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

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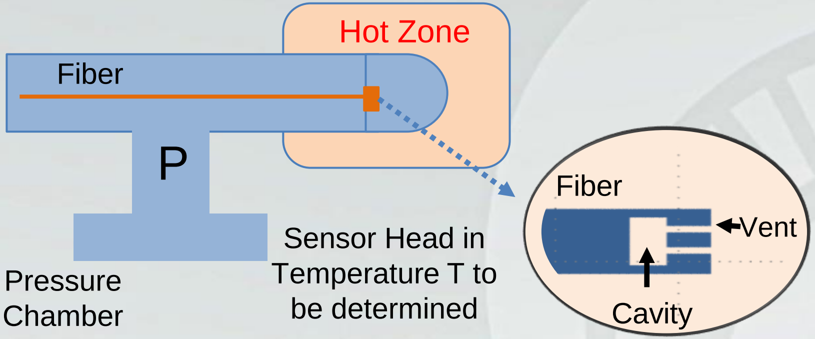
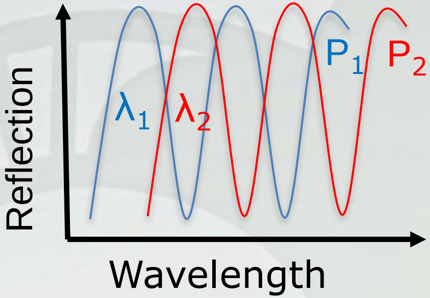
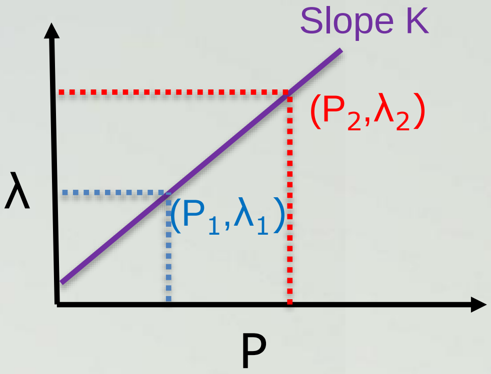
Research Goal

- Develop a fiber-optic temperature sensor system with high accuracy and long-term stability for a large temperature range (above 1000° C) for coal-fired energy systems.
  - "gas" as sensing material
  - Portable with automatic control

Principle of Operation





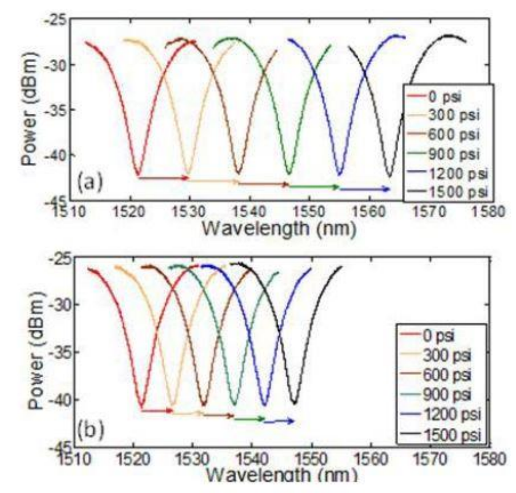


- Refractive index of gas, n is a function of Temperature (T) and Pressure (P):

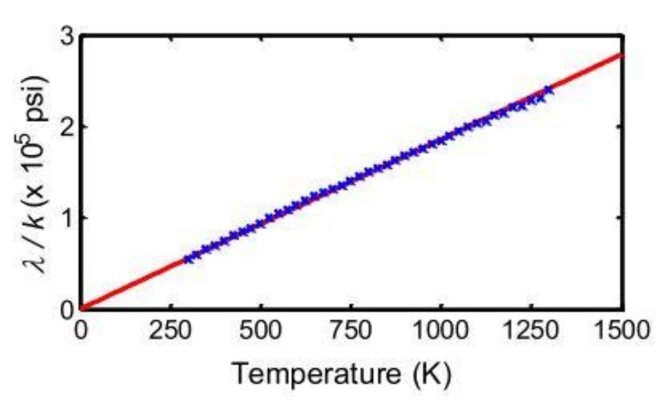
$$\lambda = \frac{2nl}{m} \quad \text{and} \quad n - 1 = \frac{\alpha P}{T}$$

