2021 Project Review

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

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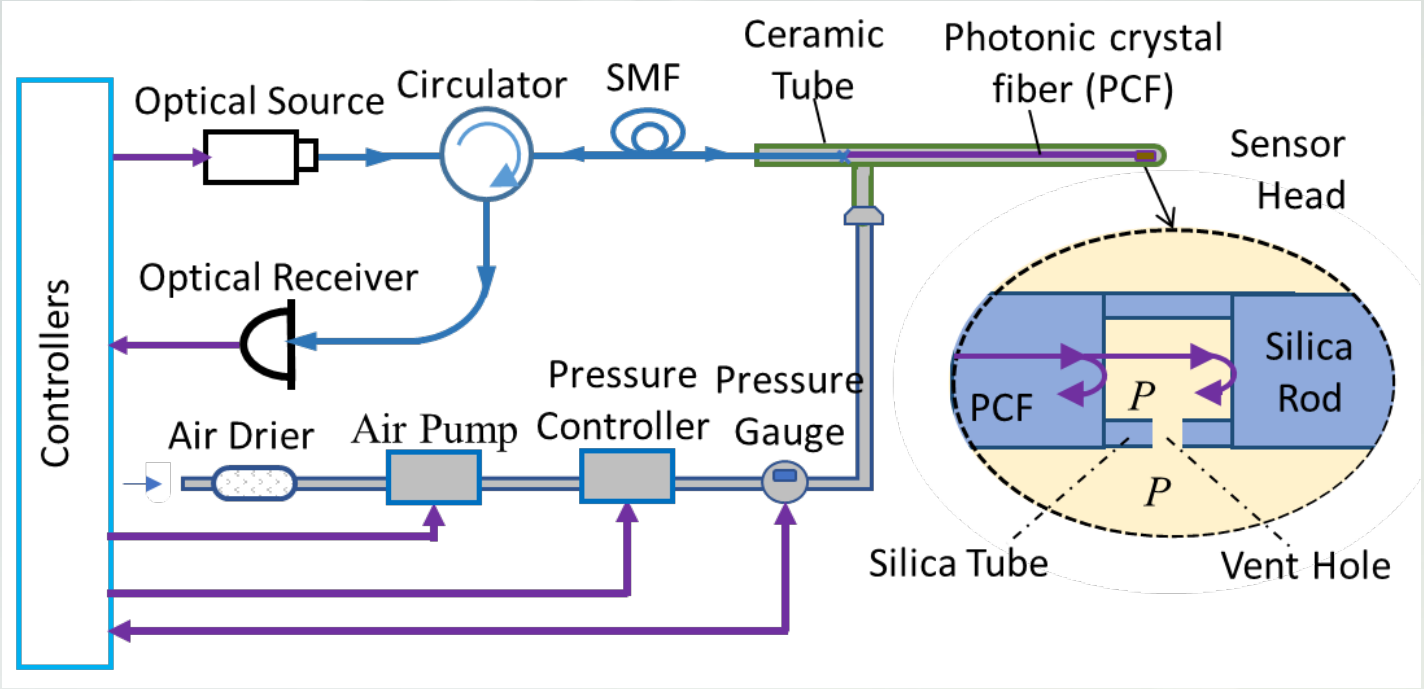
Research Goal

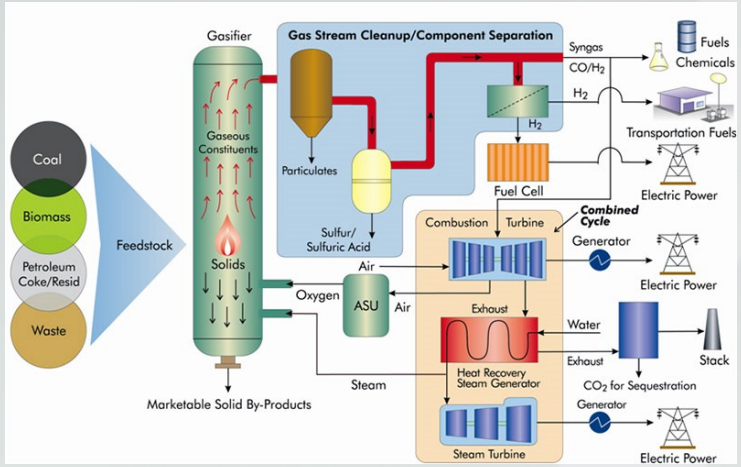
Develop a temperature sensor system that can operate at a temperature level above **1000 ºC** with **accuracy** and **long-term stability** comparable to the sensors of **low-temperature versions**.



