A Microresonator-Based Laser Doppler Velocity Sensor for Interplanetary Atmospheric Re-Entry

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18 April 2018

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Order of Presentation

- Introduction
- Measurement Principle
- Fiber-Coupled Resonator Experiments
- Proof-of-Concept Experiment with Rotating Disk
- Free-Space Coupled Resonator Experiments
- Signal Processing Approaches
- Conclusion

Motivation: Schiaparelli Crash

A €230 Million Mission Failure

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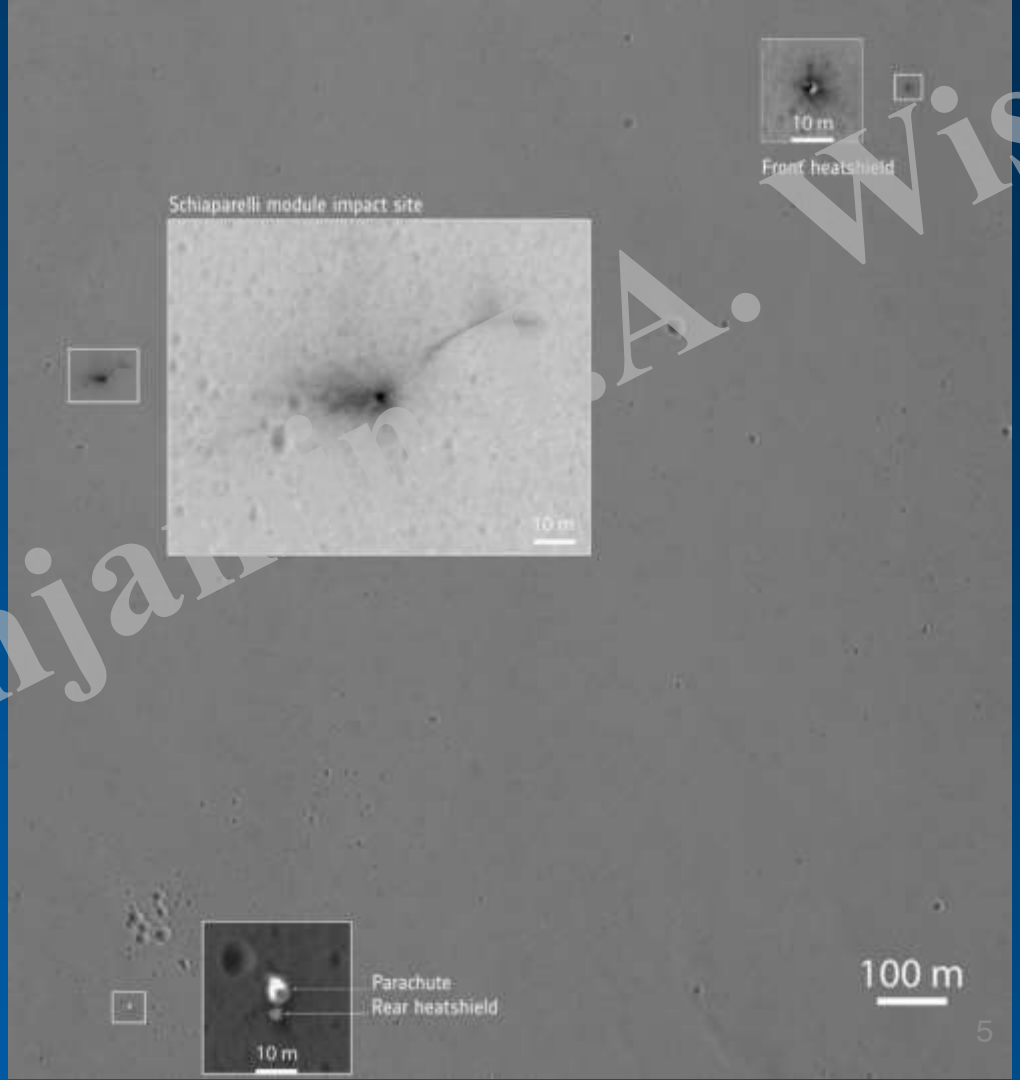
Crash Site

- Thrusters Off State
  - Burn Time: 3s (of >30s)
  - Altitude: 3.7 km
  - Velocity: 250 km/h
- Impact
  - Terminal Velocity
  - Estimated: 300-540 km/h



State-of-the-Art Velocity Sensing

- Dead Reckoning Techniques
  - Celestial Navigation
  - Magnetic Navigation
  - Inertial Navigation System (INS)
    - Often called: Inertial Measurement Units (IMU)
- Static-Pitot System
- Global Navigation Satellite System (GNSS)
  - U.S. Based Global Positioning System (GPS)
- LIDAR and LDV/PIV

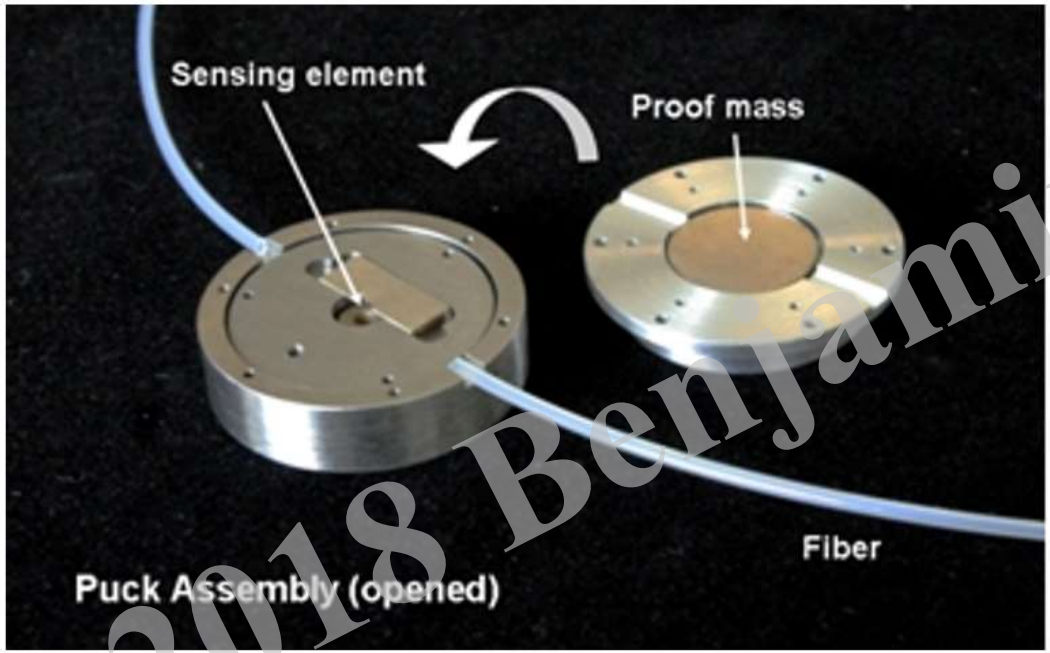
Desirable Sensor Characteristics

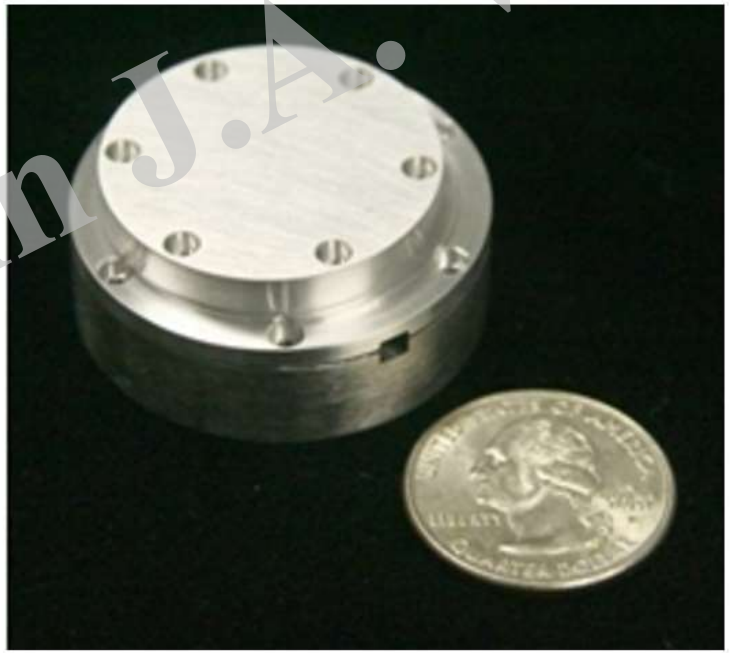
- Physically Small
- Lightweight
- High Resolution
- Non-invasive to the Flow
- High and Adjustable Depth of Field

Previous WGM Applications

- Chemical Impurity Detection in Liquids
- Opto-Mechanical Transducers/Sensor
  - Mechanical Sensing
    - Force
    - Temperature
    - Wall Shear Stress (for Aerodynamic Applications)
    - Electric-Field Strength Sensing
    - Magnetic-Field Strength Sensing
    - Seismography

Why Whispering Gallery Mode Sensors?





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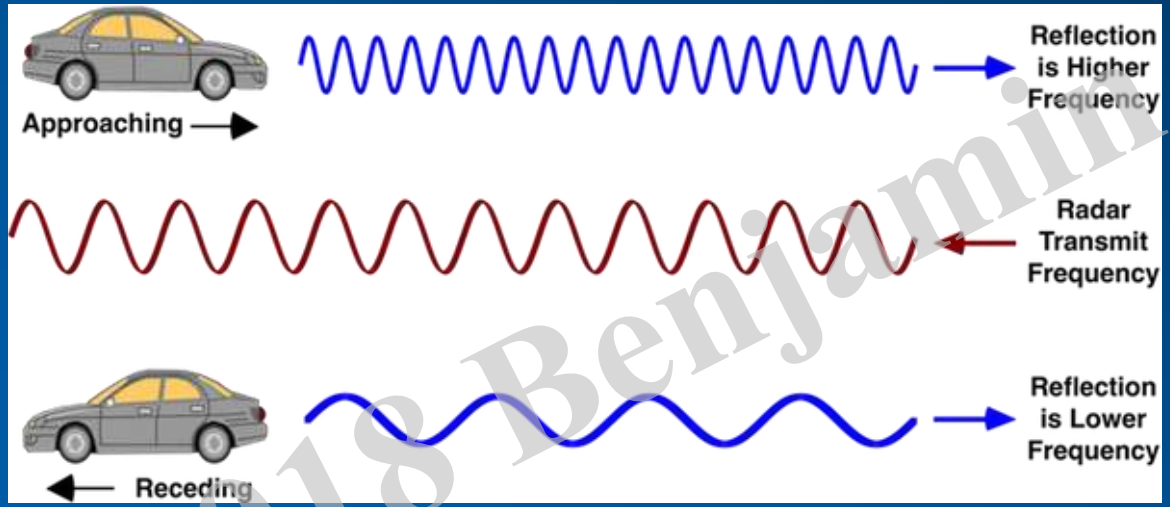
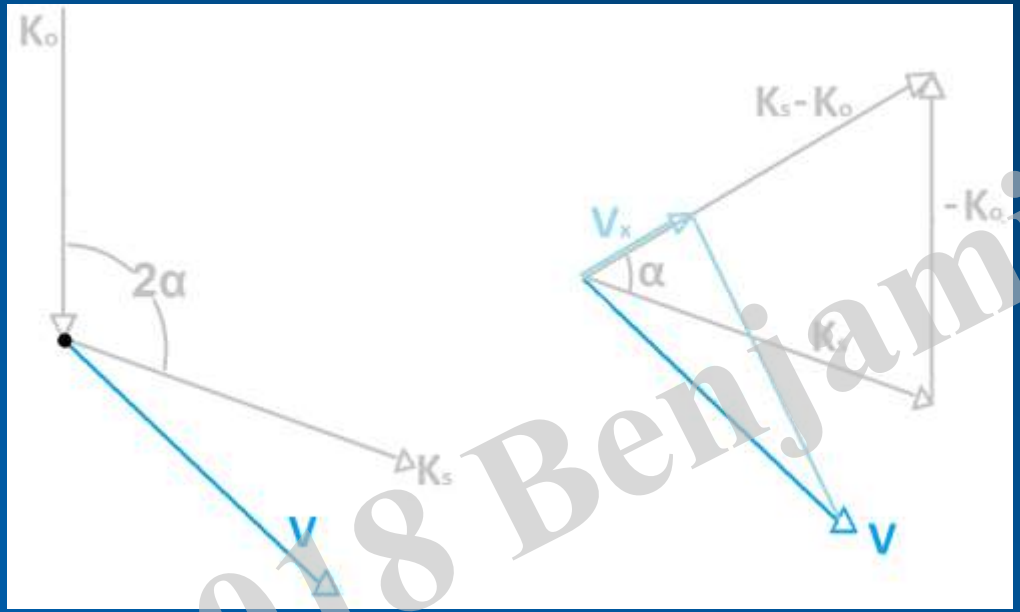
Measurement Principle

