Specialty Optical Fibers:
Fundamentals, Types, Applications & Trends

Conference Tutorial

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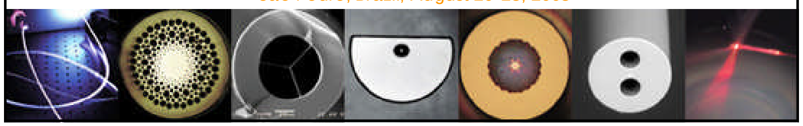
1st Workshop on SPECIALTY OPTICAL FIBERS AND THEIR APPLICATIONS

Sao Pedro, Brazil, August 20-23, 2008



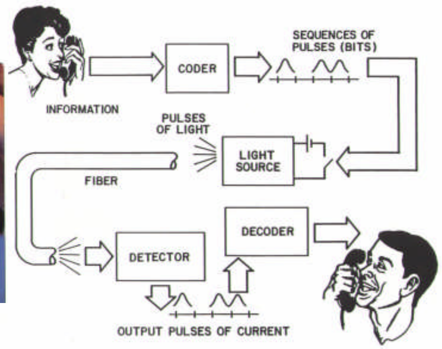
Contents

Introduction

Optical Fiber Chronology:
Major Milestones

- ***1854*** — **Light guiding in water jet— *Tyndall***
- ***1910*** — **Dielectric waveguide analysis— *Hondros & Debye***
- ***1930*** — **Early experiments with silica fibers— *Lamb***
- ***1951*** — **Image transmission by fiber bundles— *van Heel, Kapany***
- ***1961*** — **Mode analysis of optical fiber— *Snitzer***
- ***1962*** — **First semiconductor lasers demonstrated— *various groups***
- ***1963*** — **First POF— *DuPont***
- ***1964*** — **Fiber Lasers proposed & analyzed— *Snitzer***
- ***1966*** — **FO proposed for long distance comms— *Kao & Hockman***
- ***1970*** — **First fiber with < 20dB/Km loss– *Corning***
- ***1979*** — **Record low loss of 0.2dB/Km @ 1.55um**
- ***1987*** — **Er fiber amplifier demonstrated– *Payne & Desurvire***
- ***1991*** — **Holey fibers first proposed— *Russell***
- ***1996*** — ***Fist solid-core PCF fiber made***
- ***2007*** — ***Bend-insensitive fiber introduced—Corning***

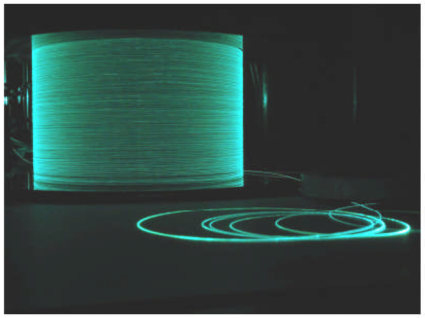
The Original Driver of Optical Fiber Technology—*Telecommunications*



Over 30 years of R&D, testing product development and broad commercial use in telecoms industry!

After Personick

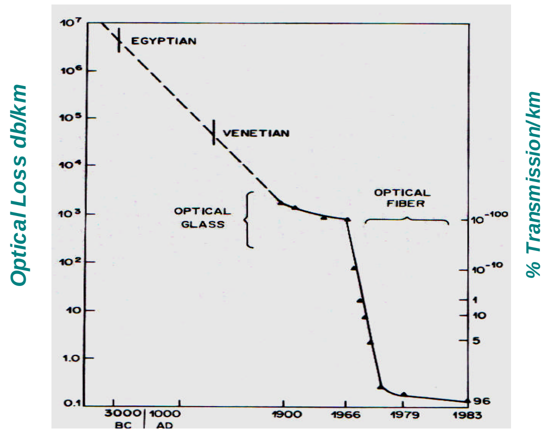
The Main Driver:
Tremendous Information Carrying Capacity



A single SM fiber has enough transmission capacity to transmit all 30,000 pages of a 20 volume Encyclopedia in just 1 second!!

After K. Thyaragajan

The Main Hurdle:
Reduction in Optical Loss



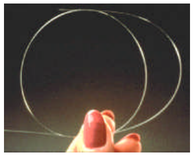
After S. Nagel

The High Transparency of Silica Glass…

Window Glass	1 inch (~3 cm)
Optical Quality Glass	10 feet (~3 m)
Fiber Optics	9 miles (~14 km)

Propagation Distance Needed to Reduce Transmitted Light Power by 50% (3 dB)

Benefits of Optical Fibers



- *Low Loss*
- *Long Haul Communications*
- *EMI immunity*
- *Intrinsically safe*
- *Passive: no need for electrical power*
- *Small size and lightweight*
- *Wide Bandwidth→ High Info Capacity*
- *Low Cost*
- *Reliable, Proven Technology*
- *Multiple Uses & Applications Beyond Telecommunications*

Optical Fiber Properties

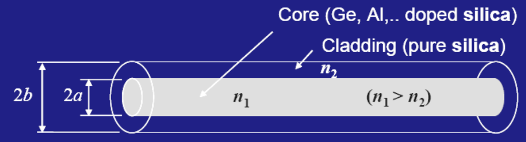
Optical Properties

Optical Fiber Waveguides:
Material & Geometry Choices

- **Glass vs. Crystals vs. Polymer**
  - Amorphous glasses (silica, fluorides, chalcogenide)
  - Single crystals (Sapphire)
  - Polycrystalline materials (Halide)
  - Polymeric (PMMA, polycarbonate, etc.)
- **Solid vs. Hollow**
  - Index guiding (TIR)
  - Reflection guiding
  - Photonic Bandgap guiding

Optical Glass Fibers:
Typical Structure

Optical fibers are cylindrical dielectric waveguides



Typical dimensions

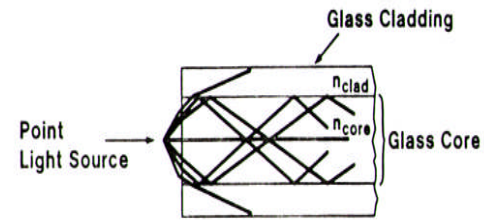
Core diameter	$2a$ = 9 to 62.5 μm
Cladding diameter	$2b$ = 125 μm

Typical values of refractive indices

Core:	$n_1 = 1.461$
Cladding:	$n_2 = 1.460$

Source: H. Fragnito

Solid Core Optical Glass Fibers:
Light Guiding—Total Internal Reflection



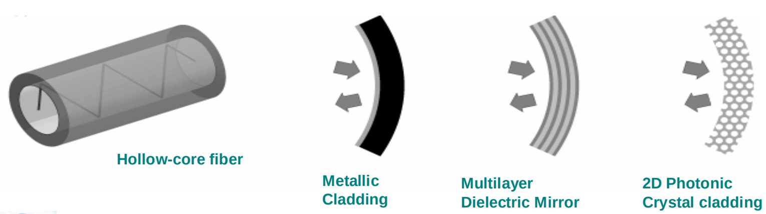
- Light is Guided by Total Internal Reflection
- $n_{core} > n_{clad}$

Actual light propagation is subject to Maxwell's equations and local boundary conditions

Hollow Core Optical Fibers:
Light Guiding Mechanisms

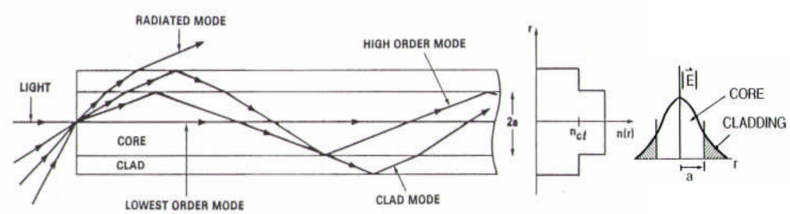
In contrast to solid core glass fibers, hollow core fibers can propagate light by:

- *TIR*
- *Bragg guiding*
- *Photonic Bandgap guiding*



Source: Omniguide

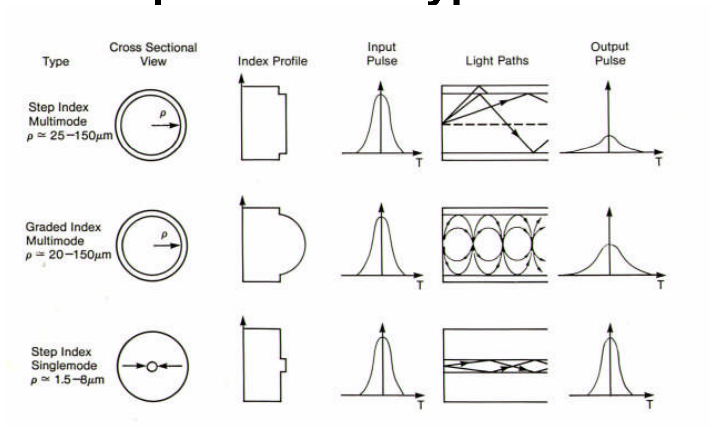
Light Guiding Characteristics



$$N.A. = \sin\theta_{max} = \sqrt{n_1^2 - n_2^2}$$

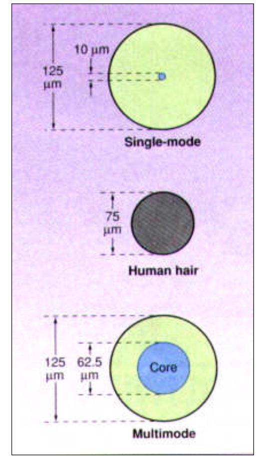
- **Mode order proportional to ray angle:**
  - *Low order modes correspond to low angle rays*
  - *High order modes correspond to high angle rays*
- **Each mode has a given velocity of propagation:**
  - *Lower order → Lower velocity (all rays arrive at same time)*

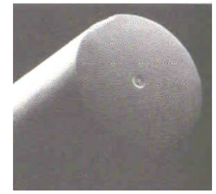
Basic Optical Fiber Types

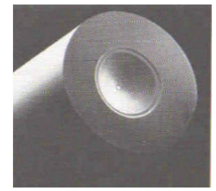


After Gianllorenzi

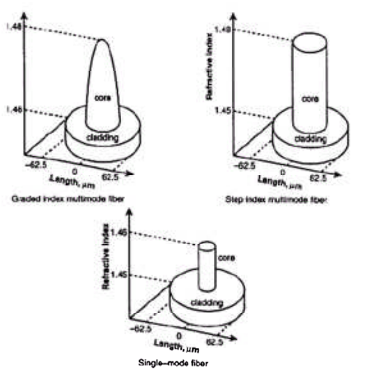
Singlemode vs. Multimode

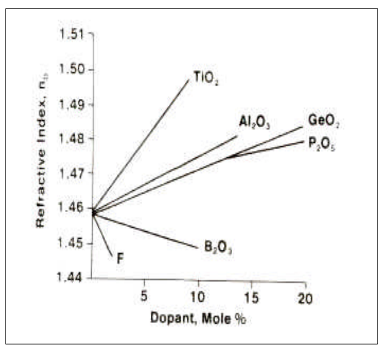






Light Guiding & Fiber Dopants





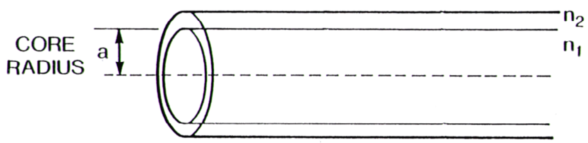
Different index profiles in fibers are tailored by adding certain dopants such as:

- **Phosphorous**
- **Boron**
- **Fluorine**

Typical Glass Fiber Compositions

	Core	*Cladding*
Multimode	$GeO_2 \bullet B_2O_3 \bullet SiO_2$	$B_2O_3 \bullet P_2O_5 \bullet SiO_2$
	$GeO_2 \bullet P_2O_5 \bullet SiO_2$	$B_2O_3 \bullet P_2O_5 \bullet SiO_2$; $F \bullet P_2O_5 \bullet SiO_2$; SiO_2
	$GeO_2 \bullet SiO_2$	
Singlemode	$GeO_2 \bullet SiO_2$	$F \bullet P_2O_5 \bullet SiO_2$; SiO_2; $P_2O_5 \bullet SiO_2$; $F \bullet SiO_2$
	SiO_2	$F \bullet P_2O_5 \bullet SiO_2$; $F \bullet SiO_2$

Waveguide Parameter (V-value)



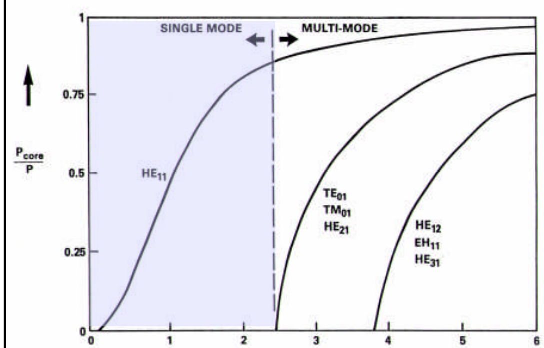
PARAMETER CHARACTERIZING WAVEGUIDE

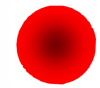
$$V = \left(\frac{2\pi a}{\lambda_o}\right) \sqrt{n_1^2 - n_2^2} = \left(\frac{2\pi a}{\lambda_o}\right)(N.A.)$$

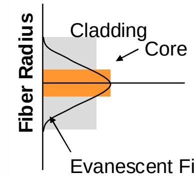
- **Singlemode operation limited to V < 2.4**
- **Cutoff wavelength λ_c = V/2.4**

Single-Mode Fiber:

Optical Power Distribution

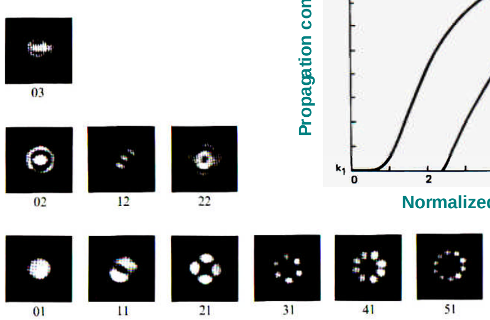


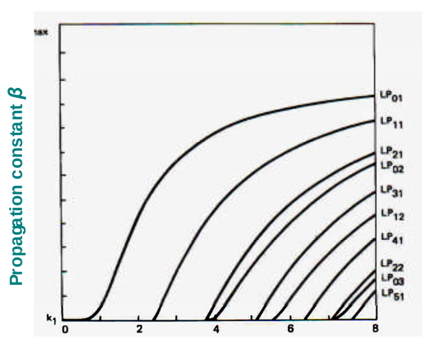




- Singlemode fibers guide optical power with a near Gaussian shape
- Light traveling in the cladding region is known as Evanescent Field