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

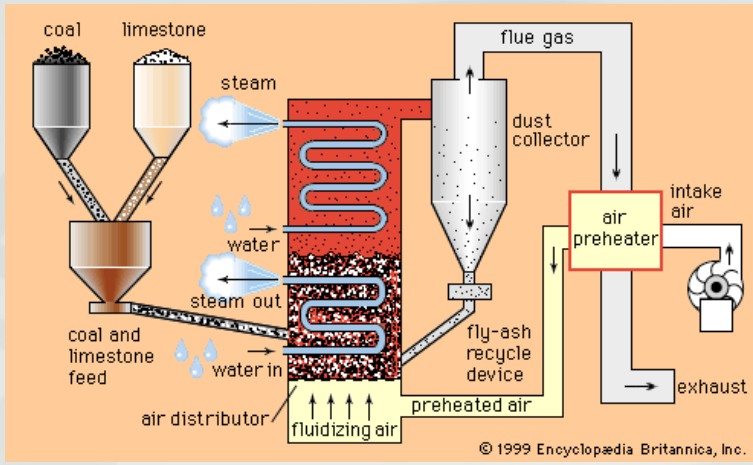
Temperature control in advanced coal-fired energy systems

Coal Gasification



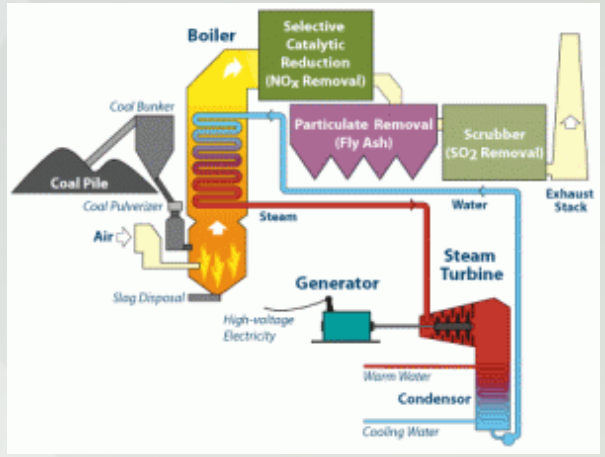
https://www.netl.doe.gov/

Fluidic Bed Combustion



https://www.britannica.com/

Ultra-Supercritical (USC) Steam Cycles

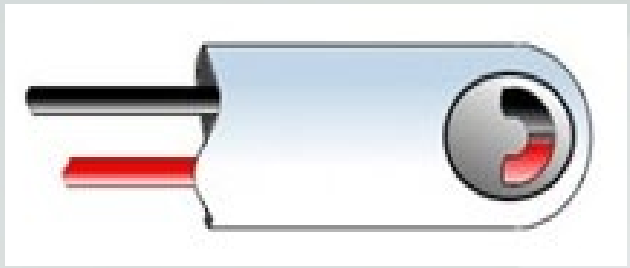


https://newenergyandfuel.com/

- Operation at extreme temperature levels (> 700 °C) 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.

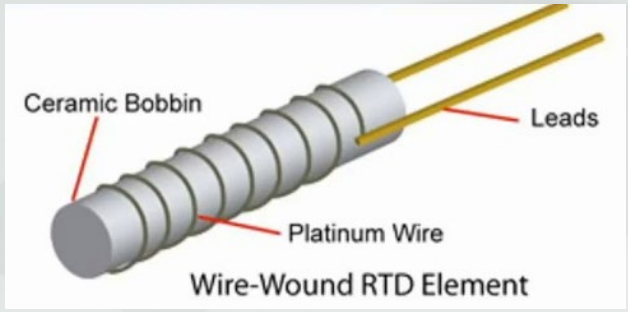
Challenges of existing contact temperature sensors