Doppler Shift Measurement



$$\Delta f = 2\frac{V_x}{\lambda}$$

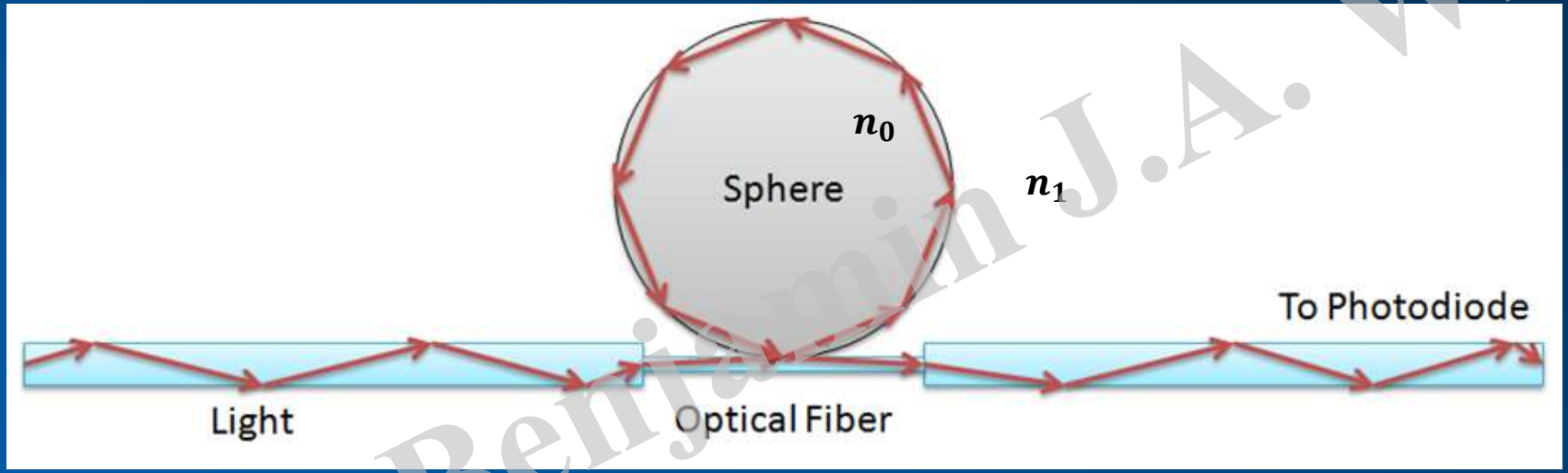
Doppler Shift Measurement



$$\Delta f = 2\frac{V_x}{\lambda}\sin(\alpha)$$

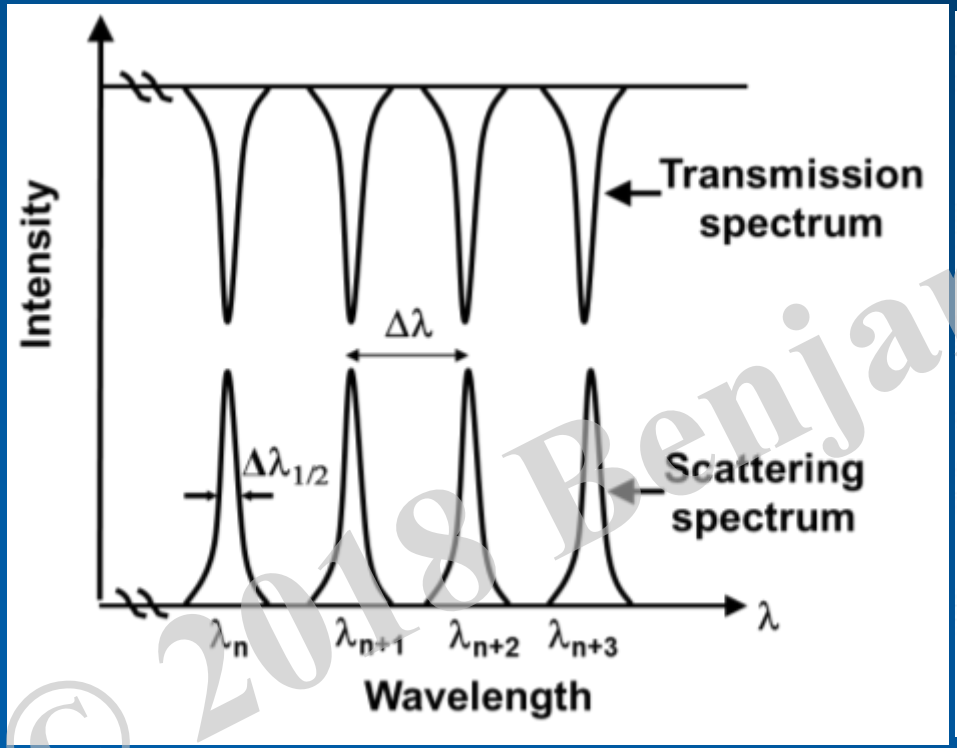
The Whispering Gallery

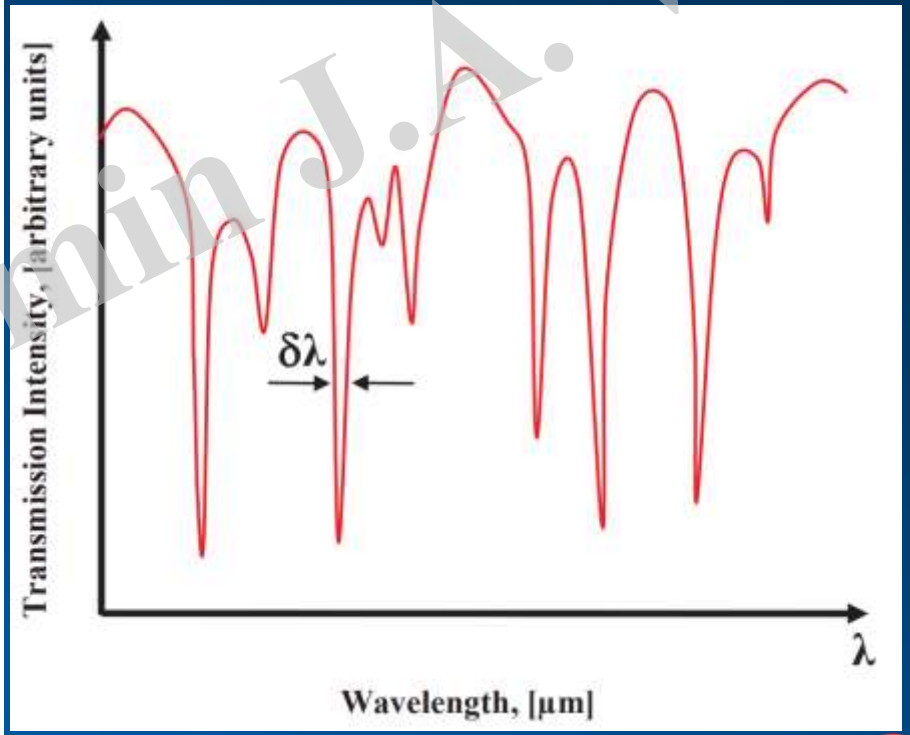
The Whispering Gallery Mode



- Resonance Condition: $2\,\pi\,r\,n_0 = l\,\lambda$ for $r \gg \lambda$

WGM Spectra





Quality Factor

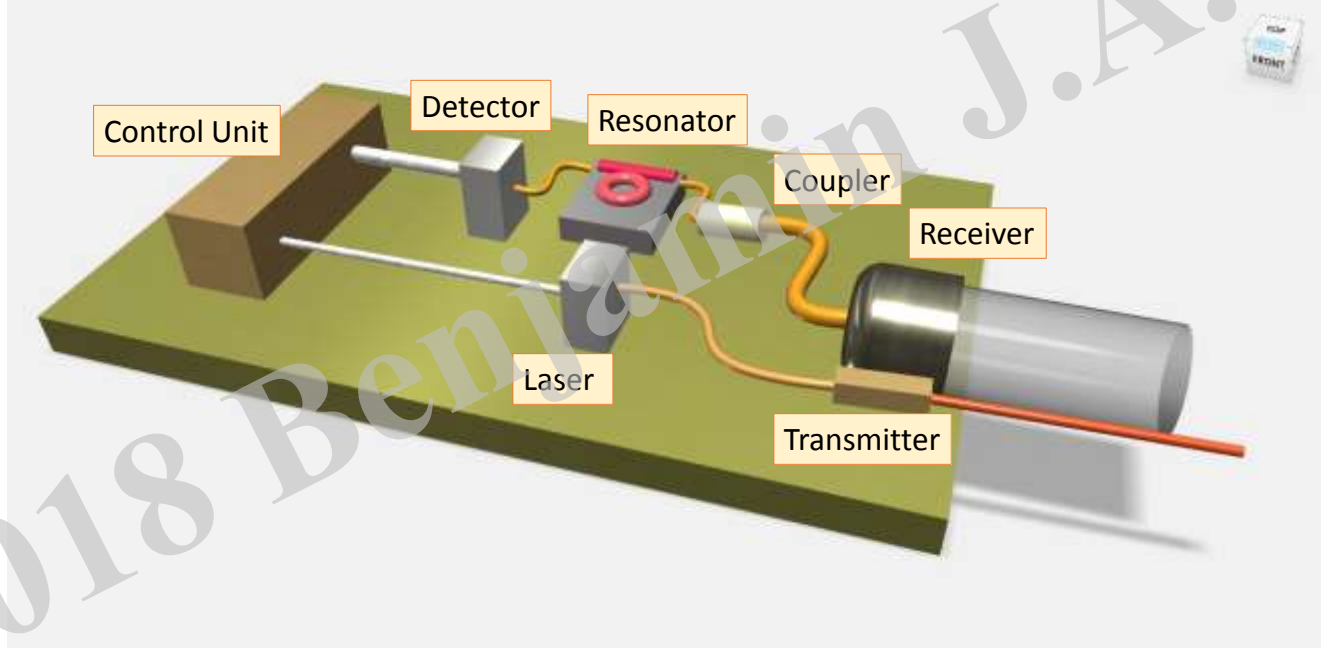
$$Q = \frac{\lambda}{\delta\lambda}$$

- Quality Factor Sets WGM-based Sensors Apart
  - $Q \geq 10^7$ routinely achieved in the Micro Sensor Lab
  - $Q \geq 10^{11}$ achieved under optimal conditions
  - $Q \geq 10^{15}$ theorized for certain materials and wavelengths of light
- Measurement Resolution
  - For a wavelength of 639nm, $Q = 6 \times 10^6$ gives a 10 fm wavelength resolution
  - Corresponds to 2.4 m/s Speed Resolution
    - Full Backscatter Configuration

