Novel Modified Optical Fibers for High Temperature In-Situ Miniaturized Gas Sensors in Advanced Fossil Energy Systems

*Gary Pickrell** and Anbo Wang**

***Department of Materials Science and Engineering*

**Center for Photonics Technology*

Electrical and Computer Engineering

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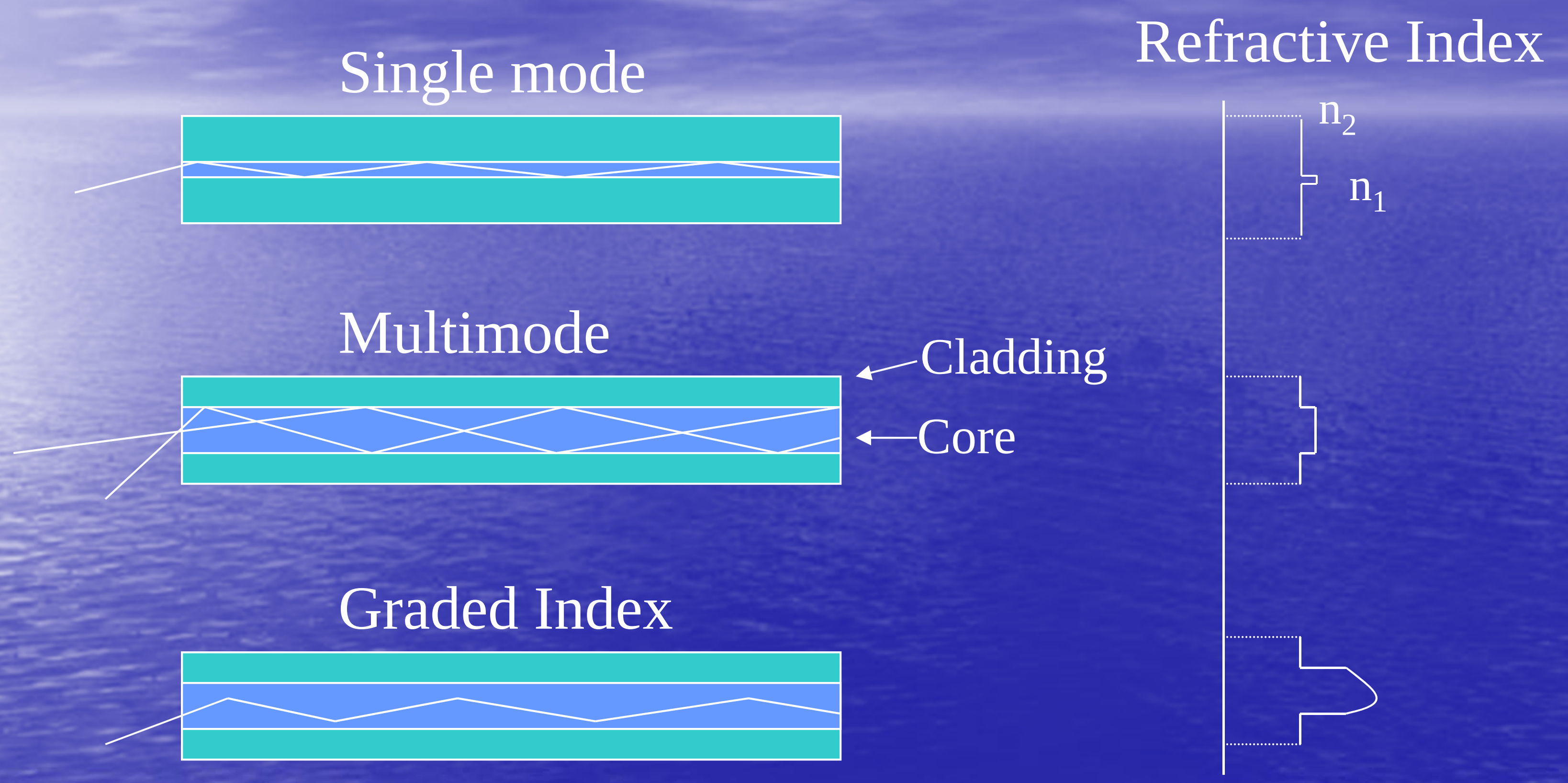
Program Manager: Robie Lewis

Project Goal

- To develop high temperature gas sensors for use in advanced power generation systems.

- Two technologies being developed
  - 3-D nanoporous silica optical fibers
  - Sapphire photonic crystal fibers

Refractive Index Profiles of Some Optical Fiber



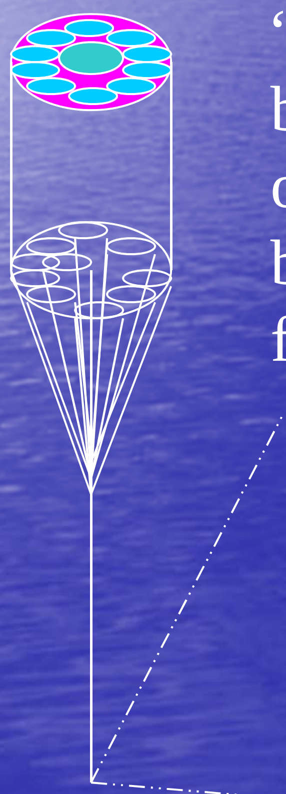
Index difference produced by dopants in either the core or cladding region

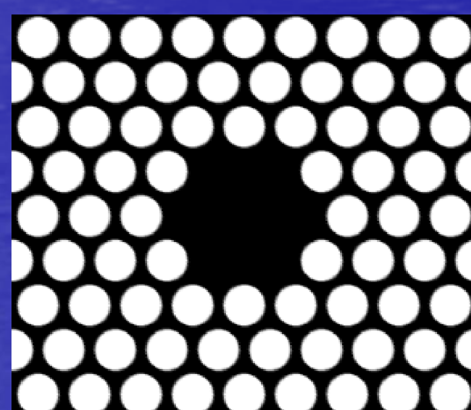
Key Point: all these fibers are solid glass core and solid glass cladding

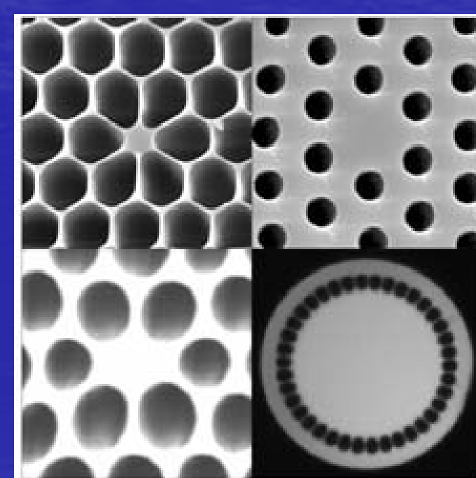
Review of Ordered Holey Fiber Structures

Holey fibers are optical fibers which have been fabricated such that the drawn fiber contains a series of air holes. The presence of the air holes confines the light within the fiber.

"Tube Stack and Draw" method has been used to produce a variety of ordered hole fibers including photonic band gap fibers and average index fibers.