Thermocouples



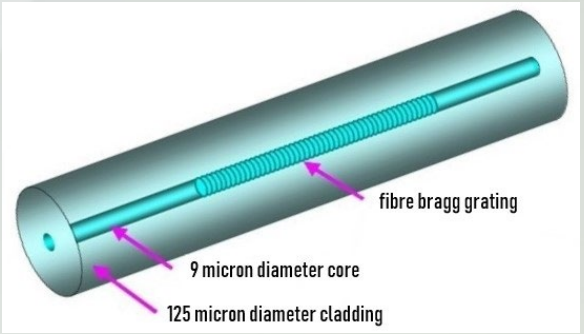
https://www.ni.com/

Resistance Temperature Detectors



https://www.designworldonline.com/

Optical Sensor

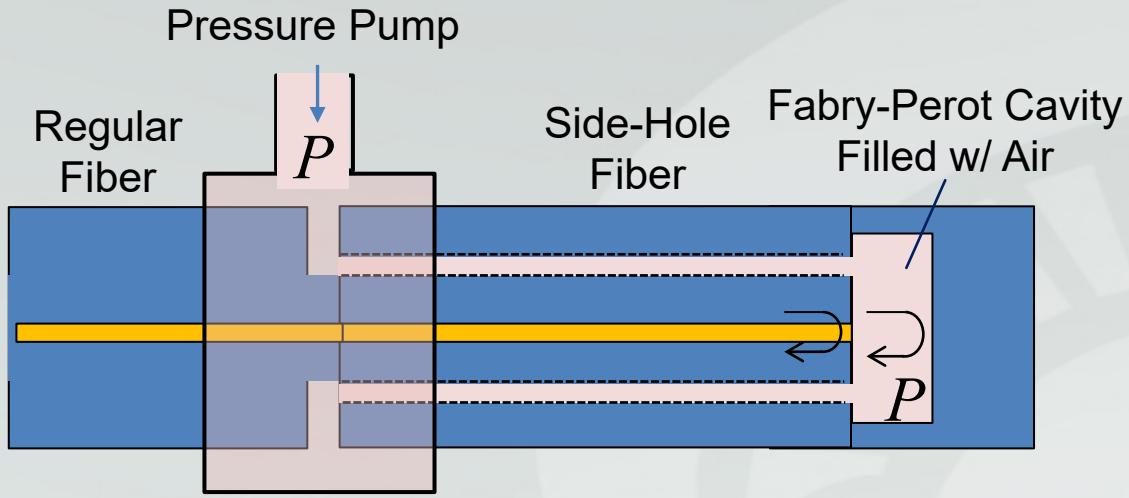


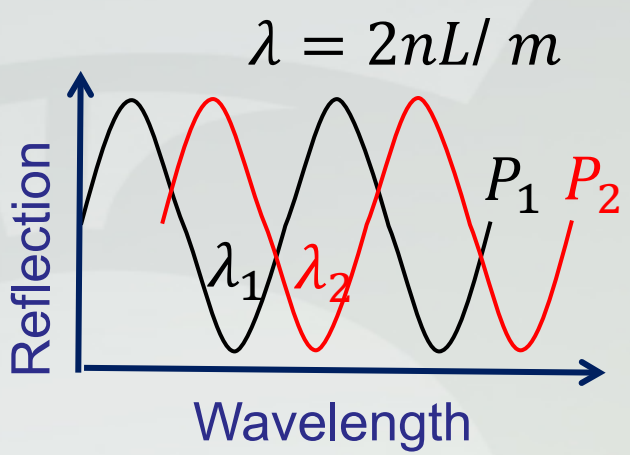
https://www.epsilonoptics.com/

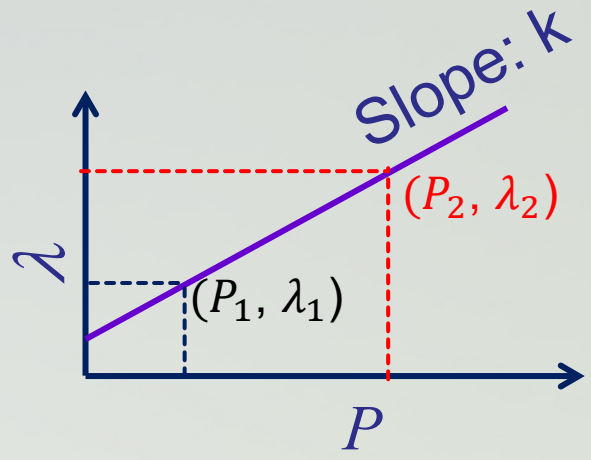
Sensing elements are some “solid” materials

- 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

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).

