Advanced Research Sensor and Controls Project Review Meeting
DOE NETL
Morgantown, WV
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SINGLE-CRYSTAL SAPPHIRE OPTICAL FIBER SENSOR

DE-FC26-99FT40685

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Outline

- Motivation & Objective
- Background and Fundamentals of Proposed Technology
- Project Scope and Work Plan
- Project Progress

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MOTIVATION AND OBJECTIVE

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Motivation

- Temperature sensor for harsh-environments:
  - Coal gasifier (major focus of prior work).
  - Gas turbine.
- Temperature measurement is critical for:
  - Gasifier start-up.
  - Process optimization.
  - Event/failure detection.
- Help make gasification cost-competitive.
  - Reduce down-time.
  - Improve operational efficiency.

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The Gasifier Environment

- Coal gasifiers - challenging harsh environment:
  - High temperatures: well above 1000^{o}C.
  - Extreme corrosion:
    - coal slag.
    - alkali vapors.
    - transition metals.

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Existing Temperature Sensors

- Precious metal-based thermocouples:
  - Typical lifetime is a few days – weeks.
    - Attack by alkali vapors and transition metals.
    - Build-up of solid coal slag affects measurement and accelerates corrosion.
- Optical pyrometers:
  - Infrared window required to maintain pressure boundary.
    - Deposition of slag & other contaminants blocks sight path.
- Acoustic pyrometers:
  - Noise from equipment in the plant obstructs signal.

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Overall Project Objective

To develop a new sensor technology that can survive and perform well with a long lifetime in a coal gasifier environment.

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BACKGROUND AND FUNDAMENTAL TECHNOLOGY

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Background: Corrosion Test

Single-crystal sapphire:

- Melts at 2050°C.
- Optical transmission > 85%.
- Chemically inert at high temperatures.
- Survived coal slag corrosion test at 1200-1300°C.

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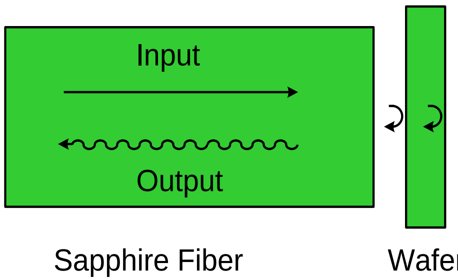
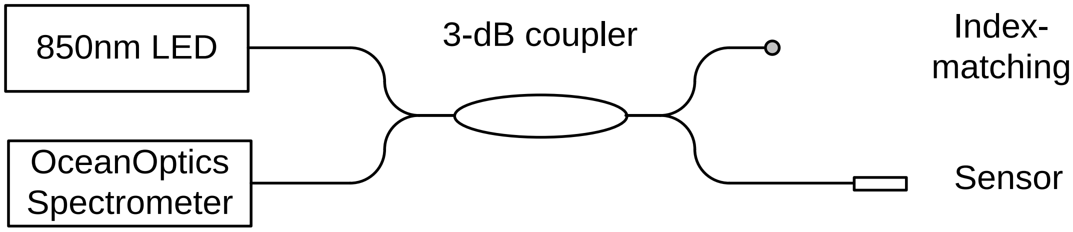
Technical Approach

- Sapphire wafer provides EFPI surfaces.
  - Single-crystal wafer is:
    - Inherently parallel.
    - Inherently flat & smooth.
- Sapphire fiber based white-light interferometry:
  - Accurate, reliable, low cost .



↑ Sapphire sensor structure.



← WLI system schematic.

Y. Zhu, Z. Huang, F. Shen, and A. Wang, “Sapphire-fiber-based white-light interferometric sensor for high-temperature measurements,” *Opt. Lett.*, vol. 30, no. 7, pp. 711-713 (2005).

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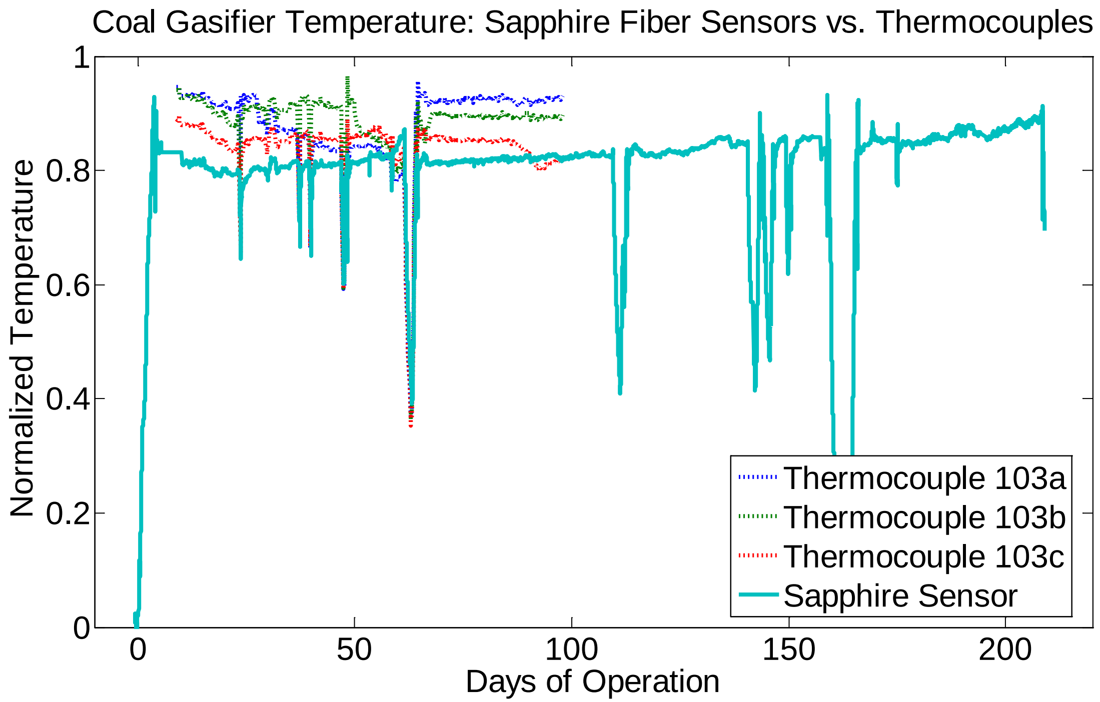
Field Test Results (I)

- Field test at Tampa Electric Co. (May 2006):
- Survived for 7 months:

  Great potential for commercial use.



