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Why Lasers Inject Perceived Sound Into MEMS Microphones:
Indications and Contraindications of Photoacoustic and Photoelectric Effects

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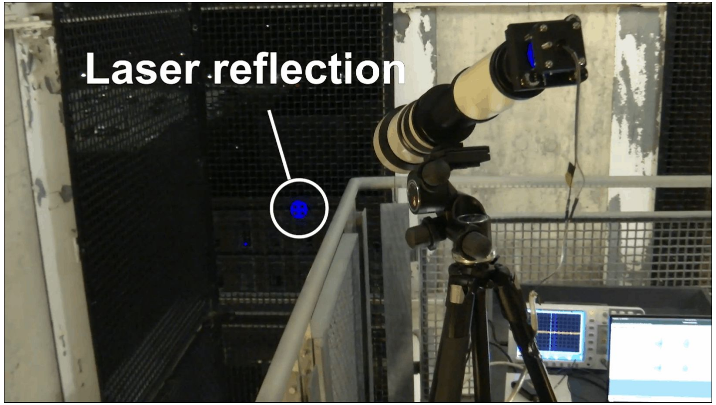
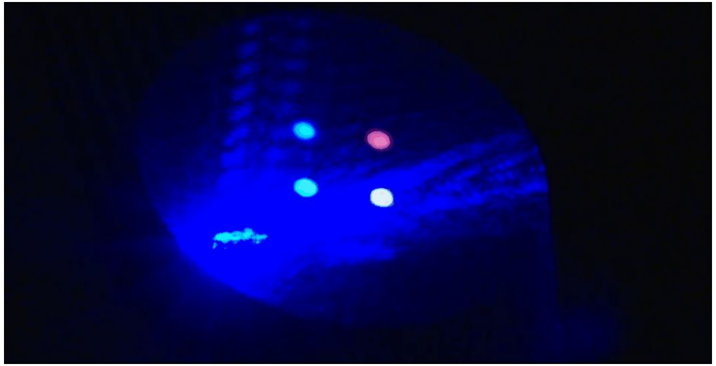
UEC TOKYO

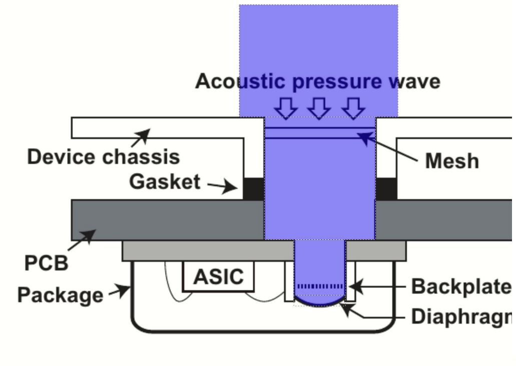
Light Commands

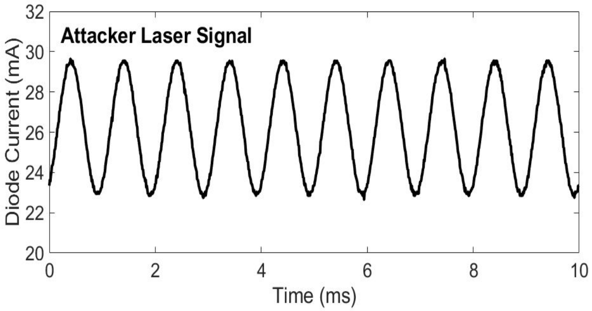


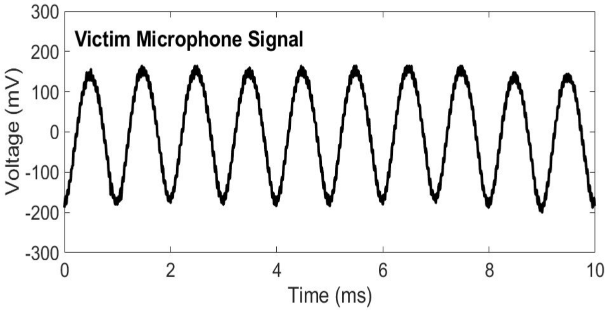


Introduction

- Amplitude-modulated light generates an undesired signal
  - Allows audio signal to be injected silently from long distance
- Hardware-level vulnerability
  - Difficult to prevent with a software update
- **Unclear what transduction mechanisms are being exploited**