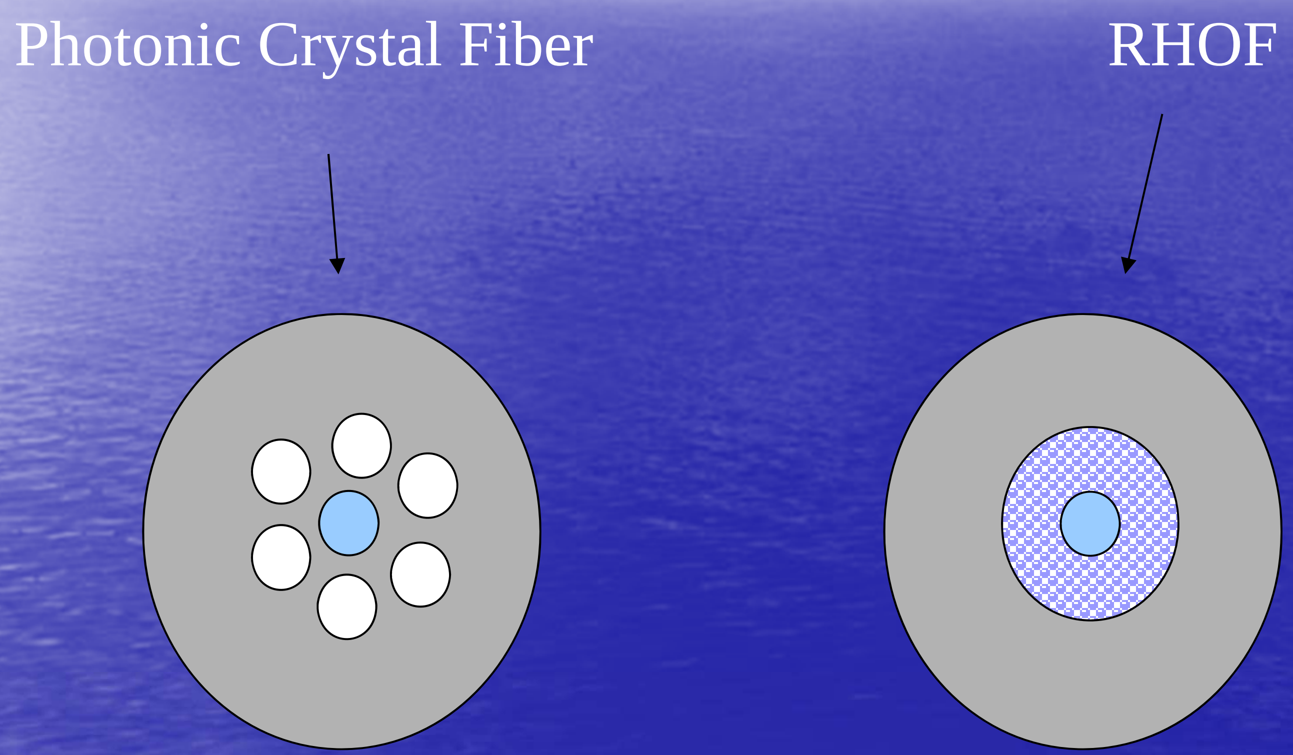




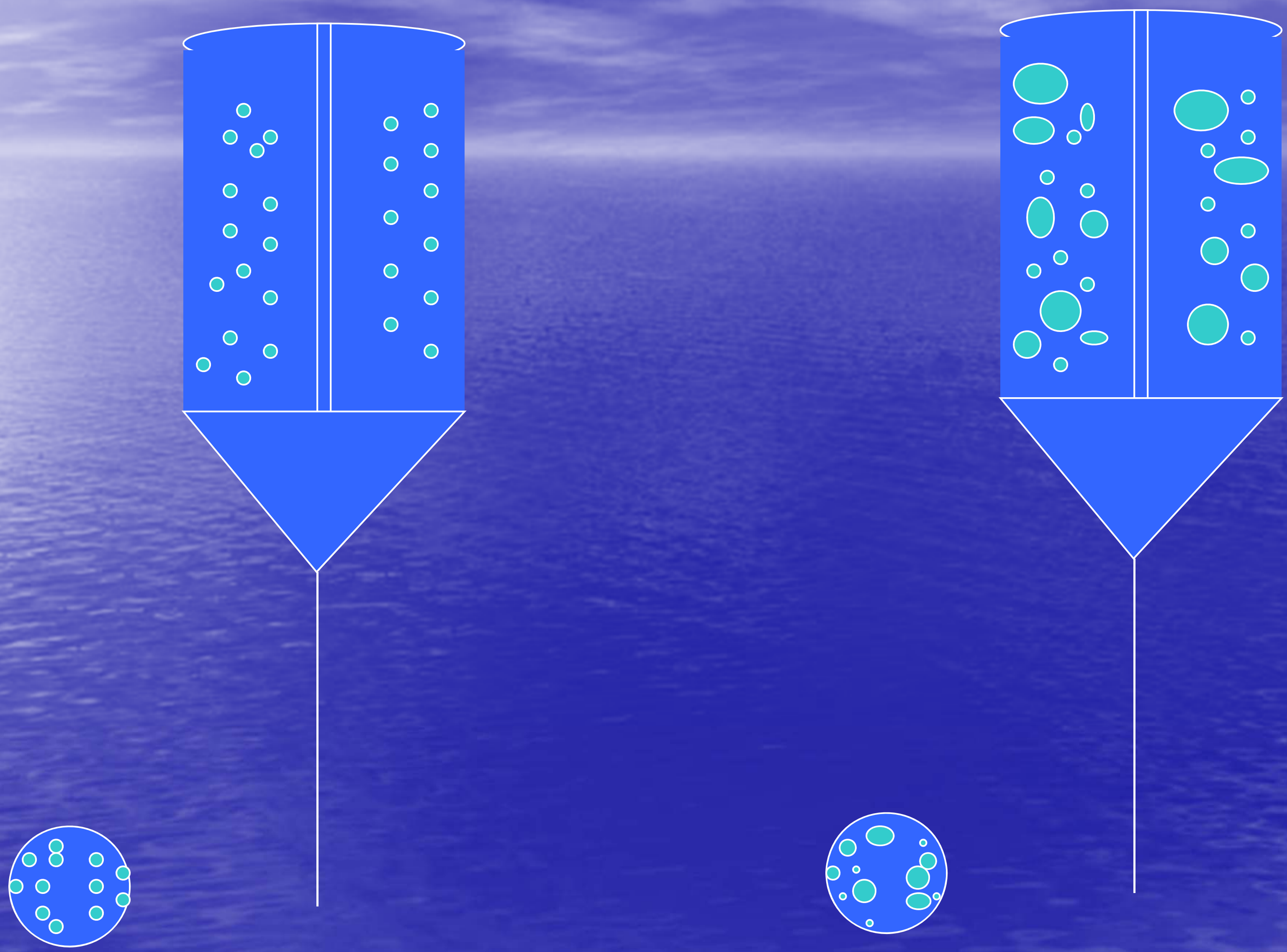


D. Kominsky, PhD Dissertation, Virginia Tech, 2005

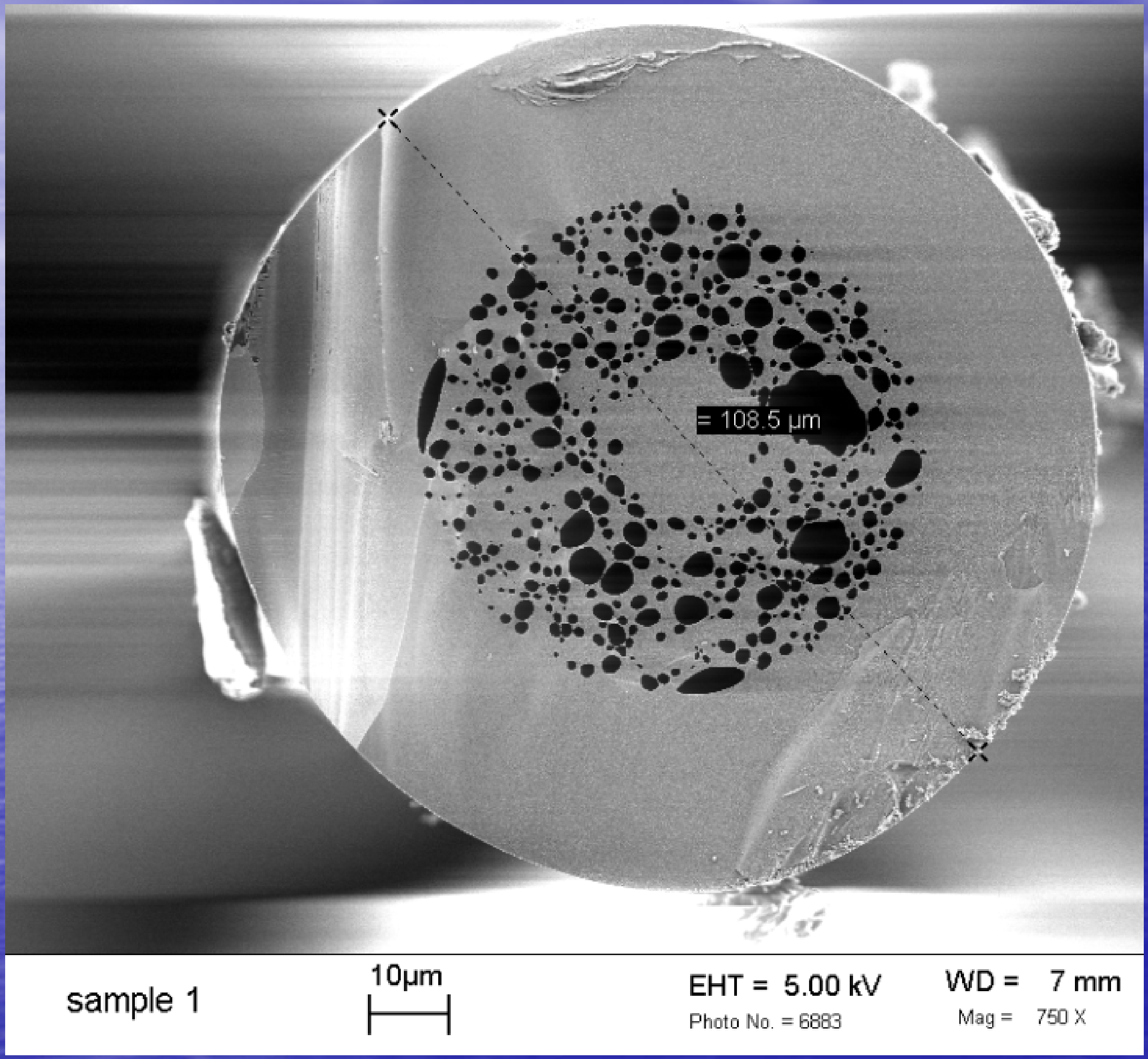
Previous concept for a new type of Holey Fiber



Random Hole Fiber Approach

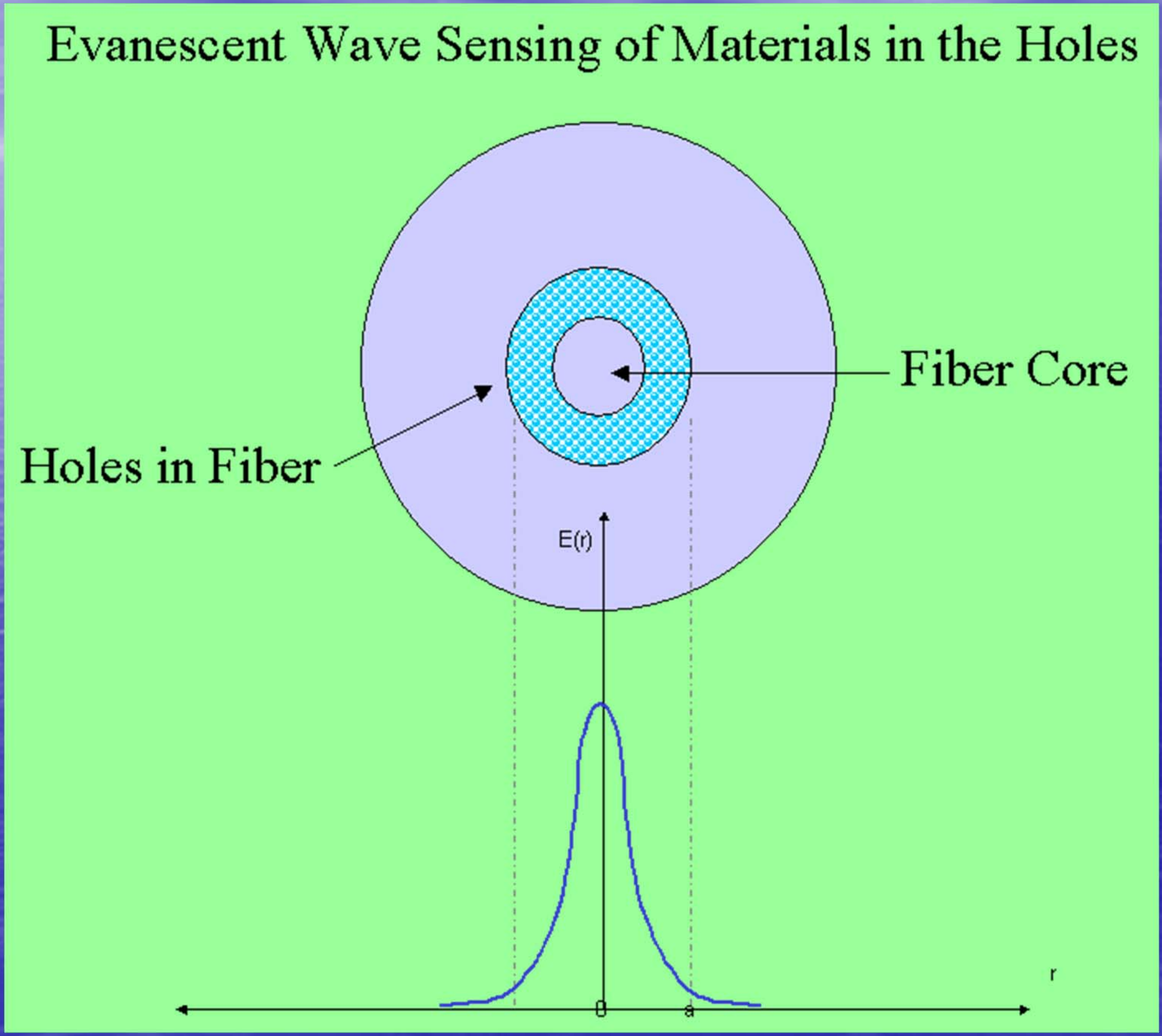


SEM Micrograph of Optical Fiber from GPP Process

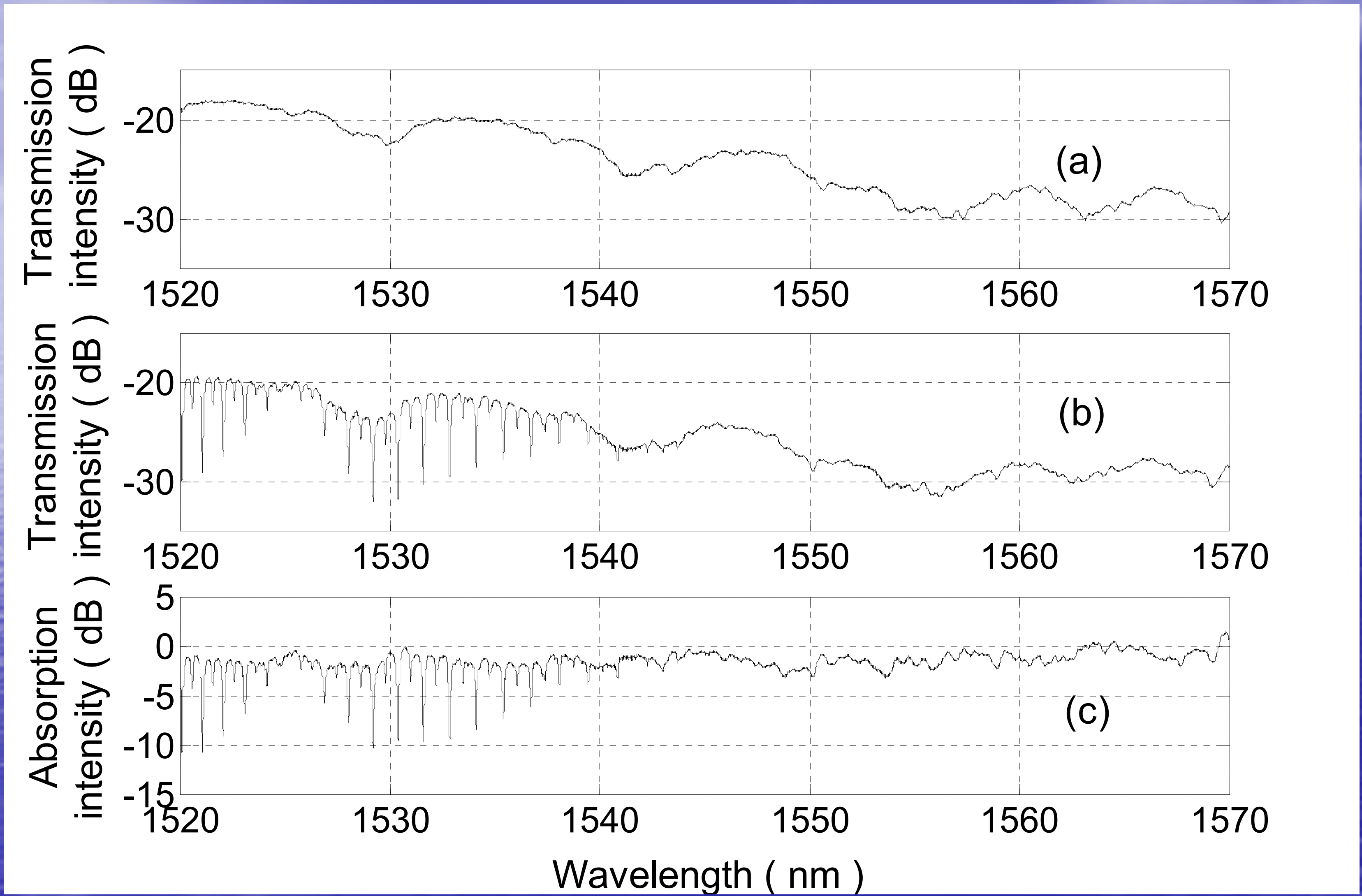


"*Microstructural Analysis of Random Hole Optical Fibers*" Gary Pickrell, Dan Kominsky, Roger Stolen, Fred Ellis, Jeong Kim, Ahmad Saffaai-Jazi, and Anbo Wang, *Photonics Technology Letters,* Vol. 16, No. 2, pg 491-93, 2004

