FOA 2193 Joint Project Kickoff Meeting

High-Accuracy and High-Stability Fiber-Optic Temperature Sensors for Coal Fired Advanced Energy Systems

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NETL

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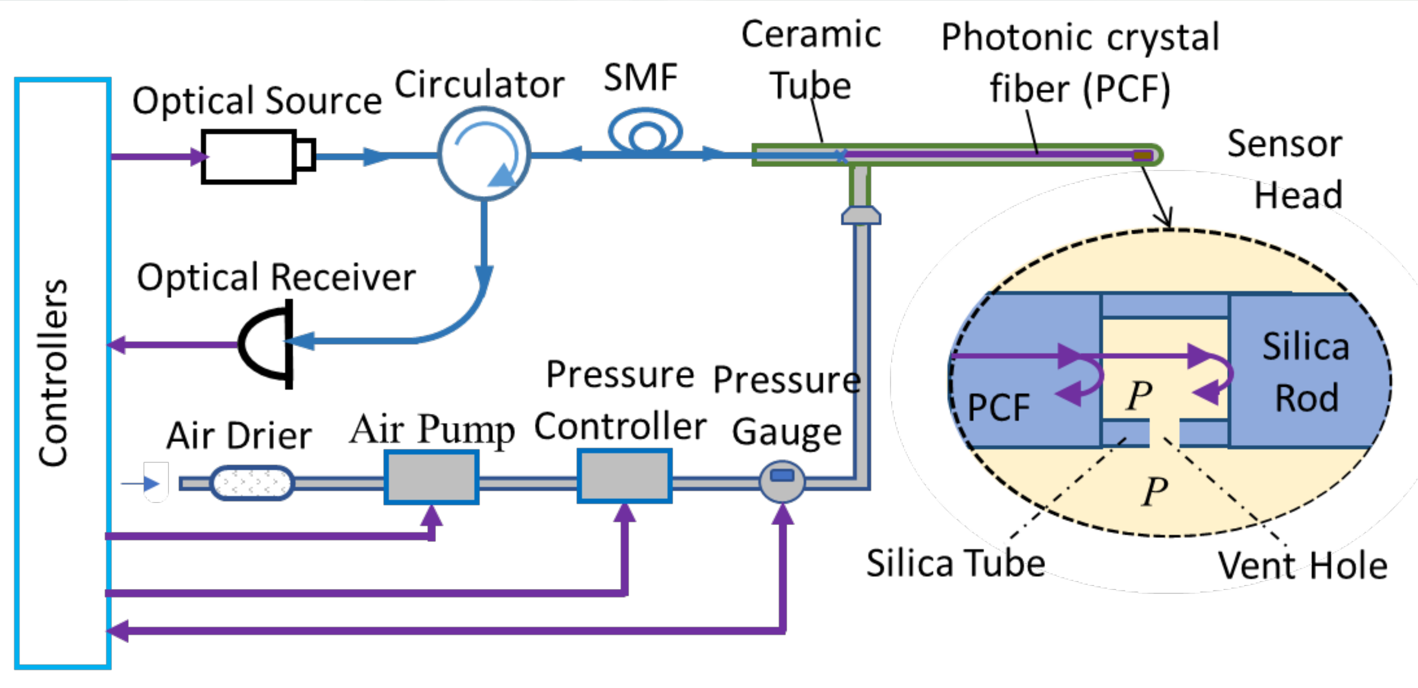
Research Goal

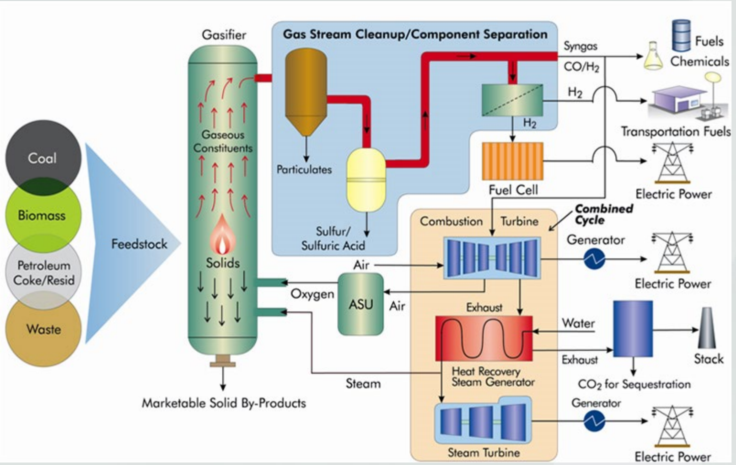
Develop a temperature sensor system that can operate at a temperature level above **1000 ºC** with **accuracy** and **long-term stability** comparable to the sensors of **low-temperature versions**.



- Using “gas” as the sensing element
- A sensing mechanism unaffected by the structural changes of the sensor head

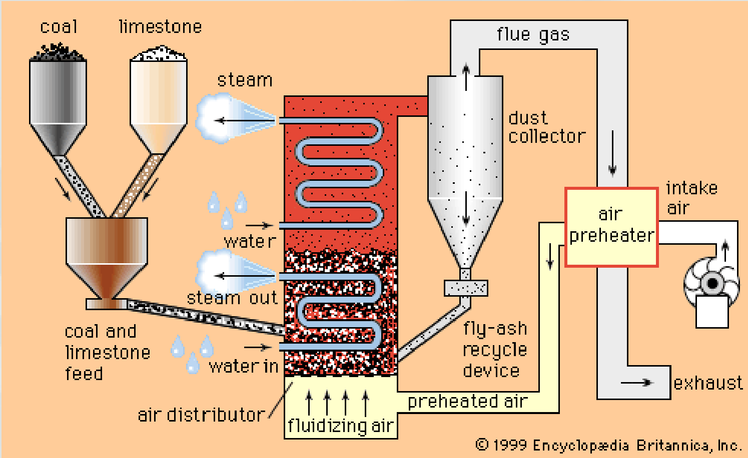
Temperature control in advanced coal-fired energy systems