Light Propagation Modes



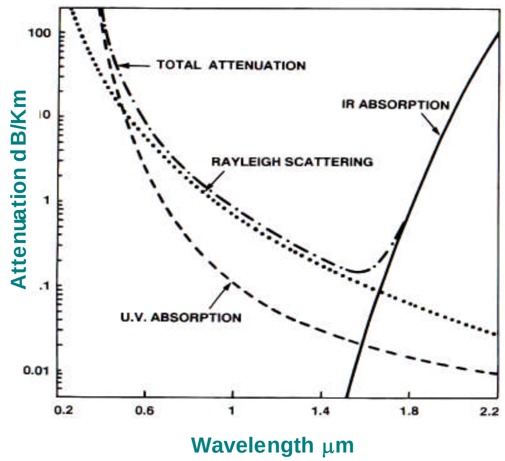


Mode Nomenclature

EXACT MODES	LP MODES
$HE_{1\mu}$	$LP_{0\mu}$
$HE_{2\mu} + TM_{0\mu} + TE_{0\mu}$	$LP_{1\mu}$
$HE_{(\nu+1)\mu} + EH_{(\nu-1)\mu}$	$LP_{\nu\mu}$

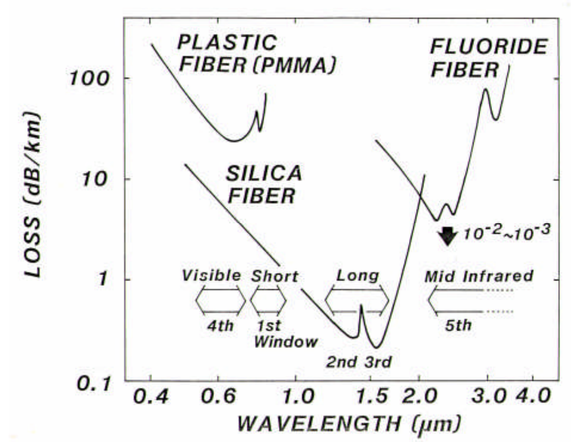
- **TE (Transverse Electric) Modes**
  - E field ⊥ to direction of propagation
- **TM (Transverse Magnetic) Modes**
  - H field ⊥ to direction of propagation
- **TEM (Transverse Electro-Magnetic) Modes**
  - Both E & H fields ⊥ to direction of propagation
- **HE and EH (Helical or Skew) Modes**
- **LP (Linearly Polarized)**
  - All other modes can be constructed with LP ones

Optical Loss Mechanisms



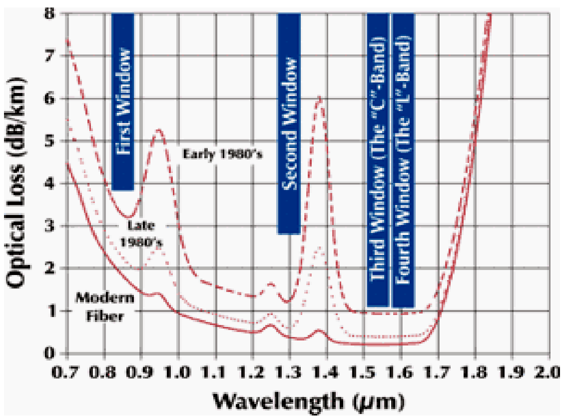
Transmission Window:

Optical Loss for Different Fiber Materials



Optical Loss Spectrum:

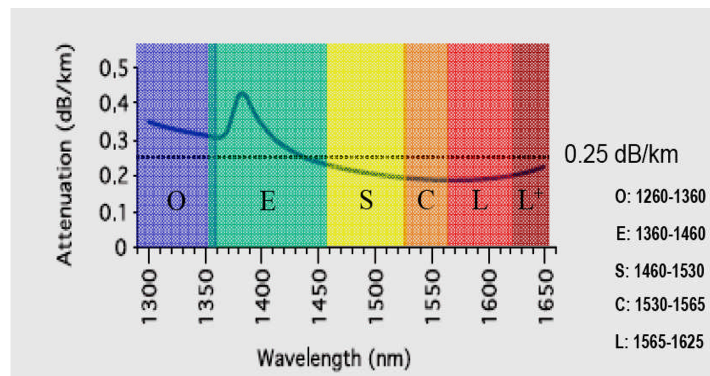
Silica Fibers



Typical attenuation

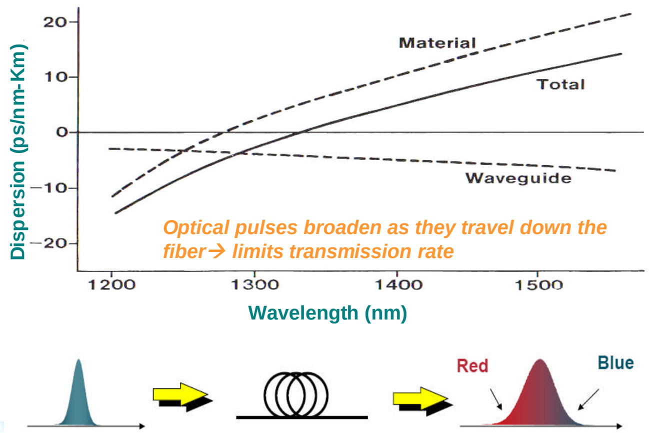
850nm:	*3.3 dB/km*
1.31µm:	*0.33 dB/km*
1.55µm:	*0.16 dB/km*
2.1µm:	*0.2 dB/m*
2.4µm:	*1 dB/m*

Optical Fiber WDM Spectral Bands Classification



Source: Corning

Dispersion



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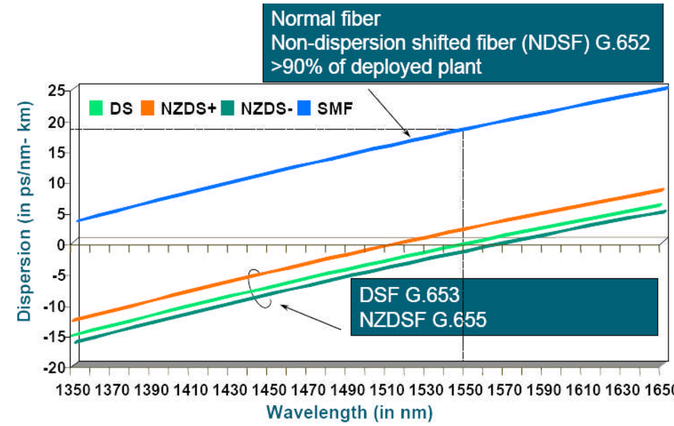
Dispersion:
Specialty Fiber Types



Source: Cisco

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Standard Single-Mode Fiber
Corning SMF-28

Fiber Parameter	Expected Value
Attenuation at 1310/1550 nm (standard quality)	0.35 / 0.22 dB/km
Cut-Off Wavelength	<1260 nm
Mode Field Diameter (@1310 nm)	9.2 µm
Numerical Aperture	0.14
Zero Dispersion Wavelength	1313 nm
Zero Dispersion Slope	$\leq$0.092 ps/(nm^2-km)
PMD Link Value	$\leq$0.1 ps/km$^{.5}$
Core-to-Cladding Eccentricity	$\leq$0.5 µm

Designed for high bitrate TDM at 1310 nm

Most widely deployed so far, introduced in 1986, cheapest

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Specialty Fiber Types

Singlemode
Multimode (step index, graded index)

Bend Insensitive
Chiral
D-Shape
Dispersion Shifted
Dispersion Flattened
Dispersion Compensating
Double Clad
Dual-mode
Electro Optic
Elliptical Core
Fluorescent
Hermetic
Hollow core
IR fibers

Large Core
Large NA
Low-Birefringence
Liquid Core
Metal-coated
Nano Fibers
Multi-Core
Photonic & Crystal fibers
Photosensitive
Plastic-clad (PCS)
Polarization maintaining
Polarizing
Polymer
Pure silica core
Rare-earth doped
Side Hole
Spun

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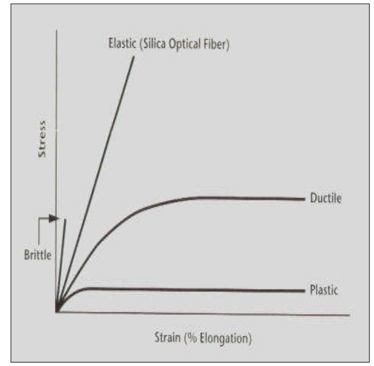
Mechanical Properties

Silica Fiber Strength



Optical fibers behave as an elastic material up to the point of failure.

Theoretical strength of silica glass determined by cohesive bond strength of constituent atoms > 20 Gpa (3-5Mpsi)!

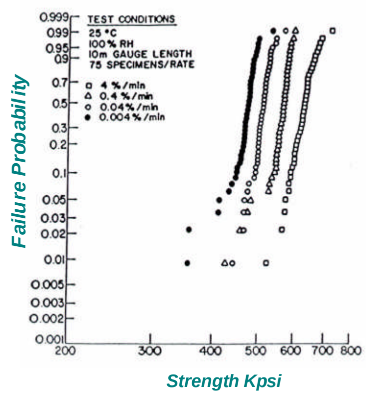
At ambient temperature & moisture, typical glass fiber strengths are on the order of 4-6 Gpa (~800Kpsi).

Actual strength is limited by surface flaw distribution.

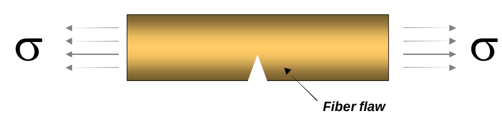
Optical Fiber Breaking Strength

Effective fiber strength is a function of:

- *Length*
- *Strain rate*
- *Temperature*
- *Relative Humidity*
- *Chemical or mechanically induced flaws*



Optical Fiber Mechanical Strength Degradation

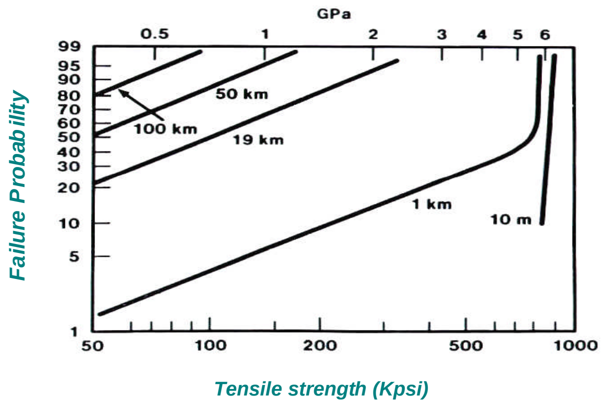


Surface flaws such as crack, scratches, pits, etc. produced mechanically or chemically (by moisture attack), act as stress concentrators that induce crack growth leading to brittle fracture under stress.

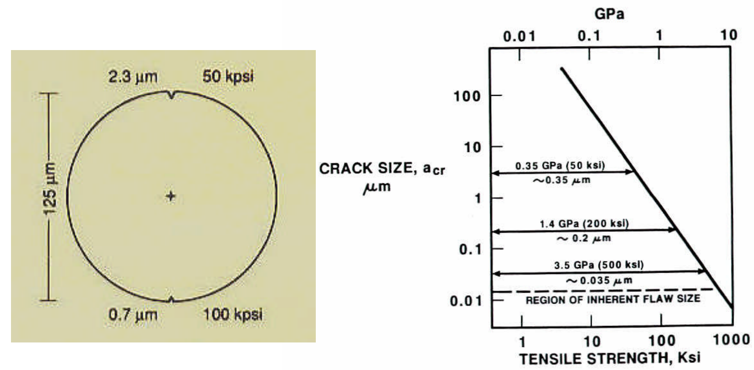
The distribution of flaws in pristine fibers is statistical in n ature

However, the longer the fiber length, the greater the probability of encountering more and larger flaws.

Fiber Strength:
Length Dependence



Fiber Strength:
Flaw Size Dependence

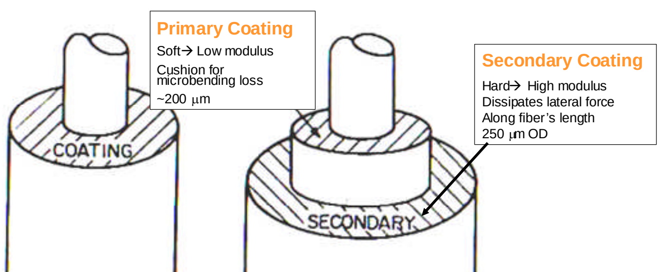


Source: Corning Inc.

Fiber Protective Coatings

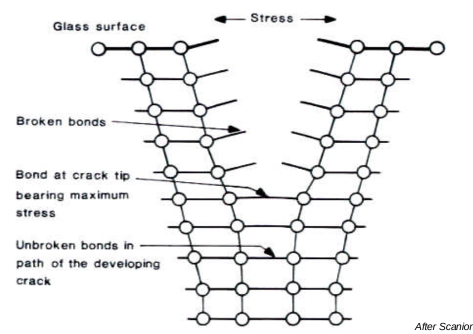
To protect against abrasion, handling, bending and moisture, fibers are coated with one or two layers of an UV-curable acrylate coating.

These layers are knows as the primary & secondary coatings

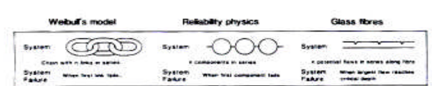


Single Coating **Double Coating**

Fiber Mechanical Failure:
Weibull model

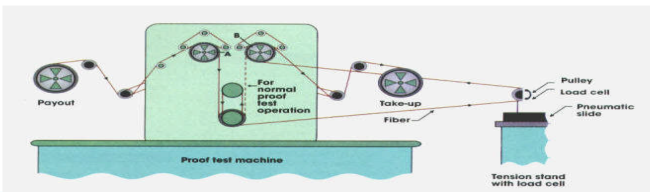


After Scanion



Proof-Testing

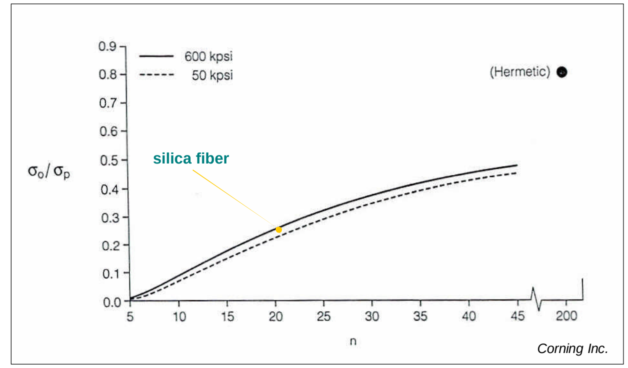
- Fiber is subjected to a short-term tensile strain during or subsequent to production. Applied load is the proof-stress value.
- Establishes minimum strain capability: fiber will break for large cracks larger than the proof-stress value.
- Typical proof-stress levels: 50Kpsi & 100Kpsi
- High proof-stress levels (>100Kpsi needed for O&G) result in:
  - *- Increase reliability*
  - *- Reduced fiber contonous length yield*
  - *- Higher cost*



Source: Corning Inc.

