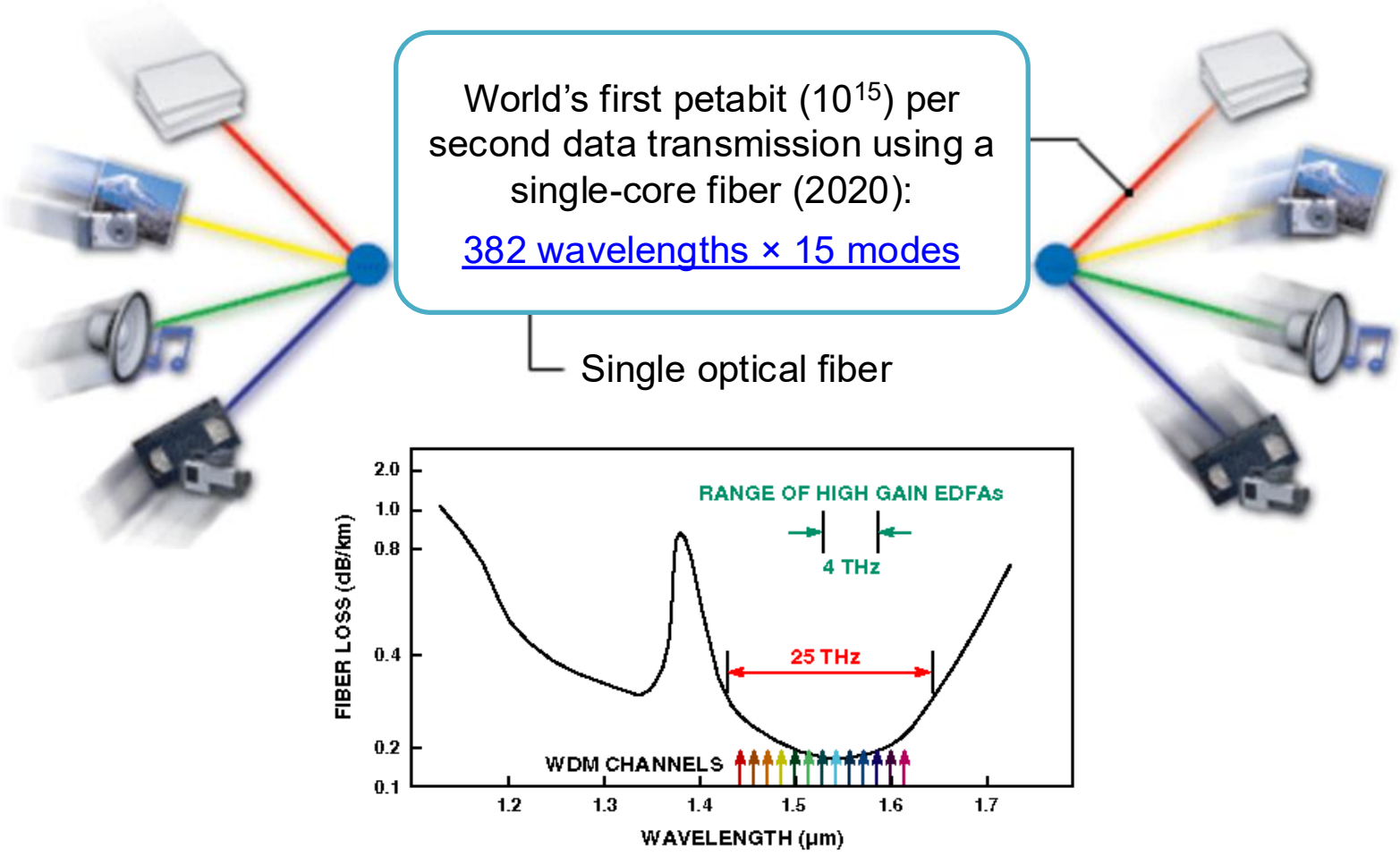
3.125G 5-6G 10G 15-20G

2004

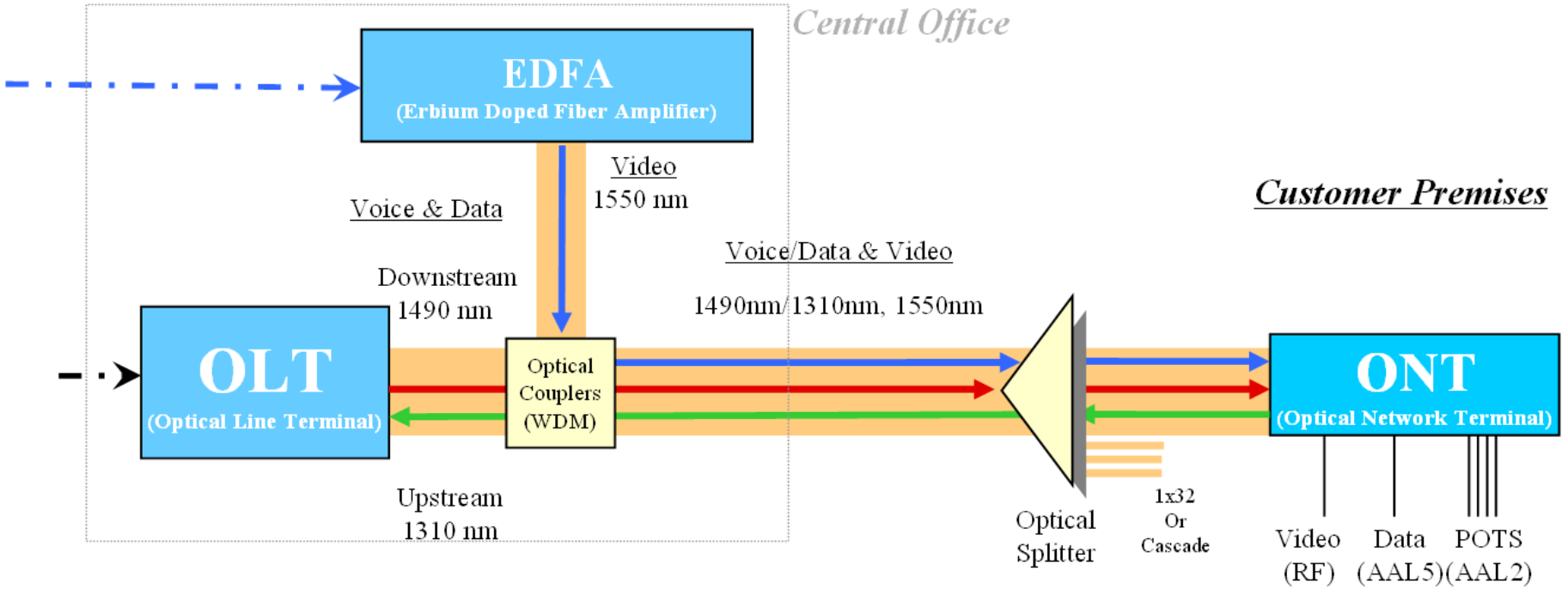