Coal Gasification



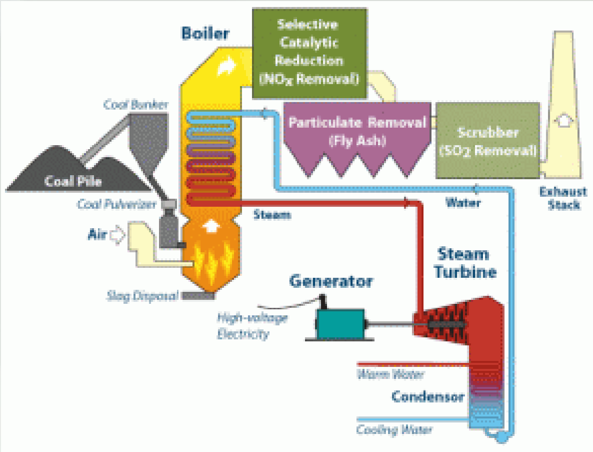
https://www.netl.doe.gov/

Fluidic Bed Combustion



https://www.britannica.com/

Ultra-Supercritical (USC) Steam Cycles

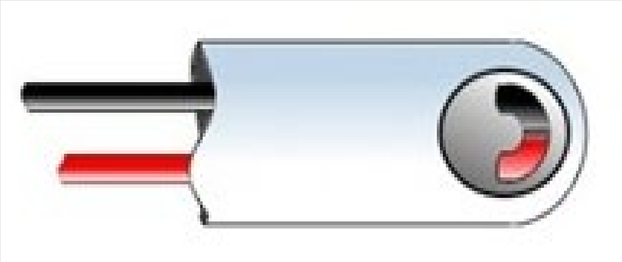


https://newenergyandfuel.com/

- Operation at extreme temperature levels (> 700 ºC) for improved efficiency and reduced emission of green-house gases
- Temperature control critical for sustained operation at optimal conditions, e.g. for USC
  - Annual average increase of 2 ◦C from ideal → 1-month reduction in USC lifetime
  - Annual average decrease of 2 ◦C from ideal → 1% increase in fuel consumption
- Need for temperature sensors w/ high accuracy and high stability in harsh environment.

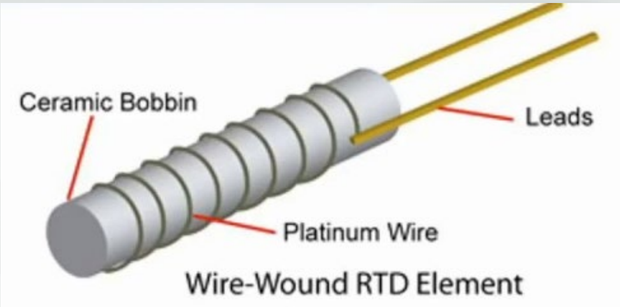
Challenges of existing contact temperature sensors

Thermocouples



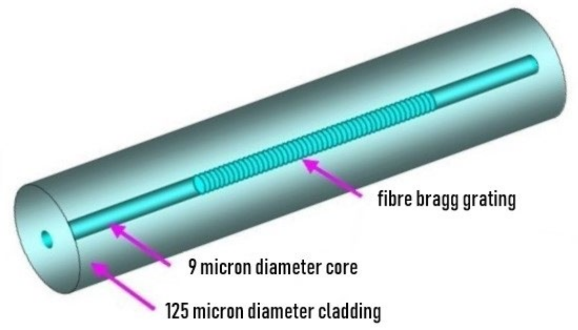
https://www.ni.com/

Resistance Temperature Detectors



https://www.designworldonline.com/

Optical Sensor

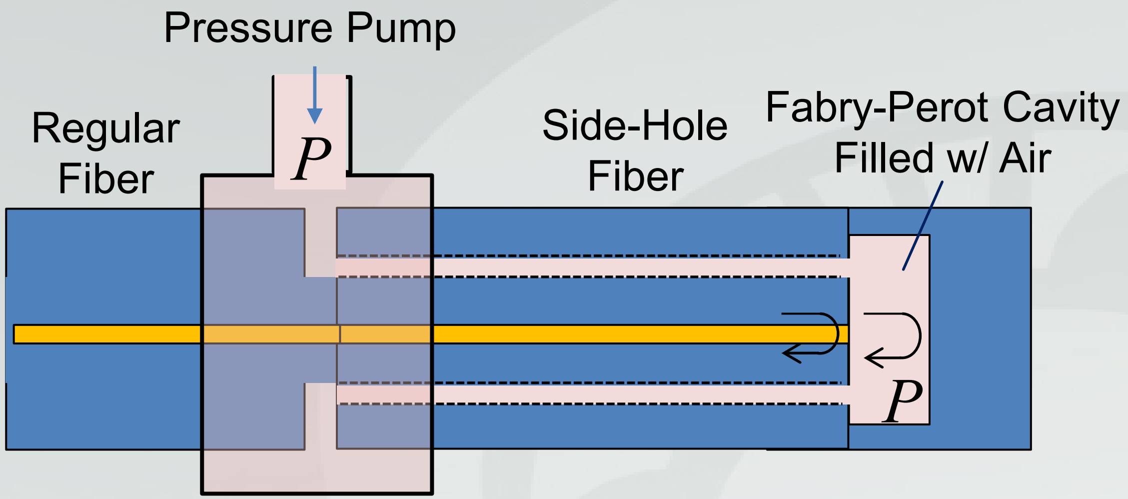


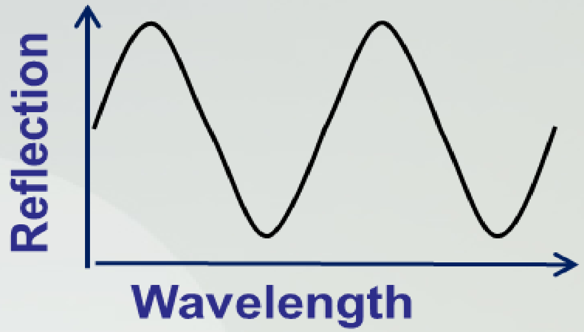
https://www.epsilonoptics.com/

Sensing elements are some “solid” materials

- Limited temperature capability
- Degraded performance at high temperature: drift, reduced accuracy
  - Structural changes (e.g. crystallization)
  - Chemical changes (e.g. oxidation)
- Cross-sensitivity to other parameters (e.g. strain, bending)
- Self-heating; electromagnetic interference

