Fiber Optic Multiplexing Technique for MEMS Pressure Sensors in CO_2 Sequestration Cavities

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General Electric Global Research

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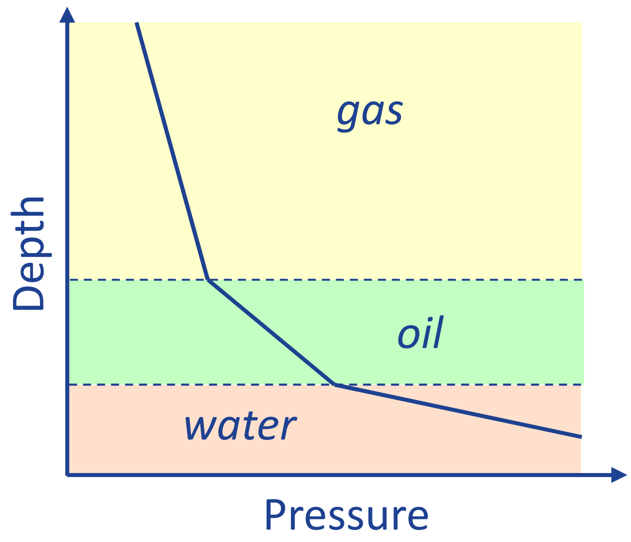
Why multiplex downhole pressure sensors?

- Monitor for CO_2 leakage
- Fluid flow
- Chemical recombination
- Fluid density vs. depth



Sensor requirements:

- 0 to 10 kpsi, 250°C
- high readout accuracy & stability
- environmental stability in sc-CO_2
- robust cable, sensor package & splicing design
- remote monitoring capability

Two Year DOE NETL-funded Project

Phase 1 tasks:

- Design, fabricate & test spliceable sensor package
- Design & demonstrate interrogation system for **multiplexed** sensors

Phase 2 tasks:

- Long term environmental test of sensor package
- Sheave stress test of sensor cable
- Remote monitoring demonstration

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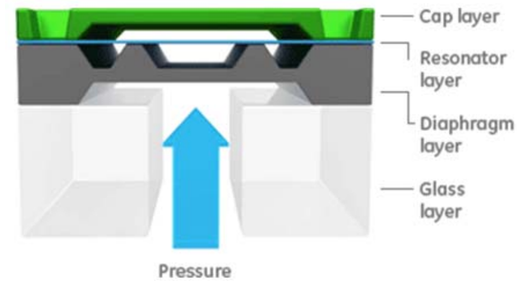
GE M&C: MEMS Pressure Sensors

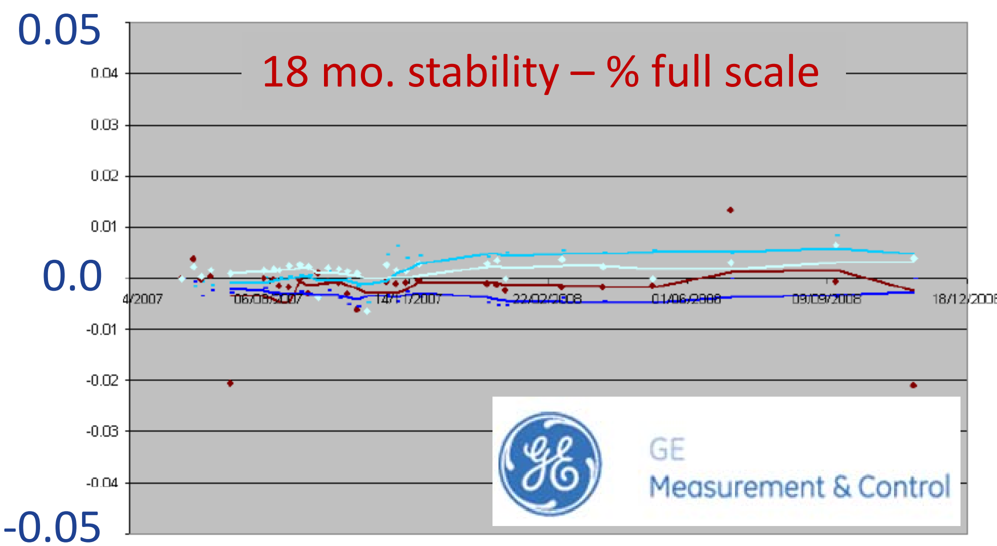
- Extremely accurate: ±0.01% FS
- Low drift: <100 ppm/year (±0.01% FS)
- Si technology (half the cost of quartz)
- Commercial: electrical readout, ≤ 85°C
- Vibrational modes: 10 - 100 kHz



Internal cross section

Butterfly resonator

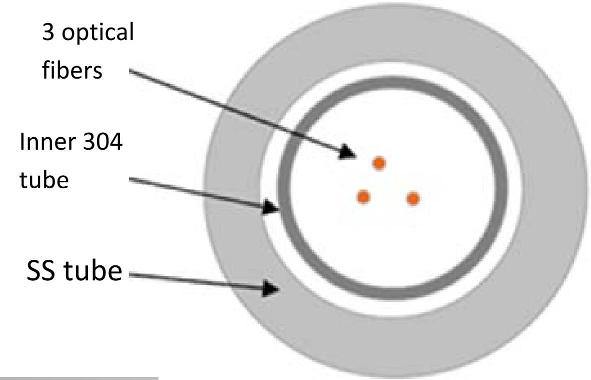
Packaged sensor



Time

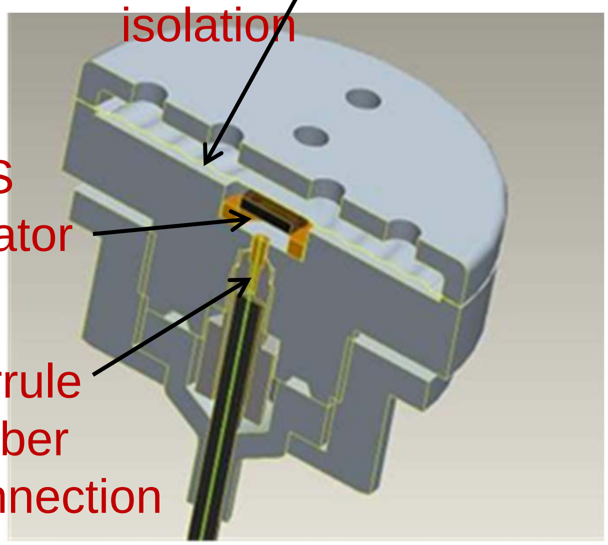
Package/Cable Design for Downhole Sensing