↑ Sensor installation.

← Measured temperature history for 7 months.

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Phase III Objectives

Objective:

The objective is to demonstrate the full capability of an integrated sapphire optical temperature sensor through the development of sapphire based sensor assemblies and performance evaluation of the sensor on a full scale coal gasifier and a bench scale aero thermal turbine combustion rig.

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PROJECT PROGRESS

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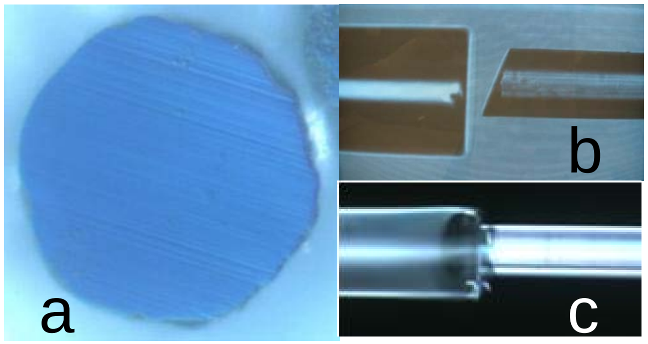
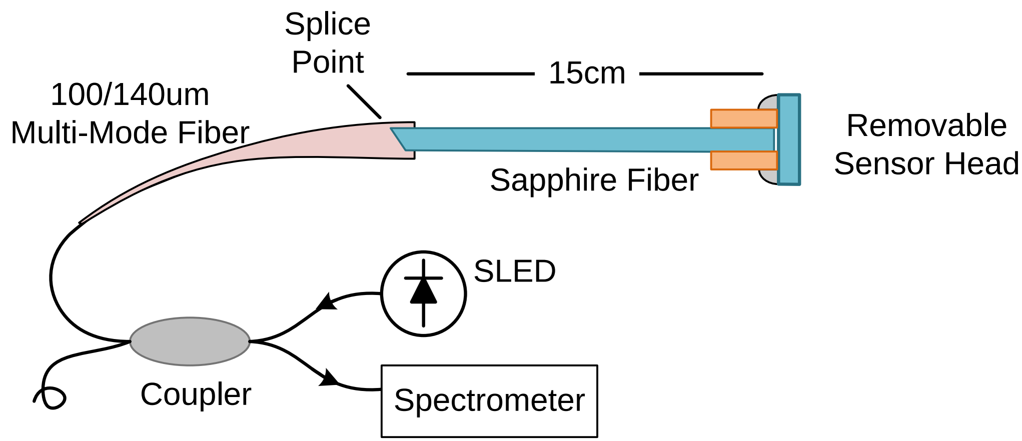
Progress (I)

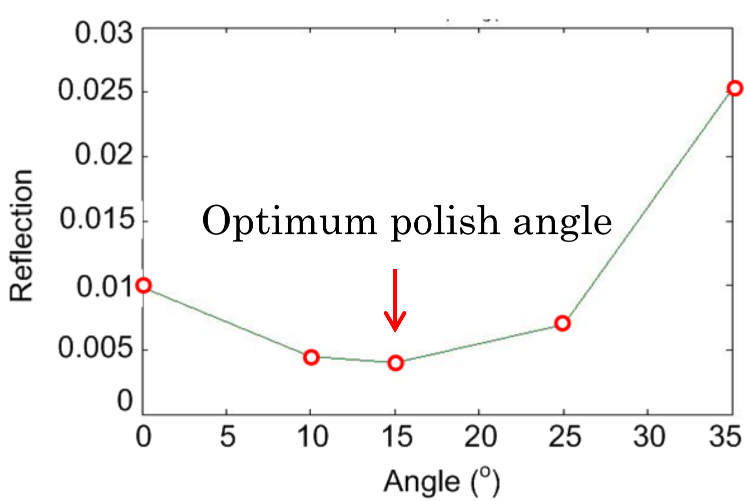
- Silica to sapphire splicing optimization:



↑ a. Sapphire fiber angle- polished end face. b. sapphire-silica splicing. c. splicing point with angle- polished sapphire fiber.



↑ System for characterizing the splicing quality



← Result showing the determination of the optimum polishing angle to yield minimum back reflection.

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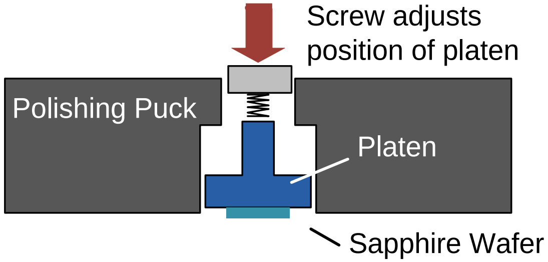
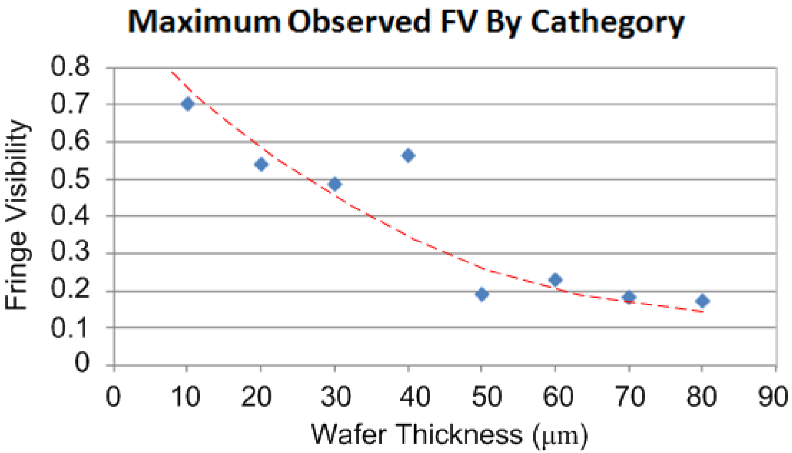
Progress (II)