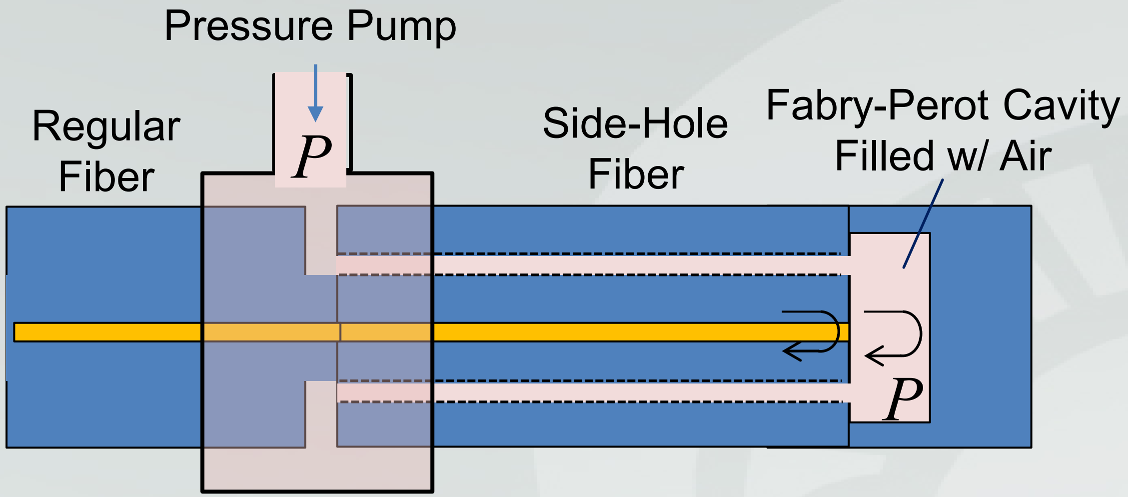
Principle of Operation

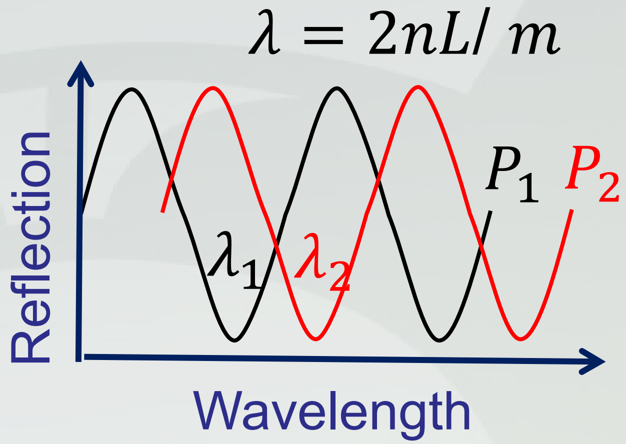


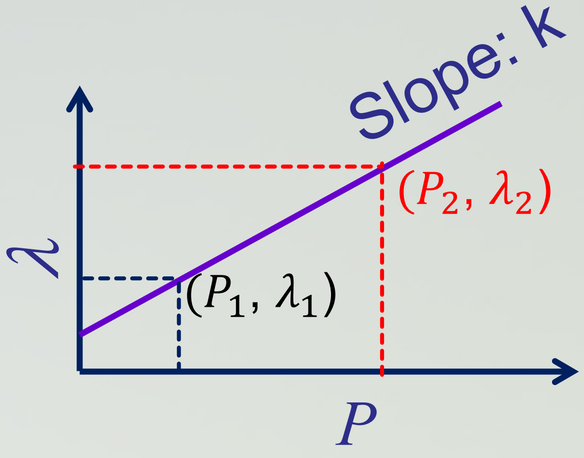


- Optical property (refractive index) of "Gas" is a function of temperature
- Inherently stable at high temperature (gas does not degrade at high temperatures)
  - No interactions among gas molecules
  - No chemical reactions
- Optical properties do NOT drift → good stability; high accuracy
- Signal cannot be affected by structural changes of the enclosure of the gas.

Fiber-optic temperature sensor – "gas" as the sensing element







- Refractive index of gas, n, is function of absolute temperature (T) & pressure (P):
- λ change linearly with P
- P can be varied and controlled to obtain slope k
- T can be deduced using $T = \alpha\lambda\ /\ k$.
- α: Inherent stable; k: insensitive to FP cavity length variation (0.1% change in k for 1000 με).

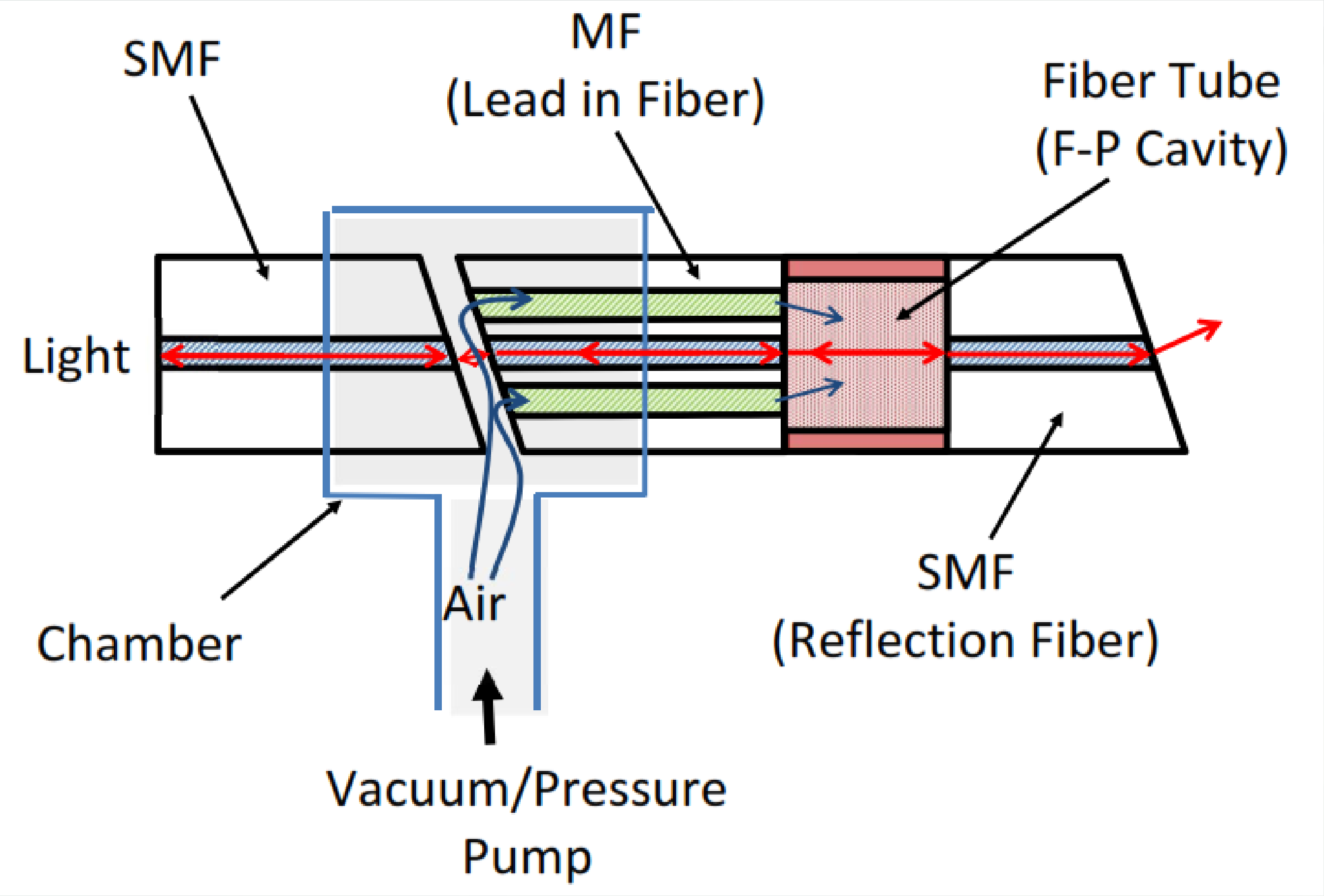
$$n - 1 = \alpha\ P\ /\ T \quad (\ll 1)$$