- Fiber optic interrogation
- Polyimide fiber coating $\Rightarrow\ \leq 300°C$
- 3 cm package diameter
- 2.5 year DOE GTO funded project



QOREX

AFL Telecommunications
A Fujikura Business



GE
Measurement & Control

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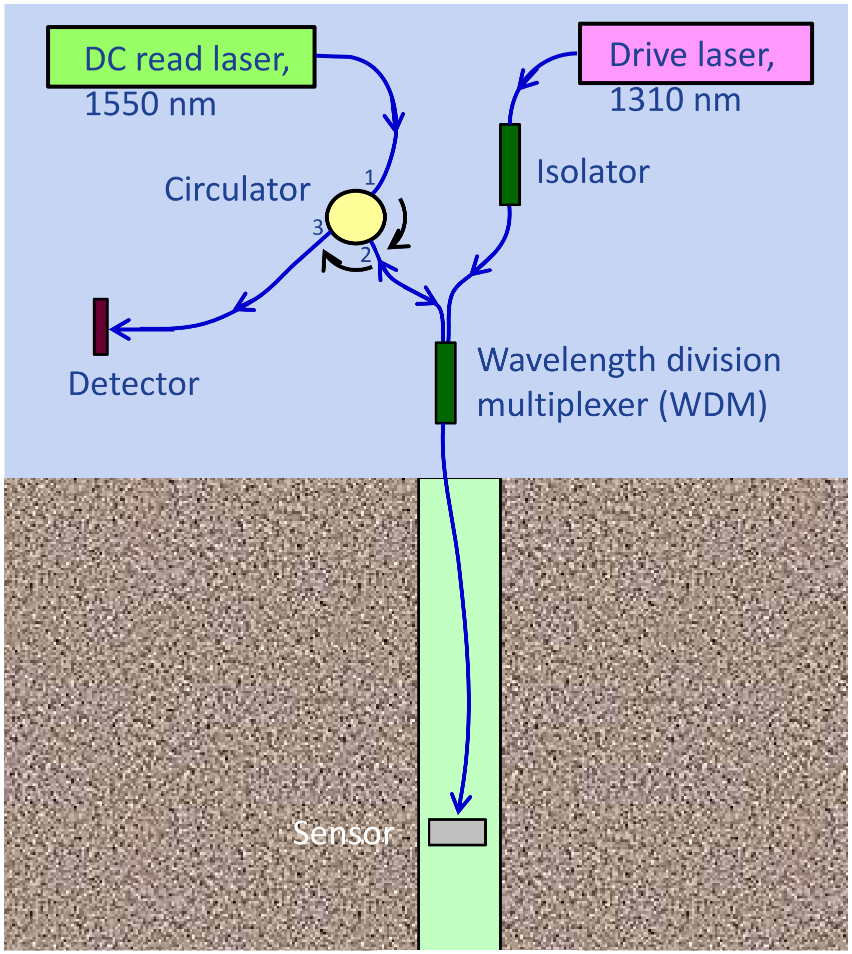
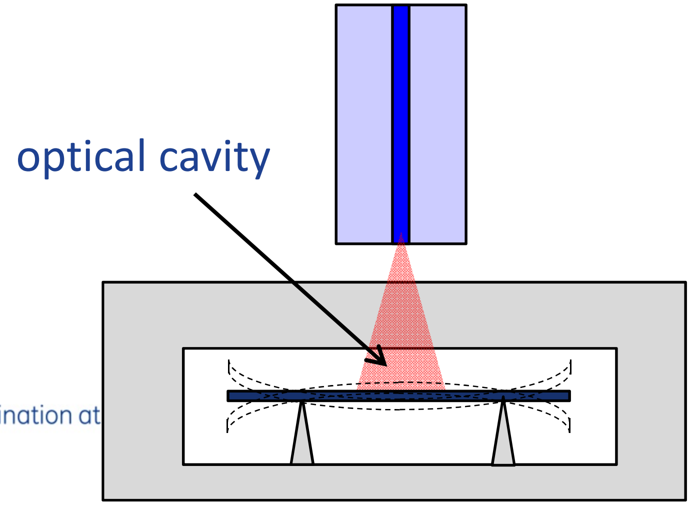
Single sensor interrogator design

- Sinusoidally modulated drive laser at sensor resonant frequency
- DC read laser at different λ
- Lock-in detection of 1*f* & 2*f* amplitude & phase
- Feedback loops to track sensor frequency





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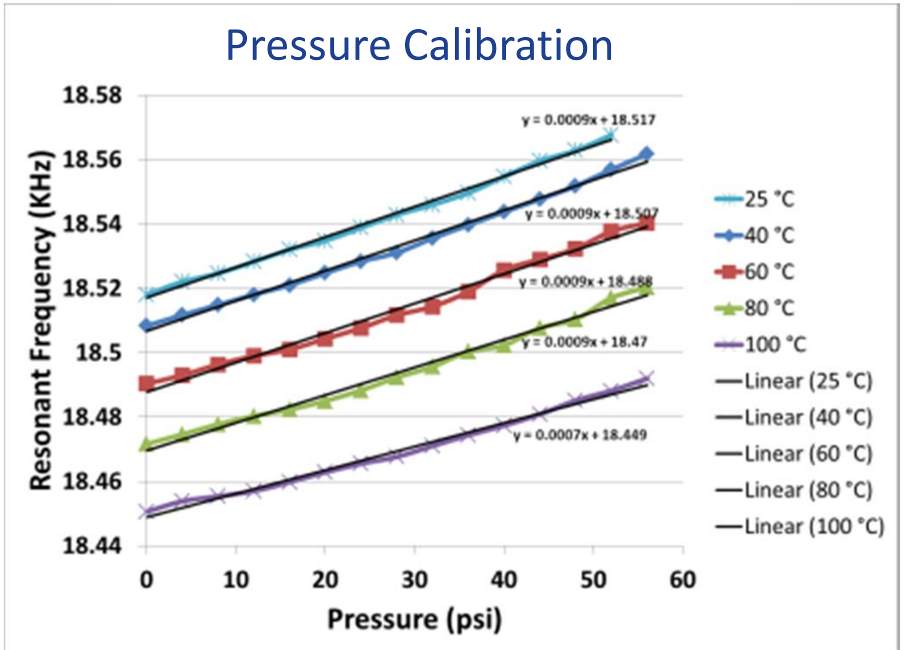
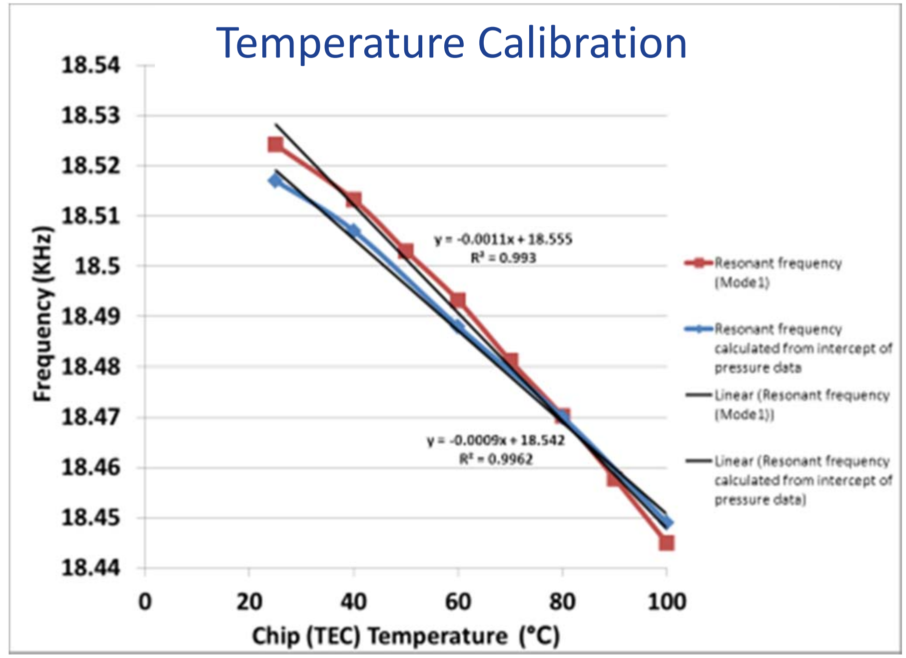
Sensor calibration for T & P