- λ changes linearly with P: $\lambda = \frac{2nl}{m}\left(\frac{\alpha}{T}P + 1\right)$
- P can be varied and controlled to obtain slope, K: $K \triangleq \frac{\partial \lambda}{\partial P} = \frac{2\alpha L}{mT}$
- T can be deduced using $T = \frac{\alpha \lambda}{K}$
- α : Inherent, stable, insensitive to FP cavity length variation

Previous Work[1]



Wavelength shift due to high pressure



Fitted line for $\frac{\lambda}{k}$ vs T to measure T

Pump used to pressurize 1500 PSI

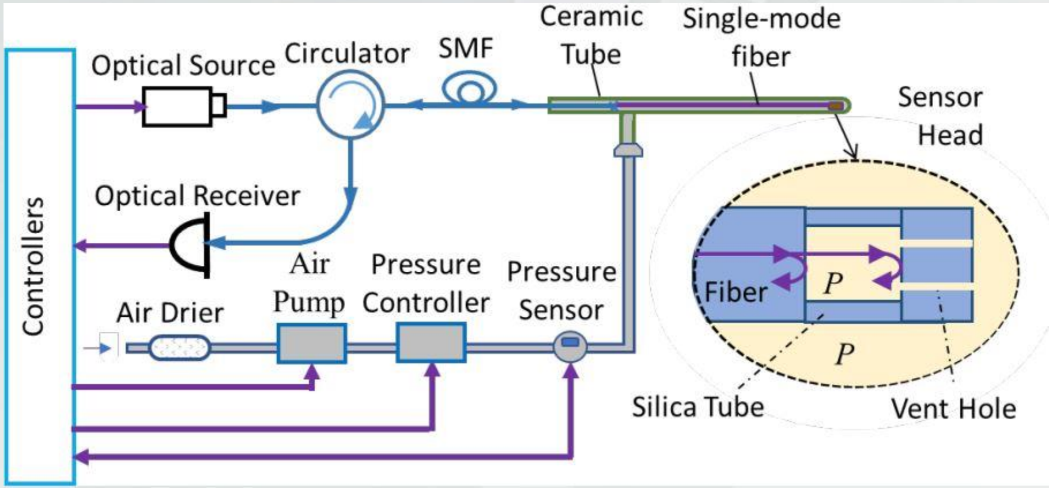
- Very high pressure needed (~1500 PSI)
- Bulk pump, manually controlled, not portable

[1] Yujie Lu, Ming Han, and Jiajun Tian, *"Fiber-Optic Temperature Sensor Using a Fabry–Pérot Cavity Filled With Gas of Variable Pressure",* IEEE Photonics Technology Letters, Vol. 26, No. 8, April 15, 2014.

System Configuration

Key to a portable, automatic system: low gas pressure

Challenges: low gas pressure → smaller wavelength shift → measurement more sensitive to wavelength & pressure errors

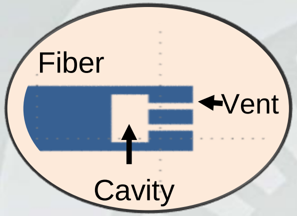


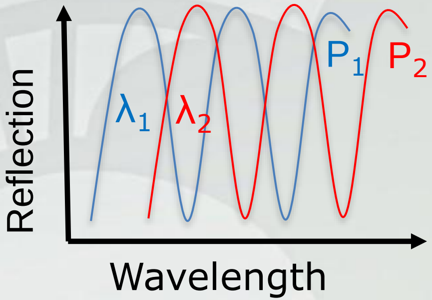
Helix Miniature Pressure Pump

Mensor Pressure Transducer

- Miniature in size, portable
- Electronically controlled
- Low pressure (100 PSI), High accuracy