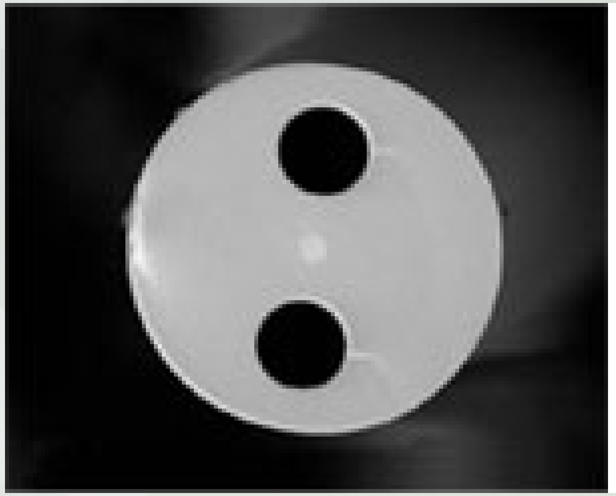
$$\lambda = \frac{2L}{m}\left(\frac{\alpha}{T}P + 1\right)$$

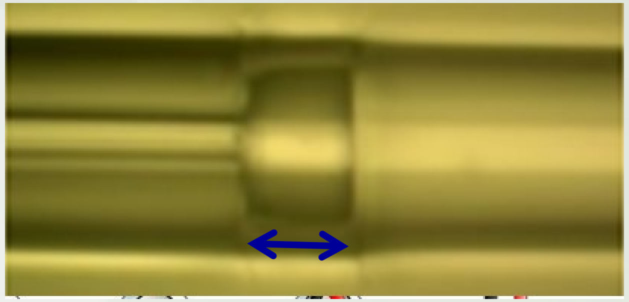
$$k \triangleq \frac{\partial\lambda}{\partial P} = \frac{2\alpha L}{mT}.$$