Chemical Sensing

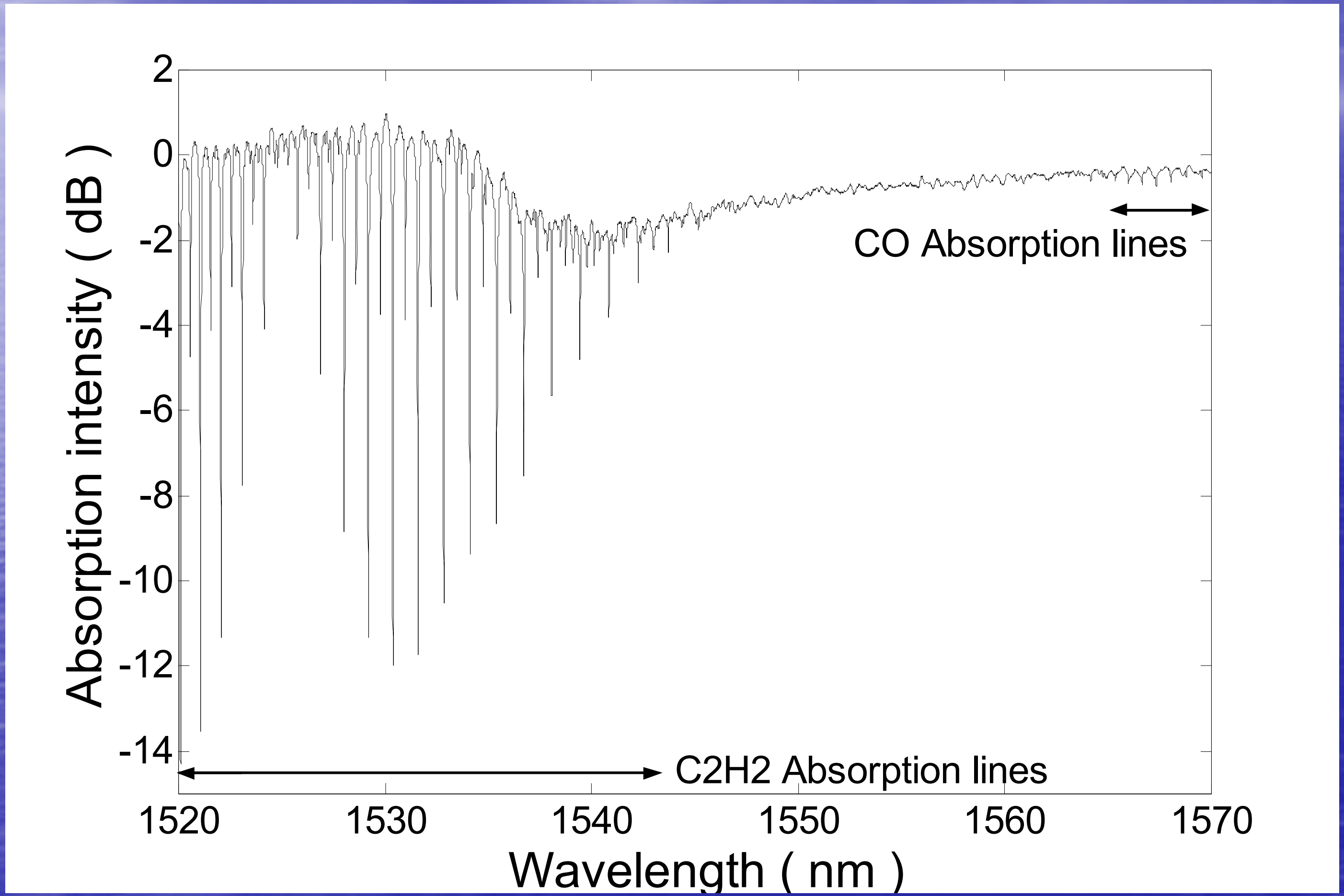


RHOF Evanescent Wave Gas Sensing - Acetylene



"Random-hole fiber evanescent wave gas sensing", G. Pickrell, W. Peng and A. Wang, *Optics Letters*, Vol. 29, No. 13, pp 1476-78, July, 2004

RHOF multiple gas species sensing



Simultaneous C_2H_2 and CO absorption spectrum

W. Peng, G. Pickrell, A, Wang Photonics Technology Letters, 2004

Improved Response Time for Chemical Sensing

Project Initiated to develop a “holey” optical fiber capable of high temperature gas detection with improved response time.

Concept was to make the holes in the fiber run perpendicular to the optical axis (instead of parallel to it as in previously demonstrated fibers) to increase the gas sensing response time of the fibers.

Stochastic Holey Fiber Development

Two types of porous fibers were designed and fabricated:

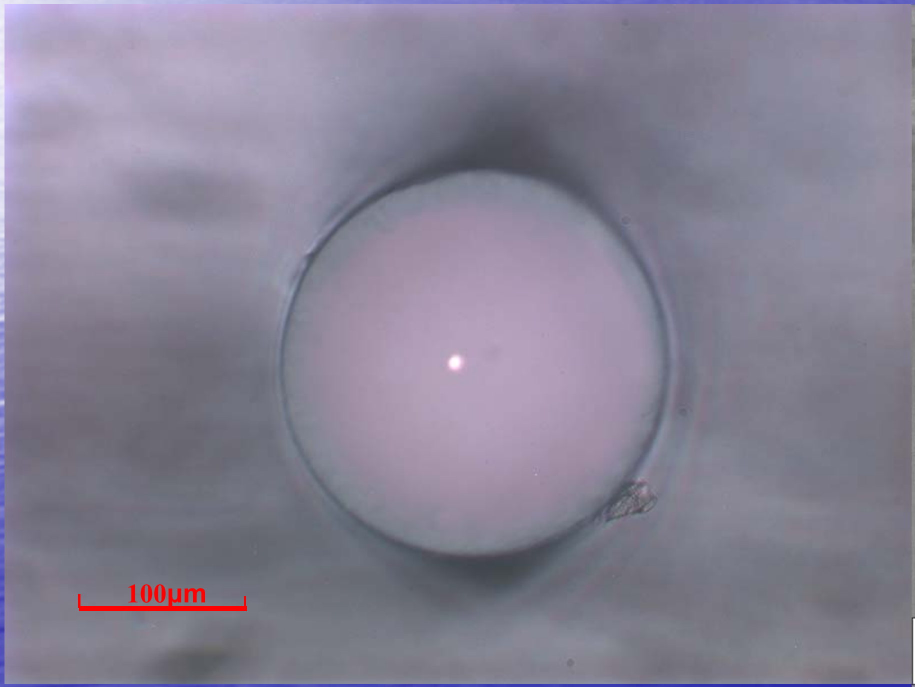
1. Stochastic porosity cladding/solid core

2. Stochastic porosity ordered hole fiber:

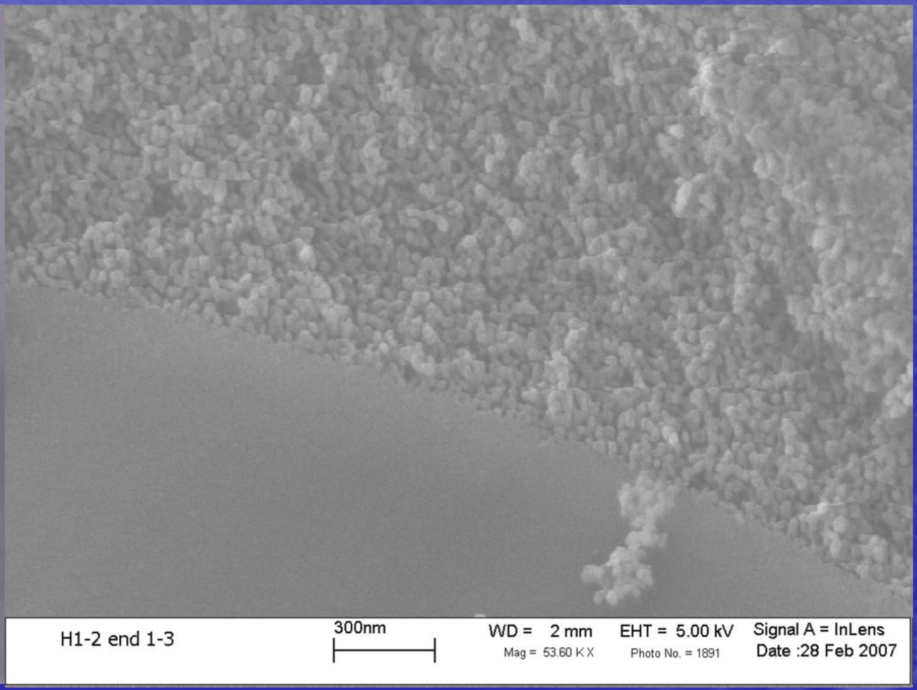
The porous structure is made of nano-scale pores throughout the fiber, pores are randomly oriented and three dimensionally interconnected.