Safe Fiber Stress:

As a function of σ_p and n value

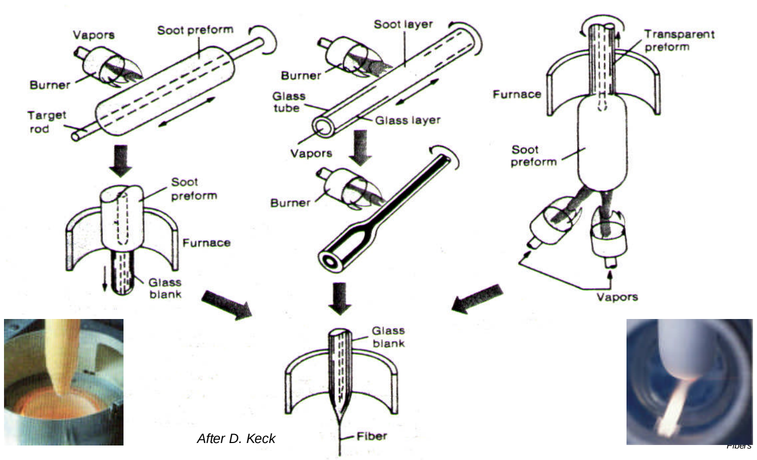


Fabrication Methods

Optical Fiber Fabrication Methods

- **Glass**
  - CVD preform→ fiber drawing
    - *MCVD—Modified Chemical Vapor Deposition*
    - *PMCVD—RF Plasma Enhanced MCVD*
    - *PCVD—Microwave Plasma CVD*
    - *OVD—Outside Vapor Deposition*
    - *VAD—Axial Vapor Deposition*
  - Rod-in-tube prefrom→ fiber drawing
  - Cast preform→ fiber drawing
  - Double crucible→ direct draw
  - Sol gel preform→ fiber drawing
  - Stack and draw→ PCFs
- **Polycrystalline**
  - Extrusion
  - Hot rolling
- **Monocrystalline**
  - Seed crystal growth from melt
  - Zone melting
- **Polymer**
  - Extrusion
  - Cast prefrom→ fiber drawing

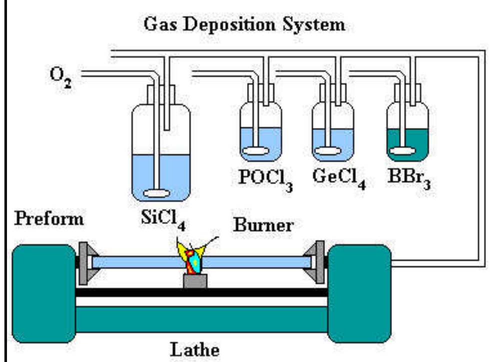
How is an Optical Fiber made?



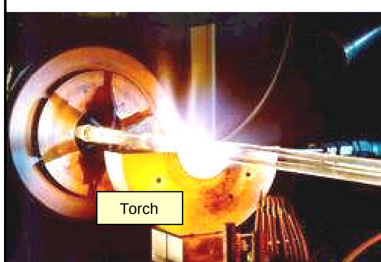
After D. Keck

MCVD Process:

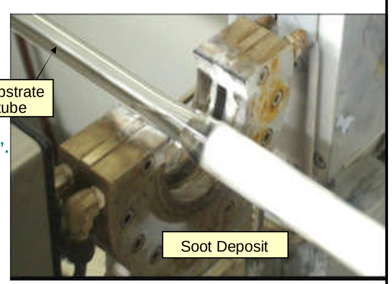
Modified Chemical Vapor Deposition



Preform Fabrication Process



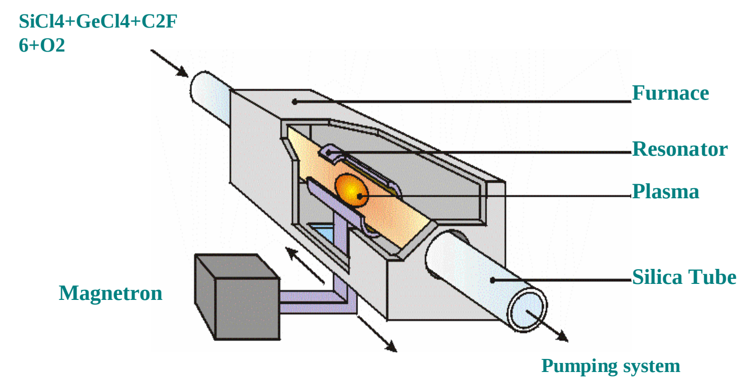
- Torch traverses slowly along tube
- Glass temperature >2300 °C
- Surface tension of inner wall drives collapse
- Deposited glass forms central region of the preform



- $SiCl_4$ reacts inside a silica tube, producing SiO_2 "soot".
- Soot deposits on inside wall of tube.
- Traversing torch builds up multiple layers.
- Soot sinters into clear glass at (2000°C)

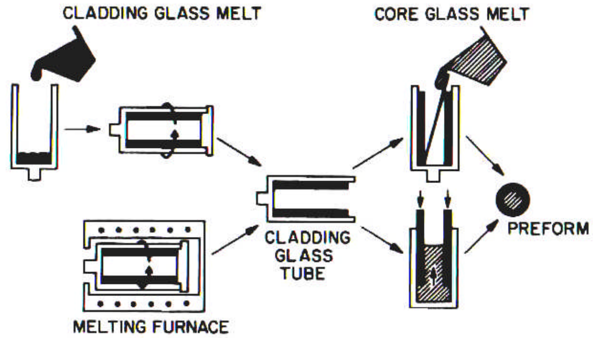
From D. DiGiovanni, OFS

PCVD Deposition System



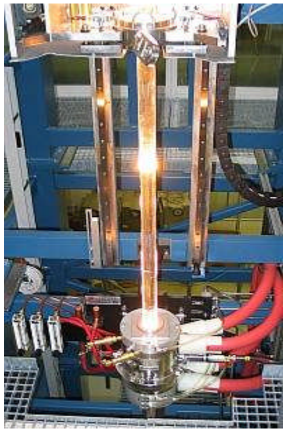
Source: YOFC

Rotational Preform Casting Process



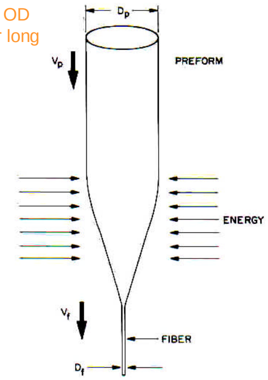
After D.C. Tran et al.

Fiber Preform Drawing



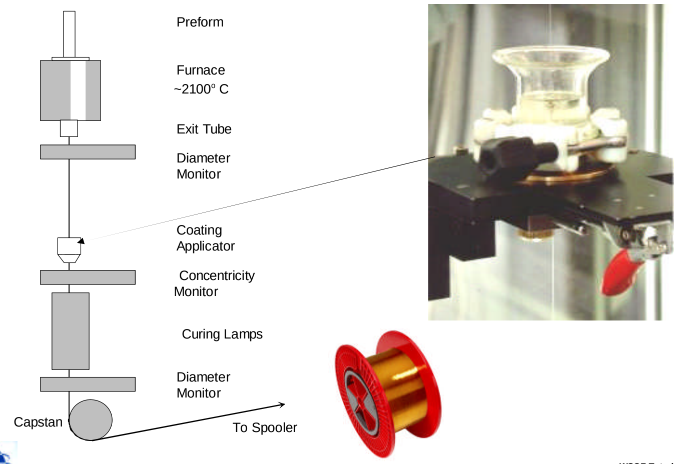
Graphite furnace ~2100°C

15 - 60mm OD
1 – 3 meter long



$$V_p/V_f = (D_f/D_p)^2$$

Fiber Drawing Process



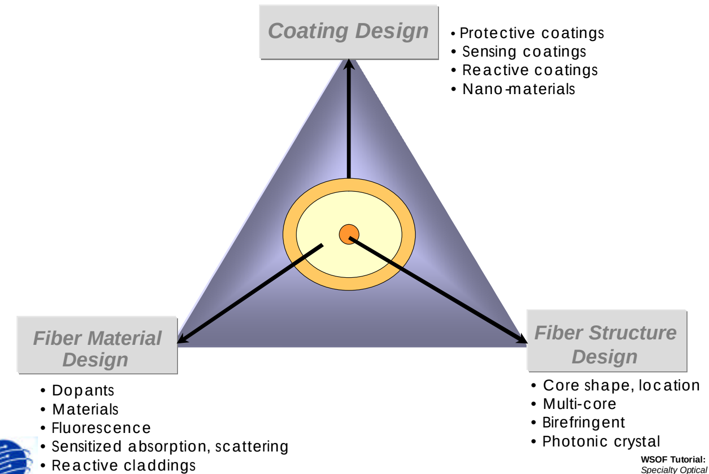
Fiber Draw Tower

Source: Special Gas Controls

- Height dictated by fiber cooling & drawing speed (8 – 30m tall)
- High temperature polishes glass surface
- Strength preserved by polymer coating
- Feedback ensures dimensional control
- Draw speed: >25 m/s (55mph)
- Fiber production >1000 km per preform

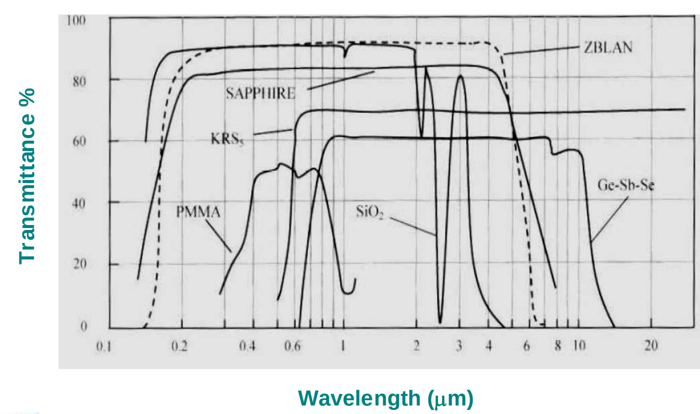
The Fiber Design Triad

Specialty Optical Fibers:
Tailoring of Fiber Design



Fiber Material Design

Optical Fiber Materials:
Spectral Transmittance



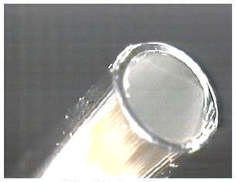
IR Optical Fibers

Fiber/Waveguide Material	Transmission Window (µm)	Typical Minimum Attenuation (dB/km @ l µm)	Typical Fiber NA	Operating Temperature °C	Ultimate Bend Radius for Typical Diameter
SiO_2	0.35-1.40	0.4 @ 1.32	0.16	<300	20 mm for 350 µm
Low OH SiO_2	0.4-2.5	12 @ 0.82	0.16-0.3	<300	20 mm for 350 µm
Sapphire	0.5-3	5000 @ 2.9	1.42	<1800	30 mm for 300 µm
Fluoride ZBLAN	0.4-5	15 @ 2.5	0.21	<200	40 mm for 330 µm
Chalcogenide	1-11	400 @ 6	0.40	<150	20 mm for 600 µm
Polycrystalline	4-15	500 @ 11	0.5	<350	20 mm for 700 µm
Hollow Glass ATIR	7-9.4	1400 @ 9.24*	0.05**	<500	300 mm for 1000 µm
Hollow Metal	3, 5-5.5, 10-13	500 @ 10.6*	0.05**	<500	300 mm for 1000 µm
Hollow Sapphire ATIR	10-17	1000 @ 10.6*	0.05**	<1800	1000 mm for 1064 µm

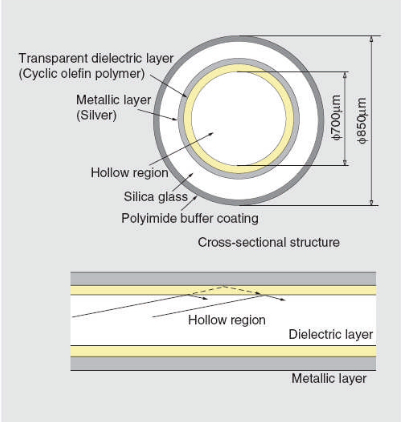
* Optimum laser modes and launch ** Effective NA

WSOF Tutorial: *Specialty Optical Fibers* *A. Mendez*

IR Optical Fibers:
Metal-Coated Hollow Waveguide



Tip of hollow fiber



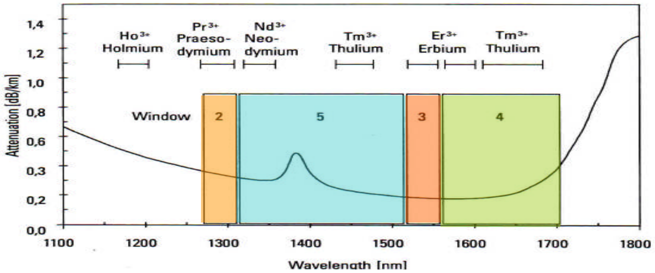
Source: Hitachi Cable

WSOF Tutorial: *Specialty Optical Fibers* *A. Mendez*

Rare Earth Doped Fibers

WSOF Tutorial: *Specialty Optical Fibers* *A. Mendez*

Rare Earth Doped Fibers:
Lasing Spectra

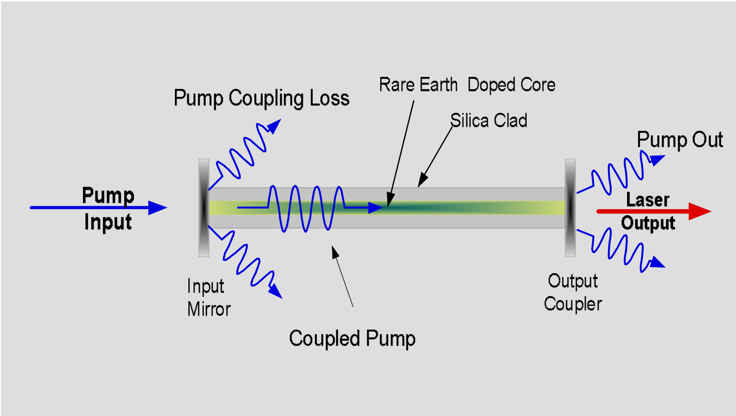


Rare earth ion	Pump wavelength (nm)	Lasing wavelength (nm)	γ_h
Nd^{3+}	~800	~ 920 - 940 ~ 1050 - 1080 ~1360	~ 0.13 – 0.15 ~0.24 – 0.26 ~0.41
Yb^{3+}	~915 - 980	~ 980 – 1140	~0.05 – 0.20
Er^{3+},Yb^{3+}	~915 - 980	~ 1530 – 1620	~0.36 – 0.44
Tm^{3+}	~790, ~1550	~ 1720 – 2100	~0.10 – 0.62

Fraction of absorbed pump converted to heat: $\gamma_h = 1 - \nu_L / \nu_p$

WSOF Tutorial: *Specialty Optical Fibers* *A. Mendez*

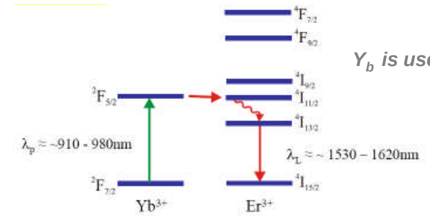
Fiber Laser Construction

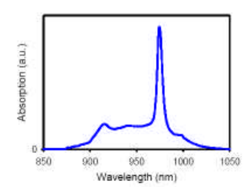


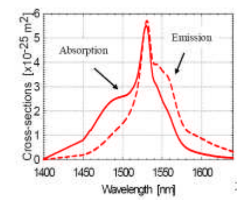
Source: Stocker Yale

Er^3 Doped Fiber Energy Levels

Y_b is used as a sensitizer.

