Development of a Ceramic Coaxial Cable Sensor-Based System for Long-Term Down Hole CO2 Sequestration Monitoring

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Title

Robust Ceramic Coaxial Cable Down-Hole Sensors for Long-Term In Situ Monitoring of Geologic CO2 Injection and Storage

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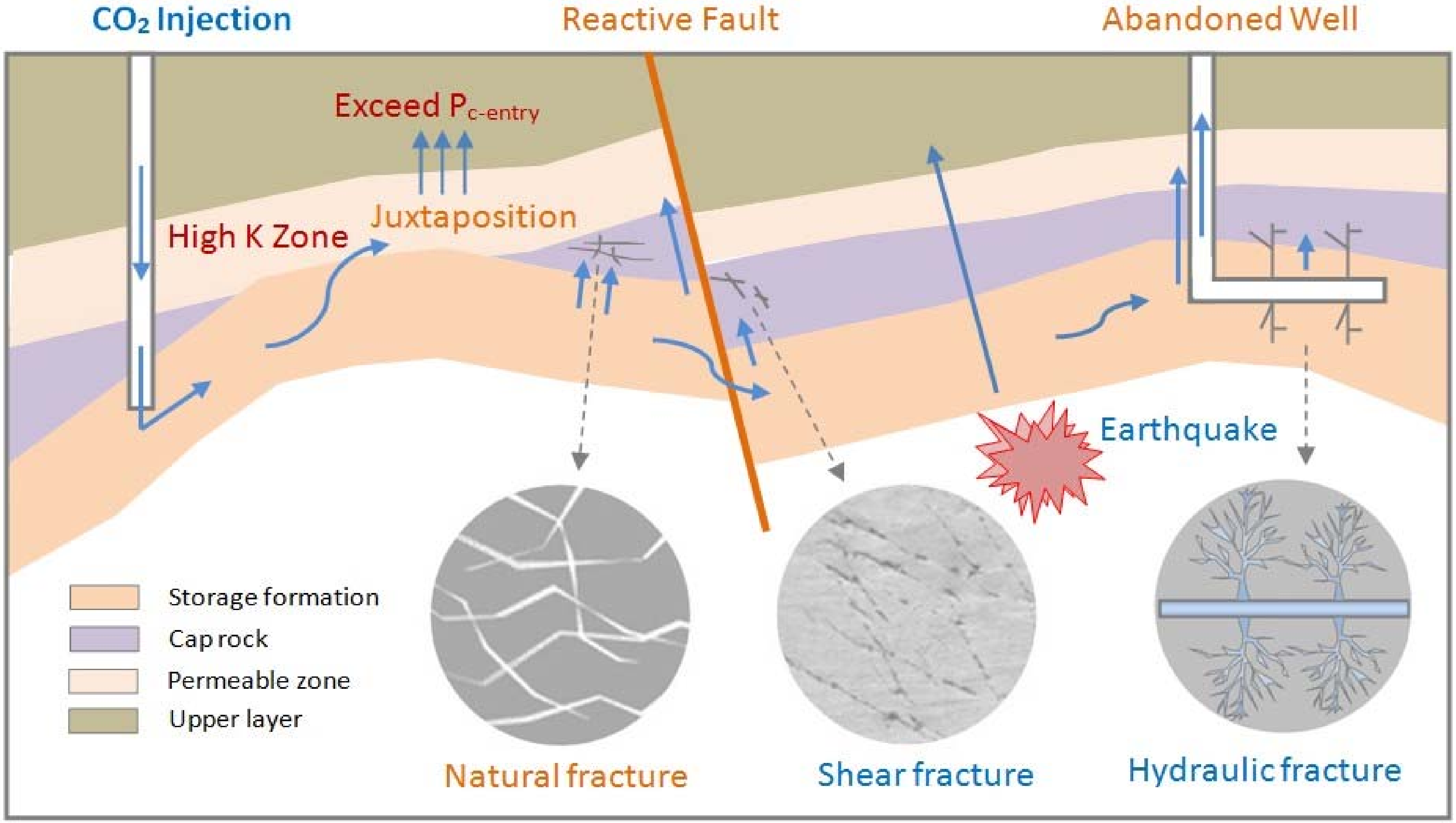
Outline

- Long term CO2 injection integrity monitoring – problem statement
- Main objective to demonstrate and develop a novel, robust, down hole sensing technology for in-situ monitoring
- To reach the objective we developed and verified the robust ceramic coaxial cable sensors at elevated temperature and pressure
  - Strain
  - Temperature
  - Pressure
- Evaluated a bench scale wellbore system
- Summary

Potential leakage pathways of CO_2



Matrix
- Capillary entry pressure
- Seal permeability
- Pressure seals
- High permeability zones

Structural
- Flow on faults
- Flow on fractures
- Flow between permeable zones due to juxtapositions

Geomechanics
- Hydraulic fracturing
- Creation of shear fractures
- Earth quake release

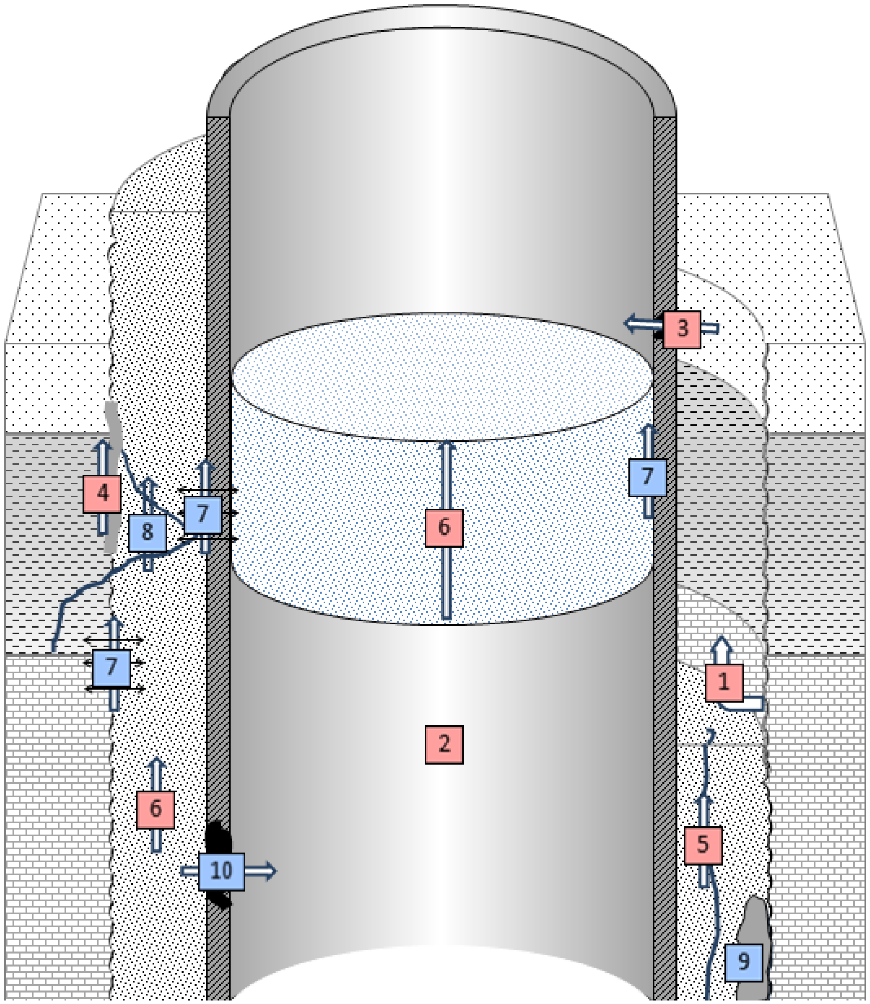
Wellbore Leakage

PRIMARY

1. Incomplete annular cementing job, doesn’t reach seal layer
2. Lack of cement plug or permanent packer
3. Failure of the casing by burst or collapse
4. Poor bonding caused by mudcake
5. Channeling in the cement
6. Primary permeability in cement sheath or cement plug

SECONDARY

7. De-bonding due to tensile stress on casing-cement-formation boundaries
8. Fractures in cement and formation
9. Chemical dissolution and carbonation of cement
10. Wear or corrosion of the casing



Long term CO_2 injection integrity monitoring – problem statement

- **Background:**
  - Subsurface geologic formations offer a potential location for long-term storage of CO2.
  - Achieve the goal to account for 99% of the injected CO2 requires advanced monitoring technology to optimize the injection processes and forecast the fate of the injected CO2
- **Status:**
  - Due to the complexity, no single data type is sufficient by itself; different monitoring and characterization approaches are deemed to be necessary.
  - In situ down-hole monitoring of state parameters (e.g., pressure, temperature, etc.) provides critical and direct data points to validate the models, optimize the injection scheme, detect leakage and track the plume.
  - Current down-hole sensors are insufficient to meet the reliability and cost requirements.

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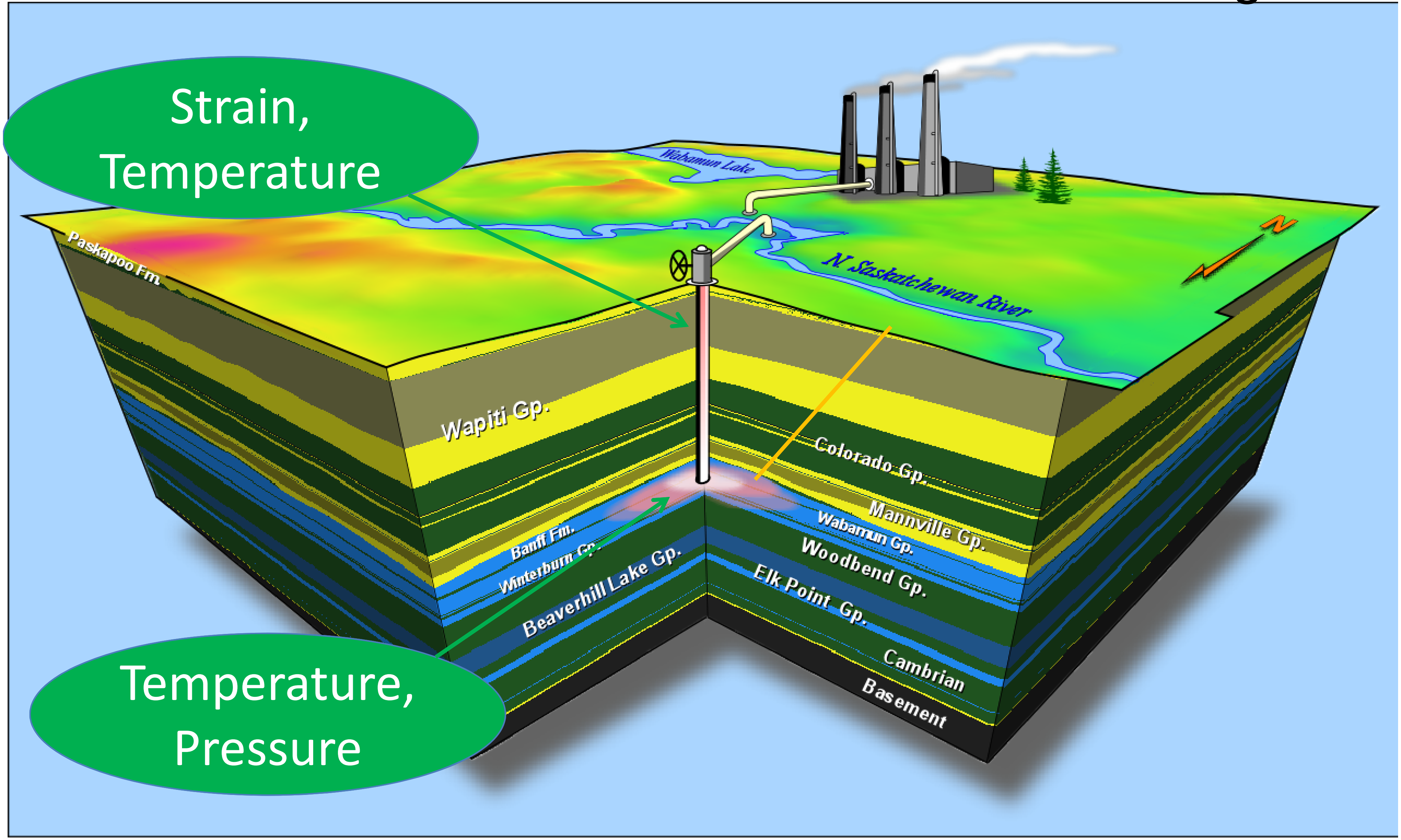
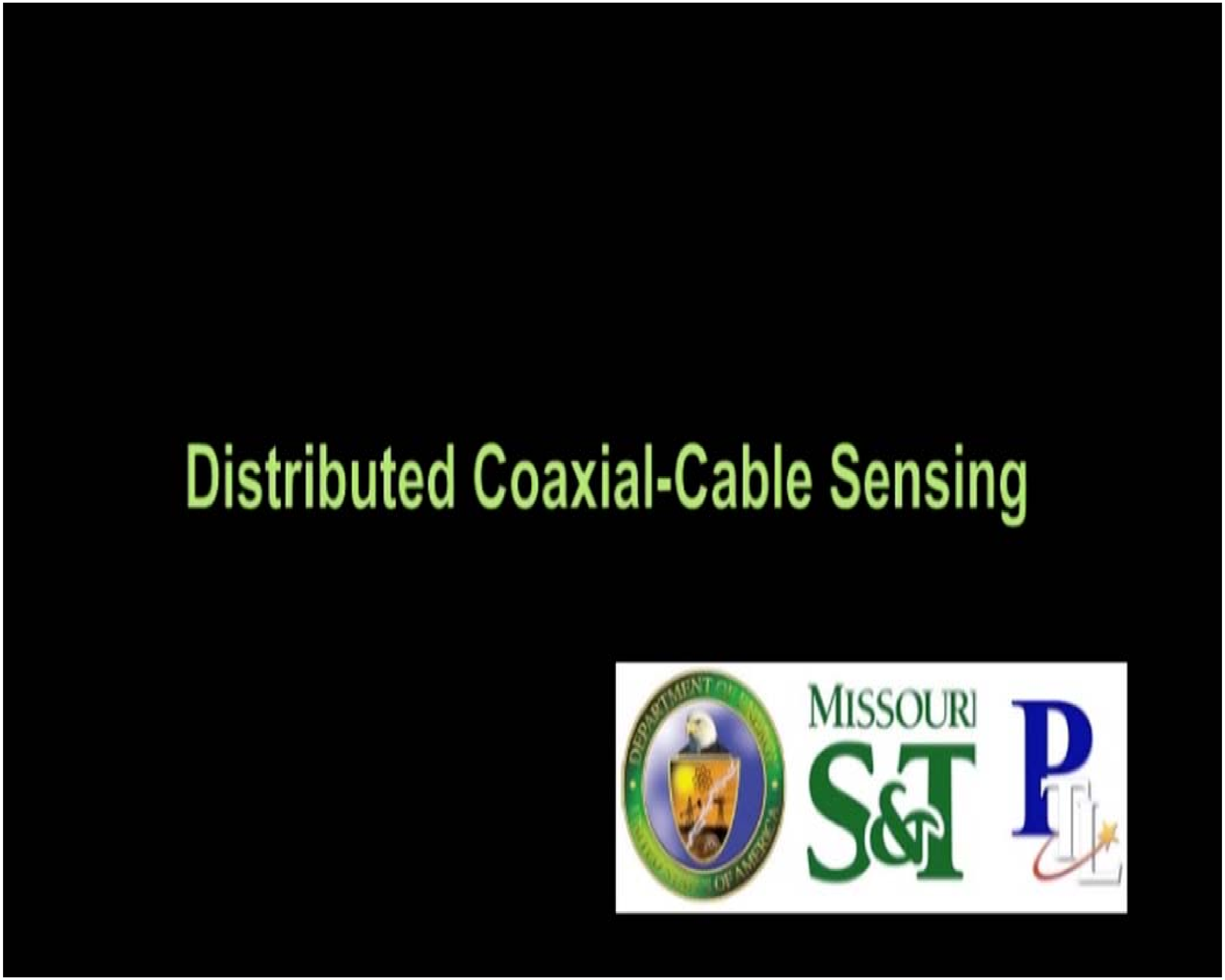
The goal is to develop a monitoring system combined for the wellbore and the reservoir monitoring