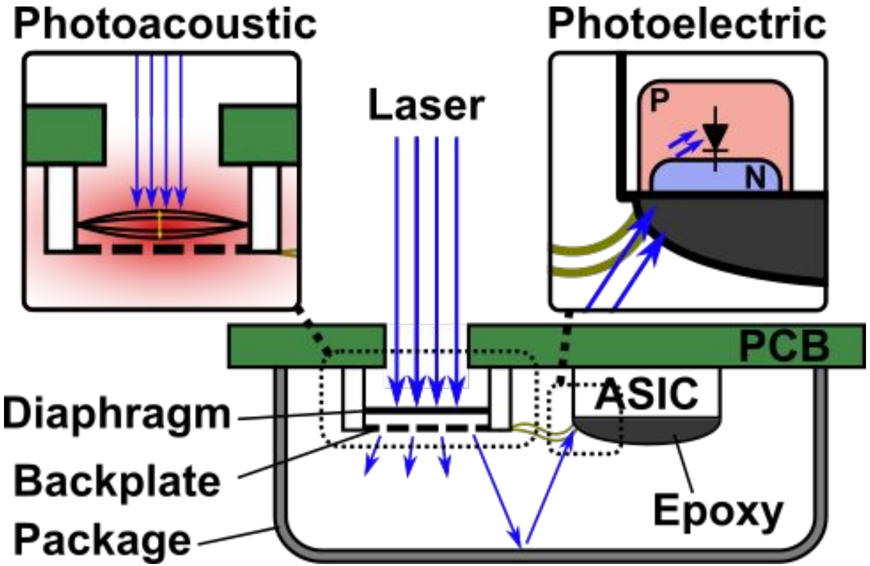


Motivation

1. Need to understand the physical causality:
   – To show what factors make attacks more effective
   – To understand which devices are most vulnerable
   – To design efficient defenses

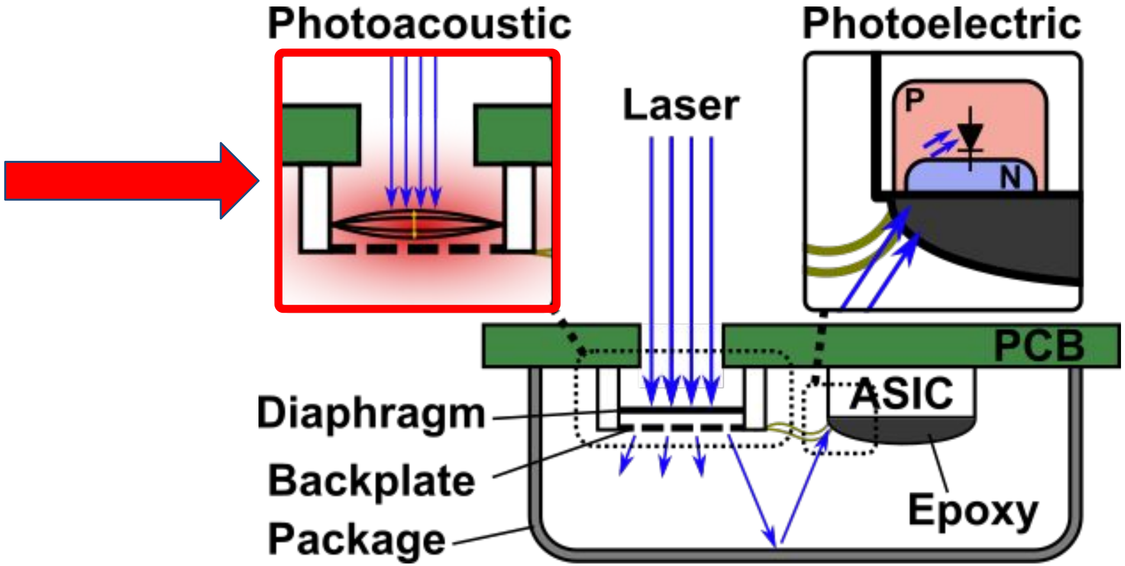
2. Potential MEMS applications for these effects

Which transduction mechanisms are converting a light signal into an electrical signal?



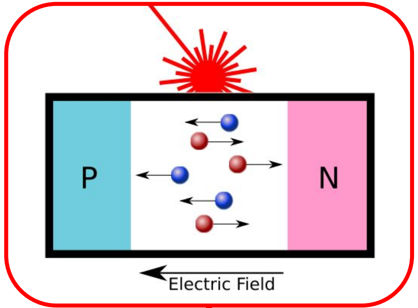
Primary Contribution

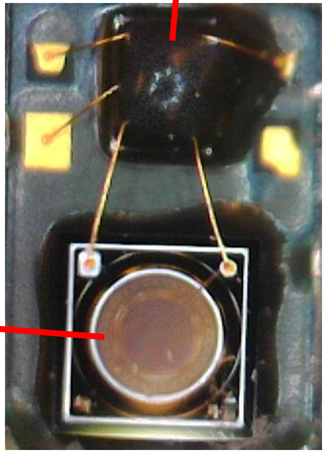
Our experiments indicate that **photoacoustic effects** are the **dominant factor** in light signal injection into MEMS microphones