Effect of Pressure and Wavelength Measurement Errors





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

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

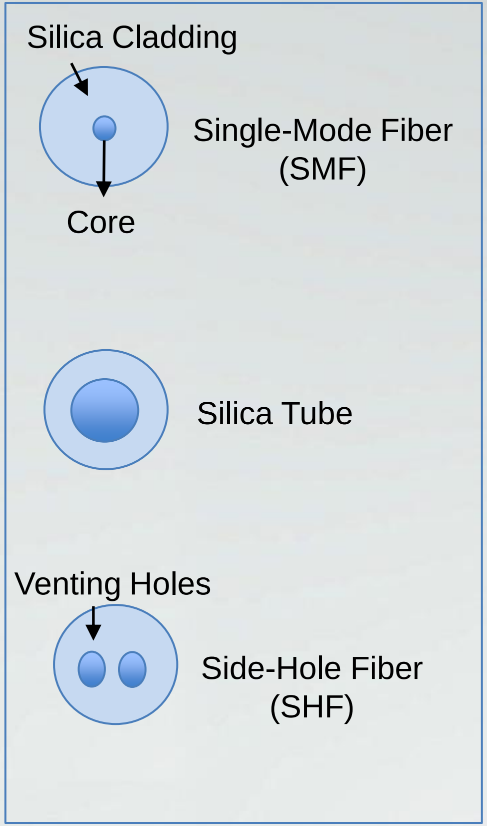
$$\frac{\lambda_1}{\lambda_2} = \frac{\alpha P_1(T+1)}{\alpha P_2(T+1)}$$

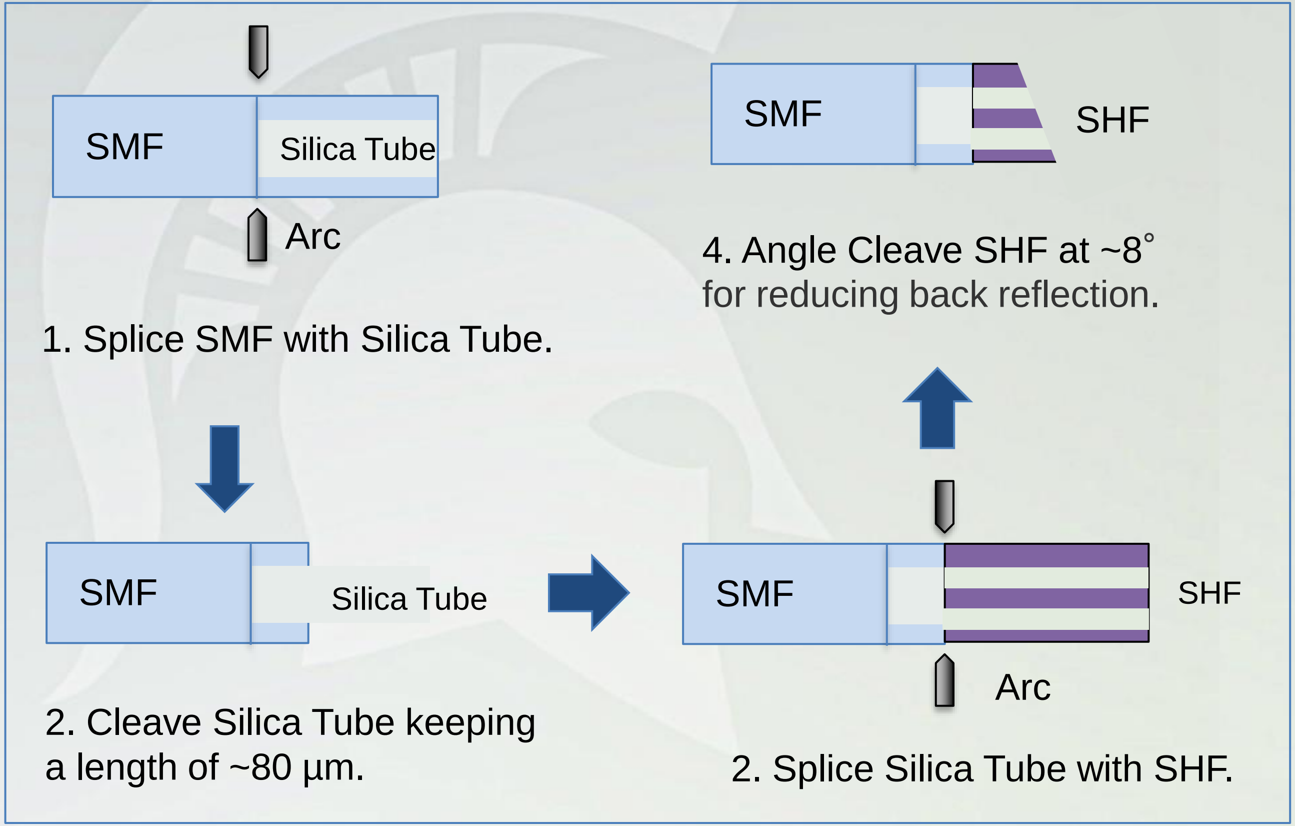
$$T = \frac{\alpha(P_2\lambda_1 - P_1\lambda_2)}{\lambda_2 - \lambda_1} = \alpha\, S$$