Fiber Characterization

- Optical and SEM micrograph of the stochastic porosity solid core fiber



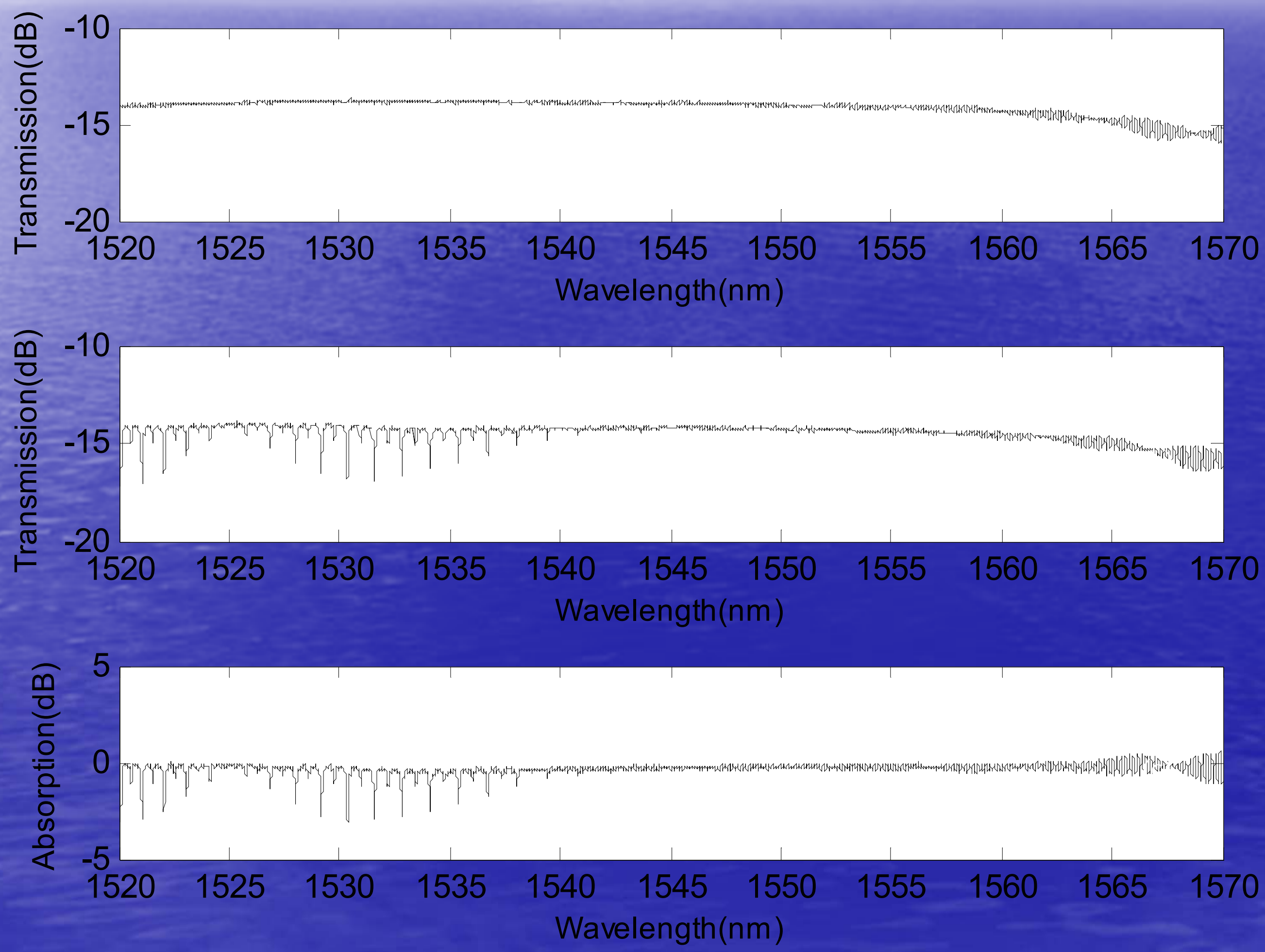
Optical micrograph of the porous clad fiber



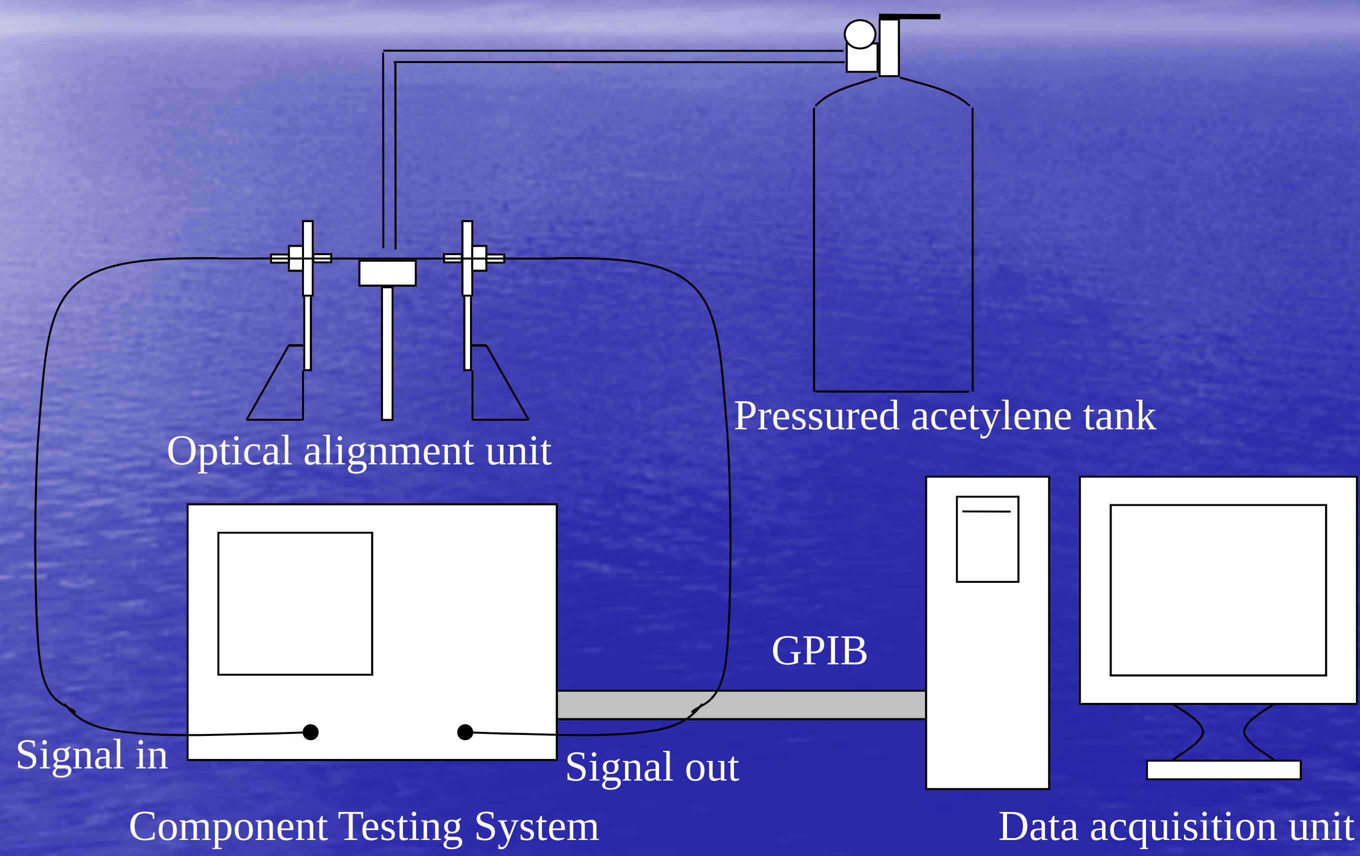
SEM micrograph of typical core-cladding interface of porous clad fiber

Gas Sensing

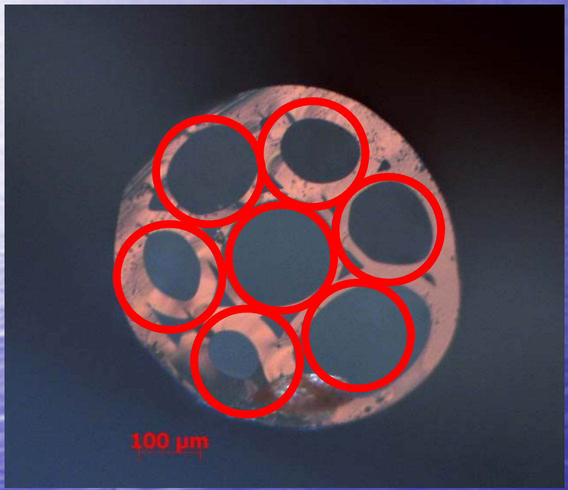
Stochastic porosity cladding solid core fiber



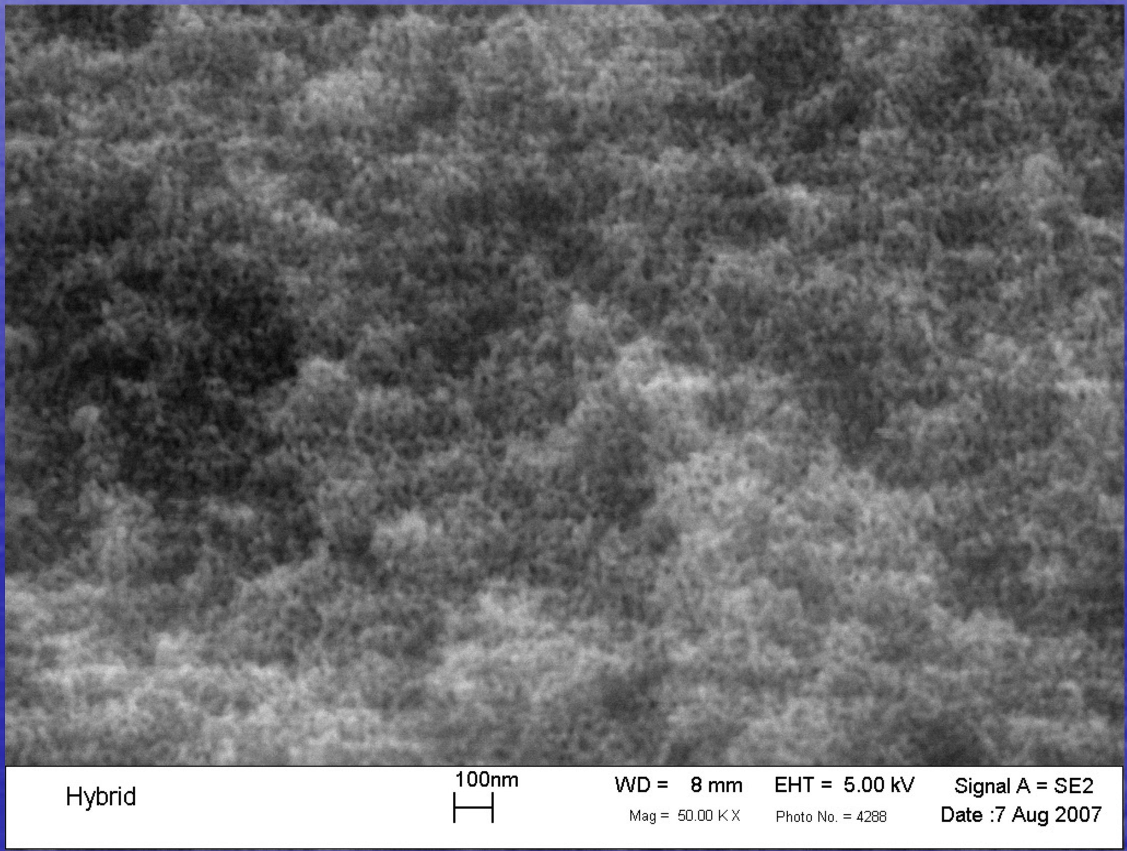
Schematic of Open Air Gas Sensor Testing System