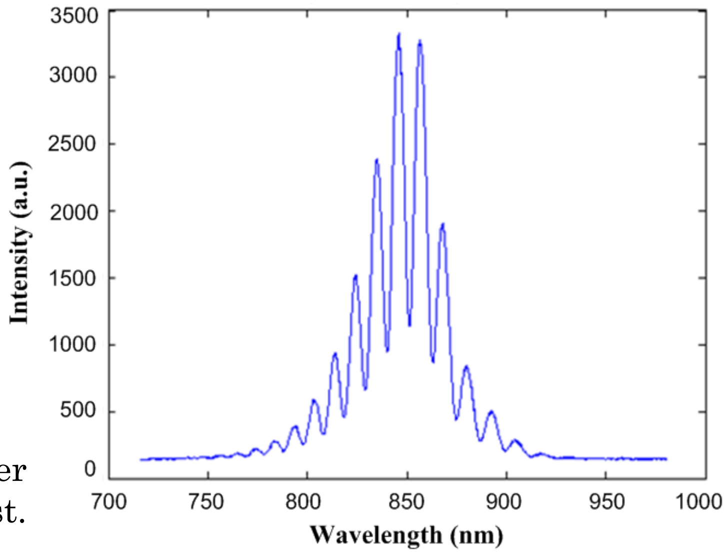
- Improved fringe quality by polishing :



↑ Polishing platen for controlled wafer thinning.

Fringe visibility as a function of wafer thickness →





Fringe of a sapphire wafer demonstrating improved contrast. →

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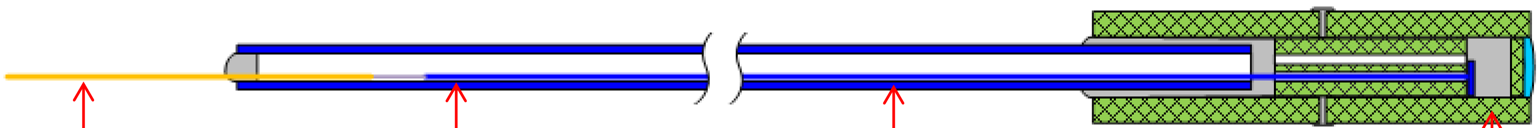
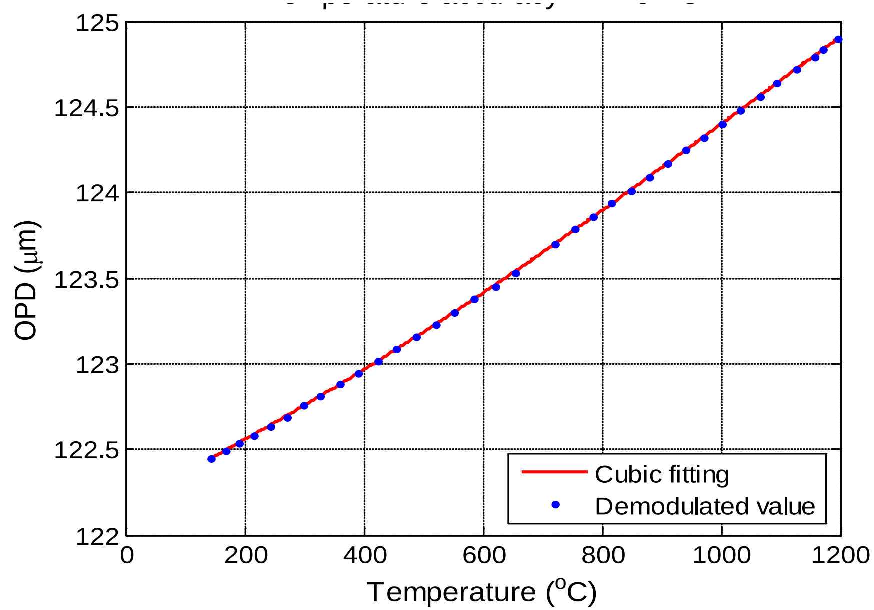
Progress (III)

- Improved sensor design:



Au-coated fiber | Bendable sapphire tube | Sensor in alumina tube



The new design allows for better protection of the sapphire components.

New sensor design: lab testing result.

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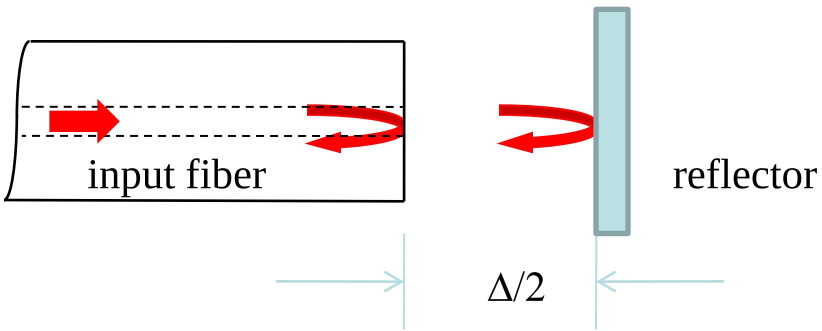
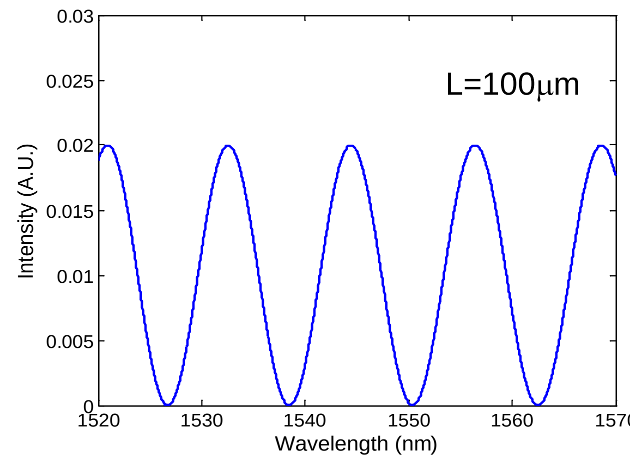
Theoretical Issues with Fiber Interferometry





It seems very logical to express the differential phase delay as

$$\varphi = \frac{\Delta}{\lambda} \cdot 2\pi + \varphi_o$$

where λ is light wavelength and φ_o is assumed to be a constant.
The output intensity is then simply given by $I = I_o(1 + \gamma \cos\varphi)$