2010+

intel

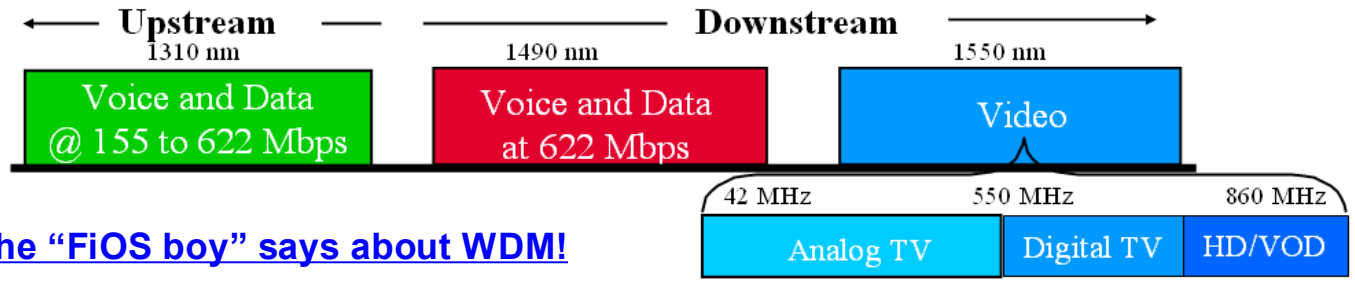
# Wavelength division multiplexing (WDM)