Pressure sensitivity: 0.7 to 0.9 Hz/psi



Temperature sensitivity: -0.9 to -1.1 Hz/°C

Sensor calibrated from 0 to 3000 psi and 20 to 260°C with ±0.1% accuracy

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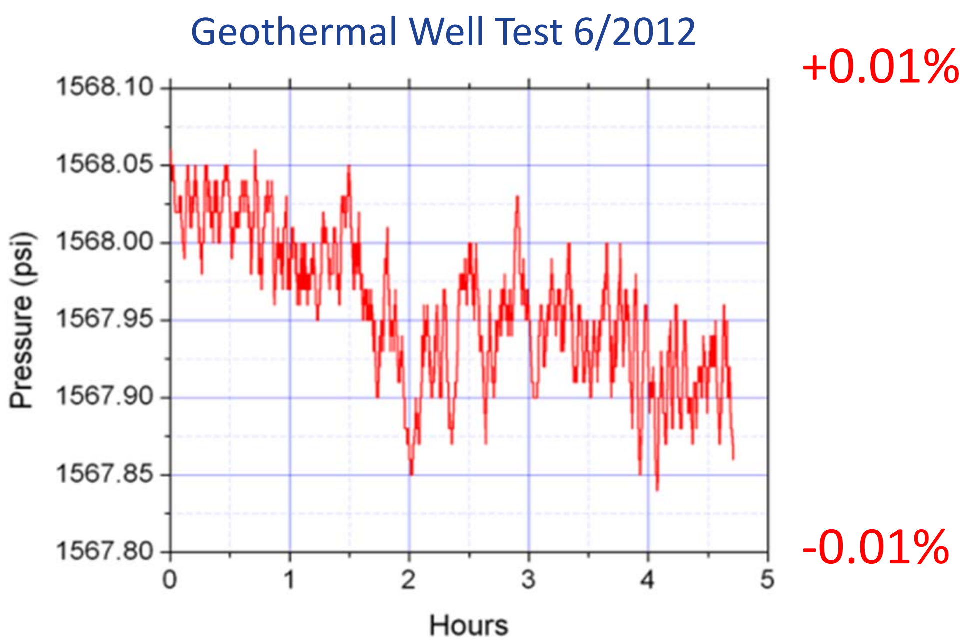
Single point pressure measurement results

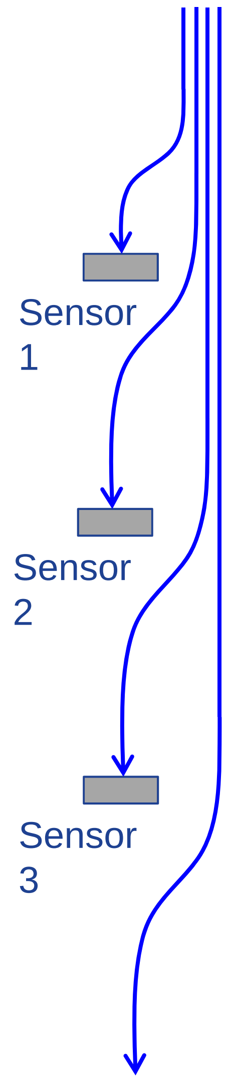


2.5 week field test in geothermal well

Project goal: multiplexed sensors

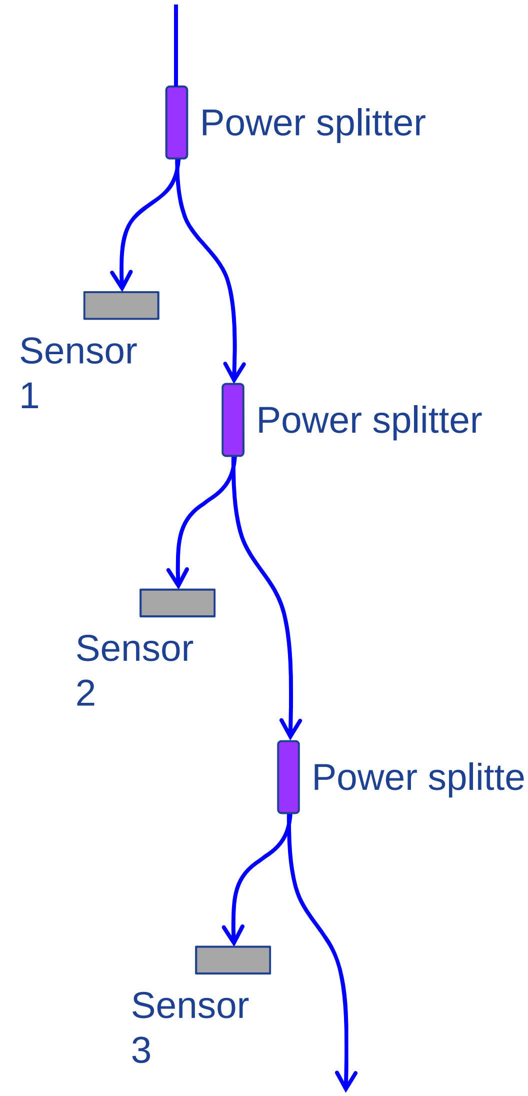
Interrogation techniques:

- Multiple fibers
  - "brute force"
  - expensive fiber cost
  - single interrogator
  - fiber splicing challenge, = N^2
  - # sensors limited ~20
- Power division
- Wavelength division



Power division multiplexing

- Use sensor resonant frequency to multiplex
- Least expensive: one interrogator
- Single fiber: (2N-1) splices
- SNR $\propto 1/N$
- Requires high *T* splitters
- ~4 sensors max?