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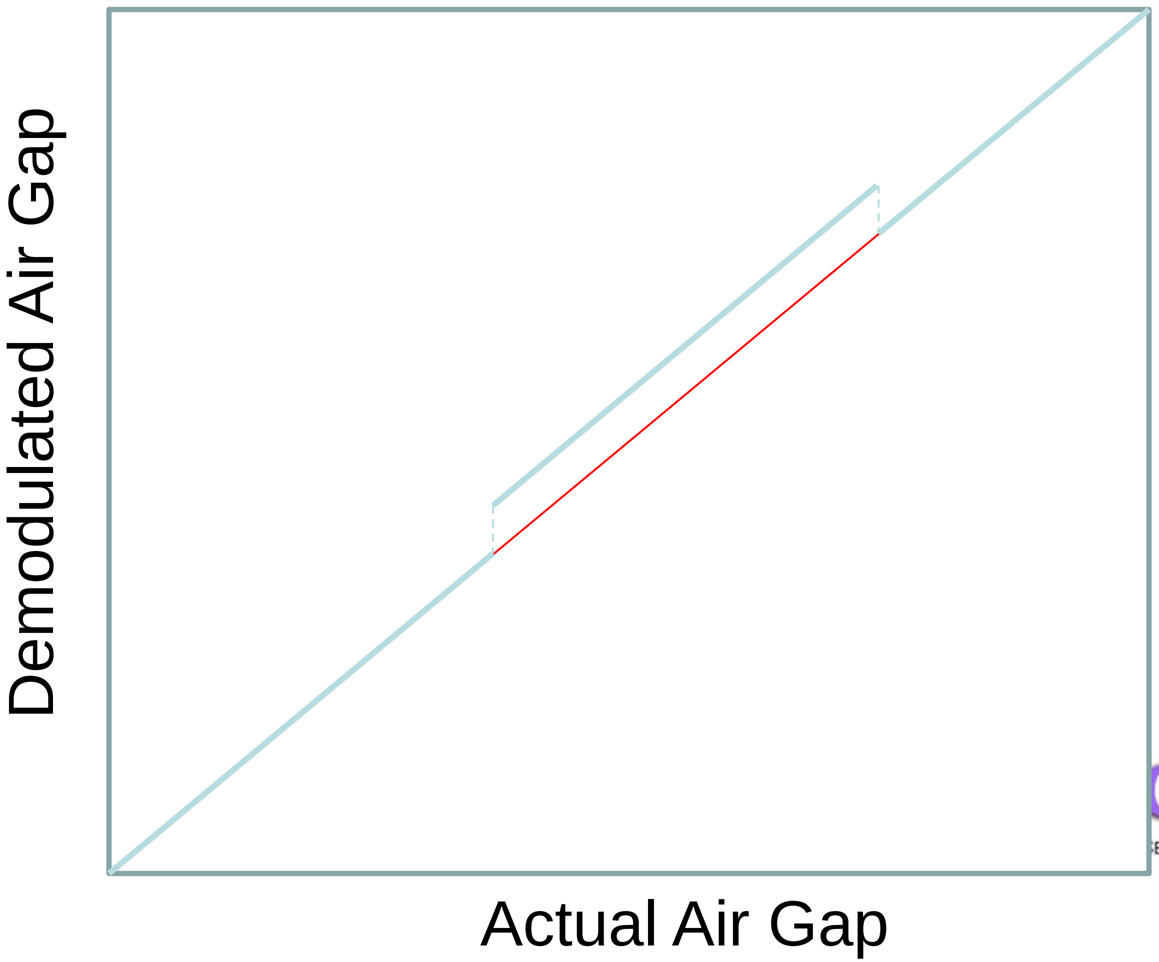
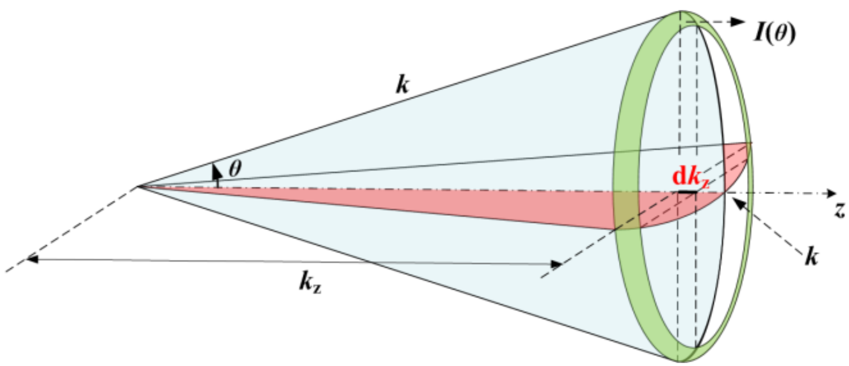
F-P Demodulation Jumps