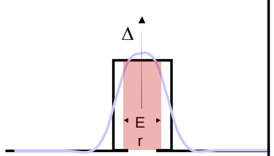






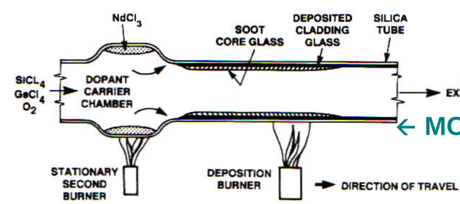
Er-Doped Fiber Development

- Use high Δ to increase pump intensity
  - This increases the inversion level
  - but background loss ~ Δ^2, so typically Δ~1-2%
- Confine erbium to center of core:
  - intensity peaks at r = 0
  - but this increases the length (less overlap with pump)
- Keep concentration low to minimize pairing
  - Good fiber has <10 dB/m absorption at 1530nm
  - This increases the required fiber length
- Co-dope with Aluminum:
  - increases solubility of rare earths (inhibits crystallization)
  - Increases sensitivity to hydrogen
  - reduces splice loss



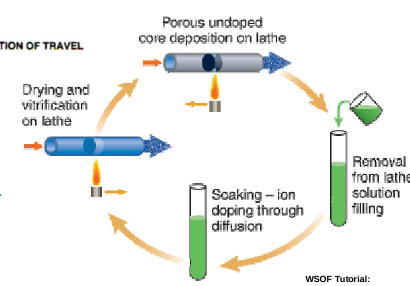
Source: D. DiGiovanni

RE Fiber Preform Doping Techniques

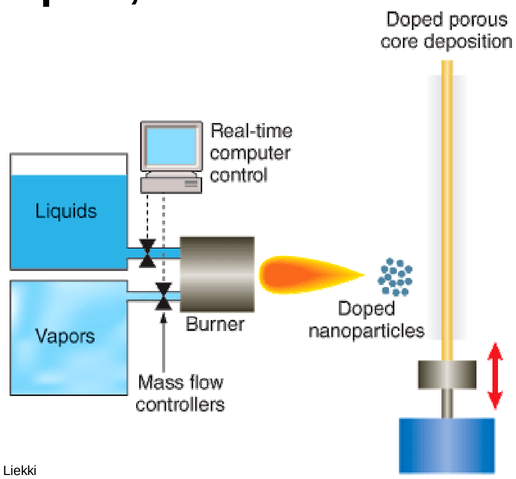


← MCVD Vapor Phase Doping

Solution Doping →

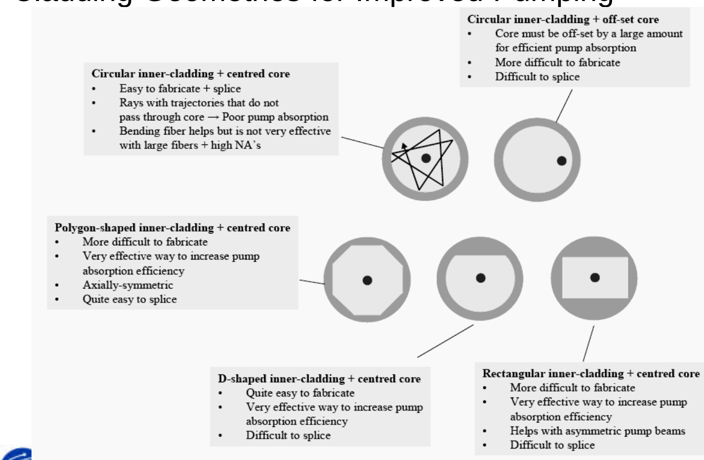


RE Fiber Preform Doping Techniques, cont.



Source: Liekki

Rare Earth Doped Fibers:
Cladding Geometries for Improved Pumping

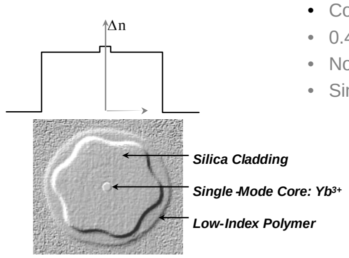


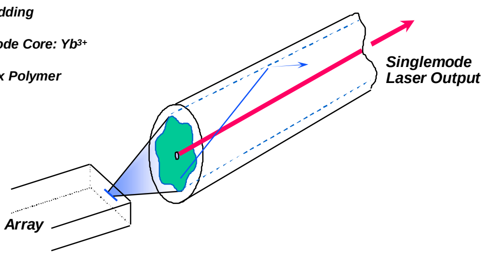
After A. Clarkson

Double-Clad Fiber Devices

Objective→Increase light brightness

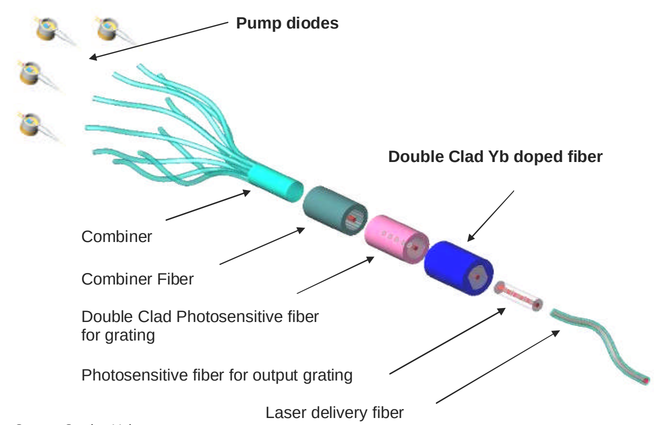
- Couple pump into cladding, not core.
- 0.45 NA fiber has huge lightguiding capacity.
- Non-circular shape eliminates helical rays.
- Singlemode output has 10^3 increase in brightness.





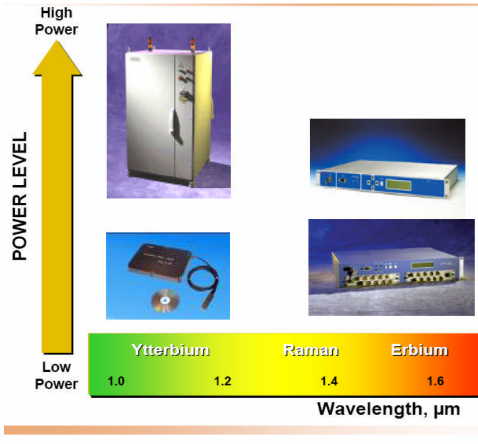
Source: D. DiGiovanni

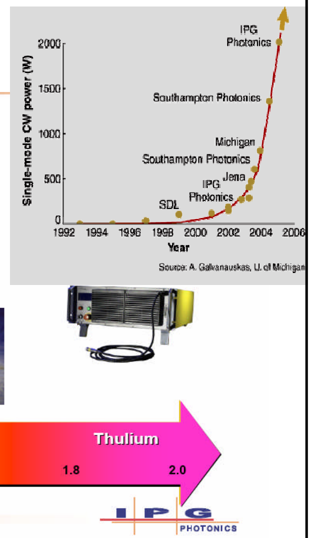
Fiber Laser:
Specialty Fiber Components



Source: Stocker Yale

Fiber Lasers:
Output Power Trend





Fiber Lasers:
Applications

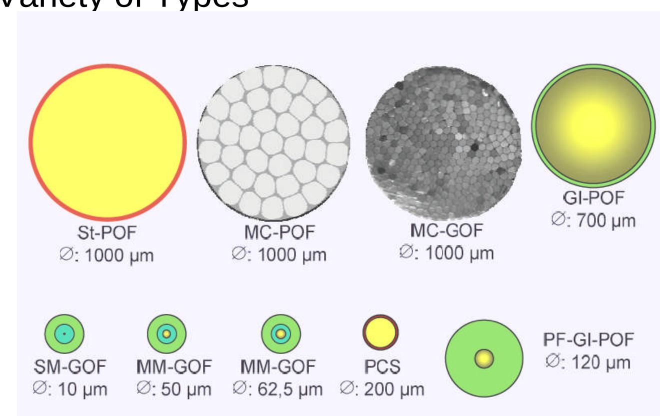
- Skin rejuvenation and wrinkle removal
- General surgery
- Urology
- Dental and ophthalmology

- Marking and engraving
- Welding and brazing
- Cutting
- Drilling
- Cladding
- Cleaning and stripping

- Obstacle warning
- Light detection and ranging
- Optical pumping
- Directed energy
- Sensing and instrumentation

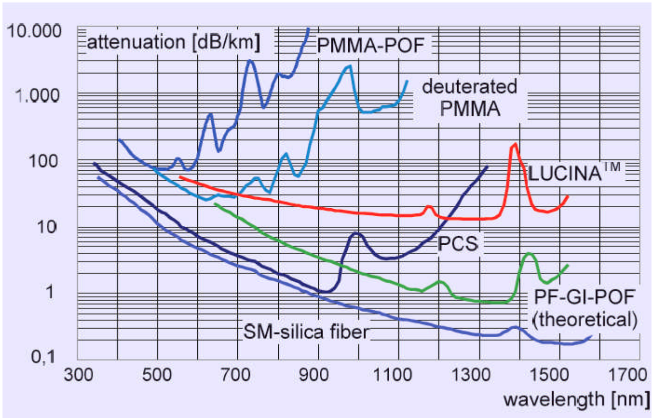
Polymer Optical Fibers

Polymer Optical Fiber (POF):
Variety of Types



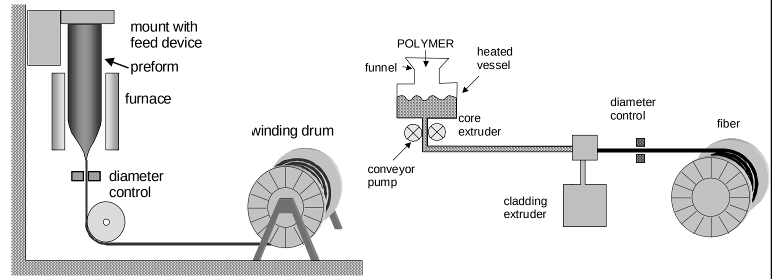
Source: H. Poisel

Polymer Optical Fibers:
Spectral Attenuation



Source: H. Poisel/POFAC

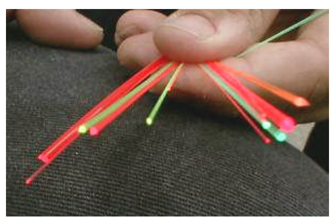
Polymer Optical Fibers:
Fabrication Techniques

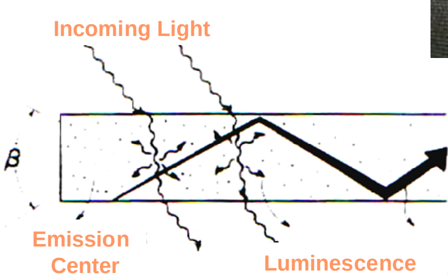


Preform Drawing **Extrusion Process**

POF Fluorescent Fibers

Plastic fiber with dye doped core and thin plastic cladding.



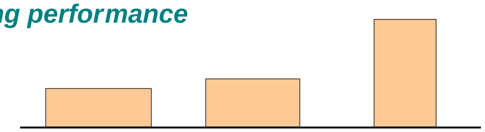


UV light absorbed along entire outside surface and energy re-emitted as visible light along fiber ends.

Fiber Waveguide Design

Step Index Fiber:
Waveguide Design

- ***Modifying Core Radius and Delta produces fibers with varying performance***

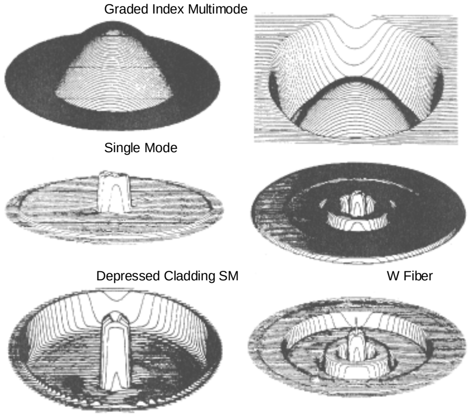


Cutoff (nm)	1000	1000	1000
Index Delta	0.36%	0.45%	1.0%
Core Radius (um)	3.3	3.0	2.0
NA	0.12	0.14	0.21
MFD 1000 nm (um)	6.9	6.1	4.1
MFD 1300 nm (um)	8.5	7.6	5.0
λ for 30mm Bend Loss = 1dB/m	1425 nm	1500 nm	>1700nm

Source: Corning

Fiber Waveguide Design:
Refractive Index Tailoring

Different waveguide designs and light guiding properties can be designed by shaping the RI of the core and/or cladding via dopants and glass modifiers.

