Micro-Structured Sapphire Fiber Sensors for Simultaneous Measurements of High-T and Dynamic Gas Pressure in Harsh Environments

DE-FE0001127

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DOE Project Kickoff Meeting in the NETL Pittsburgh

December 15, 2009

Outline

- **Background**
- **Objectives**
- **Project Elements**
- **Management Plan**
- **Research Plan and Approaches**
- **Risk Management**
- **Summary**

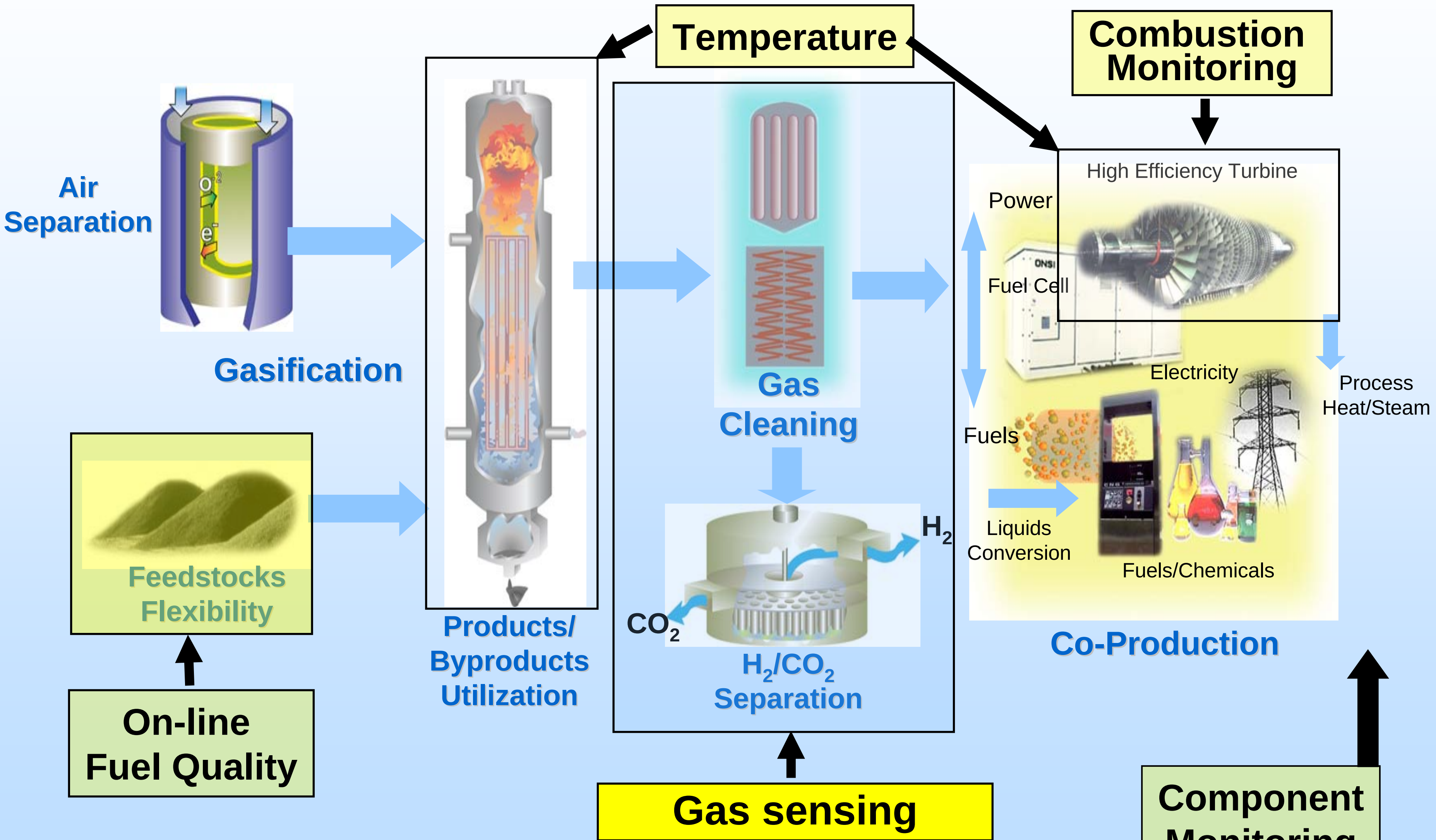
Background

- **Demands:** High-performance, reliable, in situ sensors are highly demanded for advanced process control and lifecycle management in existing and future advanced power and fuel systems
  - Improved efficiency/safety/reliability/availability/maintainability
  - Emission reduction
  - Enhanced fuel-flexibility

- **Status:** Current sensor technologies (commercial and research) capable of operating in harsh conditions are extremely limited

Prioritized Sensing Needs

IGCC based Near Zero Emission CoGeneration Plant



Provided by NETL

Objectives

- **Main objective:** Development and demonstration of sensors for simultaneous measurements of **high-T (upto 1600ºC) and dynamic gas pressure**

- **Requirements:** Survive and operate in the high-T, high-P and corrosive/erosive harsh environments for a long period of time

Temperature	**up to 1600°C, highly erosive and corrosive** **Packaging for extreme conditions**
Pressure	**Up to 1000 psi, high temperature, erosive & corrosive** **Dynamic pressure for turbine applications**

- **Very challenging engineering goals**
  - Dependable performance
  - Robustness to survive the harsh environment
  - Simultaneous measurement
  - Long term stability

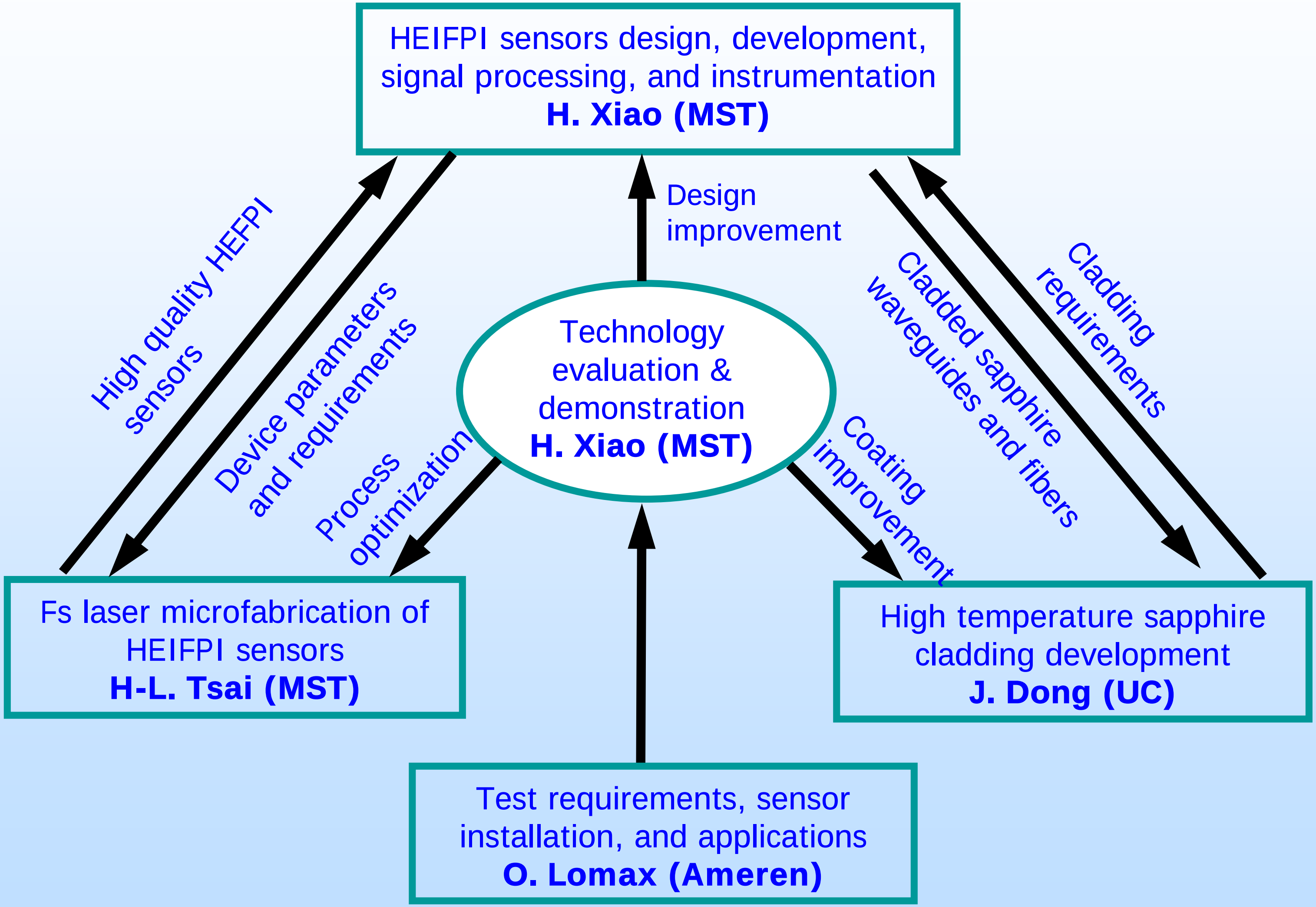
Project Elements/Overview

- **Awarded under the Advanced Research Program**
  - Perform fundamental and applied research to establish the feasibility of high temperature and dynamic gas pressure using micro-structured sapphire fiber sensors

- **Interdisciplinary team between two universities and an industry partner**
  - Missouri S&T (lead), University of Cincinnati (subcontractor), and Ameren Corp. (consultant)
  - Three-year project started on Oct. 1, 2009

- **Success criteria:**
  - Demonstrate capability in simulated laboratory environments.