Strain, Temperature

Temperature, Pressure

Source: Wabamun CO sequestration project - WASP



Distributed Coaxial-Cable Sensing

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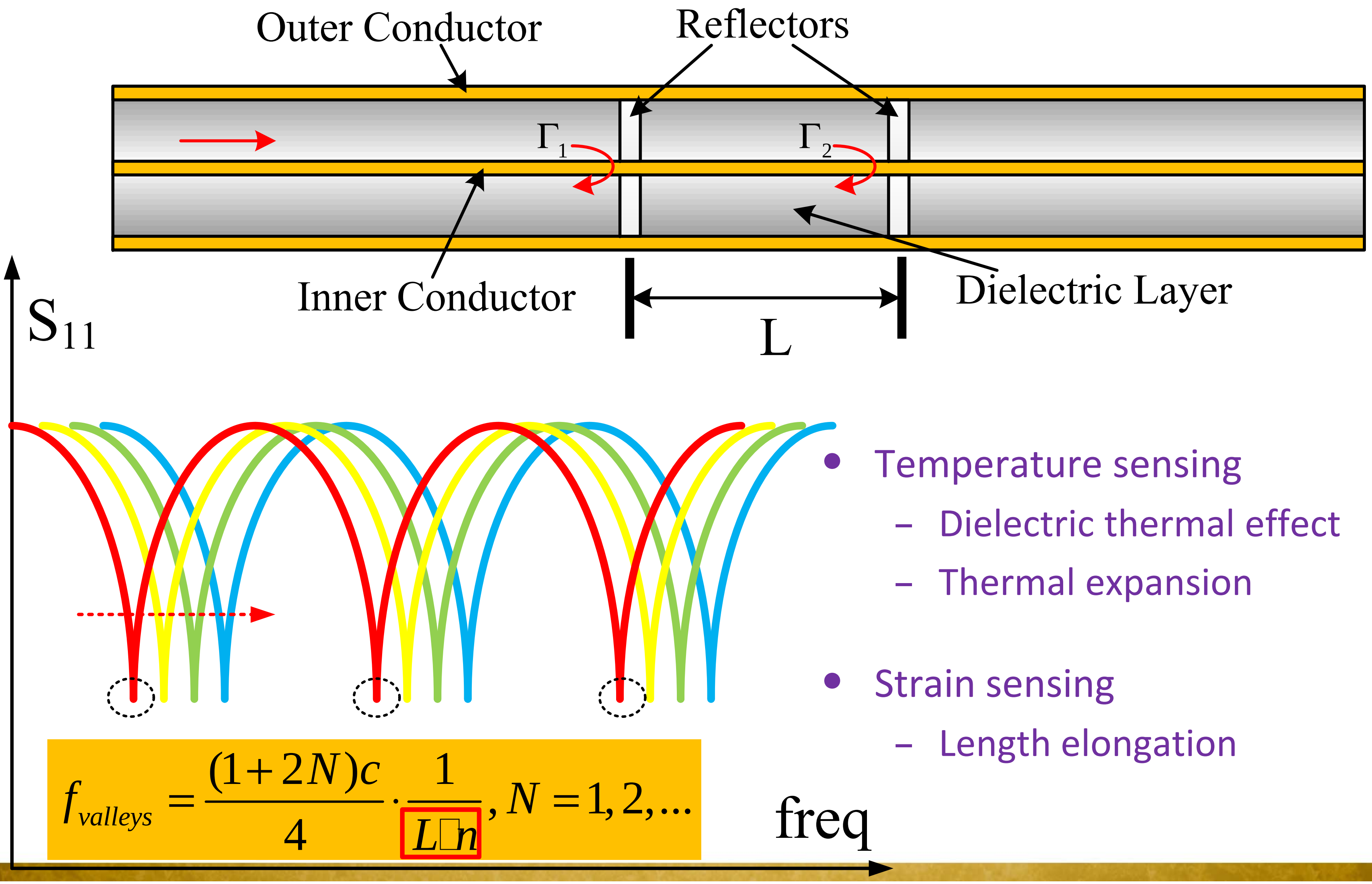
CC-FPI Sensor Principle



$$f_{valleys} = \frac{(1+2N)c}{4} \cdot \frac{1}{\boxed{L\square n}}, N = 1, 2, \ldots$$

- Temperature sensing
  - Dielectric thermal effect
  - Thermal expansion
- Strain sensing
  - Length elongation

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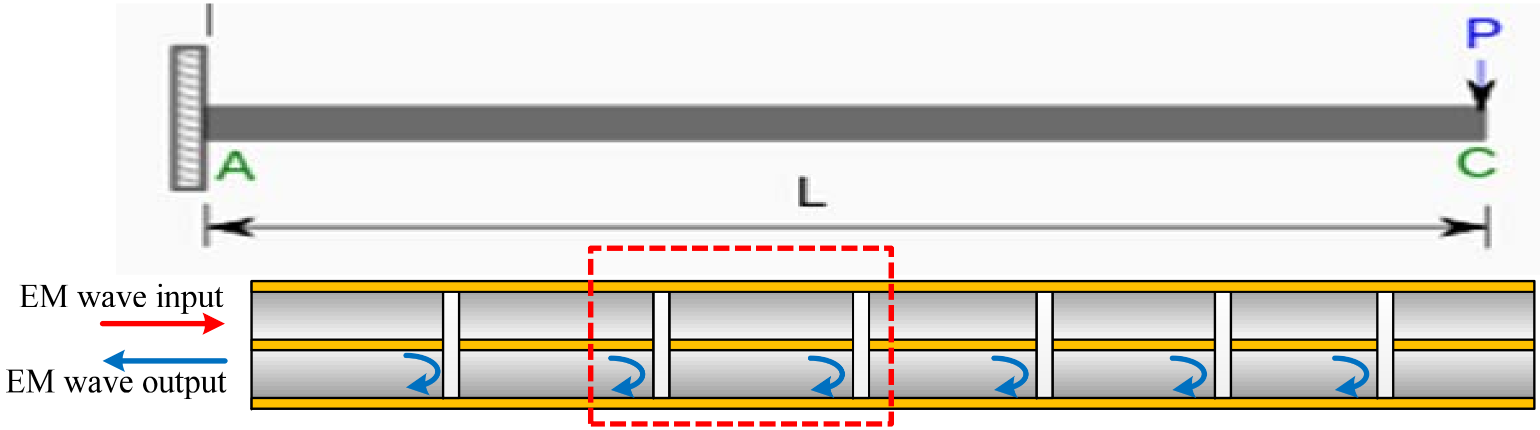
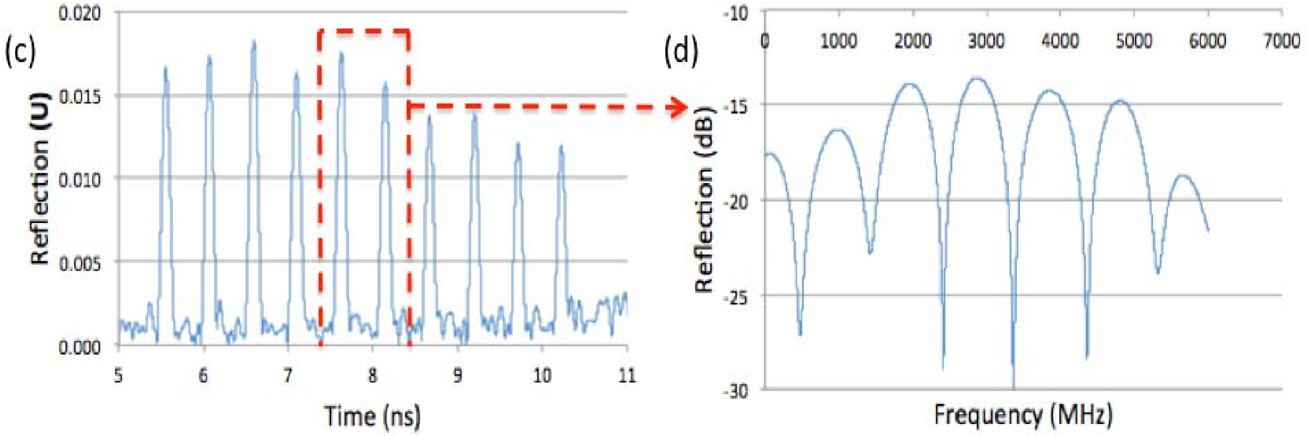
Distributed strain sensors on a cantilever