# PON Architecture (ITU-T G.983): A New Network



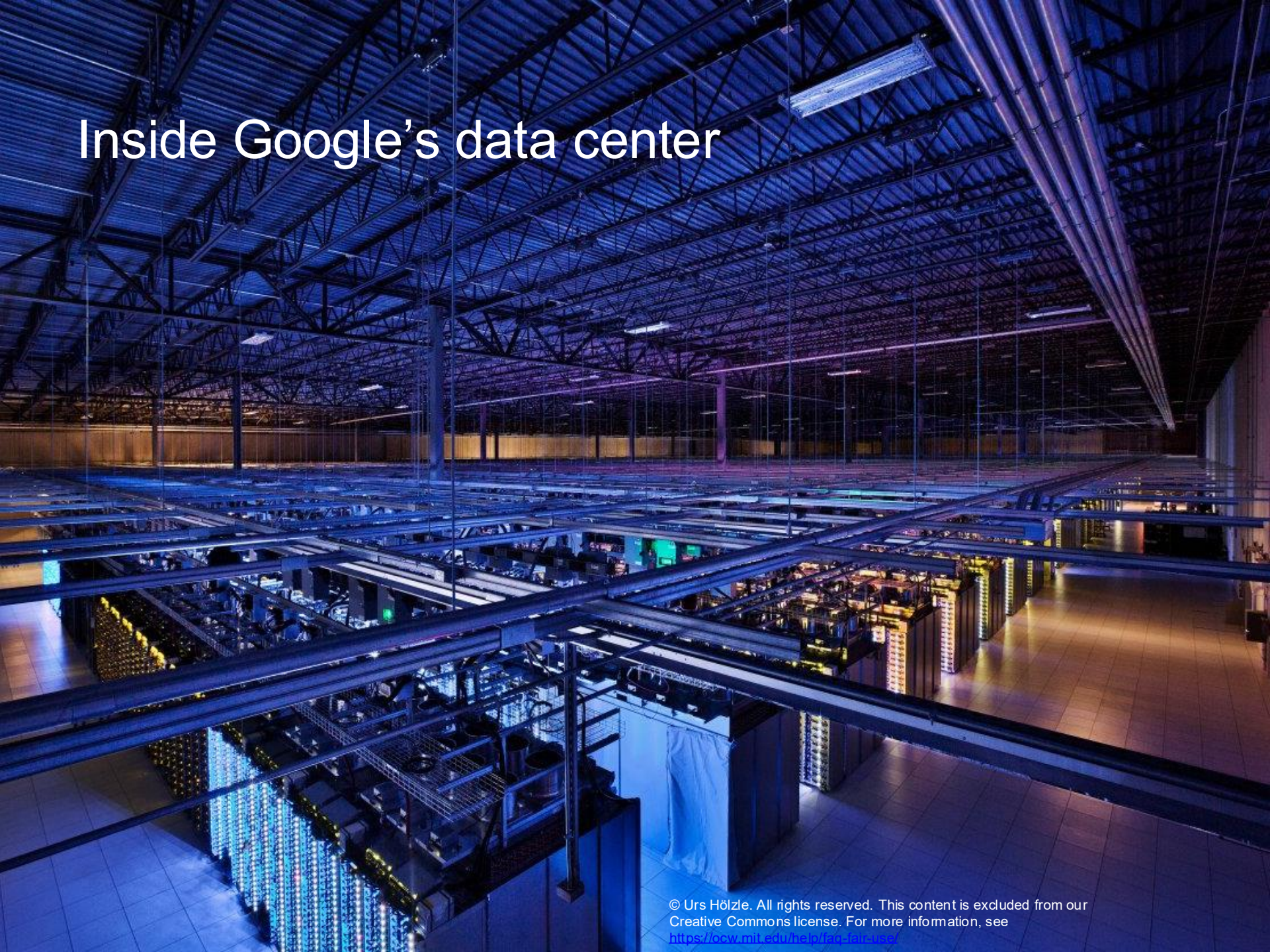

## Bandwidths & Services




[See what the "FiOS boy" says about WDM!]

© Verizon. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/
© Verizon 2004 All Rights Reserved
Information contained herein is subject to change without notice.

# Inside Google's data center



© Urs Hölzle. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Waterlogged

A midsize data center uses roughly as much water as about 100 acres of almond trees or three average hospitals, and more than two 18-hole golf courses.

**Approximate annual water usage, in gallons***




*Use varies depending on climate and other factors

Sources: California Department of Water Resources (orchards); James Hamilton (data centers); U.S. Department of Energy (hospitals); Golf Course Superintendents Association of America (golf courses)

THE WALL STREET JOURNAL.