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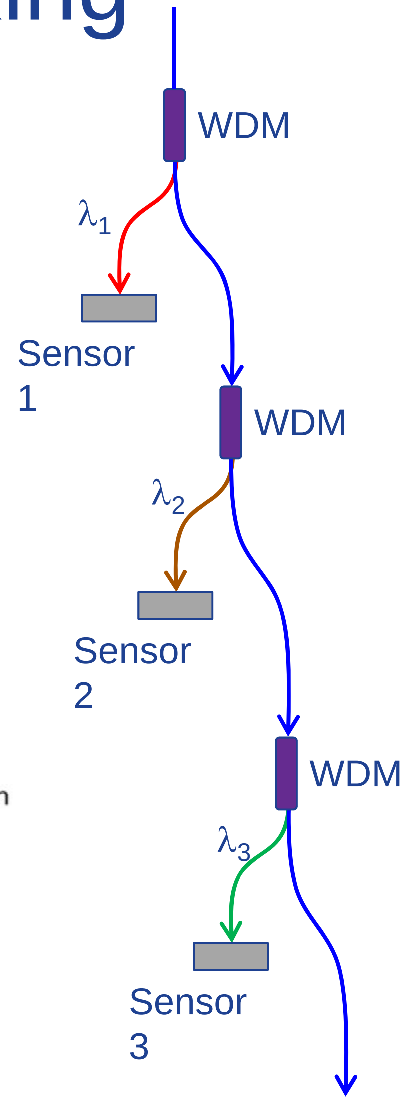
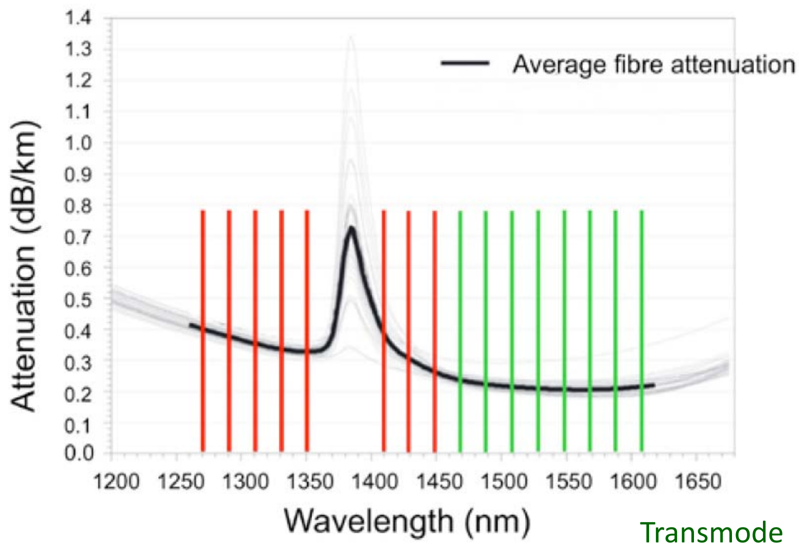
Wavelength division multiplexing

- Standard telecom approach
- ~16 CWDM wavelengths
- No read power loss
- Single fiber: (2N-1) splices
- Requires high *T* WDMs
- Requires single λ interrogator





Transmode

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Fiber optic interrogator using pulsed laser

- Single wavelength operation

  ⇒ wavelength multiplexing

- Simultaneous measurement of multiple resonant frequencies

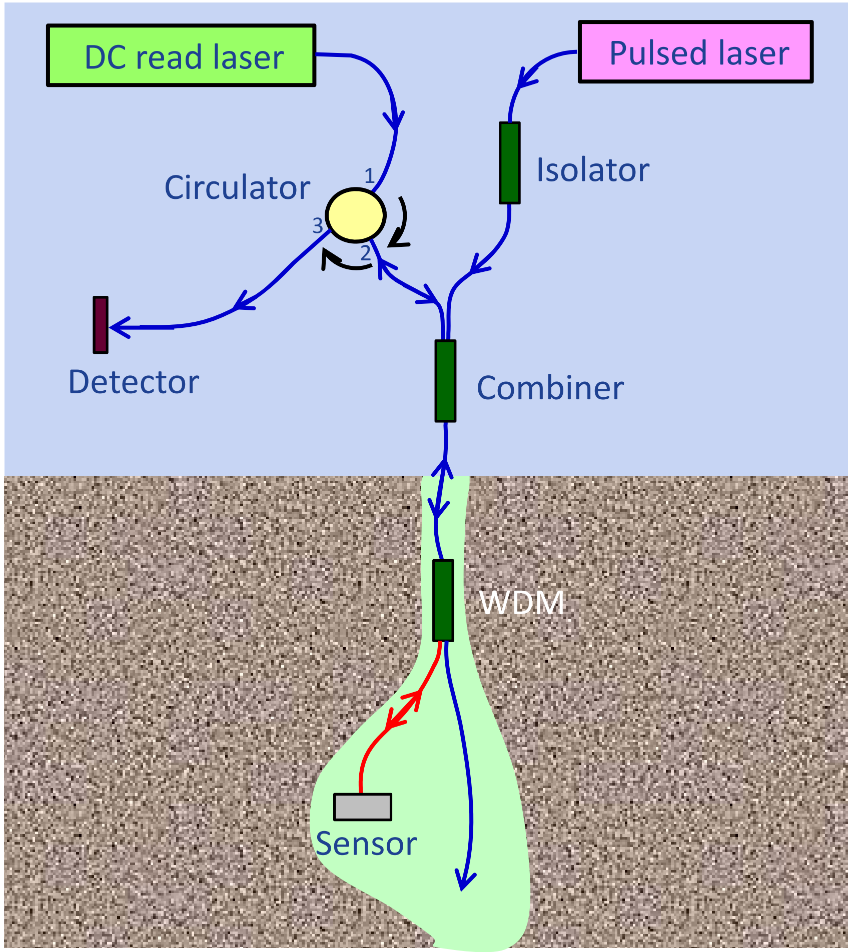
  ⇒ frequency multiplexing

  ⇒ T & P measurement

- Simplified electronics

  ⇒ no feedback loops

- Tunable laser(?)