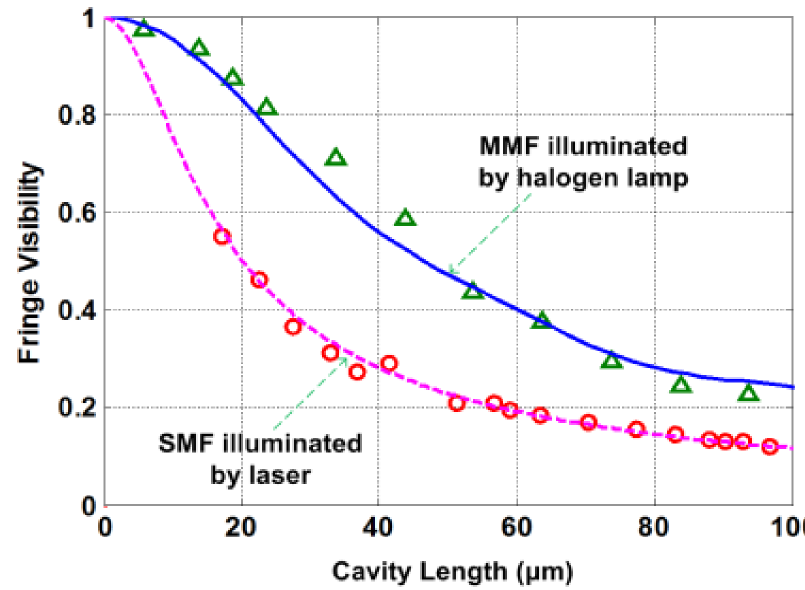


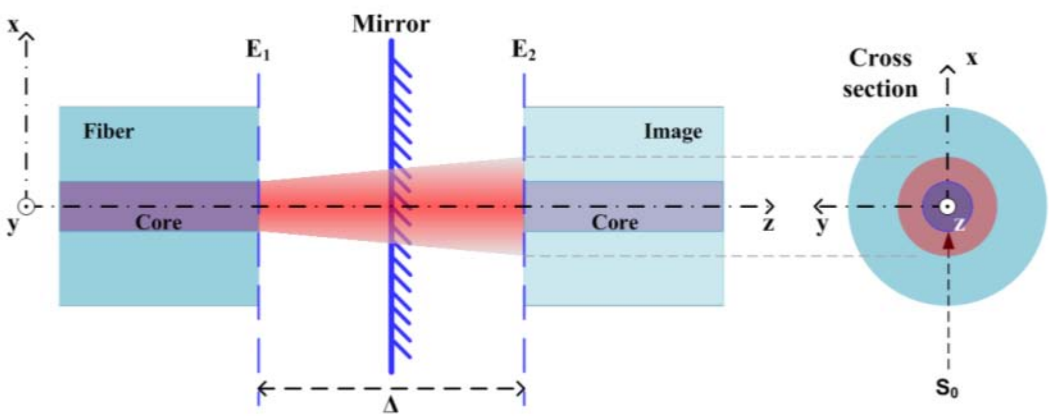
Progress (IV)

- Modeling of the low-finesse FP cavity.



↑ Model for calculating the longitudinal power distribution and interference spectra of the FP cavity. ↓





Improved model reveals parameters affecting the signal quality[1] ↑

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[1] Cheng Ma, *et al*, "Decoding the spectra of low-finesse extrinsic opticl fiber Fabry-Perot interferometers", *Optics Express*, **19**, pp.23727, 2011

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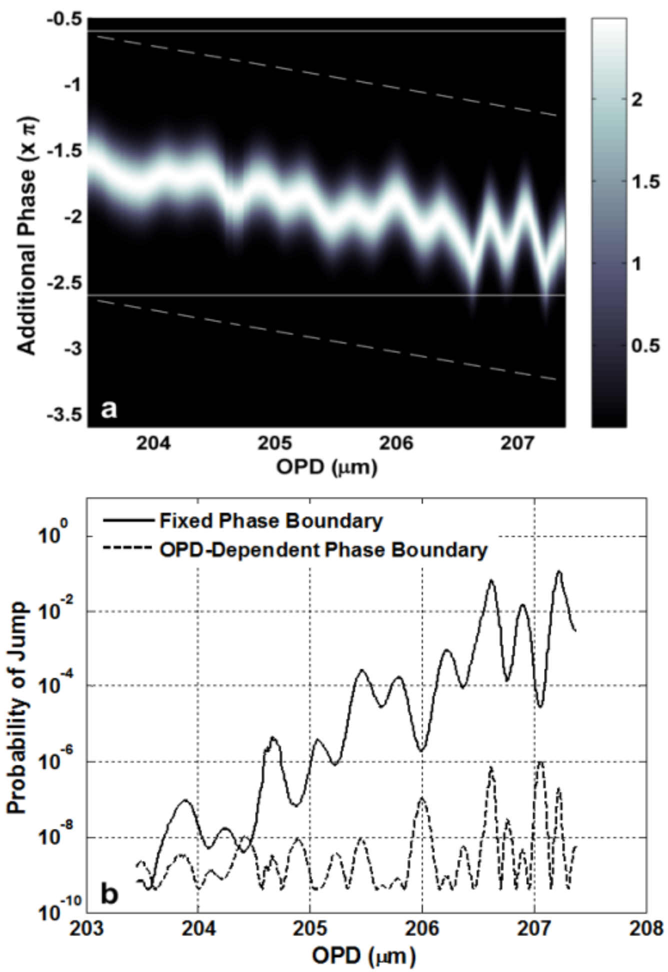
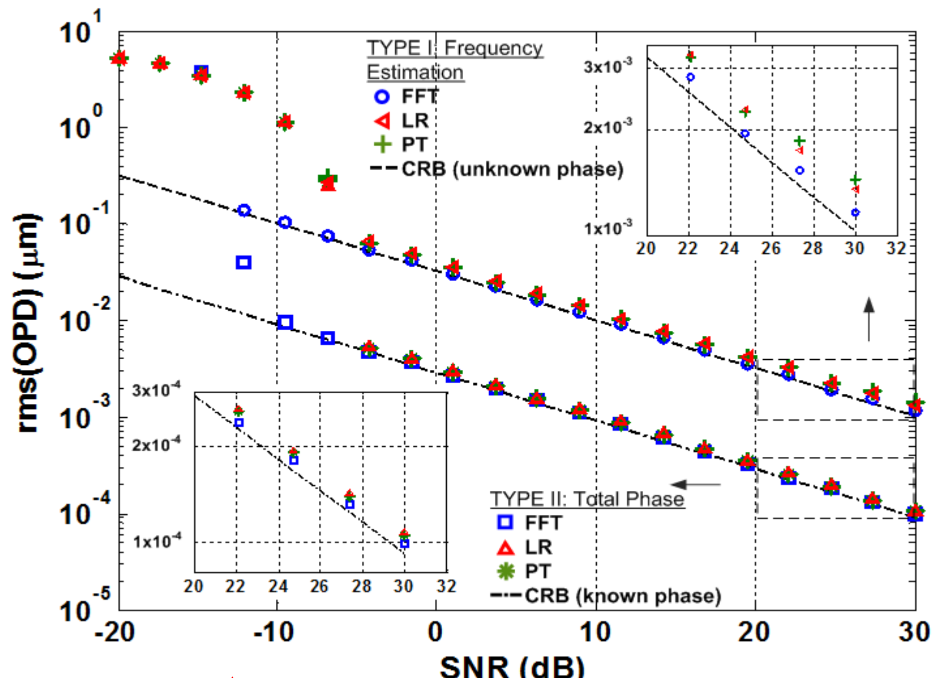
Progress (V)

- Improved WLI based signal processing.