Project Team



Two Phases

- **Phase I (18 months):** prove the concept of the sapphire fiber HEIFPI sensors for measurements of high temperature and dynamic gas pressure.
- **Phase II (18 months):** optimize, characterize and demonstrate the key functions for simultaneous measurement of temperature and dynamic gas pressure in a laboratory simulated high temperature, high pressure harsh environment.
- Team work with the engineers from Ameren Corporate (AC) to collectively **define a plan** for packaging, installing and testing our sensors and measurement system in AC's test facilities

Phase and Quarter Milestone Log

Phases and Tasks		Deliverables (reports on the following specific topics/results)	Report (quarter)
Phase I (18 months)	Subtask 1.1	Deliver Project Management Plan (PMP) 30 Days after award	1st
	Subtask 1.1	Update PMP as required	As needed
	Subtask 2.1	a) Models of HEIFPI sensor in response to temperature and pressure b) Structural parameters of the HEIFPI sensor to guide device fabrication	2nd
	Subtask 2.2	Sapphire fiber HEIFPI sensors with reasonable signal quality	4th
	Subtask 2.3	a) List of candidate cladding materials and characterization results	3rd
		b) High temperature coating demonstrated on sapphire substrates and evaluation results	5th
	Subtask 3.1	Temperature measurement data up to 1600°C	5th
	Subtask 3.2	Dynamic gas pressure measurement data at room temperature	6th
Phase II (18 months)	Subtask 4.1	a) Optimal procedures and laser parameters for high-quality device fabrication	8th
		b) High quality sapphire fiber HEIFPI sensors obtained	9th
	Subtask 4.2	a) Cladded sapphire fibers obtained and characterized	9th
		b) Performance characteristics obtained for cladded sapphire fibers	10th
	Subtask 4.3	a) A functional measurement system with all components integrated	8th
		b) Proof-of-concept test results of the prototype system	9th
	Subtask 5.1	A fully optimized measurement system integrated with high quality sapphire sensors	10th
	Subtask 5.2	Comprehensive test results of sensor and measurement system	12th
	Subtask 5.3	A plan for installing/testing developed sensors in Ameren facility	12th

Project Gantt Chart

TECHNICAL TASKS	YEAR 1				YEAR 2				YEAR 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1. Project Management	←	—	—	—	—	—	—	—	—	—	—	→
Task 2. Development of HEIFPI sensors	←	—	—	—	→							
Subtask 2.1 Sensor design	X	X										
Subtask 2.2 Sensor fabrication	X	X	X	X								
Subtask 2.3 Cladding material identification	X	X	X	X	X							
Task 3. Proof-of-concept tests of the developed sensors				←	—	→						
Subtask 3.1 Measurement of high temperature				X	X							
Subtask 3.2 Dynamic gas pressure at room temperature					X	X						
Task 4. Instrumentation, system integration and tests					←	—	—	—	—	→		
Subtask 4.1 Optimization of sensor fabrication					X	X	X	X	X			
Subtask 4.2 Development of double-cladding						X	X	X	X	X		
Subtask 4.3 Instrumentation, system integration and tests					X	X	X	X	X			
Task 5. Optimization and technology demonstration									←	—	—	→
Subtask 5.1 System optimization and integration									X	X		
Subtask 5.2 Technology demonstration										X	X	X
Subtask 5.3 Transition spec, test plan development												X
Project reports				**AR**				**AR**				**FR**

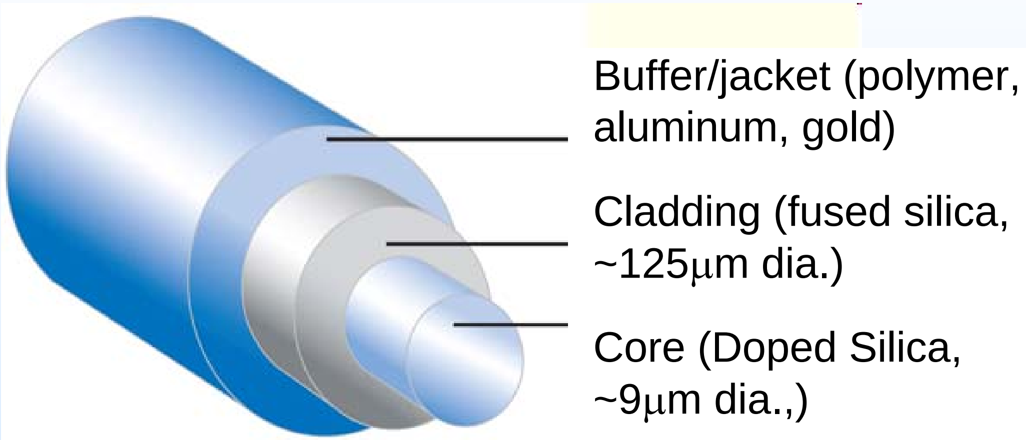
Phase I ↑ Phase II

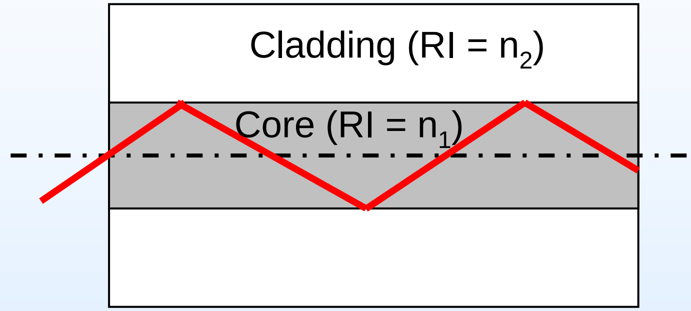
Approaches/Innovations

- **Dependable Performance:** Novel concept of micro-structured sapphire fiber Hybrid Extrinsic and Intrinsic Fabry-Perot (HEIFPI) interferometer
- **Robustness:** Assembly-free, one-step fs laser micromachining of the sensor directly on a sapphire fiber
- **Simultaneous measurement:** Novel WDM-based instrumentation and advanced digital filtering-based signal processing
- **Long-term stability:** Novel double-cladding sapphire fiber cladding technology and low NA excitation method
- **Demonstration:** Tests and performance evaluations in simulated high temperature laboratory conditions