$$\frac{\delta T}{T} \sim \frac{\sqrt{2}\,\delta\lambda}{\lambda_2 - \lambda_1} + \frac{\delta P_2}{P_2} \qquad (P_2 \gg P_1)$$

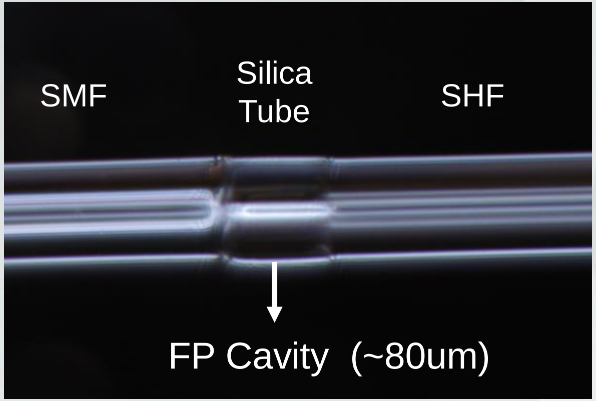
- If P_2 is reduced, wavelength shift $(\lambda_2 - \lambda_1)$ reduces linearly
- Slight error in $\delta\lambda$ and δP_2 causes large error in δT

Sensor Fabrication Steps

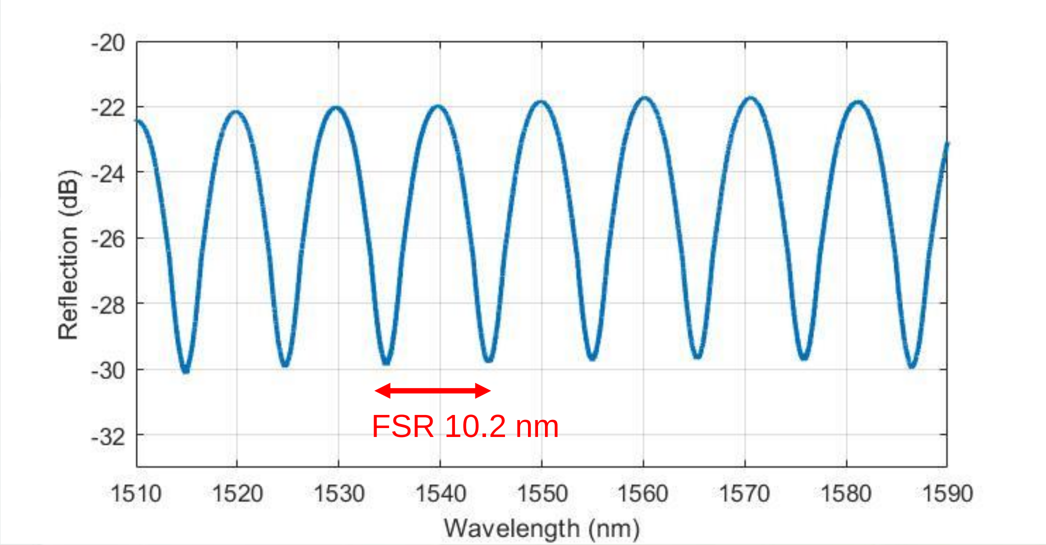




Fabricated Sensor

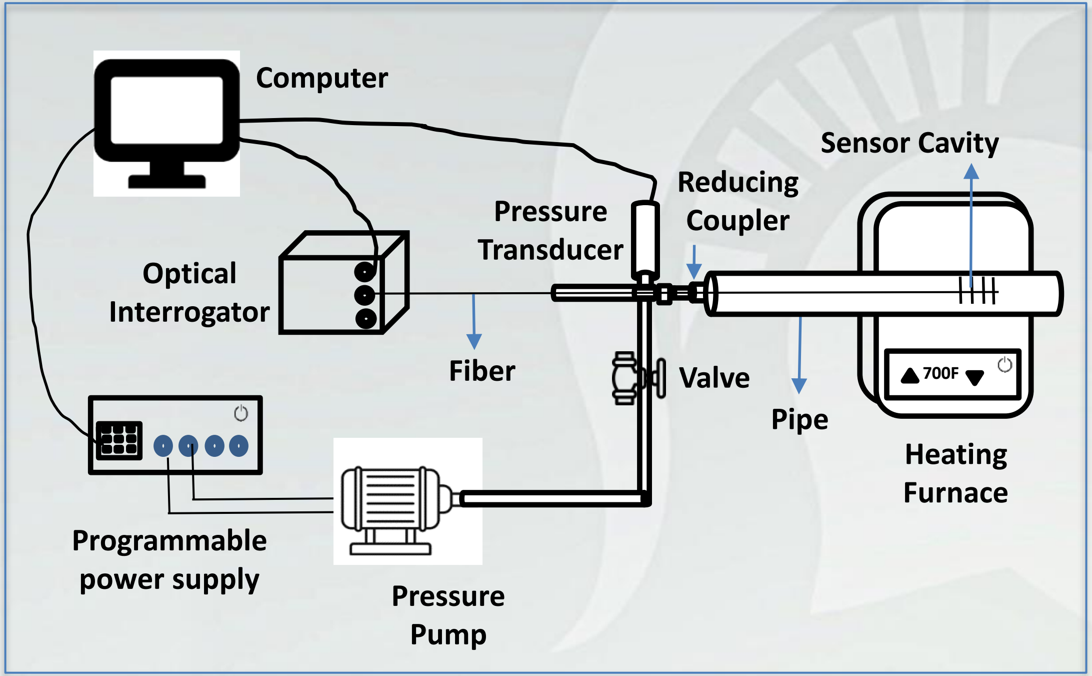


Sensor Microscopic View



Sensor Initial Reflection Spectrum

Experimental Setup



Helix Miniature Pump

Mensor Pressure Transducer

Solenoid Valve

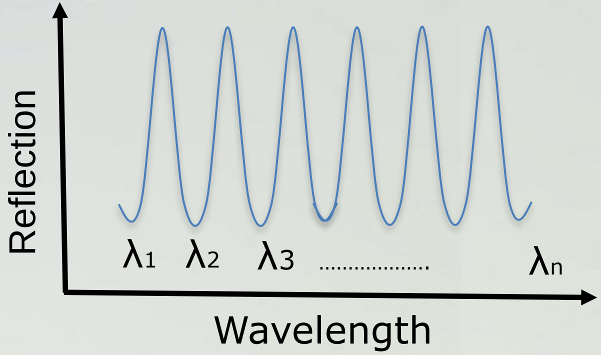
Programmable Power Supply

Hyperion Si-155 Optical Interrogator

Thermo-scientific Lindberg/Blue M™ Furnace

Sensor Initial Stability Test

- Sensor Valley Wavelength was measured by an optical interrogator with 1 KHz scanning rate for 1 min of duration at room temperature (20 C).
- Sensor Resolution (stability) was found 2.4 pm when no pressure applied (0 PSI_g).