© Microsoft. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/



© Microsoft. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Microsoft: Project Natick

© Business Standard Ltd. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Active optical cable (AOC)

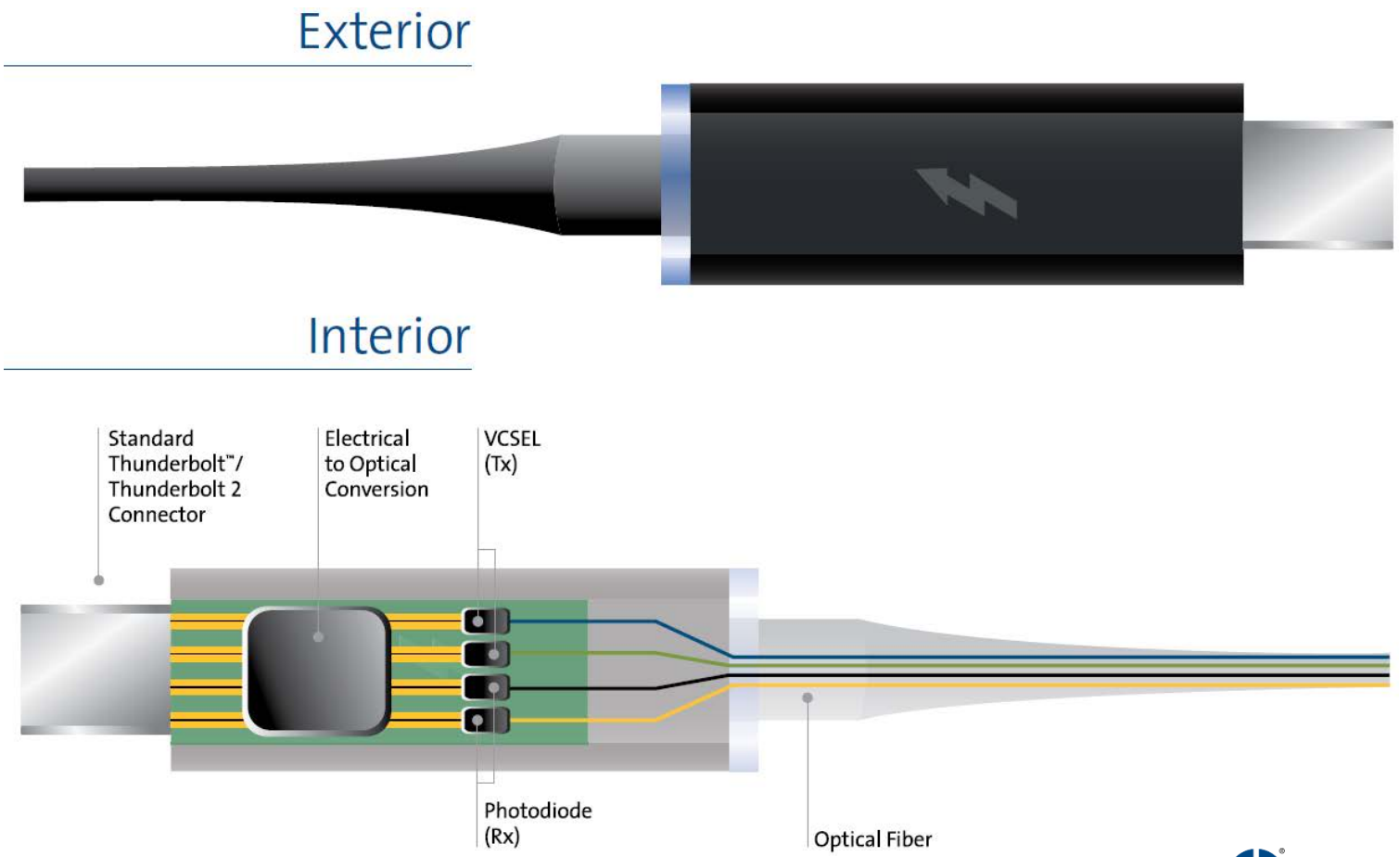
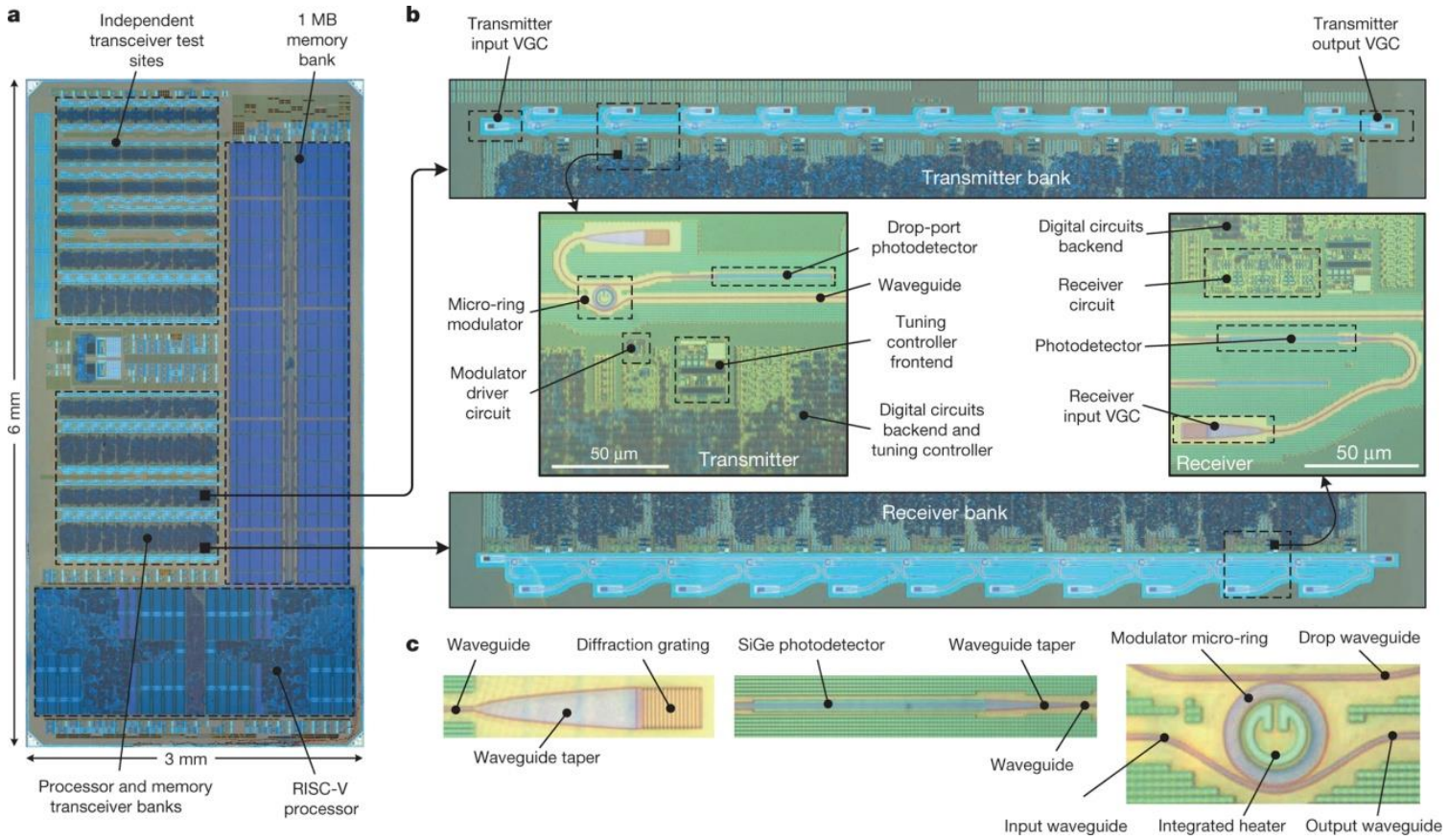