Optical Fiber Sensor

- **Optical fiber: A light pipe made of fused silica materials**





Total internal reflection when $n_1 > n_2$

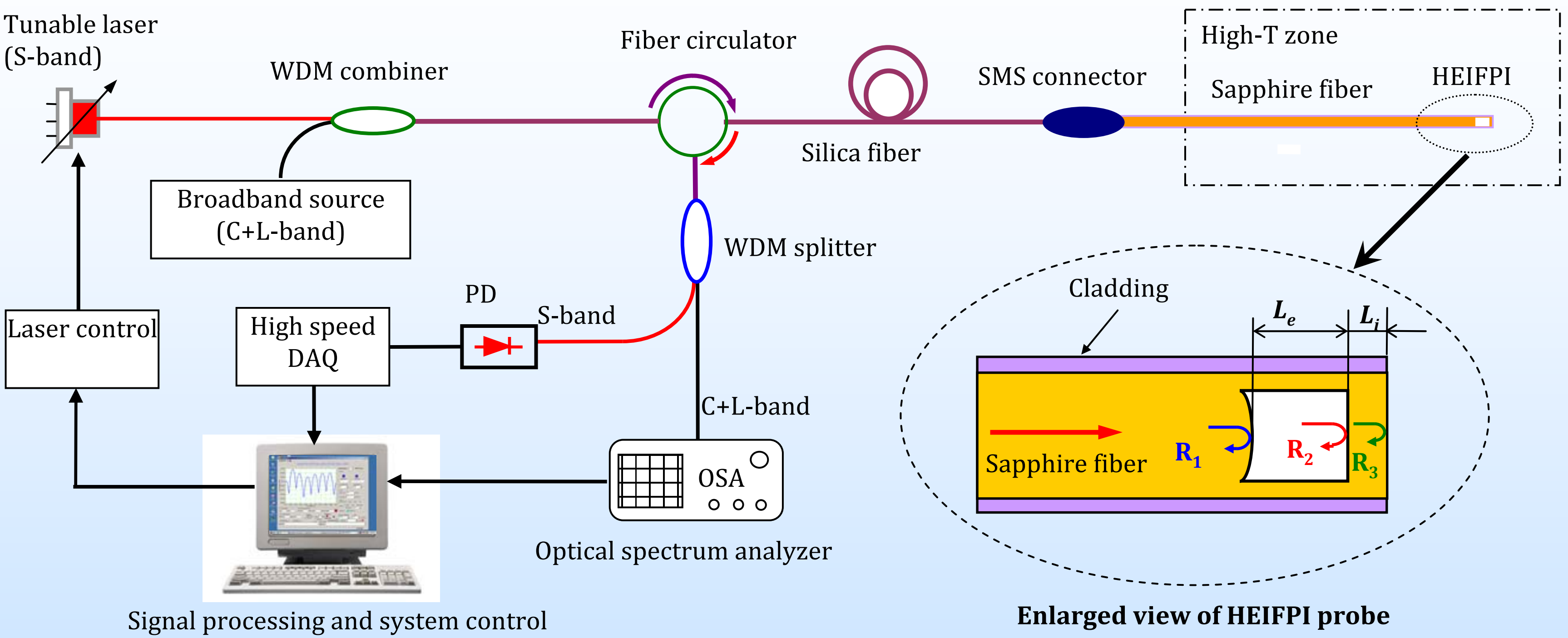
- **Fiber sensors: proven advantages for applications in hostile environments**
  - Small size/lightweight
  - Immunity to electromagnetic interference (EMI)
  - Resistance to chemical corrosion
  - High temperature capability
  - High sensitivity
  - remote operation
  - Multiplexing and distributed sensing

Sapphire fiber sensors

- **Silica fiber sensors**
  - Core-cladding structure provides excellent waveguide
  - Demonstrated for measurements of various physical and chemical parameters
  - Operate only up to ~1100^{o}C for short period time and ~600^{o}C for long period of time

- **Sapphire fiber sensors**
  - Single crystalline material with high melting temperature (2053^{o}C)
  - Do not have cladding → unprotected waveguide
  - How to fabricate them?

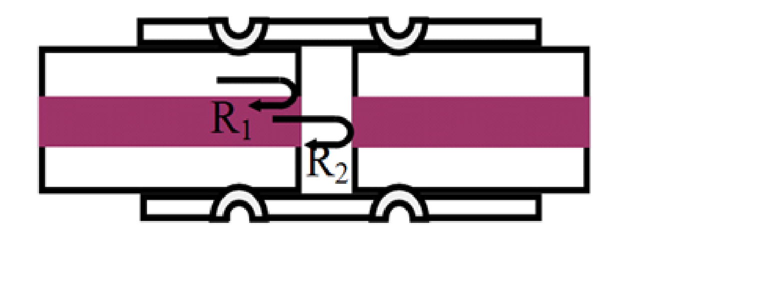
Sensor System

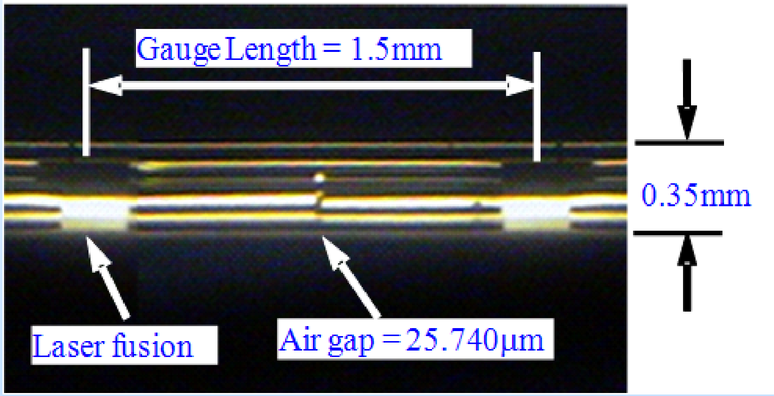


- **Sensor probe: a hybrid extrinsic and intrinsic Fabry-Perot interferometer (FPI)**
  - FP cavity for temperature measurement
  - Deflectable diaphragm for dynamic pressure measurement

MicroAssembly based Sensors

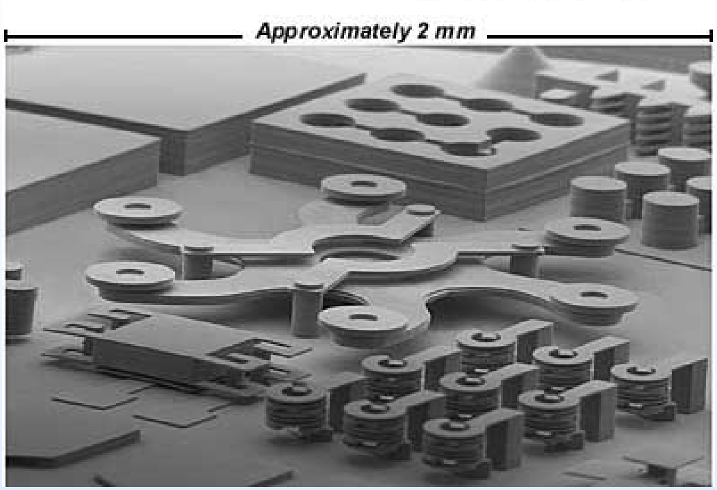
- **Micro Assembly:** The conventional way to fabricate silica fiber sensor
- **Disadvantage:** Complicated process, time consuming, non guaranteed performance, minimum robustness(CTE difference), high cost
- Fusion based assembly cannot apply to crystal materials such as sapphire
- **Conclusion:** micro-assembly is not a valid solution for high temperature harsh environment applications

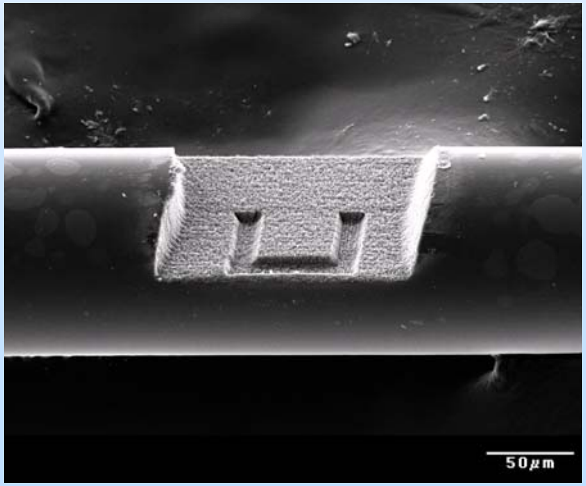




Micromachining Based Sensors

- **Micromachining review**
  - Micro electro mechanical system (MEMS)
  - Ultrafast (fs) laser micromachining
- **Advantages**
  - Dependable performance is guaranteed by design
  - Robustness (No CTE mismatch)
  - Low cost and fast
- **Conclusion**
  - Micromachining: A good way to fabricate sensors for harsh environments





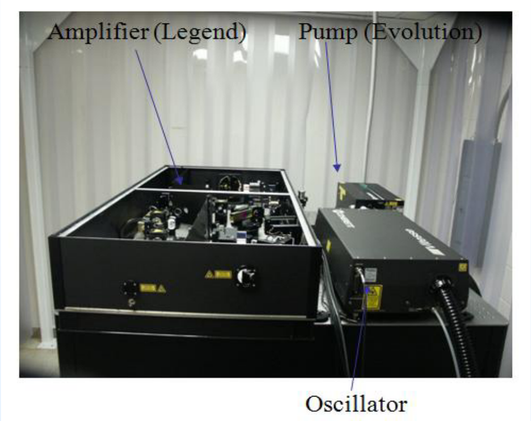
Why fs Laser Micromachining?