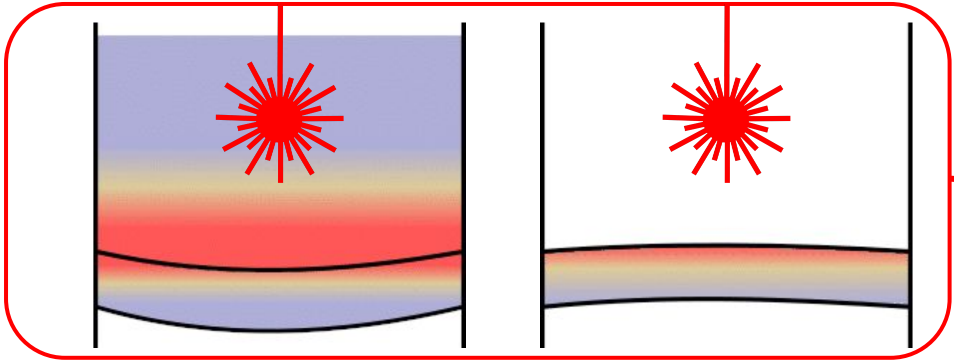


Transduction Mechanisms

- Photoelectric Effects on ASIC
  - Reverse-Biased P-N Junctions
- Photoacoustic Effects on Membrane
  - Air heating “Thermal-Piston” Model
  - Thermoelastic waves & bending