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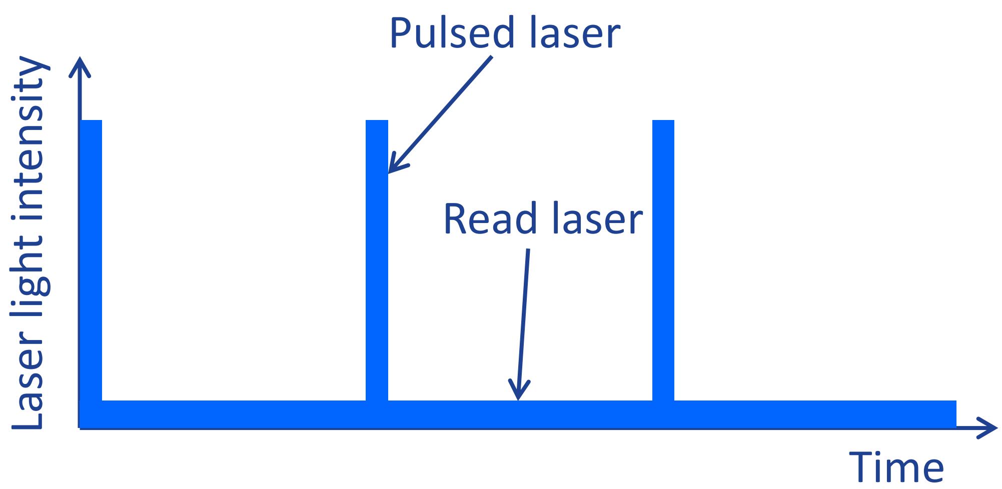
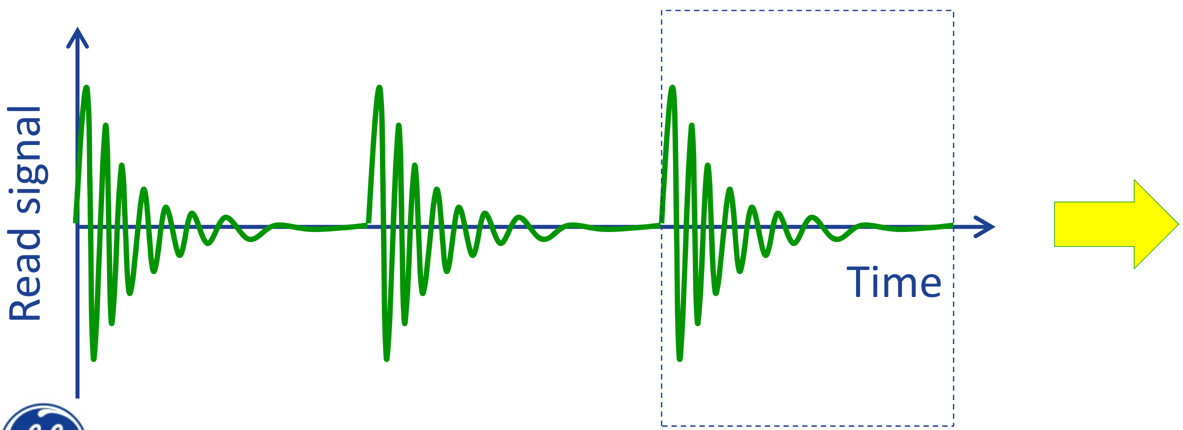
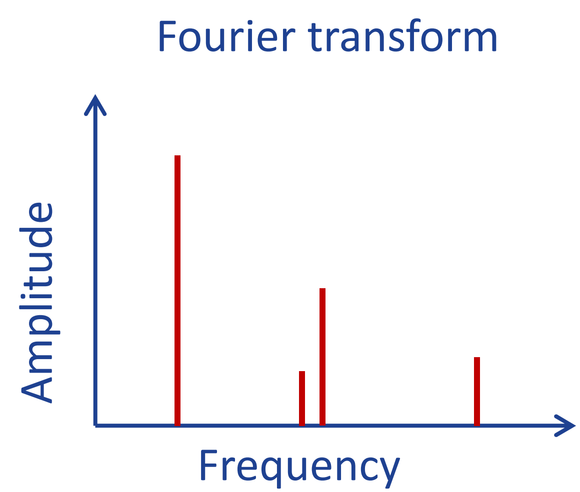
Interrogation method

