Noninvasive Optical Sensor Development for Real-Time SOFC Monitoring

Youngseok Jee[1,2], Jacob L. Poole[1], Shiwoo Lee[1,2], Thomas Kalapos[1,2], Harry W. Abernathy[1,2], Gregory A. Hackett[1], Michael P. Buric[1], Benjamin T. Chorpening[1], Aidong Yan[3], Sheng Huang[3], Kevin Chen[3], and Paul R. Ohodnicki[1]

[1]US Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA; [2]AECOM Corporation, Pittsburgh, PA; [3]University of Pittsburgh, Pittsburgh, PA

Research & Innovation Center

NATIONAL ENERGY TECHNOLOGY LABORATORY

Abstract

Optical based sensors which exhibit inherent advantages such as the electrical wiring-free configuration, compatibility with broadband wavelength and distributed interrogation, and the elimination of electrical sparks in flammable atmospheres are currently under development in the Solid Oxide Fuel Cell project at National Energy Technology Laboratory (NETL). An overview of the program is presented as well as recent results on (1) distributed temperature and chemical composition monitoring throughout the internal of the anode and cathode stream during operation and (2) oxide functionalized optical fiber based chemical sensing.

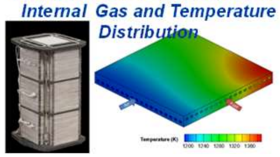
Sensor development at NETL for harsh environmental applications

Short Term Focus

	Coal Gasifiers	Combustion Turbines	Solid Oxide Fuel Cells	Advanced Boiler Systems
Temperatures	Up to 1600°C	Up to 1300°C	Up to 900°C	Up to 1000°C
Pressures	Up to 1000psi	Pressure Ratios 30:1	Atmospheric	Atmospheric
Atmosphere(s)	Highly Reducing, Erosive, Corrosive	Oxidizing	Oxidizing and Reducing	Oxidizing
Examples of Important Gas Species	H_2, O_2, CO, CO_2, H_2O, H_2S, CH_4	O_2 Gaseous Fuels (Natural Gas to High Hydrogen), CO, CO_2, NO_x, SO_x	Hydrogen from Gaseous Fuels and Oxygen from Air	Steam, CO, CO_2, NO_x, SO_x

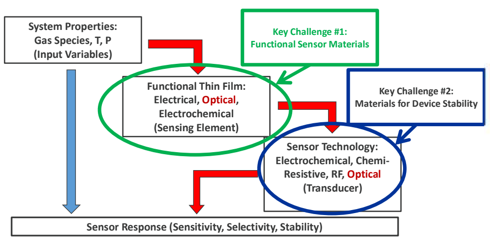
SOFC Temperature : 700-800°C
Anode Stream : Fuel Gas (e.g. H_2-Containing)
Cathode Stream : Air or O_2

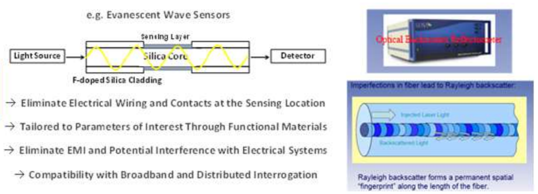
Example : Solid Oxide Fuel Cells Internal Gas and Temperature Distribution



Incompatible with Traditional Sensing Technologies

1) Limits of High Temperature Electrical Insulation
2) Limited Access Space
3) Requires Multi-Point Sensing
4) Electrified Surfaces
5) Flammable Gas Atmospheres



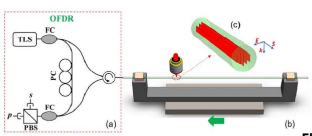


Optical Fiber Based Sensors are Particularly Well-Suited for Harsh Environment and Electrified System Applications.

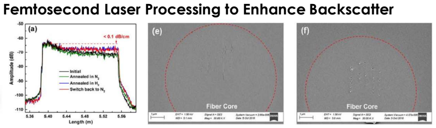
Key Technical Challenges to Enable In-Situ Optical Fiber Based Fuel Cell Sensing

1) Functional Sensor Layers for Targeted Species of Interest (H_2, CO, CO_2, CH_4, H_2O, etc.)
2) Increased Stability Optical Fibers and Associated Packaging Methodologies
3) Novel Sensor Integration and Interrogation Techniques and Methodologies

Femtosecond Processing of Silica Fibers for Enhanced Backscatter

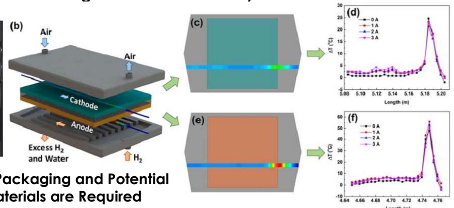


Femtosecond Laser Processing to Enhance Backscatter



Elevated Temperatures Near the Anode Stream Inlet Due to the High Thermal Conductivity of the Fuel Gas Stream.

University of Pittsburgh



Additional Studies of Silica Fiber Sensor Packaging and Potential Exploration of Alternative Fiber Materials are Required

Unmodified silica fibers exhibit weak backscattering that is unstable at SOFC relevant temperatures in H_2 gas streams and difficult to reliably track.