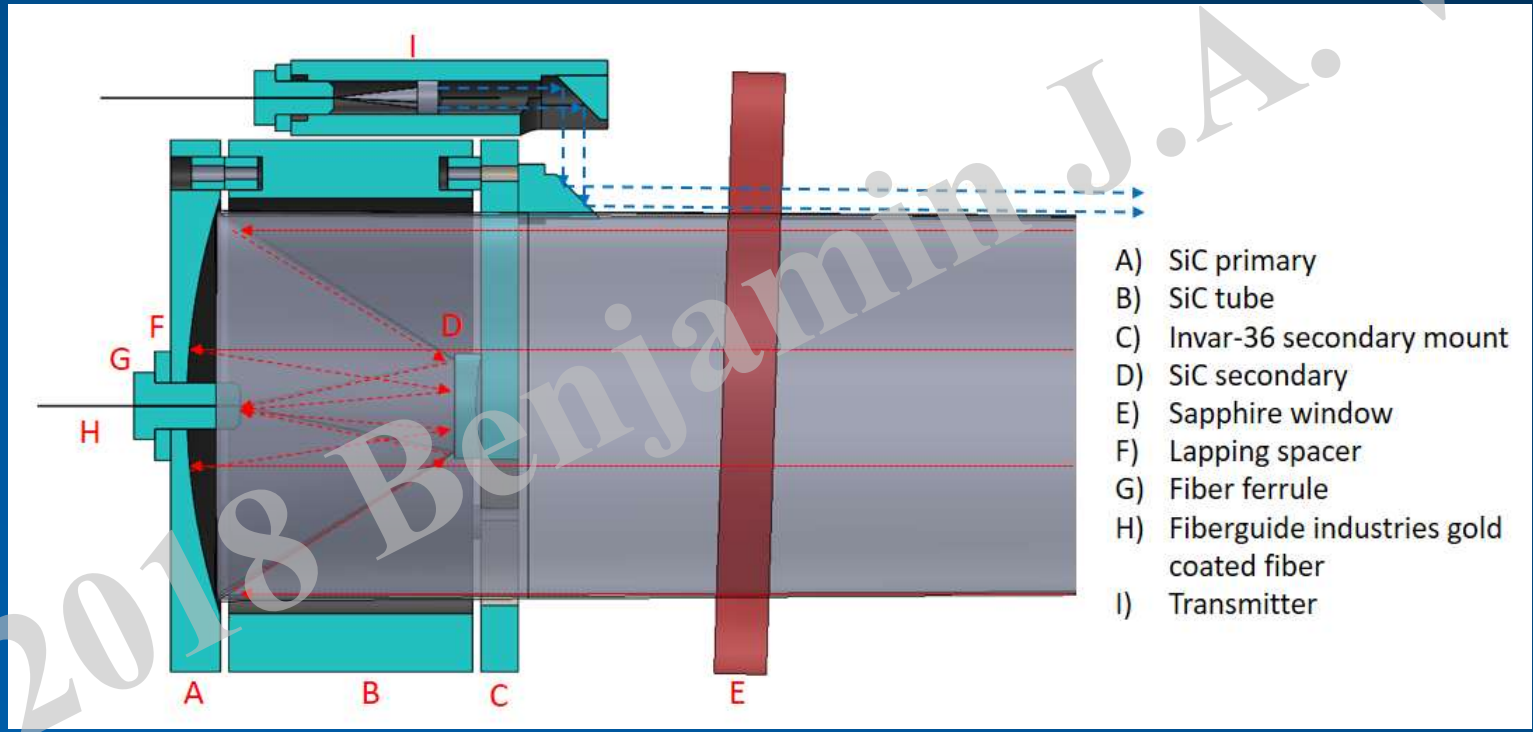
Desirable Sensor Characteristics

- Physically Small ✓
- Lightweight ✓
- High Resolution ✓
- Non-invasive to the Flow
- High and Adjustable Depth of Field