Optical and SEM micrograph of the stochastic porosity ordered hole fiber

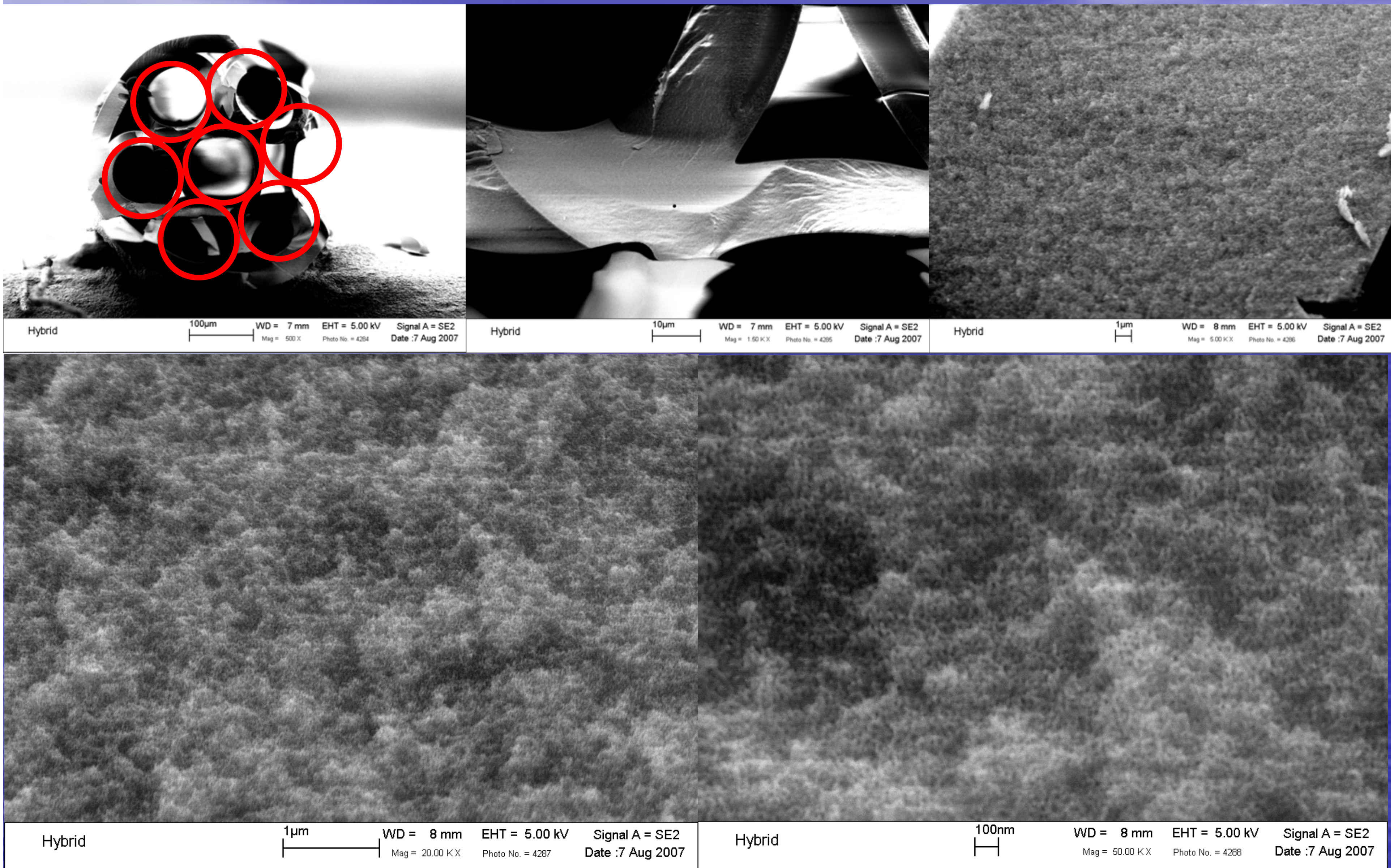


Optical micrograph of the ordered hole fiber



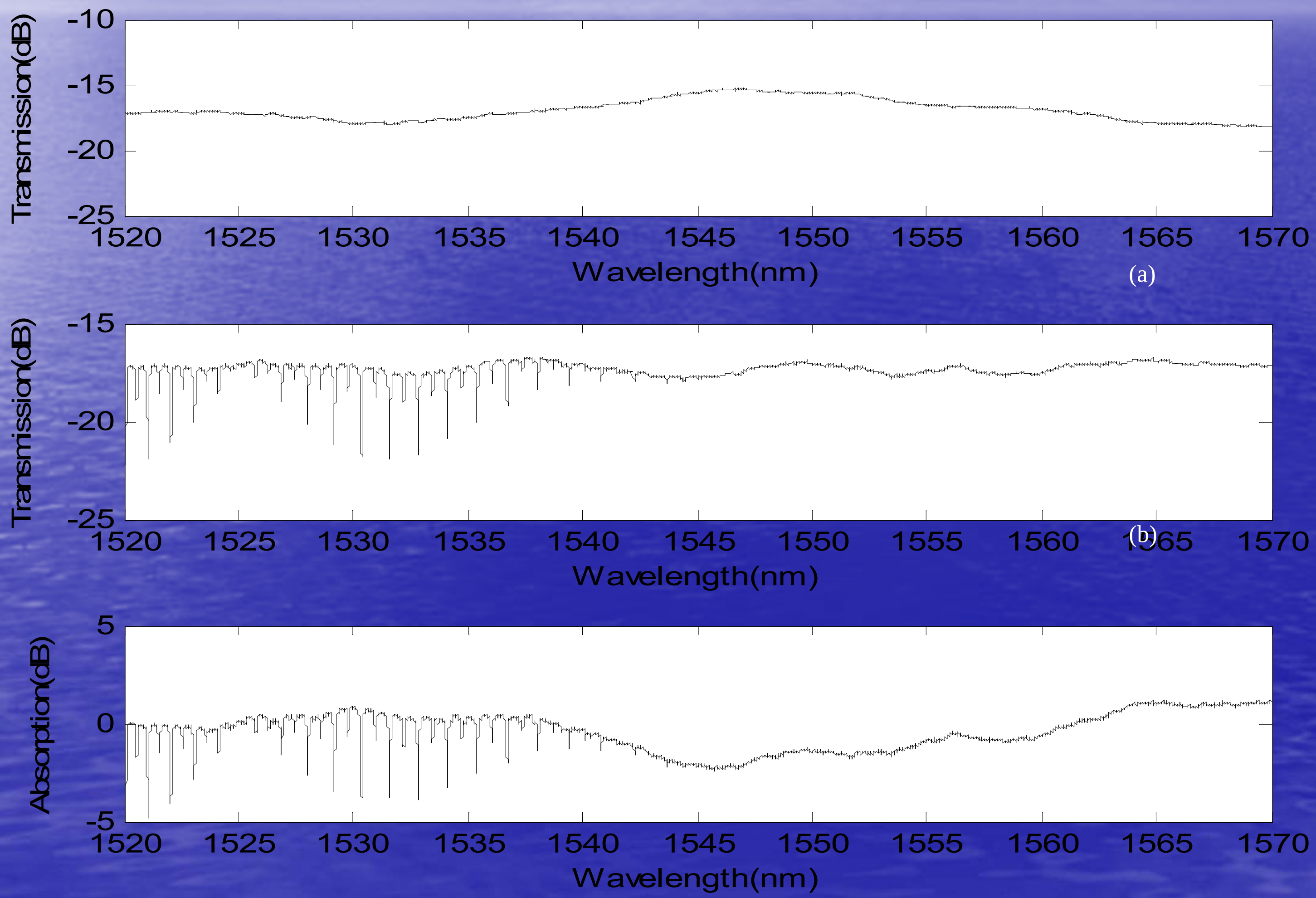
Porosity in ring structure of the stochastic porosity ordered hole fiber

SEM Analysis of Stochastic Porosity Ordered Hole Fiber

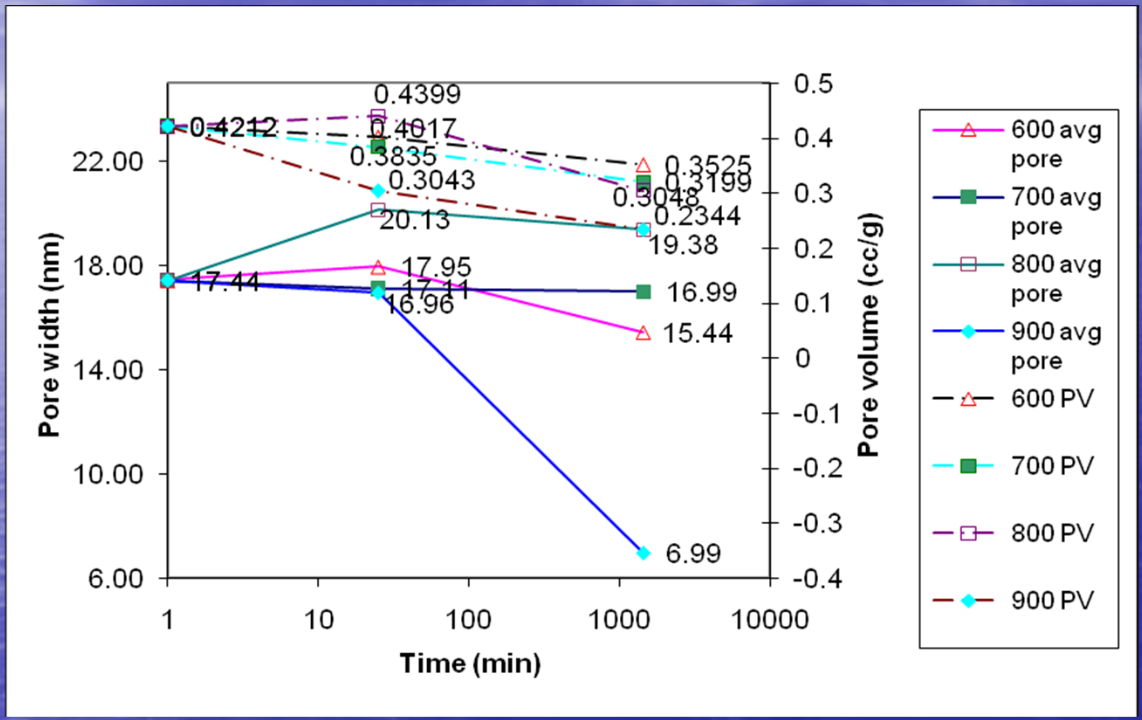


Results

Ordered hole fiber sensor data

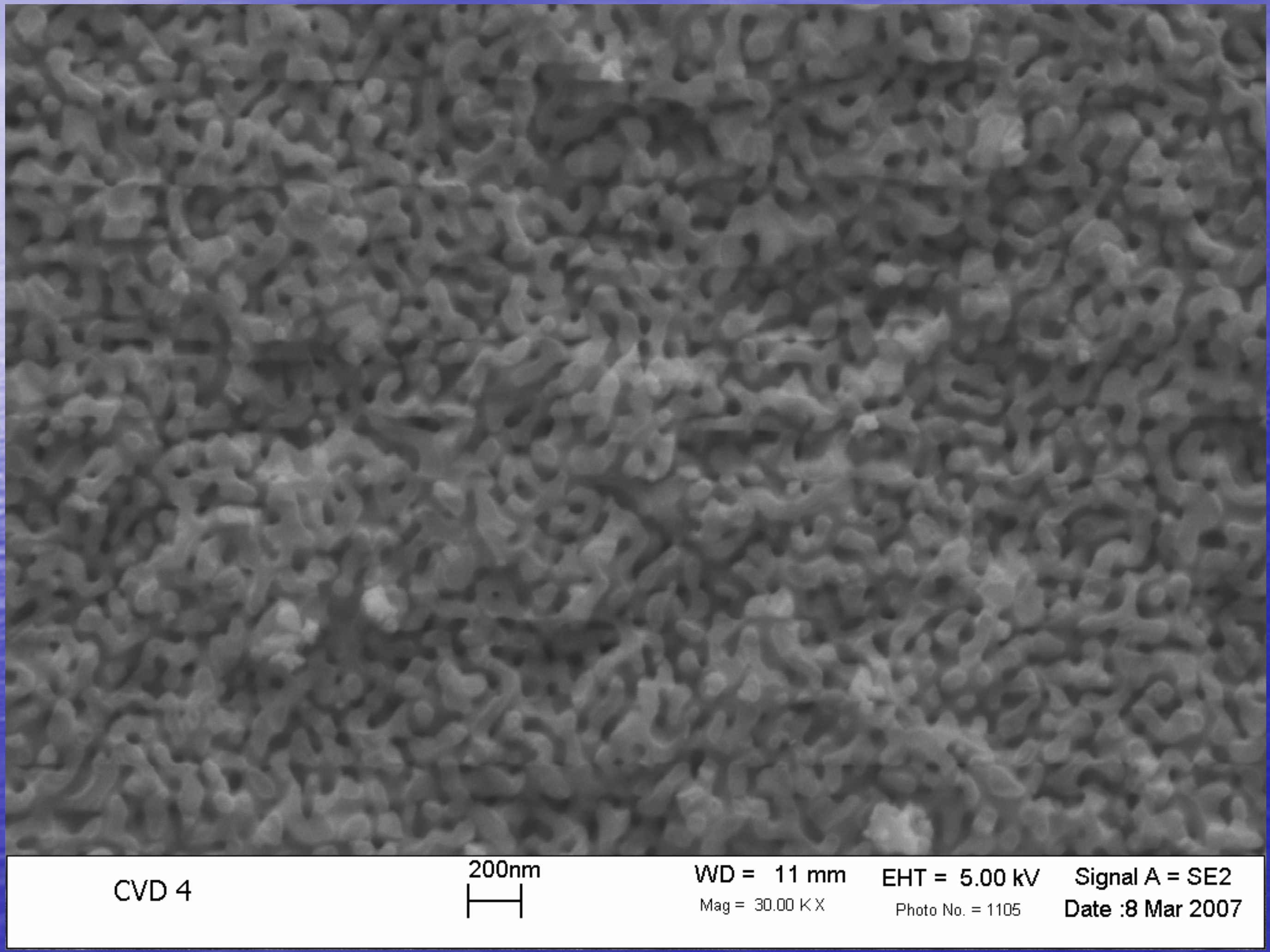


Pore Morphology Changes as a Function of Temperature



Determination of the gas sensing capability at high temperatures is ongoing.