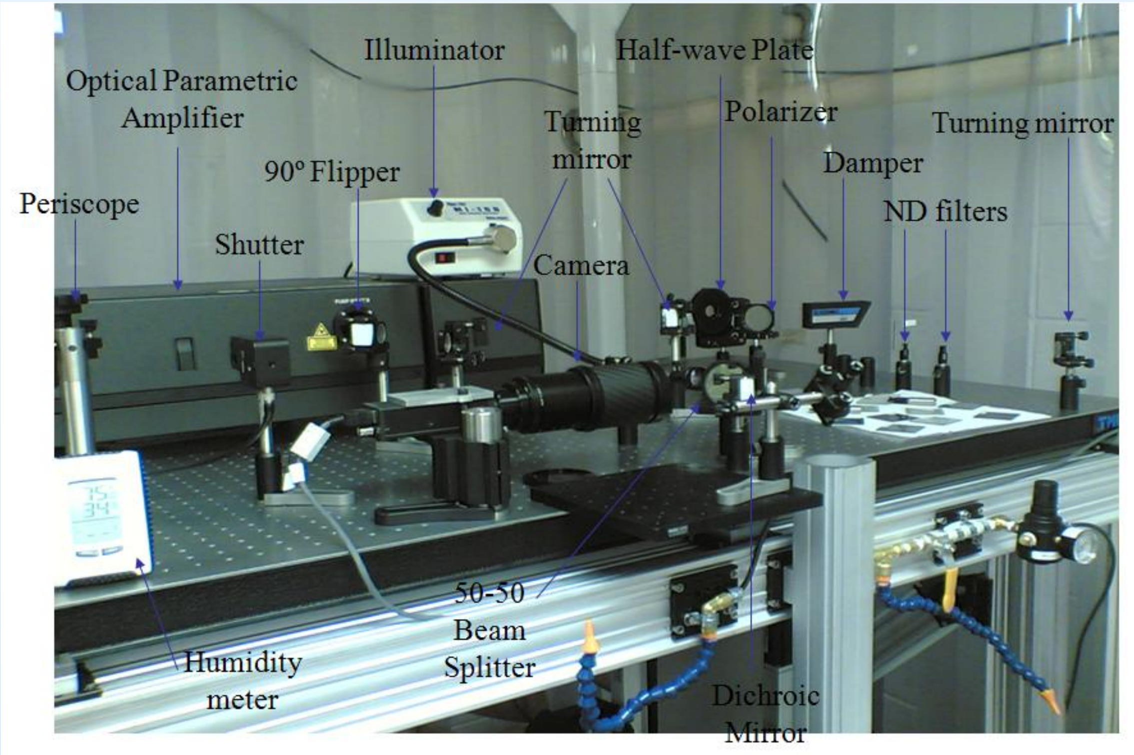
- **Challenge:** directly fabricate micro or nano structures on a small size cylindrical substrate such as an optical fiber

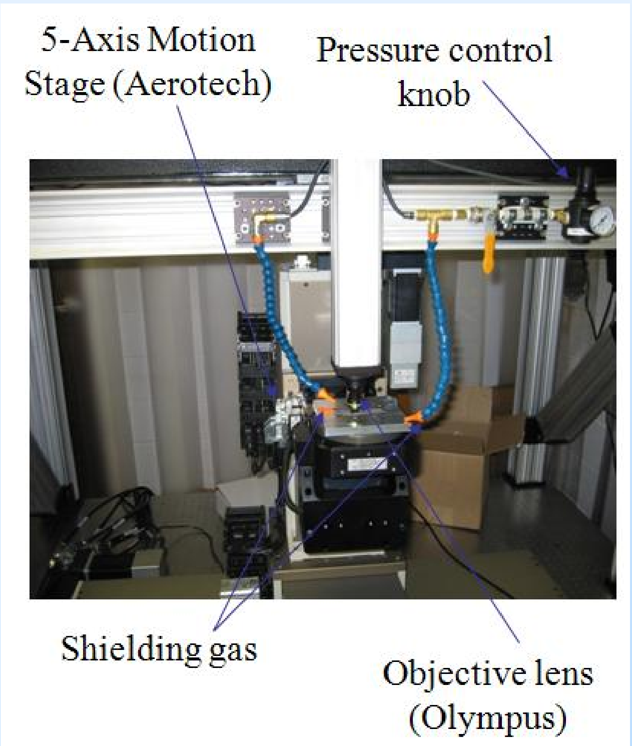
- **Well established IC technology** (etching, photolithography) will not work since they are designed for ***flat substrate*** fabrication only.

- **Femtosecond (fs) laser micromachining:**
  - High accuracy (sub-micron),
  - One-step, fast ablation, 3D fabrication capability
  - Works on a diverse variety of materials including metal, silica, polymer, sapphire, etc.

Existing Fs Laser Micromachining System

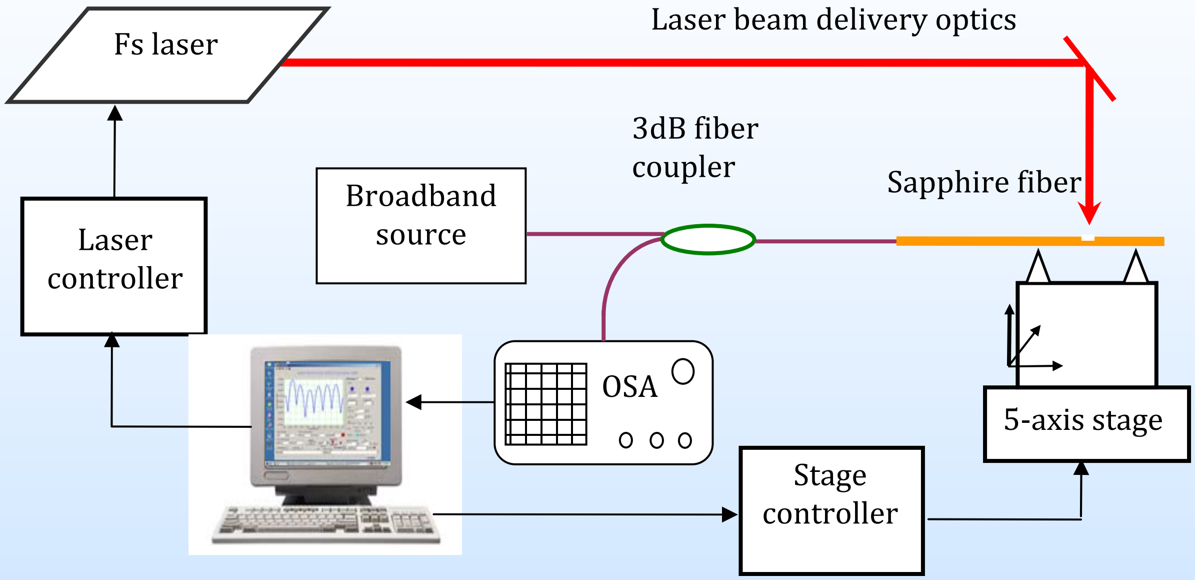


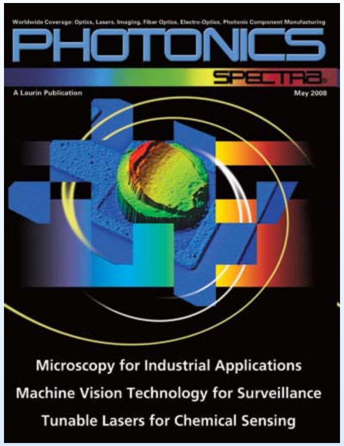




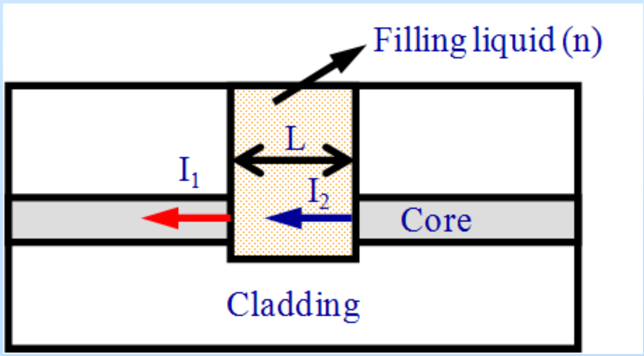
Fiber Inline Fabry-Perot Interferometer (FPI)

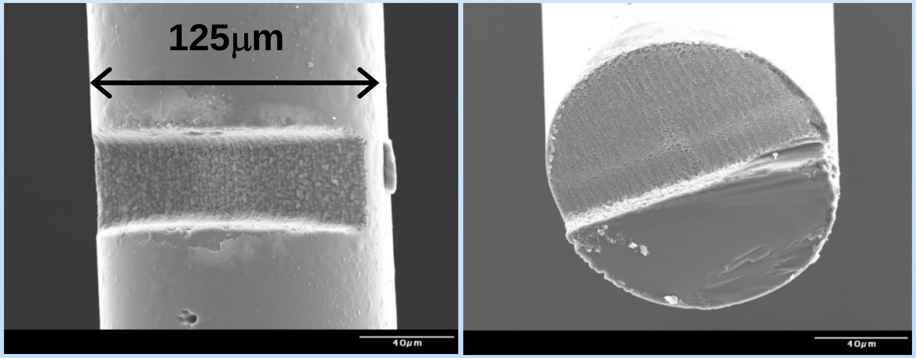
An open cavity accessible to external environment: Very small ~125µm