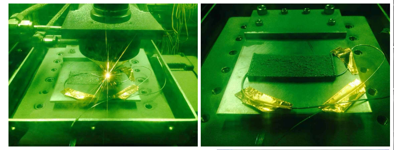
A technique for femtosecond laser enhancement of backscatter has been developed and applied to increase the reliability and temperature stability of the backscattered signal.

Trial tests have been initiated in the test stands at NETL Morgantown showing peaks in temperature at the gas stream inlets associated with gas thermal conductivity, with more trials to commence in coming weeks.

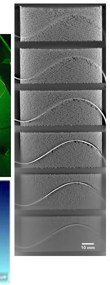
Additive Manufacturing of "Smart Interconnects"

University of Pittsburgh

LENS Embedding Within a High Temperature Part



CT Scans to Investigate "Internal Structure" of Parts with Embedded Sensors

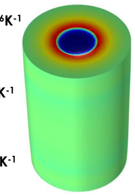


Residual Stresses within an Embedded Optical Fiber at Temperature

CTE Stainless Steel 316 ~15.8x$10^{-6}K^{-1}$

CTE Nickel ~13x$10^{-6}K^{-1}$

CTE Silica ~4.9x$10^{-7}K^{-1}$



Simulation and experimental results are targeting to enable successful fabrication of additively manufactured "smart interconnects" with embedded temperature and strain sensing capabilities.

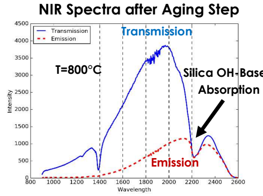
The Laser Engineered Net Shaping process is being applied as the primary embedding technique.

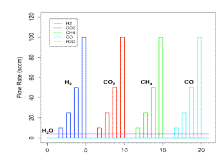
Embedded strain monitoring appears limited by the residual stresses generated as a result of the thermal expansion coefficient mismatch of the fiber and metallic part resulting in delamination at a critical temperature of ~300-400°C. A combination of simulations and experiments are trying to derive solutions.

Sol-gel based LSTO sensor for the high temperature application

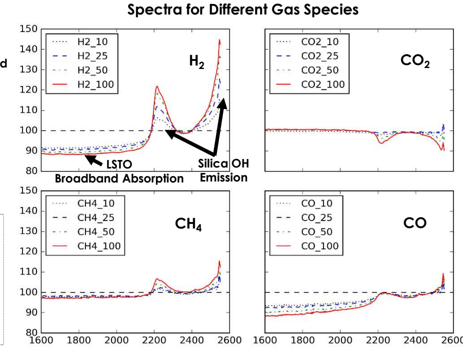
A perovskite ($La_{0.3}Sr_{0.7}TiO_3$) thin film coated on the optical fiber using sol-gel method with Ti-isopropoxide, and Sr/La-nitrates. Broad band absorption from metal oxide layer and localized thermal emission peaks from hydroxyl defects in silica fiber exhibited obvious peaks in near infrared range with H_2 and CO_2.

NIR Spectra after Aging Step

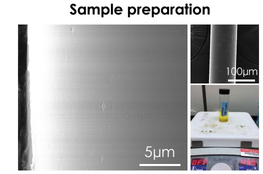




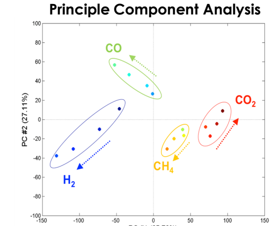
Spectra for Different Gas Species



Sample preparation



Principle Component Analysis

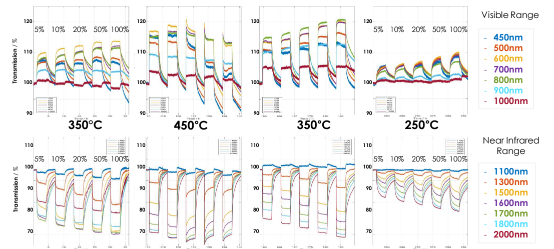


Two Principle Components

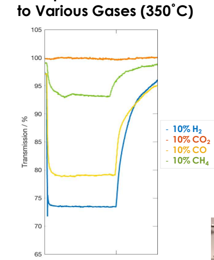
An Increased Emphasis is Being Placed on Discriminating Multi-Component Species within Complex Gas Mixtures Through Advanced Multi-Variate Techniques

NIR and VR intensity results from ITO Based Sensor : Collaboration

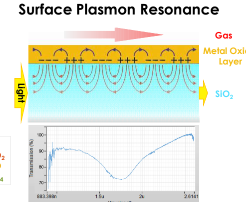
Relative responses to 5-100% H_2 at 250-450˚C



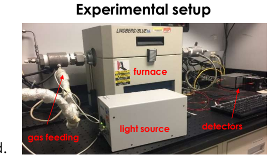
Responses at 2000nm to Various Gases (350˚C)



Surface Plasmon Resonance



Experimental setup



High Electronic Conductivity Indium Tin oxide (ITO) was prepared via sol-gel method.
The surface plasmon resonance absorption peak increases in the near infrared range (NIR), yielding a transmission decrease resulting from a free carrier increase.
Visible range increases in transmission are observed but are yet to be characterized in detail.
350°C was required for reasonable response times, but at higher temperatures instabilities were observed.

U.S. DEPARTMENT OF ENERGY

Science & Engineering To Power Our Future