Increased Pore Size through Special Processing Conditions



3-D Solid Phase

With

3-D Porous Phase

Response Time Improvement

The response time of the fiber on the order of a second. This is an improvement of approximately 1000-10,000 times when compared to random hole or ordered hole fibers published data.

Current Project

- Project Authorization Number issued January, 2012
- Two main thrust areas
  - 3-D Nanoporous Silica Fiber
  - Sapphire Photonic Crystal Fiber

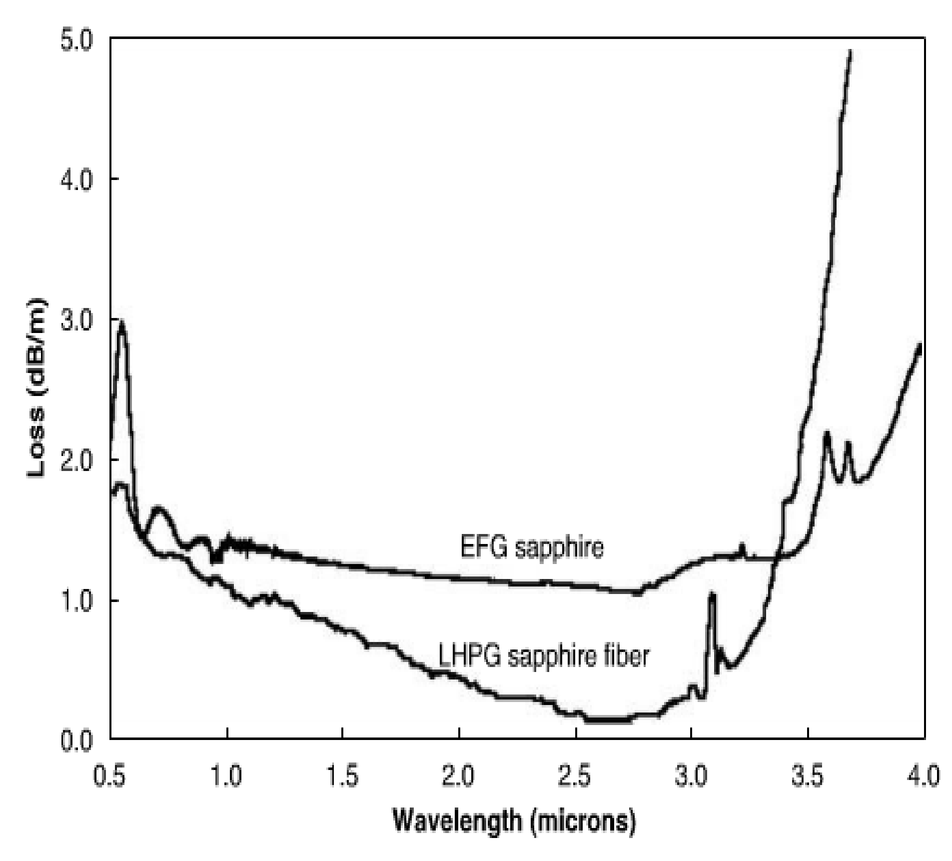
Subtask	Work Schedule Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
4.1 Sapphire Photonic Crystal Fiber Fabrication												
M1: Fabrication of SPCF				**Δ**								
4.2 Modeling of the Sapphire Photonic Crystal Fiber Optical Properties												
4.3 Fabrication of the Optimized Sapphire Photonic Crystal Fiber Structures												
4.4 Development of Long Wavelength Fiber Interrogation Instrumentation												
M3: Long Wavelength Instrumentation Development										**Δ**		
4.5 Optical Property Testing and Characterization of the Sapphire Photonic Crystal Fibers												
4.6 Testing of the Sapphire Photonic Crystal Fiber Gas Sensing Capabilities												
M5: SPFC gas sensing test												**Δ**
5.5. Development of suitable joining technologies between the sensor and the standard lead-in/lead-out fibers												
M2: Development of porous glass fiber joining technologies						**Δ**						
5.6 Sensor system sensitivity improvement												
5.7 Signal processing improvement												
5.8 Investigation of pore size and fiber geometry on the observed optical properties												
M4: Characterization of Pore structure/optical property relationship									**Δ**			
5.9.1 Development of optical fiber sensor packaging methods												
5.9.2 Prototype fabrication for laboratory testing												
M6: Prototype porous glass fiber sensor fabrication												**Δ**
Final Report Preparation												
Technical Progress Report	Q	Q	Q	A	Q	Q	Q	A	Q	Q	Q	F

Sapphire Photonic Crystal Fiber Development

- Currently working on development of sapphire photonic crystal fibers
  - Fabrication
  - Modeling
  - Testing

Background

- Single Crystal Sapphire (α-Al_2O_3)
  - Continuous crystal lattice
    - Hexagonal structure
    - No grain boundaries
    - Grown on c-axis
  - Refractive index
    - 1.744 at 1.693μm with a operation range from 1.75 – 3.2μm
  - Broad transmission window (0.19μm to 5.2μm)
    - Loss minimum of 0.13dB/m at 2.94μm
  - Resists corrosion in harsh, high-temperature environments
  - Can transmit at infrared wavelengths

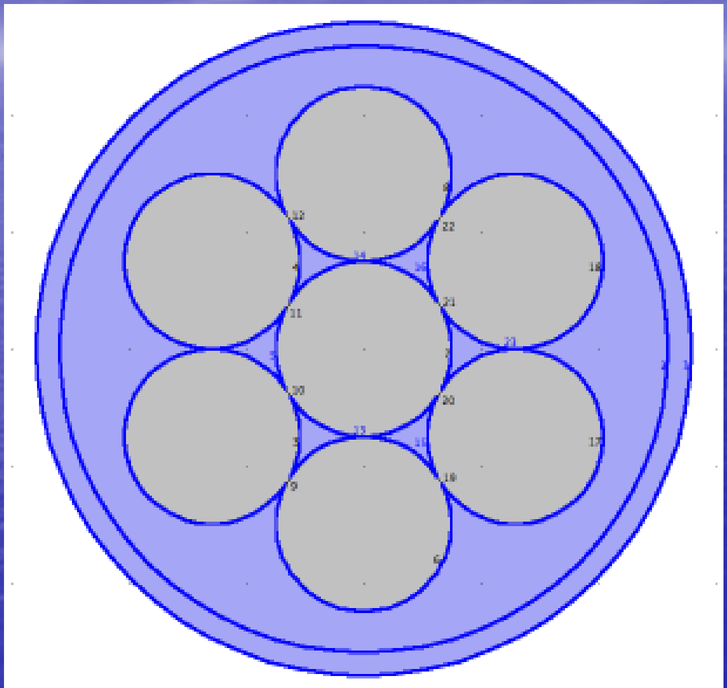


Loss transmission of EFG vs. LHPG growth methods for single crystal sapphire from J. J. Fitzgibbon, H. E. Bates, A. P. Pryshlak, and J. R. Dugan, "Sapphire optical fibers for the delivery of Erbium:YAG laser energy," in *Biomedical Optoelectronic Instrumentation*, A. Katzir, J. A. Harrington, and D. M. Harris, eds., SPIE 2396, 60–70 (1995).

Currently no commercially available high temperature cladding for sapphire

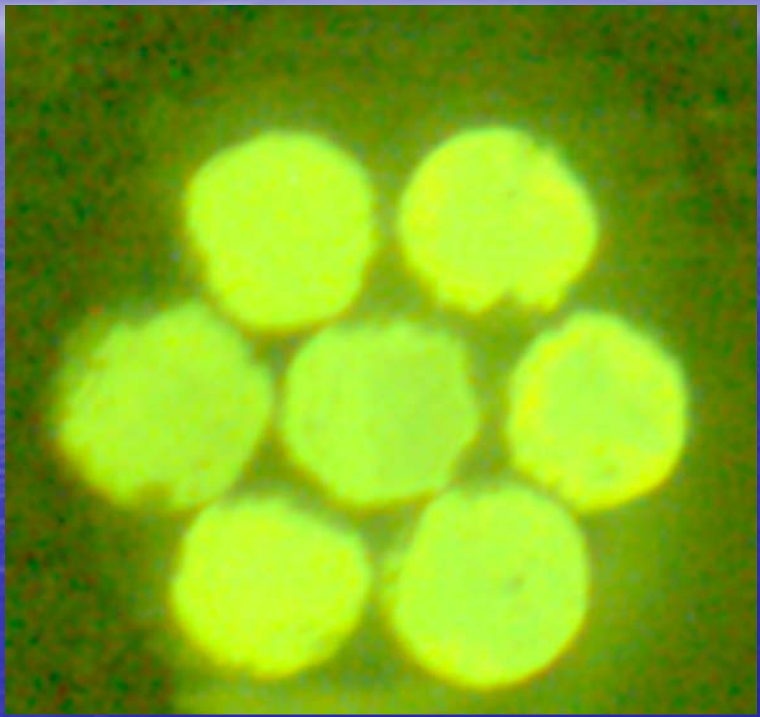
- Fiber Protection
  - Harsh environments
  - Mechanical stability
- Limit attenuation
  - Surface contamination
- Decrease effective refractive index difference
  - Reduction of modes in MMF
- Cladding for single mode operation
  - Sapphire high refractive index (1.744 at 1.693μm)

Sapphire photonic crystal – wanted to make this structure



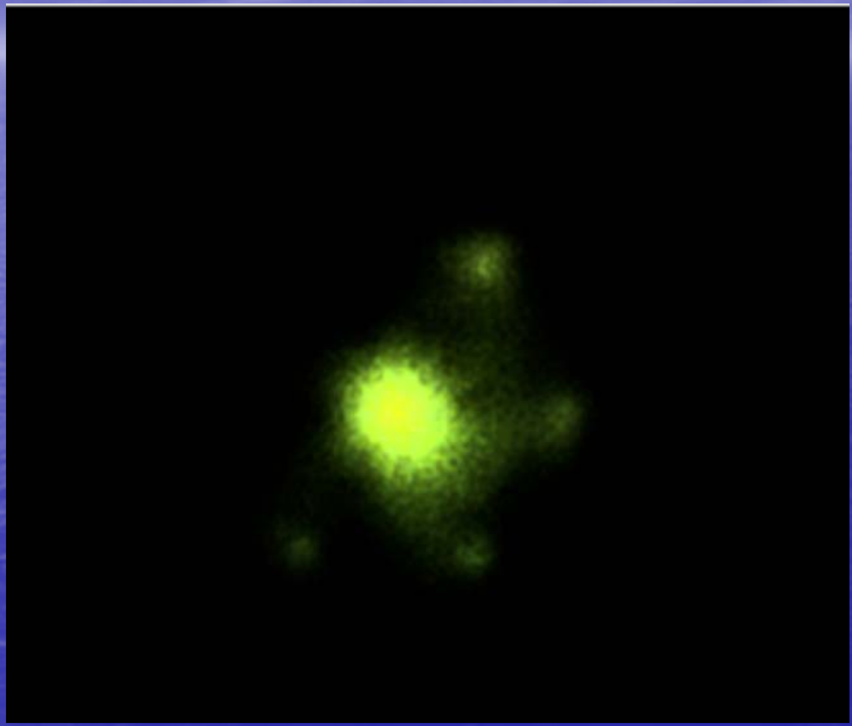
- 7-rod structure surrounding a single rod of single crystal sapphire. The air (blue) region is set to n = 1.0 and sapphire (grey) (α-Al_2O_3) is set to n = 1.74618
- First sapphire photonic crystal fiber produced
  - 70µm diameter single crystal sapphire rods that were 15cm in length (z-direction)

Sapphire Photonic Crystal Fiber – after firing at 1600°C



First Sapphire Photonic Crystal Fiber Produced

Sapphire photonic crystal



Micrograph of transmitted light in the sapphire photonic crystal fiber structure under white light illumination from the backside of the fiber.

