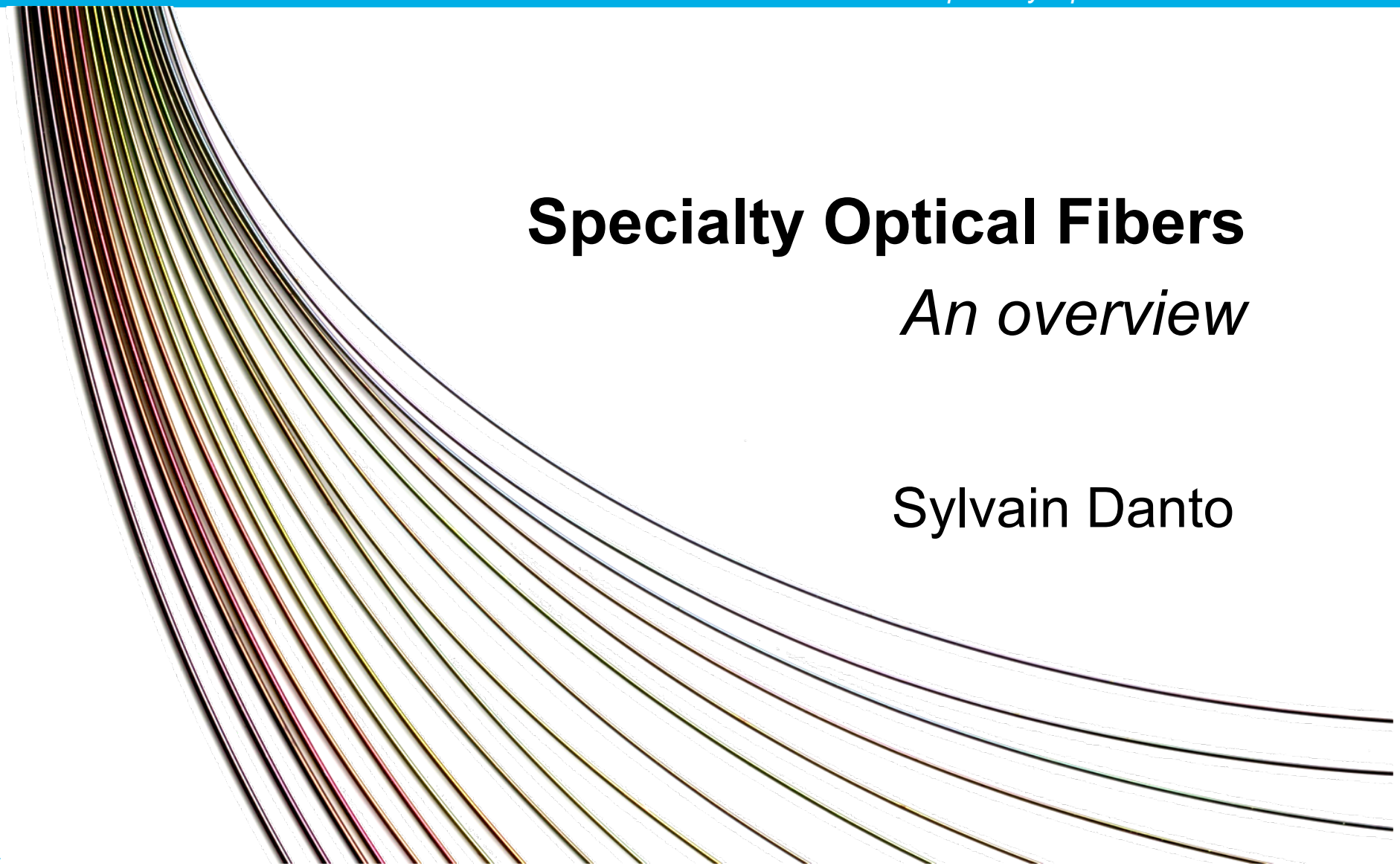
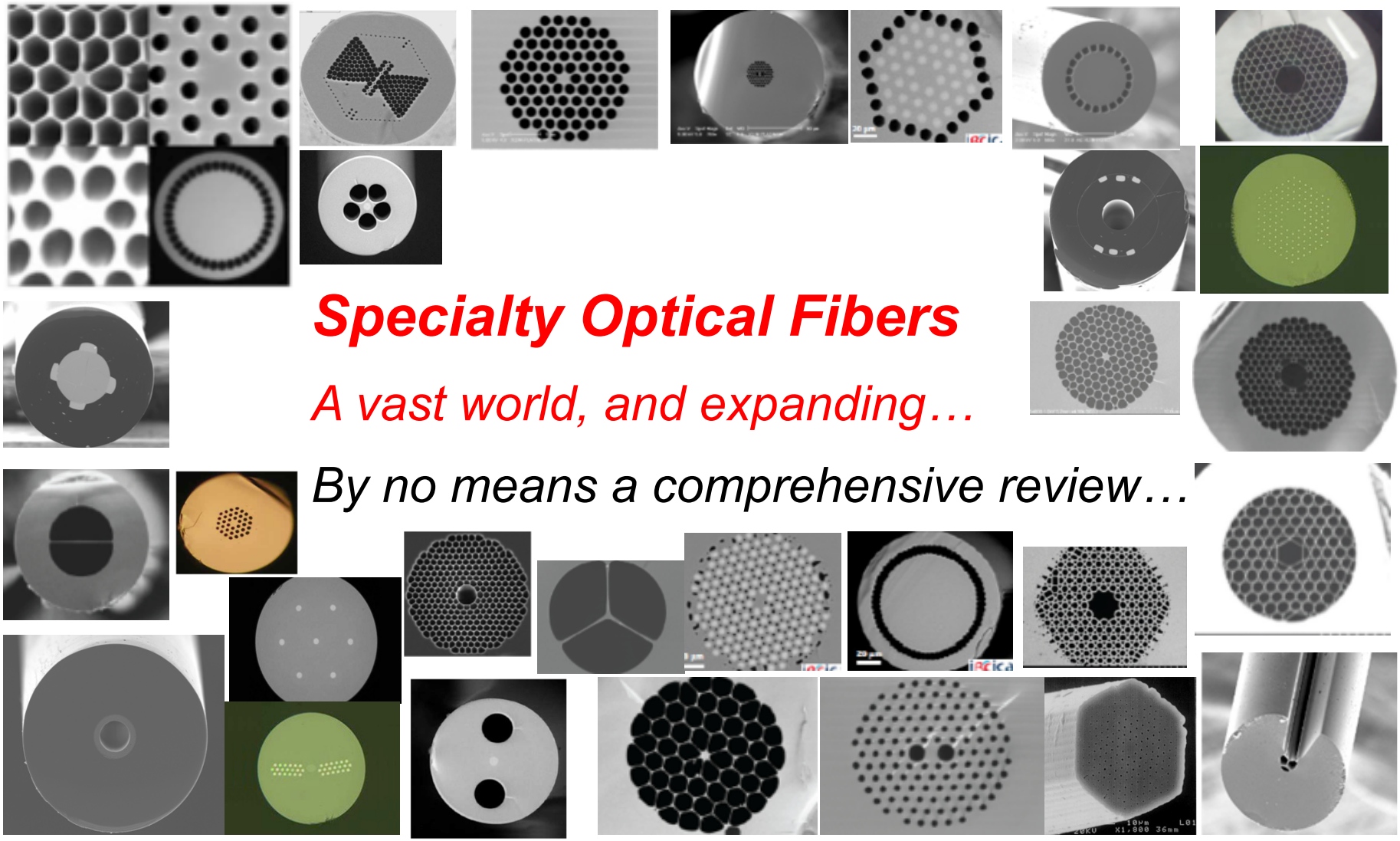


Specialty Optical Fibers

An overview

Sylvain Danto

Preamble



Specialty Optical Fibers

A vast world, and expanding…

By no means a comprehensive review…

Background - Generalities

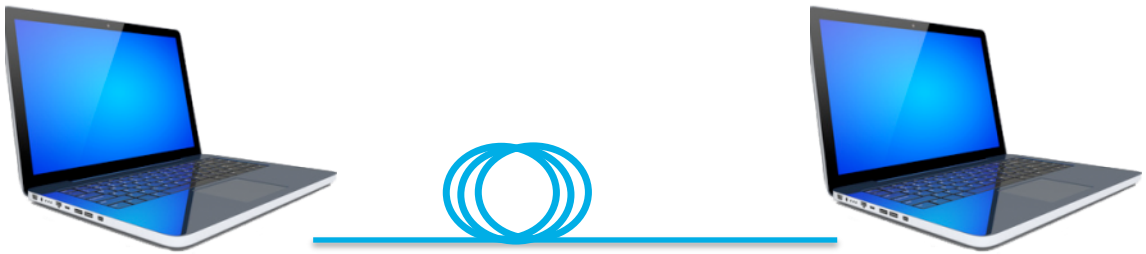
Specialty Optical Fibers

What is it?

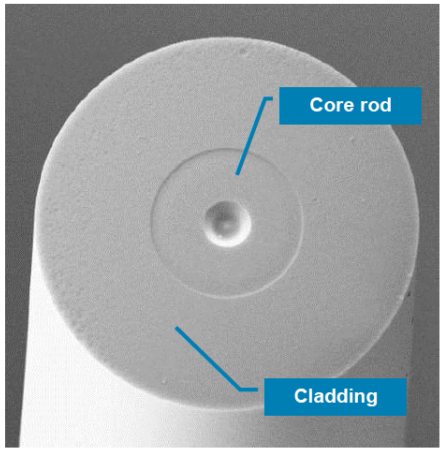
What it's not…

Background - Generalities

❑ Telecom Fibers



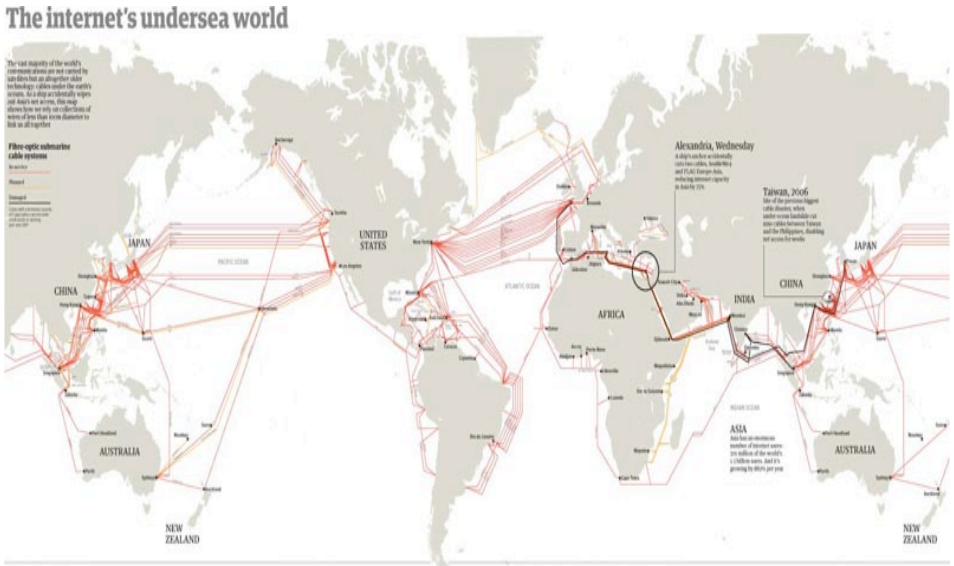
Telecom Fibers: *What Do They Look Like ?*



Core / Core Rod
- Guides light inside fiber
- RI increase through GeO_2 doping
- Diameter: 9 µm (single mode)
- Core rod comprises doped core and undoped core cladding

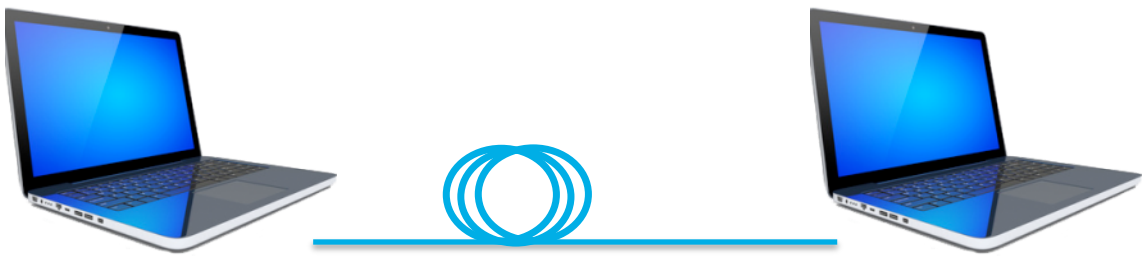
Cladding
- Undoped fused silica
- Diameter: 125 µm

Coating
- Typically acrylate
- Diameter: 250 µm



Background - Generalities

❑ Telecom Fibers



❑ Specialty Fibers… *Pretty much all the rest.*

UV – IR spectroscopy

Fiber bundles for UV applications

Industrial laser applications

Medical applications

SOFs vs Telecom fibers

- ❑ Shorter lengths
- ❑ Smaller (niche) markets
- ❑ More expensive

Background - Generalities

❑ Applications

Optics / Photonics

- Lasers
- Photonic-crystal fibers for short fs/ps pulses
- Supercontinuum, Raman amplification
- Optical switching
- Bend insensitive
- Dispersion shifted/flattened/compensating
- Double clad
- Electro-optic