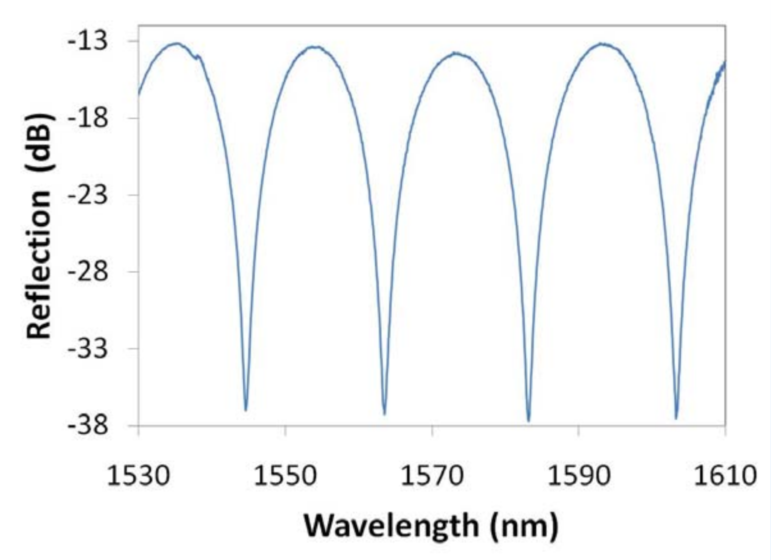
Featured in Photonics Spectrum, May 2008

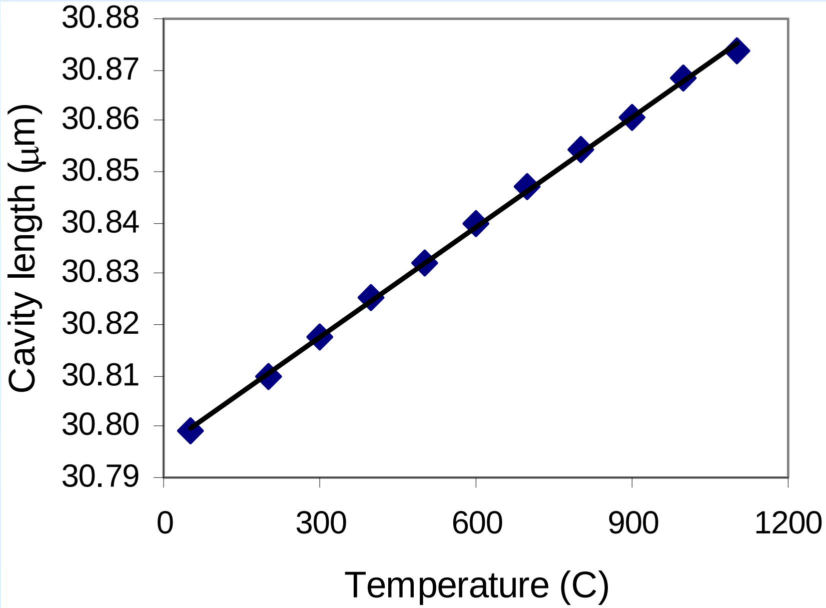




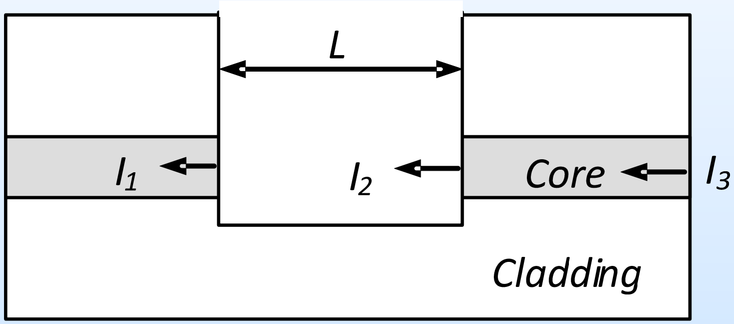
Survived High Temperatures

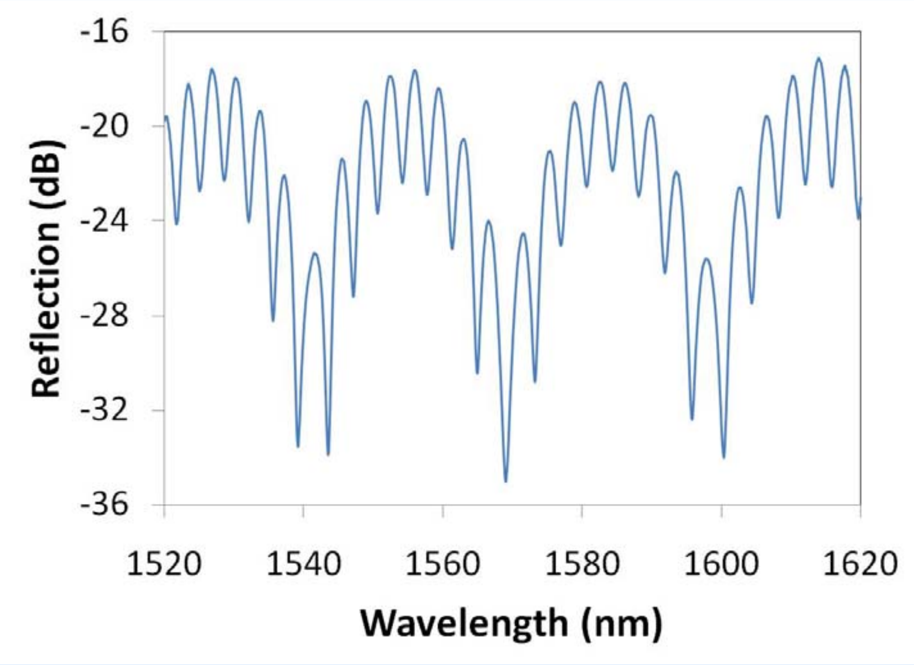
- ✓ High quality interference signal (>20dB visibility)
- ✓ High temperature capability (tested up to 1100^{o}C)
- ✓ Temperature measurement (linear response)





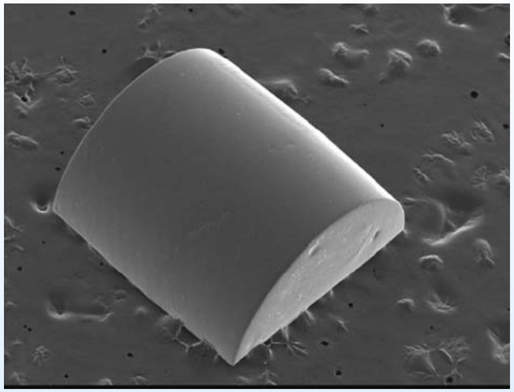
Simultaneous Multi-Parameter Measurement

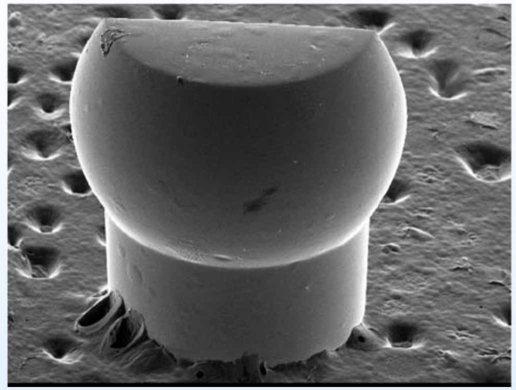


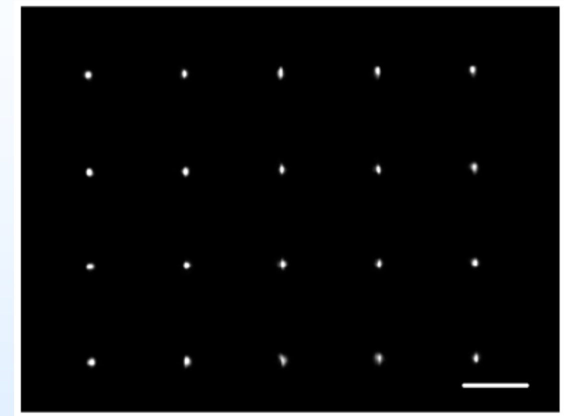


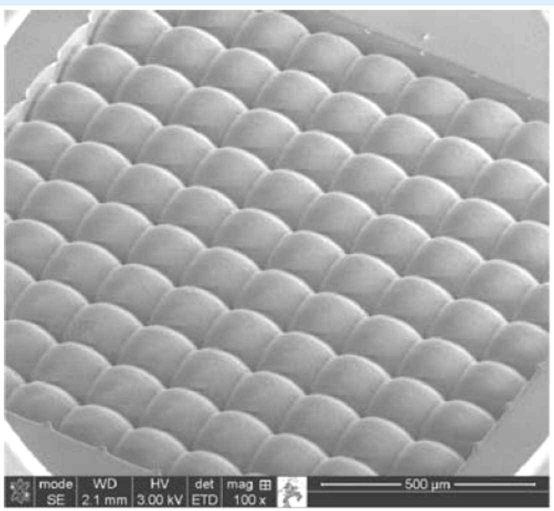
- ✓ Dual FP cavity configuration
- ✓ Intrinsic FPI cavity length 200µm (Solid)
- ✓ Extrinsic FPI cavity length 60µm (Open)
- ✓ **Simultaneous measurement** of multi parameters (T, p, ε and RI)