$$T = \alpha\lambda\ /\ k.$$

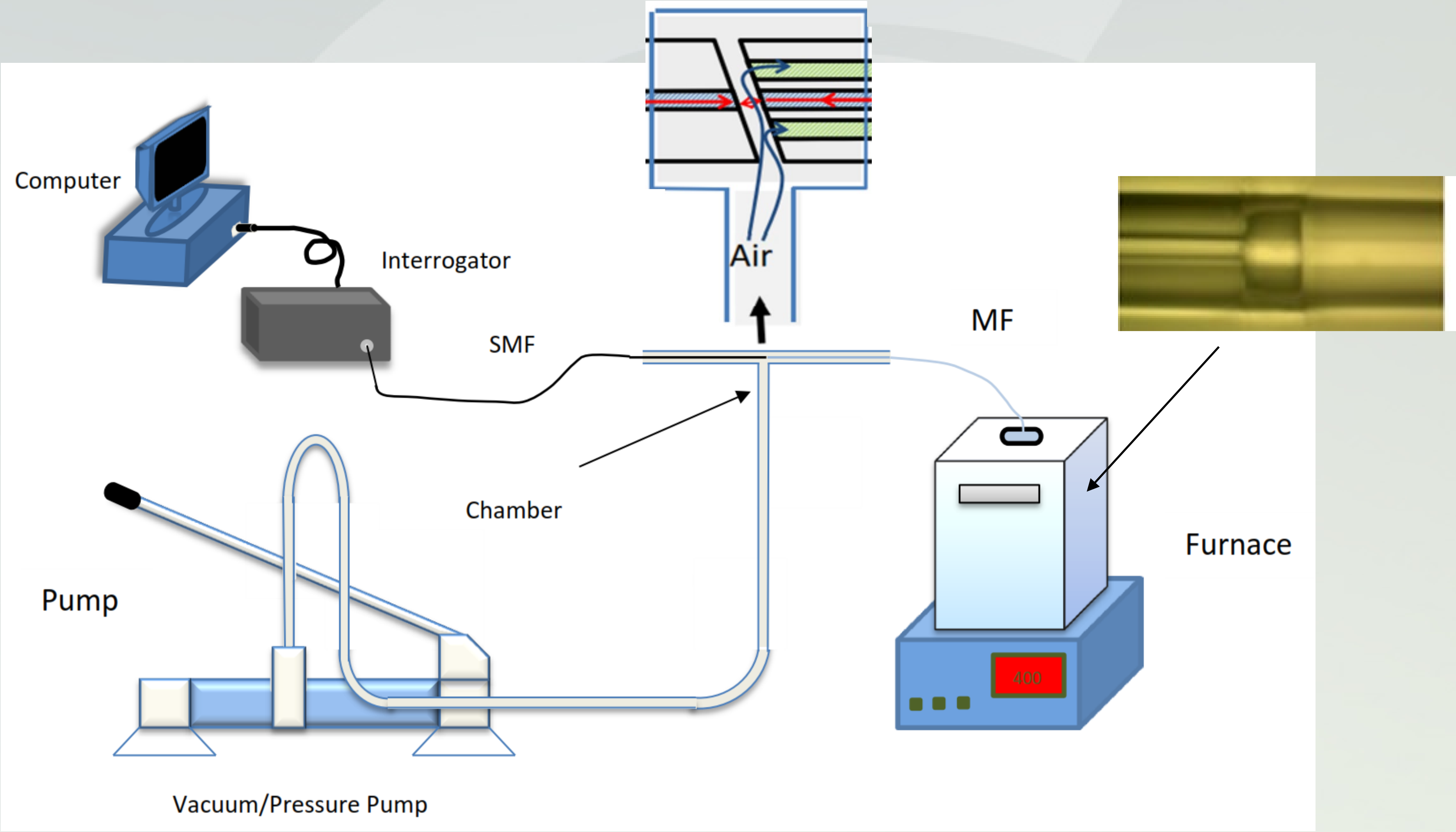
Preliminary result – Experimental setup





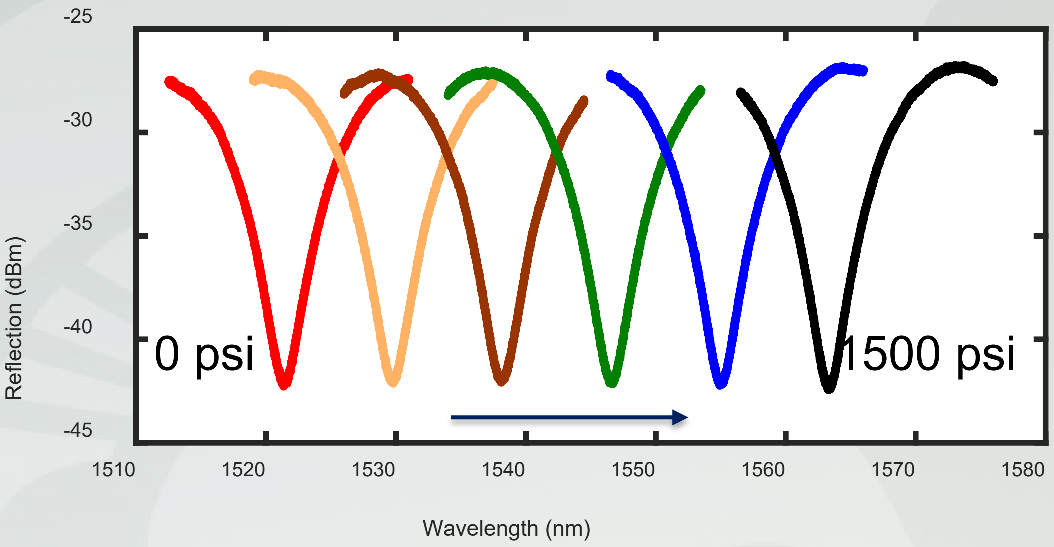


Preliminary result – Experimental setup

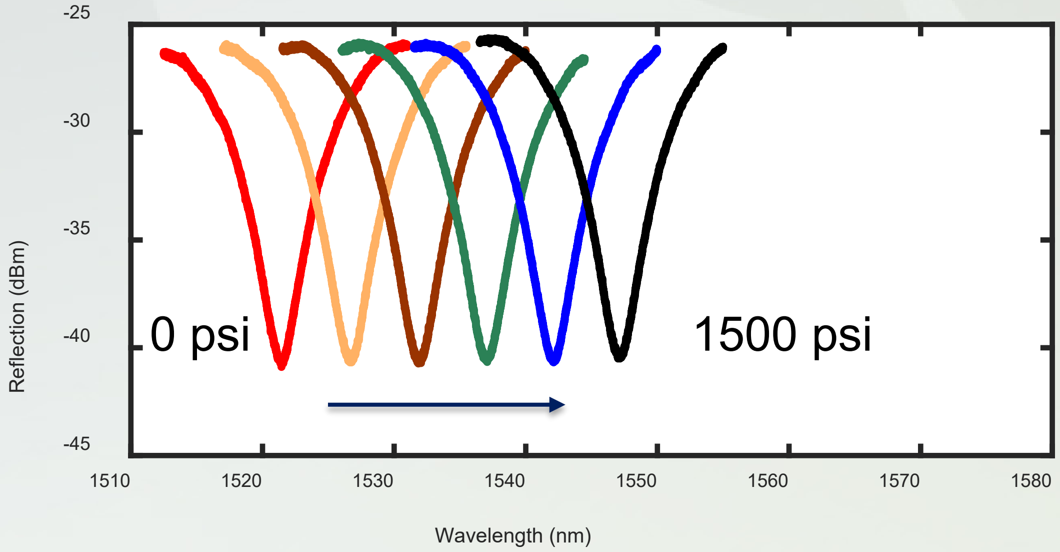


Preliminary result – Spectral shift vs. P at two different T levels