Smart fibers

- High-performance fibers
- Sensing / Monitoring fibers
- Conducting / Piezoelectric fibers
- Chromic / Photovoltaic fibers

- Fluorescence
- IR fibers
- Large core
- Low-birefringence
- Multi core
- Photonic and Crystal fibers
- Photosensistive
- Polarization maintaining
- …

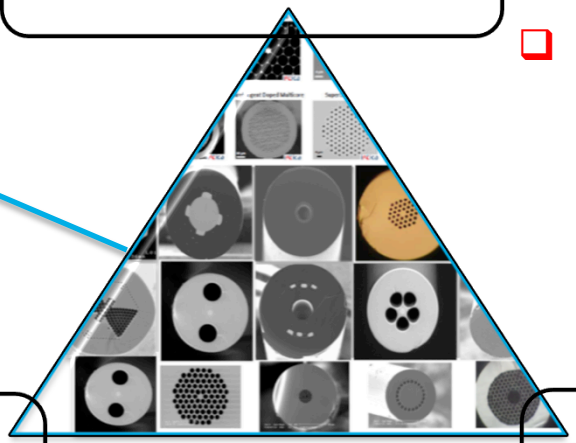
Fiber optics

- ❑ Low-cost technology
- ❑ Large surface area
- ❑ Electro-Magnetic Immune (EMI)
- ❑ Flexible, compact, light-weight

Background - Generalities

❑ Fiber Design Triad

Specialty Optical Fibers



Materials

- ***Glass*** *(silica, fluoride, chalcogenide…)*
- ***Polymer*** *(PMMA, polycarbonate…)*
- ***Dopants, Rare-earth, fluorescent ions***
- ***Metals***

Design

- ***Solid-core***
- ***Hollow-core***
- ***Multimaterial***

Processing

- ***Cladding*** *(hard, soft, metallic…)*
- ***Coating*** *(CVD…)*
- ***Post-drawing treatment***

Background - Generalities

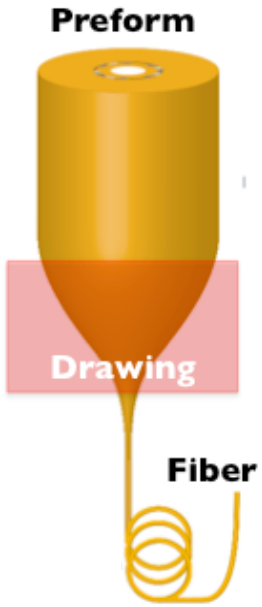
❑ Fiber Fabrication

Preform-based methods

- CVD-derived (MCVD, PCVD…)
- Rod-in-tube
- Direct casting
- Direct mechanical drilling
- Stack-and-draw
- Preform extrusion

Non-preform based methods

- Double crucible
- High-pressure microfluidic



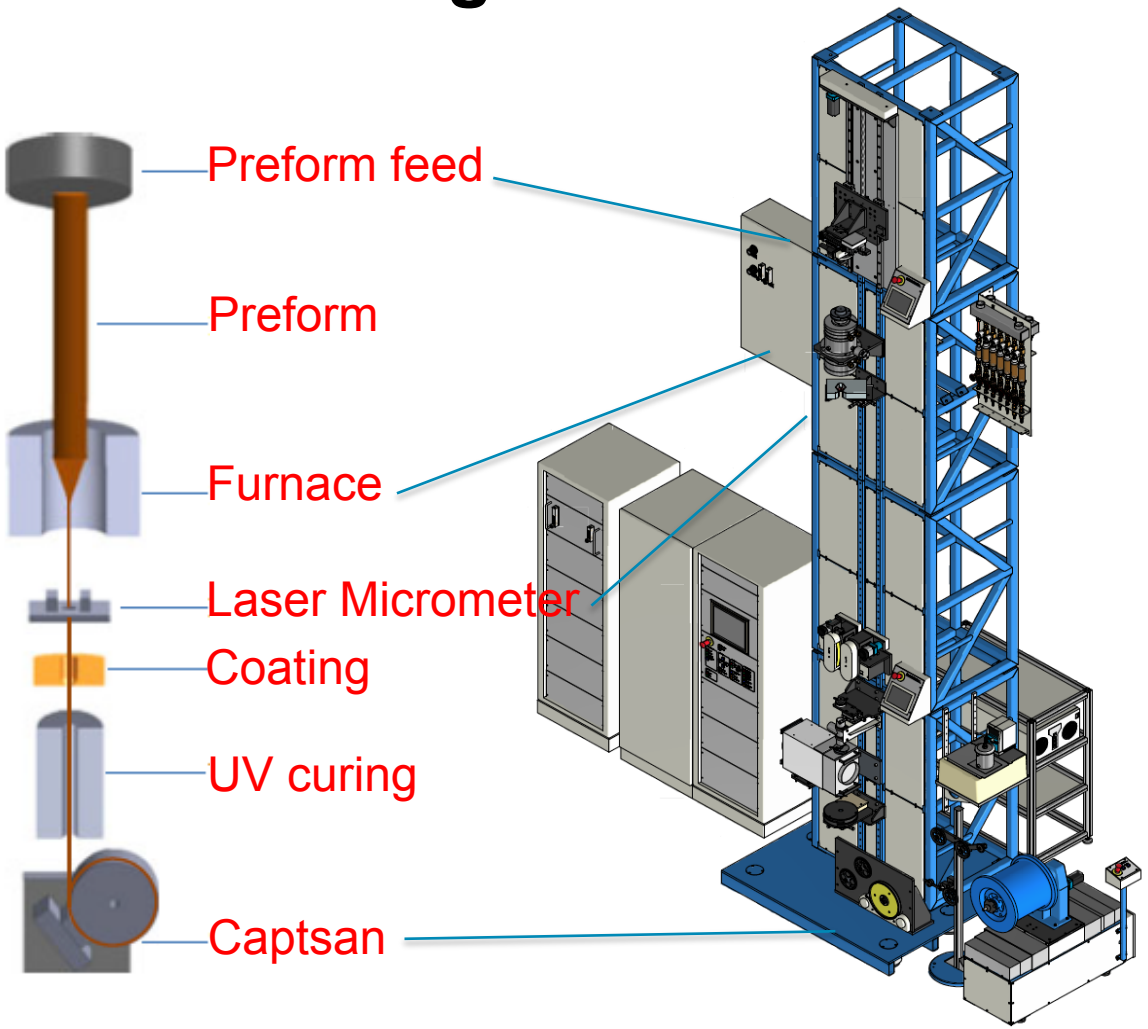
Standard method

Fiber drawing

[OmniGuide]

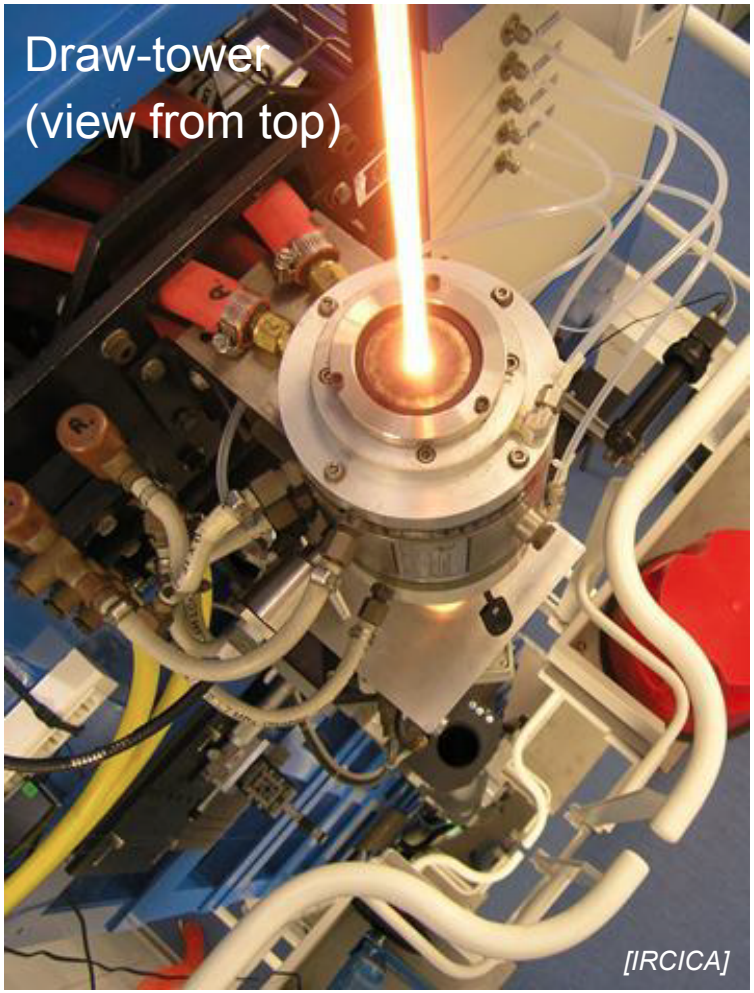
Background - Generalities

❑ Fiber Drawing



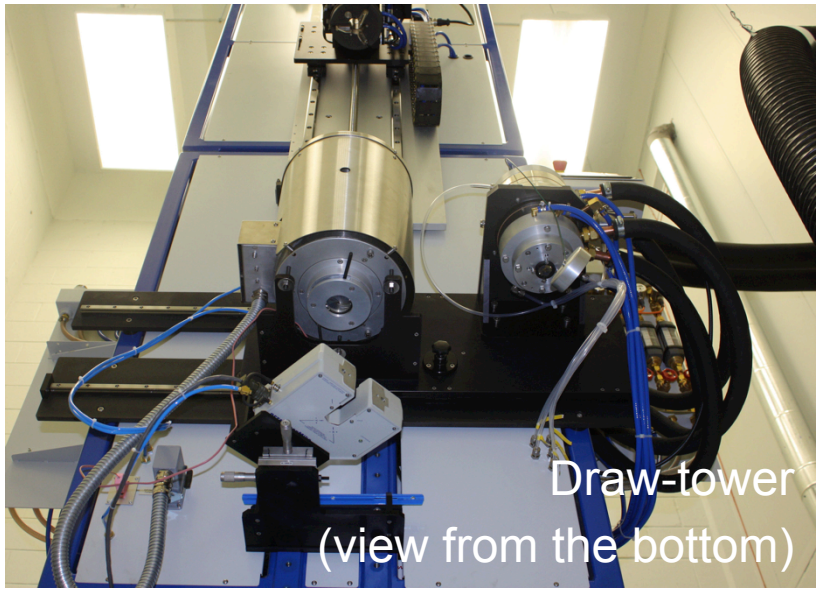
Background - Generalities

❑ Fiber Drawing



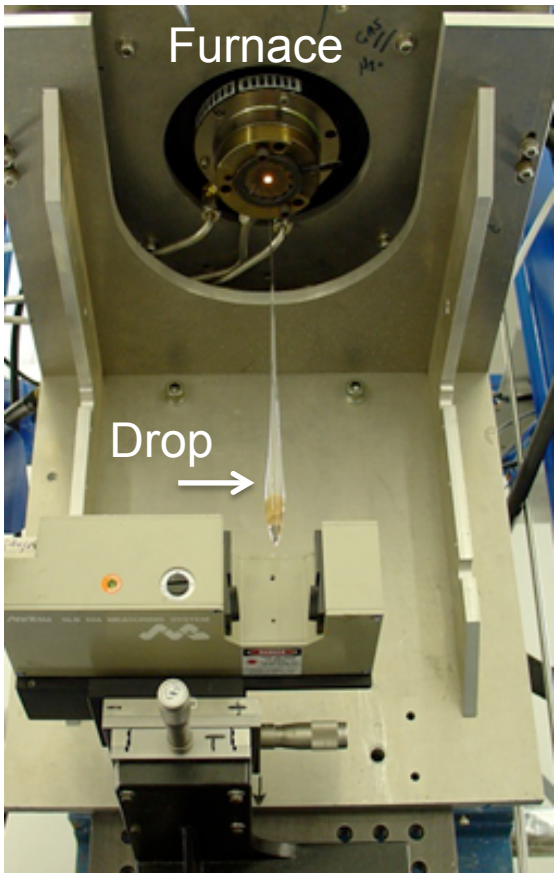
Fiber drawing technology

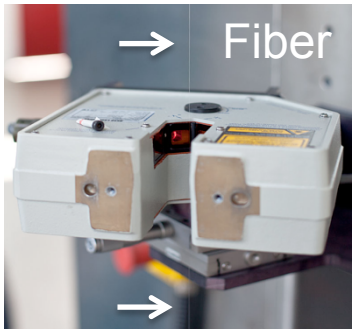
- ❑ Low cost
- ❑ Reliable, proven techno
- ❑ Simple
- ❑ Generate surface