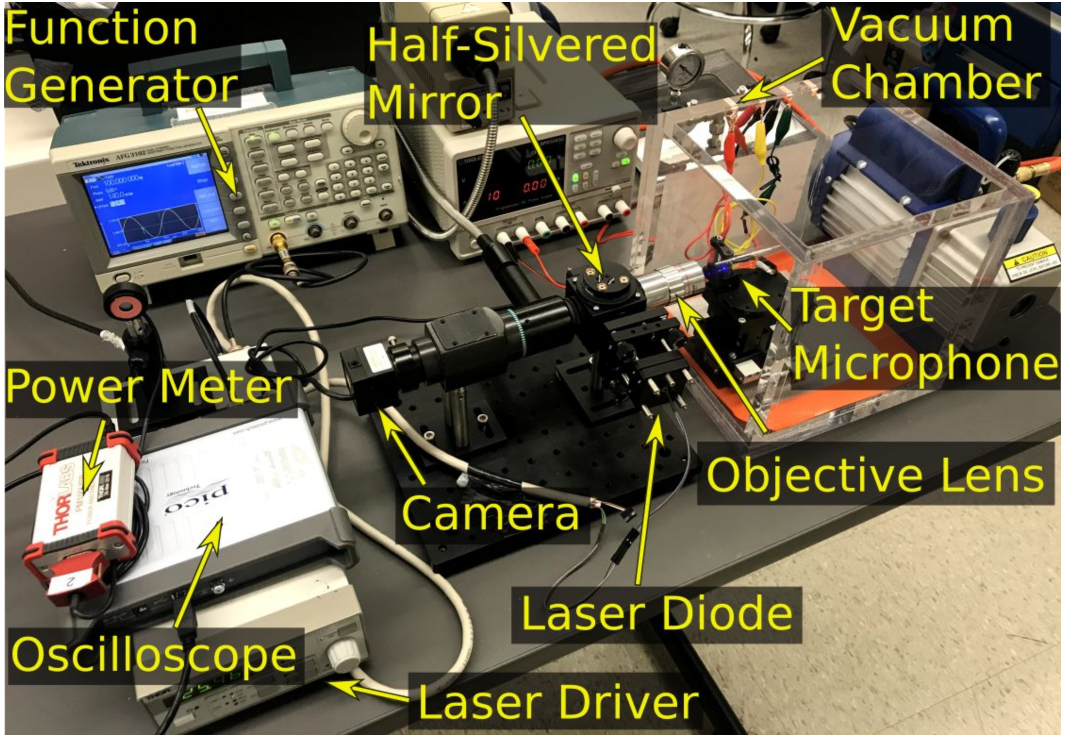




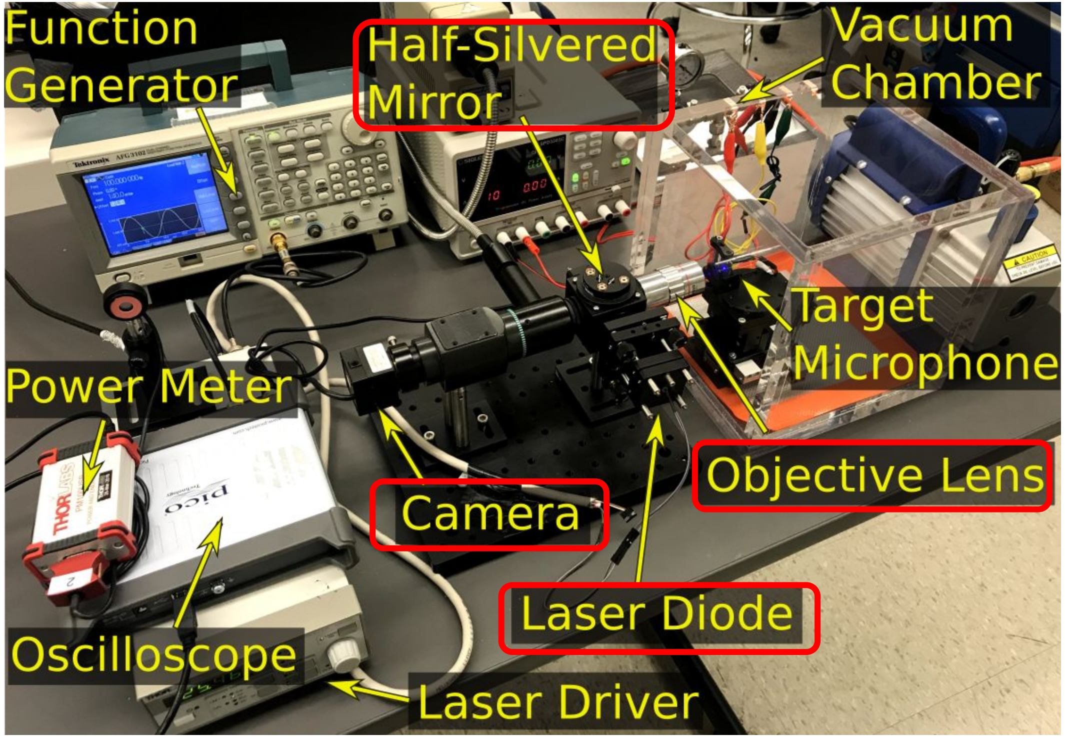
Experimental Methodology

- Develop precise and generalizable setup
- Find variables where photoacoustics and photoelectricity have different responses:
    1. Signal Frequency
    2. Laser Color
    3. Air Pressure