Pressure increases from 0 to 1500 psi in a step size of 300 psi

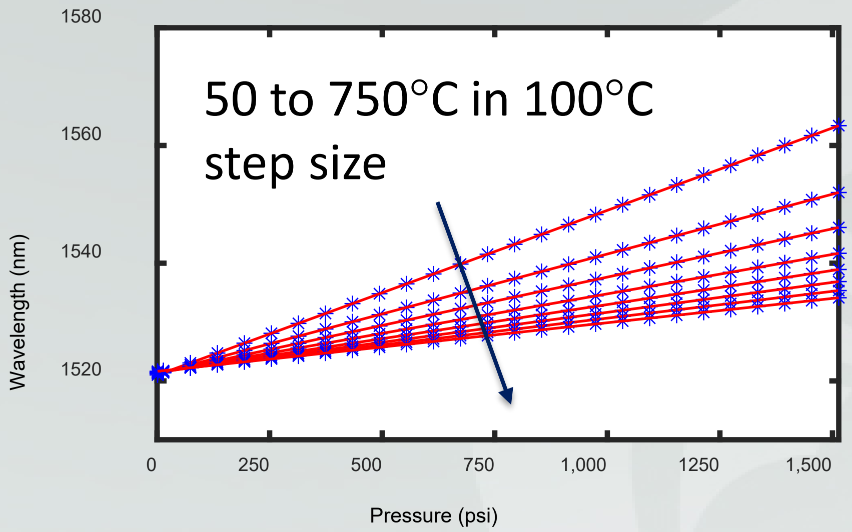


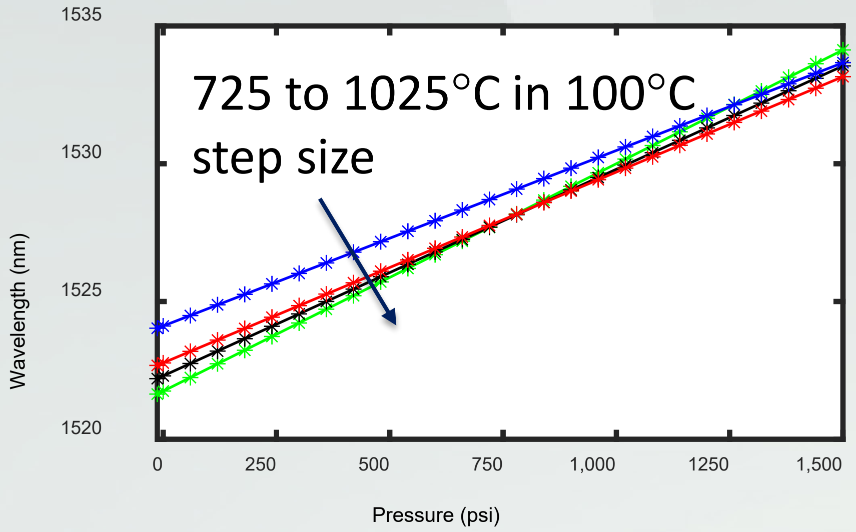
25 °C

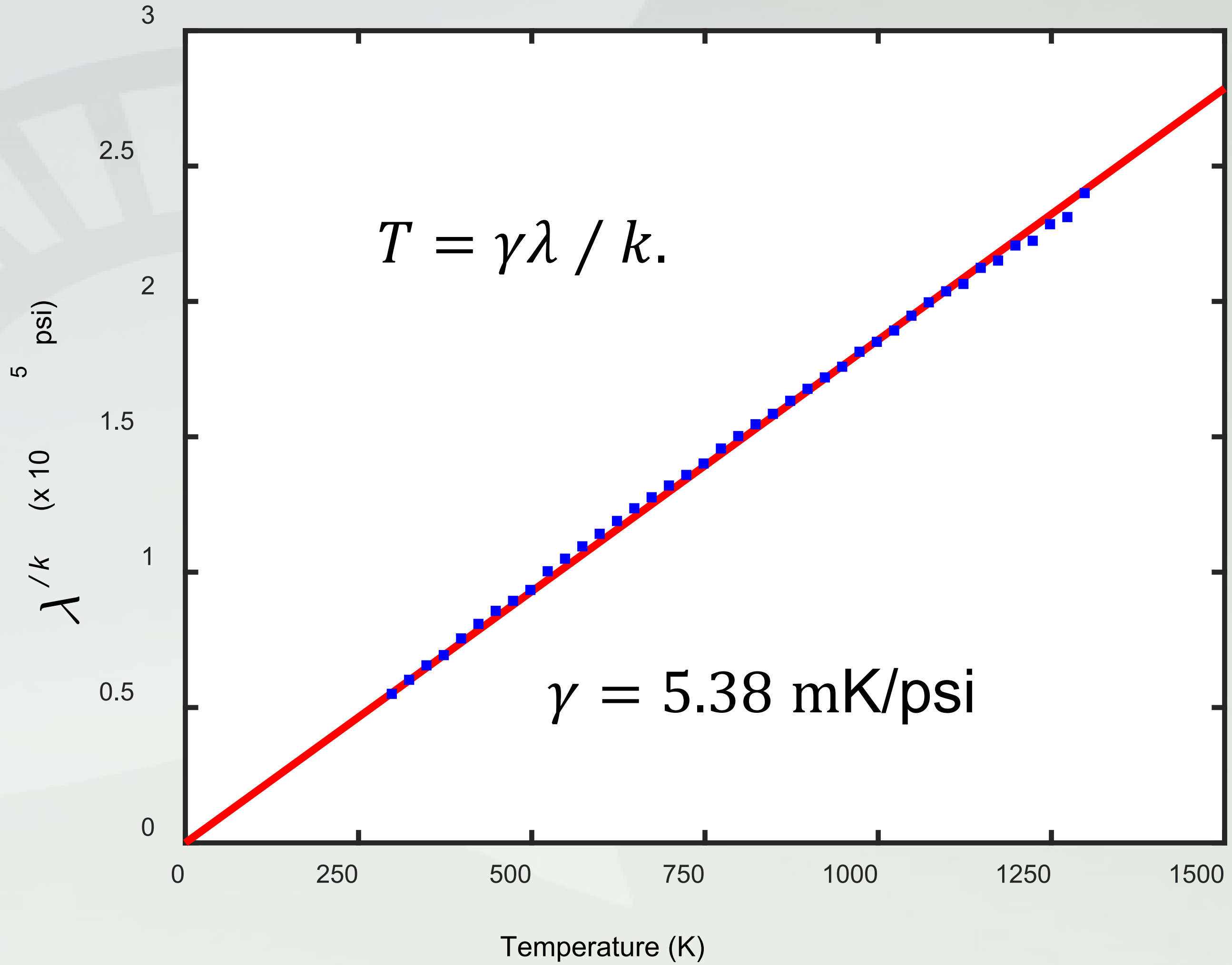


200 °C

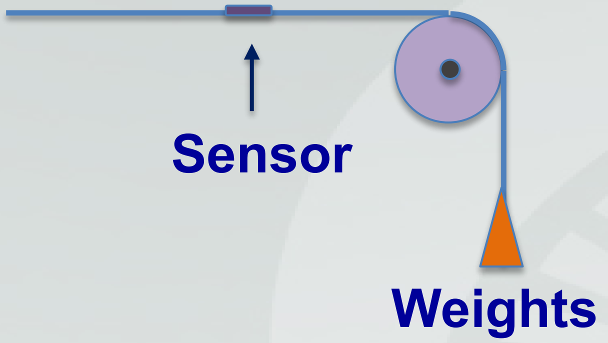
Preliminary result – Spectral shift vs. Pressure