- A cable with multiple FPIs is bonded on a cantilever

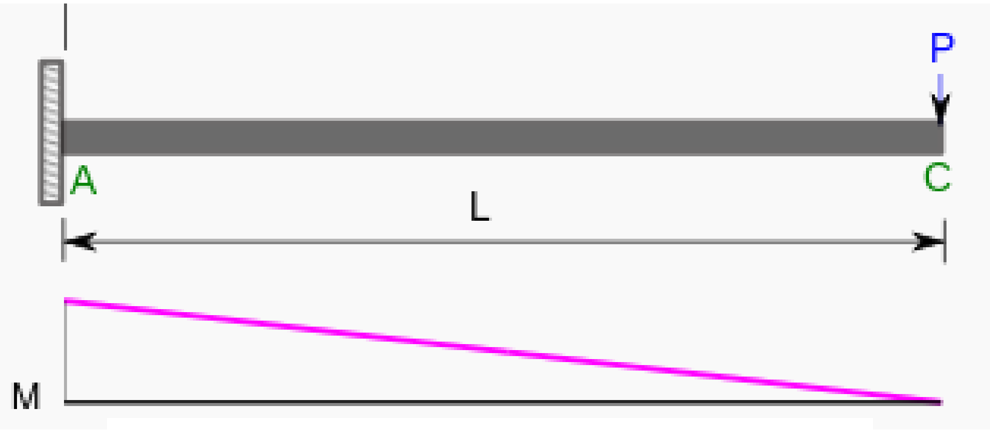


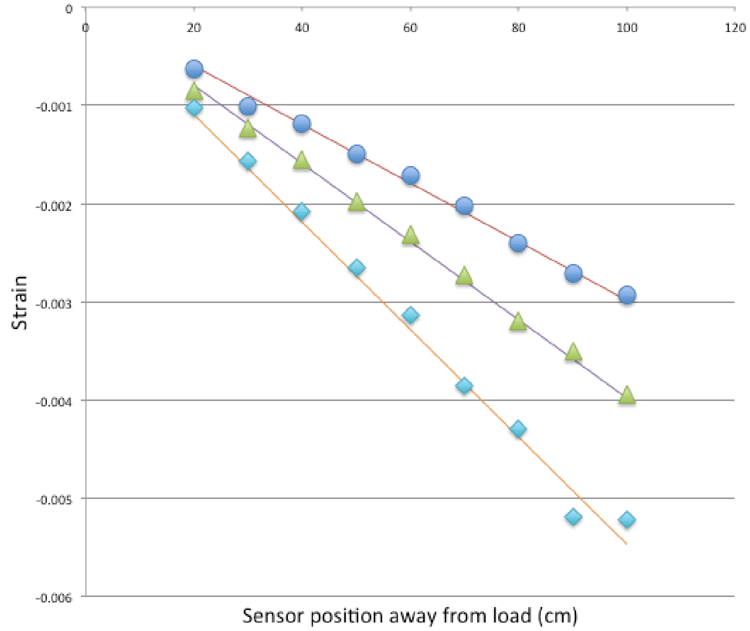


Gate/filter the reflectors **Strain is related to spectrum shift**

Strain distribution on a cantilever

- Press one end and fix the other end





bending moment

$$M(x) = P(x - L)$$

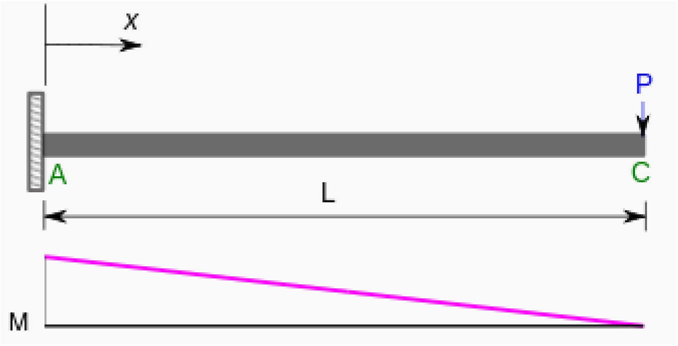
bending strain

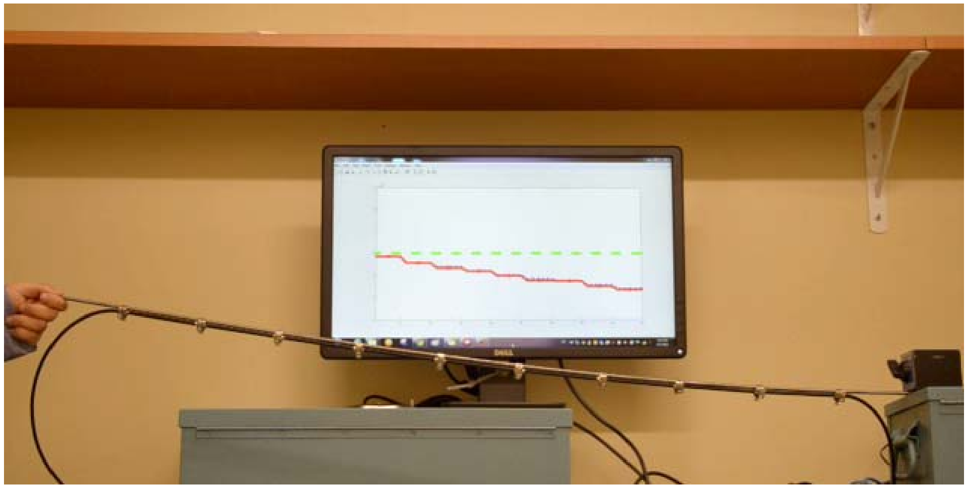
$$\varepsilon = \frac{Mz}{EI}$$

strain distribution of nine sections on the cantilever with three end load

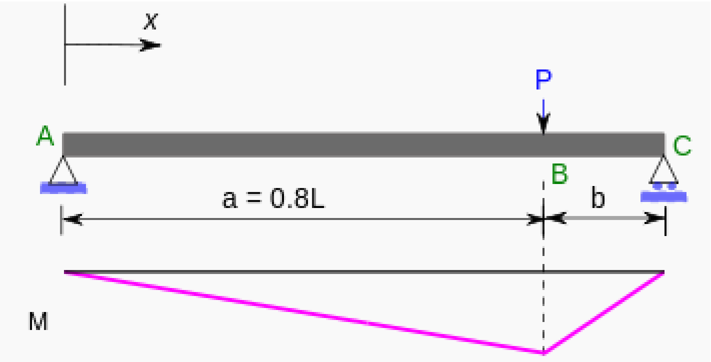
Real time distributed strain monitoring

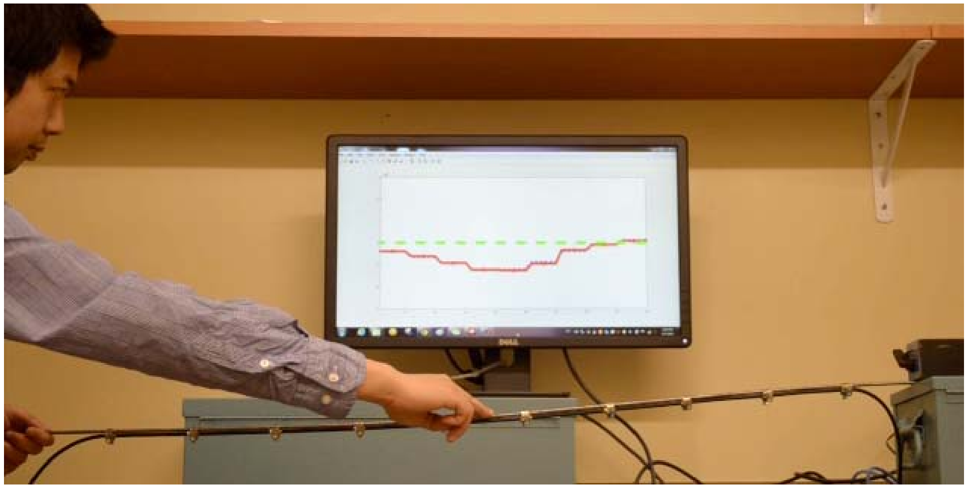
Bend at one end





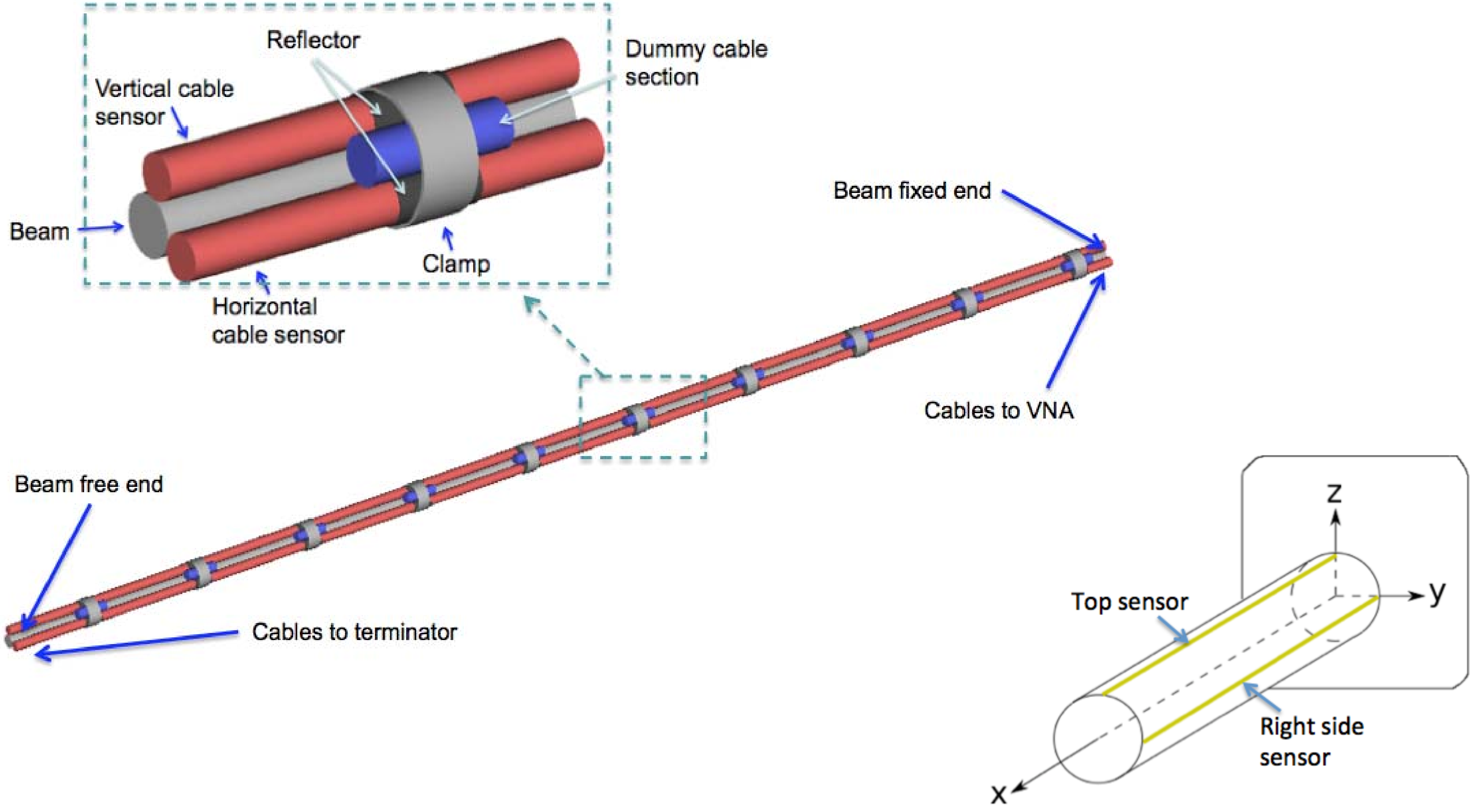
Press in the middle





Beam shape strain sensor

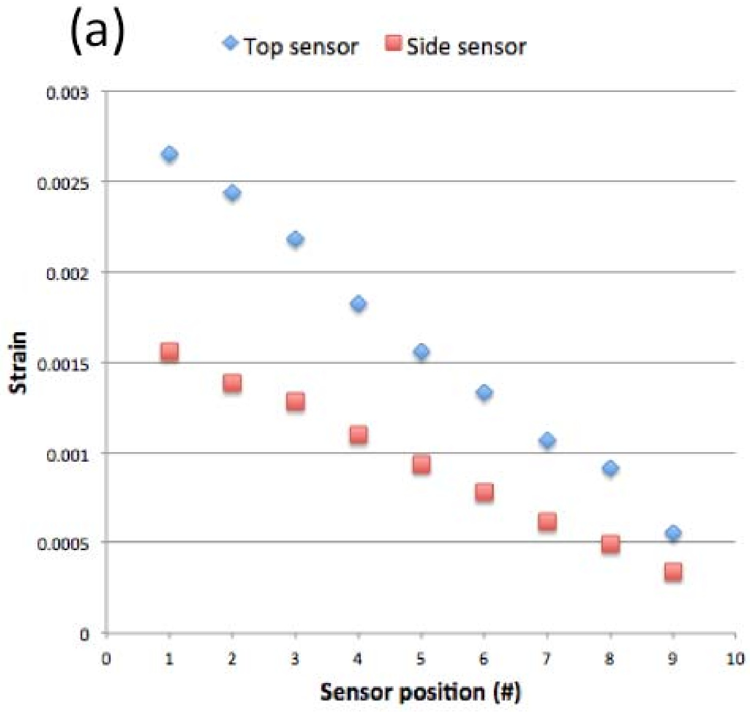
- A pair of distributed strain sensors are implemented to monitor strains at y and z direction

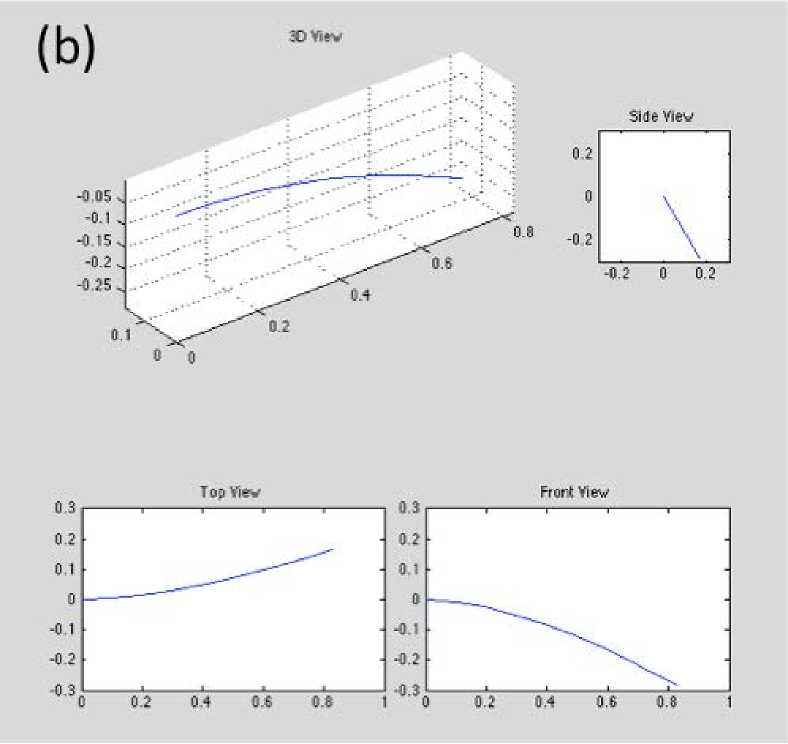


Displacement-Strain-Transformation

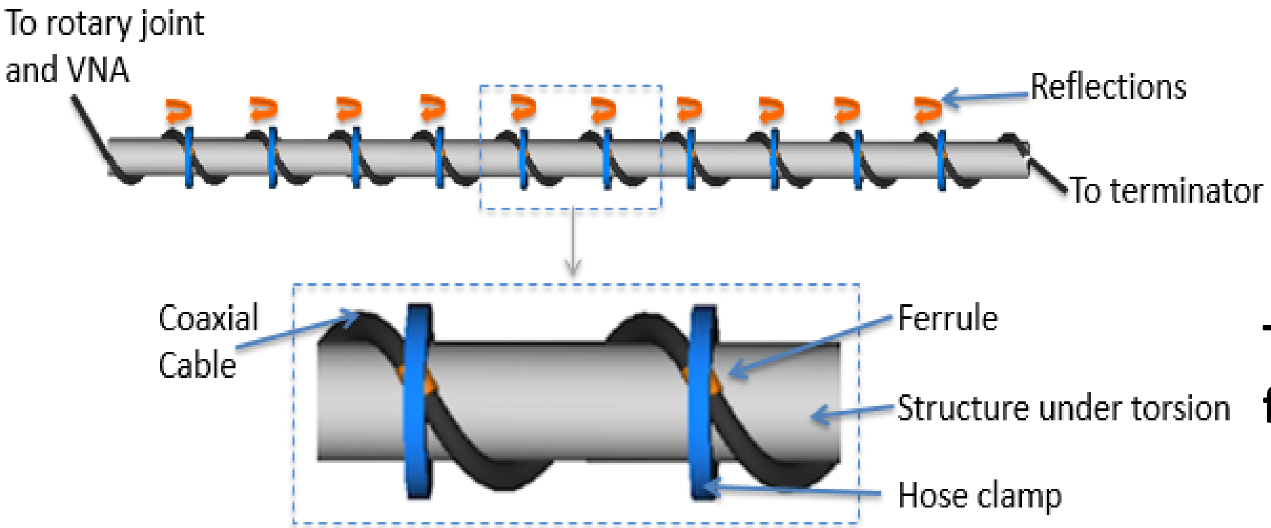
- Displacement is an integral of distributed strain

$$y[i] = \frac{1}{r}\sum_{n=1}^{i}\left(\sum_{m=1}^{n} \varepsilon_{top} L_m\right) L_n \qquad z[i] = \frac{1}{r}\sum_{n=1}^{i}\left(\sum_{m=1}^{n} \varepsilon_{side} L_m\right) L_n$$



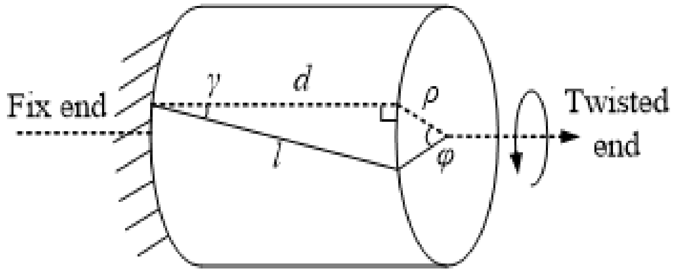


Coaxial cable torsion sensor



Multiple-reflectors to form FPIs in one cable

The fixed reflectors are fixed on the structure

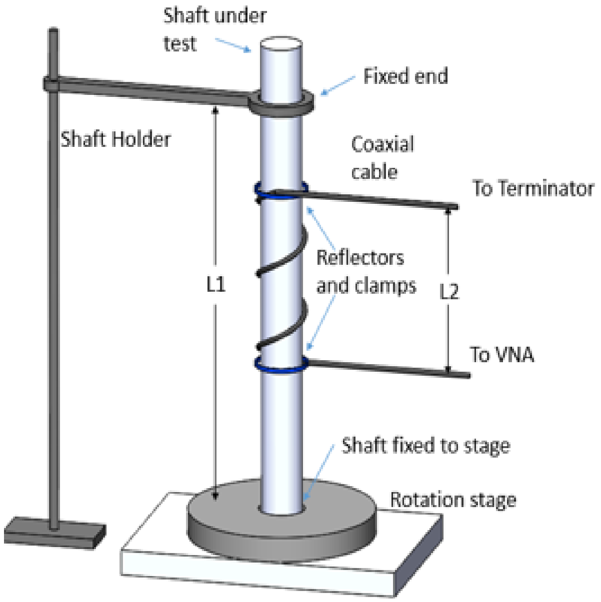


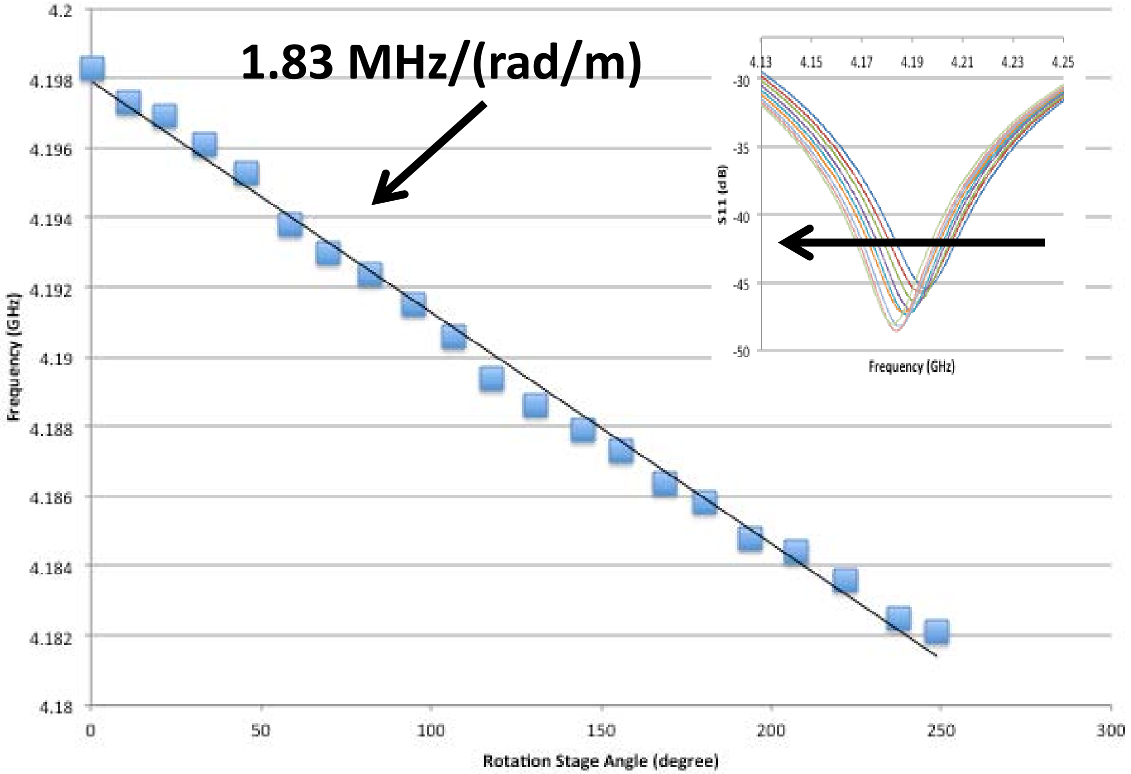
The torsion is related with measured strain

$$\frac{\Delta l}{l} = \frac{\rho^2\varphi^2}{d^2+(\rho\varphi)^2}\left(\frac{\Delta\varphi}{\varphi}\right) = \sin^2\gamma\left(\frac{\Delta\varphi}{\varphi}\right)$$