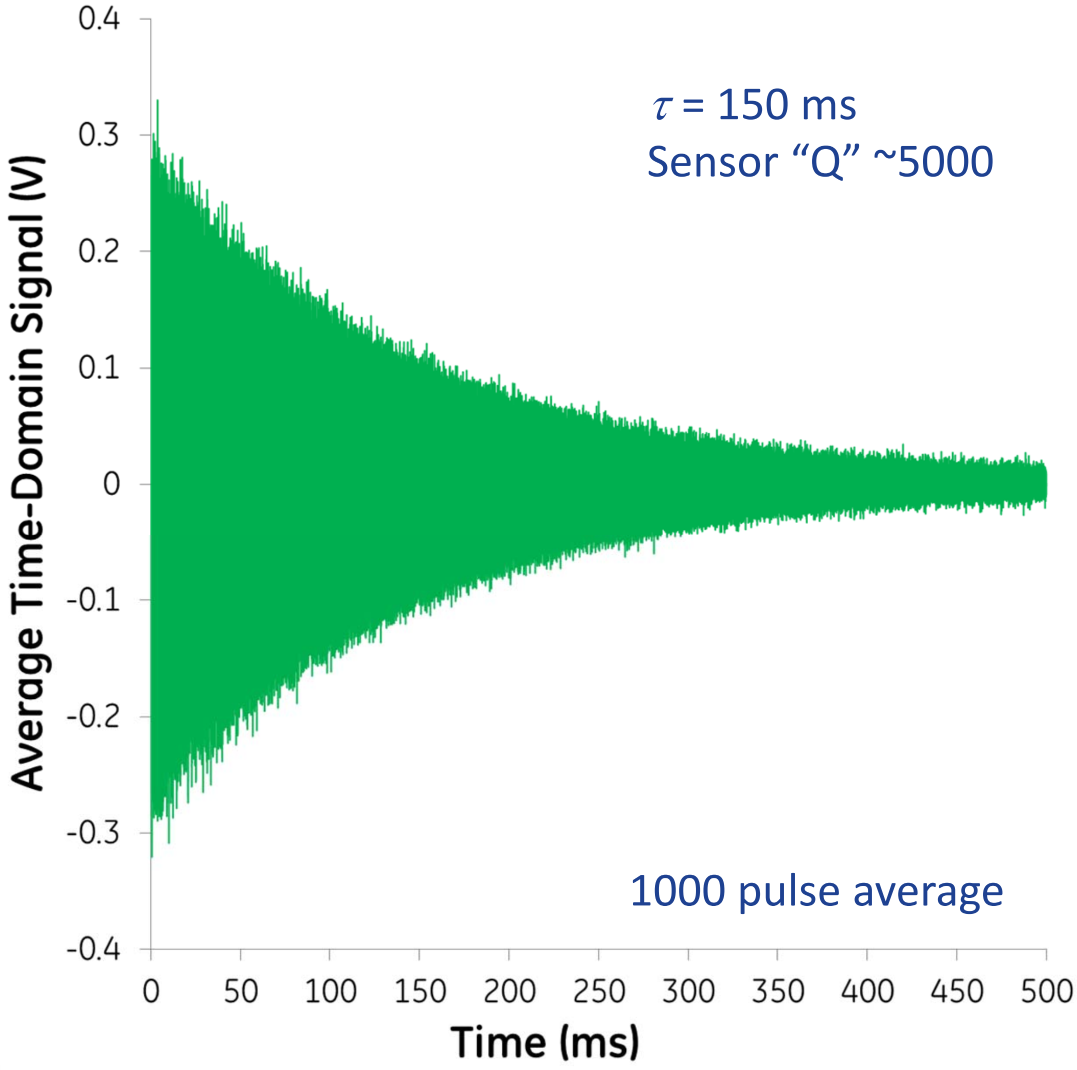


- High power laser pulse excites MEMS sensor
- Low power DC laser for frequency readback





Averaged Time-Domain Data



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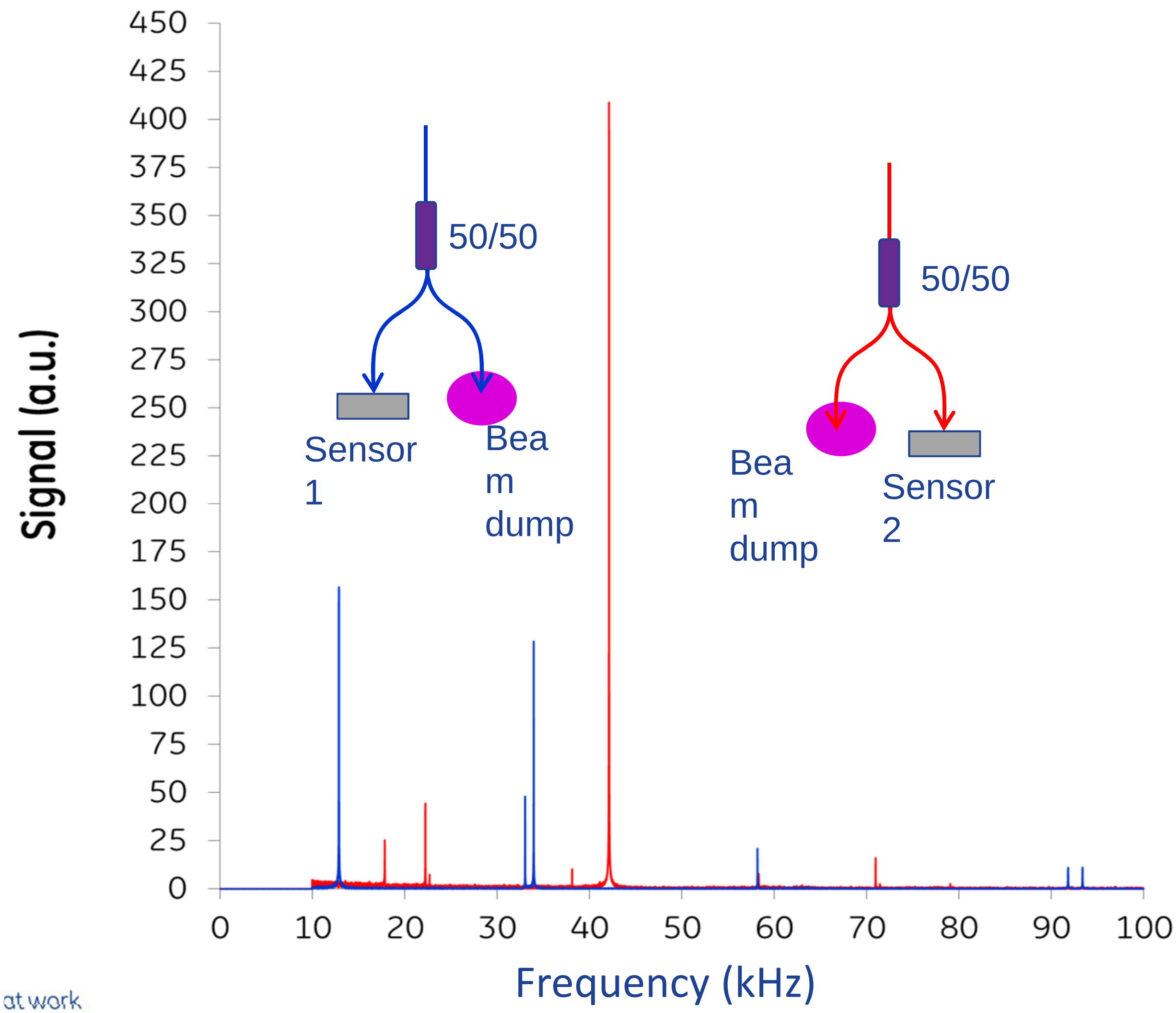
Vibrational Spectrum of *Separate* Sensors from Pulsed Laser Interrogator