Improved signal processing reaches the theoretical limit of resolution[1]

a. A non-constant phase term was analyzed. b. A special treatment of the phase term results in dramatically reduced jump probability[1]

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[1] Cheng Ma and Anbo Wang, "On the signal processing of WLI low-finesse fiber optic Fabry-Perot sensors", to be submitted to *Applied Optics*

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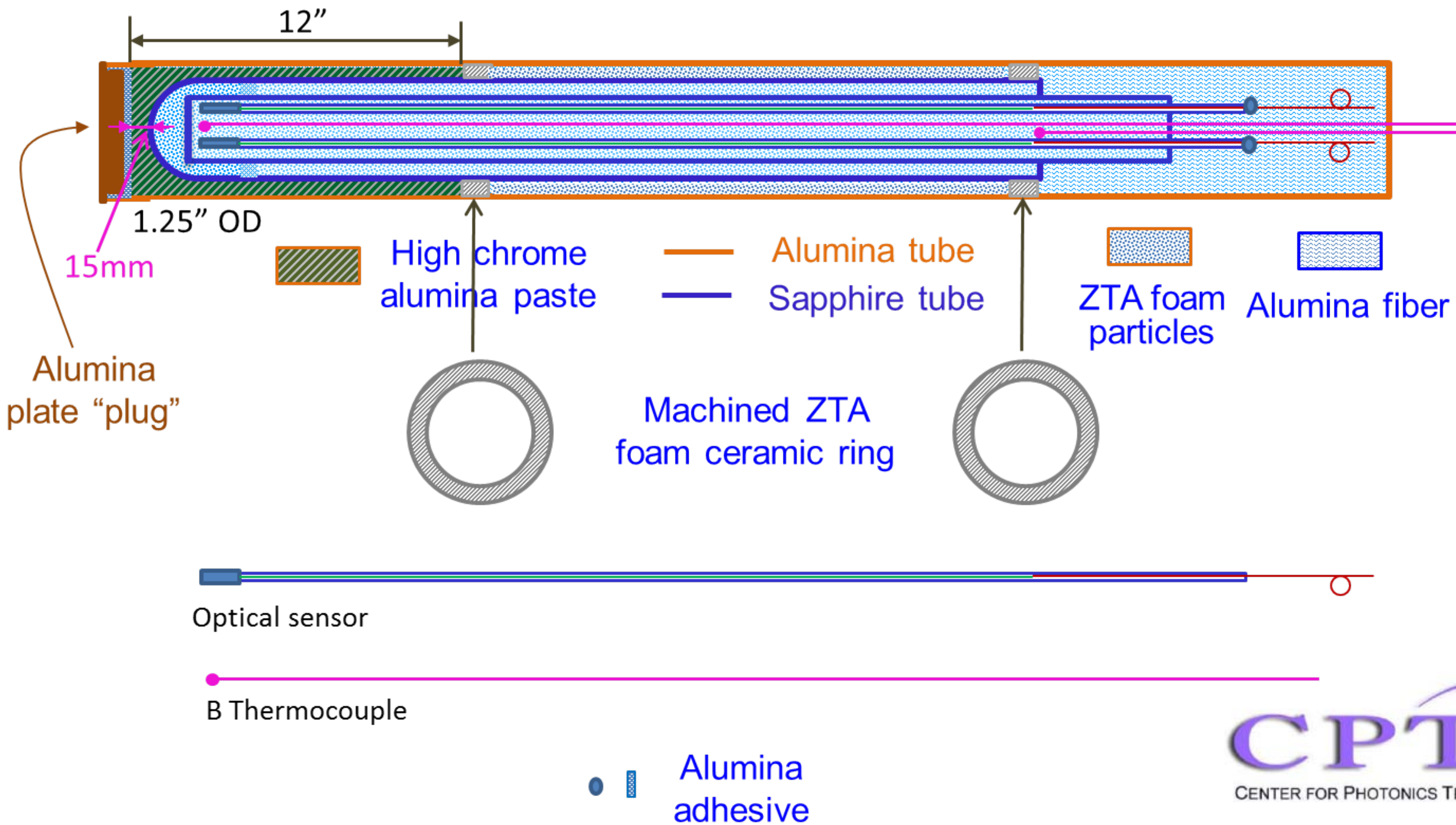
Progress (VI)

- Improved sensor packaging:



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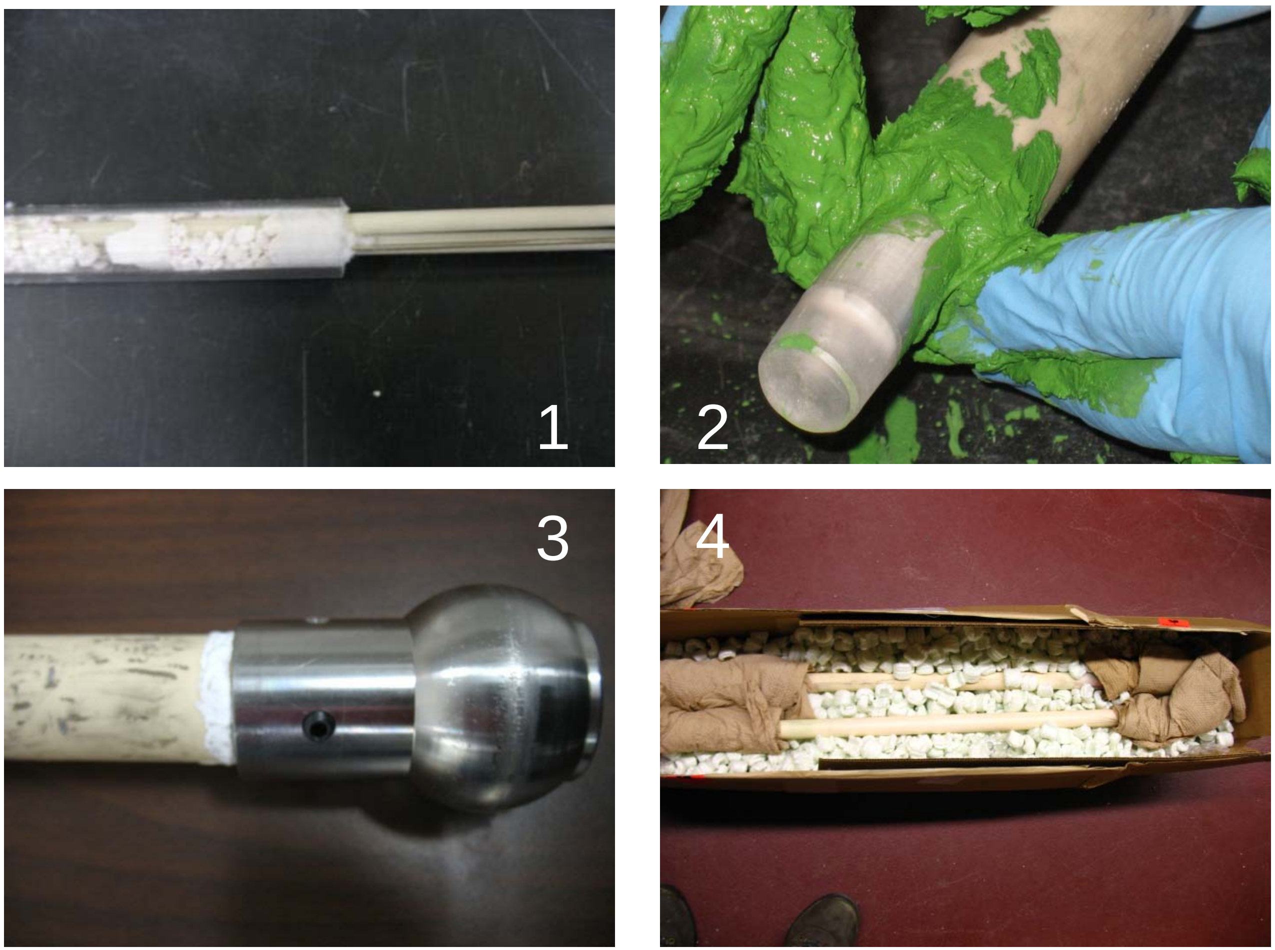
Progress (VI), *contd.*