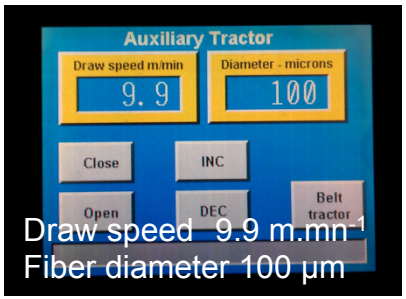


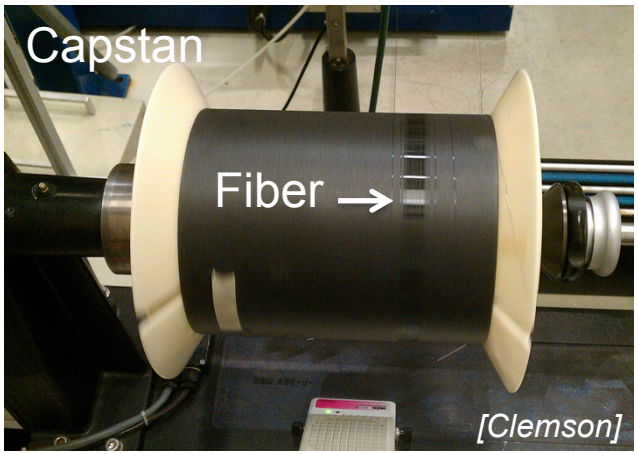
Background - Generalities

❑ Fiber Drawing









Specialty Optical Fibers

Illustrations

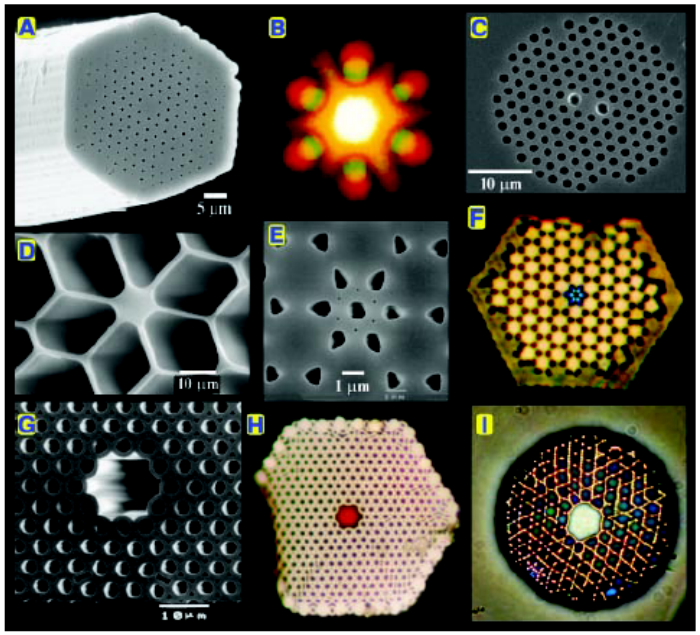
Microstructured Fibers

❑ Definition

Optical fibers constructed with a lattice of voids (air holes) along their length

⟹ Provide unique optical properties impossible to obtain with standard fibers

Endlessly single-mode guidance, adjustable dispersion, large mode area, nonlinear properties



(Russel, Univ. of Bath, 2003)

Difference with conventional fibers

- ❑ Large structural flexibility
- ❑ Large index contrast
- ❑ Guiding properties come from microstructure instead of materials composition

Microstructured Fibers

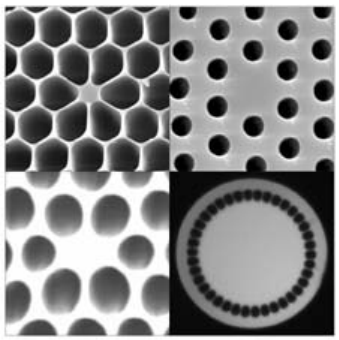
❑ Definition

Optical fibers constructed with a lattice of voids (air holes) along their length

⟹ Provide unique optical properties impossible to obtain with standard fibers

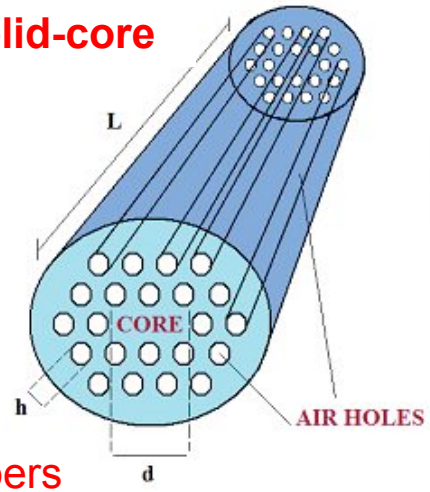
Endlessly single-mode guidance, adjustable dispersion, large mode area, nonlinear properties

Two light-guiding mechanism

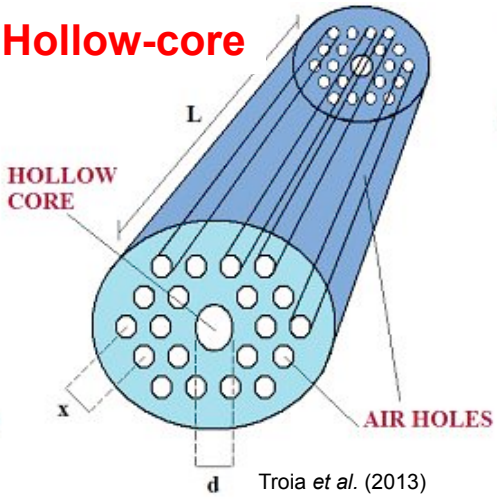


Effective index
Photonic Crystal Fibers (PCF)

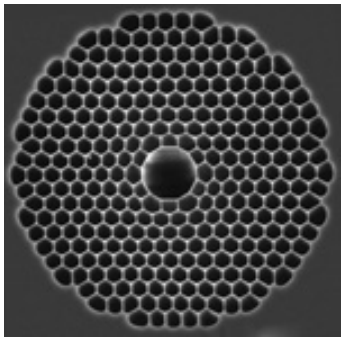
Solid-core



Hollow-core



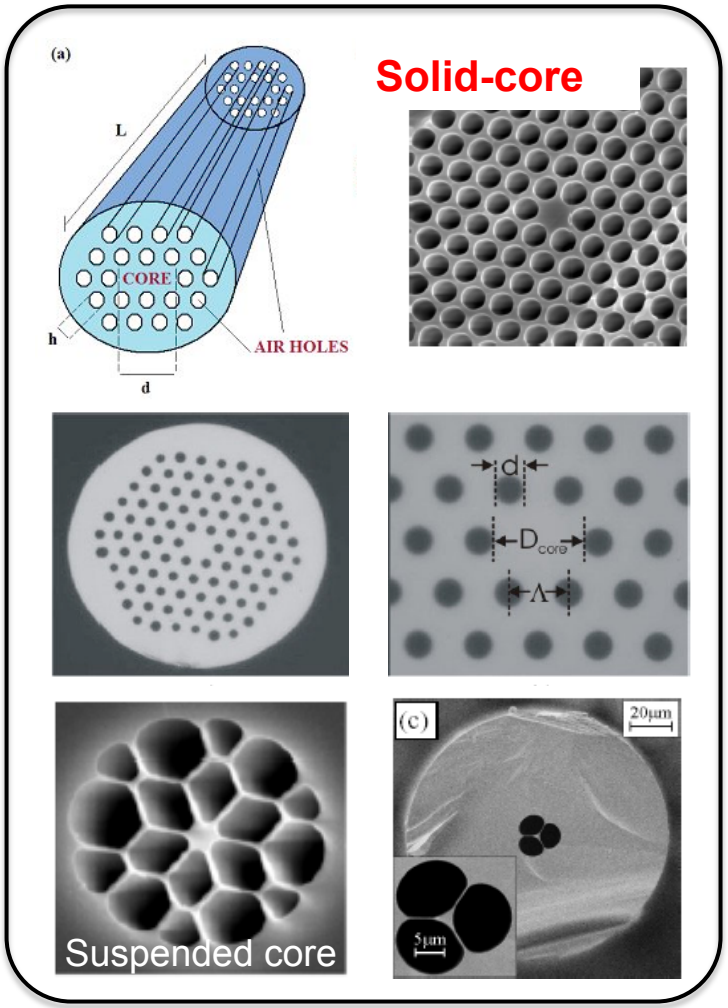
Troia *et al.* (2013)



Photonic BandGap
Photonic bandgap fibers (PBGF)

Microstructured Fibers

❑ Solid-core Fibers



Properties

- ❑ Periodic microstructured region with air holes
- ❑ Core localized as a defect (= lack of hole)
- ❑ Holey cladding forms *effective* low-index material

Guiding mechanism by Total Internal Reflection ($n_{core} > n_{clad\_eff}$)

- ❑ Much higher Δn contrast than in doped silica
- ❑ Effective core area A_{eff} ~ 1-1000 mm^2

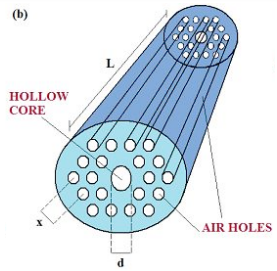
Very large (high power) or very small (non-linearity)

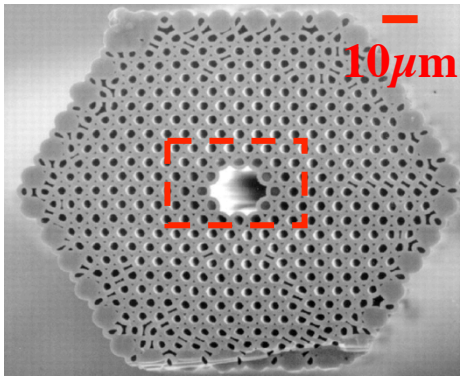
- ❑ Monomode in short wavelengths (n_{eff} clad strongly depending on the wavelength)
- ❑ Adjustable chromatic dispersion

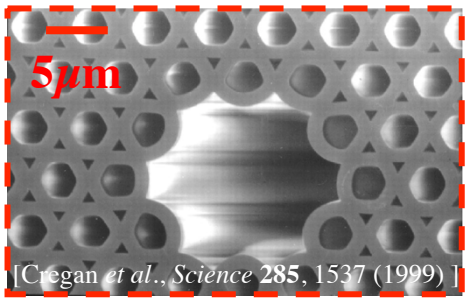
Microstructured Fibers

❑ Hollow-core PBG Fibers

Hollow-core







[Cregan *et al.*, *Science* **285**, 1537 (1999)]

Properties

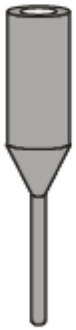
- ❑ Periodic microstructured cladding region with air holes to guide light in a hollow core
- ❑ Depending on their wavelengths, photons are either allowed to travel through the structure (allowed bands) or not (forbidden bands, or photonic band-gap - PBG)
- ❑ In PBG regions the light remains strongly confined in the core
- ❑ Unlike solid-core fibers here: n_{eff} clad > n core
- ❑ High threshold power for nonlinear effects or material damages
- ❑ Core can be filled with gasses, particles…
- ❑ No Fresnel reflections at open fiber ends

Microstructured Fibers

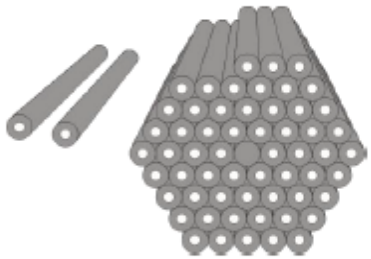
❑ Fibers Fabrication

Stack-and-draw

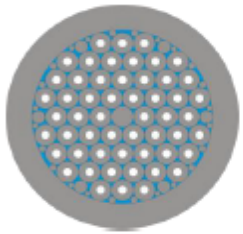
Multi-steps fabrication through compact assembly of capillaries



Capillaries



Stacking



Fusing

Drawing

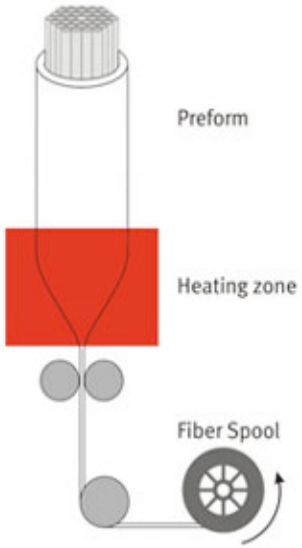


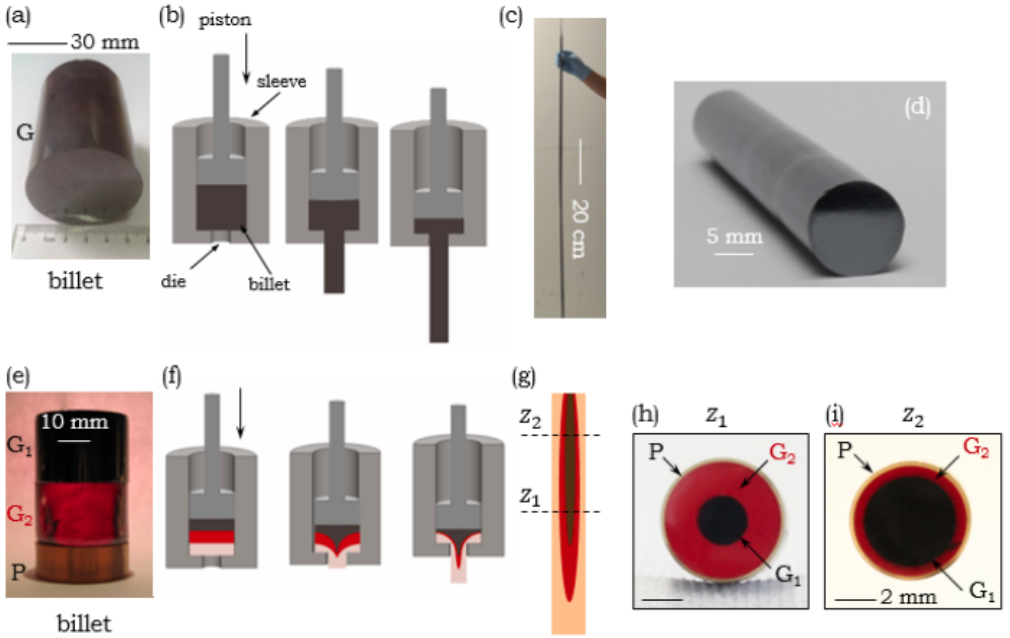
Illustration: [PhLAM – Lille] [NKT] [GCL – Rennes]