Image © Corning, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/help/faq-fair-use/

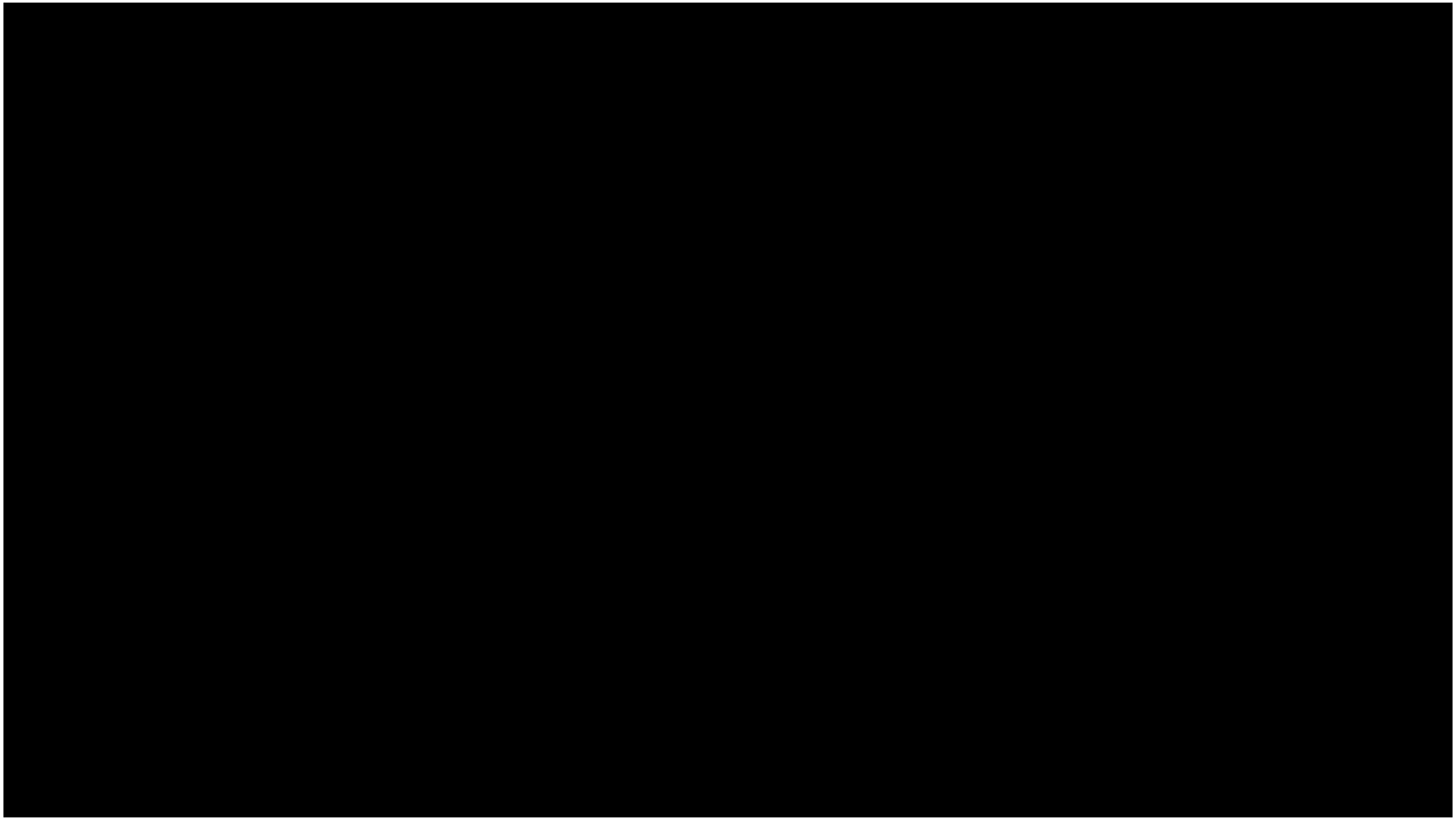
# Co-integration of photonics and electronics