- Improved sensor packaging: probe assembly.



1~4: Blank probe assemble process.

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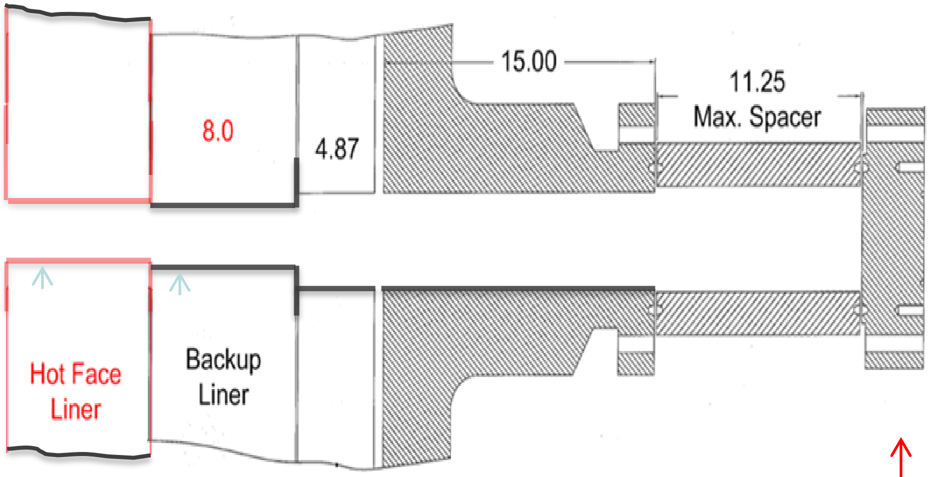
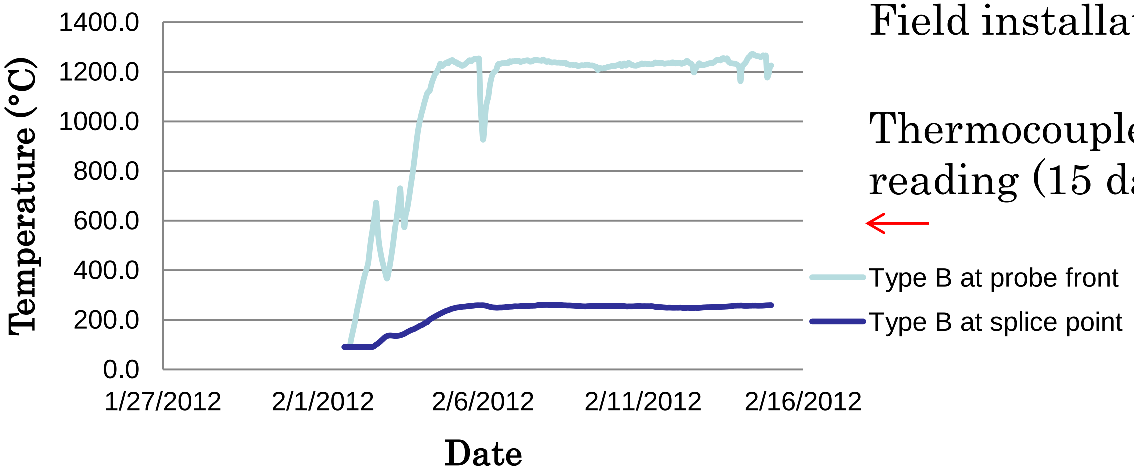
Progress (VII)

- Blank probe field test (starting Feb 1, 2012):



Field installation.

Schematic drawing of the cross-section of the refractory wall.



Thermocouple reading (15 days).