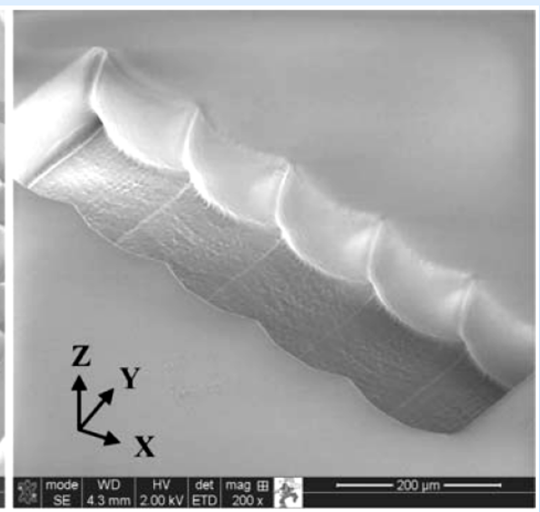
MicroMachined Lens and Lens Array

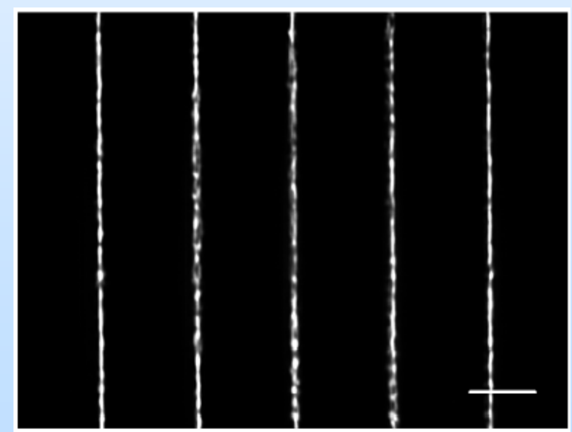






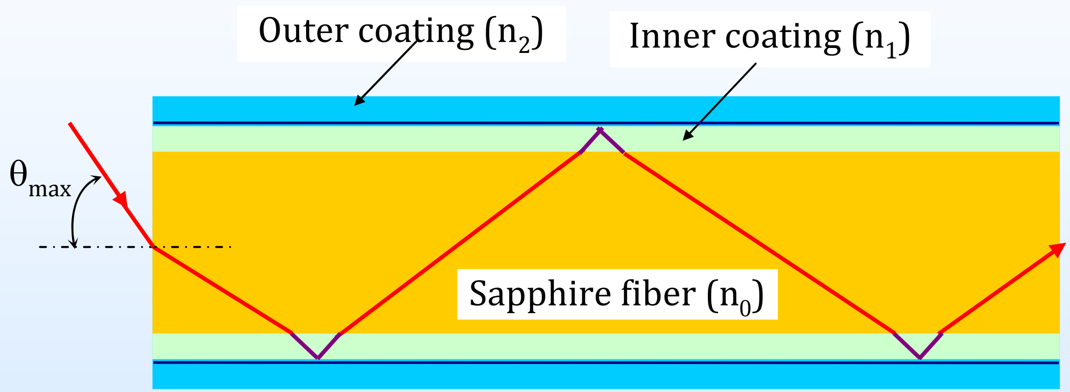




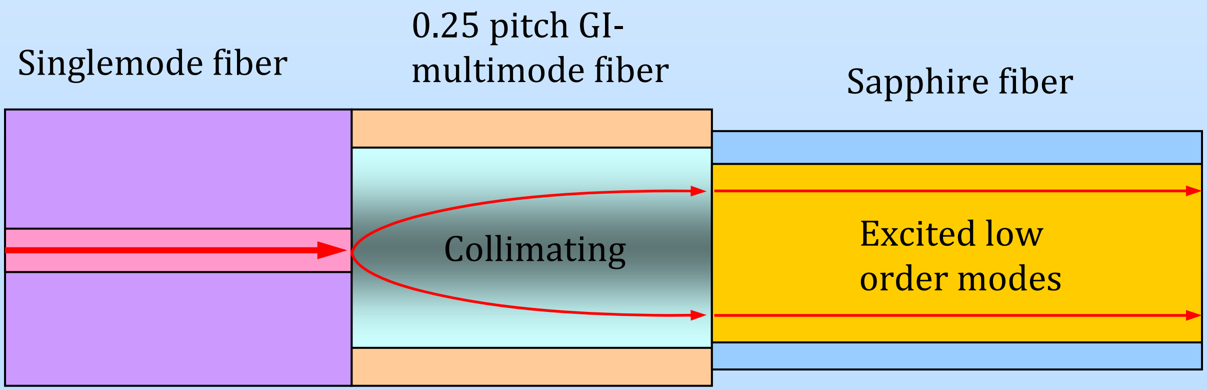


Sapphire Fiber Cladding and Excitation

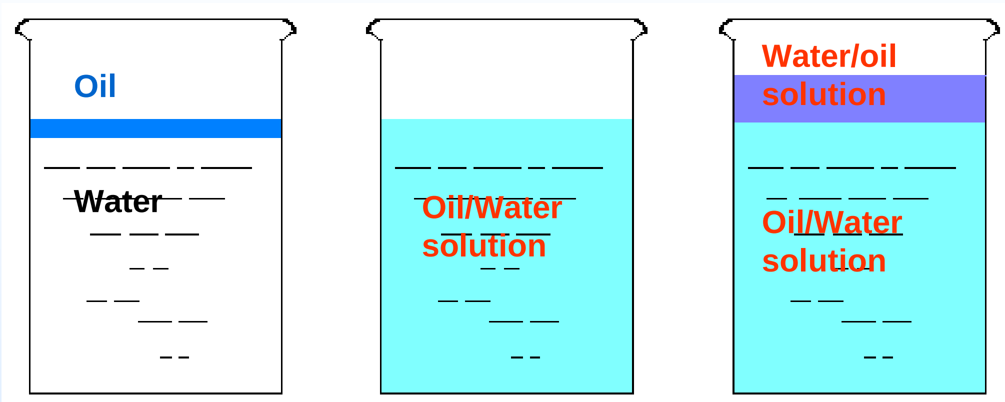
- **Novel double-layer cladding design for better chance to satisfy the optical and thermal/mechanical requirement**

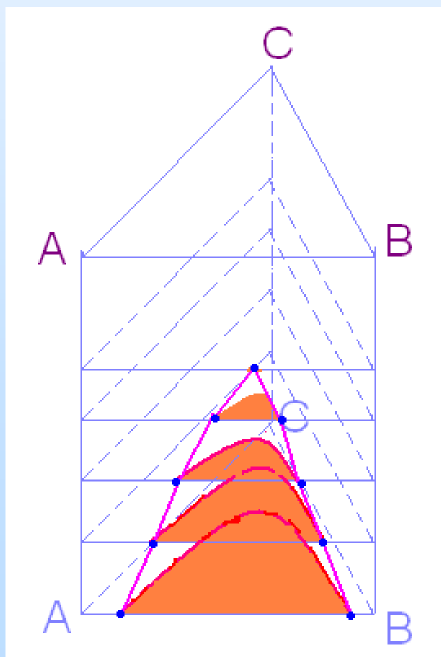


- **Low NA excitation through a self-collimating graded index (GI) fiber lens for improved optical performance**