A single torsion sensor test

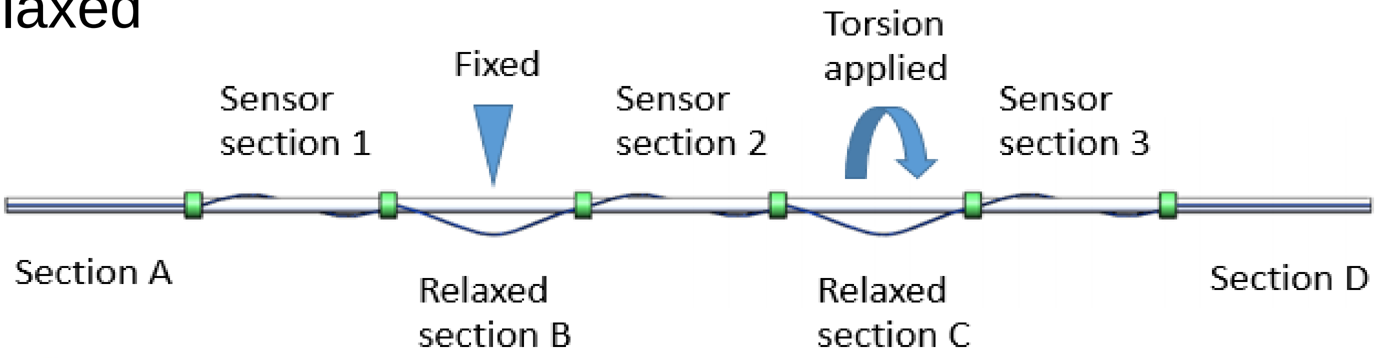
Fix at on end, rotate the other end

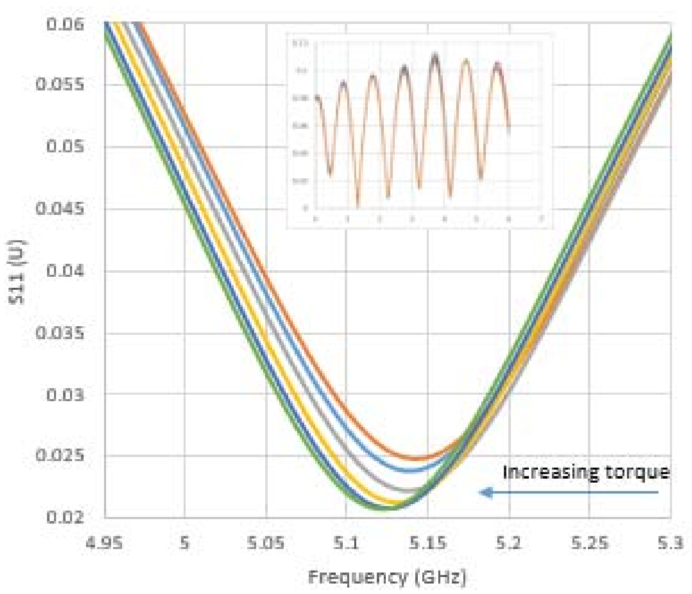


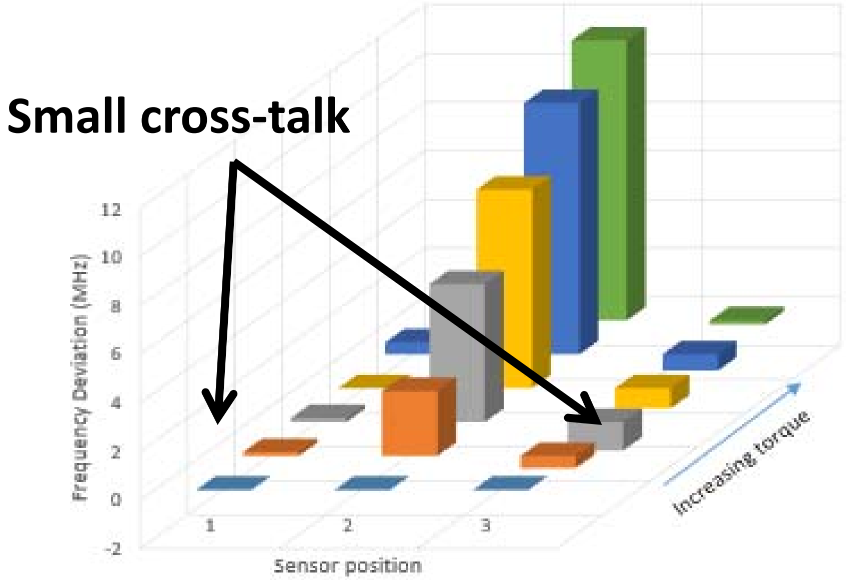

1.83 MHz/(rad/m)

Distributed torsion sensor test

- The central sensor is under torque, while the other two is relaxed





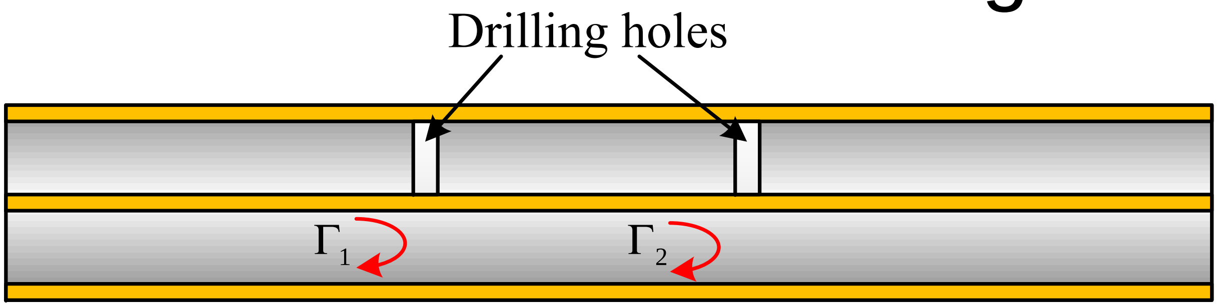


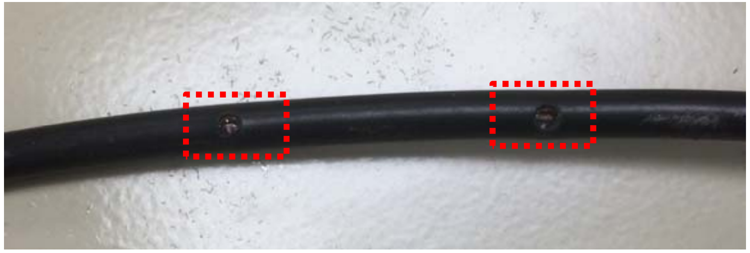
Small cross-talk

Torsion response in central sensor

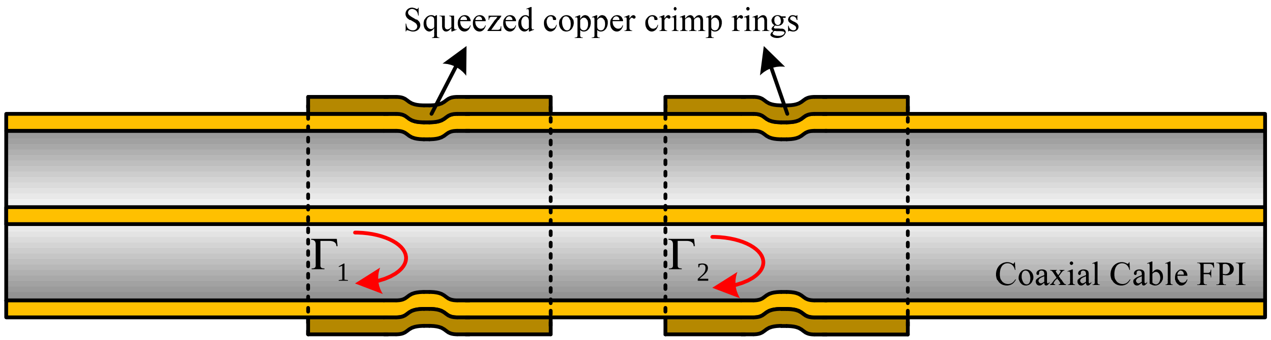
Torsion distribution of three sensors

CCFPI Sensor design development



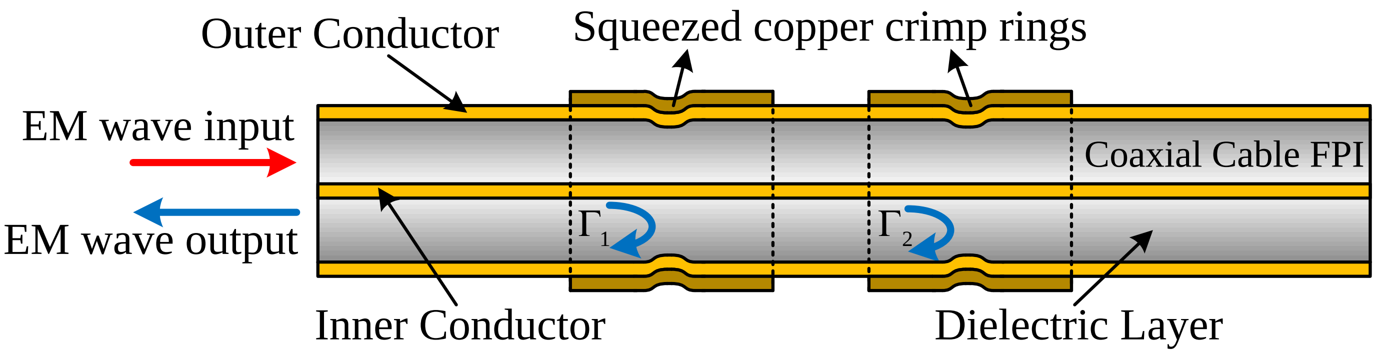


- Half-way holes
  - Unstable structure
  - Package issue



- Crimp ferrule
  - Easy fabrication
  - No further packaging needed

CCFPI Strain Sensors



$$\frac{\Delta f_N}{f_N} = \overbrace{\left(\frac{P_{eff}}{2} - 1\right)}^{\textbf{Strain sensor}} \Delta\varepsilon - \underbrace{\left(\frac{\alpha_{TCK}}{2} + \alpha_{CTE}\right)}_{\textbf{Temperature cross talk}} \Delta T$$

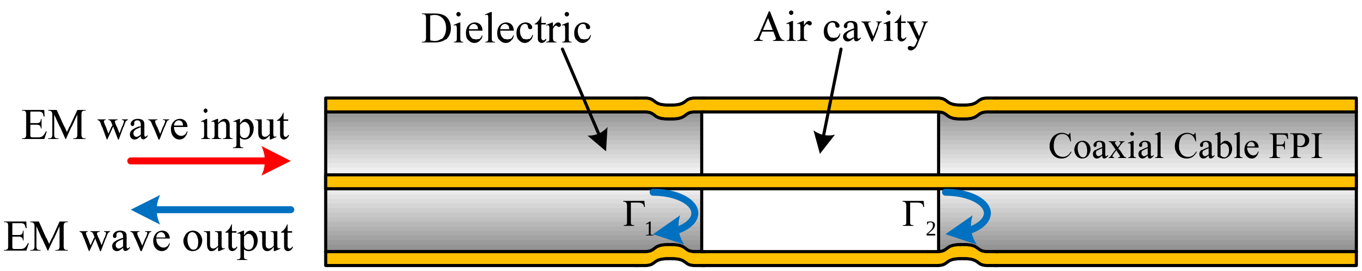
Coaxial Cable Strain Sensor

- Strain sensor is sensitive to temperature

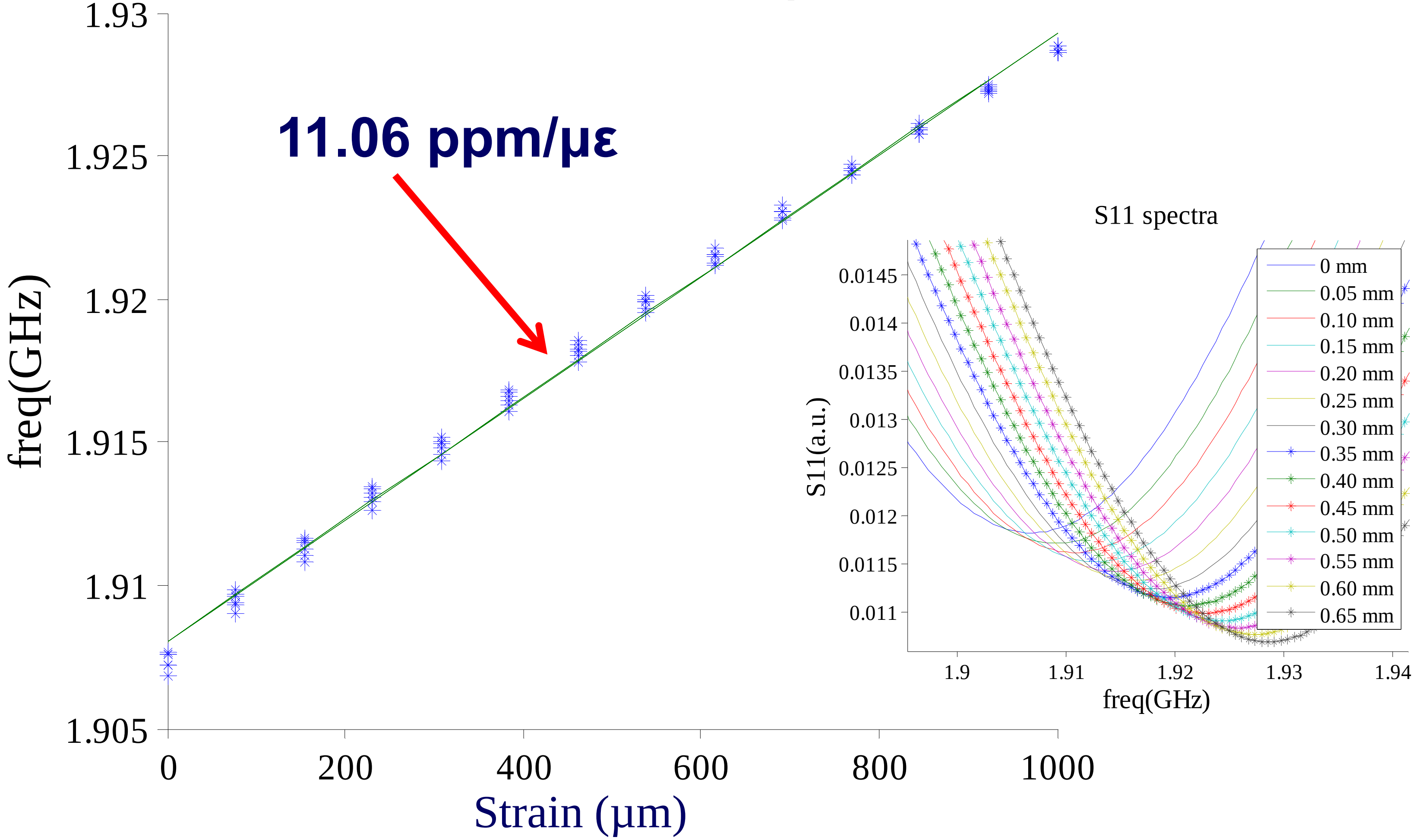
$$\frac{\Delta f_N}{f_N} = \underbrace{\left(\frac{P_{eff}}{2}-1\right)}_{\text{Strain induced}}\Delta\varepsilon - \underbrace{\left(\frac{\alpha_{TCK}}{2}+\alpha_{CTE}\right)}_{\text{Temperature induced}}\Delta T$$