Overall System Schematic



The Transmit/Receive Telescope



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Tuning Methods

$$2\,\pi\,r\,n_0 = l\,\lambda$$

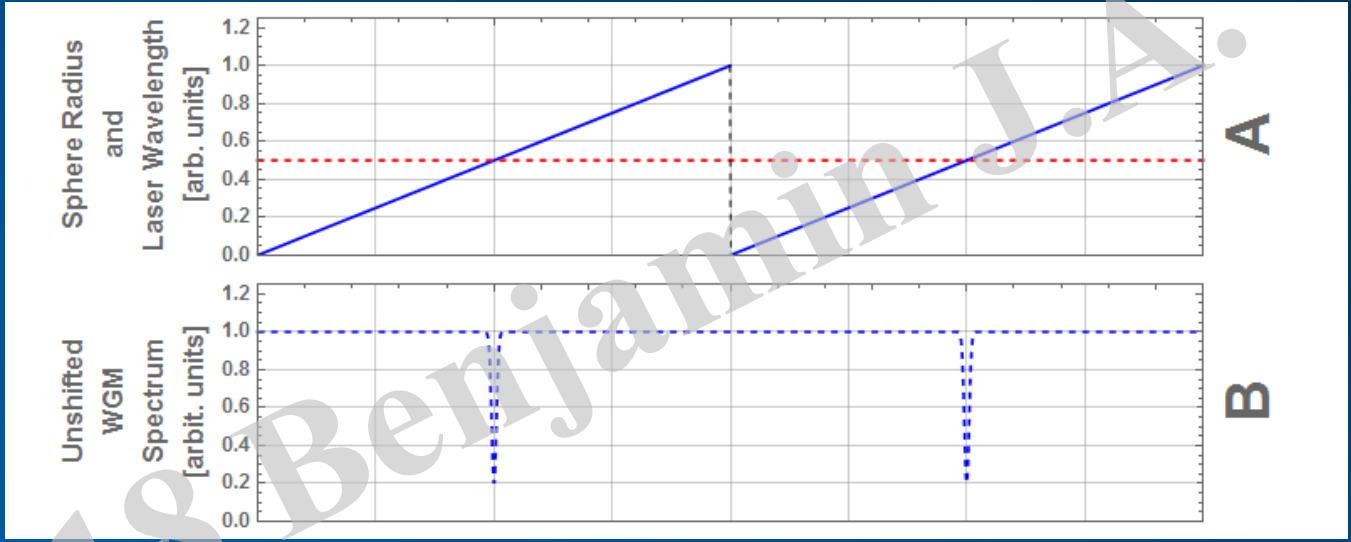
Piezo-Tuning of Resonator

$$\lambda = [\frac{2\pi n_0}{l}]r$$

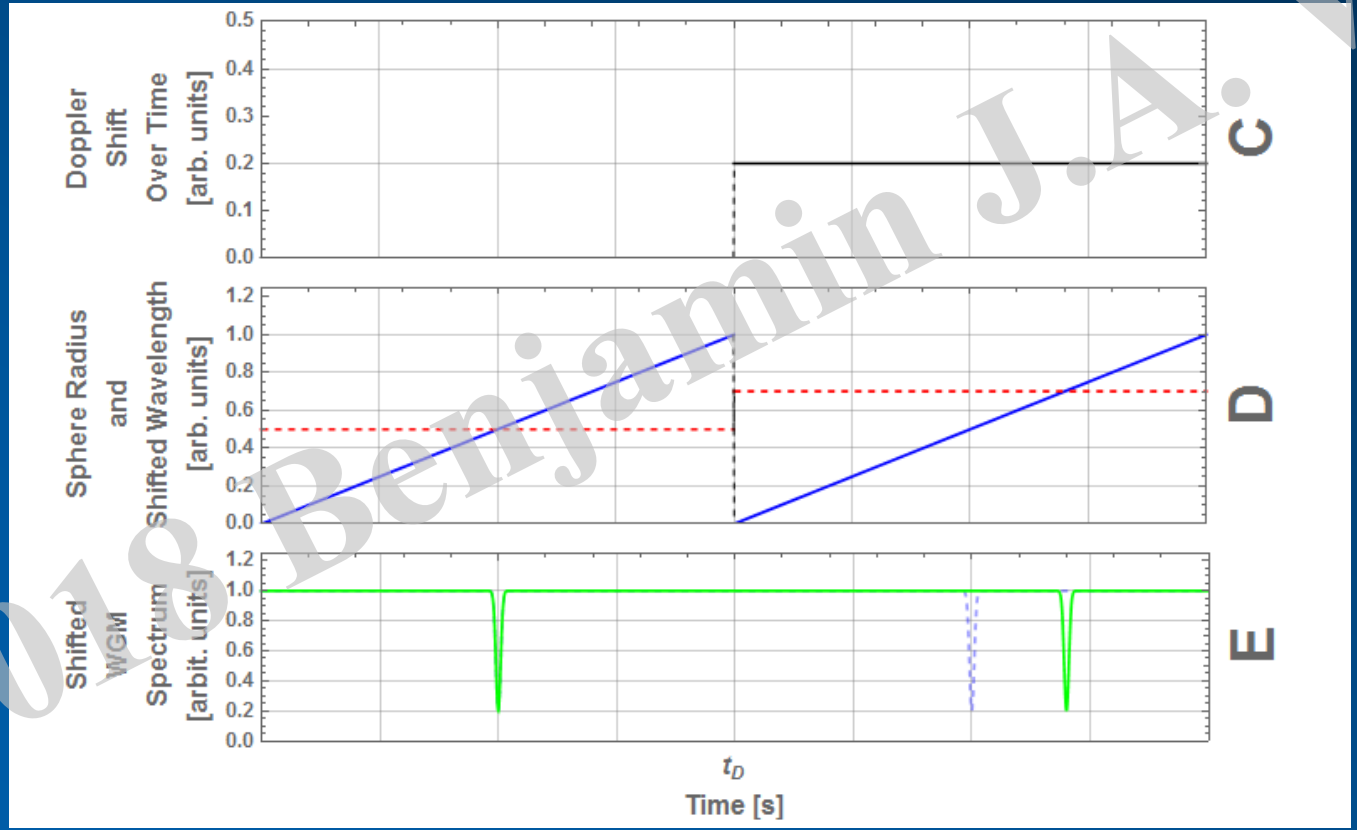
Laser-Tuning of Resonator

$$l = [2\pi r n_0]\frac{1}{\lambda}$$

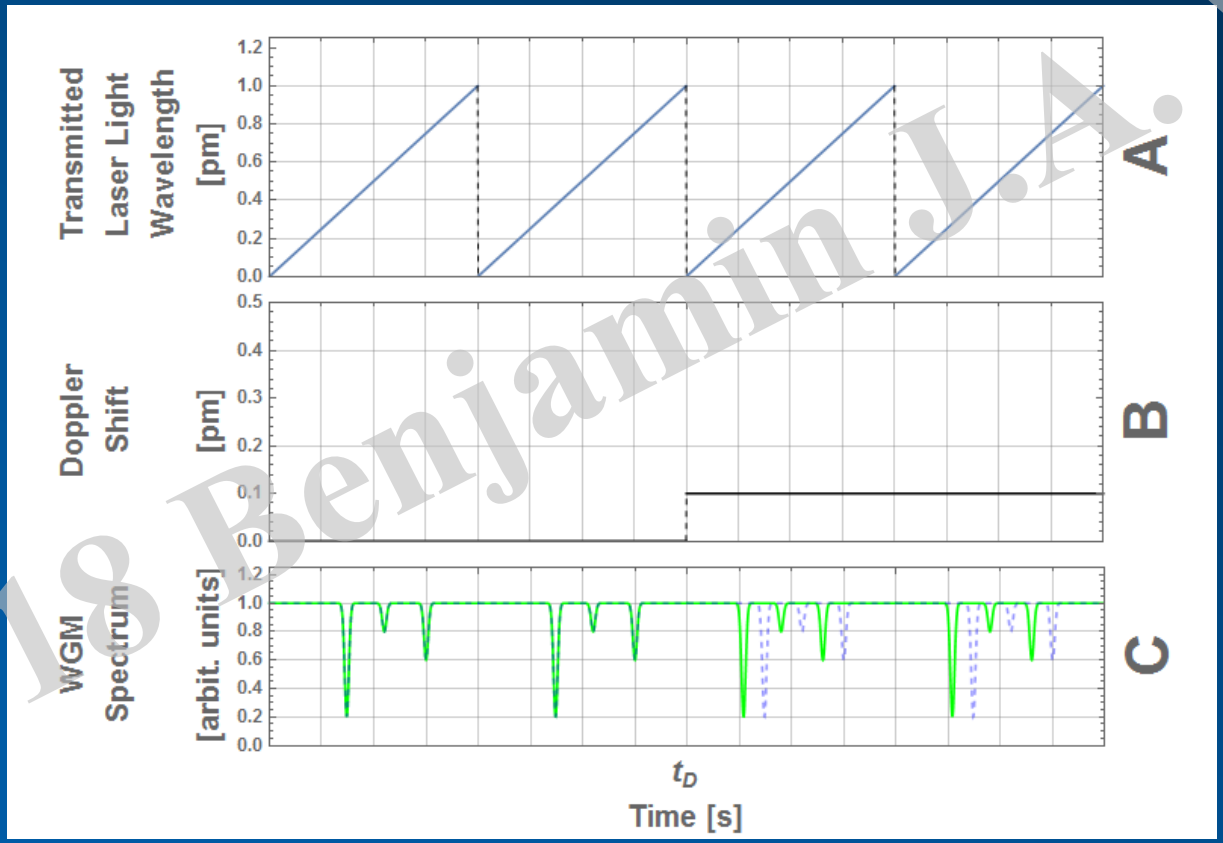
Piezo-Tuning of WGM Microresonators



Piezo-Tuning of WGM Microresonators



Laser-Tuning of WGM Microresonators



Fiber-Coupled Resonator Experiment

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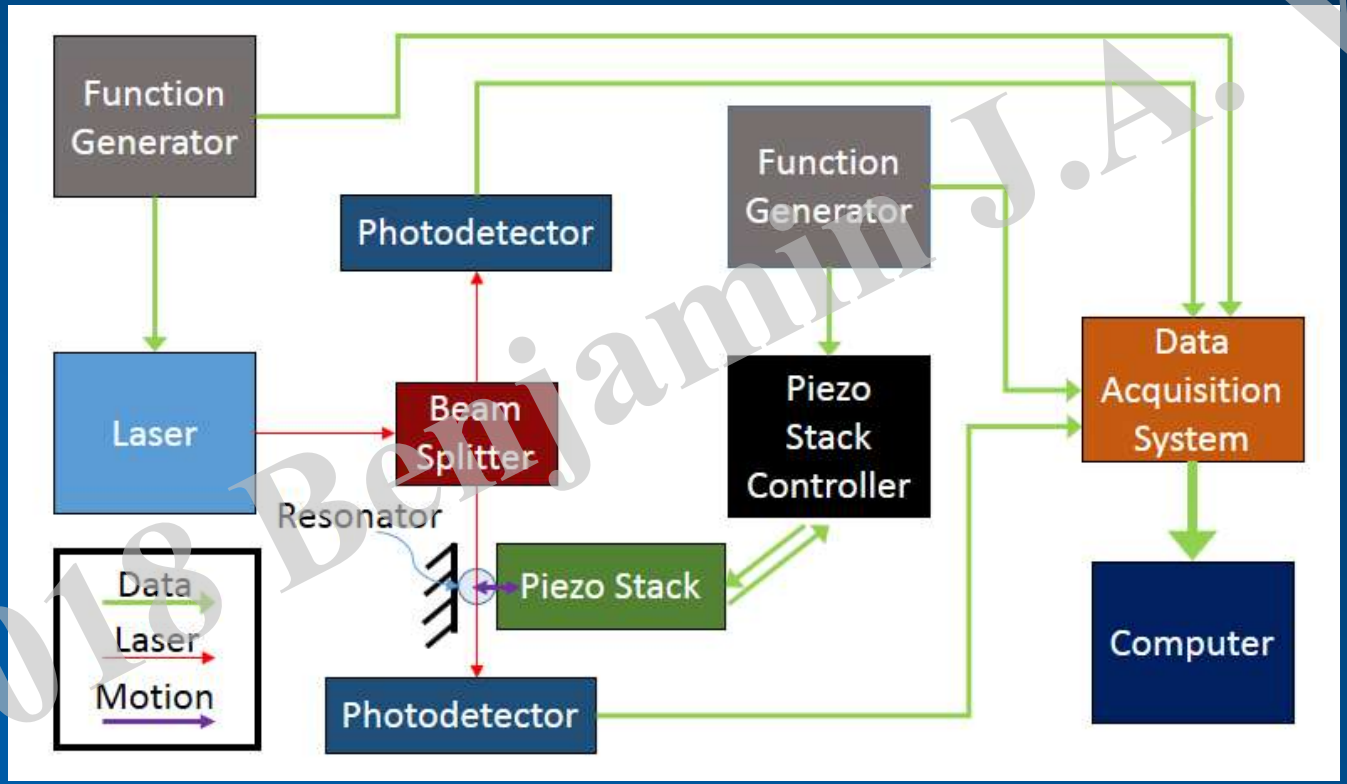
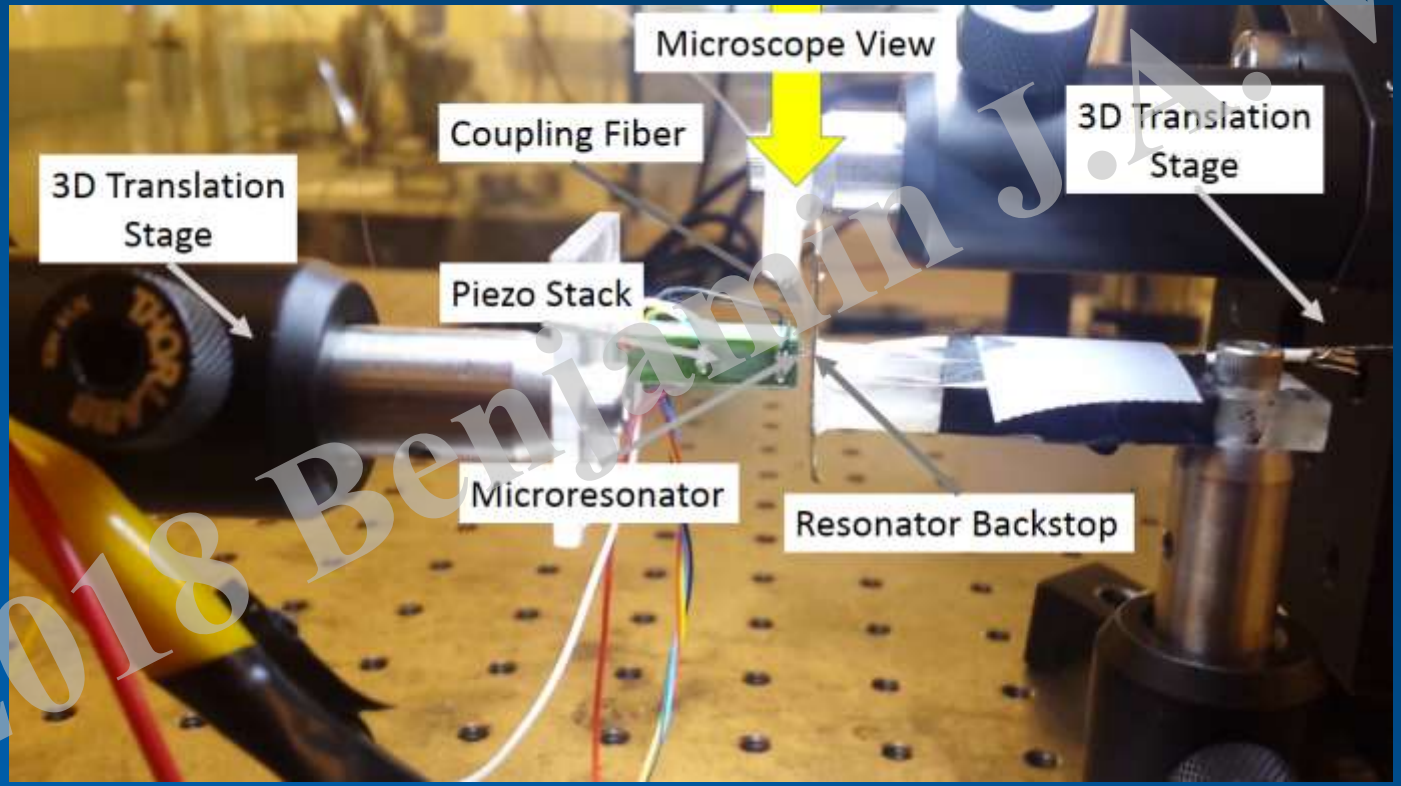
Piezo-Modulated Resonance Excitation