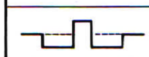
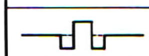


Dopant Effects in Silica Glass

	INDEX n	EXPANSION α	VISCOSITY η	STABILITY	DURABILITY	DISPERSION λ_0	RAYLEIGH SCATTERING	IR LOSS	COST
GeO_2	↑	↑	↓	●	↓	↑	↑↑	●	↑
P_2O_5	↑	↑	↓↓	●	↓↓	●	↑	↑	●
B_2O_3	↓	↑	↓↓	●	↓↓	●	?	↑	●
F	↓↓	●	↓	●	↓↓	●	?	●	●
TiO_2	↑↑	↓	↓	↓	?	↑	?	●	●
Al_2O_3	↑	↑	↓	↓↓	?	↑	?	●	●

After Morrow

Popular Singlemode Fiber Designs

INDEX PROFILE	FIBER TYPE	MAIN FEATURES
	STEP – INDEX MATCHED CLADDING	OPTIMIZED AT 1300nm
	DEPRESSED CLADDING	LOW ATTENUATION LOW SENSITIVITY TO BENDING
	W FIBER	DISPERSION FLATTENED
	PURE SILICA CORE	VERY LOW ATTENUATION
	TRIANGULAR CORE	DISPERSION SHIFTED (OPTIMIZED AT 1550nm)
	SEGMENTED CORE	DISPERSION SHIFTED LOW SENSITIVITY TO BENDING
	MULTIPLE CLADDING	DISPERSION MODIFIED (SHIFTED OR FLATTENED)

(------: SiO_2 level)

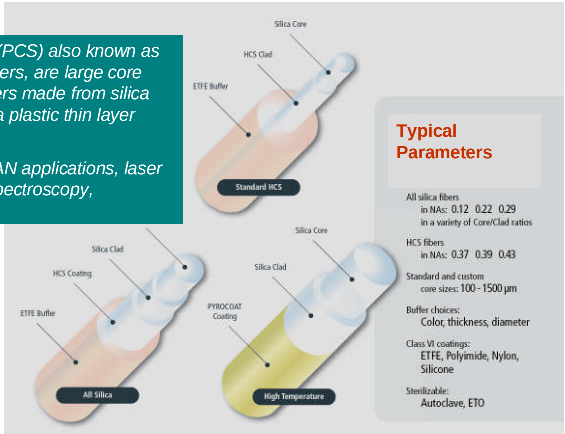
Source: CSLT

Plastic Clad Fibers

Hard-Clad Fibers

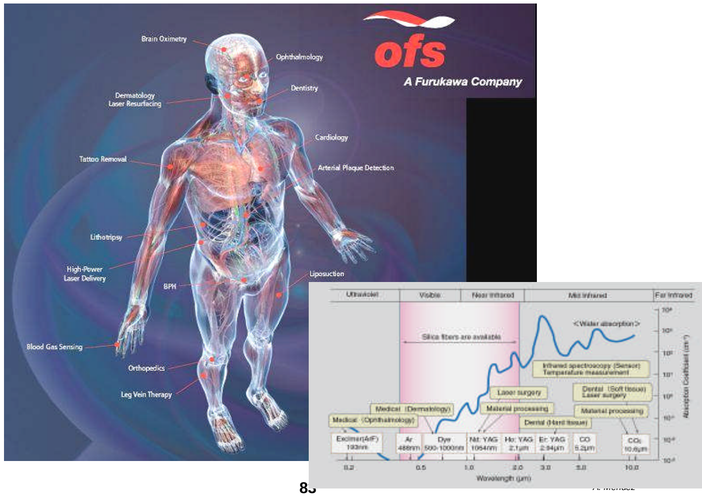
Plastic-Clad silica fibers (PCS) also known as hard-clad silica (HCS) fibers, are large core (>100 μm) multimode fibers made from silica glass that typically have a plastic thin layer acting as cladding.

Common uses include LAN applications, laser delivery, fiber sensors, spectroscopy, illumination, etc.



Source: OFS

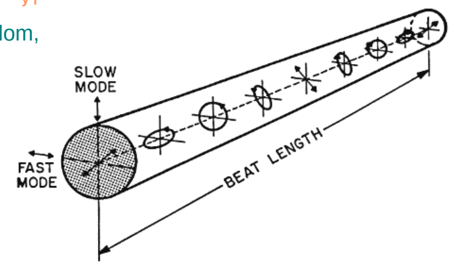
Hard-Clad Fibers:
Medical Applications



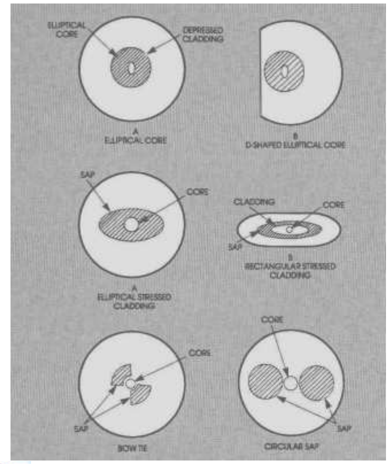
Polarization Maintaining Fibers

Polarization Modes & Birefringence

- In a regular fiber, light transfers back and forth between the 2 polarization states with a period known as the Beat Length $L_B = \lambda/B$
- Birefringence "B" is the index difference between the 2 polarization axes. $B = |n_x - n_y|$
- For an ordinary fiber, B is random, and L_B is ~ 10m.
- A polarization maintaining fiber has a large B ~10^{-4} thus forcing light to propagate along preferential polarization fiber axes.

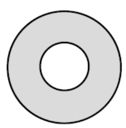


Polarization Maintaining Fibers

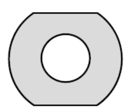


Stress regions within the cladding are formed to induce birefringence in the fiber's core. Thus, promoting linearly polarized light to travel in specific orthogonal directions along the fiber.

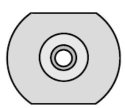
Elliptical Core & D-Shaped Fibers



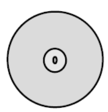
Silica substrate tube



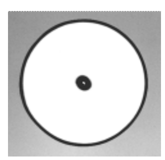
Shaved Tube



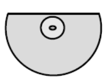
Deposition of Core & Cladding



Tube Collapse



Fiber drawing

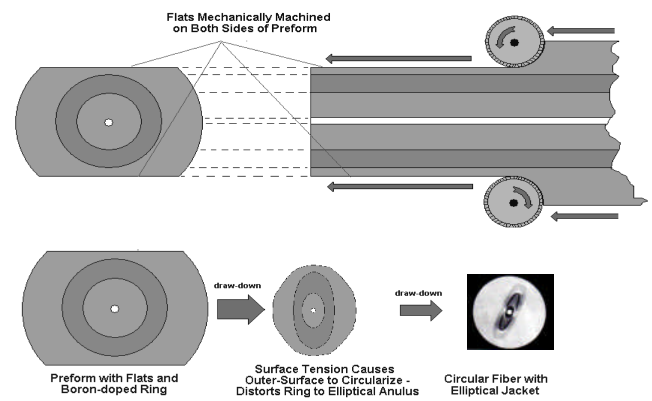


Shaving of Preform Flat

Fiber drawing

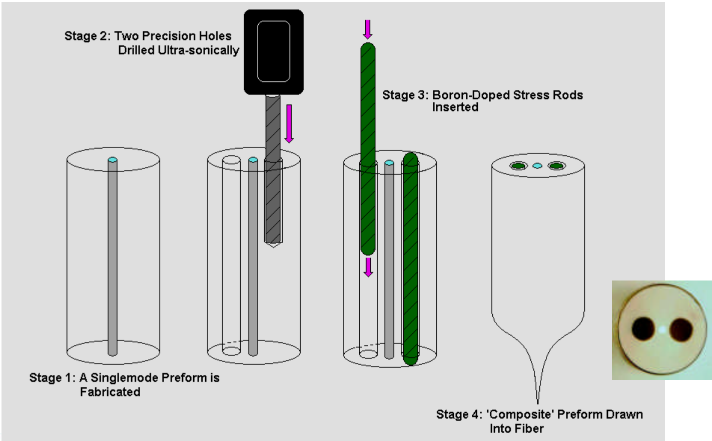
Source: KVH

E-Core Fiber:
Fabrication Process



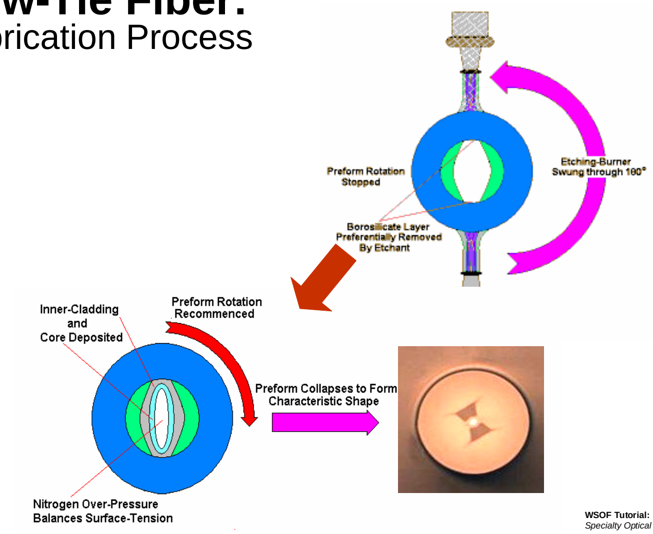
NB: Draw-down is not to scale

Panda Fiber:
Fabrication Process

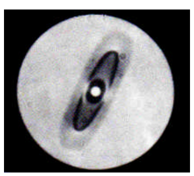


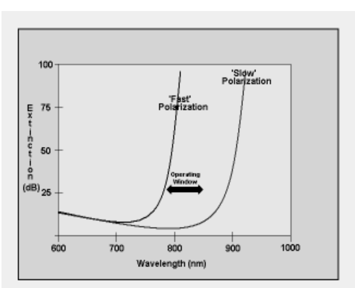
Source: Fibercore

Bow-Tie Fiber:
Fabrication Process



Polarizing Fiber





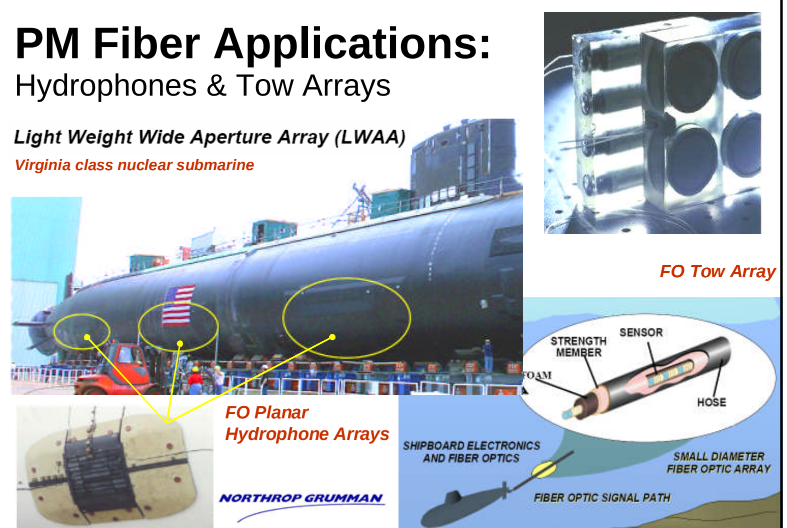
- A highly (~40%) birefringent fiber with a "W" type index profile.
- Light polarized along slow axis is guided more strongly than polarized light along the fast axis.
- Second polarization state is forced to be cutoff.
- Have broad wavelength operating range: 30-50nm.

Source; 3M

PM Fiber Applications:
Hydrophones & Tow Arrays

Light Weight Wide Aperture Array (LWAA)

Virginia class nuclear submarine



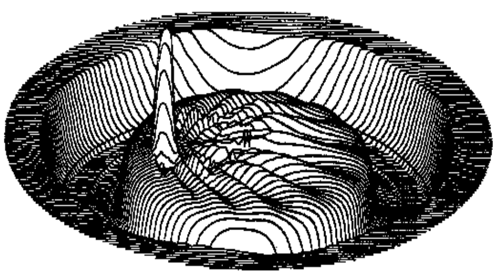
PM Fiber Applications:
Fiber Optic Gyros (FOG)

- Mobile Antenna Pointing & Stabilization
- Vehicle Navigation
- Autonomous Vehicle Navigation
  - Material Handling Equipment
- Torpedoes
- Weapons Simulators
- Video Camera Stabilization
- Open & closed-loop designs
- 1,2,3, 6 axes
- Typically PM fiber with 80um OD.

Source: KVH

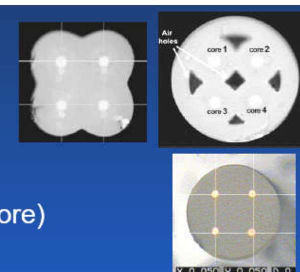
Exotic Singlemode Fibers

Offset Core Fiber



Multi-Core Fibers

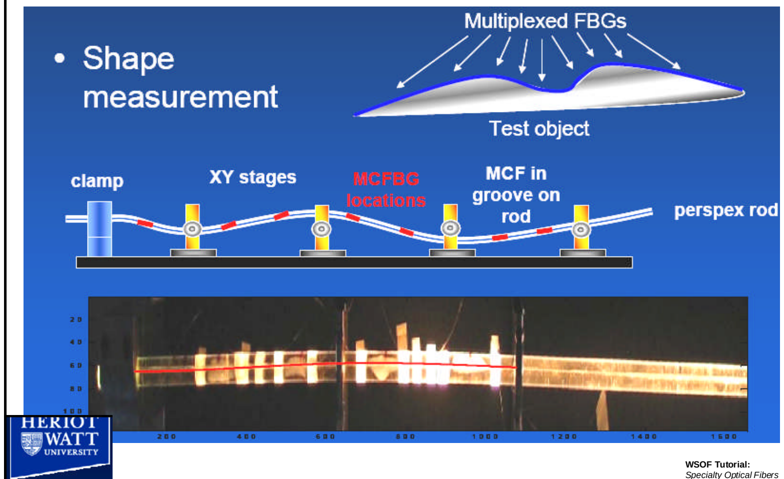
- Multiple shaped preforms (France Telecom, and HesFibel Ltd*, Turkey)
- Drilled circular preform (Fibercore)



Applications

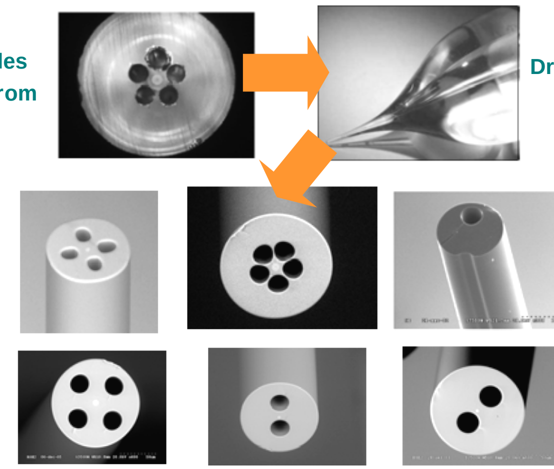
- *FBG Arrays*
- *Shape sensing*
- *Bending sensors*

Multi-Core Fibers:
Shape Measurement



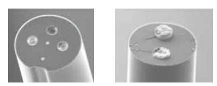
Fibers With Holes

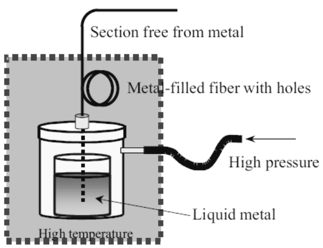
Drill holes into prefrom



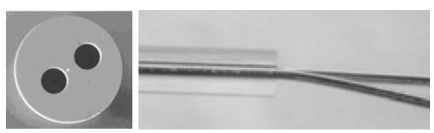
Draw fiber

Electro-Optic Fibers:
Fabrication





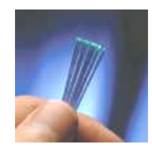
1. Electrodes are formed by injecting melted liquid into a pre-drilled fiber



2. Fiber is side-polished to contact electrodes

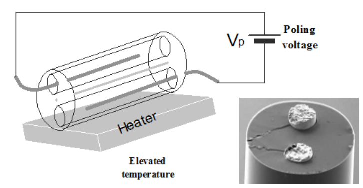
3. External wires are connected to electrodes

Electro-Optic Fiber:
Why Is It Attractive?