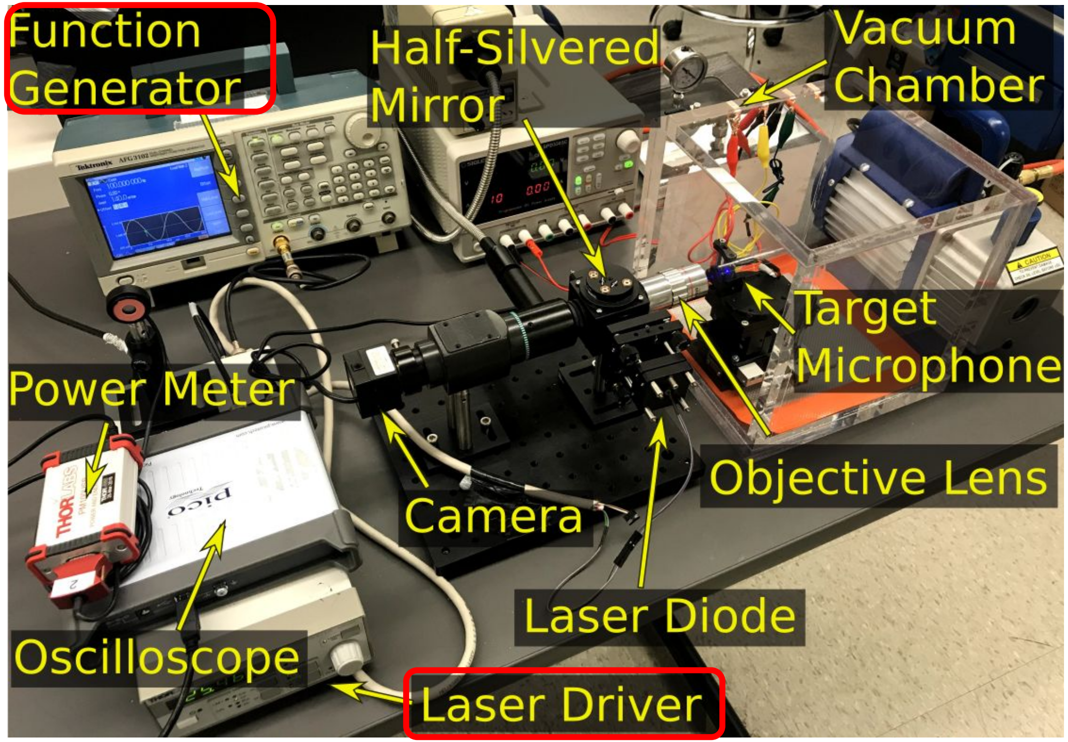
Experimental Setup



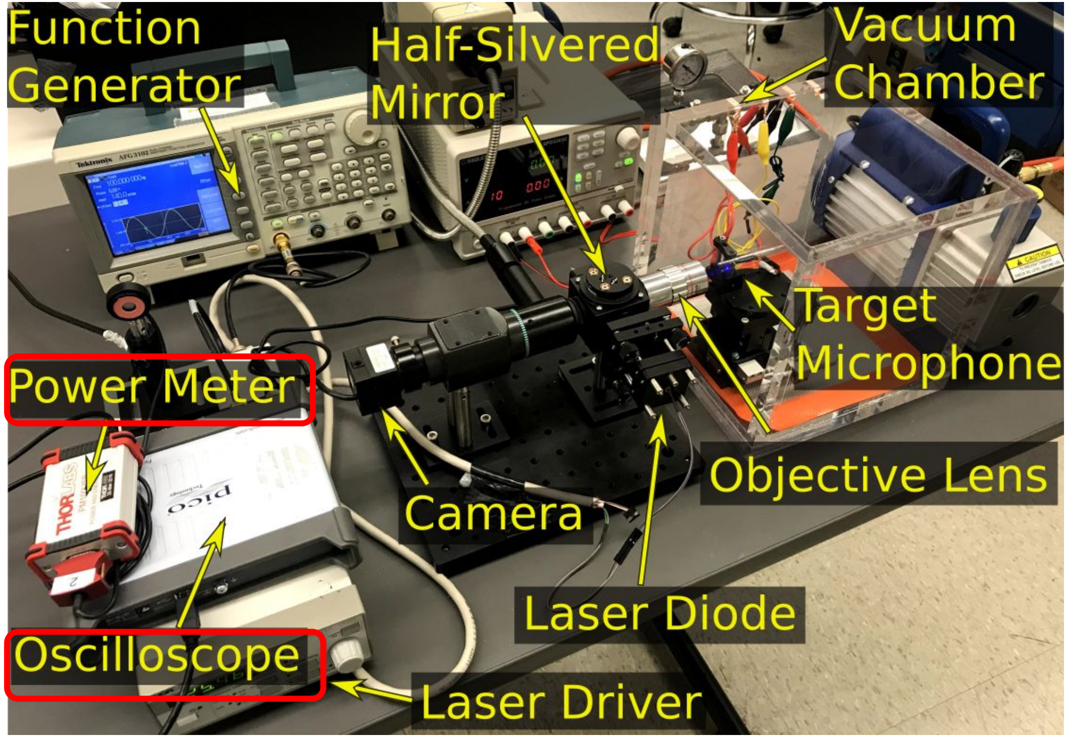
Experimental Setup



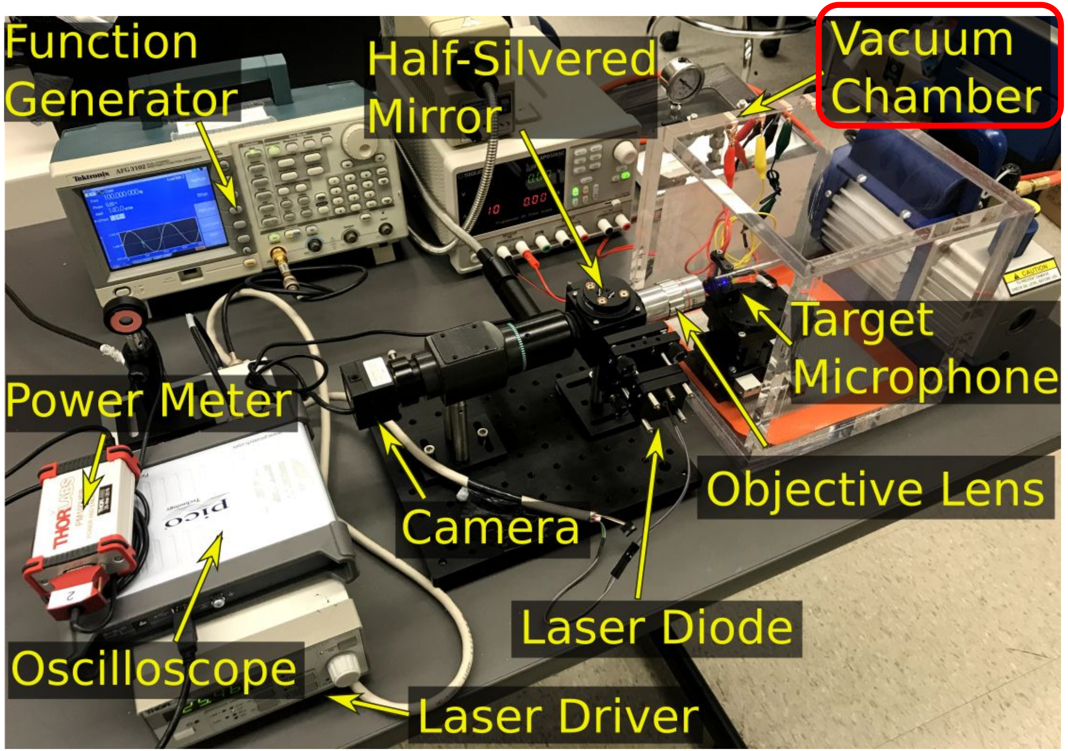
Experimental Setup



Experimental Setup



Experimental Setup

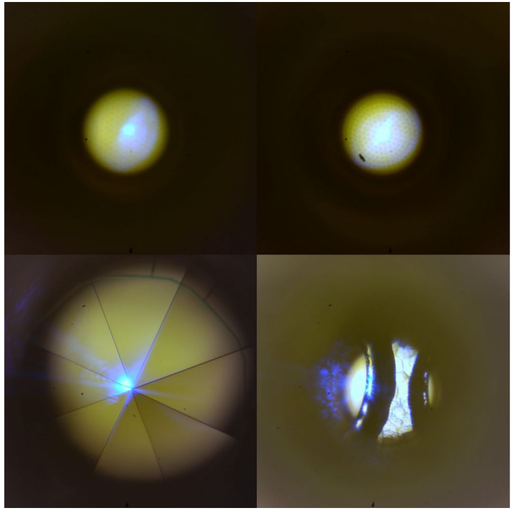


Target Microphones

- Capacitive-sensing
  - Single Diaphragm:
    - Knowles SPU0410
    - CUI Devices CMM3526
  - Dual Diaphragms:
    - Knowles SPA1687
- Piezoresistive-Sensing
  - Single Diaphragm:
    - Vesper VM1010

Knowles SPU0410

CUI Devices CMM3526

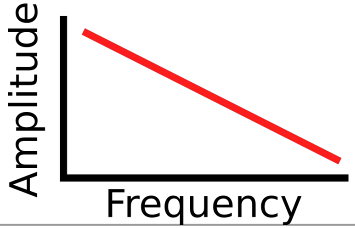
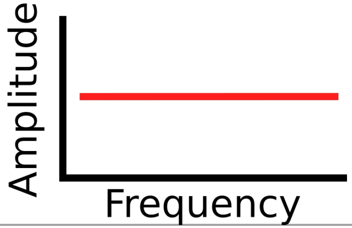