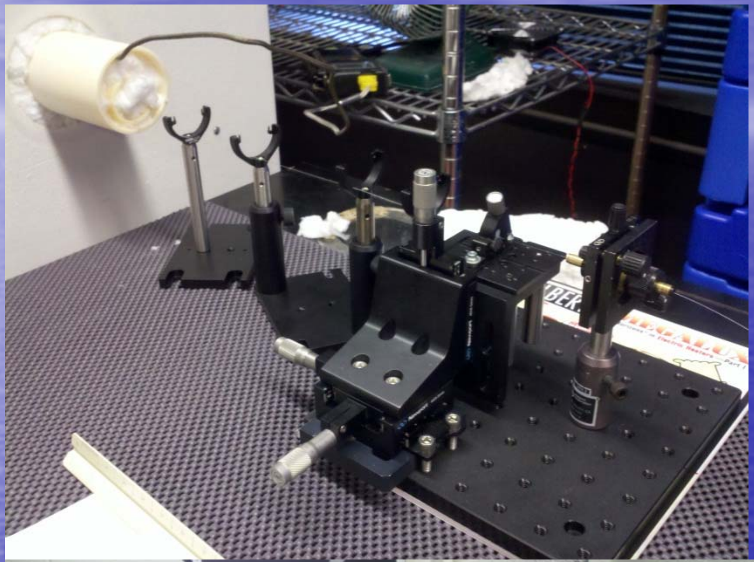
Sapphire photonic crystal development

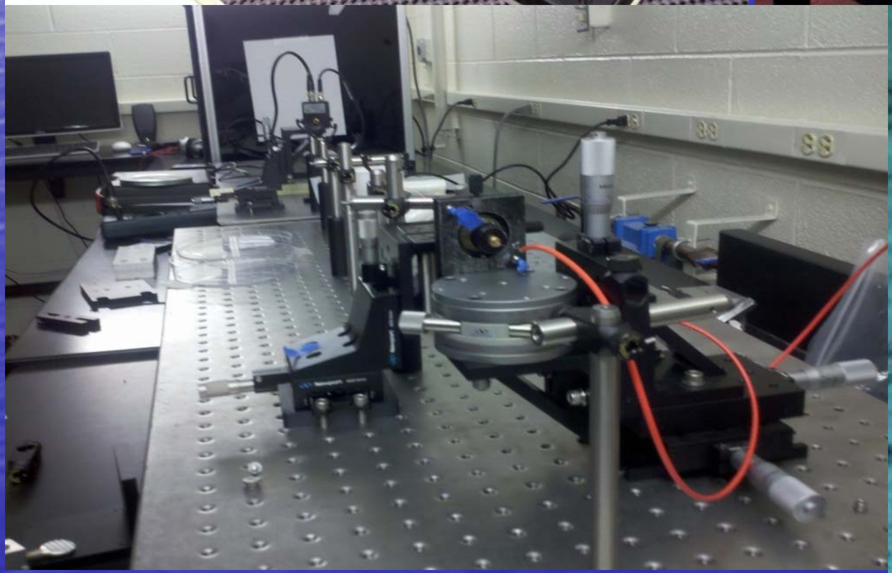
Sapphire Photonic Crystal Fiber tied by platinum wire.

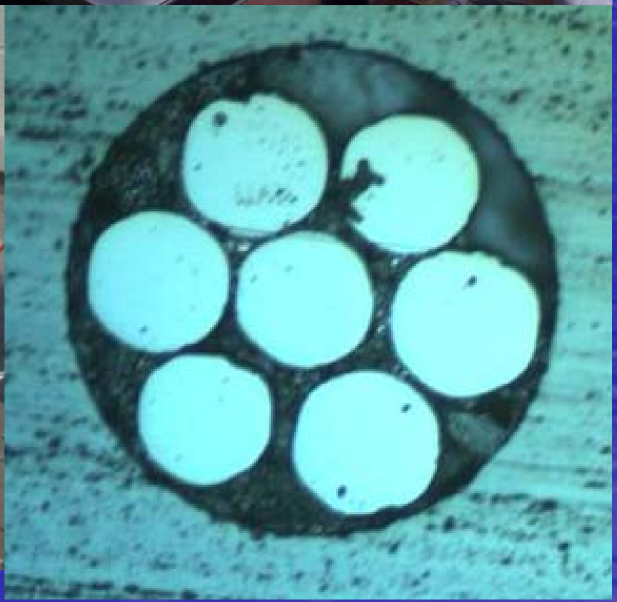
Sapphire Photonic Crystal Fiber Fabrication

- One of the newer sapphire photonic crystal fibers being polished

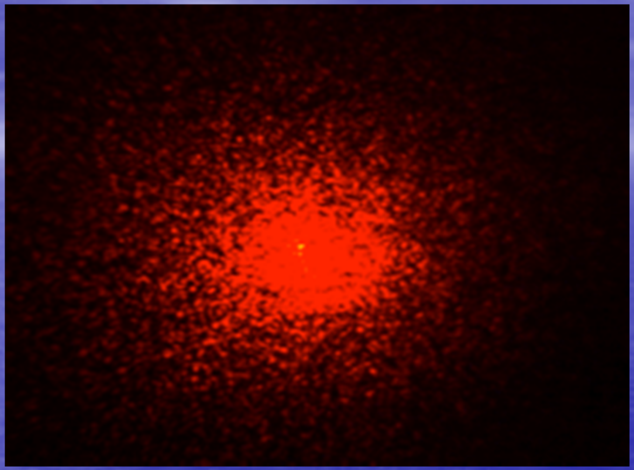
Sapphire Photonic Crystal Fiber Testing



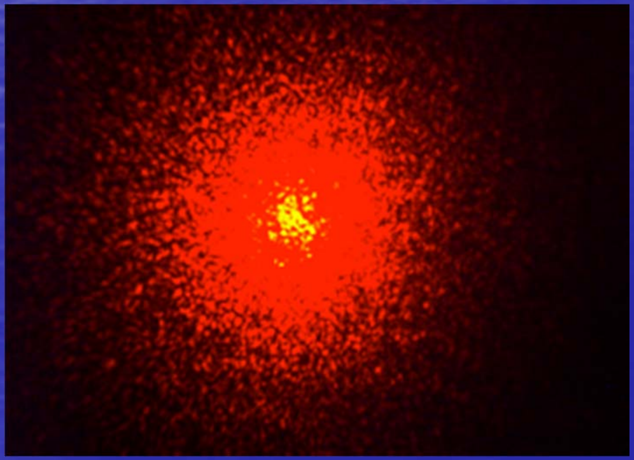




Far Field Pattern Measurements



Far-field pattern for a single rod of single crystal sapphire.



Far-field pattern for the sapphire photonic crystal fiber.

COMSOL Modeling

- Modeling of the modes in these fibers has begun with COMSOL Multiphysics 4.0a modeling software
- Modeling steps include:
  - Select materials
  - Physical Settings in RF Module
  - Meshing
  - Solving
  - Post-processing

COMSOL Modeling

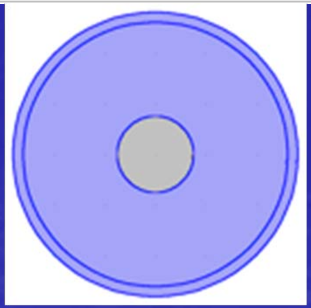
- Air (blue region)
  n=1.0

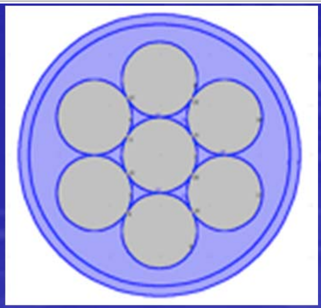
	Property	Name	Value	Unit	Property group
✓	Electric conductivity	sigma	0	S/m	Basic
✓	Relative permittivity	epsilonr	1.000	1	Basic
✓	Relative permeability	mur	1.000	1	Basic
	nu0	nu0	nu0(T)		Basic
	Density	rho	rho(pA,T)	kg/m^3	Basic
	Heat capacity at constant pressure	Cp	Cp(T)	J/(kg*K)	Basic
	Speed of sound	c	cs(T)	m/s	Basic
	Ratio of specific heats	gamma	1.4	1	Basic
	Thermal conductivity	k	k(T)	W/(m*K)	Basic
	Dynamic viscosity	mu	eta(T)	Pa*s	Basic
	Refractive index	n	1.0	1	Refractive index
	Refractive index, imaginary part	ki	0		Refractive index

- Sapphire (α-Al_2O_3 in grey region)
  n=1.74618

	Property	Name	Value	Unit	Property group
	Density	rho	3965	kg/m^3	Basic
	Coefficient of thermal expansion	alpha	6.5e-6	1/K	Basic
	Heat capacity at constant pressure	Cp	730	J/(kg*K)	Basic
	Relative permittivity	epsilonr	5.7	1	Basic
	Electric conductivity	sigma	0	S/m	Basic
	Thermal conductivity	k	35	W/(m*K)	Basic
	Young's modulus	E	400e9	Pa	Young's modulus and Poisson's ratio
	Poisson's ratio	nu	0.22	1	Young's modulus and Poisson's ratio
	Refractive index	n	1.74618	1	Refractive index
	Refractive index, imaginary part	ki	0		Refractive index

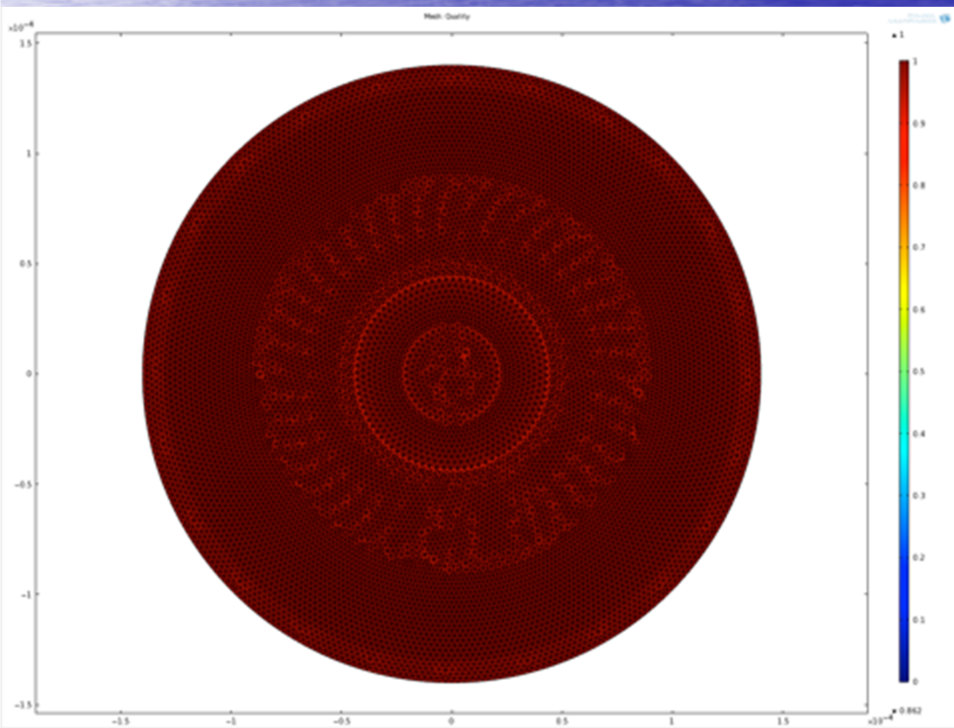
- All listed values with a free space wavelength = 1.55μm