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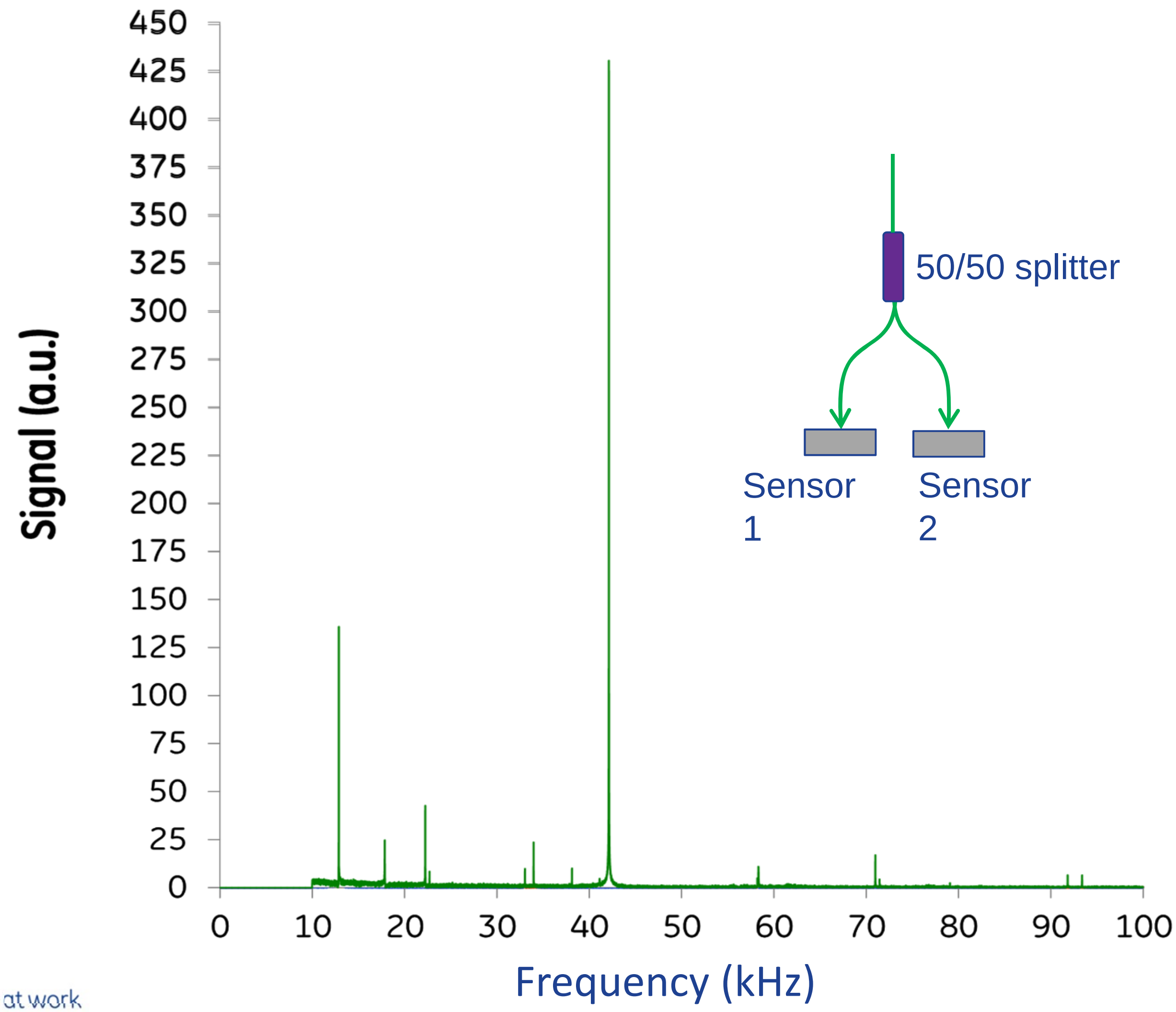
Vibrational Spectrum of *Combined* Sensors from Pulsed Laser Interrogator



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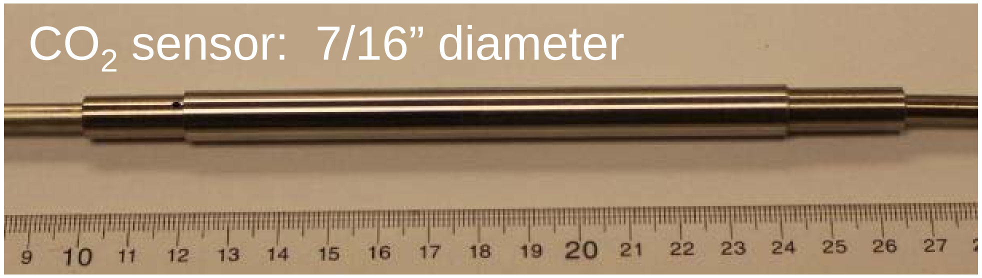
Spliceable sensor package design

Single point

Spliceable



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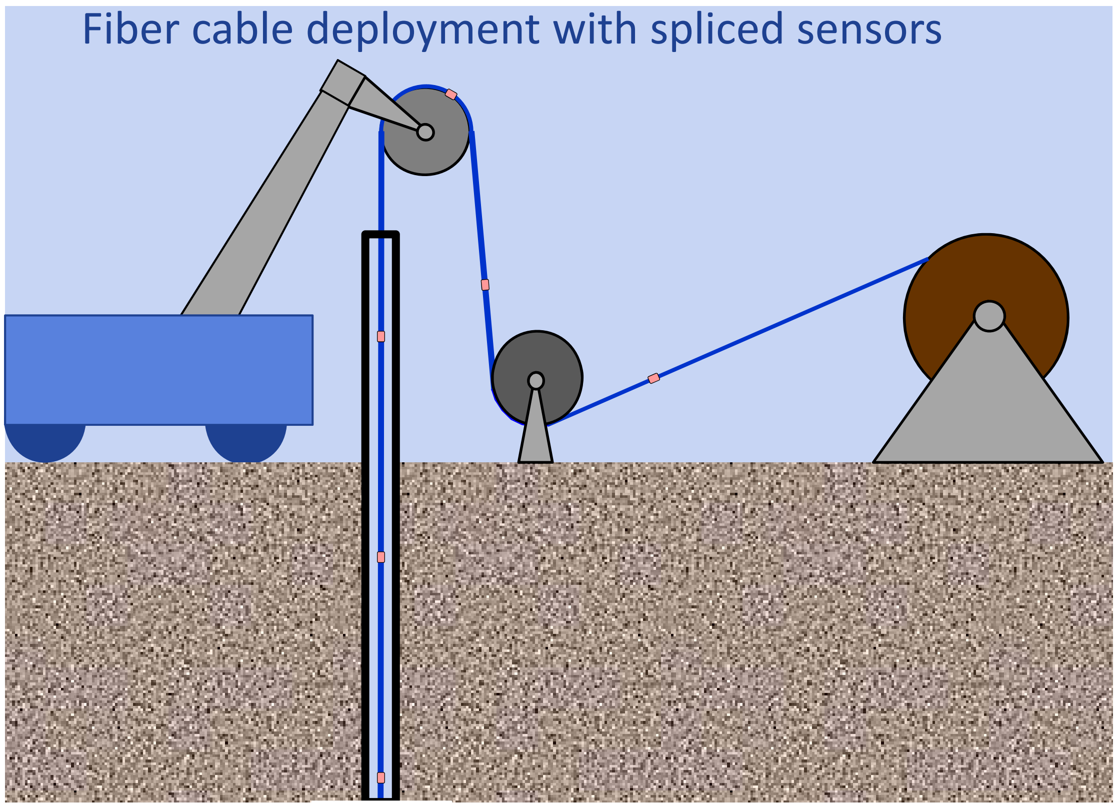
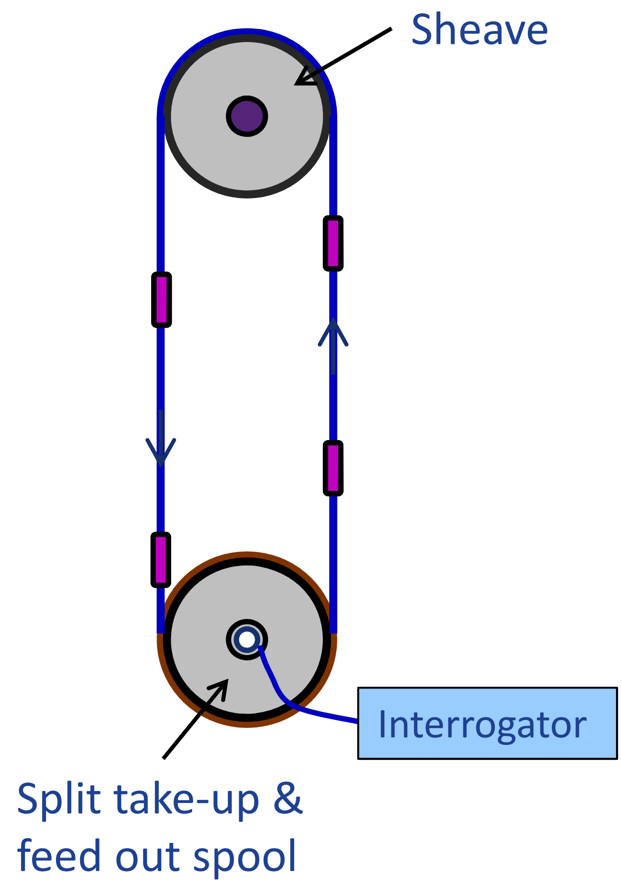
Environmental Stability Testing