Phase Equilibrium System to Achieve Long term Stability

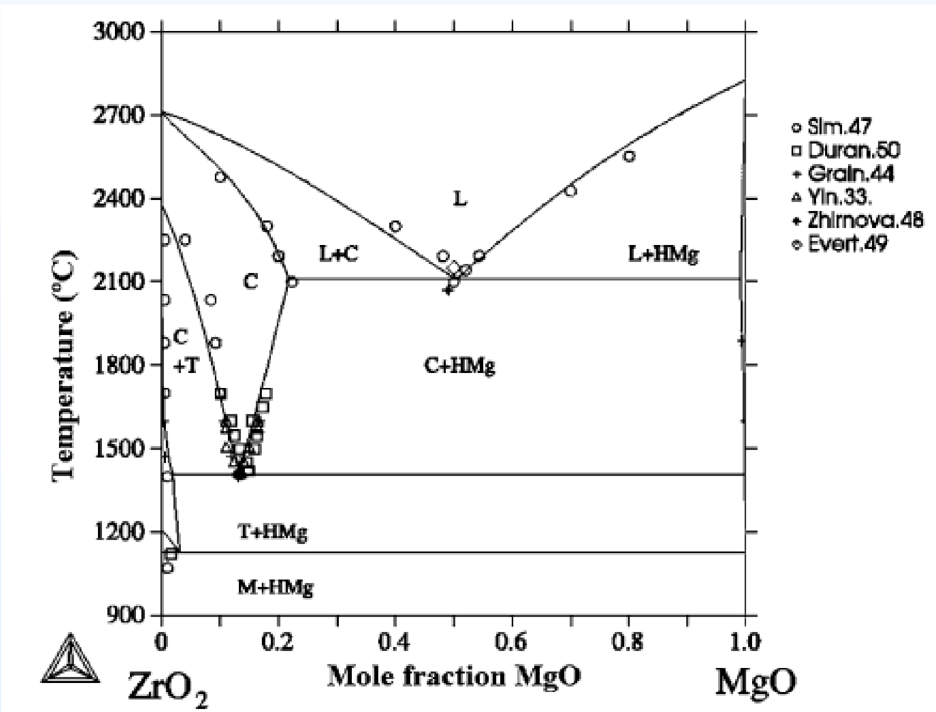


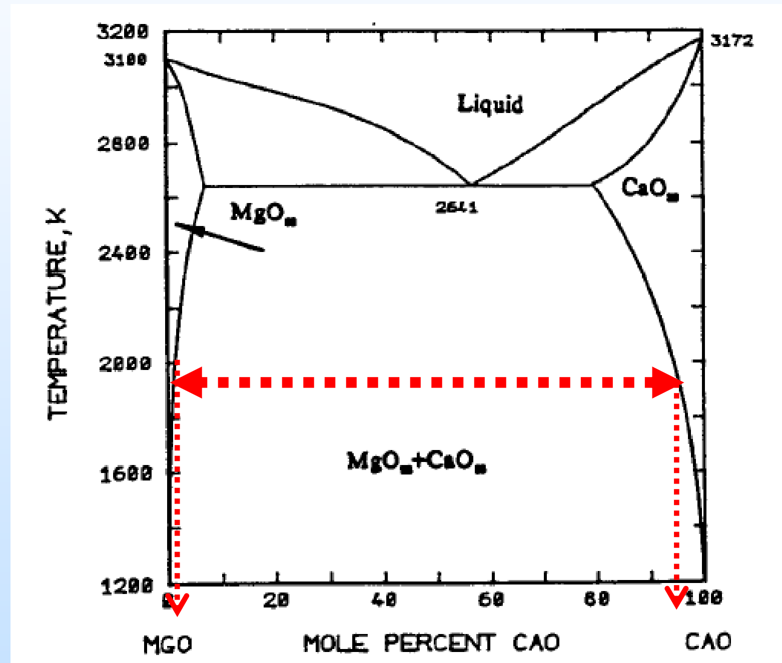


- **Thermodynamic equilibrium system has the ultimate stability as long as *<u>T and P remain constant</u>* and *<u>no chemical reaction</u>* to create new compounds**

Solid Phase Diagram

Complication: new compounds often formed at high temperature



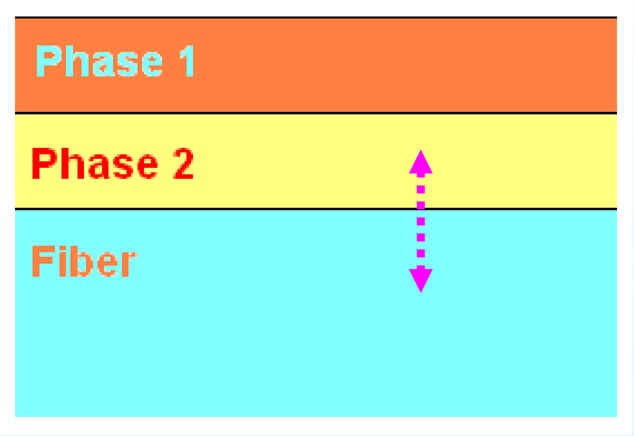


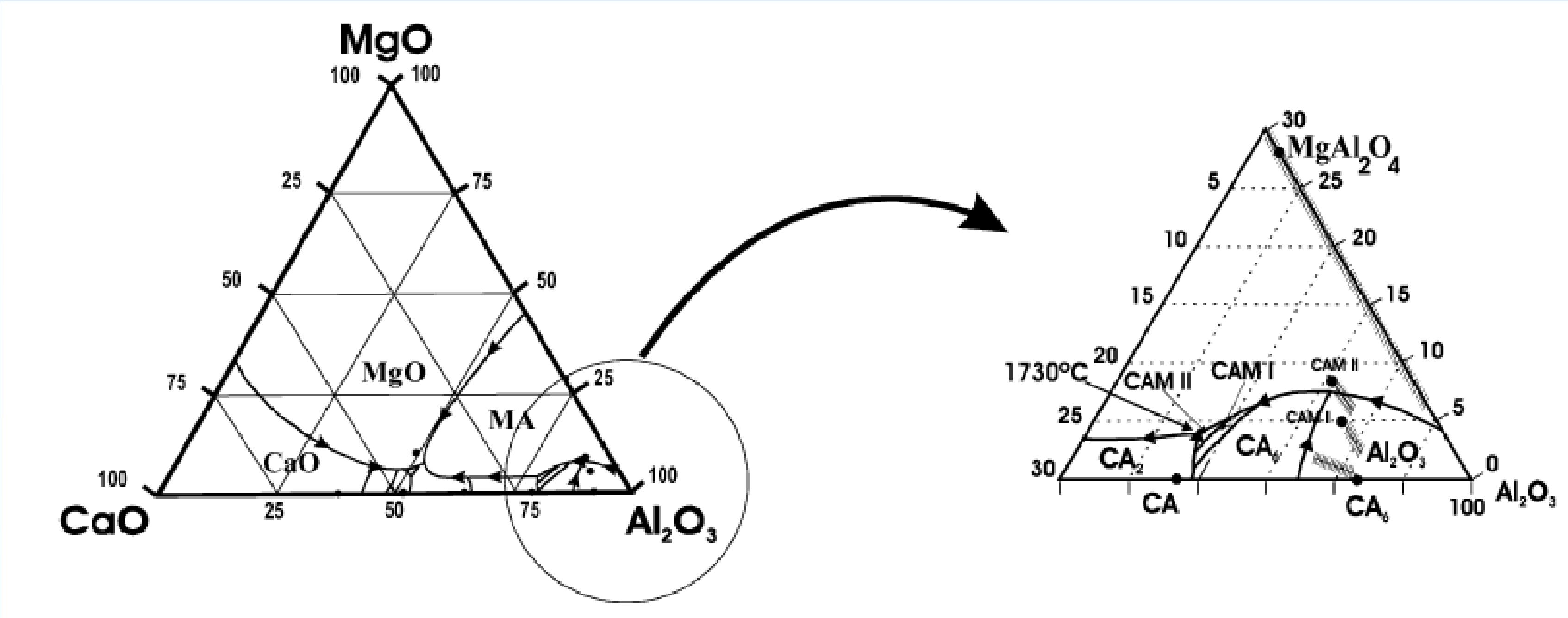
Calculated MgO–CaO phase diagram according to the evaluation by Jin and Du (20). For abbreviations of the phases see Table 2.