Piezo-Modulated Resonance Excitation



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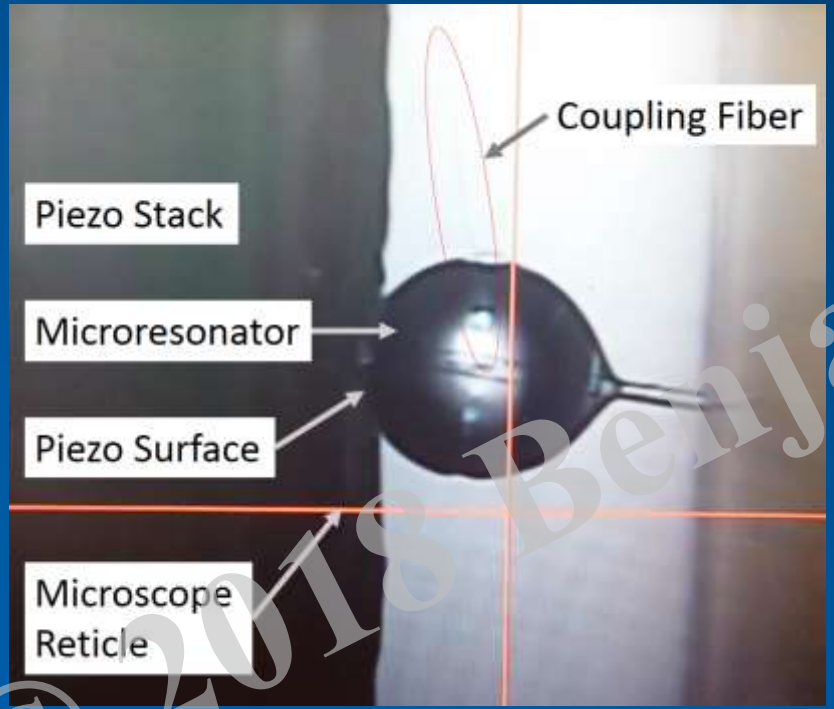
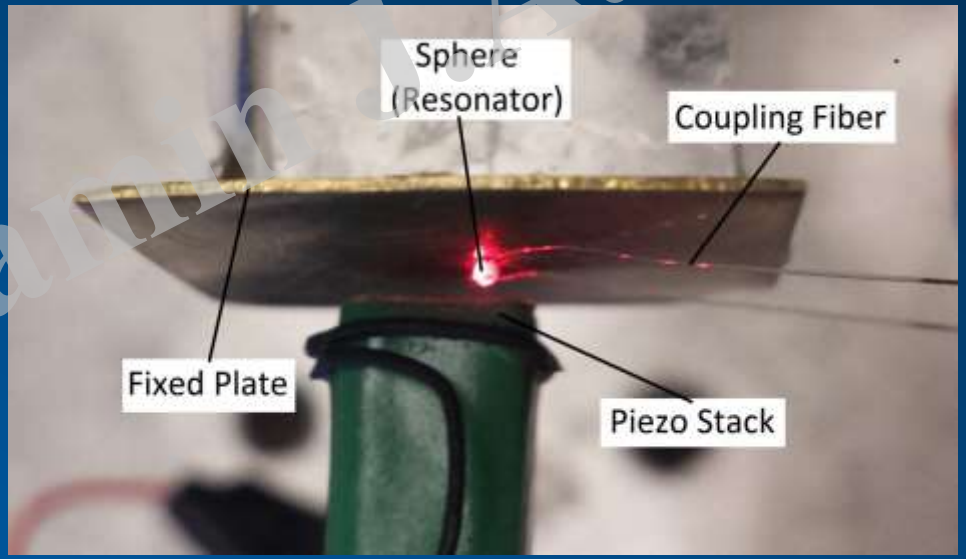
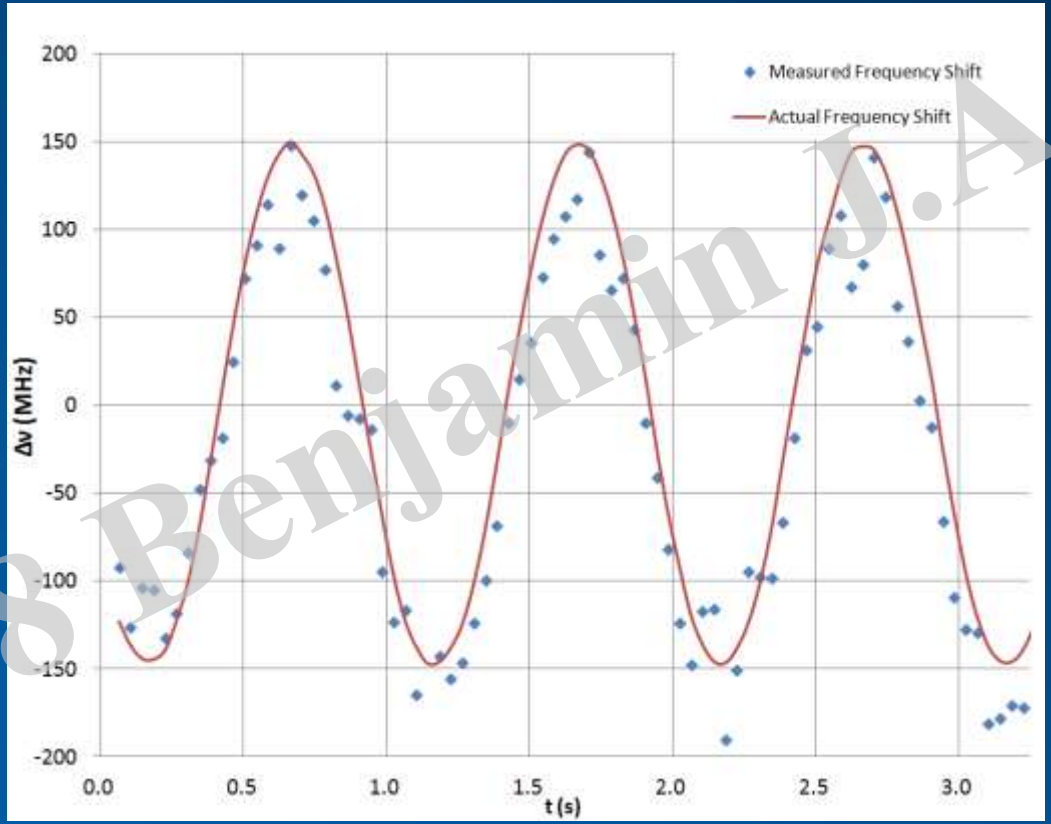




Piezo-Modulated Resonance Excitation Results



Proof-of-Concept Experiment with Rotating Disk Target

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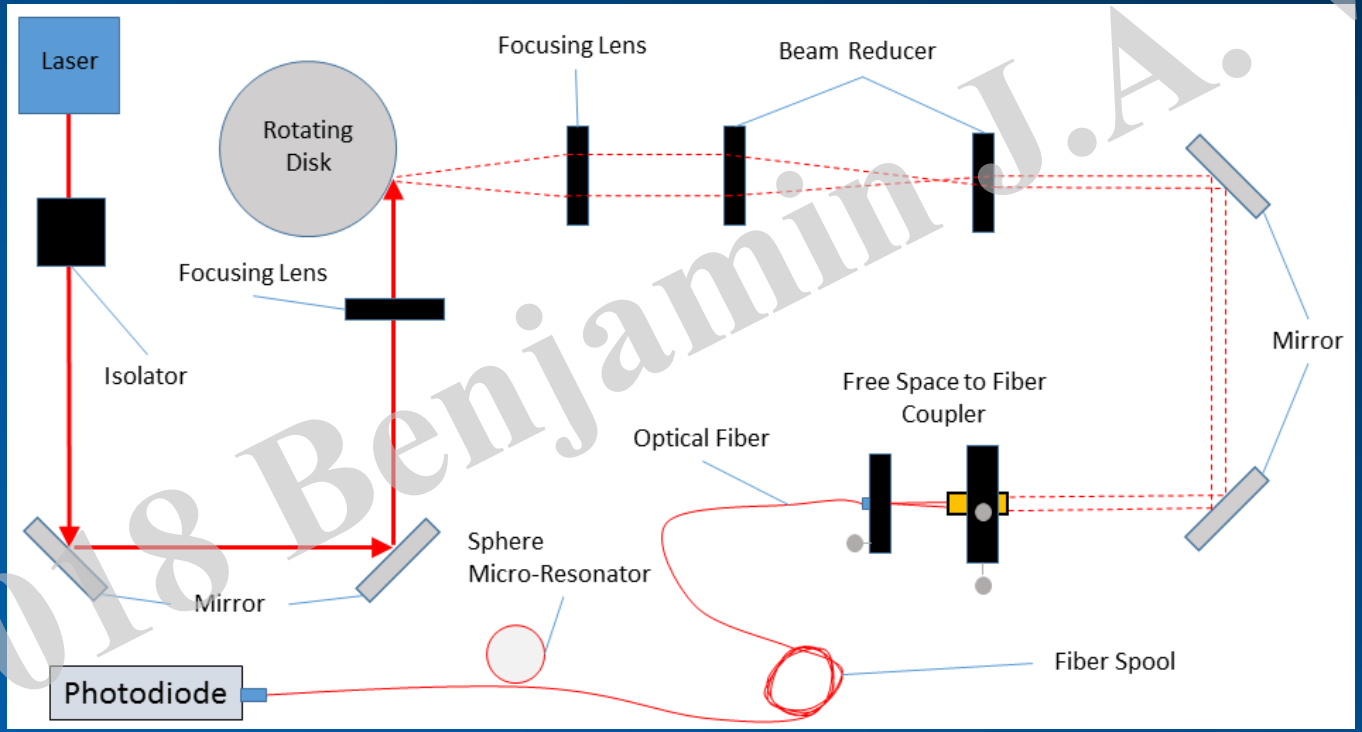
Laser-Modulated Resonance Excitation



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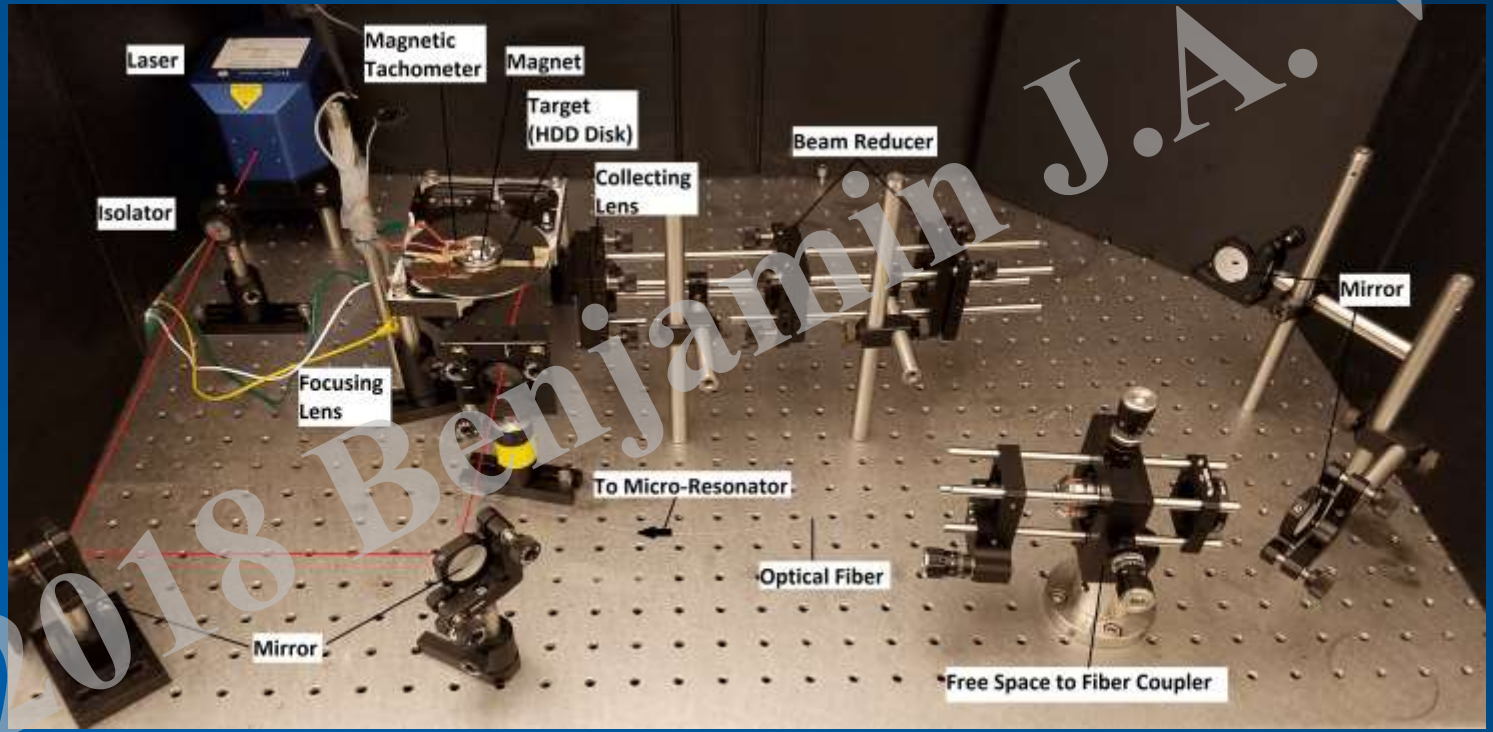