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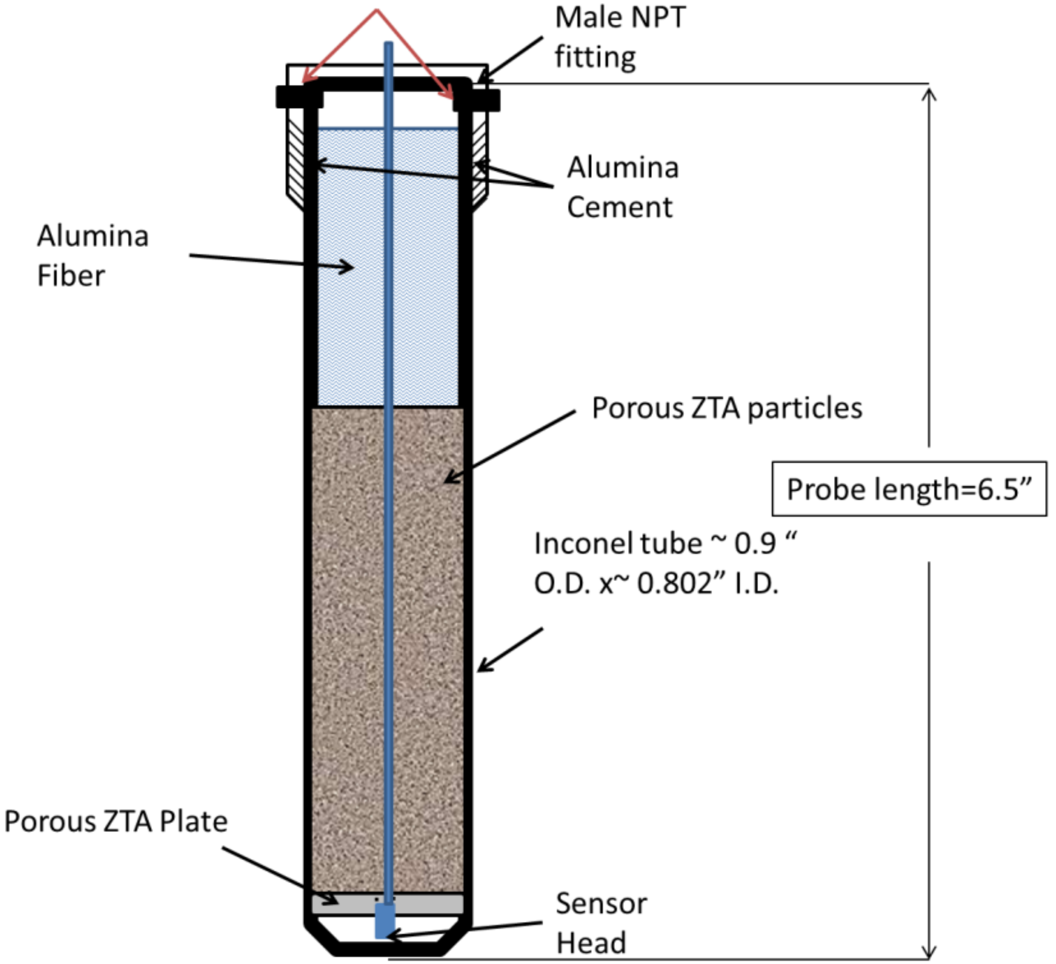
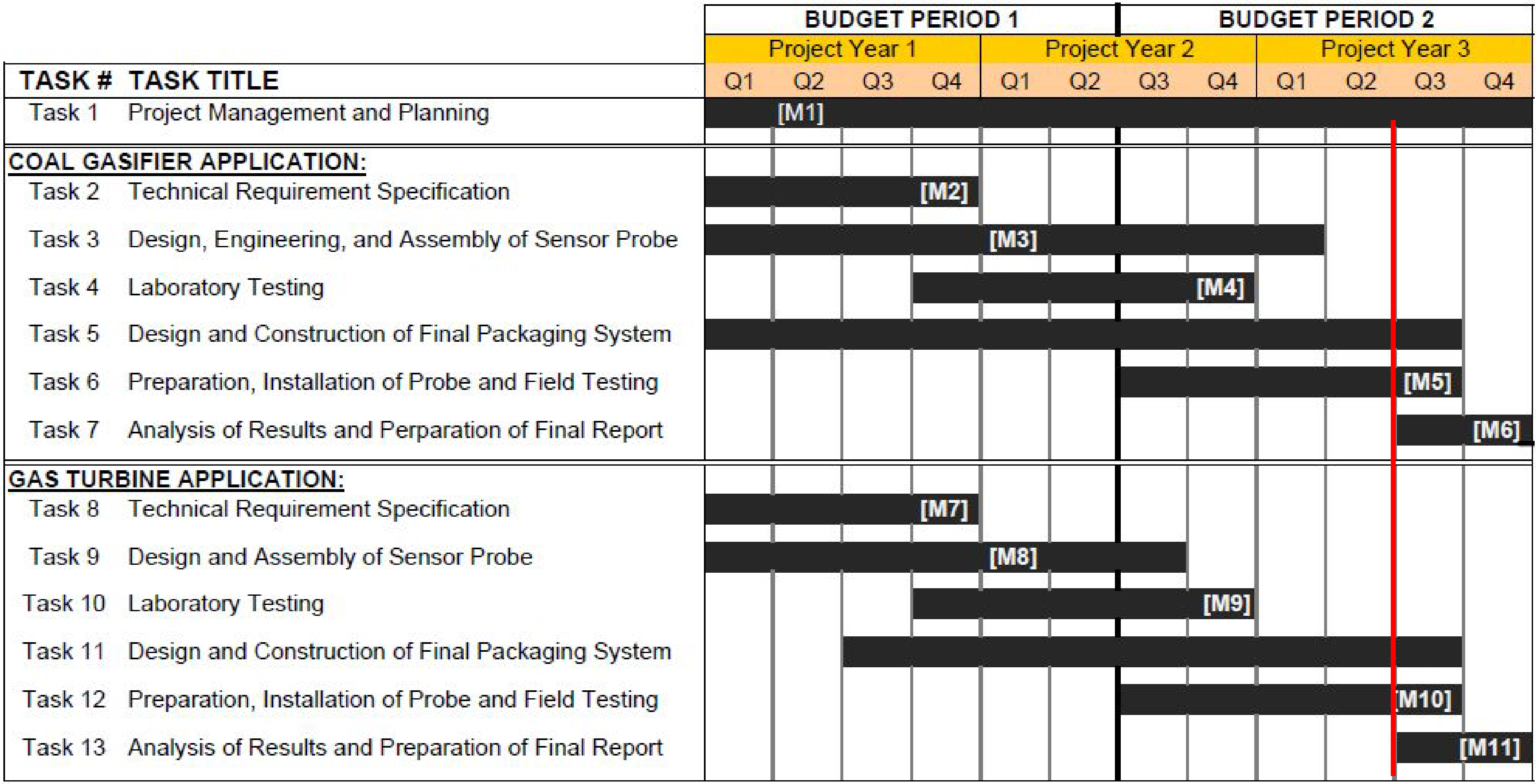
Progress (VIII)

- Probe design for field testing at NETL:



Progress (Summary)



Acknowledgement

We cordially thank our industrial collaborator Eastman Chemical Co. for their help with the sensor probe package design and field installation.

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