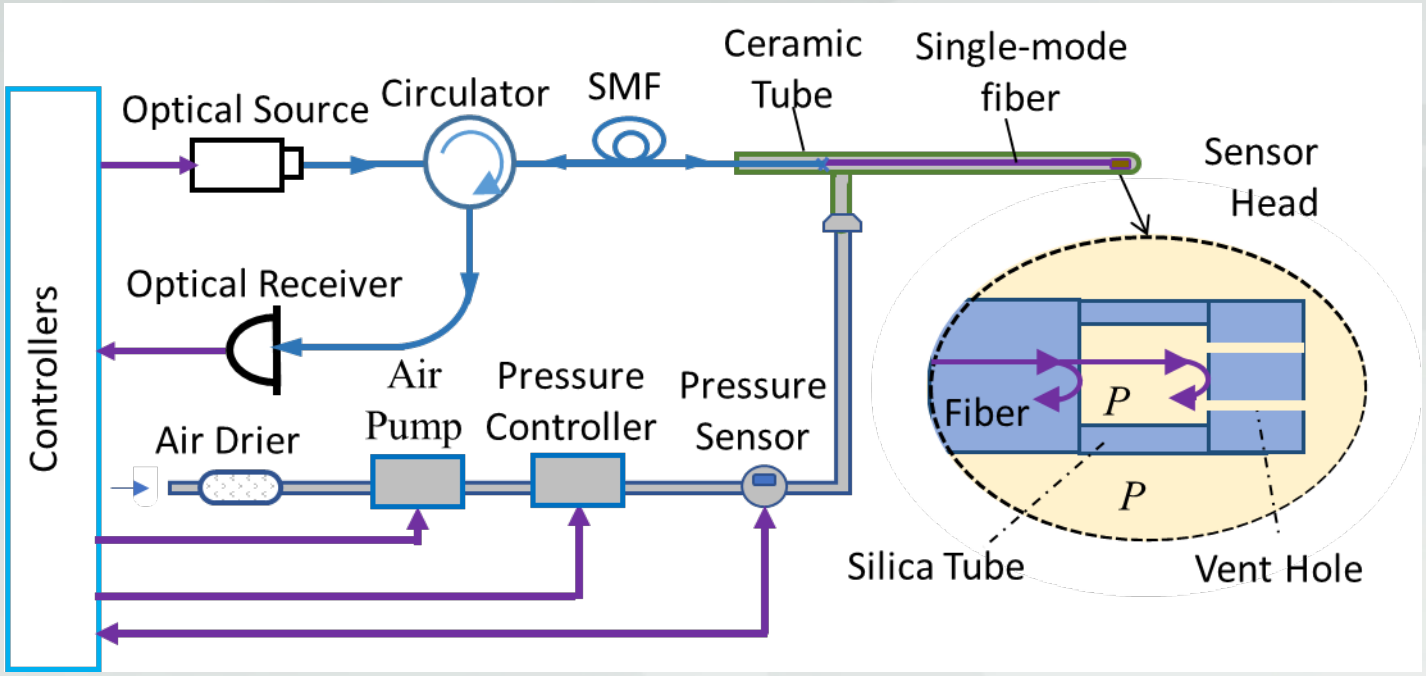
$$n - 1 = \alpha\, P \,/\, T \quad (\ll 1)$$

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

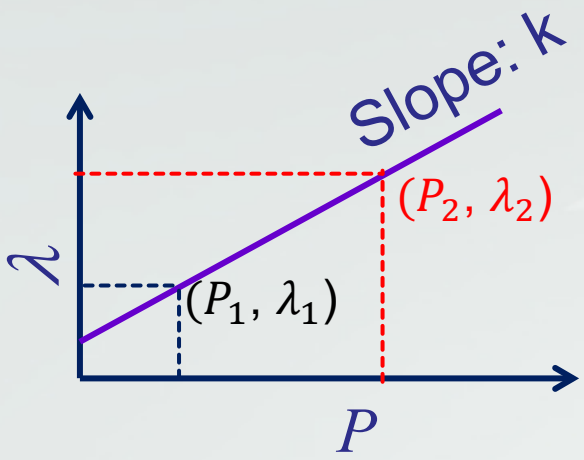
$$k \triangleq \frac{\partial\lambda}{\partial P} = \frac{2\alpha L}{mT}.$$

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

System configuration and a more accurate formula for temperature



- Pressurization through a ceramic tube
- Venting hole on sensor head to avoid pressure-induced structural changes
- Compared to $T = \alpha\,\lambda/k$, we obtained a more accurate formula for calculating T :