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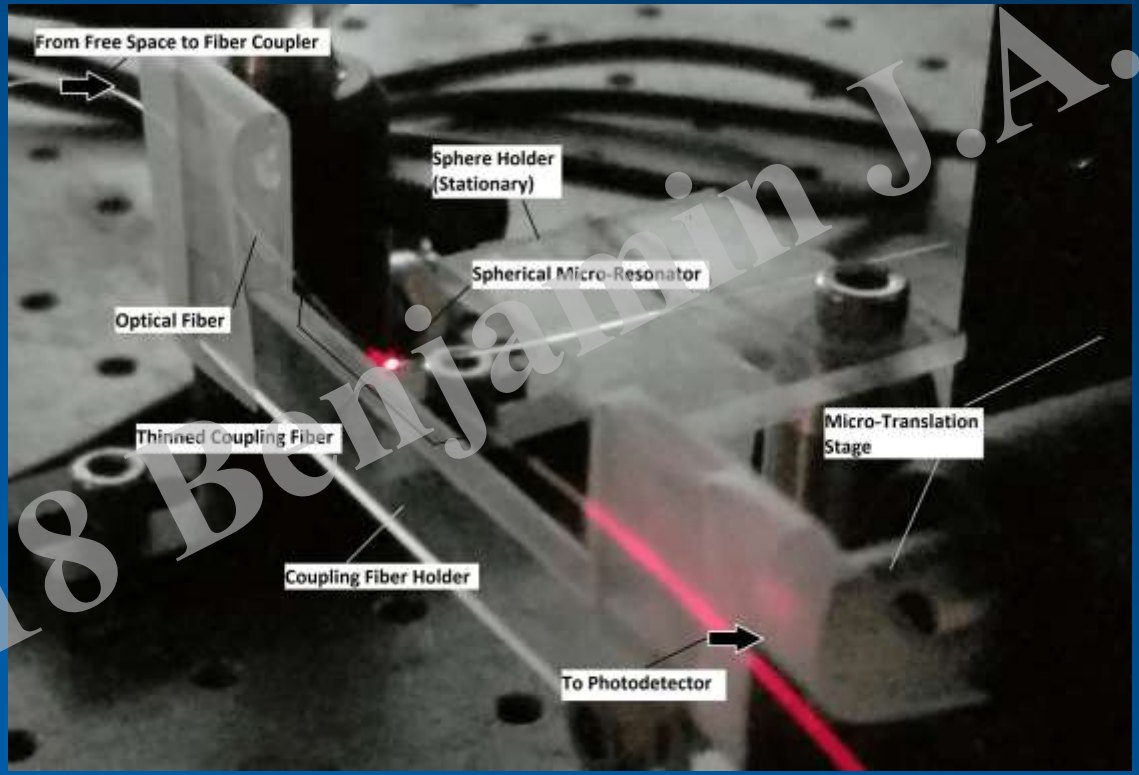

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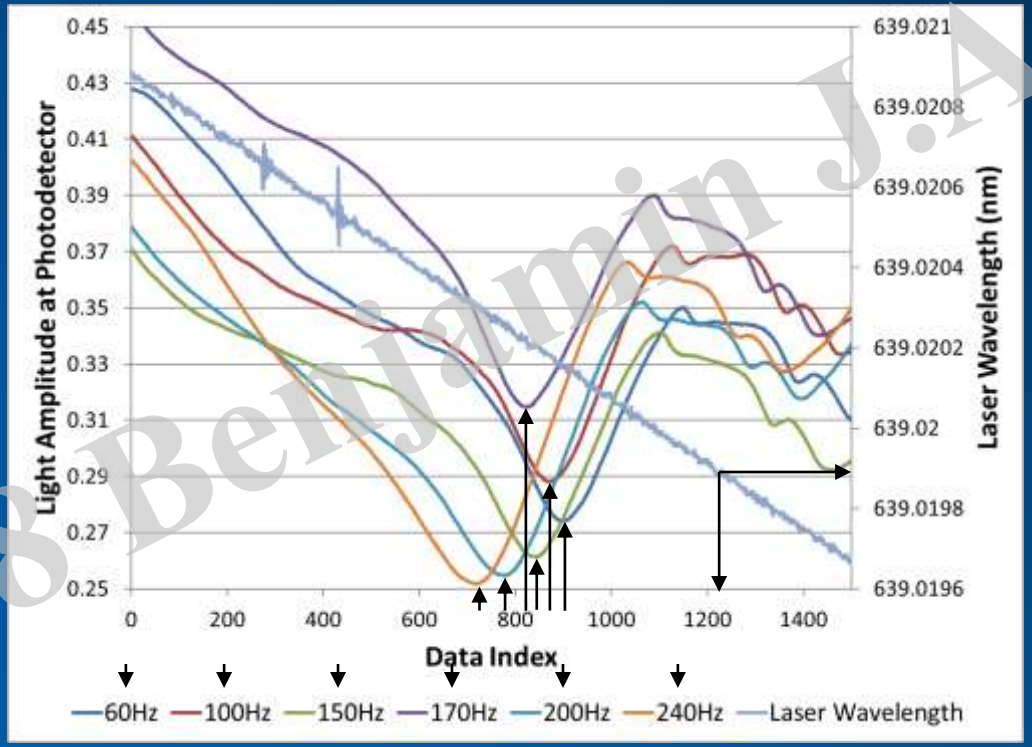

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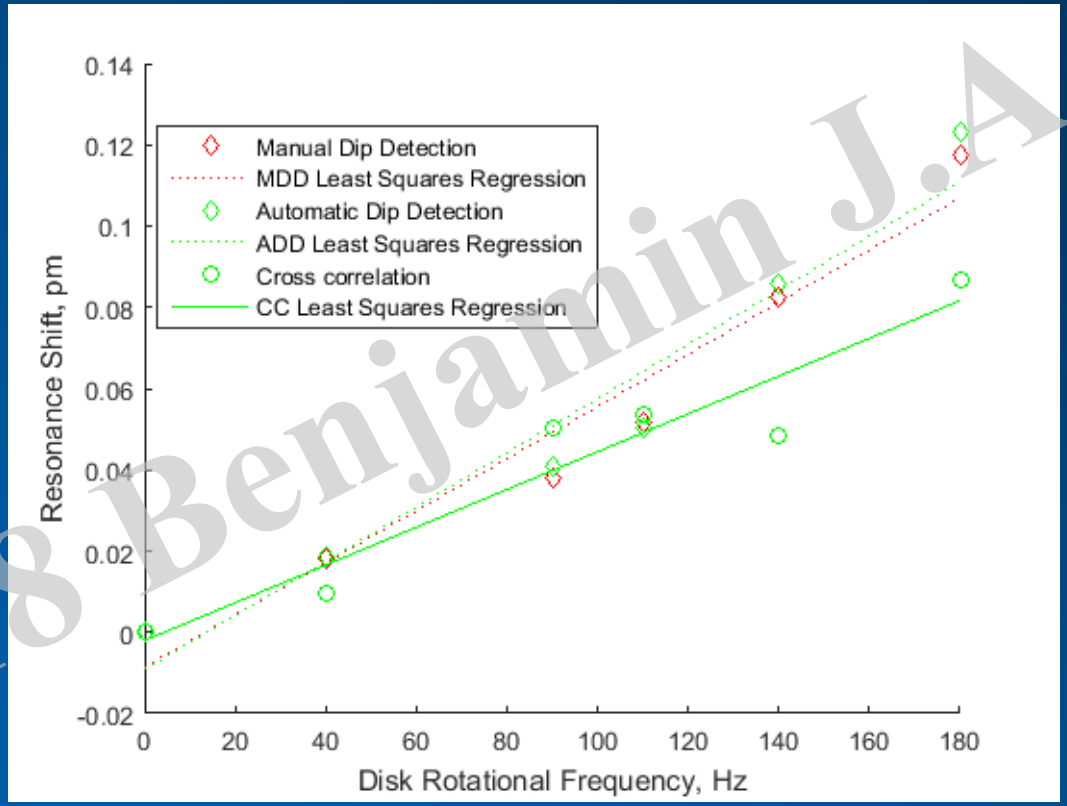

Free-Space Coupled Resonator Experiment

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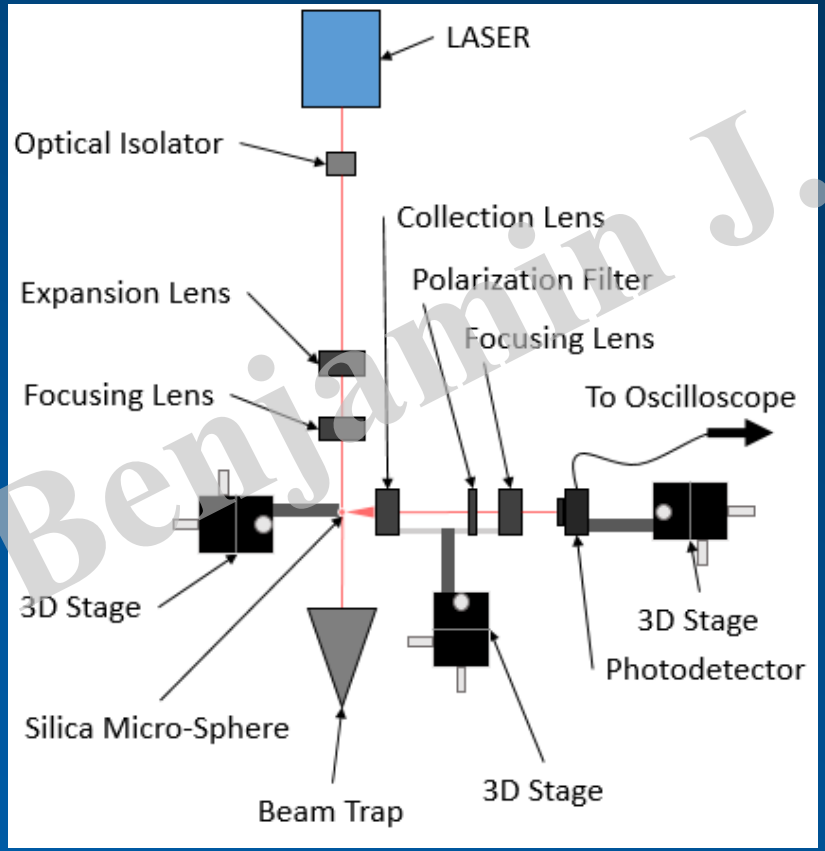
Free-Space Coupled Resonator Experiment



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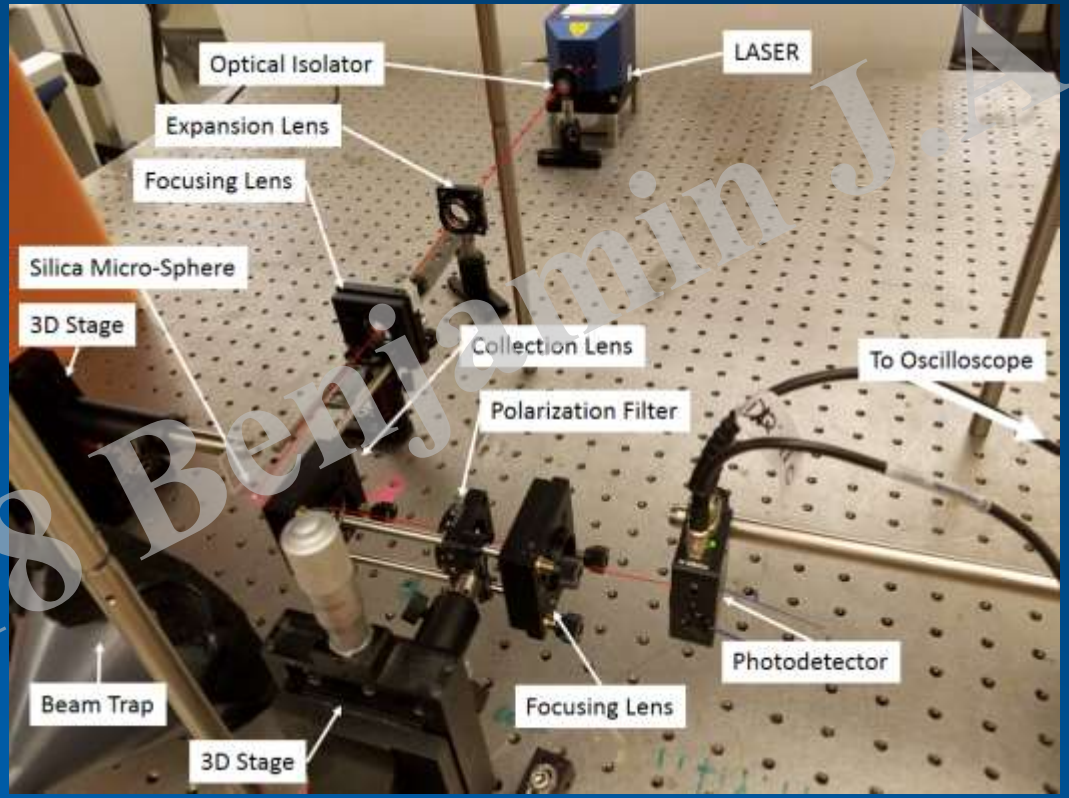