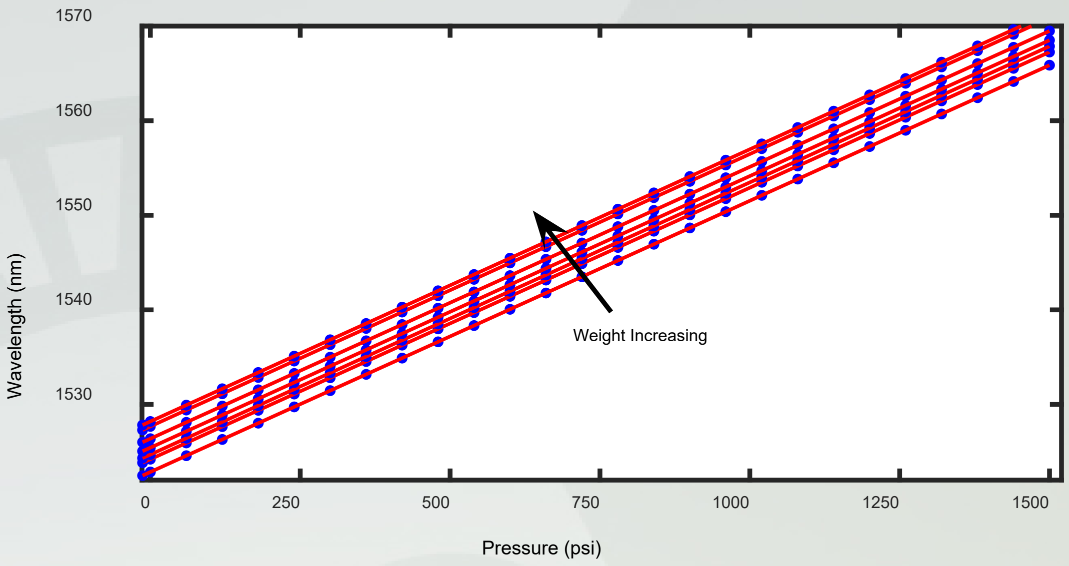




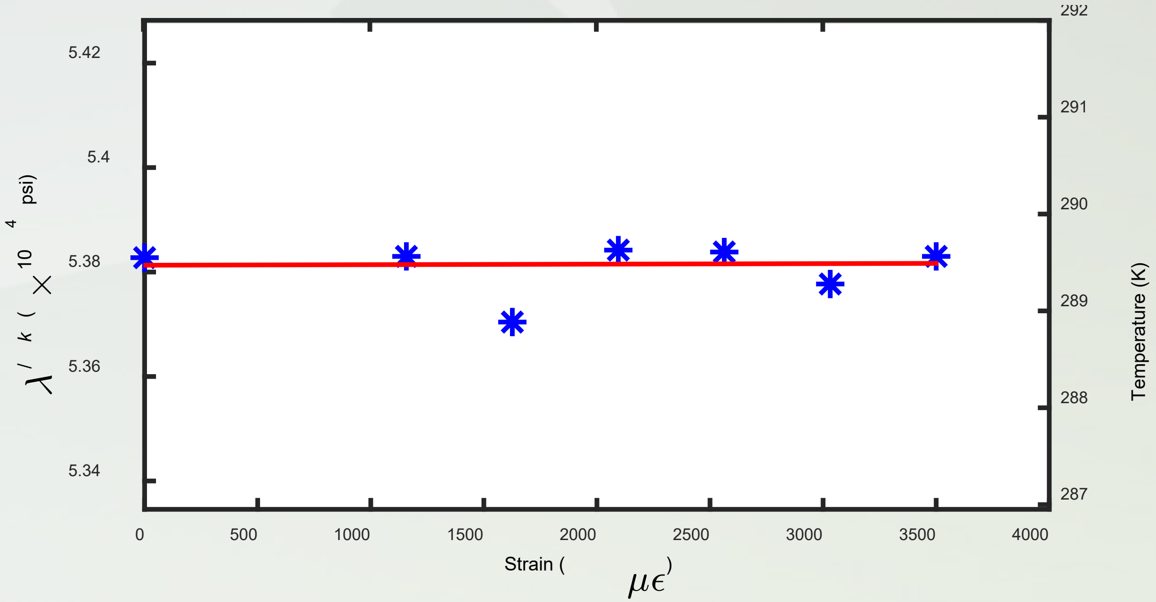


Preliminary result – Strain-insensitive measurement

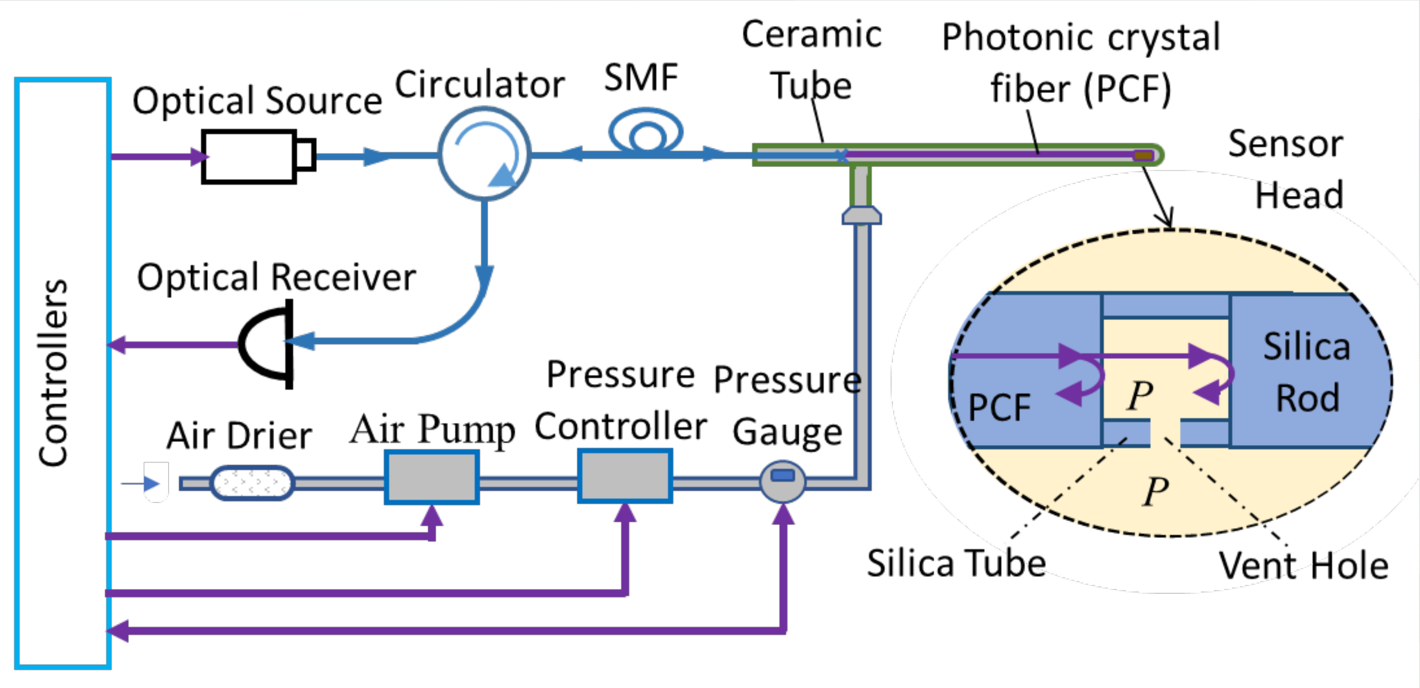


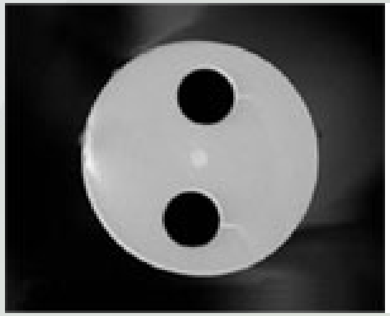


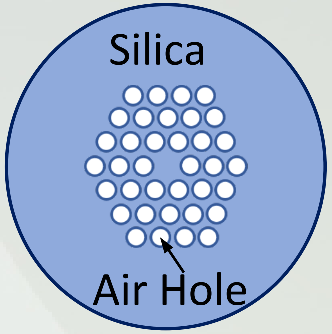
- Measurement at room temperature;
- Strains of different levels (0 – 3600 με) applied by adjusting weights
- T measurement variation < 1 °C (FBG Sensor: 3600 με ~ 360 °C)