Multilayer Sensor Structure

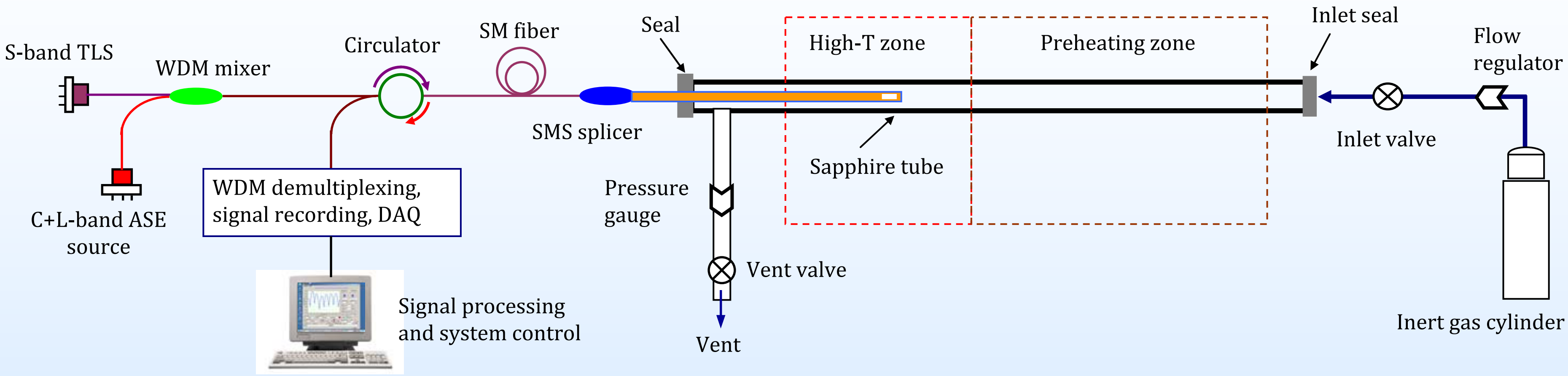
Multilayer sensor structure:

Challenge – stability between fiber and coating





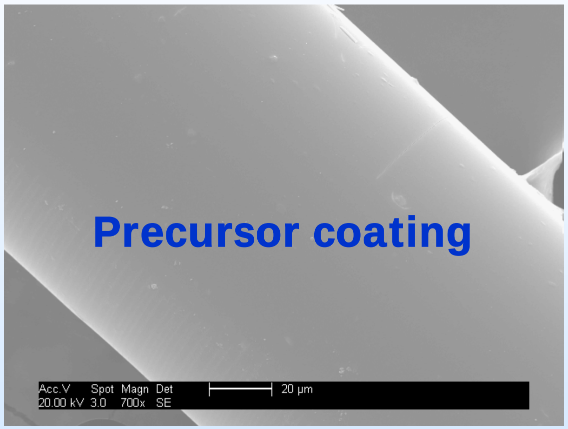
Sensor Characterization

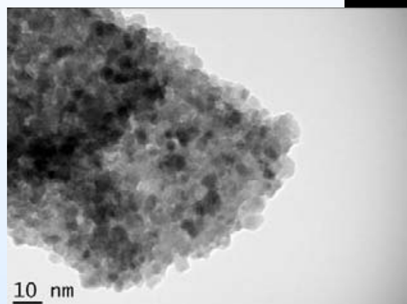


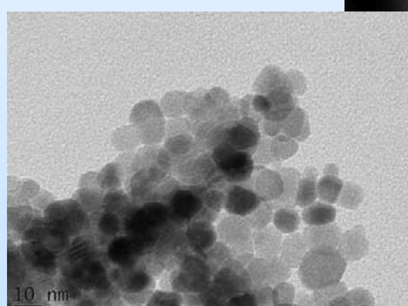
- **Sensors will be evaluated under simulated conditions in lab.**
- **Design and implementation of the test facility will be improved with the inputs from engineers of Ameren Corp.**

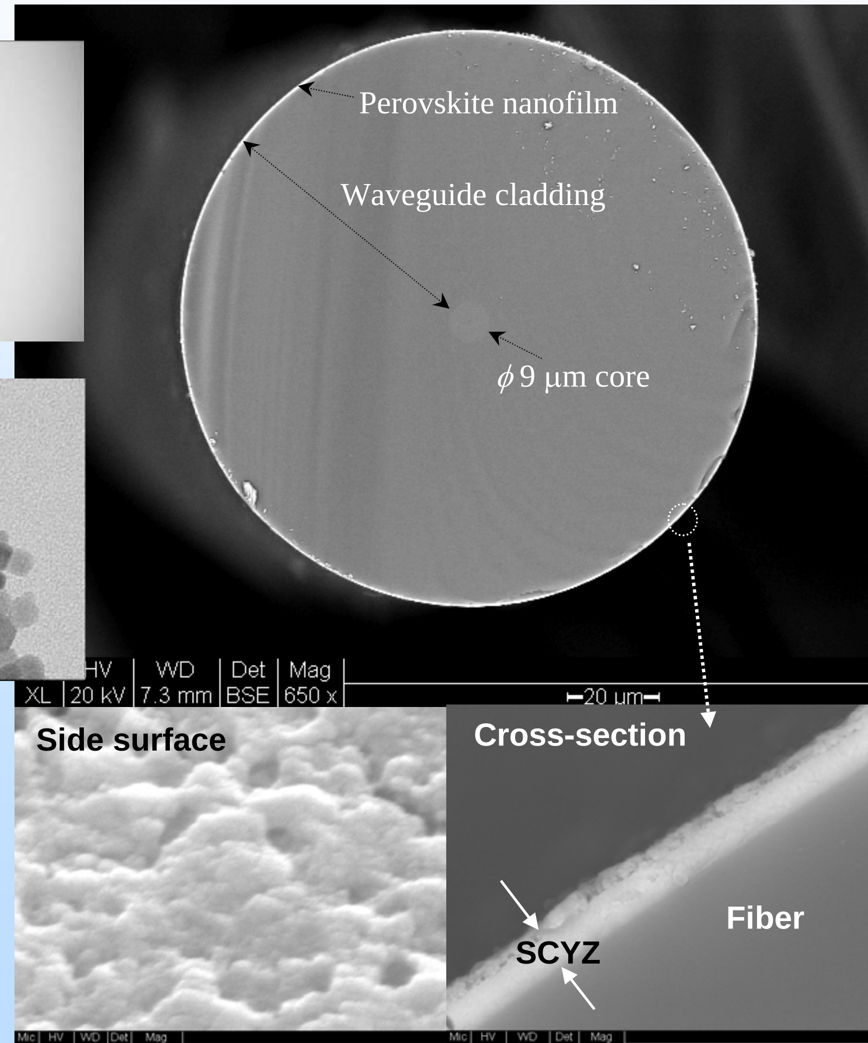
Prior Successes in Coating Ceramic Films on Optical Fibers

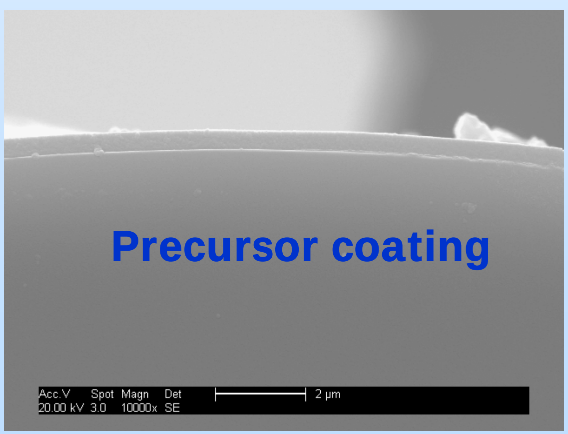
Various ceramic thin films have been successfully coated on optical fibers before for gas sensing











Risk Management

- **Very Challenging (high risk but high pay off)**
- **Potential risk #1: Robustness and long term stability.**
  - **Issues:**
    - Deformation of the sensor structure
    - Degradation of the cladding upon long term exposure to high-T.
  - **Mitigation:**
    - Structure and material stability improved by thermal shock treatment at a temperature higher than the application temperature.
    - HEIFPI sensor structure has the unique capability of self-referencing through the concurrent measurements of the lengths of the two cavities.
    - Testing of the sensor longevity (e.g., continuous exposure and thermal cycling in high temperatures) will be conducted and other stability improvement methods will be investigated.

Risk Management

- **Potential Risk #2: Sensor packaging, installation and protection**
  - **Issues:**
    - New concept, mainly focuses on fundamental research to prove the feasibility through laboratory tests and demonstrations.
    - Testing conditions and new facilities need to be established
  - **Mitigation:**
    - Collaborate with industry partner AC to guide research towards practical applications.
    - AC team will provide expert consultations on sensor design/fabrication, system instrumentation and sensor testing/evaluations throughout the project.
    - Team will develop a detailed plan for packaging and installation of the developed sensors onto the AC turbine facilities for pilot tests.

Summary

- **Innovative approaches to tackle the very challenging problems**
  - **Dependable Performance**: Novel concept of micro-structured sapphire fiber HEIFPI interferometer
  - **Robustness**: Assembly-free, one-step fs laser micromachining of the sensor directly on a sapphire fiber
  - **Simultaneous measurement**: Novel WDM-based instrumentation and advanced digital filtering-based signal processing
  - **Long-term stability**: Novel double-cladding sapphire fiber cladding technology and low NA excitation method
  - **Focus on practical applications:** Interdisciplinary collaborations and working with industry partner