Microstructured Fibers

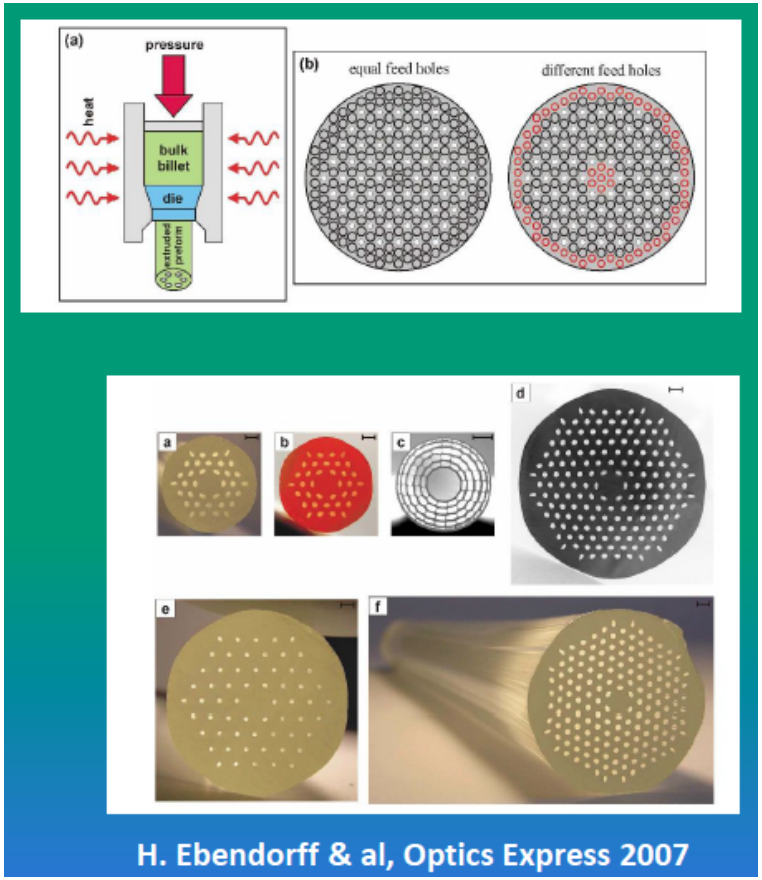
❑ Fibers Fabrication

Preform Extrusion

Chalcogenide glass preforms *(Pr. Abouraddy - UCF)*



Polymer preforms *(Pr. Monro – Adelaide)*

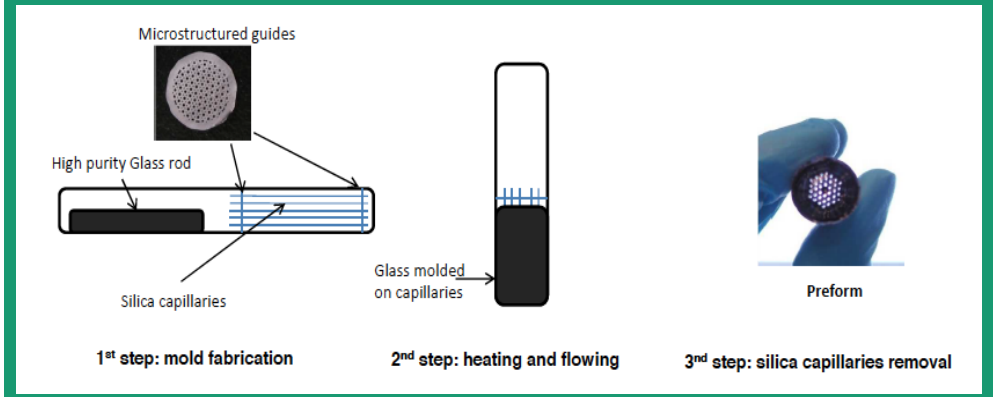


(a), (e), (f) lead silicate glass
(b) bismuth glass
(c) (d) polymer

Microstructured Fibers

❑ Fibers Fabrication

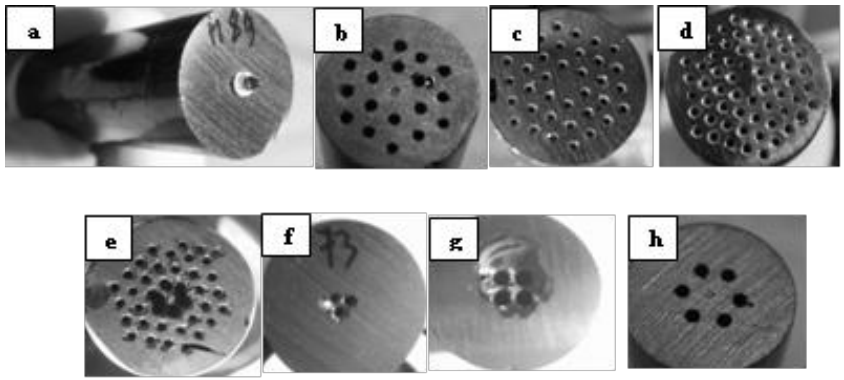
Direct preform casting



Glasses and Ceramics Laboratory – Rennes

Coulombier *et al.*, Optics Express 2010

Direct preform drilling

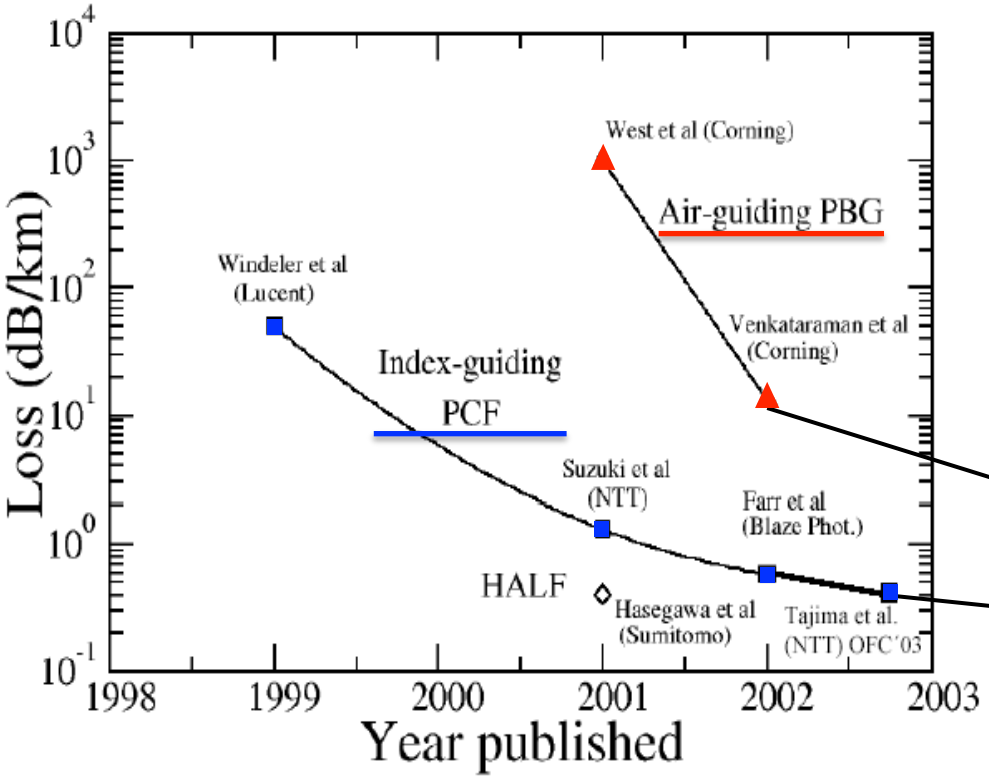


(Pr. Smektala-University of Burgundy, Dijon)

- ❑ Short elaboration time
- ❑ Large design possibilities
- ❑ No interstitial holes
- ❑ Cost effective

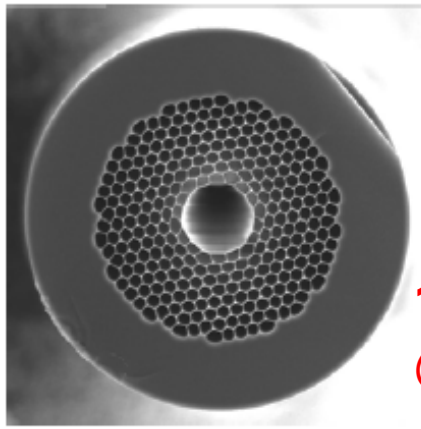
Microstructured Fibers

❑ Losses in Microstructured Fibers

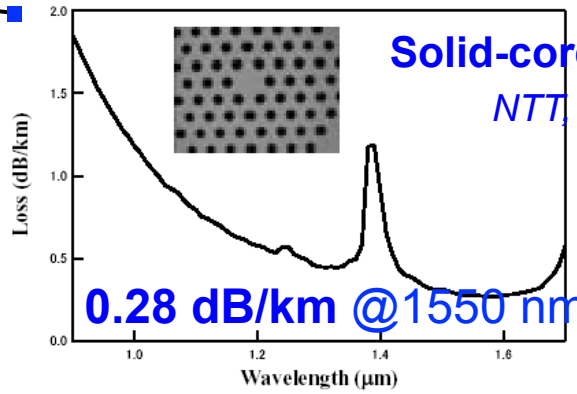


Hollow-core Fibers

BlazePhotonics OFC'04



1.7 dB/km
@1565 nm



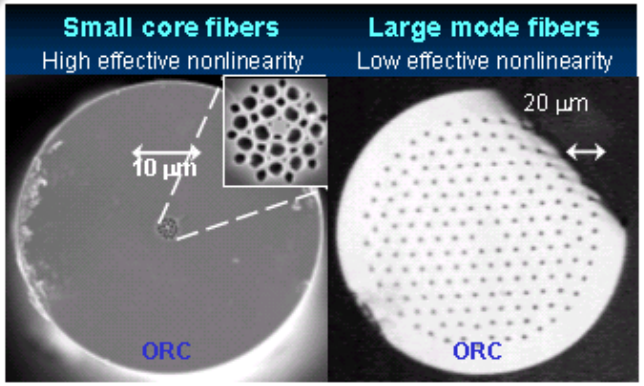
Solid-core Fibers

NTT, ECOC'03

0.28 dB/km @1550 nm

Microstructured Fibers

❑ Applications



Small Core Area Fibers (Highly Nonlinear Fibers)

- Small core sizes (down to 1 µm) + very large core/clad Δn

➔ Very small effective areas / high nonlinear coefficients

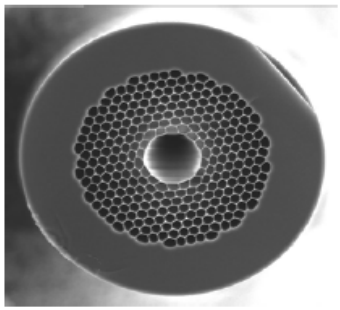
Large Mode Area Fibers

- High powers without nonlinear effects / material damage
- Low fiber loss
- Core sizes up to 25 µm

Solid-core

Applications include Raman amplification / Dispersion management / Optical parametric amplification / Supercontinuum generation / Wavelength conversion / Polarization maintaining / Metrology…

Hollow-core



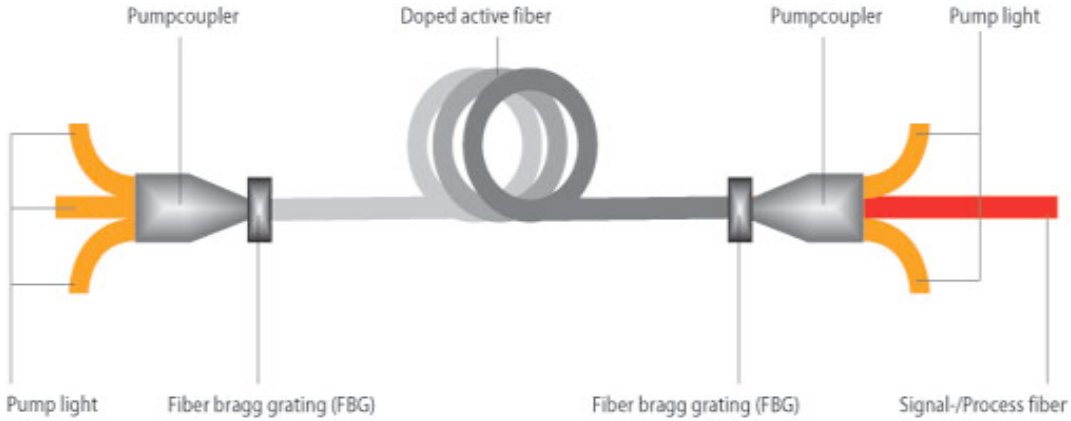
Applications includes Telecommunication (guiding with low loss / no non-linearity) / Compensation of chromatic dispersion / Gyroscopes / High power pulse transmission / Pulse compression / Gas lasers / Sensing…