Research work - System configuration

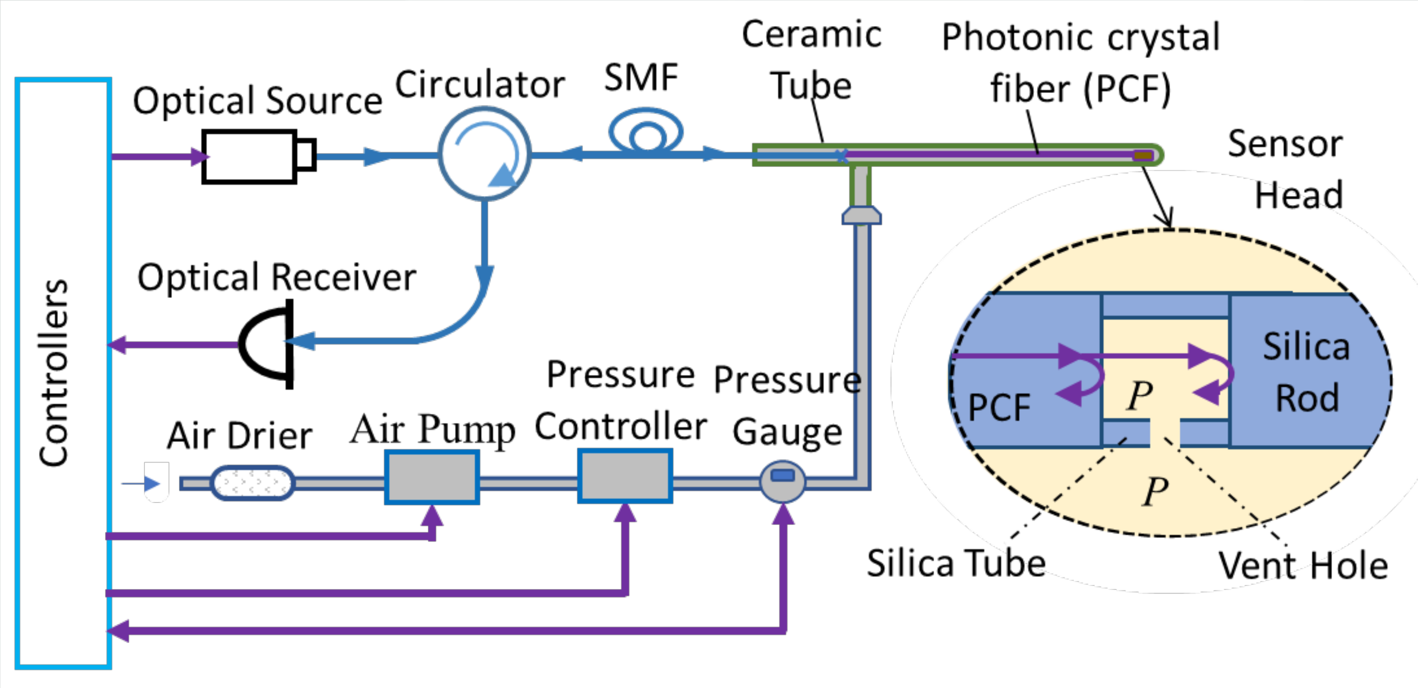






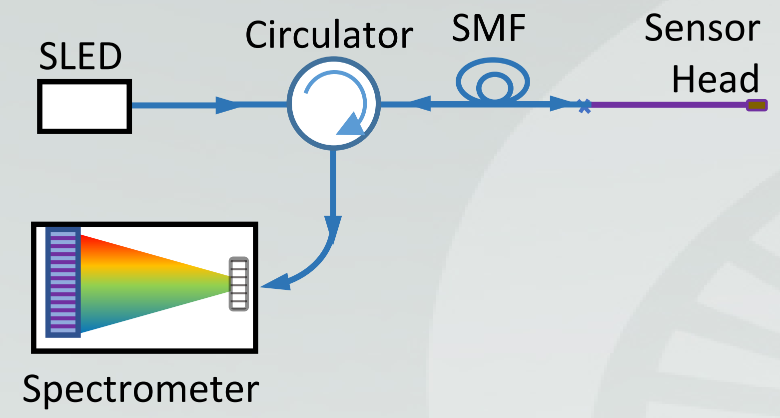
- Pressurization through a ceramic tube rather than through the small holes in the fiber → faster speed
- Venting hole on sensor head to avoid pressure-induced structural changes
- All-silica photonic crystal fiber to increase the temperature range to > 1200 ◦C (temperature of regular fiber is limited by dopant diffusion)

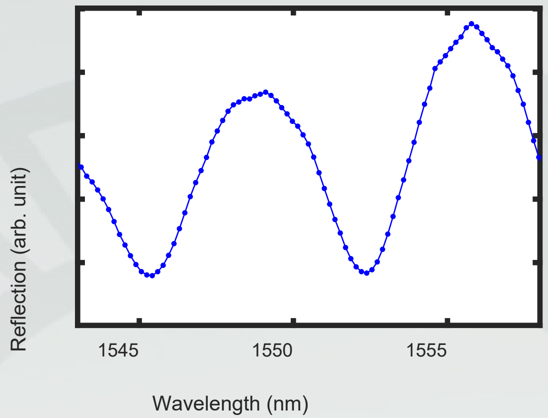
Research work – Pressurization system

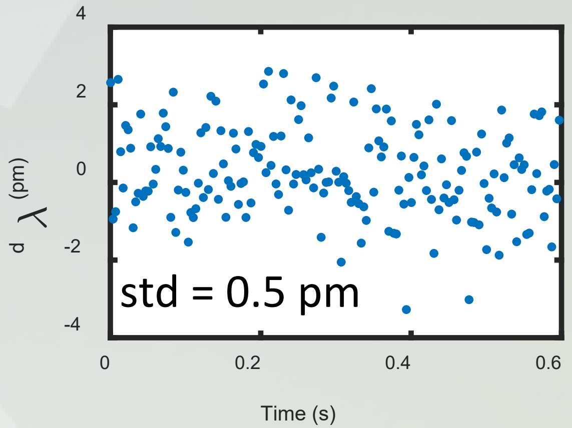


- Dry air for consistent air compositions
- Miniaturized air pump and pressure controller
- High-accuracy pressure sensor (0.01%)

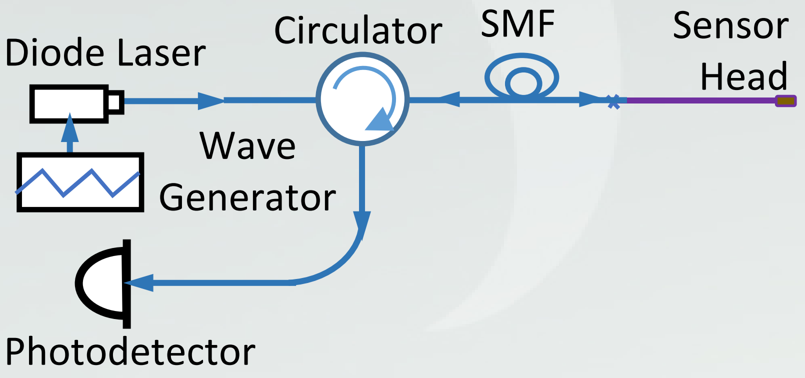
Research work – Sensor Interrogation

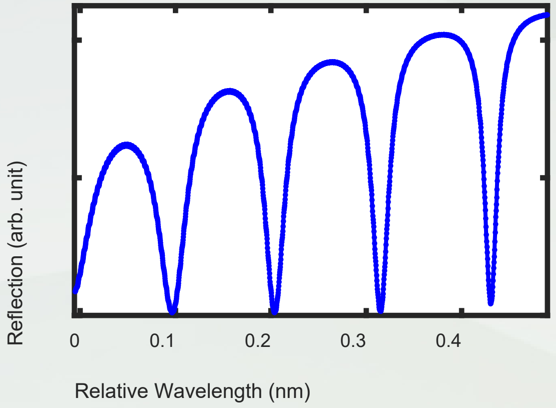


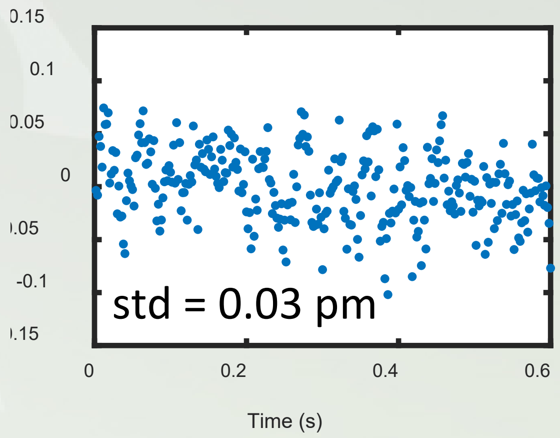




Interrogation using white light system







Interrogation using wavelength scanning laser

Research work – Sensor Characterization and Test

- Using metal fixed point cells to generate temperature references (accuracy: ~ 0.001 ◦C)
  - Tin – 231.928 ◦C
  - Aluminum - 660.323 ◦C
  - Silver – 961.78 ◦C
  - Copper - 1084.62 ◦C
- Resolution
- Accuracy
- Long-term drift
- Compare with thermocouples (R, S, or B type)
- Test results will provide feedback for sensor system optimization.

Summary

- High-accuracy, high-stability temperature sensor is critical for the safe and efficient operation of advanced coal-fired energy systems
- Using "gas" as the sensing element eliminates many drawbacks inherent to sensors using solid materials as the sensing elements
- Preliminary study has shown promising results
- To make this technology a viable solution in coal-fired energy system
  - Portable pressure system with automatic and precise control
  - Accurate sensor interrogation methods
  - Characterization and testing at high temperature levels
  - Other issues: sensor packaging; effects of air composition variations; effect of maximum pressure on measurement accuracy and resolution