6 mo. test @ 250°C, 10 kpsi CO_2

Sensor Package Robustness

Sheave "deployment" lab stress test of spliced cable





Remote monitoring

100 KB of data/hour $\Rightarrow$ ~ 252 MB/month

	Cellular	Satellite
Hardware	Sierra 3G/4G Gateway Cost: ~$400 http://www.sierrawireless.com/	Hughes BGAN M2M 9502 Cost: ~$1940 http://www.skymira.com/
Data Plan	Verizon - 1 GB $25/month	Satellite Data Plan – 252 MB $2,268/month
Dimensio n/Weight	5.6” x 3.8” x 1.6” 0.9 lb	10.8” x 10.8” x 3.3” 8.4 lbs

Conclusions

Pulsed laser interrogator works and can multiplex sensors!

- ~4 – 5 sensors/wavelength
- CWDM: ~8+ channels
- multiple fibers $\Rightarrow$ ~30 to 200 sensors/cable

Remaining work:

- fully characterize multiplexing capability
- complete & test sensor package in lab
- demo remote monitoring capability

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Acknowledgments

We would like to thank the National Energy Technology Laboratory and the GE Measurement and Control business for their financial support of this project!

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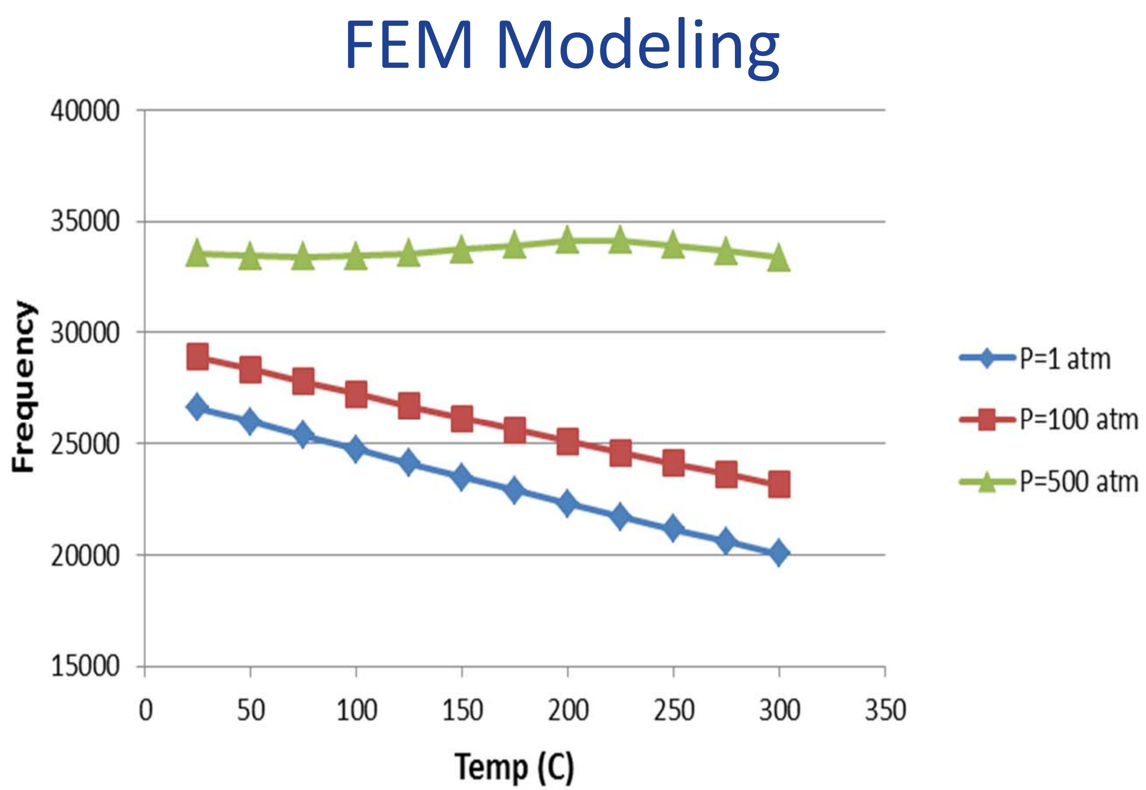
BACKUP

Potential for simultaneous measurement of temperature & pressure

Need at least two resonant modes with independent functions of T & P



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Why multiplex on a single fiber?

- Reduced cost of fiber in cable
- Simplify sensor package in cable
  - Hermetic seal required for each fiber at both ends of package
- Simplify splicing of fiber
  - single fiber: (2N-1) splices
  - fiber/sensor: N^2
- Enable many more sensors/cable
- Reduced interrogator cost(?)