Fiber Lasers

❑ Definition

Fiber lasers

Laser in which the active gain medium is an optical fiber doped with rare-earth elements (Erbium, Ytterbium, Neodymium, Dysprosium, Praseodymium…)



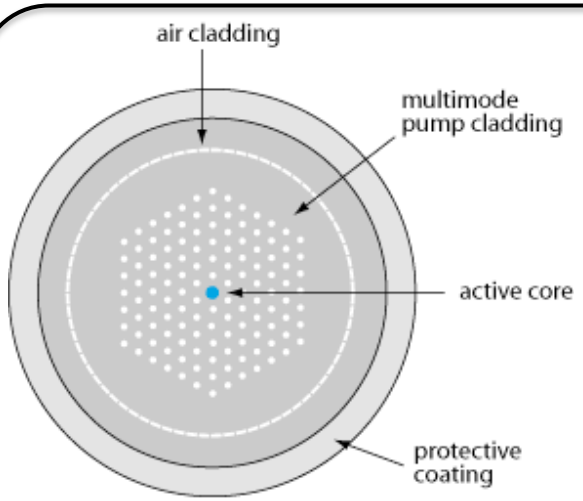
- ❑ Fiber laser cavity is constructed monolithically by fusion splicing different types of fibers
- ❑ Fiber Bragg gratings replace conventional dielectric mirrors to provide optical feedback
- ❑ Fiber lasers are pumped by semiconductor laser diodes or by other fiber lasers

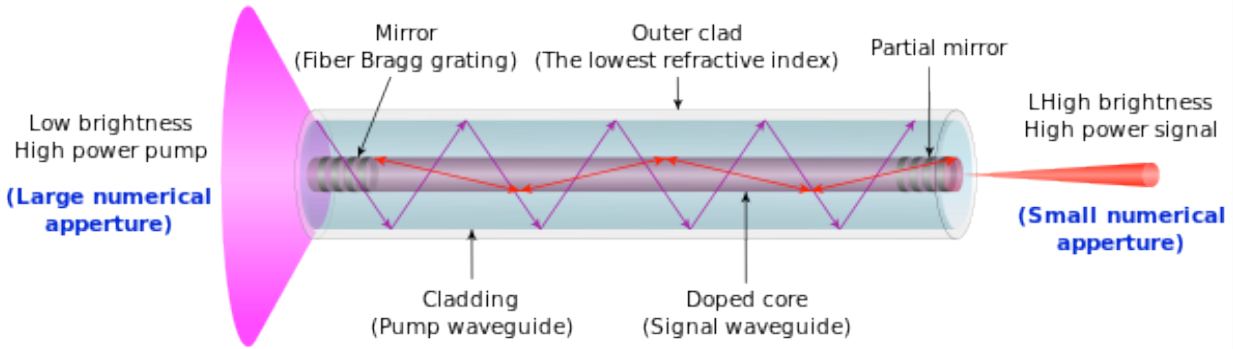
Fiber Lasers

❑ Design

Modern high-power fiber lasers

Nearly always realized with Rare-Earth-doped double-clad fibers





Structure of a double-clad fiber with an air cladding [RP Photonics]

The pump light is launched into an inner cladding rather than into the (much smaller) fiber core, in which the laser light is generated

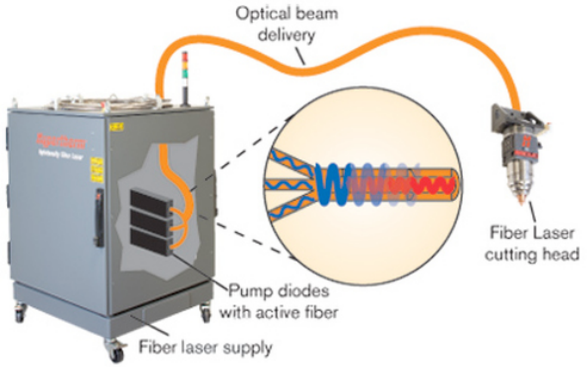
Fiber Lasers

❑ Advantages of fiber lasers

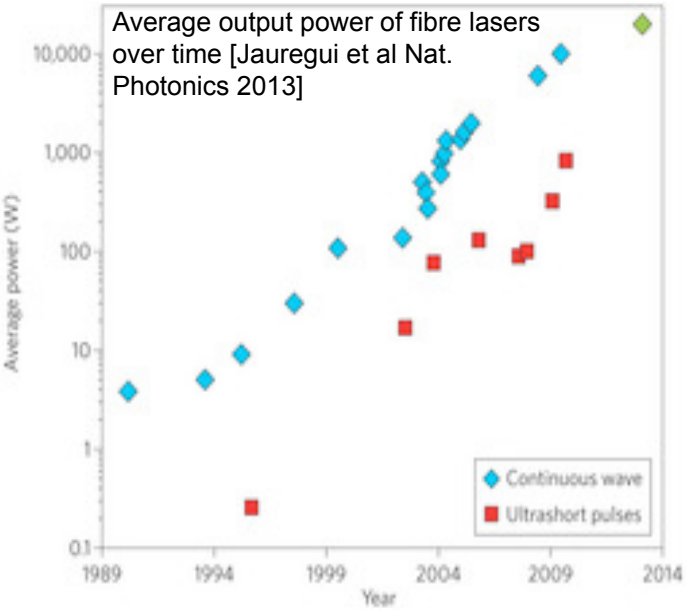
- ❑ **Flexibility** - Light already coupled into a flexible substrate

Allows for easily delivering on target

- ❑ **Compactness** - can be bent and coiled to save space
- ❑ **Reliability:** high vibrational stability, extended lifetime



- ❑ **High output power** - Can support kilowatt levels of continuous output power
- ❑ **Efficient cooling** due to fiber's geometry (high surface to volume ratio)
- ❑ **High optical quality** due to the fiber's waveguiding properties reduce or eliminate thermal distortion of the optical path
- ❑ **High peak power and ultra-short pulses** – Enable effective marking and engraving

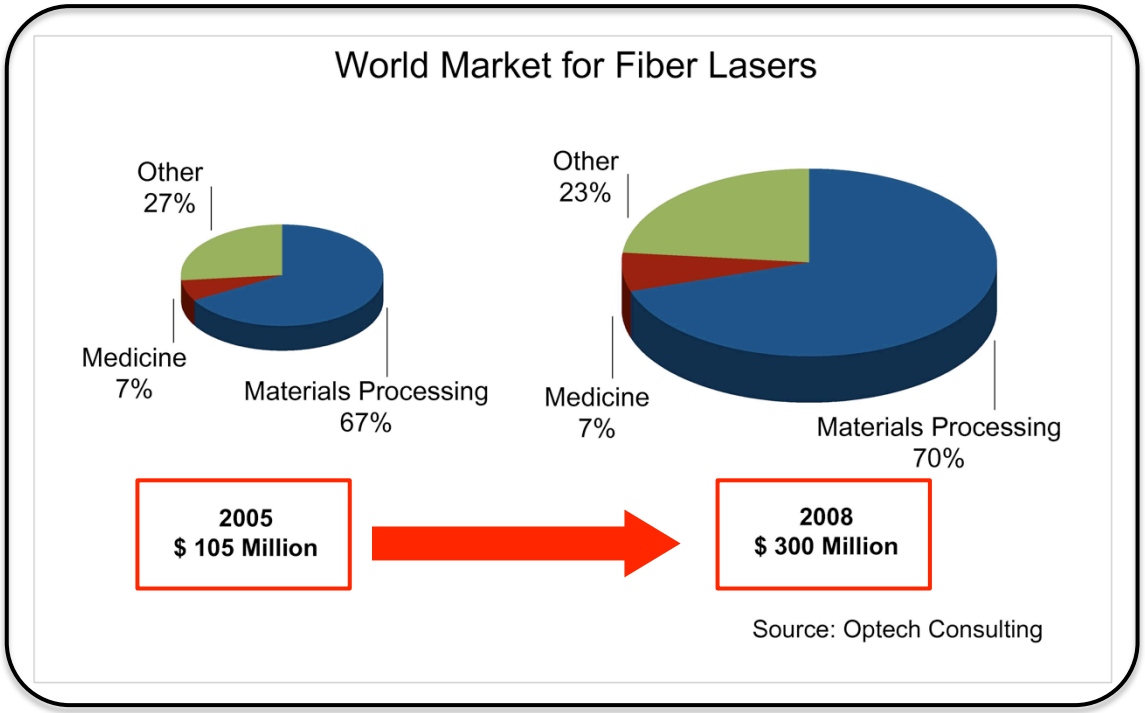


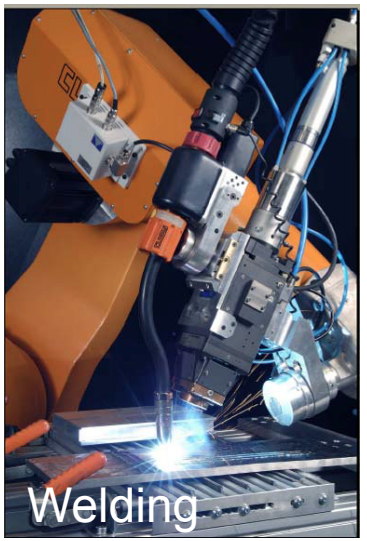
Fiber Lasers

❑ Applications

Some applications of fiber lasers

Material processing, Telecommunications, Spectroscopy, Medicine, Distance measurements, Tracking, Directed weapons…

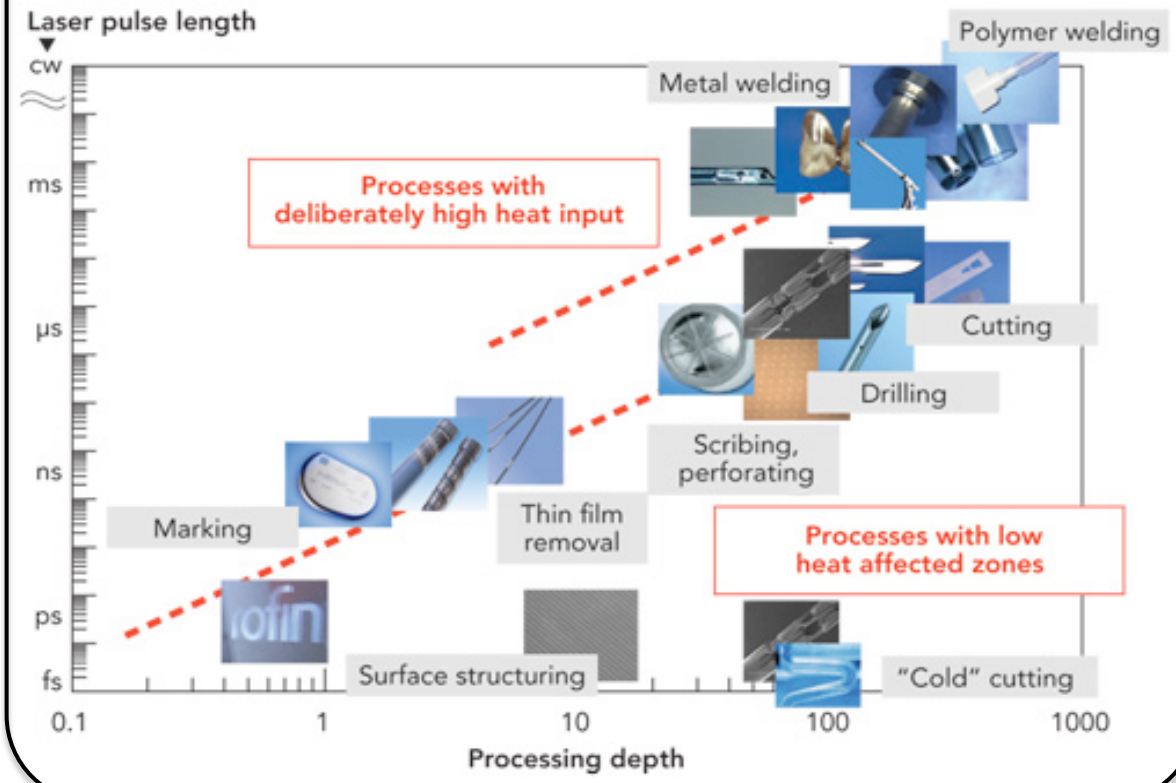


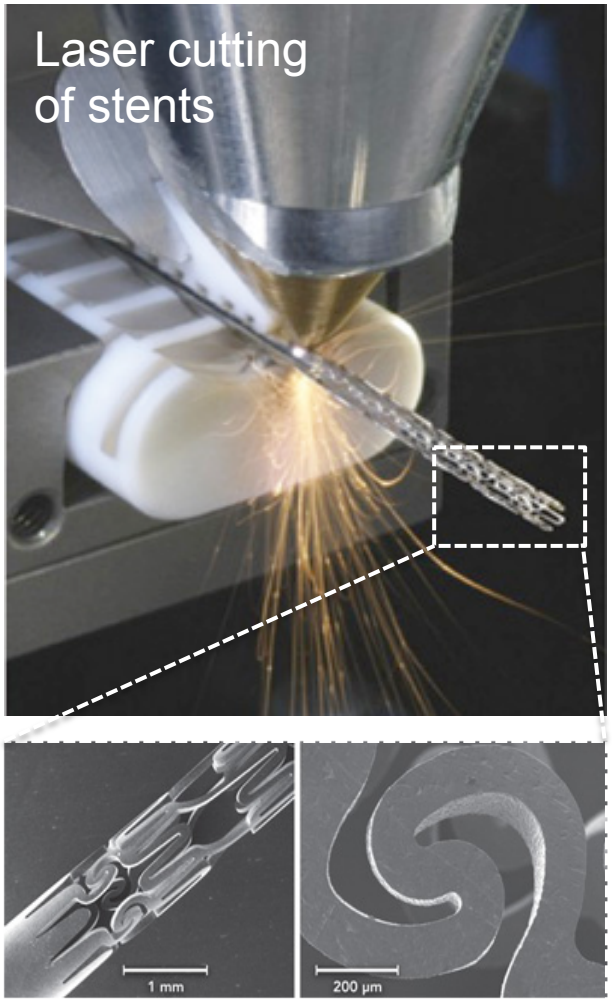


Fiber Lasers

❑ Applications

Fiber lasers for production of medical devices (ROFIN)