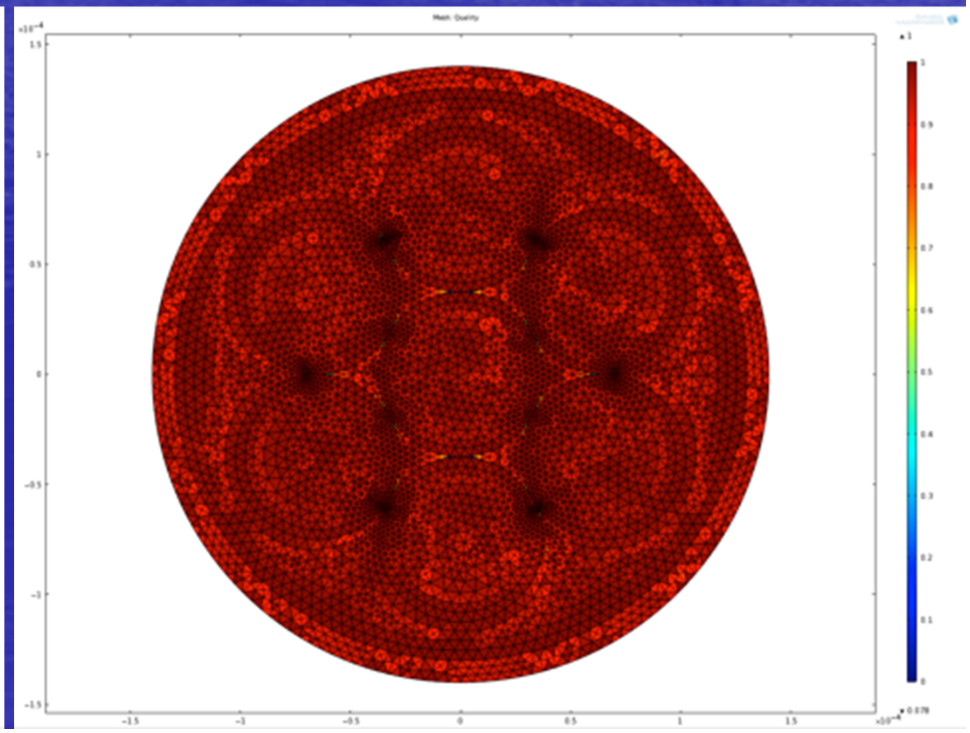




Preliminary Work
Comsol modeling

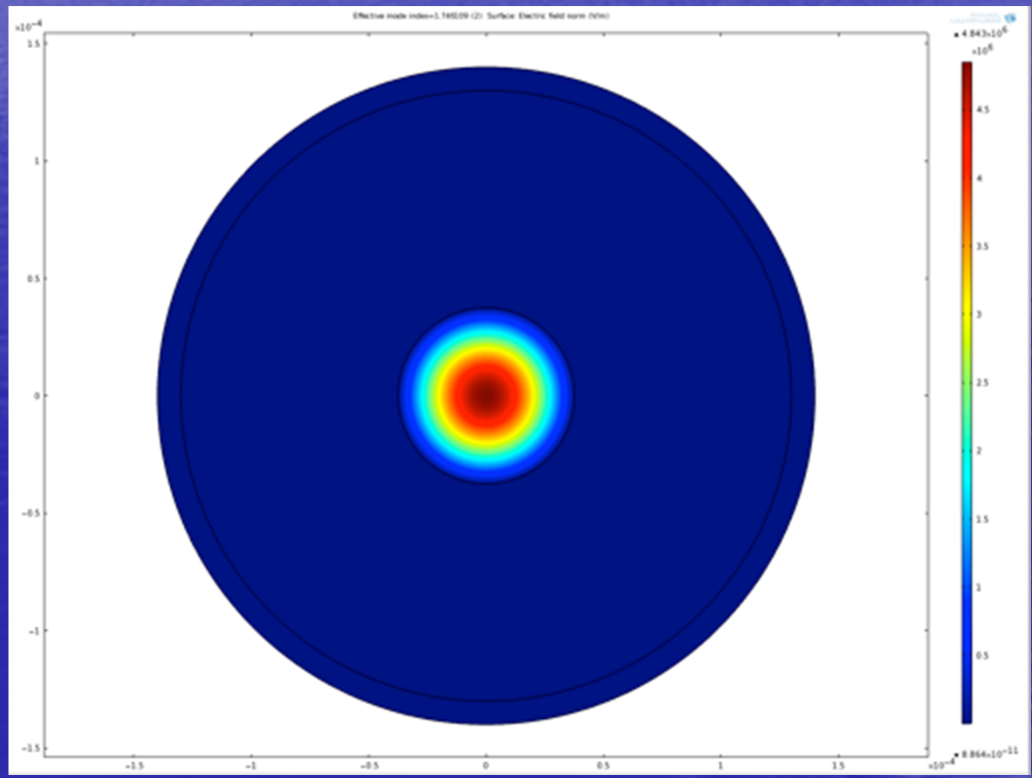
- Precision related to refinement of the mesh
- Limitation of the mesh is the memory of the computer that will be solving the boundary equations





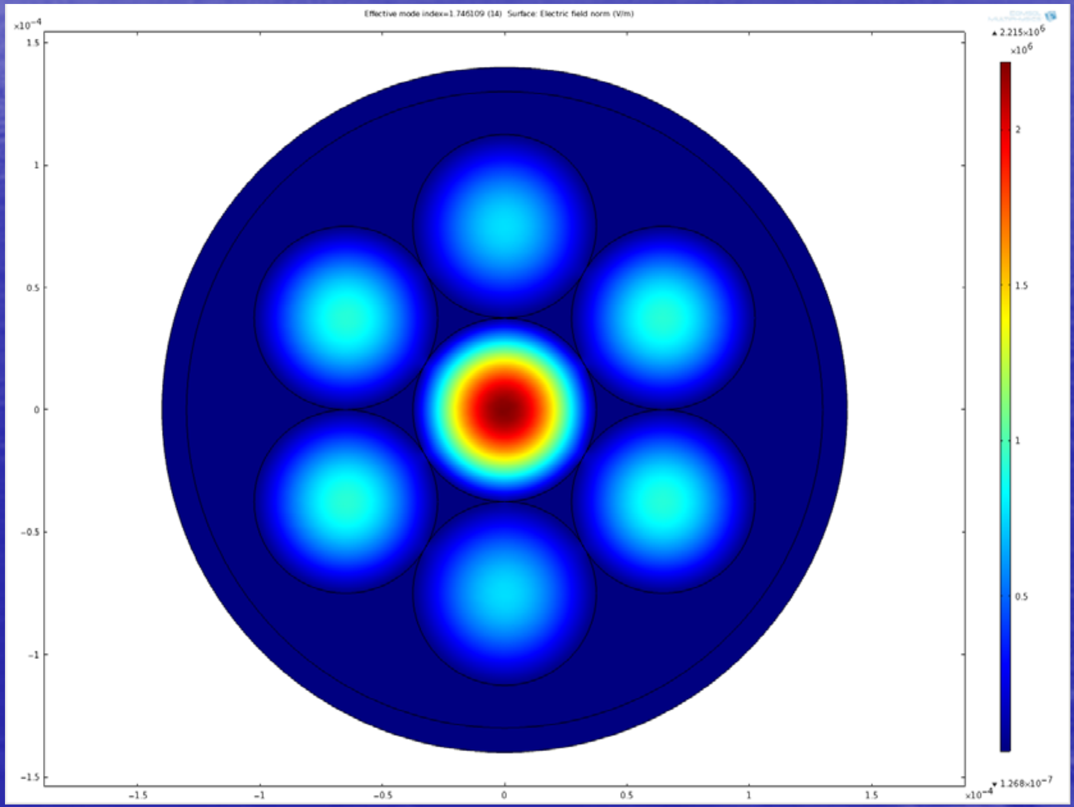
Preliminary Work Comsol modeling

- Single rod Sapphire Photonic Crystal Fiber
- Highly multimode
- The resultant lowest order fundamental hybrid linearly polarized mode (LP_{01}) is shown at right at 1550nm with an effective mode index = 1.746109
- Confinement Loss L_c= 2.0166e-8 dB/km



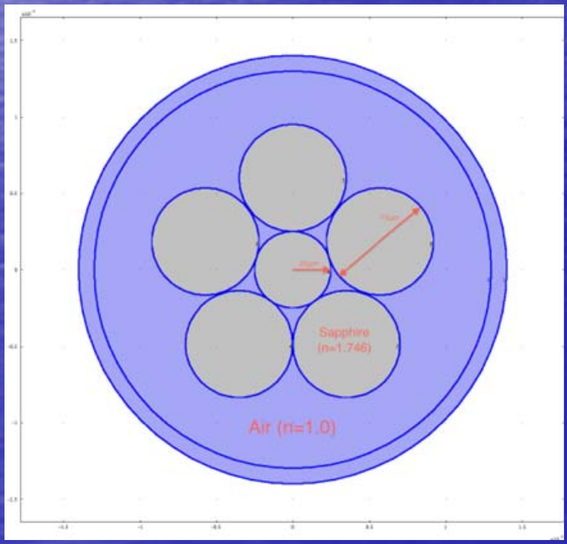
Preliminary Work
Comsol modeling

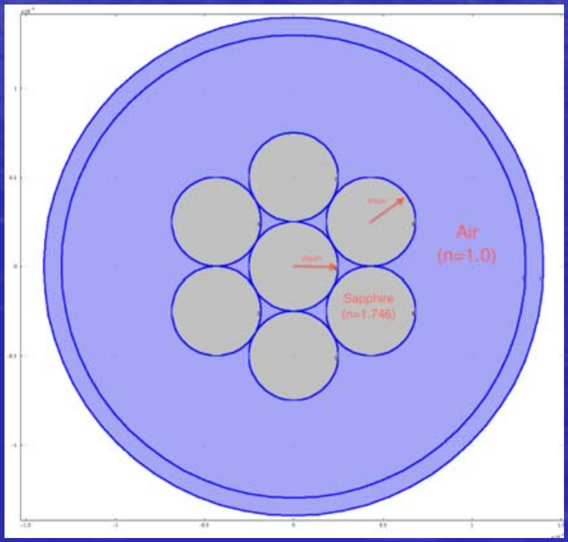
- Six ring Sapphire Photonic Crystal Fiber
- Highly multimode
- The resultant lowest order fundamental hybrid linearly polarized mode (LP_{01}) is shown at right at 1550nm with an effective mode index = 1.746109
- Confinement Loss L_c= 1.3933e-6 dB/km



COMSOL Modeling

- Investigating additional methods for increased modal reduction
  - 1. 50µm core surrounded by 5 70µm rods of single crystal sapphire fiber (left).
  - 2. 50µm core rod of single crystal sapphire surrounded by 6 50µm diameter single crystal fibers bundled in a hexagonal arrangement (right).

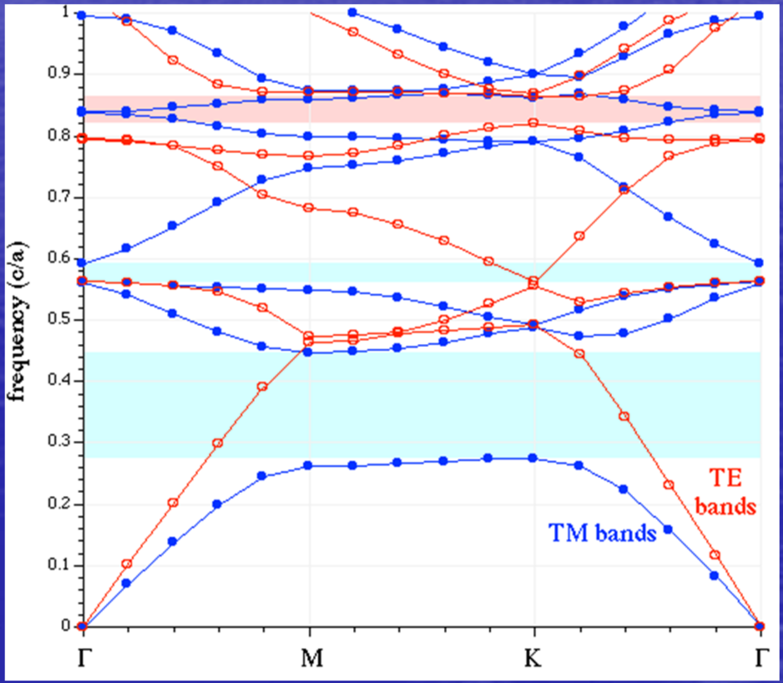




MPB Modeling

MIT Photonic Bands Program

- Compute the eigenvalues of Maxwell's equations for plane waves in the frequency domain
- Predict the feasibility of creating a photonic band gap within the holey single crystal sapphire fiber



http://ab-initio.mit.edu/wiki/images/5/51/Tri-rods-bands.gif

Thanks for Listening