☐ **Hollow coaxial cable to minimize temperature cross-talk:**

$\boldsymbol{\alpha_{TCK} = 0}$



Strain Response



11.06 ppm/με

Temperature cross talk is reduced to 20 ppm/℃, which is very close to the theoretical minimum of 16.6 ppm/℃ (limited by the CTE of copper)

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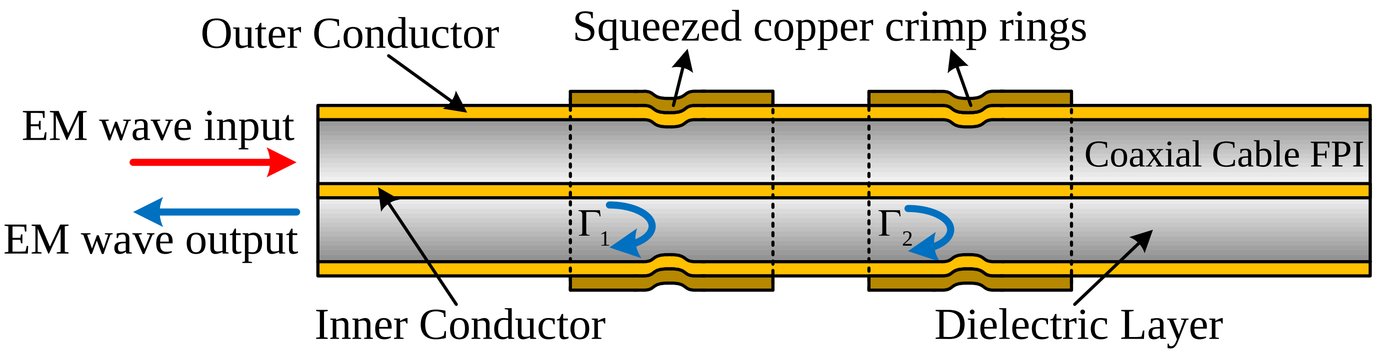
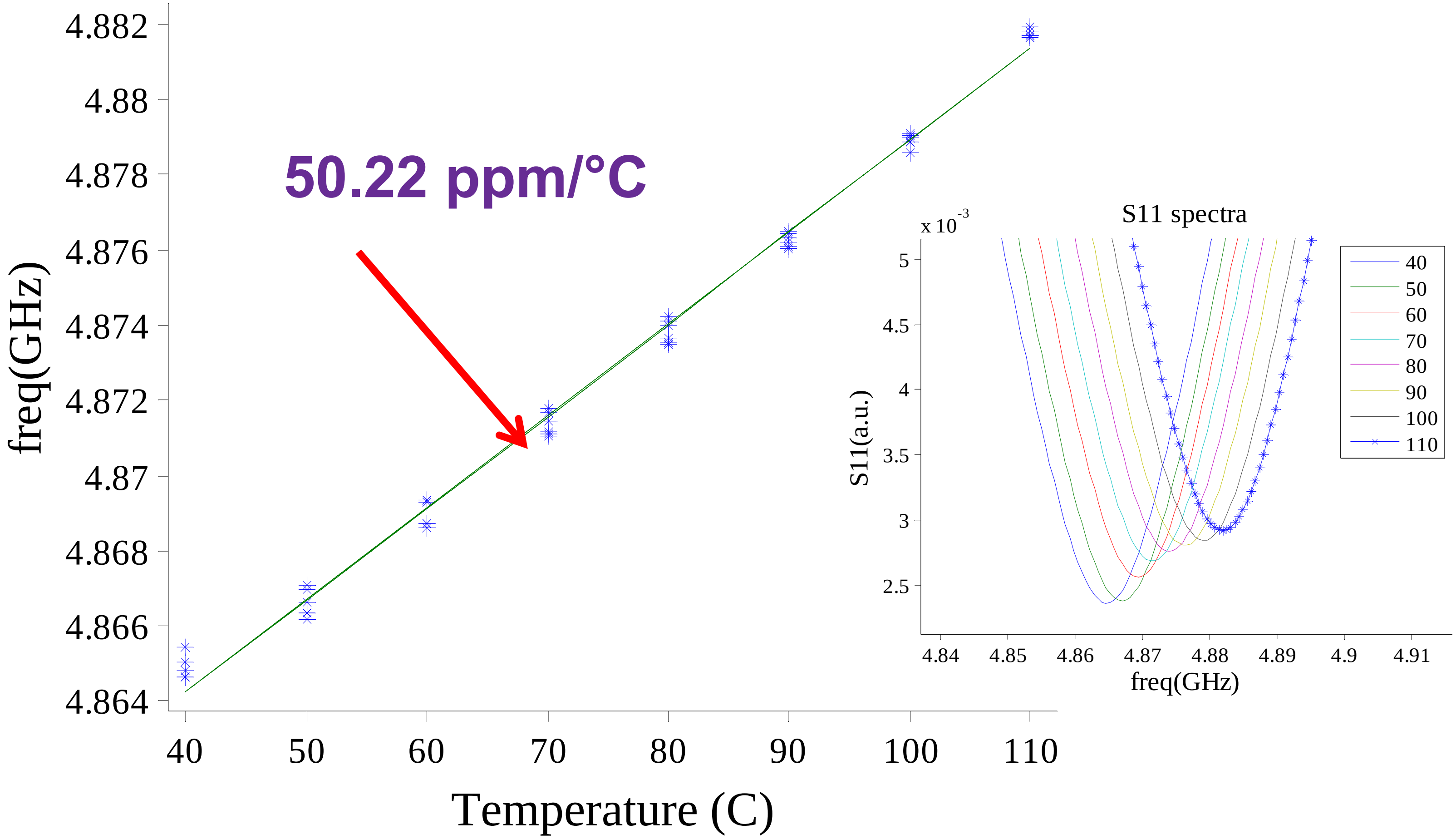
Coaxial Cable Temperature Sensor

- Reflectors are generated by crimped copper rings



Temperature Response

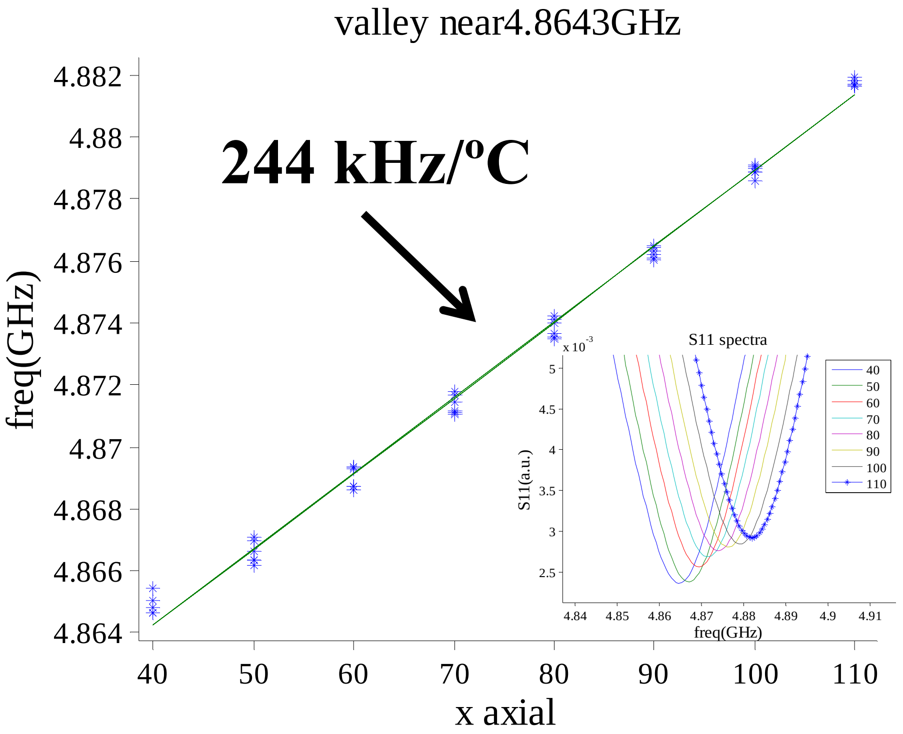

50.22 ppm/°C

- Repeatable linear temperature response with high sensitivity

Temperature response

- **Both materials and lengths will vary with temperature**

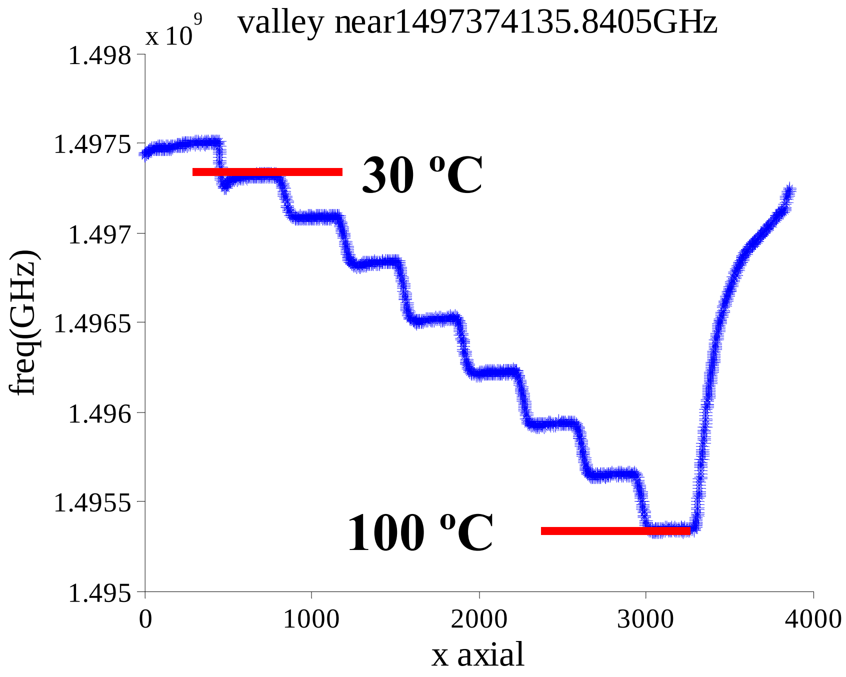
$$\frac{\Delta f_N}{f_N} = \left(\underbrace{\frac{\alpha_{TCK}}{2}}_{\text{Dielectric}} + \underbrace{\alpha_{CTE}}_{\text{Physical expansion}} \right)\Delta T$$



244 kHz/ºC

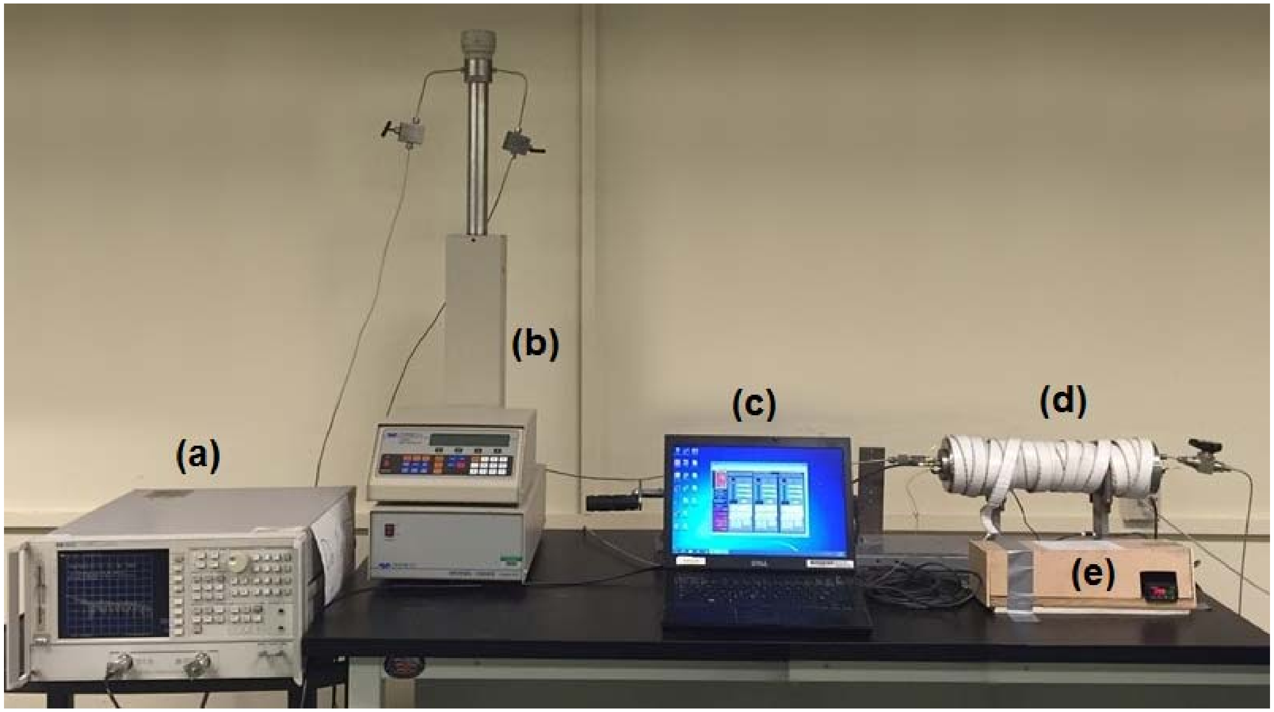
- Test setup uniformity
  - ±1.9 ℃ @ 100℃
- Deviation of four tests
  - ±3 ℃

Temperature response



- Temperature sensitivity
  - 18 ppm/ºC
- CTE of copper
  - 16.6 ppm/ºC

Pressure effects test set up



(a) VNA;

(b) pump;

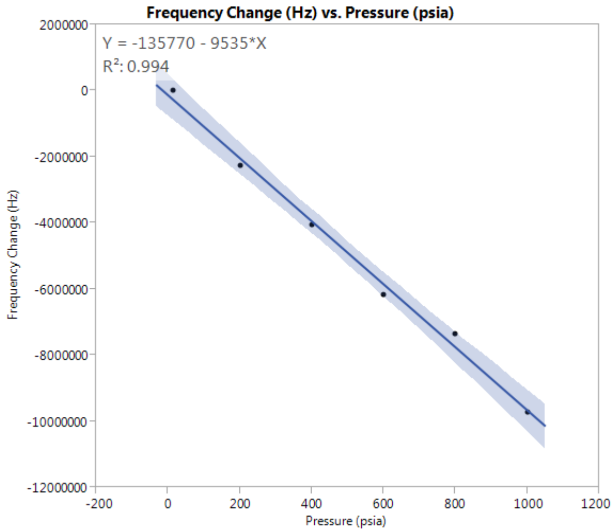
(c) data acquisition;

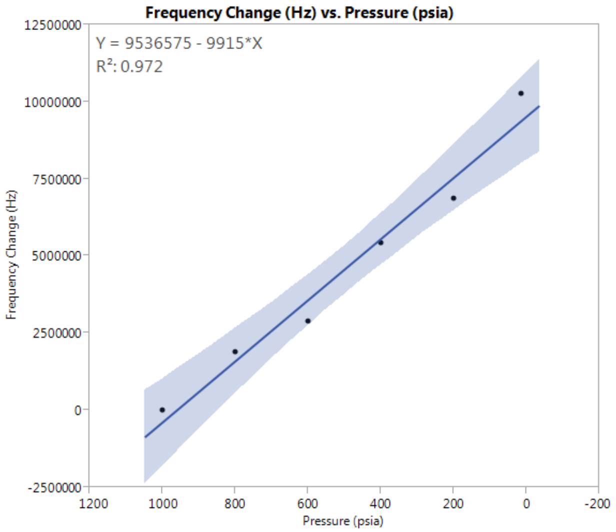
(d) HPHT cell;

(e) temperature controller.