Recalling $$\frac{\delta T}{T} \sim \frac{\sqrt{2}\,\delta\lambda}{\lambda_2 - \lambda_1} + \frac{\delta P_2}{P_2} \qquad (P_2 \gg P_1)$$

$$\bar{\lambda} = \frac{\sum \lambda_i}{n}$$

Resolution $= \partial\bar{\lambda}$ over time dt

= 2.4 pm

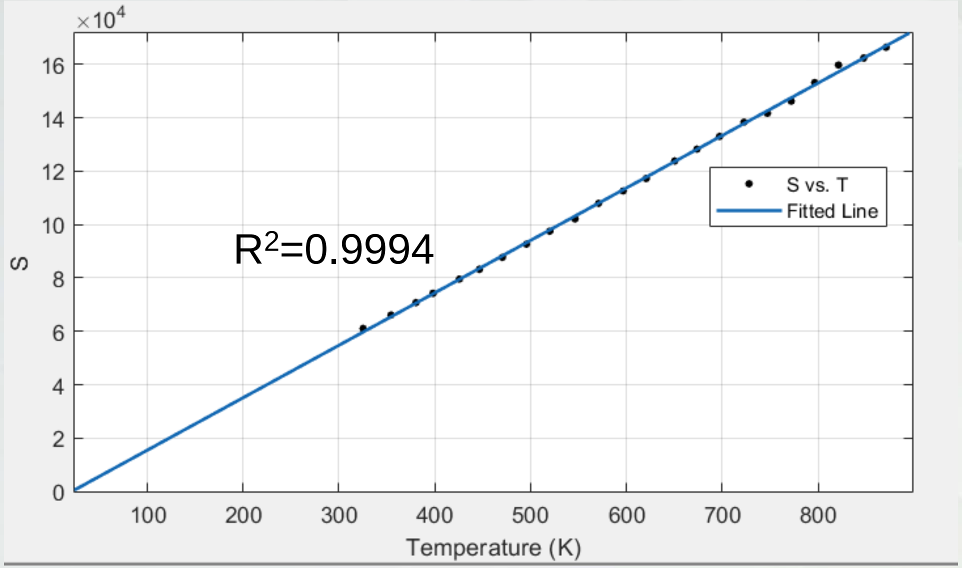
At $T = 1000\ K$, to get $\delta T = 0.05\ K$, at 2.4 pm of $\delta\lambda$,

$$\delta P_2 = \left(\frac{0.05}{1000} - \frac{\sqrt{2} * 2.4e{-12}}{1.074e{-9}}\right) * 100 = 0.31 \text{ PSI}$$

With a high accuracy pressure gauge and a solenoid valve, we are able to reduce the pressure fluctuation δP_2 < 0.03 PSI

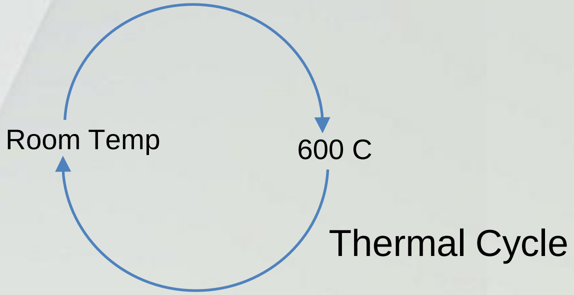
Linearity between S and Temperature T

Reminding the theory, $T = \frac{\alpha(P_2\lambda_1 - P_1\lambda_2)}{\lambda_2 - \lambda_1} = \alpha\, S$, we plot *T vs S* graph:



- T vs S graph shows excellent linearity with R^2 value of 0.9994

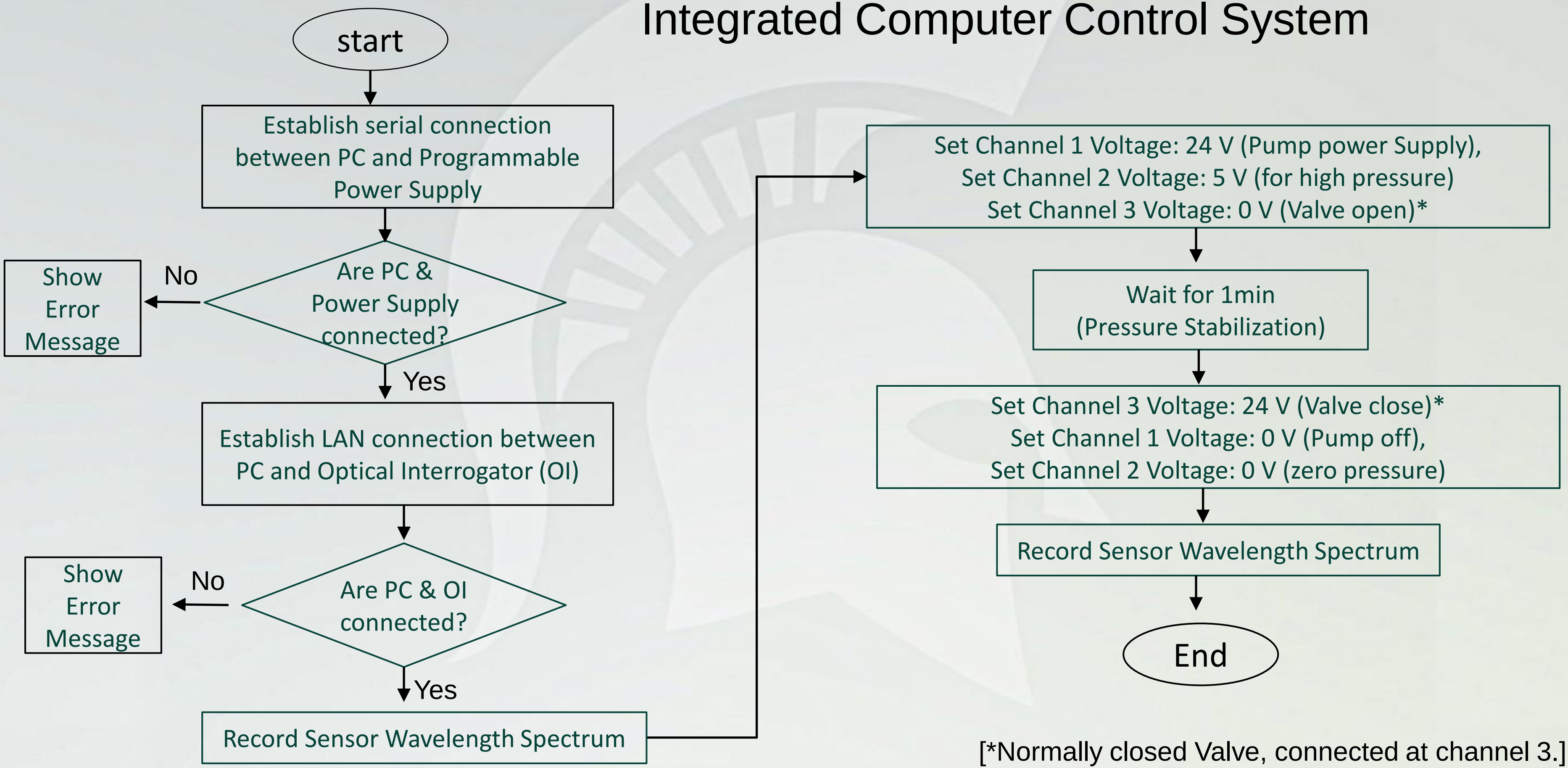
Sensor Repeatability Test



- Multiple thermal cycles were repeated in three (3) different days.
- In each cycle, temperature was raised from room temp to ~600 C.
- Obtained the similar slope coefficients.
- Showed excellent temperature accuracy, especially at room temp.