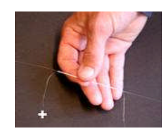


Conventional fibers allow only light-guiding characteristics.

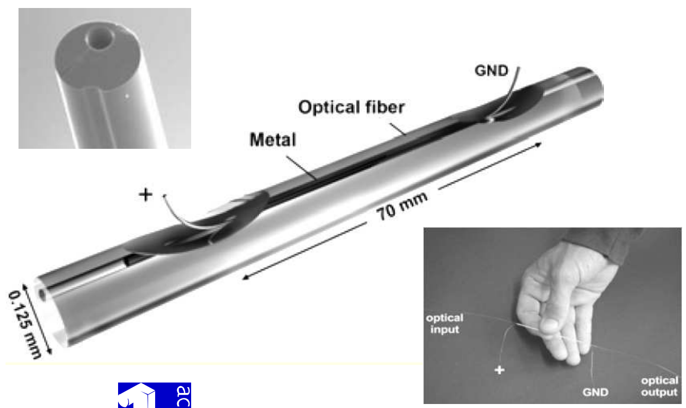
Electro-optic fibers allow for the <u>manipulation</u> of light via external electrical control signals.



Electro-optic active fibers can be used to build a variety of all-fiber, low cost optical devices such as modulators, polarizers, switches, delay lines, etc.



EO Fiber Polarization Switch:
Device Concept

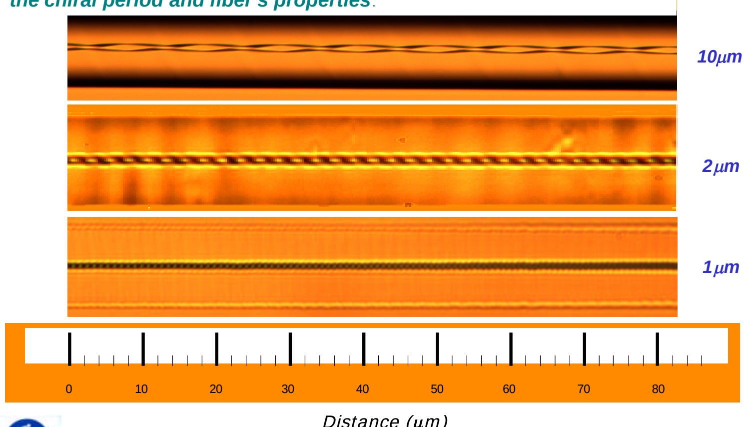


EO Fiber Polarization Switch:
Operating Principle

- An optical fiber is fitted with a small metallic conductor section (~ few cm).
- An electrical current in injected into the conductor, thus inducing a number of localized effects:
  - Thermal
    - Thermo-optic index change
    - Thermal expansion
  - Mechanical
    - Shock pressure wave (short current pulse)→ localized strain which induces bi-refringence
  - Acoustic
    - Induced vibration from sudden expansion & contraction of glass

Chiral Optical Fibers

Fiber is twisted continuously as is being drawn. Twist pitch defines the chiral period and fiber's properties.



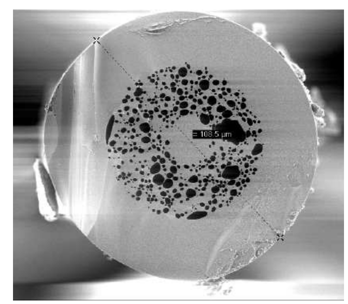
Source: Chiral Photonics

Random Hole Optical Fiber (RHOF)

Cladding region is filled with randomly oriented air holes ranging in size from 100 nm to a few μm.

The fiber is made by drawing a preform assembly comprising a solid silica core, surrounded by a porous, sol-gel fabricated, cladding—containing gas-producing powders—and a final protective silica substrate tube.

During fiber drawing, the cladding pores become cylindrical holes running the length of the fiber.



Source: V. Tech

Photonic Crystal Fibers

Microstructure Fibers

Optical fiber constructed with a lattice of voids (air holes) along its length → provide unique optical properties impossible to obtain with solid fibers.

Very large index of refraction differences

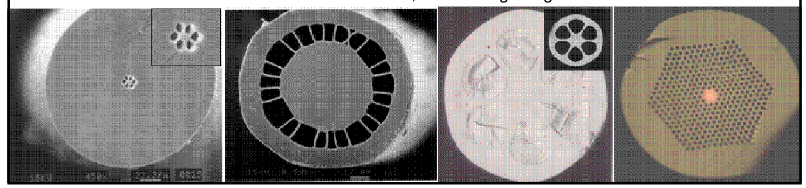
- 1.0 (air) to 1.45 (undoped silica): Δn ~0.45
- Doped silica fiber: Δn ~0.03

Voids can be filled with functional materials allowing dynamic properties

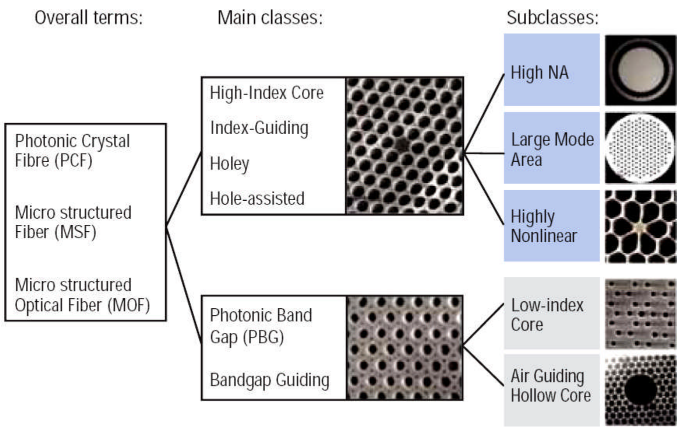
- Control local index with temperature, electrical field, magnetic field, etc.

Photonic bandgap operation

- Periodic structure creates resonance, like a 2-D grating.



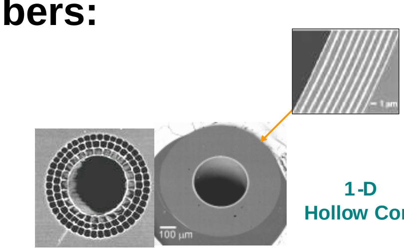
Microstructure Fibers: Classification



Source: Newport Corp.

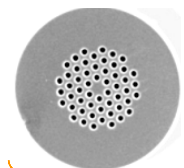
Microstructure Fibers: 1D & 2D Structures

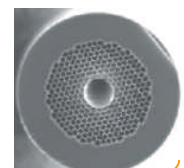
1-D Solid Core



1-D Hollow Core

2-D Solid Core



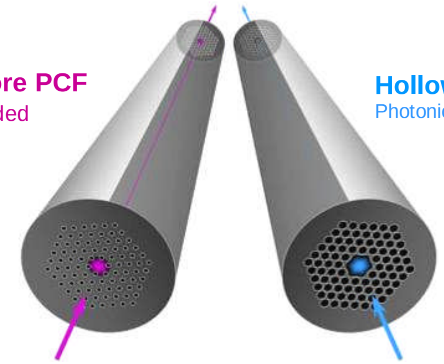


2-D Hollow Core

Photonic crystal Fibers (PCF)

Microstructure Fibers:
Two Light Guiding Designs

Solid-core PCF
Index-Guided



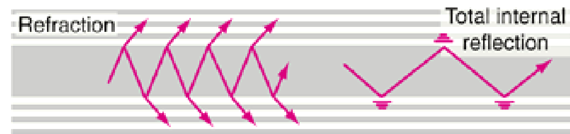
Hollow-core PCF
Photonic Band Gap Guided

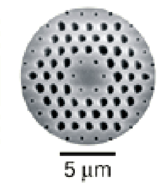
Key feature is the presence of an ordered lattice of air channels running the length of the optical fiber.

A solid or hollow core design determines the type of light guiding mechanism.

Source: OSA

Photonic Crystal Fibers:
Index Guided



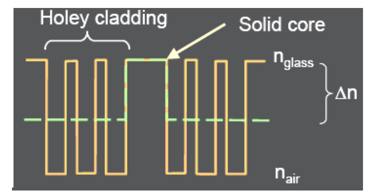


Un-doped silica glass is used for both core and cladding regions. Core is solid.

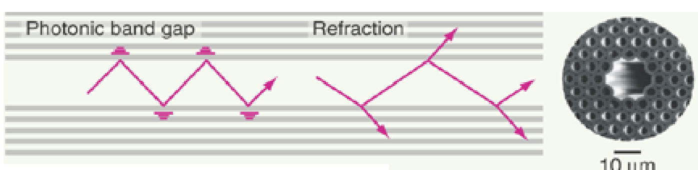
Placement of air channels (n = 1) in the cladding creates an "effective" index below that of the solid core region.

Light is confined and guided by total internal reflection. NA can approach 1.

Different designs can be achieved by varying de index delta, channel spacing, size & diam.



Photonic Crystal Fibers:
Photonic Band Gap Guided

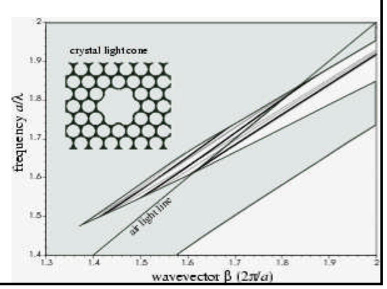


Un-doped silica glass is used for both core and cladding regions. Core is hollow (air).

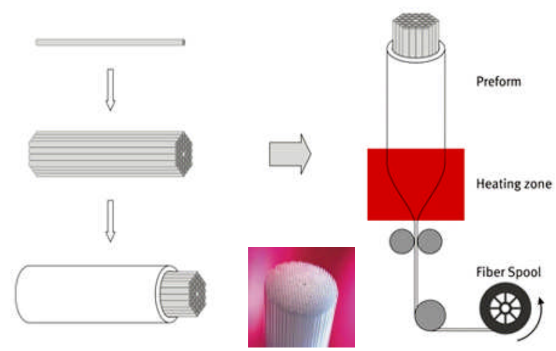
Placement of air channels (n = 1) in the cladding creates a 2-D photonic bandgap structure.

Constructive interference is produced by scattered light refracted at the core/cladding interfaces of the periodic lattice structure.

Light can only propagate in specific regions.

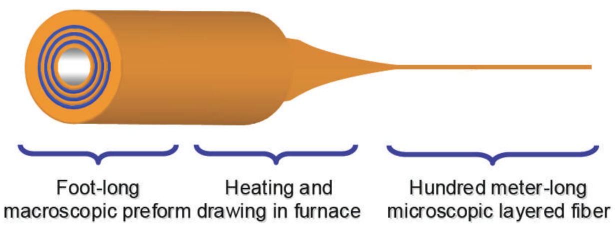


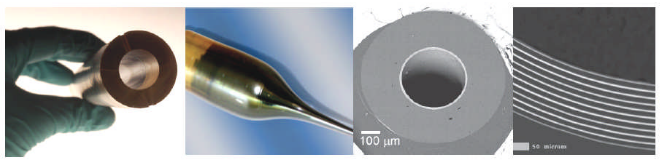
PCF Fabrication:
Stack-and-Draw Process



Source: Crystal Fibres

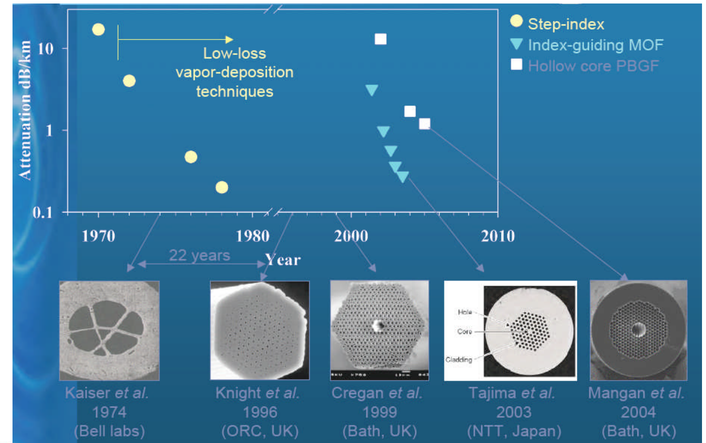
Hollow Core Bragg Fiber:
Fabrication Process





Source: OmniGuide

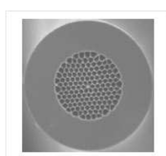
Photonic Crystal Fibers:
Historical Loss Reduction