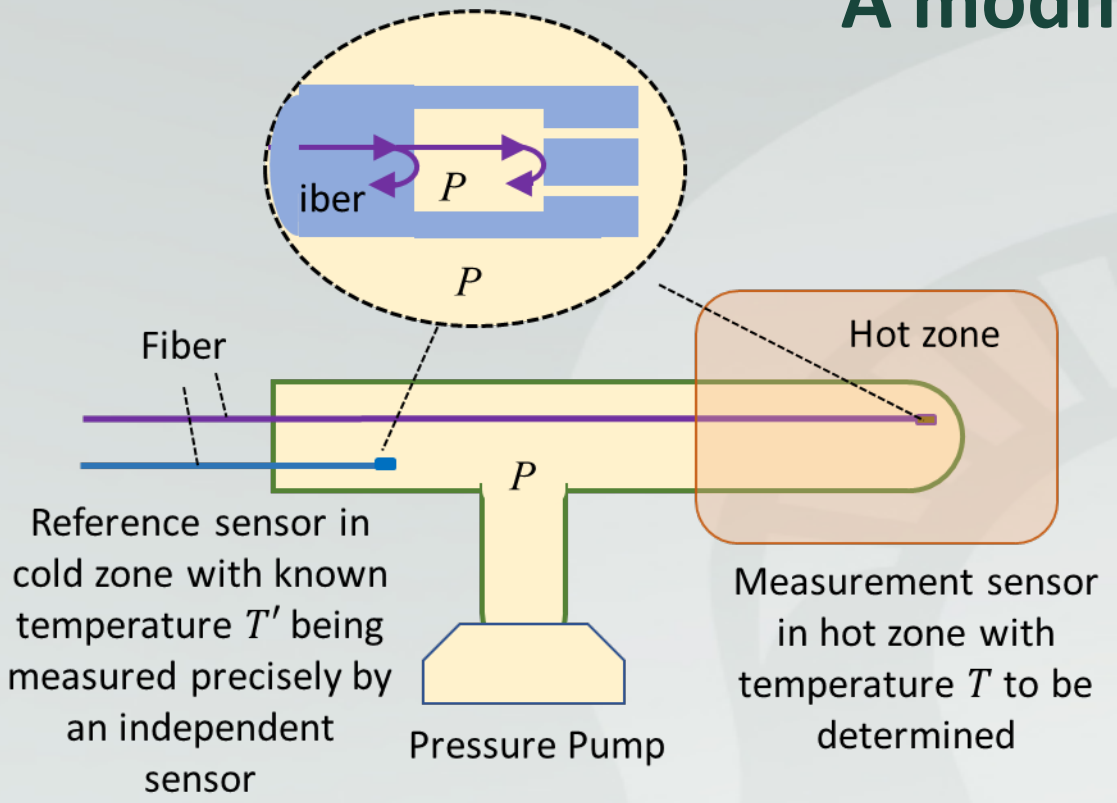


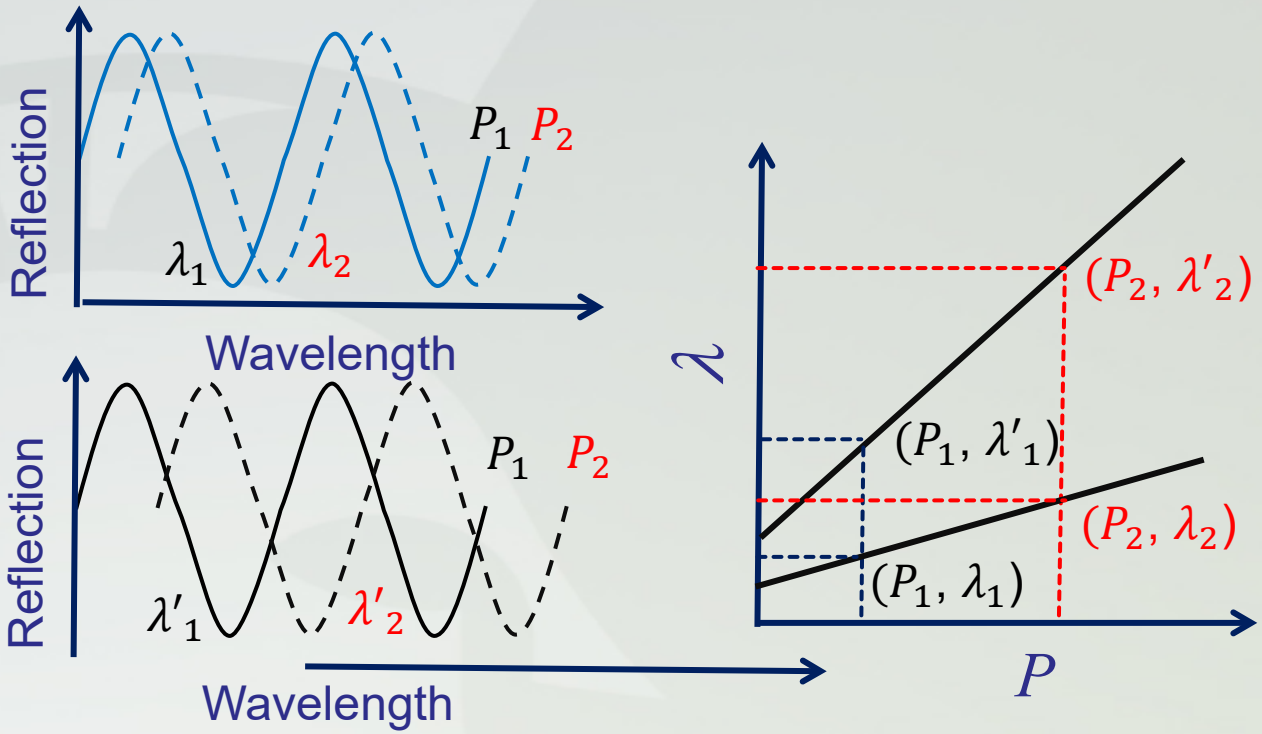
$$\lambda_1 = \frac{2L}{m}\left(\frac{\alpha}{T}P_1 + 1\right)$$

