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

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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

- **Single mode**
- **Multimode**
- **Graded Index**

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
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.
Previous concept for a new type of Holey Fiber

Photonic Crystal Fiber

RHOF
Random Hole Fiber Approach
Chemical Sensing

Evanescent Wave Sensing of Materials in the Holes

Holes in Fiber

Fiber Core

E(τ)
Simultaneous $C_2H_2$ and CO absorption spectrum

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

(a) Transmission(dB)

(b) Transmission(dB)

(c) Absorption(dB)
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

(a) Transmission (dB)

(b) Transmission (dB)

(c) Absorption (dB)
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

CVD 4

WD = 11 mm
Mag = 30.00 kX

EHT = 5.00 kV
Photo No. = 1105

Signal A = SE2
Date: 8 Mar 2007
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
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<td><strong>M1: Fabrication of SPCF</strong></td>
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<td>4.2 Modeling of the Sapphire Photonic Crystal Fiber Optical Properties</td>
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<td>4.4 Development of Long Wavelength Fiber Interrogation Instrumentation</td>
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<td><strong>M3: Long Wavelength Instrumentation Development</strong></td>
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<td>4.5 Optical Property Testing and Characterization of the Sapphire Photonic Crystal Fibers</td>
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<td>5.8 Investigation of pore size and fiber geometry on the observed optical properties</td>
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<td><strong>M4: Characterization of Pore structure/optical property relationship</strong></td>
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<td>5.9.1 Development of optical fiber sensor packaging methods</td>
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<td><strong>M6: Prototype porous glass fiber sensor fabrication</strong></td>
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<td>Final Report Preparation</td>
<td>Q Q Q A Q Q</td>
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<td>Technical Progress Report</td>
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</table>
Sapphire Photonic Crystal Fiber Development

• Currently working on development of sapphire photonic crystal fibers
  – Fabrication
  – Modeling
  – Testing
• Single Crystal Sapphire (α-Al$_2$O$_3$)
  - Continuous crystal lattice
    - Hexagonal structure
    - No grain boundaries
    - Grown on c-axis
  - Refractive index
    - 1.744 at 1.693μm with an 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

*Background*

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) ($\alpha$-$\text{Al}_2\text{O}_3$) 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
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)**
  \( n = 1.0 \)

- **Sapphire (α-Al\(_2\)O\(_3\) in grey region)**
  \( n = 1.74618 \)

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

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<thead>
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<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Property group</th>
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<td>Relative permittivity</td>
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<td>( \rho_o(T) )</td>
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<td>( C_p(T) )</td>
<td>J/(kg*K)</td>
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<td>Refractive index, imaginary part</td>
<td>( k_i )</td>
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<td>Refractive index</td>
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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
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 \(L_c = 1.3933 \times 10^{-6} \text{ dB/km}\)
• Investigating additional methods for increased modal reduction
  – 1. 50\(\mu\)m core surrounded by 5 70\(\mu\)m rods of single crystal sapphire fiber (left).
  – 2. 50\(\mu\)m core rod of single crystal sapphire surrounded by 6 50\(\mu\)m diameter single crystal fibers bundled in a hexagonal arrangement (right).
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