Pressure response on temperature sensor at constant temperature

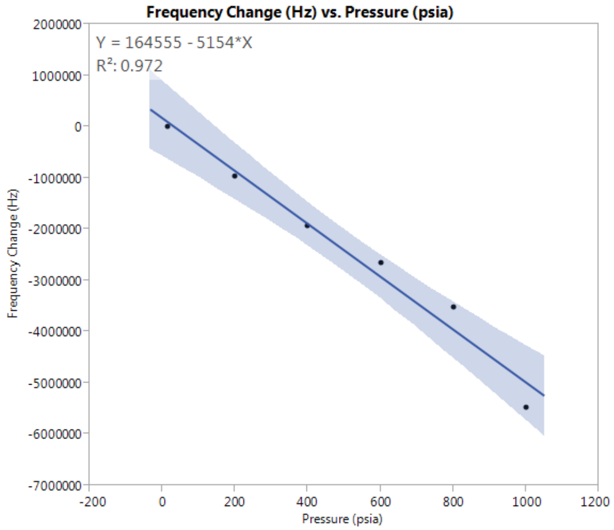
40 °C

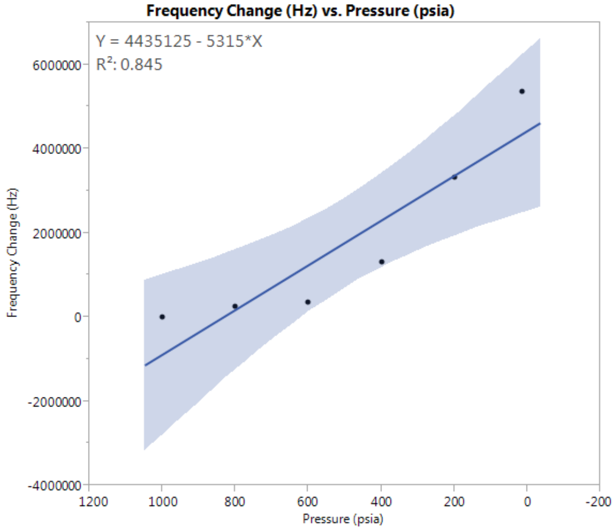




40 °C

80 °C





80 °C

Pressure effect on Temperature sensor

STATISTICAL RESULTS

Source	S.S.	F Ratio	Prob>F
Temp	8.7e+14	2100	<0.0001*
Pres	3.1e+14	751	<0.0001*
Temp*Pres	1.1e+13	28.9	<0.0001*
Temp*Temp	7.8e+12	19.0	<0.0007*
Pres*Pres	6.0e+12	14.5	<0.0019*

$$\Delta \mathrm{F} = 817 \times 10^{3} + 10.43 \times 10^{6} \times \left(\frac{\mathrm{T} - 67.5}{42.5}\right) - 6.24 \times 10^{6} \times \left(\frac{\mathrm{P} - 507.35}{492.65}\right) - 2.45 \times 10^{6} \times \left(\frac{\mathrm{T} - 67.5}{42.5}\right) \times \left(\frac{\mathrm{P} - 507.4}{492.7}\right) + 1.86 \times 10^{6} \times \left(\frac{\mathrm{T} - 67.5}{42.5}\right) \times \left(\frac{\mathrm{T} - 67.5}{42.5}\right) + 1.62 \times 10^{6} \times \left(\frac{\mathrm{P} - 507.4}{492.7}\right) \times \left(\frac{\mathrm{P} - 507.4}{492.7}\right)$$

Modified temperature sensor minimized pressure effect

STATISTICAL RESULTS

Source	S.S.	F Ratio	Prob>F
Temp	3.23e+14	178	<0.0001*
Pres	7.52e+11	0.413	0.5307
Temp*Pres	4.85e+10	0.027	0.8727
Temp*Temp	1.15e+12	0.635	0.4390
Pres*Pres	3.78e+10	0.021	0.8874

$$\Delta F = -6.262 \times 10^6 - 6.362 \times 10^6 \times \left(\frac{T - 67.5}{42.5}\right)$$

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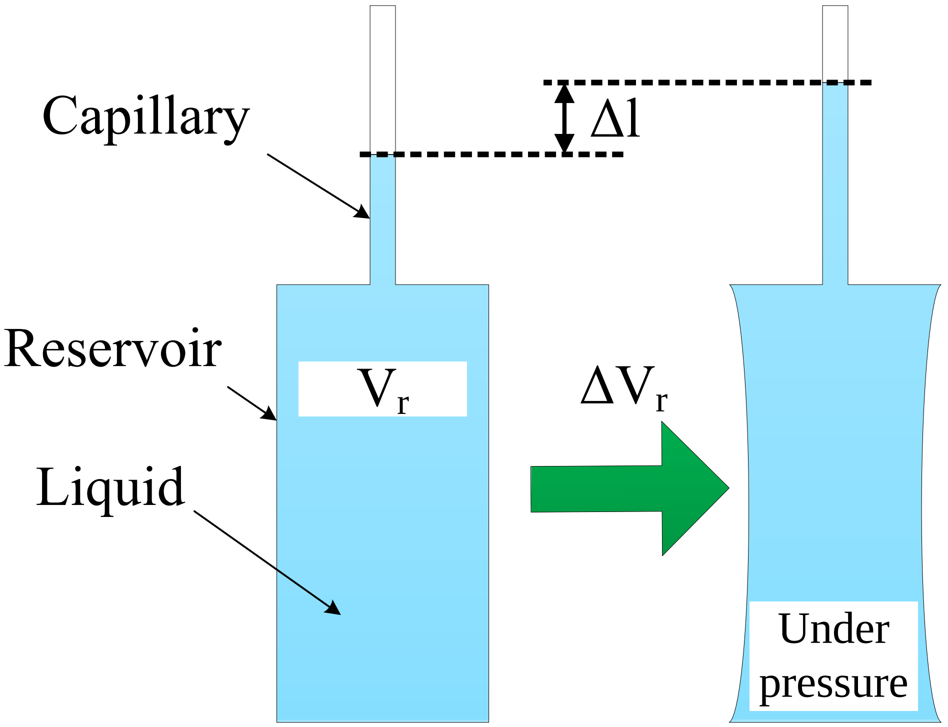
Microwave pressure sensor

- Principle: reservoir and capillary for amplification similar to the liquid in glass thermometer



Pressure-induced deformation

$$\frac{\Delta V_r}{V_r} = \frac{pD}{4tE}(5-4v)$$

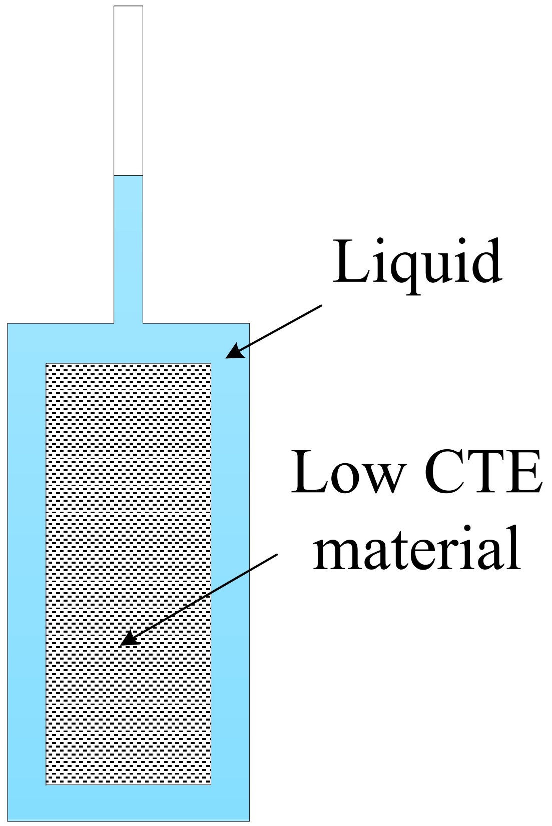
The deformation is manifested by liquid column

$$\Delta l = \frac{\Delta V_r}{S_c}$$

Capillary area

Temperature cross-talk reduction

- The pressure sensor is also sensitive to temperature
- Fill low CTE material to minimize liquid volume



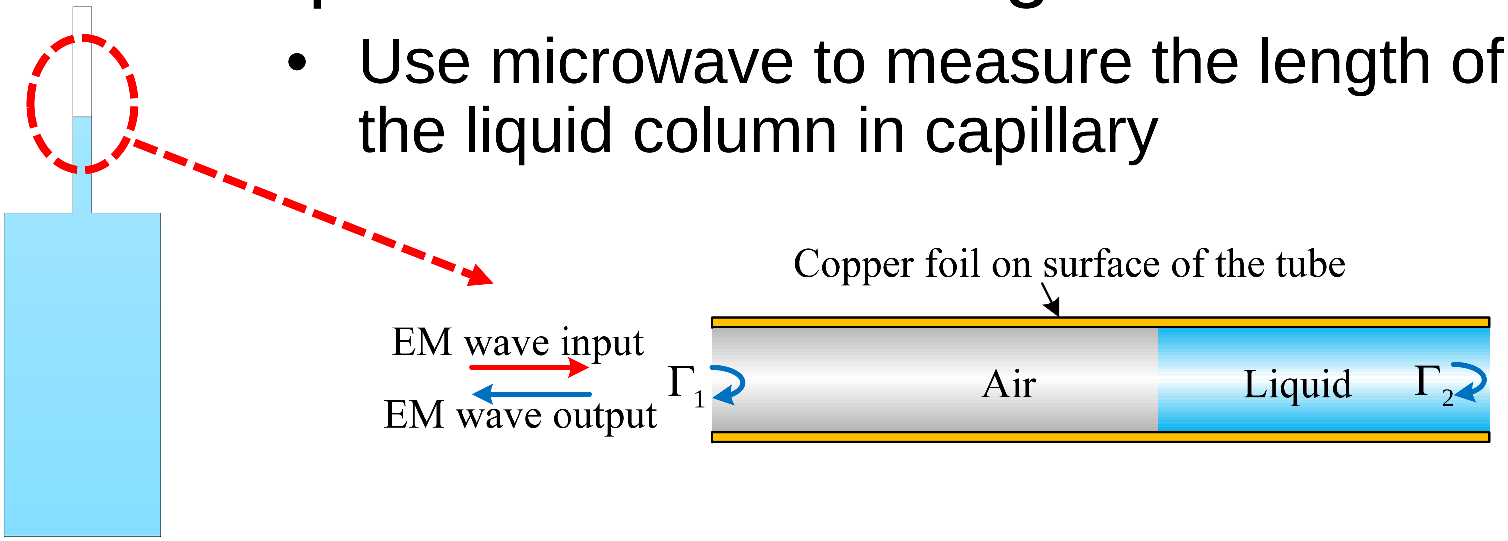
Reservoir volume: the same ⇒ **Pressure sensitivity: the same**

Liquid volume: reduced ⇒ **Temperature sensitivity: small**

$$Xtalk_T \propto \frac{\boxed{V_{liquid}}}{V_{reservoir}}$$

Liquid column interrogation

- Use microwave to measure the length of the liquid column in capillary



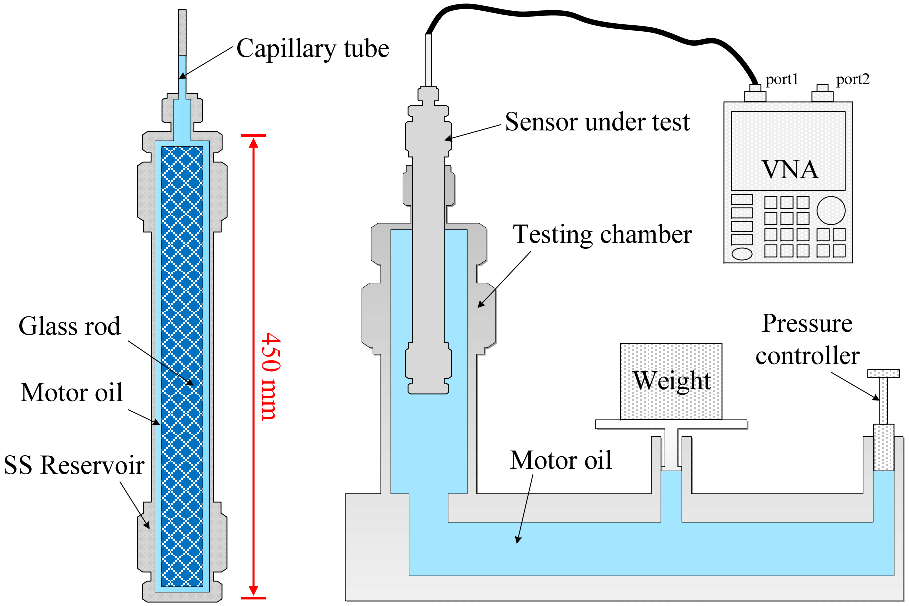
- **Microwave travels slower in liquid than air**
- **The electrical length between two reflectors is liquid column dependent**

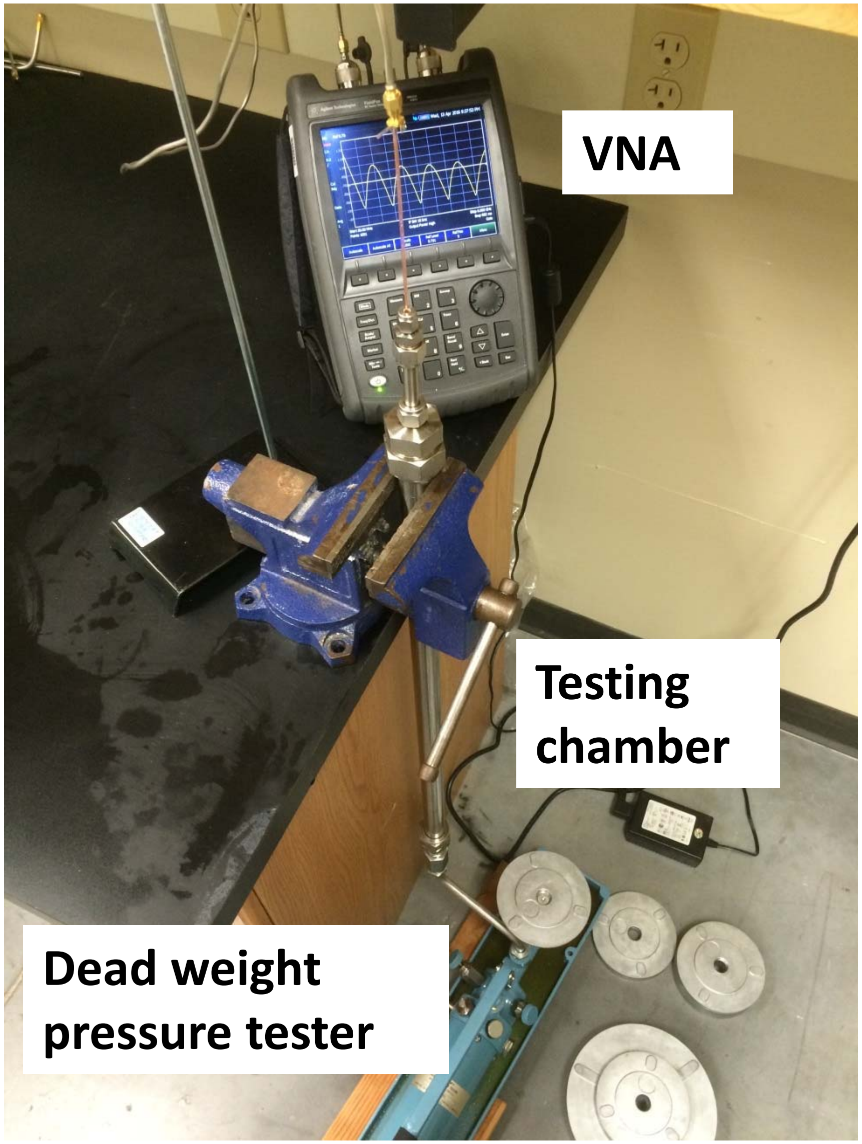
$$\Delta L = \Delta\varepsilon\Delta l \quad \Longrightarrow \quad \frac{\Delta f}{f} = -\frac{\Delta L}{L}$$