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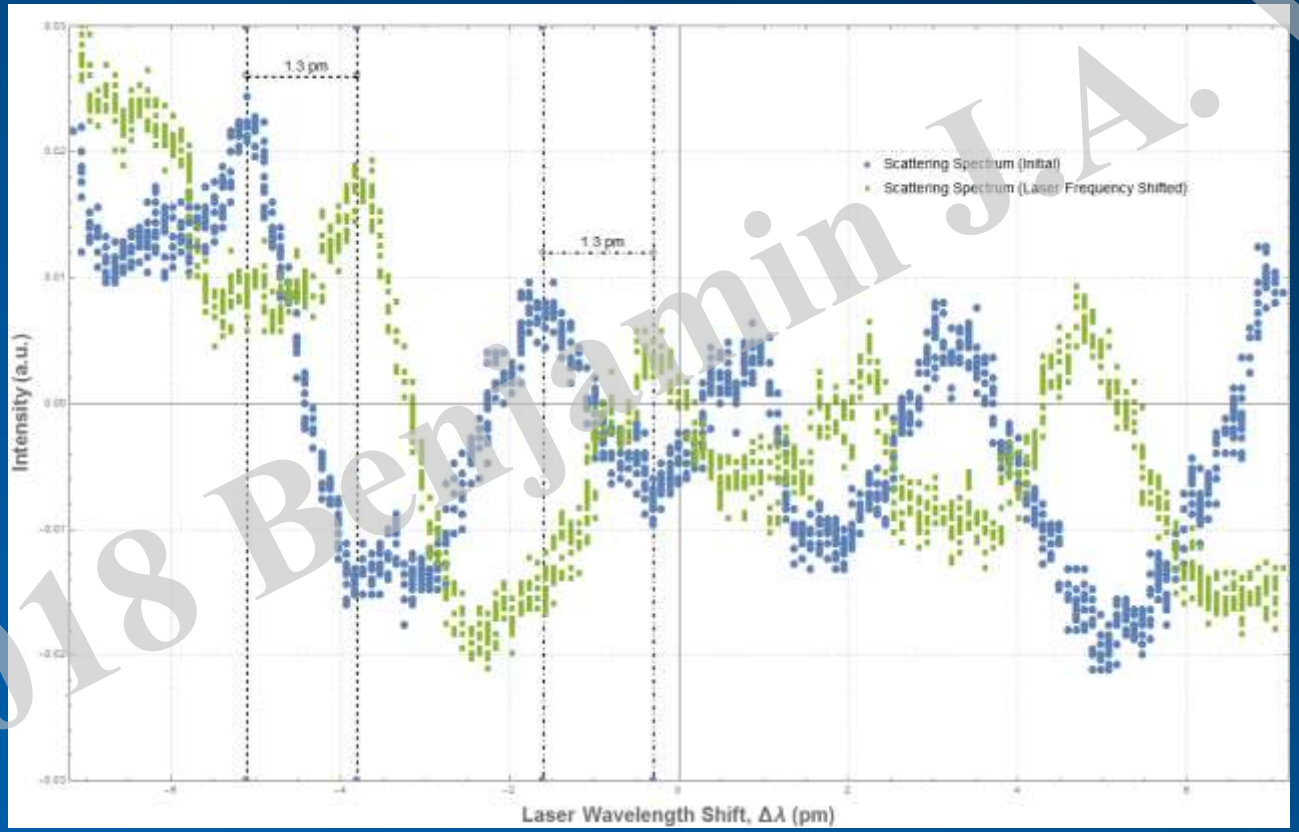

Signal Processing Approaches

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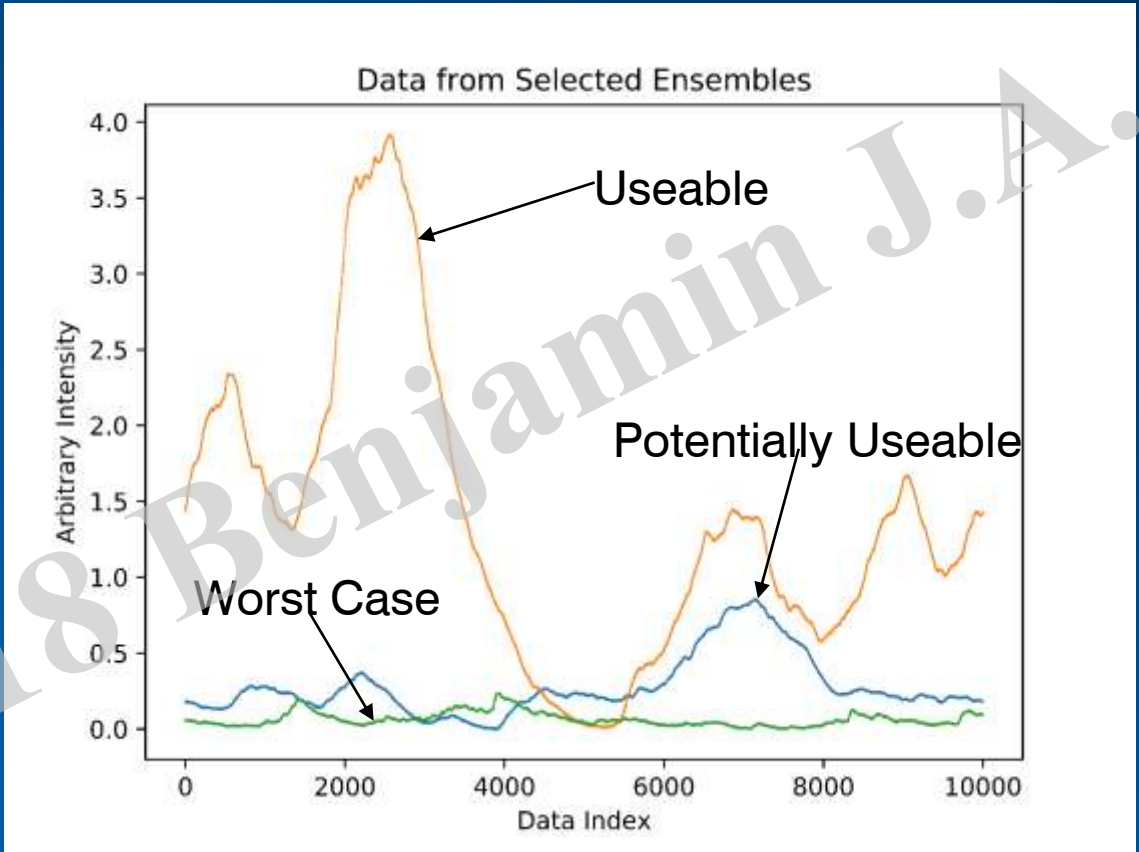
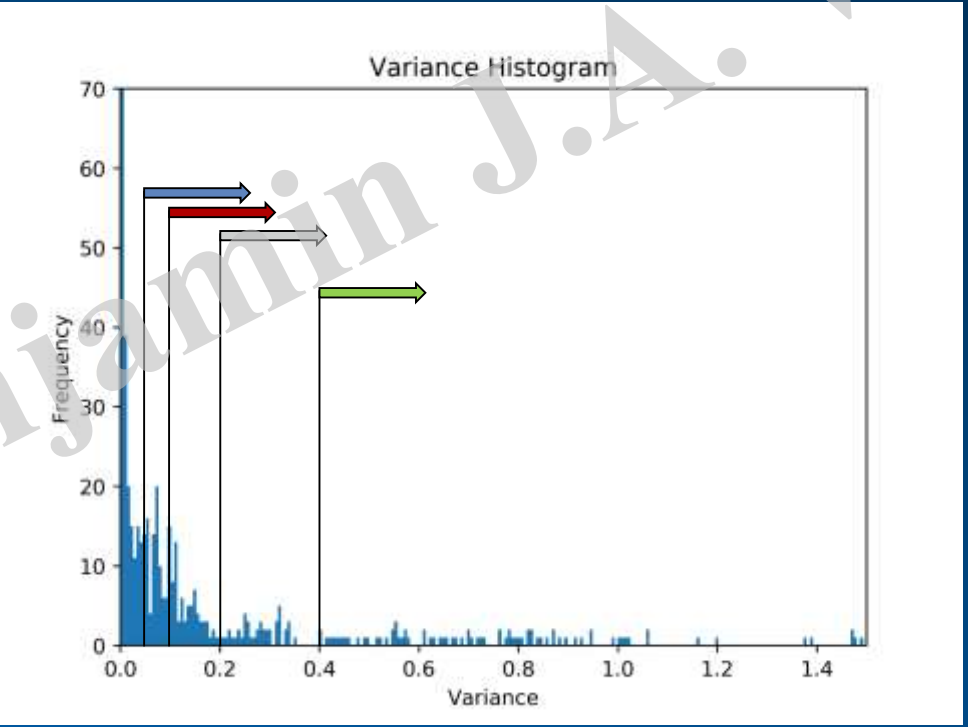
Signal Processing Motivation