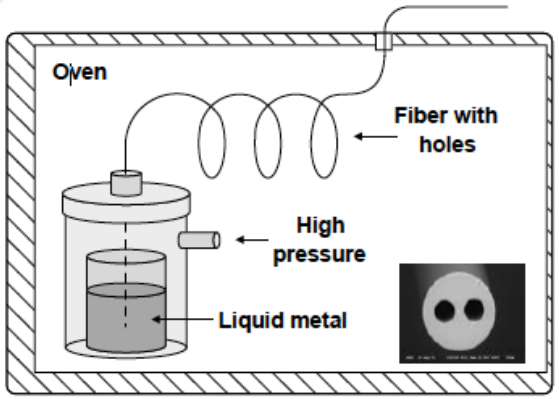


Macrostructured Fibers

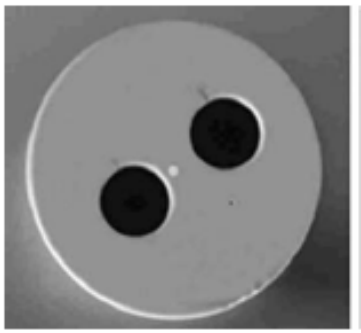
❑ Electro-Optic fibers

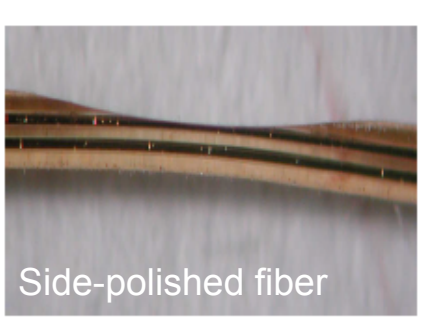
Objective Allow for the manipulation of light via external electrical input

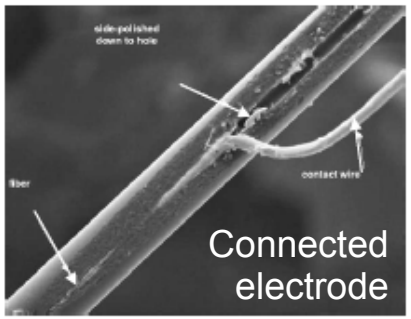
Active control of the refractive index through the electro-optical effect, control of the fiber birefringence through the passage of current in the electrode, poling…



Continuous electrodes >10 m

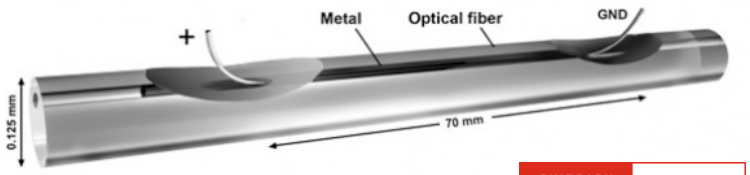






Potential applications

modulators, polarizers, switches, delay lines…

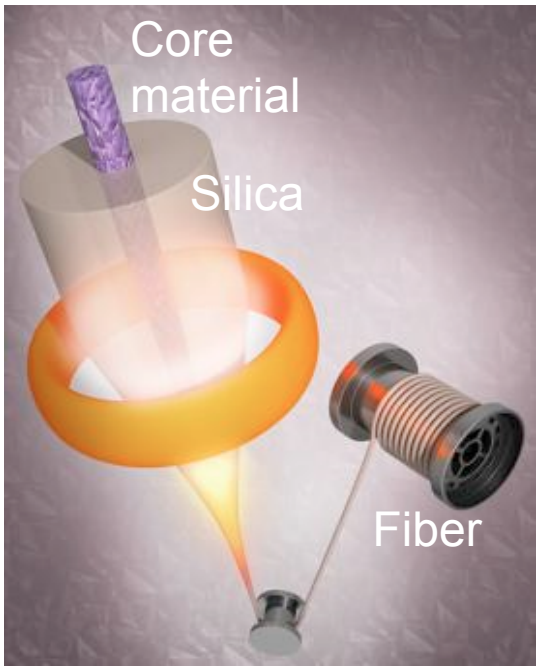


SWEDISH ICT ACREO

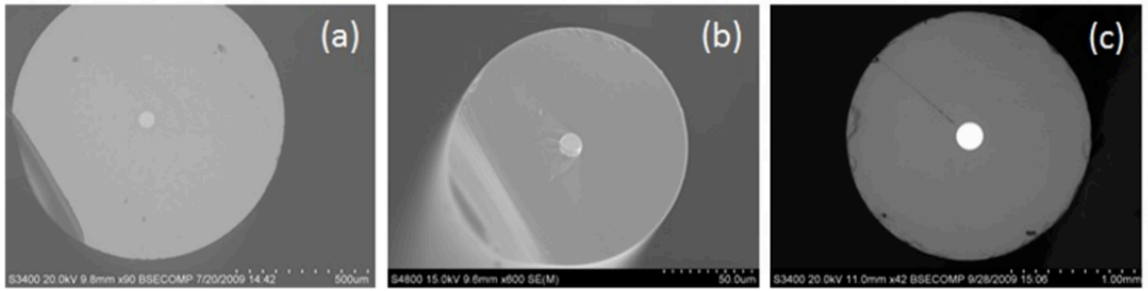
Crystalline semiconductor-containing Fibers

❑ Molten core Fibers Pr. Ballato (Clemson University) / Pr. Dragic (Urban Champaign)

Vision Unlike glasses, semiconductors possess mechanical, optical and electronic properties of great interest for photonic and optoelectronics systems



Glass-clad optical fibers with crystalline cores (Si, Ge)



Advantages

- Long lengths (> 100's m to km)
- Compatible with existing fiber fabrication infrastructure

Limitations

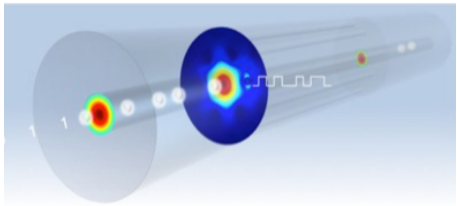
- Thermochemical reactions (diffusion) with the silica cladding leading to scattering from precipitated oxide phases
- Currently optical losses remains high (~ dB/cm)

Crystalline semiconductor-containing Fibers

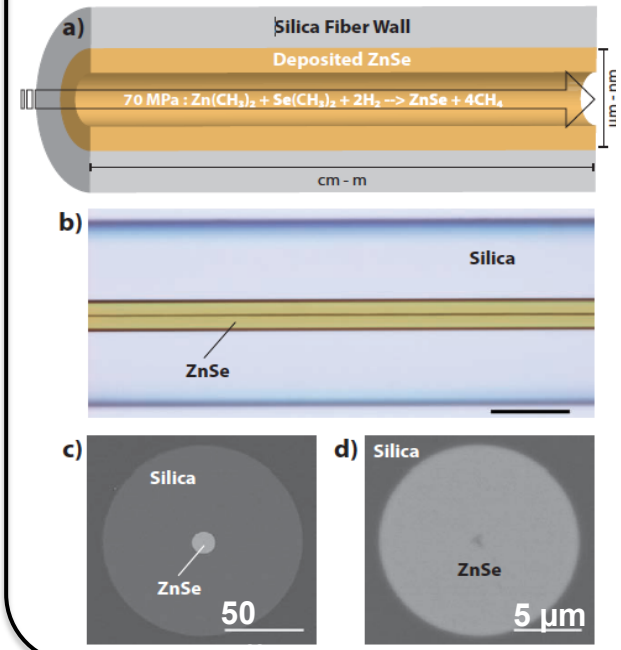
❑ High-Pressure CVD methods - Pr. Badding (Penn State University)

Vision To developed fully-integrated crystalline semiconductors-containing optical fiber for hybrid optoelectronic functions

Potential applications Improved telecommunications, improved laser technology, more-accurate remote-sensing devices



Fabrication of crystalline (ZnS, ZnSe) fiber waveguides into silica fibers



A high pressure precursor mixture is configured to flow into a capillary.
When the capillary is heated, well-developed annular films are deposited.

Advantages of the HPCVD

- Amenable to amorphous and crystalline semiconductors
- Higher optical damage thresholds than glasses

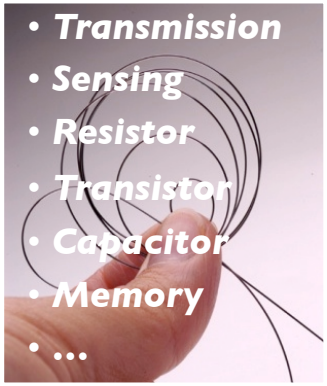
Limitation of the HPCVD

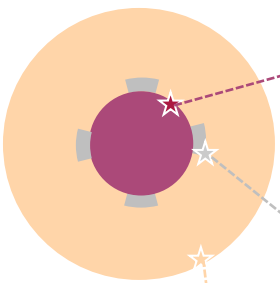
- Slow growth rate
- High losses ~1 dB/cm (grain boundary / bulk inhomogeneity)

Multimaterial Fibers

❑ Pr. Fink - MIT

- ❑ Simultaneous processing of multiple material classes
- ❑ Numerous geometrical structures with ~nm resolution
- ❑ Integrated in-fiber devices and fabric systems with unusual / sophisticated functionalities



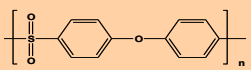


AMORPHOUS SEMICONDUCTORS

As, Se, S, Ge, Te, Si, Sn

- Amorphous semiconductors (p-type)
- Glass transition temperature: 160-210 °C
- Refractive index @1.5 microns: 2.4-3.4
- High electrical conductivity
- CTE for As2Se3: 25*10^-6/C
- Photoconductivity

HIGH-Tg TERMOPLASTICS

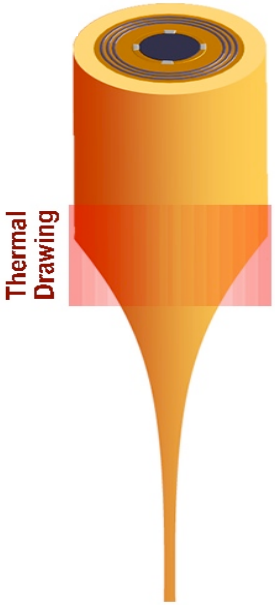


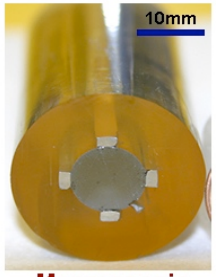
- Electrical Insulators
- PES, PEI
- Amorphous thermoplastics
- Glass transition temperature: 150-240 °C
- Refractive index @1.5 microns: 1.6
- Availability: Thin films (8-150 microns)

METALS

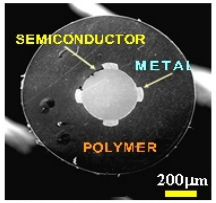
In, Sn, Bi(43%)-Sn(57%)

- Metals
- Crystalline Materials
- Melting Temperature: 140-232 °C
- T_m has to be lower than the drawing temperature
- Good wetting of glass and polymer
- Use of Flux to prevent oxidization
- Low viscosity at drawing Temperature