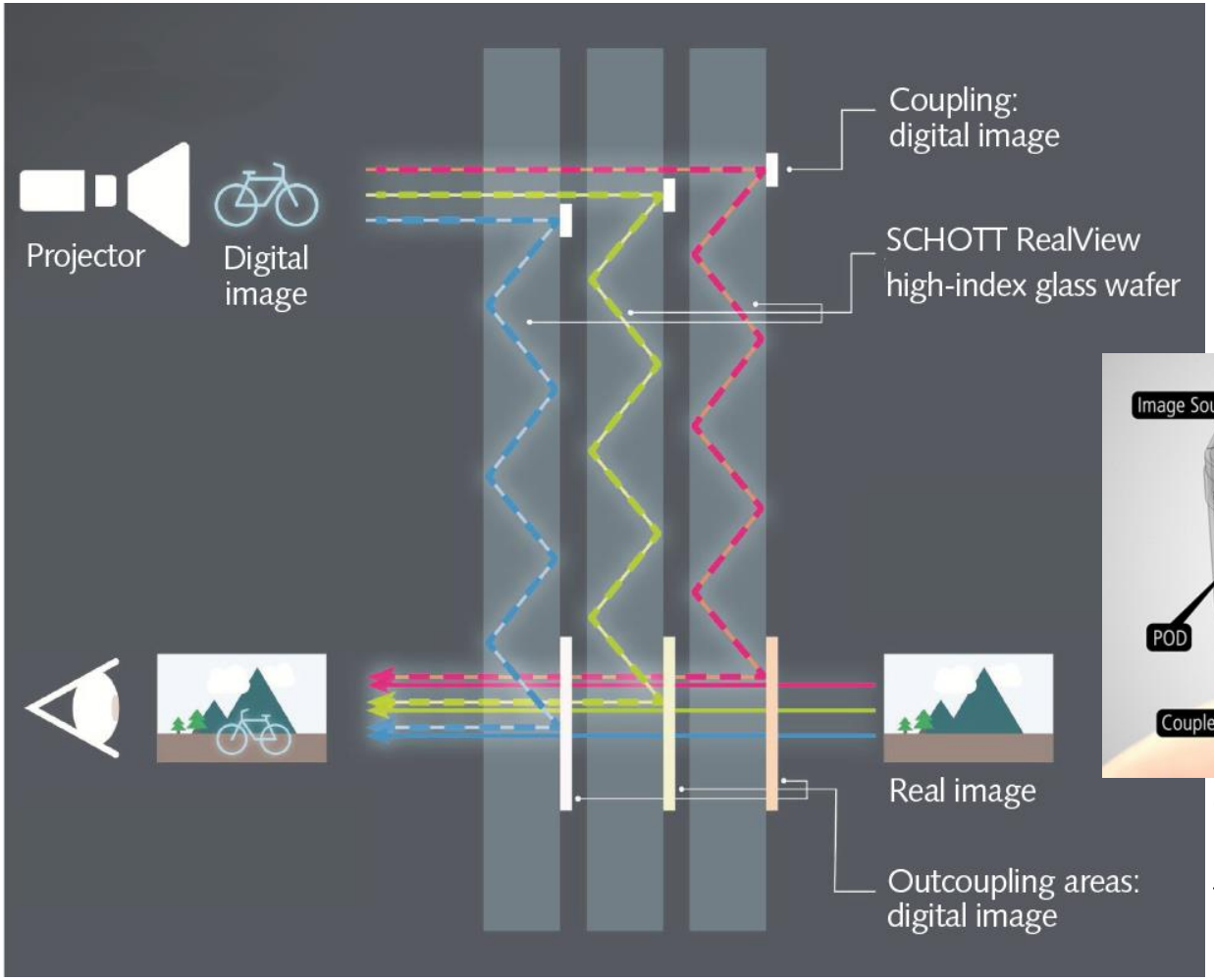

Sun *et al.*, *Nature* **528,** 534-538 (2015)

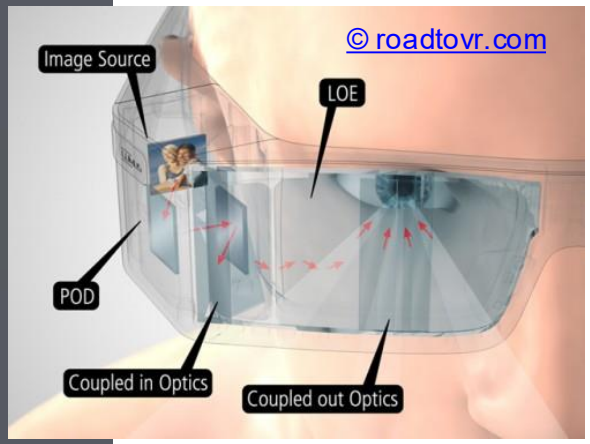
© Springer Nature. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# Augmented reality (AR)



# Augmented reality: how it works




© Ben Lang. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

© Laser Focus World. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# High refractive index glass for AR