$$\lambda_2 = \frac{2L}{m}\left(\frac{\alpha}{T}P_2 + 1\right)$$

$$\frac{\lambda_1}{\lambda_2} = \frac{\alpha P_1/T + 1}{\alpha P_2/T + 1} \Rightarrow T = \frac{\alpha(\lambda_1 P_2 - \lambda_2 P_1)}{\lambda_2 - \lambda_1}$$

A modified approach





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

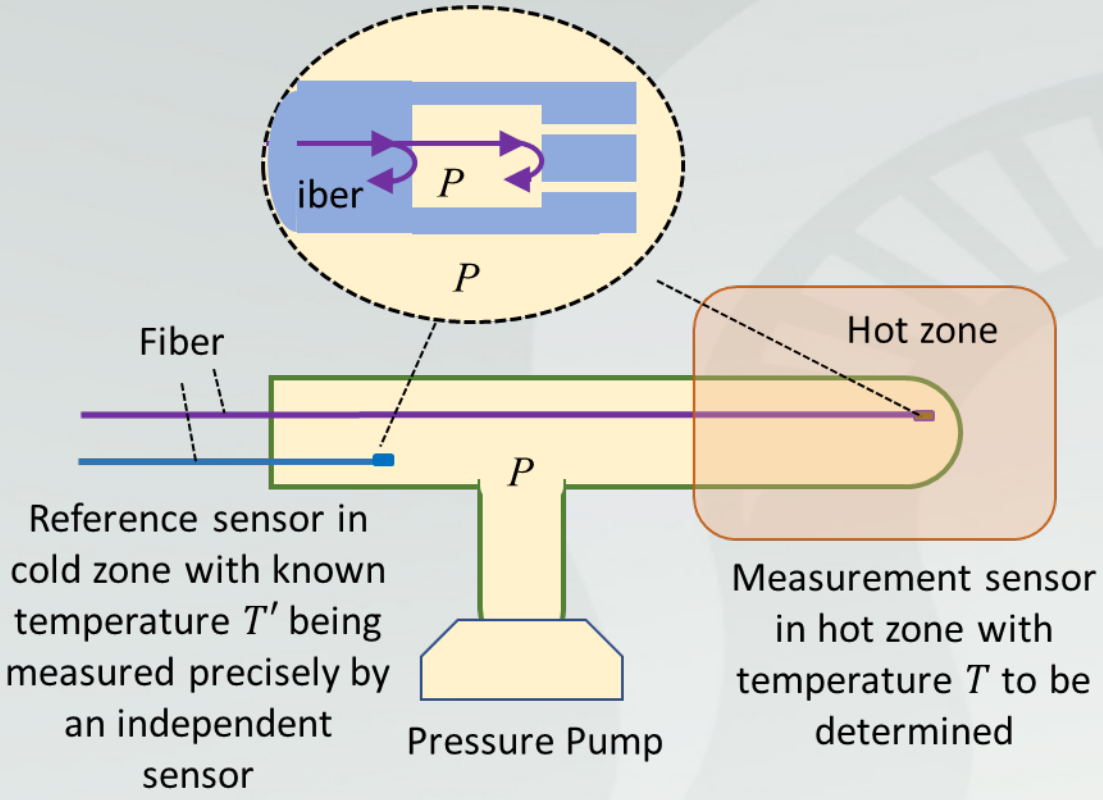
$$\lambda' = \frac{2L'}{m'}\left(\frac{\alpha}{T'}P + 1\right)$$

$$\frac{\Delta\lambda'}{\Delta\lambda} = \frac{L'/m'}{L/m}\frac{T}{T'}$$

$$\frac{L'/m'}{L/m} \approx \frac{\lambda'_1}{\lambda_1}$$

$$\Rightarrow \quad T = \frac{\Delta\lambda'}{\Delta\lambda}\frac{\lambda_1}{\lambda'_1}T'$$