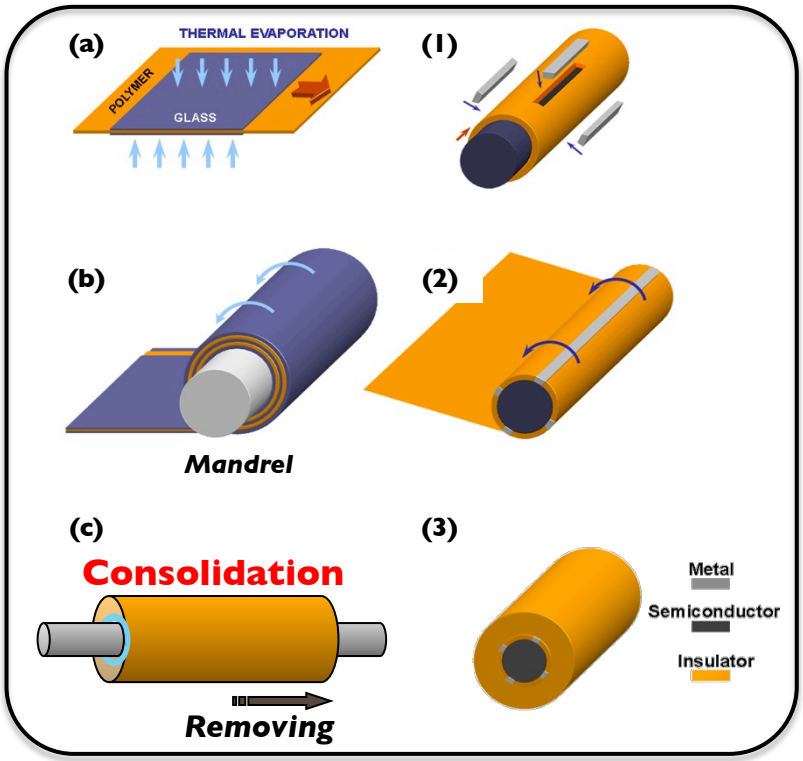
Macroscopic Preform

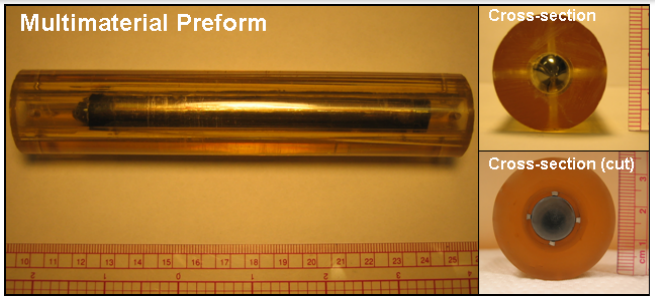


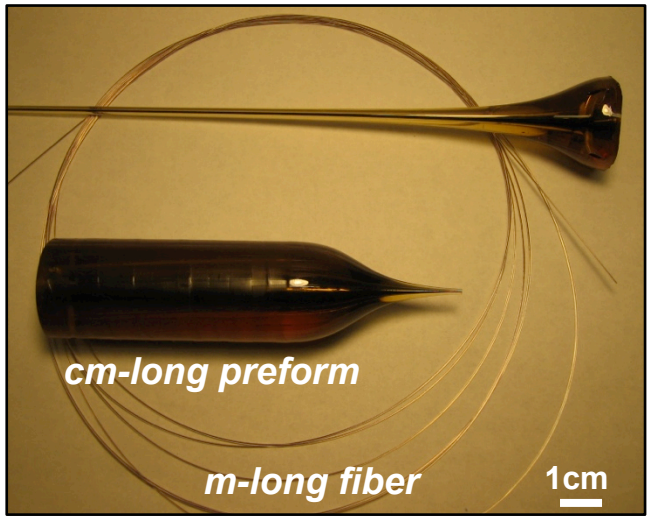
Kilometer-long Nanostructured Fiber

Multimaterial Fibers

❑ Pr. Fink - MIT





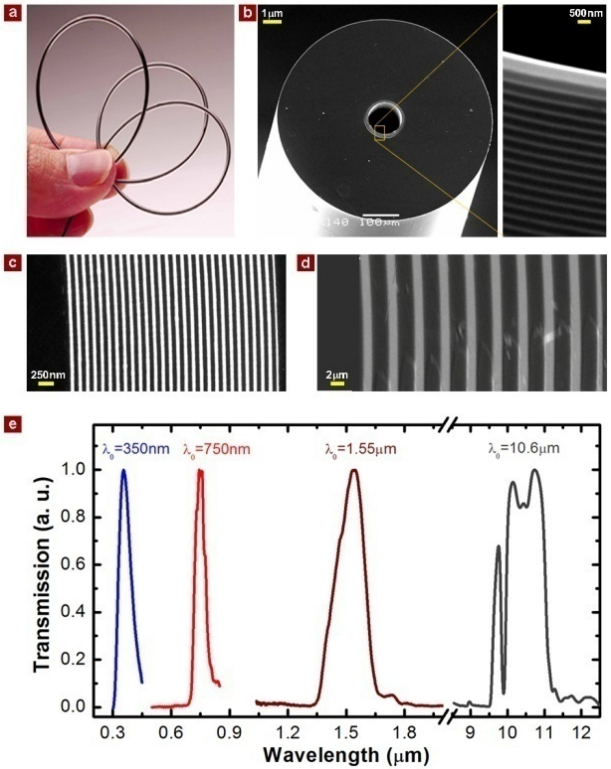


Multimaterial Fibers

❑ Pr. Fink - MIT

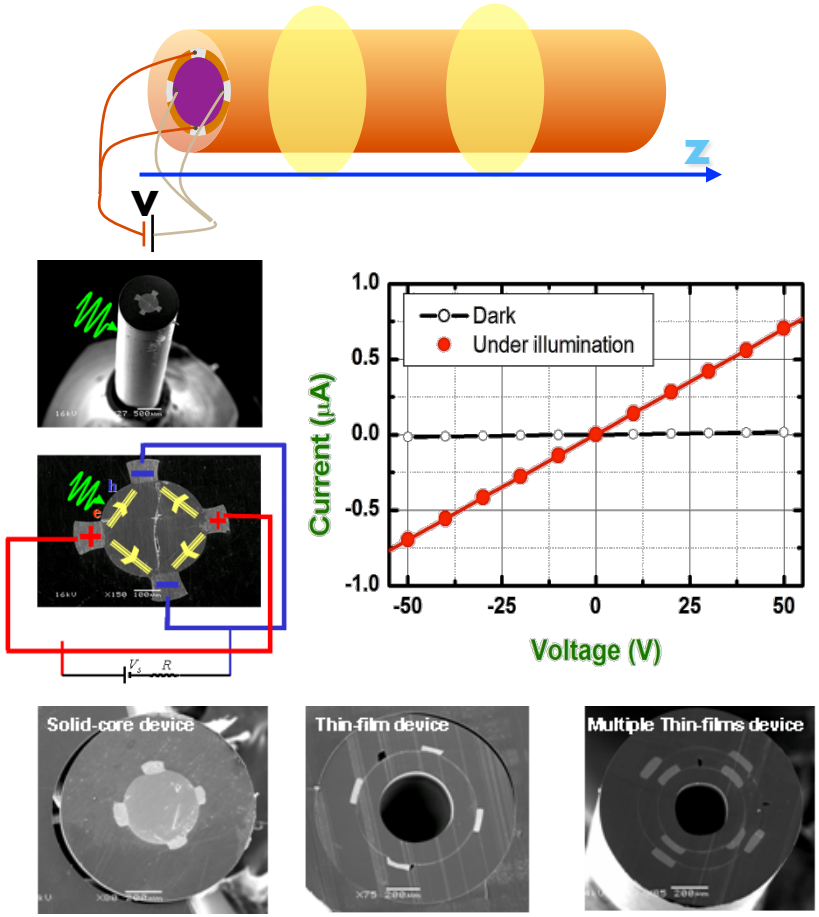
Omnidirectional mirror lining along fiber axis

- ❑ Light guidance through air (low losses)
- ❑ Control of the position of the band-gap



B. Temelkuran *et al.*, *Nature* 420 (2002) 650

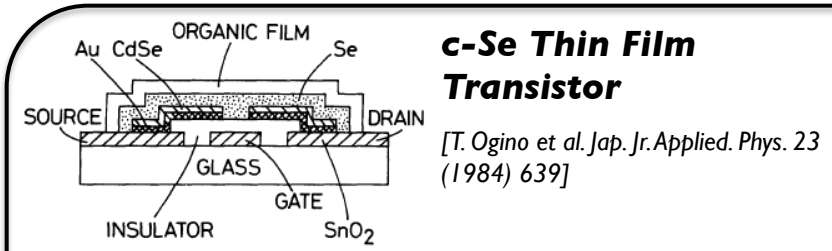
Photo-detecting Fiber



Bayindir M. *et al.*, *Nature* 431 (2004) 826

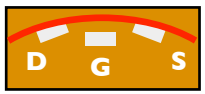
Multimaterial Fibers

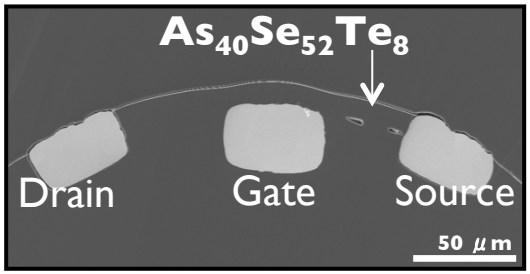
❑ Pr. Fink - MIT

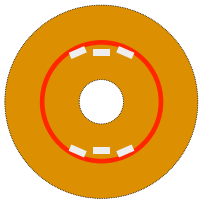


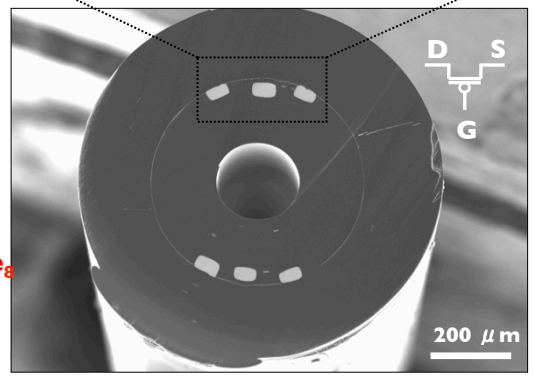
c-Se Thin Film Transistor

[T. Ogino et al. Jap. Jr. Applied. Phys. 23 (1984) 639]





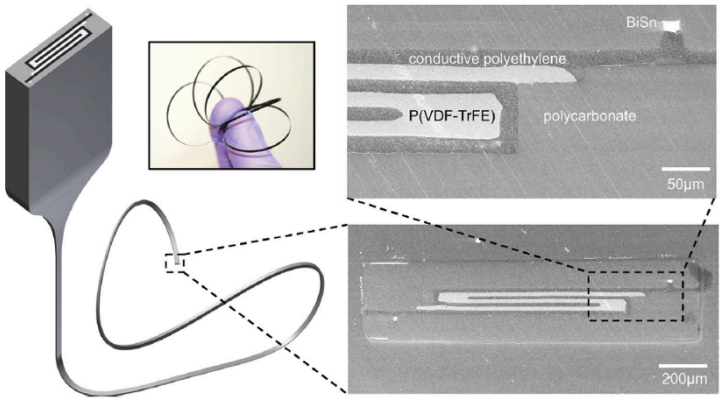




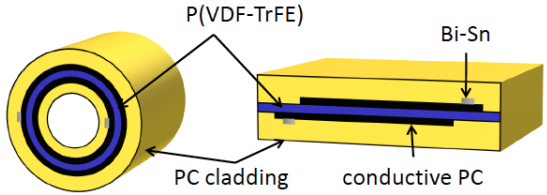
c-As40Se52Te8
PES
Sn

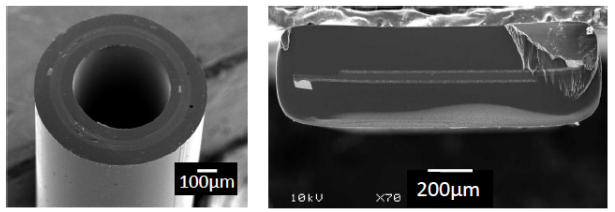
Danto *et al. Adv. Mat.* (2010)