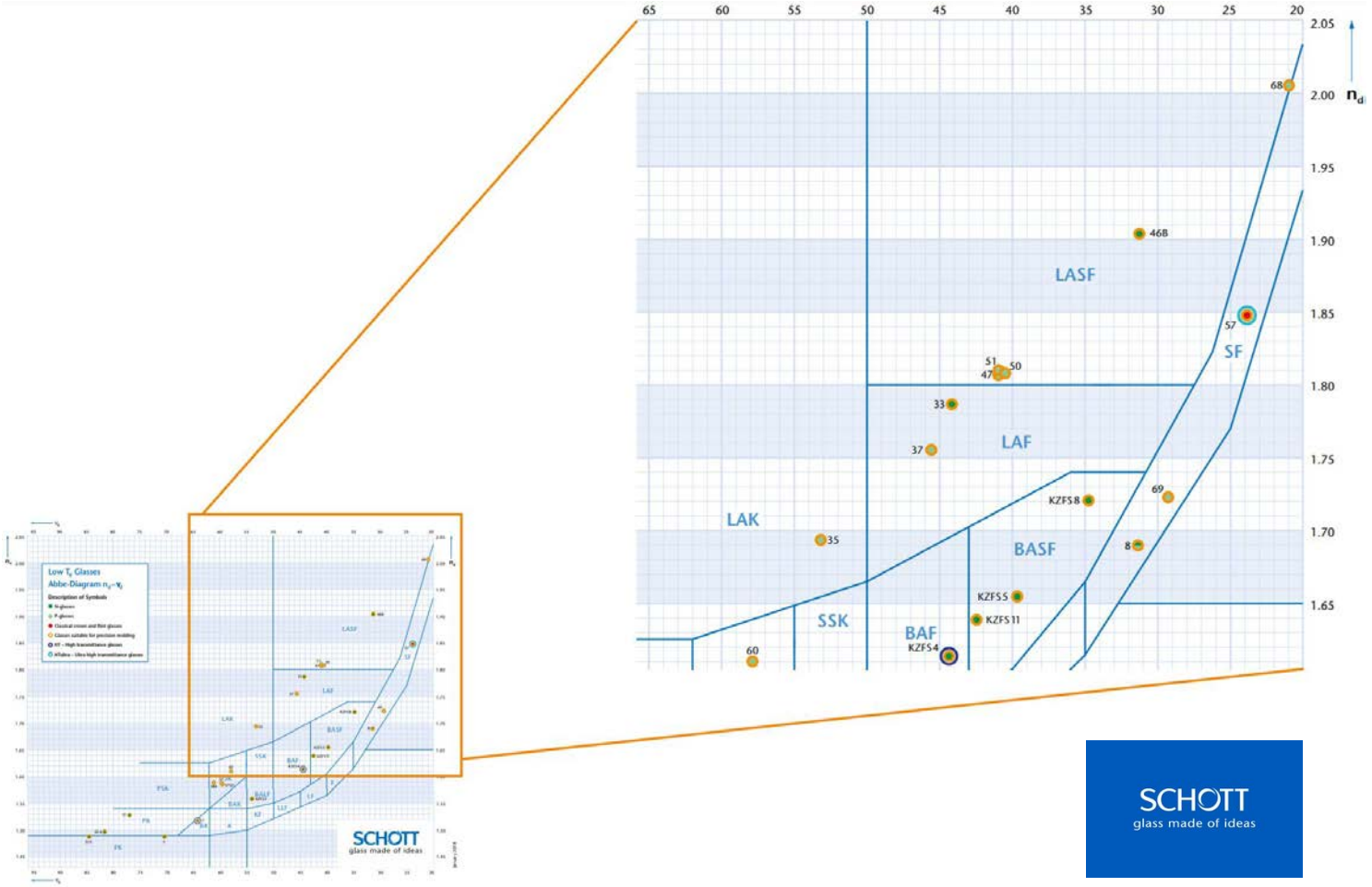
# High refractive index glass for AR

SCHOTT
glass made of ideas

| Augmented Reality device requirement | Customizeable properties of SCHOTT RealView® | Typical properties |
|---|---|---|
| Field of view | Refractive index | 1.5, 1.6, 1.7, 1.8, 1.9 |
| Image quality (resolution, contrast, brightness, ...) | High transmission | Optical glass grade |
| | Low birefringence | No polarization dependency of waveguide |
| | High homogeneity | Optical glass grade |
| | Flatness and thickness homogeneity | TTV < 0.8 µm |
| | | Local slope < 0.16 arcmin |
| | | Wedge < 0.03 arcmin |
| | | Warp* uncoated / coated < 20 µm / < 50 µm |
| | | BOW* uncoated / coated < 10 µm / < 20 µm |
| | Roughness uncoated / coated | $R_a$ < 1.0 nm / 1.5 nm |
| | Anti reflective coating | Tailormade to customer requirements |
| | Cosmetic | 40 / 20 scratch / dig |
| Form factor (light, weight, thin) | Low wafer thickness | ≥ 0.3 mm |
| | Specific weight | Depending on glass type |
| | Glass strength and stability | Compatible with automated wafer handling equipment |
| Mass manufacturing process | Wafer size | 150 mm, 200 mm, 300 mm |
| | High volume processing and quality control | Full metrology capabilitites in mass production environment. Statistical process control established. |

© Schott. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# High refractive index glass for AR




© Schott. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

# 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

Applications of integrated photonics

- Digital communication systems & augmented reality

MIT OpenCourseWare
https://ocw.mit.edu/

3.071 Amorphous Materials
Spring 2025

For information about citing these materials or our Terms of Use, visit:
https://ocw.mit.edu/terms.