Vesper VM1010

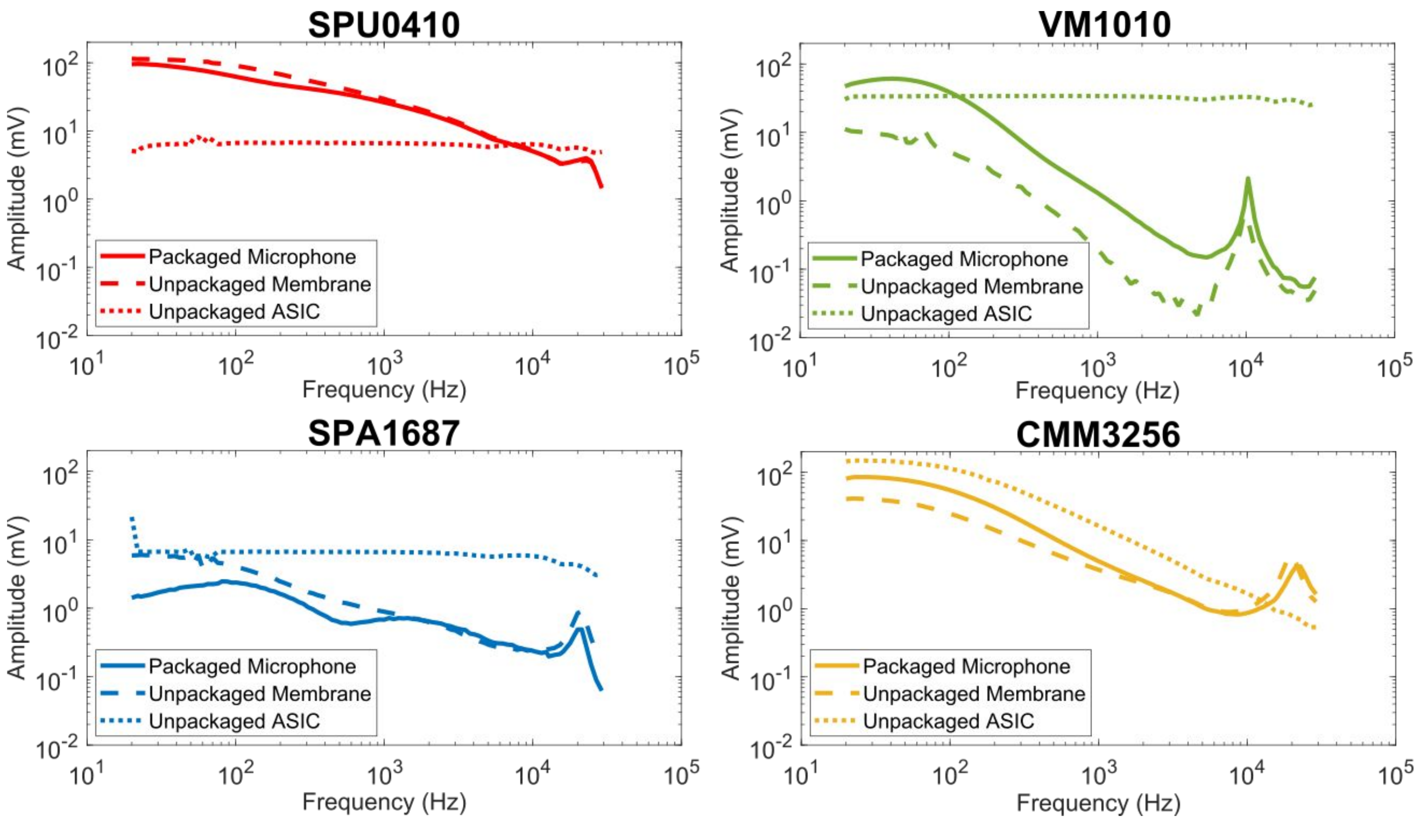
Knowles SPA1687

Experiment #1: Signal Frequency

- Measure frequency response of laser injection
  - On both the membrane and the ASIC
- Photoacoustics (based on thermal effects) have slower response
- Photoelectricity mainly affected by circuit frequency response:
  - Designed to have a flat response in audio frequencies

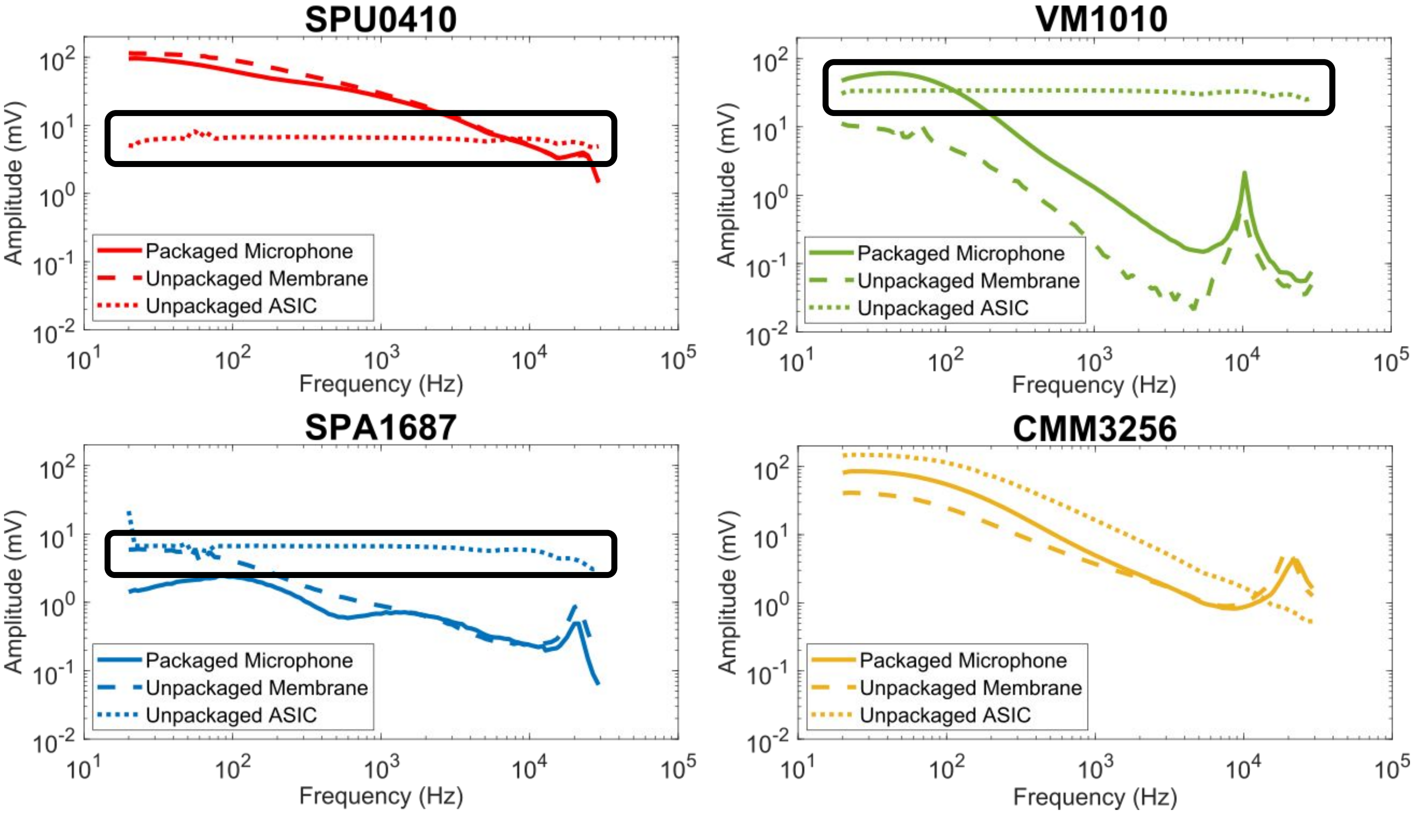
Photoacoustics: Low Frequency Bias	**Photoelectricity**: Flat Frequency Response
	