Piezoelectric Fiber



Carbon loaded polymers act both as electrodes and as high-viscosity boundaries





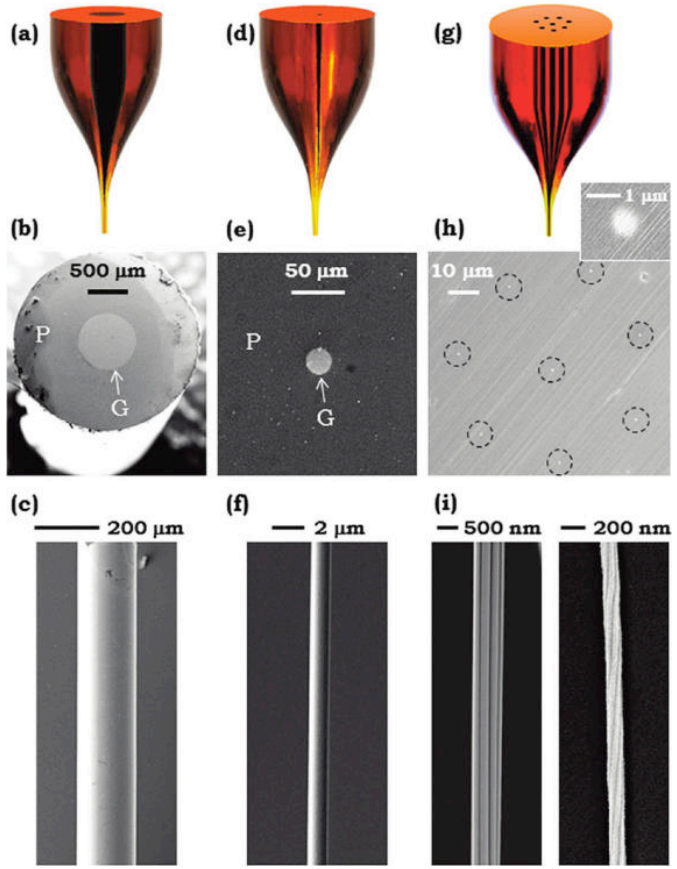
Egusa *et al. Nature* (2010)

Multimaterial Fibers

❑ Pr. Abouraddy – CREOL UCF

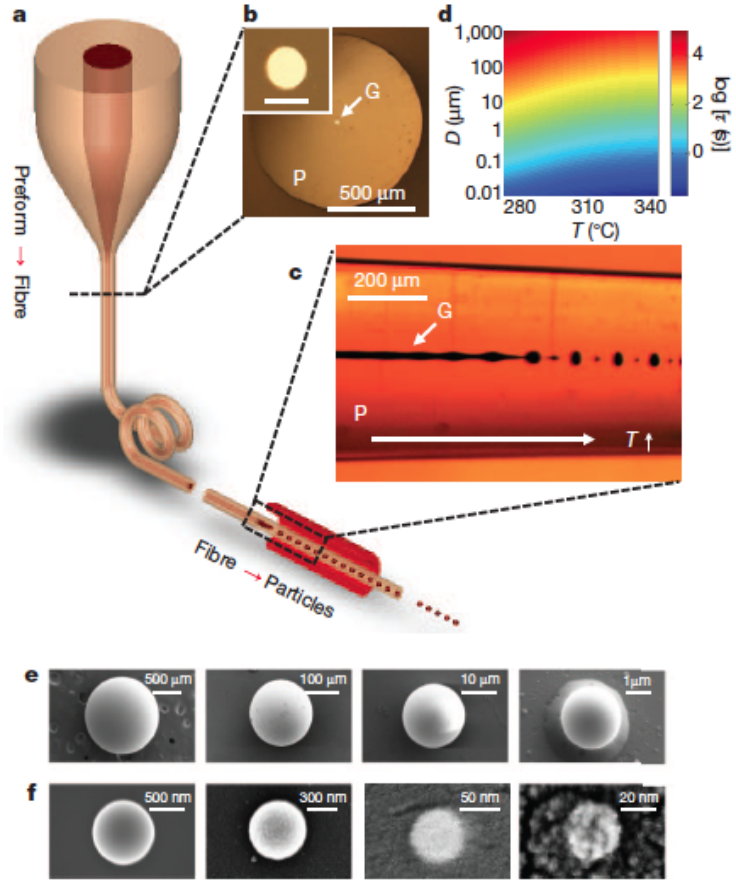
In-line fiber-drawing synthesis

Size-tunable micro-/nano-wires



Kaufman *et al.* Nanoletters 11 (2011) 4768

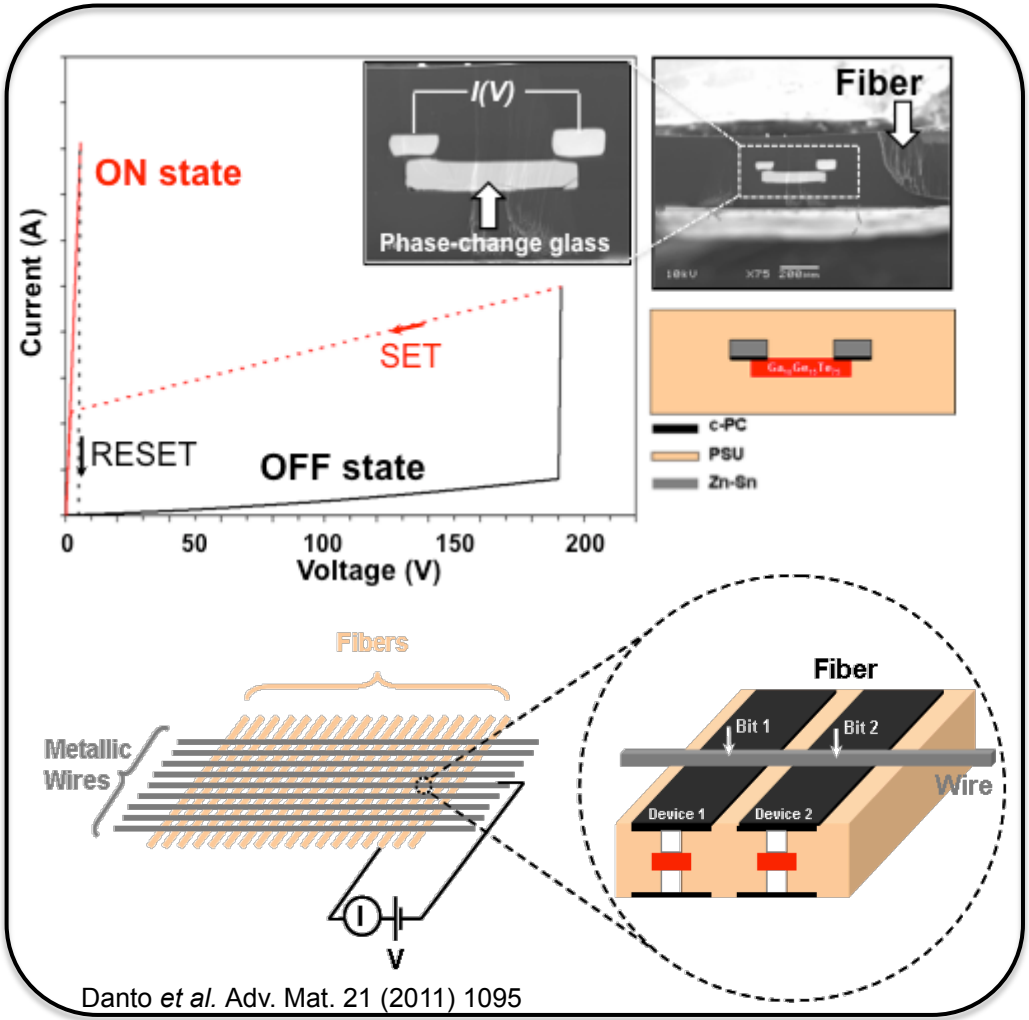
Size-tunable particles



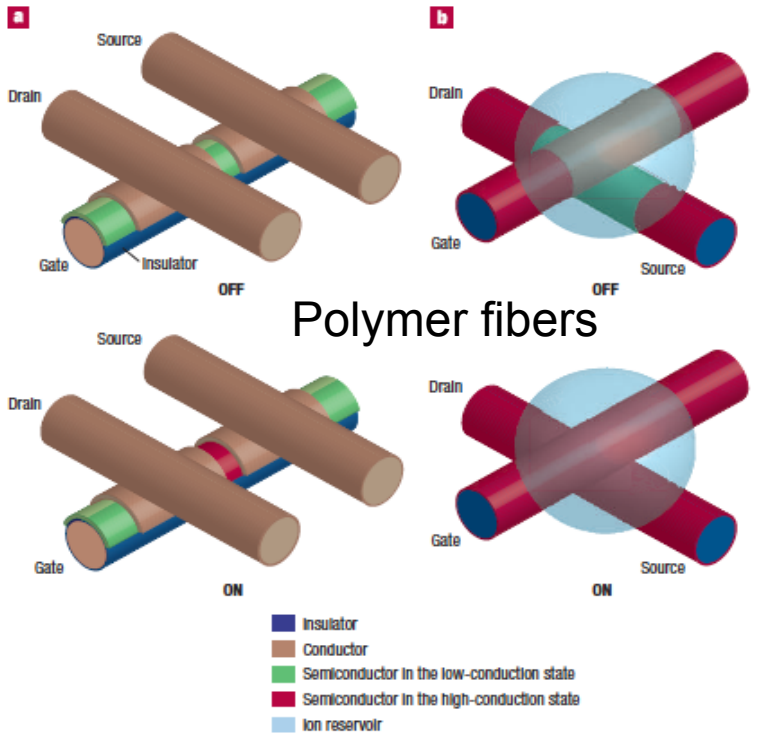
Kaufman *et al.* Nature 487 (2012) 463

Towards smart fibers, smart textiles

❑ Fiber-based electronic devices (cross-bar architectures)



Danto *et al.* Adv. Mat. 21 (2011) 1095



Organic Field Effect Transistor (OFET)

ON/OFF switching through charge accumulation

Wire ElectroChemical Transistors (WECT)

ON/OFF switching via ions depletion from the polymer channel through the solid electrolyte

Mahiar *et al.* Nature Mat. 6 (2007) 357

Conclusion

❑ Actors

Worldwide

ofs A Furukawa Company — Your Optical Fiber Solutions Partner™ | ofsoptics.com

THORLABS formerly IRphotonics

CorActive

INO

NUFERN®

Verrillon an AFL company

OmniGuide® SURGICAL

MAX-PLANCK-GESELLSCHAFT

NKT Photonics the power of light

fiberguide SM industries — THE FIBER OPTIC SOLUTIONS COMPANY — A HALMA COMPANY

CeramOptec®

SWEDISH ICT ACREO

COHERENT.

CORNING

IPG PHOTONICS

THE UNIVERSITY of ADELAIDE

Conclusion

❑ Actors

France

EOLITE SYSTEMS
Fiber lasers

CEMENTYS
Durable Infrastructure Monitoring
Fiber sensors

LE VERRE FLUORÉ
Verres et Céramiques

Amplitude SYSTEMES
Nothing but ultrafast.
Fiber lasers

IXFIBER AN IXBLUE COMPANY
Fiber optic gyroscopes

Xlim Institut de recherche

Draka
Specialty fibers

LEUKOS Innovative Optical Systems
Supercontinuum

IRCICA

ICB Laboratoire Interdisciplinaire Carnot de Bourgogne

Conclusion

❑ Overall

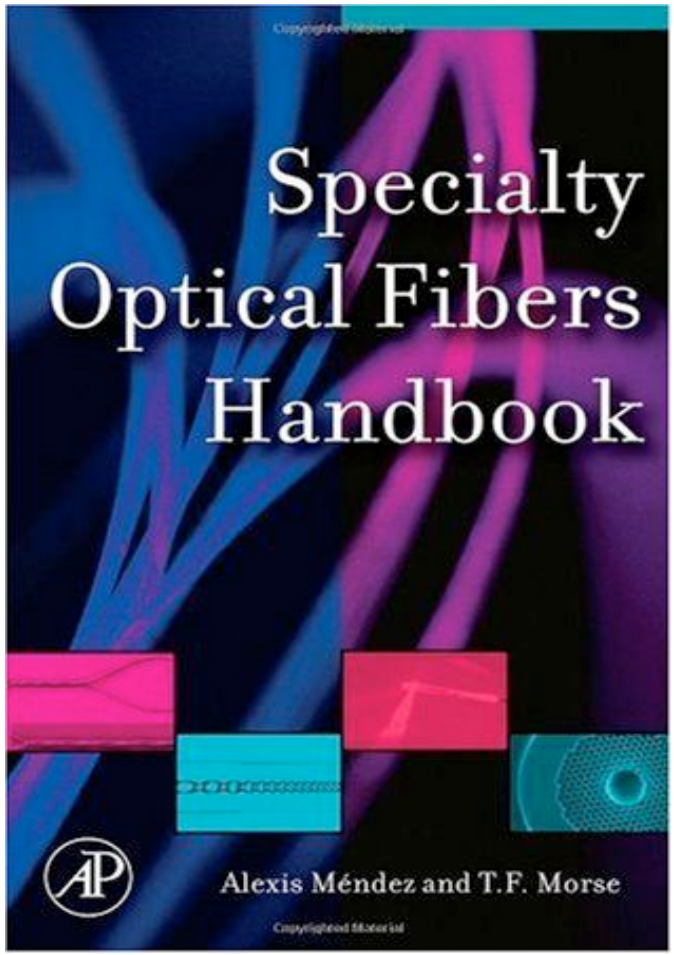
- ❑ **A new and exciting field of research…**
- ❑ A broad set of specialty fibers
- ❑ A broad set of applications (weaponry, communication links, avionics, energy, biomedical… so far centered mainly on laser delivery and sensing)
- ❑ A fair number of research groups and manufacturers around the world. The field is active but the community is very dispersed
- ❑ R&D work requires infrastructures and fabrication facilities

Some challenges

- ❑ New materials combination / New fiber-device architectures
- ❑ Improvement of the processing
- ❑ Tight-up of the Academics / Industry partnership

Conclusion

Further Reading



Thank you !!!

Sylvain Danto

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Research Scientist ICMCB - *University of Bordeaux*