Thermal Cycle	Real Temp *Tr*	Measured Temp *Tm*	Difference *δT=|Tr-Tm|*
1st Cycle (Day 1)	21.05	21.07	0.02
	598.38	596.77	1.61
2nd Cycle (Day 2)	21.25	21.37	0.12
	599.90	593.44	6.46
3rd Cycle (Day 3)	21.5	21.27	0.23
	601.26	597.49	3.77

Integrated Computer Control System



[*Normally closed Valve, connected at channel 3.]

Challenges for Obtaining High Accuracy

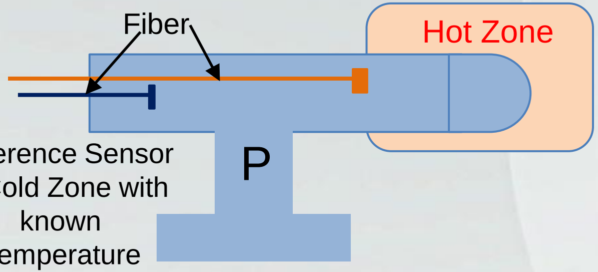
- Precise Pressure Control: A solenoid valve is used to limit pressure fluctuation *δP<0.03 PSI*. High accuracy pressure gauge (*accuracy: 0.020%*) is used for precise pressure reading.
- Sensor Fabrication: Appropriate splicing parameter is necessary for a good sensor fabrication.
- High speed scanning device (>1kHz) is needed for recording sensor spectrum. We used Hyperion Si-155 Device with ±1 pm accuracy.
- Accurate Temperature Measurement is required to obtain slope K. We used DP9602 thermo-logger and Pt-100 thermo-sensor with accuracy ±0.01 C for temperature measurement.

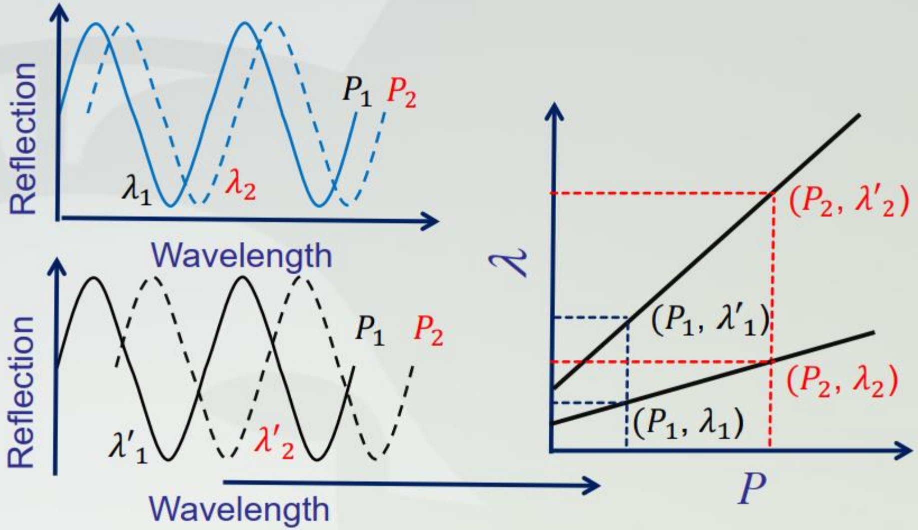
Summary

- Designed a fiber-optic temperature sensor system that uses ‘gas’ as sensing element and required less pressure to operate.
- Successfully fabricated sensors with resolution around 2.4 pm.
- Established a linear fitted equation to obtain coefficients for accurate temperature measurement.
- Developed an integrated computer-controlled system for pressure control and data acquiring.

Future Plan

- Use a two-sensor method for temperature measurement.





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

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

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

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

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

Future Plan (cont’d)

- Improve precise pressure control system and temperature measurement to obtain high accuracy.
- Acquire High Temperature (~1000 C) Sensor reliability.

Acknowledgement and Disclaimer

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Thank You!

Questions??