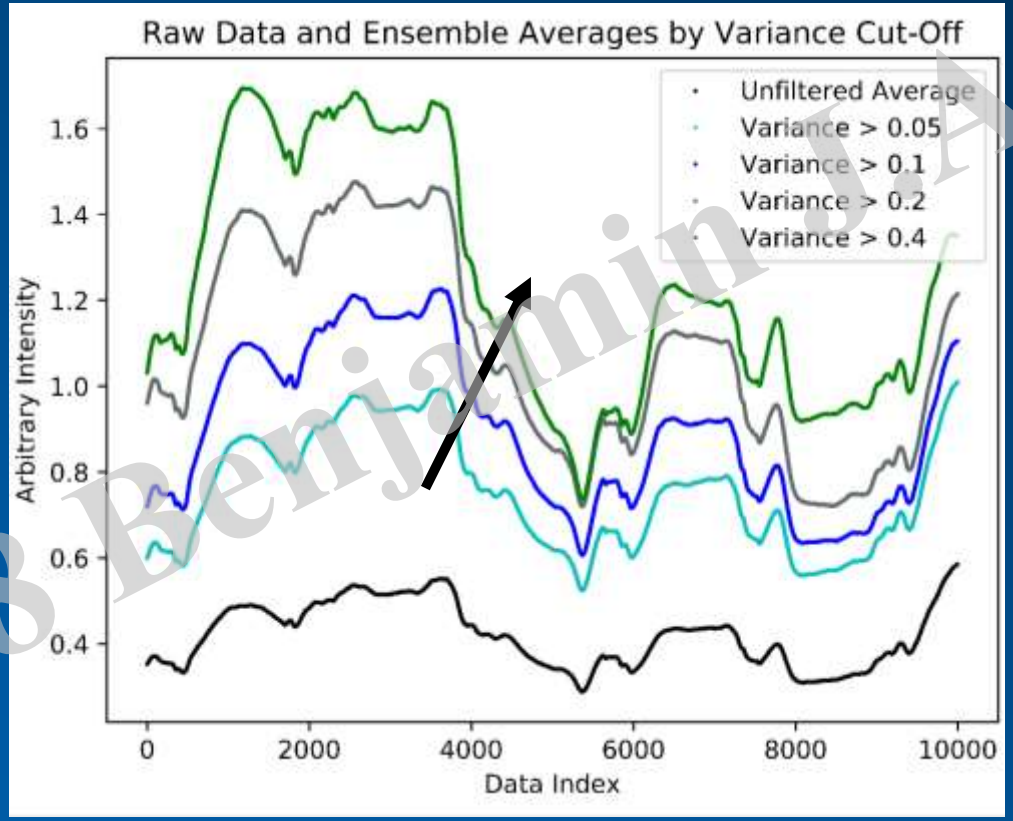


Variance Filtering

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2$$



Variance Filtering Results



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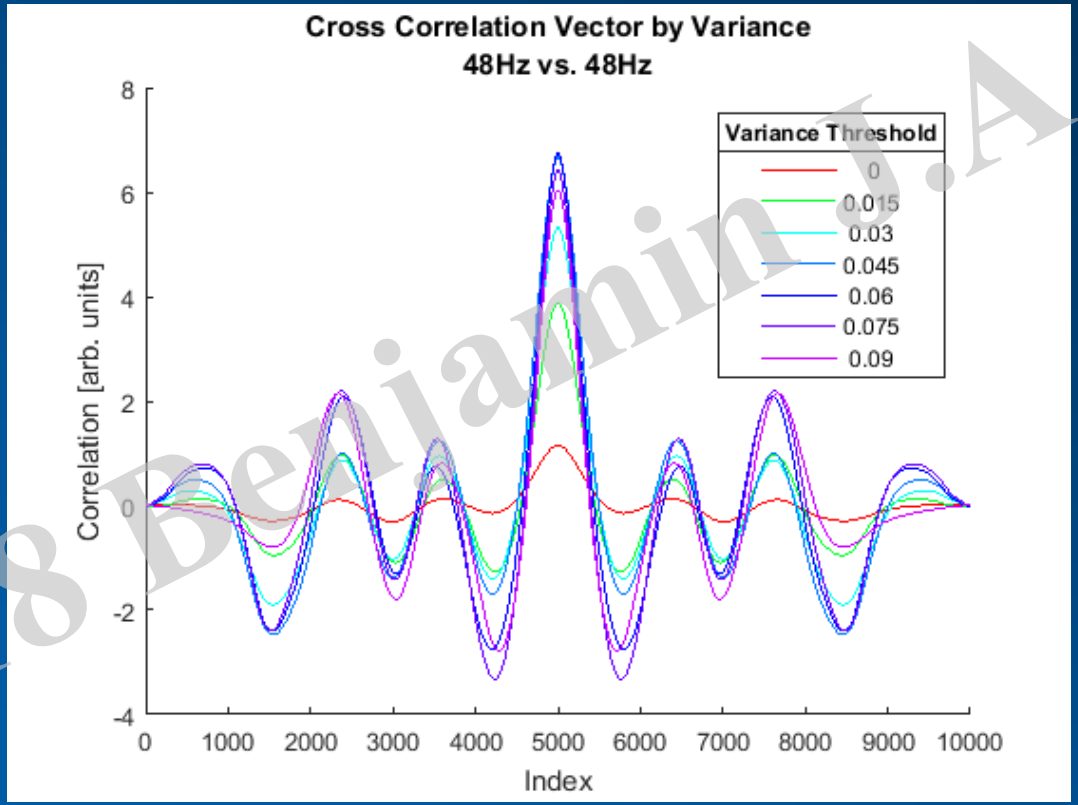

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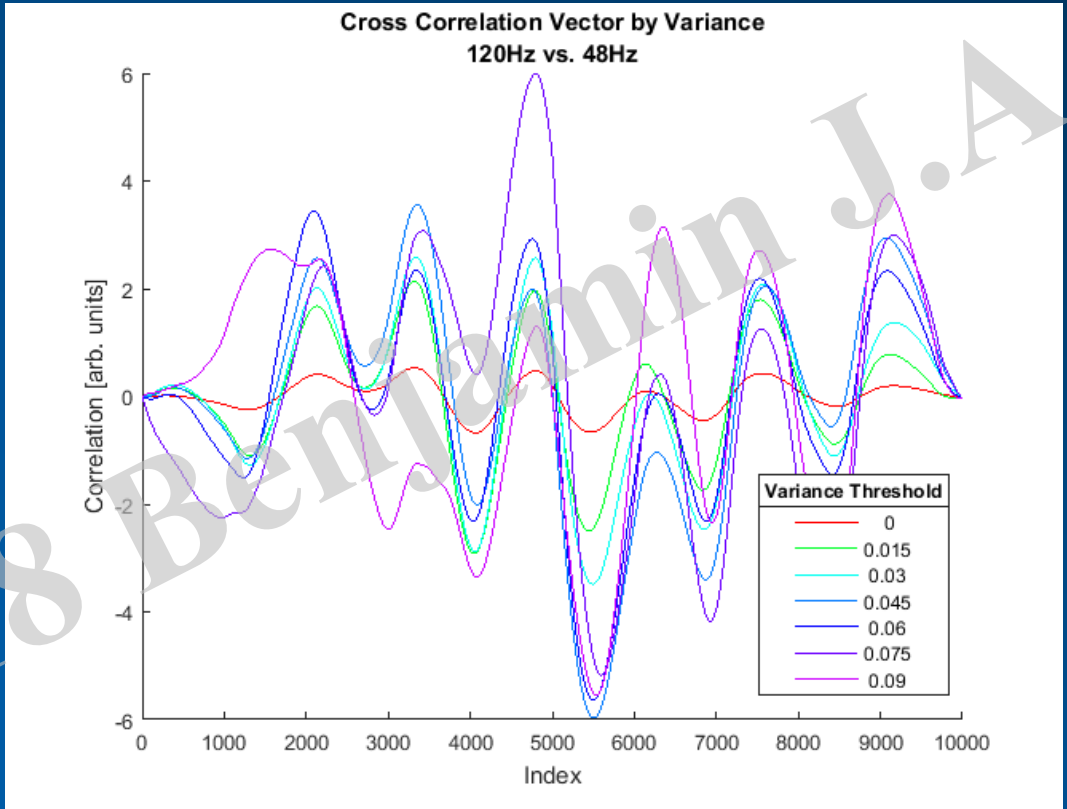

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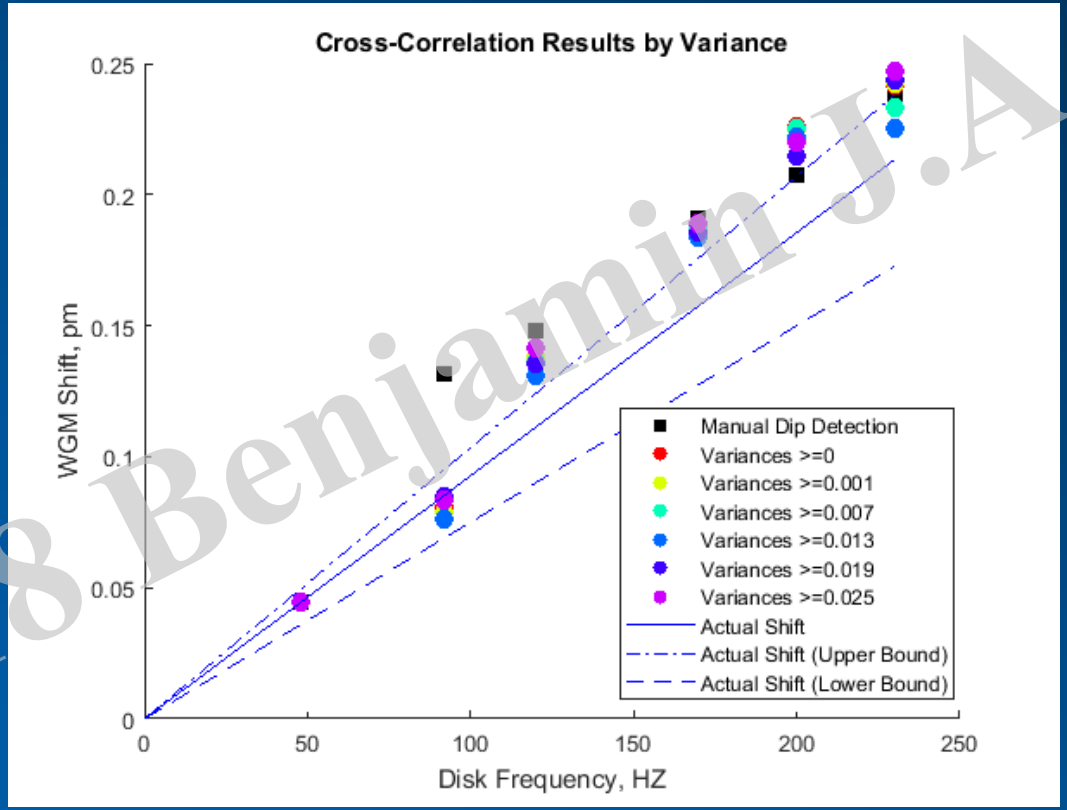
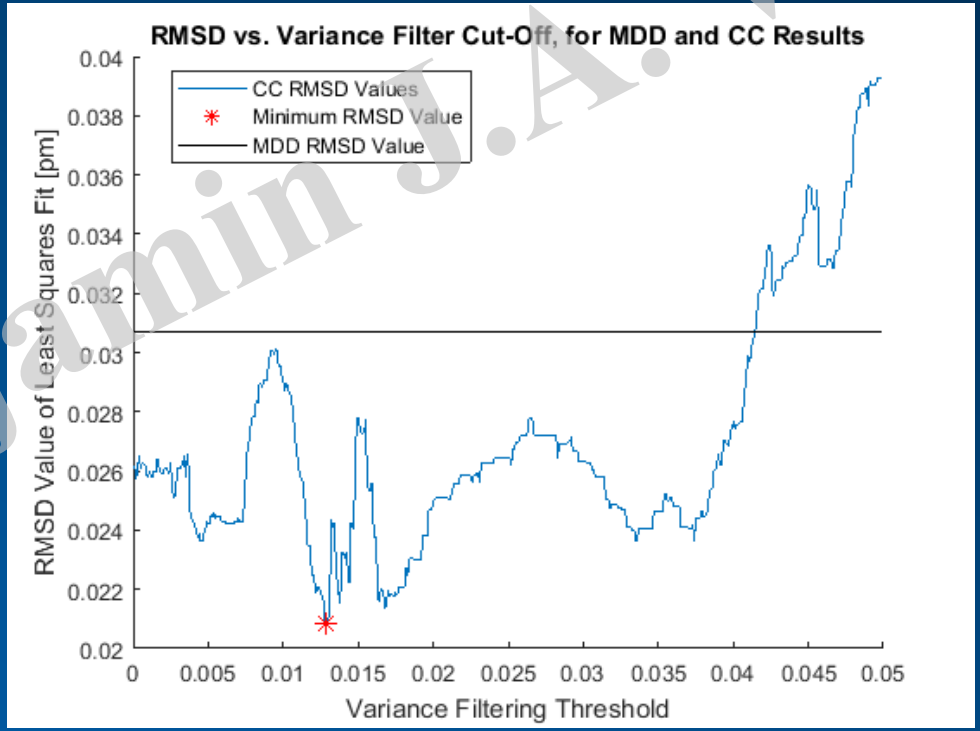


Variance Filtering Results

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}}$$



Conclusion

- Explored Various Tuning and Coupling Methodologies
- Demonstrated Doppler Shift Detection from a Solid Moving Target is Possible
- Demonstrated the Need for and Tested a New Signal Processing Approach to Mitigate Intermittent Signals
- Results Were Very Encouraging
  - At the Proof-of-Concept level, we were able to measure Doppler shift due to relative motion, with a miniaturized single-beam LIDAR device
  - We were able to overcome or mitigate some of the major challenges of this method

Acknowledgements

- Dr. Otugen
- My Thesis Committee Members:
  - Dr. Fourguette
  - Dr. Ioppolo
  - Dr. Willis
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  - Dr. Farzin Amzajerdian, Program Manager
- My Family and Friends, for all their love and support
- You, the audience, for your patient attention

Resultant Papers and Presentations

- Wise, B. J., Eghbalifarkoosh, V., Otugen, V., and Fourguette, D. "*A Microresonator Based Laser Velocity Sensor*." 2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum (Jan 2018)
- Benjamin J.A. Wise, Jaime DaSilva, and Elie R. Salameh, "*An Improved Compact Atmospheric Speed Sensor for Mars Mission*" 2018 Bluebonnet Symposium on Thermal-Fluid Sciences. (April 2018)