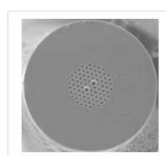
Source: T. Monro, OFS-19

Photonic Crystal Fibers:
A Broad Variety of Types & Functions

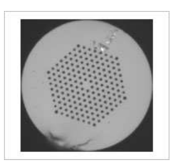
Endlessly Single-mode



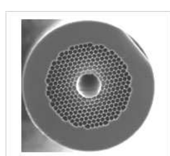
High Nonlinearity



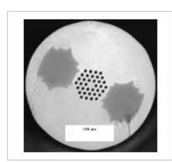
Polarization Maintaining



Large Mode Area



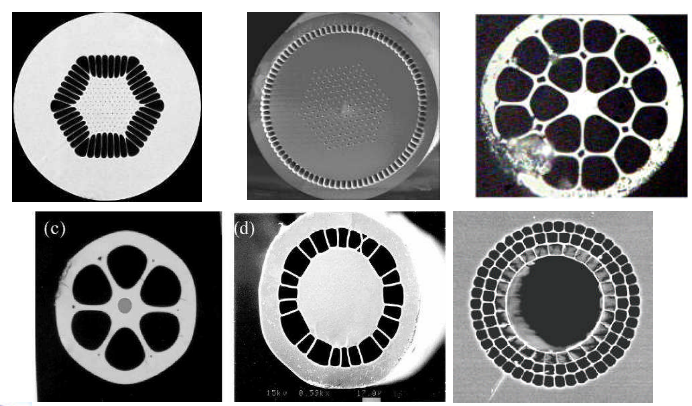
Hollow Core



Polarizing Fiber

Source: Crystal Fibre/Blaze Photonics

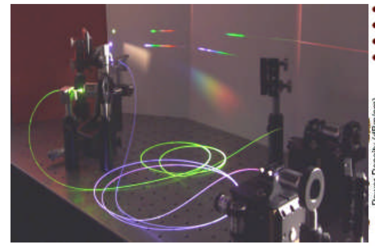
Other Microstructure Fiber Designs



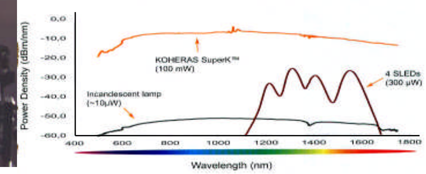
PCF Applications:

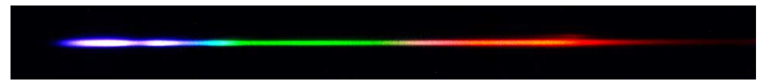
- **Telecommunications**
  - Dispersion compensation
  - Transmission fibers
  - Broadband SM fibers
- **Lasers**
  - Double Clad fibers (laser cavity)
  - Large Area fibers (high power transmission)
  - White Light Sources
- **Sensing**
- **Metrology**
- **Medical**
  - Optical Coherence Tomography

PCF Applications:
Ultra-Broad White Light Source



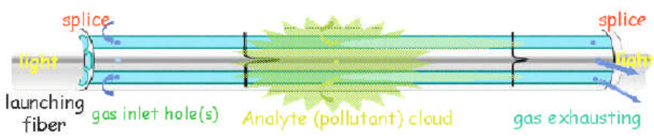
- High brightness
- Ultra broad spectrum
- Compact robust design
- No cooling

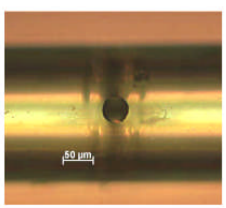




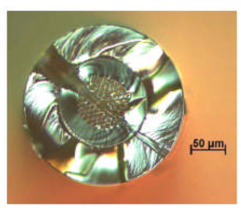
From: Ranka, J. K., Windeler, R. S., and Stentz, A. J., Conference on Lasers and Electro-Optics, 1999.

PCF Applications:
Gas Sensor





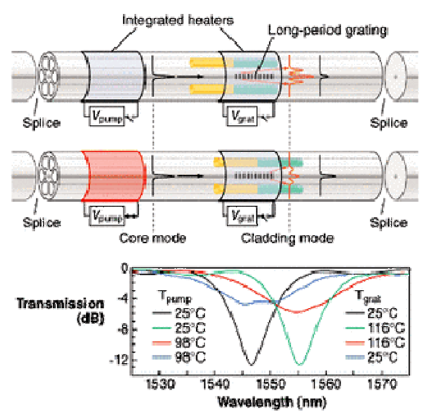
Side laser-drilled hole

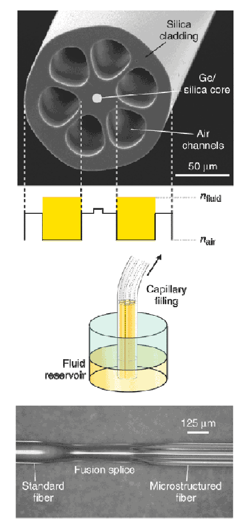


Fiber Cross-section

Source: IPTH

PCF Applications:
Microfluidic Devices





Source: U. Sidney

Fiber Coatings

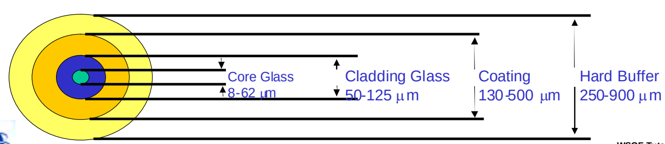
Optical Fiber Coatings

- **Environmental Protection**
  - Abrasion
  - Moisture ingress
  - Hydrogen diffusion
  - Chemical attack
  - Temperature resistance
  - Mechanical bending
- **Sensing**
  - Fluorescence
  - Swelling
  - Chem/Bio reactive
  - Magnetic
  - Acoustic
  - Piezoelectric

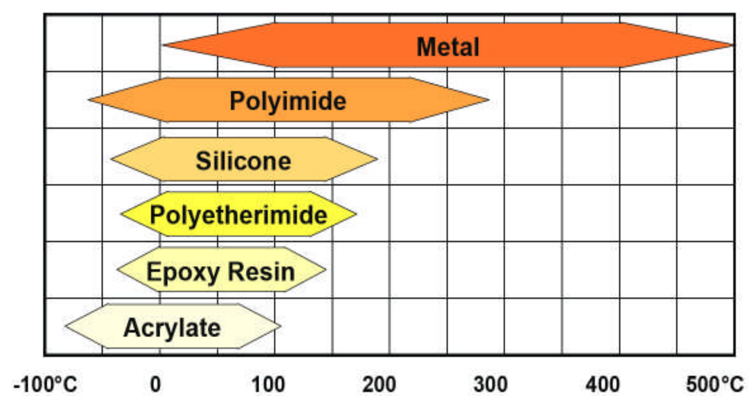
Fiber Structure & Coatings

Buffer/Jacket Type	Material* Temperature Range
Hytrel (elastomer)	-40 to +135ºC
PVC	-35 to +90ºC
Polyurethane	-50 to +80ºC
TPE	-20 to +105ºC
FEP	-100 to +200ºC
PVDF	-50 to +150ºC
ETFE	-125 to +150ºC
PFA	-200 to +260ºC
Nylon	-65 to +105ºC
PEEK	-55 to +240ºC

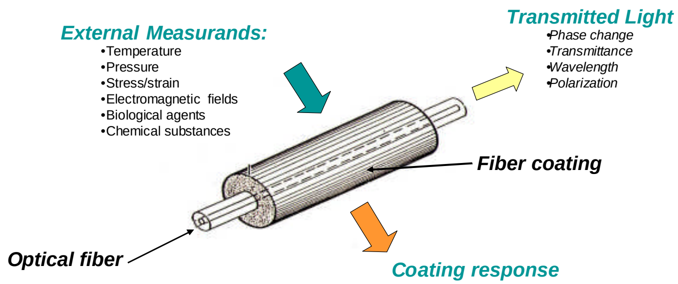
- **Coating**
  - Acrylate, Silicone, Polyimide
- **Buffer/Jacket**
  - Nylon, Hytrel, Tefzel, PEEK, etc.



Fiber Coatings/Jacket Materials:
Operating Temperature Range



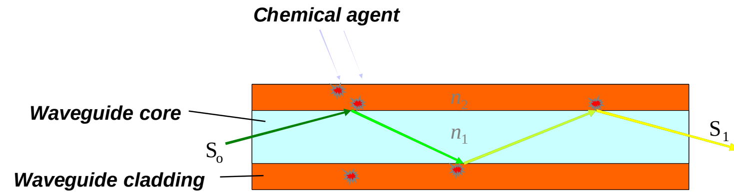
Active Fiber Coatings



An area hardly explored in the Specialty Optical Fiber field…

Evanescent-Wave Sensor Principle

Chemically-Induced Cladding Change

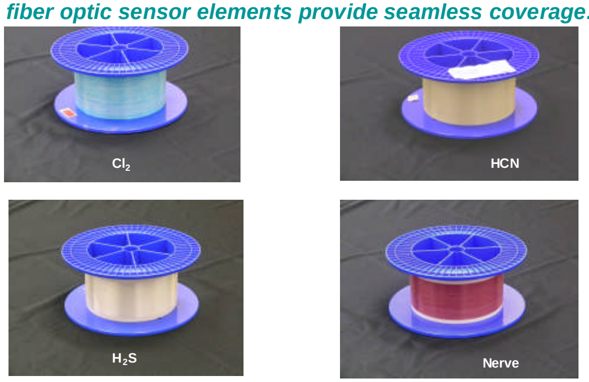


- Presence of chemical agent in cladding region changes optical properties
- Light propagating through sensor waveguide is affected by changes in exposed region

Source: IOS Inc.

DICAST® Chem Sensor Fibers

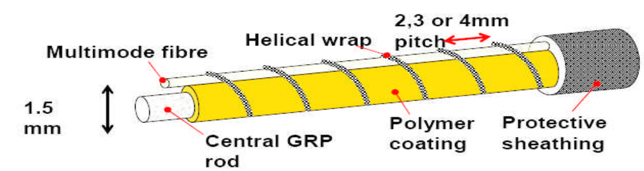
Fully distributed, intrinsically sensitive, chemically active, cladding-based, fiber optic sensor elements provide seamless coverage.

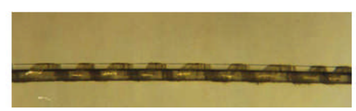


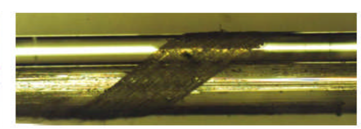
Source: IOS Inc.

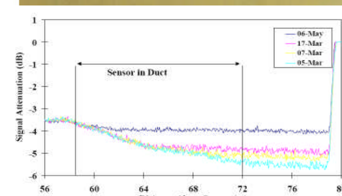
Water Leak Detection:

Distributed Moisture Sensor









A special polymer coating swells in the presence of moisture, expanding and producing microbending losses on the strapped multi-mode fiber.

Source: B. Culshaw

Hermetic Coating Fibers

Hermetic Fiber Coatings

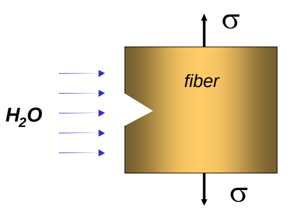
Hermetic fiber coatings provide protection against:

- **Moisture Ingress** → *mechanical degradation*
- **Hydrogen gas diffusion** → *optical loss*

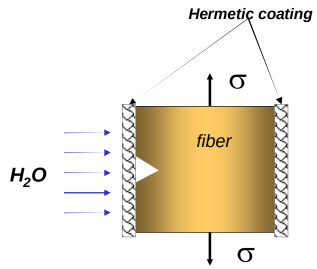
Stress Corrosion:
The Need for Hermetic Coatings

Need to provide optical fibers with a barrier against:

- *Moisture ingress*
- *Chemical attack*
- *Hydrogen gas diffusion*



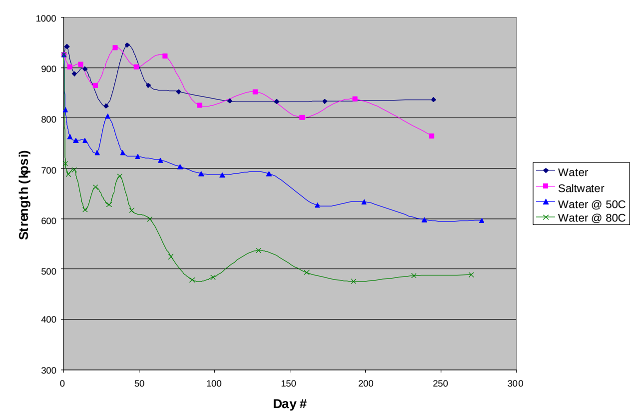
Fatigue = Flaw + Moisture + Stress (Stress Corrosion)



Flaws do not grow and tend to "heal" over time due to absence of moisture

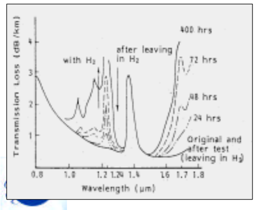
Stress Corrosion:
Water Exposure

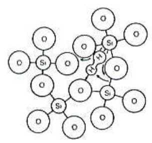
Standard Fiber



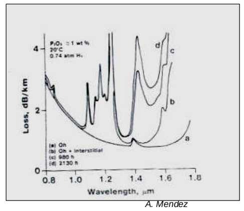
Types of Hydrogen-Induced Loss Mechanisms

- **Interstitial**
  - Dominates at low temperatures (<150 °C)
  - Driven by pure molecular H2 diffusion into silica glass interstitial sites
  - Reversible
  - Insensitive to glass composition
  - Peak absorption peak @ 1.24μm
  - Time scale of days to months
  - Losses determined equilibrium H2 concentration
- **OH Reaction**
  - Dominates at high temperature (>150° C)
  - Driven by chemical reaction of H_2 molecules with fiber dopants
  - Irreversible—losses are permanent
  - Very sensitive to glass composition
  - Peak peak @ 1.41μm
  - Time scale of hours to days
  - Loss determined by reaction kinetics





After J. Kreidl



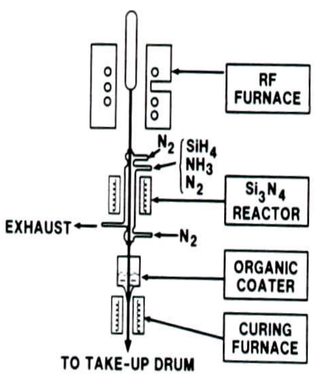
A. Mendez

Types of Hermetic Coatings

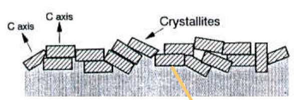
- **Metallic**
  - Al
  - Au
  - Cu
  - In
  - Tin
- **Organic**
  - Oxides (TiO_2, SnO_2, Al_2O_3)
  - Nitrides (SiN, SiON)
  - Carbides (SiC, TiC)
  - Carbon (amorphous, diamond-like)