Electrical length **Liquid column**

Spectrum shift with electrical length variation

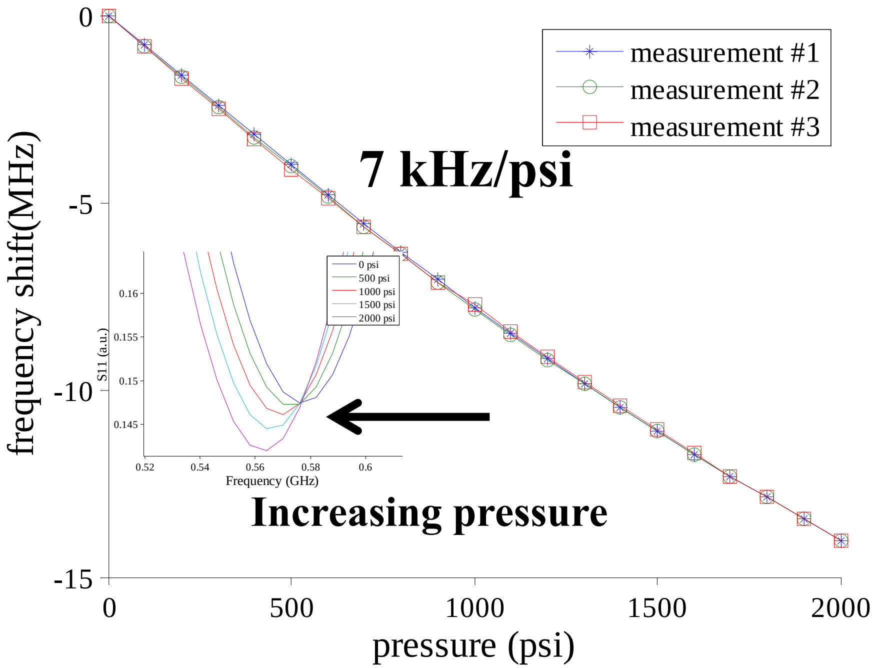
Pressure sensor test setup





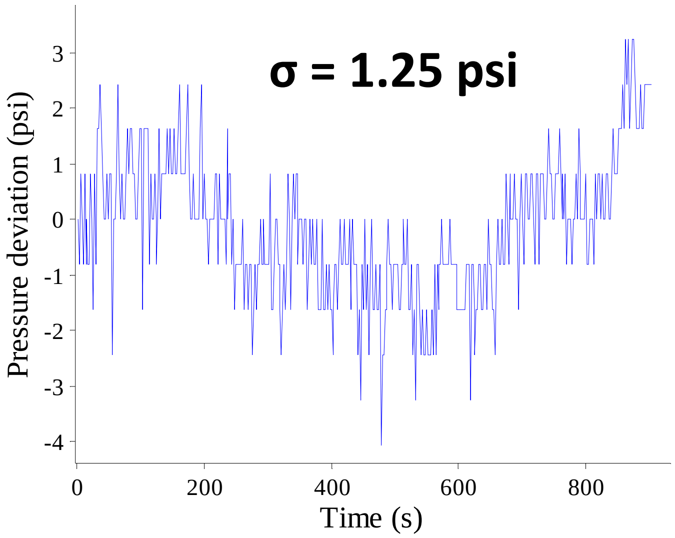
Pressure test results

- Sensitivity



- **Stable and repeatable**
- **Detection limit ~ 1 psi**

- **Stability**



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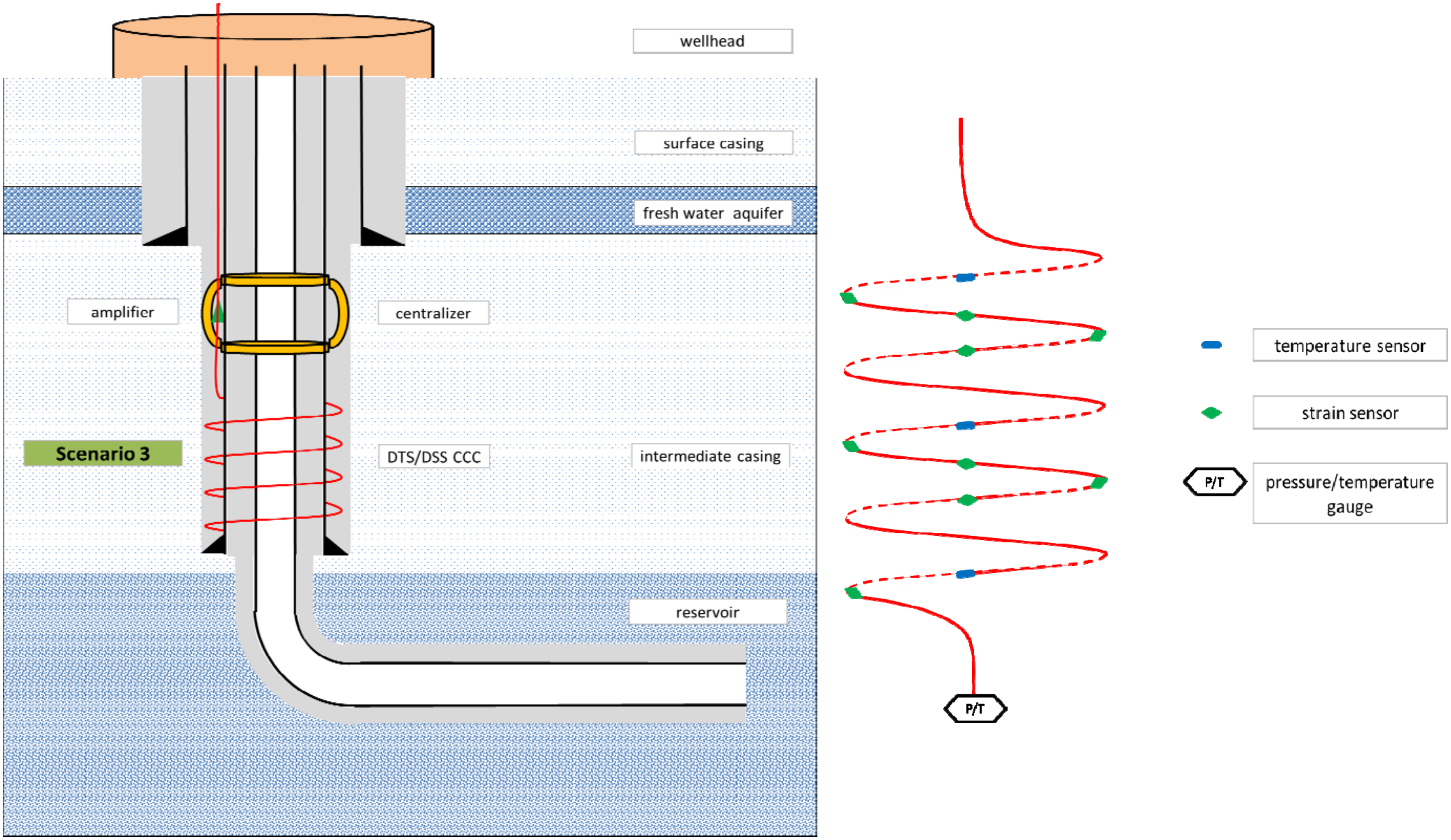
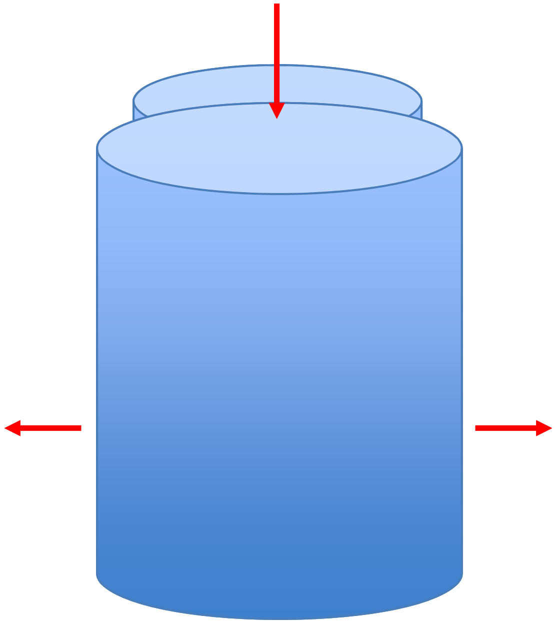
- Summary

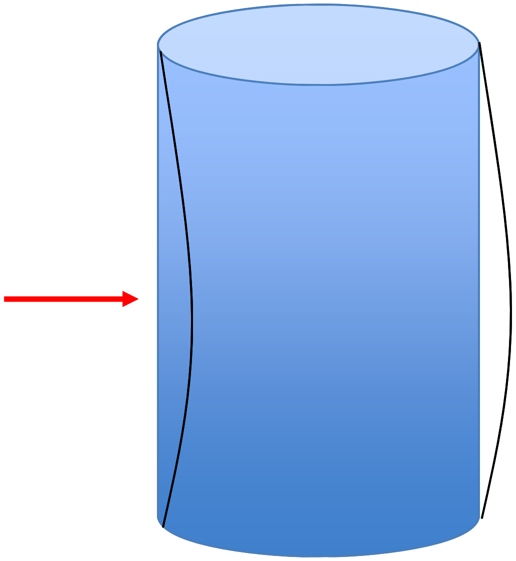
Proposed coaxial cable sensing system deployment method