A modified approach – Pros and Cons



$$T = \frac{\Delta\lambda'}{\Delta\lambda}\frac{\lambda_1}{\lambda'_1}T'$$

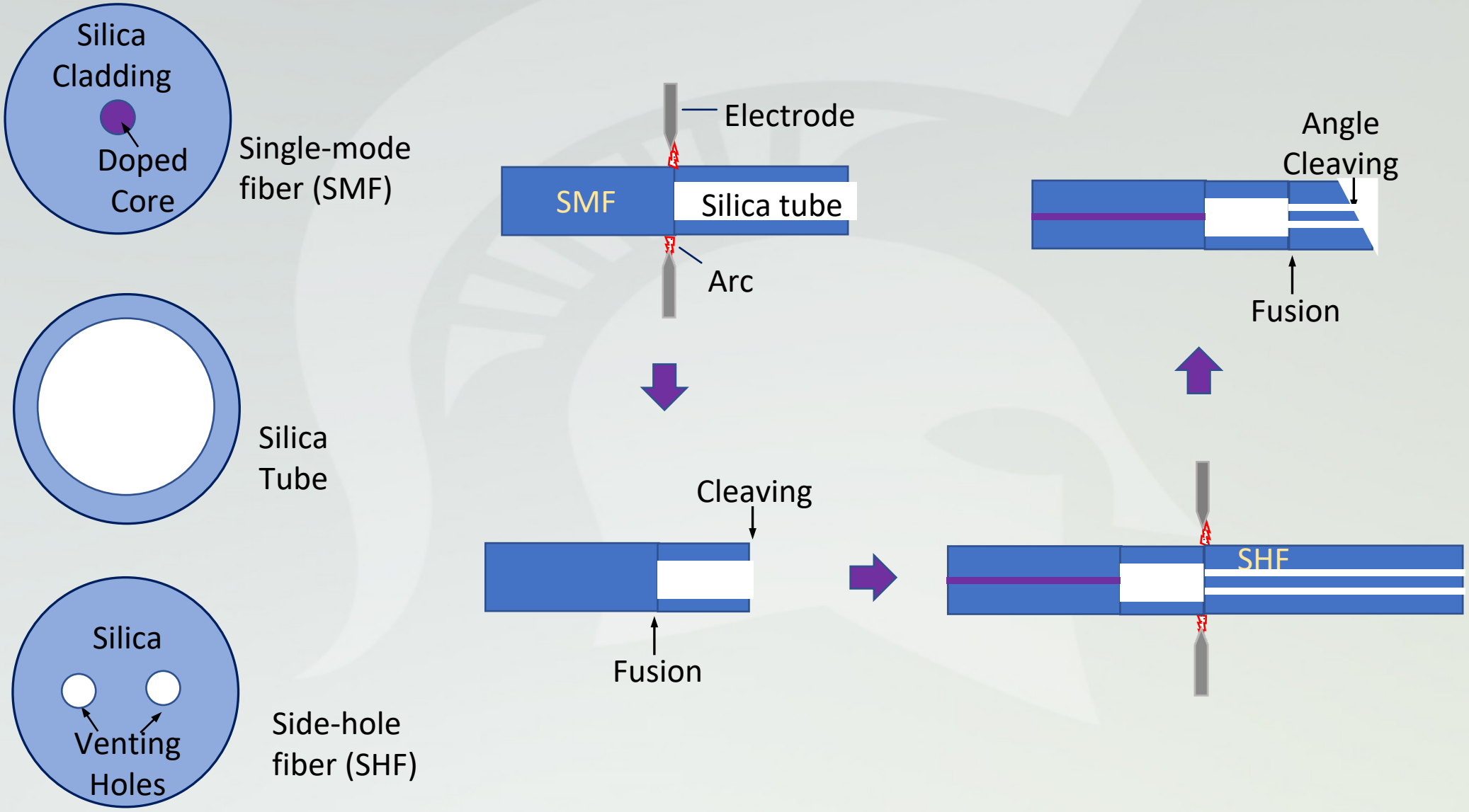
Pros:

- No need for precise pressure measurement and pressure control
- Need for characterization of gas refractive index

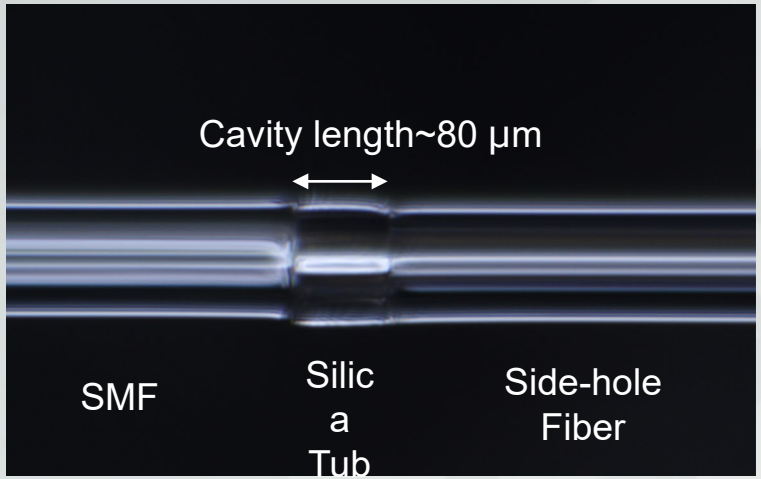
Cons:

- Need of two optical sensors
- Need of a high-accuracy reference temperature sensor

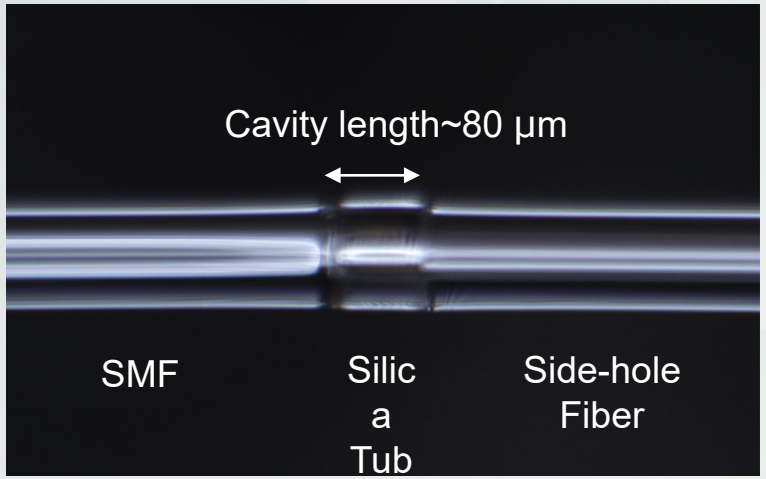
Sensor Fabrication Process



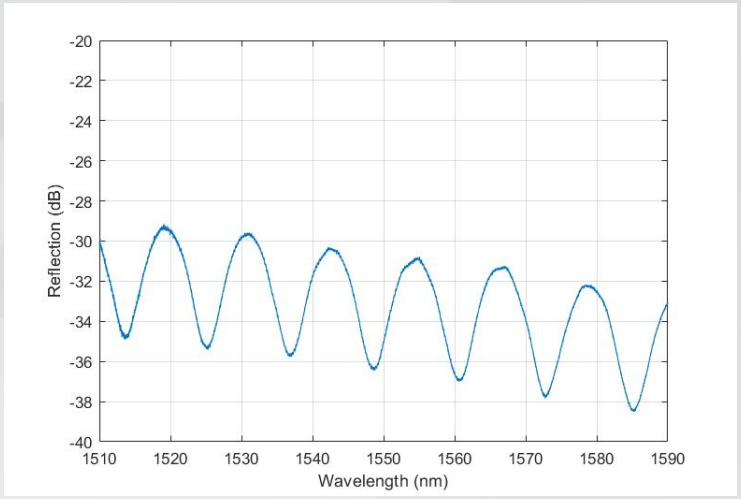
Sensor Fabrication Results



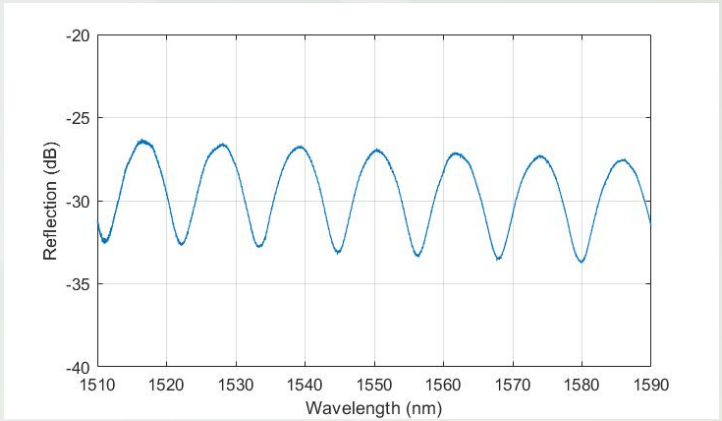
1st Sensor Microscopic View



2nd Sensor Microscopic View



Reflection Spectrum of 1st Sensor



Reflection Spectrum of 2nd Sensor

First testing system development

- Acquired miniaturized air pump and pressure controller (maximum pressure: 100 psi)
- Acquired high-accuracy temperature reference sensor (0.01 °C)
- Developing computer programs for control and data log of optical interrogators, pressure pumps, and reference temperature sensors

100 psi air pump

Electronic pressure controller

Summary

- Modified data processing for more accurate temperature reading
- Designed a modified sensor system configuration that does not need precise pressure measurement and control
- Optimized the fabrication process and successfully fabricated several sensor head
- Acquired some key components for building a test system for the sensors

Acknowledgement and Disclaimer

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