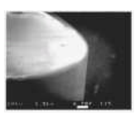
WSOF Tutorial: *Specialty Optical Fibers* *A. Mendez*

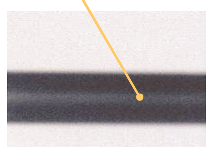
Fabrication of Carbon-Coated Fibers



Carbon coatings are typically:
- *Amorphous*
- *Formed by tiling of carbon crystallites*
- *20-100nm thick*







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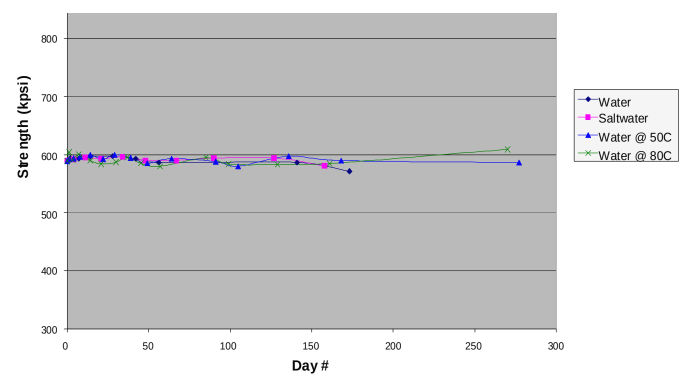
Stress Corrosion:
Water Exposure

Hermetic Fiber



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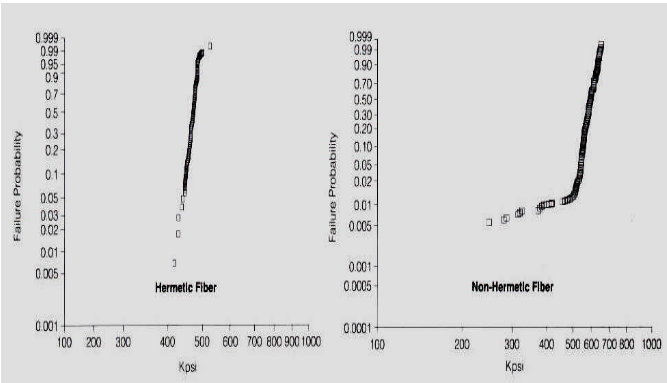
Hermetic Fiber:
Mechanical strength vs. standard fiber



Corning Inc.

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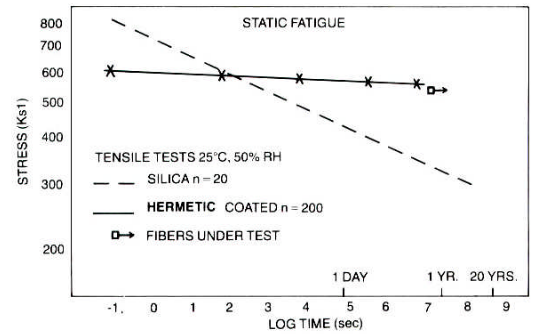
Hermetic Fiber:
Improved Static Fatigue



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Fiber Mechanical Lifetime

The time-to-failure (fiber lifetime) under a constant applied stress is calculated by:

$$t_f = (\sigma_p / \sigma_a)^n$$

where: t_f = Time to failure (seconds)
σ_p = Proof-test stress
σ_a = Application stress
n = Fatigue resistance

- *Hermetic fibers can withstand higher applied stresses*
- *Standard fibers: operate at 20% proof-test level*
- *Hermetic fibers: can operate at 80% proof-test level*

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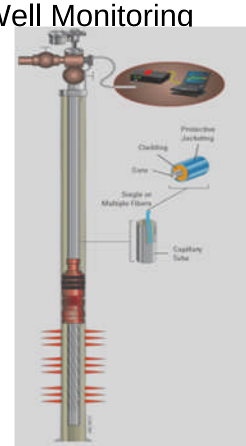
Downhole Applications:
Well Monitoring



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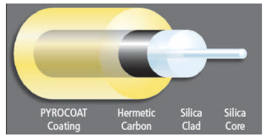
Carbon-Coated Fibers:
OFS

ofs
Leading Optical Innovations

Optical Properties	GEO 1310 11	GEO 1310 16
Operating wavelength	1310/1550 nm	1310/1550 nm
Cutoff wavelength	≤1290 nm	≤1290 nm
Mode field diameter @ 1310 nm	9.3 ± 0.5 µm	6.7 ± 1.0 µm
Mode field diameter @ 1550 nm	10.5 ± 1.0 µm	7.5 ± 1.0 µm
Attenuation @ 1310 nm	≤0.7 dB/km	≤0.8 dB/km
Attenuation @ 1550 nm	≤0.6 dB/km	≤0.6 dB/km
Numerical aperture (nominal)	0.11	0.16
Dimensions/Geometric Properties		
Core diameter (nominal)	8.4 µm	6.3 µm
Clad diameter	125 ± 2 µm	125 ± 2 µm
Coating diameter	155 ± 5 µm	155 ± 5 µm
Clad non-circularity	<2.0%	<2.0%
Coating concentricity	≥80%	≥80%
Core/clad offset	≤1.0 µm	≤1.0 µm
Coating/Buffer Descriptions		
Coating material	Hermetic Carbon/PYROCOAT	Hermetic Carbon/PYROCOAT
Operating temperature	-65 to +300°C	-65 to +300°C
Mechanical and Testing Data		
Short-term bend radius	≥4 mm	≥4 mm
Long-term bend radius	≥4 mm	≥4 mm
Proof test level	≥200 kpsi (1.38 GPa)	≥200 kpsi (1.38 GPa)
Product Description Code	**SMT-A1310JZ**	**SMB-D1310JZ**
Order by Part Number	**BF05717**	**F9001-01**



Typical Applications

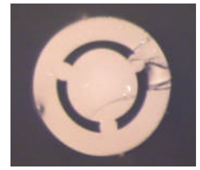
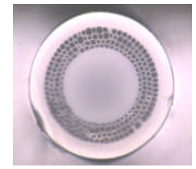
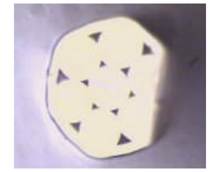
- Data links
- Single-mode sensors
- Down-hole deployment
- Above-ground well networking
- Raman back-scattering

Features and Benefits

- Tough glass for harsh environments
- Wavelength performance at both 1310 and 1550 nm
- Choice of NAs: 0.11 and 0.16
- High survivability in water, high temperatures, high pressure, and active chemical environments
- Abrasion resistant
- Long lengths up to 14 km

Carbon-Coated Fibers:
New Designs

Verrillon THE FIBER IN FIBEROPTICS

- ***Fiber with air gaps to slow down H_2 ingress***
- ***Multiple air hole designs***
- ***With and without carbon coatings***
- ***Protection is only temporary- diffusion delay –and hydrogen eventually completely diffuses in.***

Metal-Coated Fibers

Metal-Coated Fibers:
Pros & Cons

Advantages

- High temperature operation
- Hermetic to H_2
- Moisture barrier
- High-power laser delivery
- Solderable
- Higher strength
- No outgassing
- Sterilizeable (autoclave)
- Corrosion resistant
- Radiation resistant

Disadvantages

- Higher optical loss
- Difficult to strip coating
- Limited continuous length
- Difficult to re-coat
- Plastic deformation

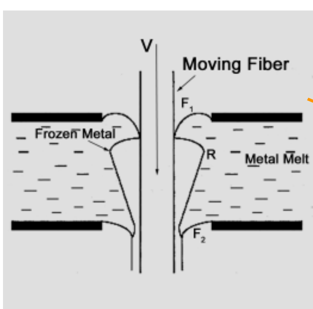
Metal-Coated Fibers:
Key Characteristics

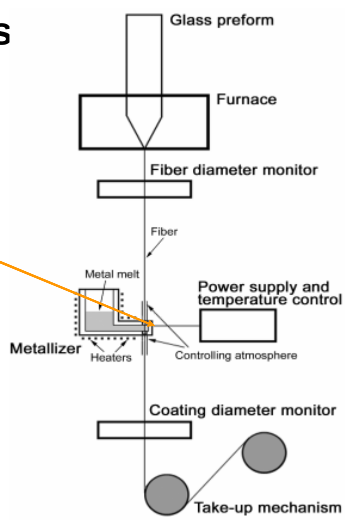
- **Metal Coatings Available**
  - Gold <700℃
  - Aluminum <450℃
  - Tin <150℃
  - Copper <400℃
  - CuBall <500℃
- **Coating Thickness**
  - 15 to 150 µm (depending on metal)
- **Length**
  - Typically limited to 10s to 100s of meters.
  - Maximum continuous length < 1 Km
- **Loss**
  - Much greater than conventional fibers: extra 2-5dB/km
  - Loss increase due to coating microbending effects on fibers upon cooling & loss at cladding-metal interface.
- **Price**
  - Excessive: $10-$100 USD/meter → key barrier

Metal-Coated Fibers:
Fabrication Methods

- **Freeze Coating (melt dipping)**
- **Evaporation**
- **Sputtering**
- **Ion Plasma**
- **Electroplating**
- **Electroless Plating**

Metal-Coated Fibers
Freeze Coating Method

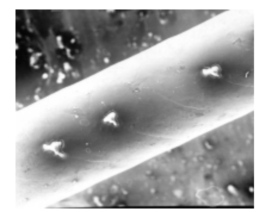


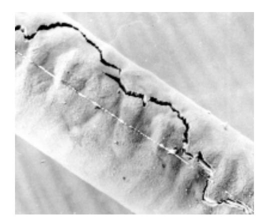


Source: FORC, Russian Academy of Sciences

Metal-Coated Fibers:
Common Coating Problems

- Pinholes
- Delamination
- Cracking
- Thickness uniformity
- Morphology





Source: FORC, Russian Academy of Sciences

Metal-Coated Fibers:
Applications

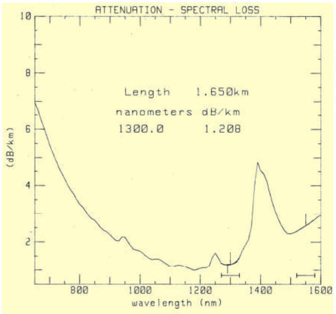
- **High-Temperature**
  - GasTurbines
  - Rockets & Jet Turbines
  - Furnaces
  - Power Plants
  - Nuclear Reactors
  - Oil & Gas Wells
- **Low-Temperature**
  - Cryo Sensing
  - Spacecraft & Aerospace
- **Room Temperature**
  - Bio-medical
  - Chromatography (metal-coated hollow tubes)

Metal-Coated Fibers:
IVG Fiber—Cu SM Coated Fiber

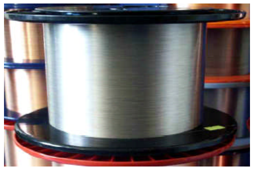
Specifications

	Cu800	Cu1300	Cu1300-200
Operating wavelength	800 - 900 nm	1300 - 1600 nm	1300 - 1600 nm
Cut-off wavelength	< 770 nm	< 1250 nm	< 1250 nm
Attenuation (@ 850 and 1310 nm)	10.5 dB/km	5.5 dB/km	<1 dB/km
Numerical aperture	0.13	0.13	0.13
Mode field diameter	6 um	9 um	9 um
Cladding diameter	125 um	125 um	200 um
Coating diameter	165 um	165 um	260 um
Core-clad concentricity	< 0.5 um	< 0.5 um	< 0.5 um
Cladding offset	< 5 um	< 5 um	< 5 um
Proof test	100 kpsi	100 kpsi	100 kpsi
Short-term bending radius	> 10 mm	> 10 mm	> 15 mm
Long-term bending radius	> 15 mm	> 15 mm	> 25 mm
Operating temperature range	< 600° C	< 600° C	< 600° C

Metal-Coated Fibers:
Oxford Electronics—CuBall MM Fiber



Fibre Type	GI50-125CB	GI50-200CB
Core diameter µm	50	50
Cladding diameter µm	125	200
Coating diameter µm	165	260
Attenuation dB/km	12-15	<1.5



Graph of Loss vs Wavelength for CuBALL GI50-200CU

Market Perspective

Specialty Fiber Manufacturers

ofs, Nufern, Crystal Fibre, Fibercore, StockerYale, Corning, Fujikura, CorActive, Chiral Photonics, Polymicro Technologies, LLC, IVG Fiber, Verrillon, j-fiber Jena, FiberLogix, CeramOptec, OmniGuide, fiberguide industries, INO, Liekki, Sumitomo, acreo

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Specialty Fibers:
Average Selling Prices

Type of Fiber	Price per Meter
Conventional single-mode fiber	$0.20
Dispersion compensating fiber	$1.50
Polarization-maintaining fiber	$3
UV photosensitive fiber	$5 to $10
Erbium-doped fiber	$5 to $10 (standard) $100 (custom)
Hollow silica waveguides (IR)	$150 to $700
Microstructured fiber	$20 to $50 (large quantity) $200 to $400 (small quantity)

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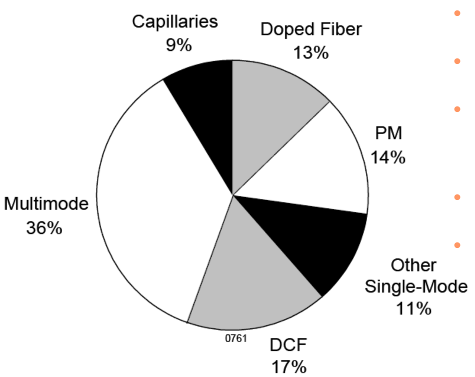
Specialty Fiber Market Revenues by Segment (2003)



- Very fragmented market
- Broad variety of fiber types
- Diversity of applications fields and uses
- Small growth 5-10%/yr
- Total market estimated at $200-$300 Million USD

Source: Strategies Unlimited

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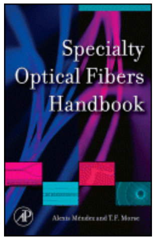
Further Reading



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Conclusions

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Conclusions

- There is a broad and diverse set of specialty fibers.
- Major activity is centered nowadays in PCFs, POFs and high power fibers for fiber laser applications.
- PCFs are a novel, disruptive technology. More is to come…
- In most instances, R&D work in this area requires to have infrastructure or access to a fabrication facility.
- There is a fair number of research groups and manufacturing companies around the world. Activity is healthy but community is very dispersed.
- Commercial markets are very niche and extremely fragmented. Total market is ~ $200M USD, and growing at 10% annually.
- Certain applications will see an explosive growth, such as in fiber lasers, oil & gas sensing, bio-medical laser delivery.

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Obrigado!

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