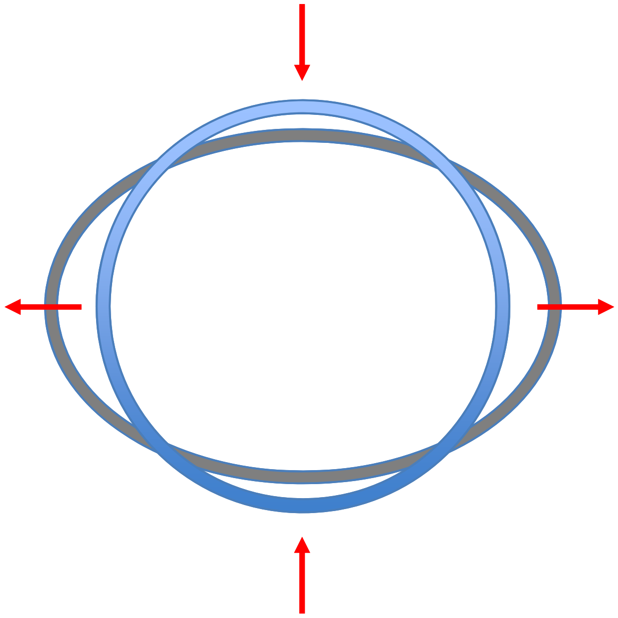
Casing deformation modes



Axial and Radial

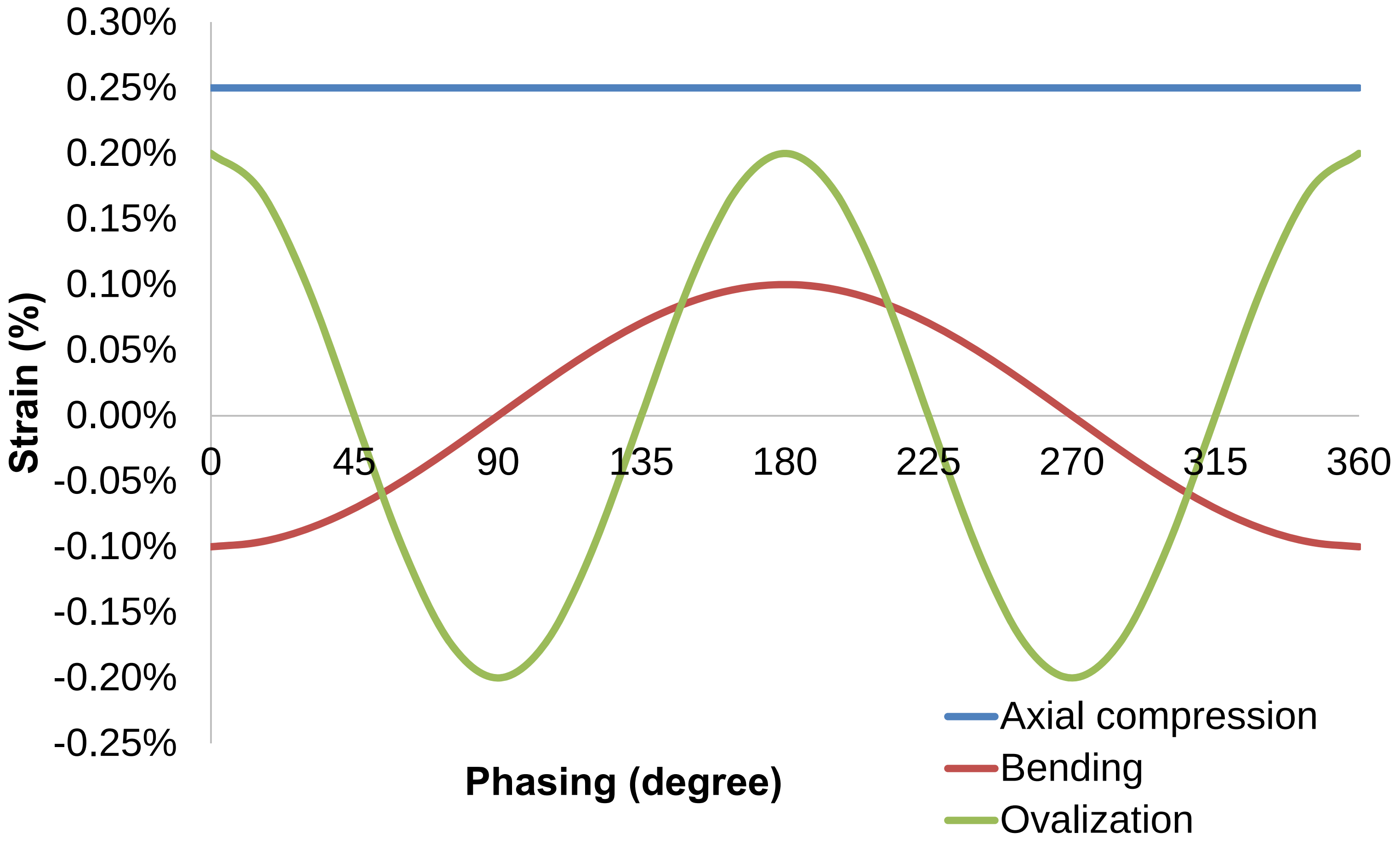


Bending



Ovalization

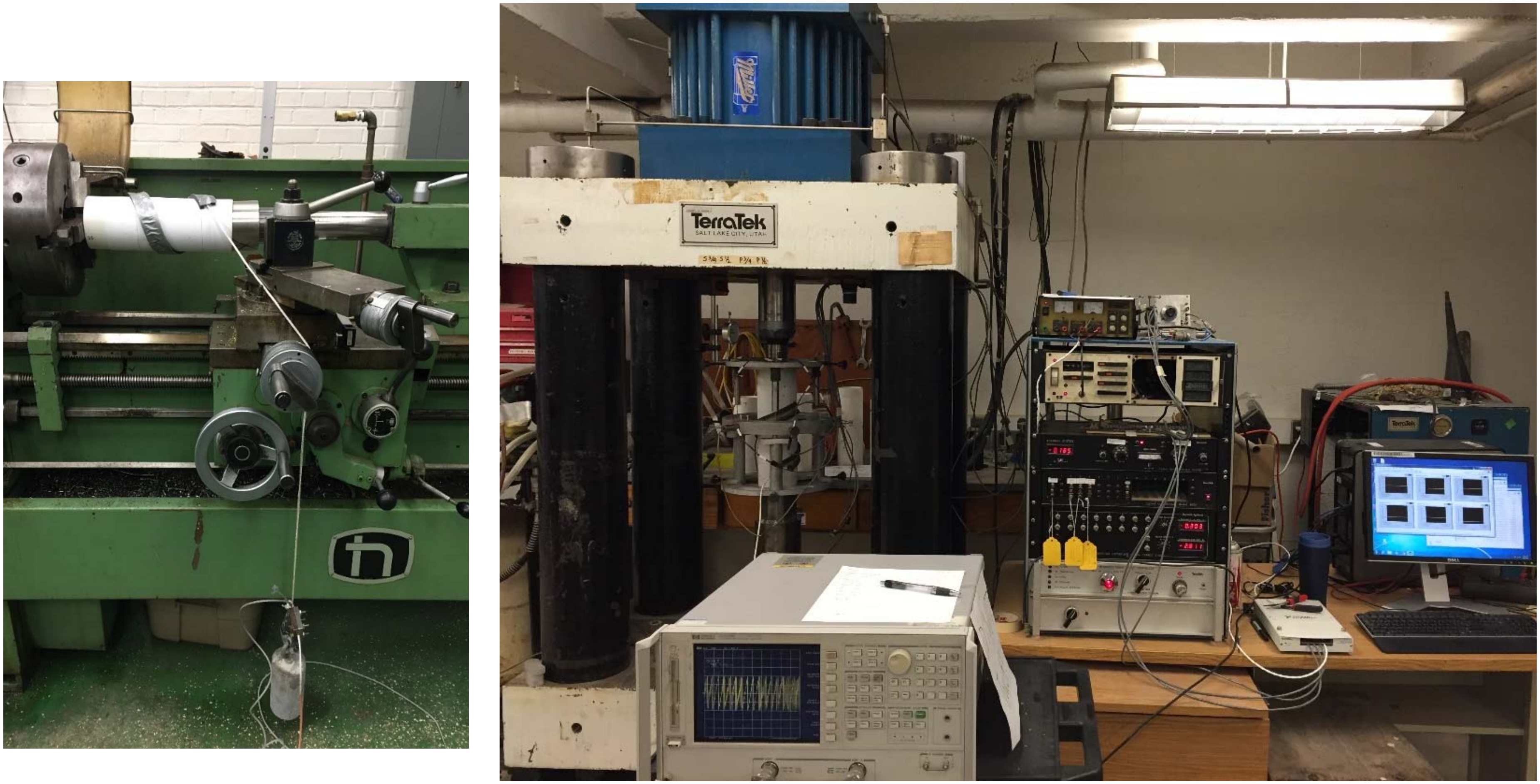
Wrapped sensor response to a specific deformation mode



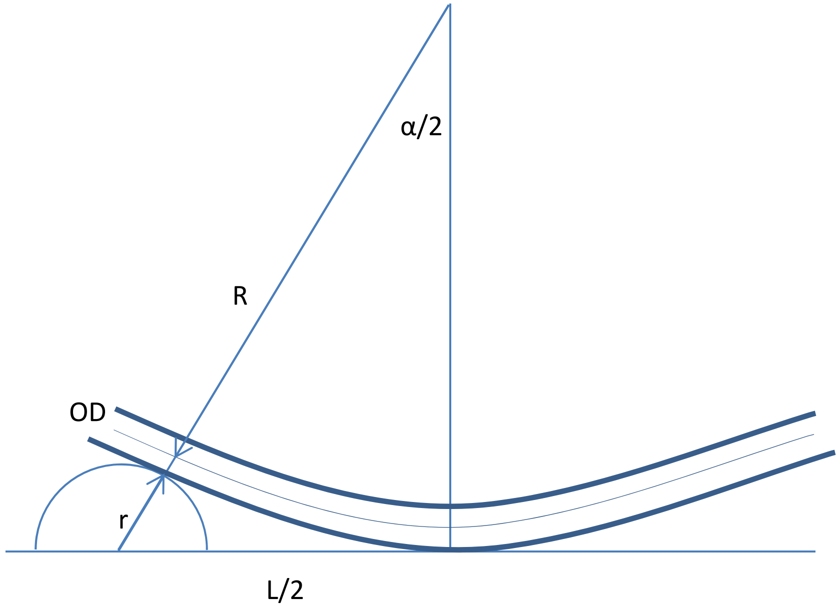
3.2 Casing imaging system

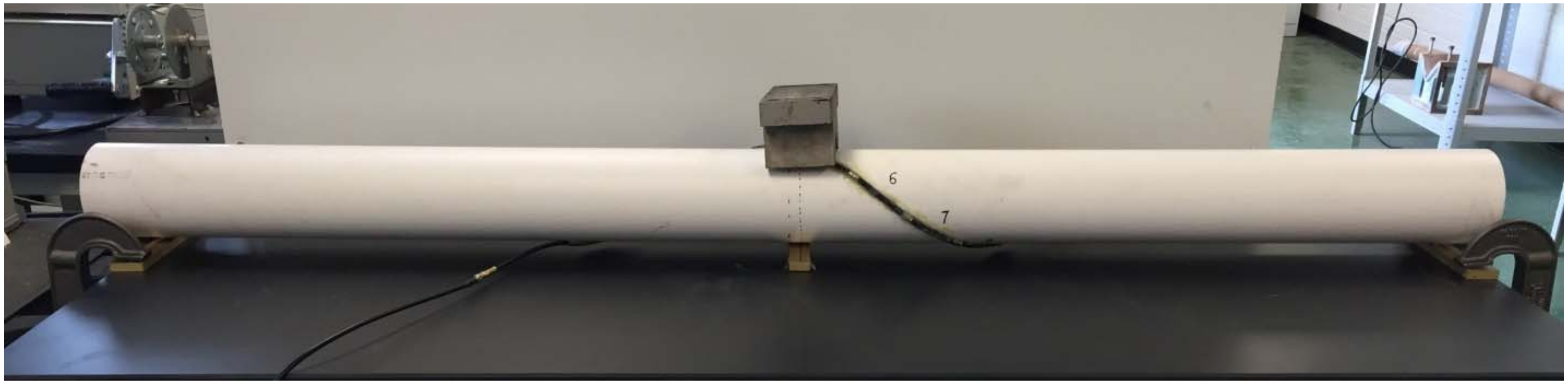
Deformation Mode	Pipe OD (inch)	Sensor Length (inch)	Wrapping Angle (degree)
Axial Compression/ Radial Expansion	4.5 (PVC)	4	23
Bending	4 (PVC)	3	55
	6 (Steel)	3	35
Ovalization	6 (PVC)	3	35
	6 (Steel)	3	35

Axial compression test set up



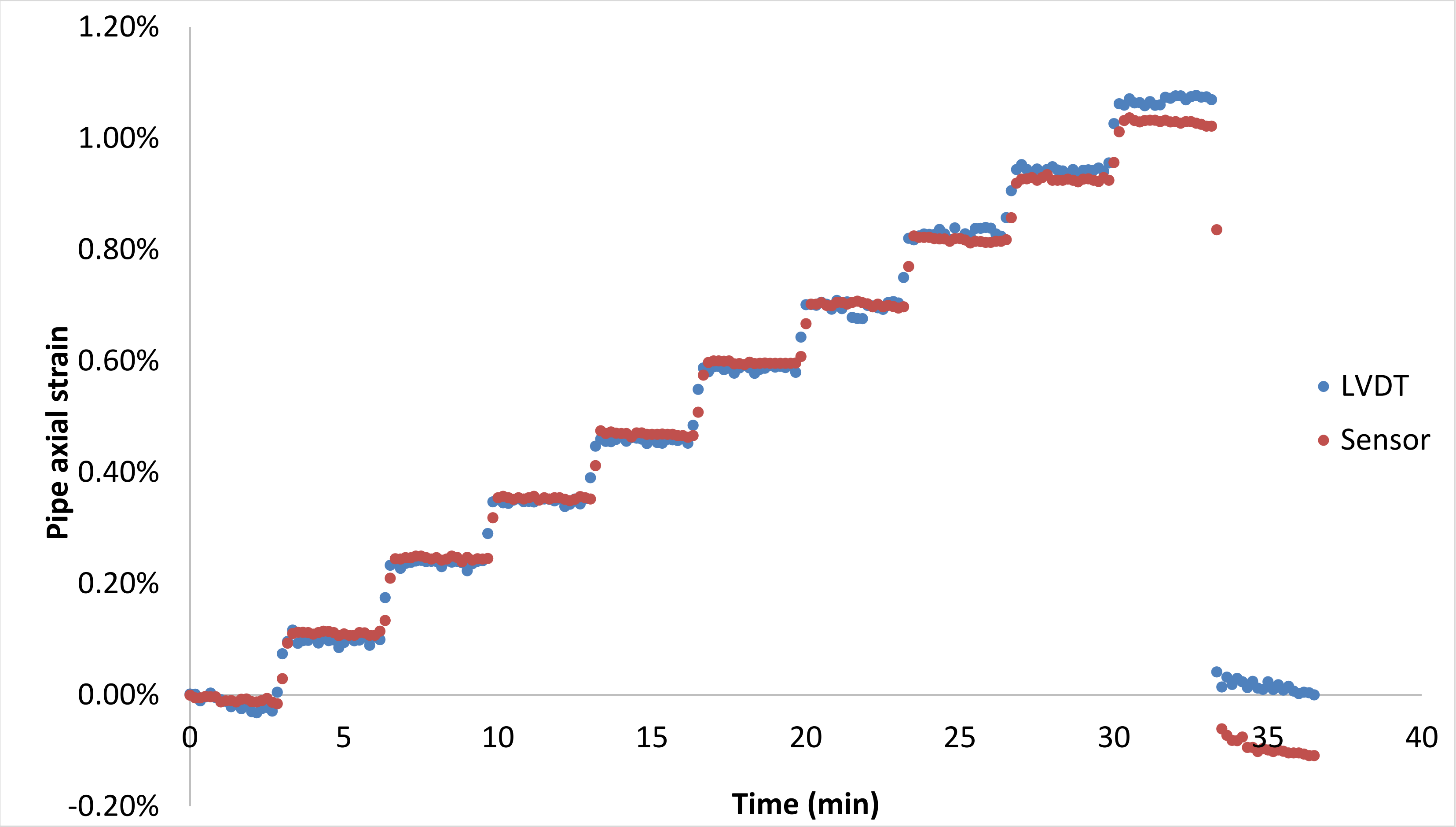
Bending test setup



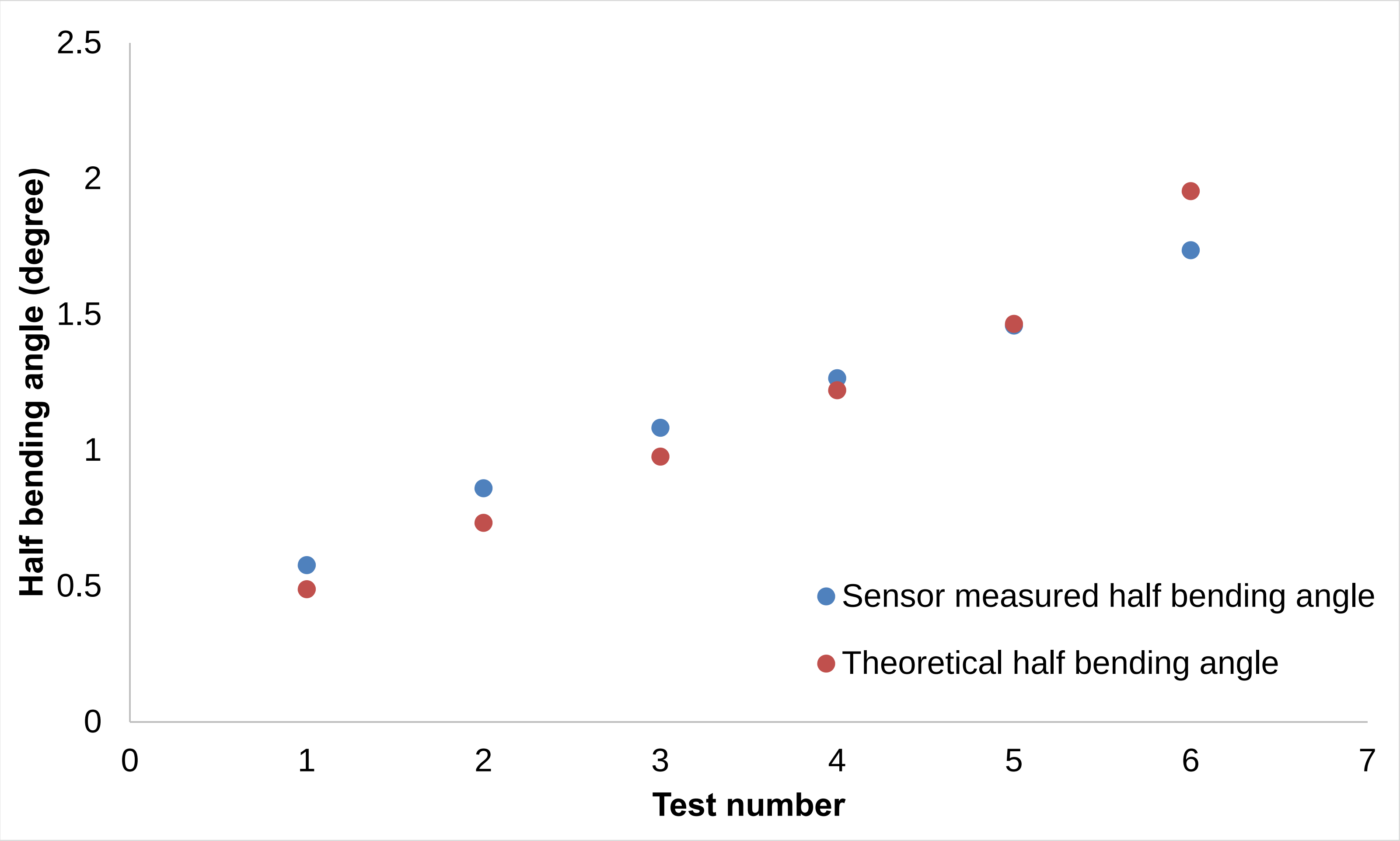


Ovalization test set up

PVC pipe axial strain results



PVC pipe bending results



Observations from pipe testing

- A prototype of the distributed coaxial cable casing imager has been developed and tested on both PVC and steel pipes
- The casing imager has good performance in casing axial compression monitoring for strain up to 1%
- There is a good match between theoretical and measured bending angle for bending angle up to 4 degrees
- The measured pipe ovalization follows the theoretical curve for pipe ovality up to 3%
- Pipe original roundness and straightness has a strong influence on bending and ovalization results
- The pre-stressing and epoxy properties influenced measurements especially when deployed on the steel pipe

Outline

- Long term CO2 injection integrity monitoring – problem statement
- Main objective to demonstrate and develop a novel, robust, down hole sensing technology for in-situ monitoring
- To reach the objective we developed and verified the robust ceramic coaxial cable sensors at elevated temperature and pressure
  - Strain
  - Temperature
  - Pressure
- Evaluated a bench scale wellbore system
- Summary

Summary

- Distributed strain and temperature rigid coaxial sensors for down hole conditions have been developed and are verified at down-hole conditions
- The pressure sensor is developed and validated
- Distributed sensing concept using coaxial cable is proven
- A bench scale prototype with distributed coaxial cable sensors was wrapped with an angle to a pipe and replicated the imposed strain behaviour