Results #1: Signal Frequency



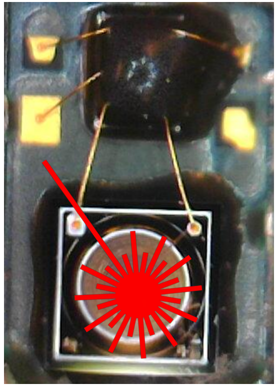
Results #1: Signal Frequency

Flat Frequency Response on ASIC

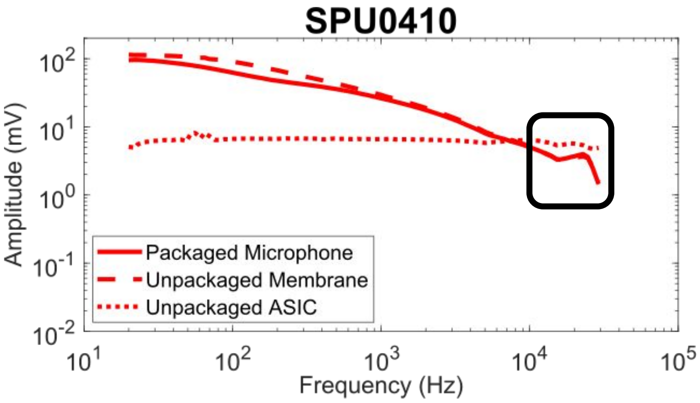


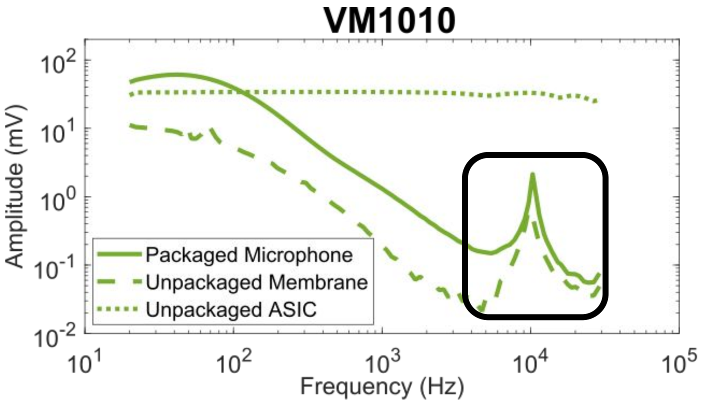
Results #1: Signal Frequency

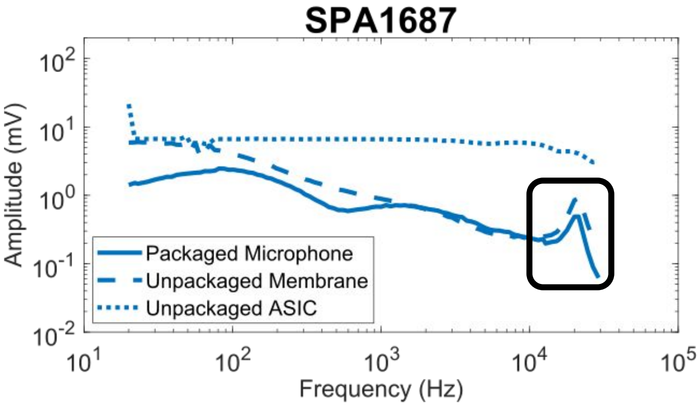
Low-Frequency Bias on Membrane

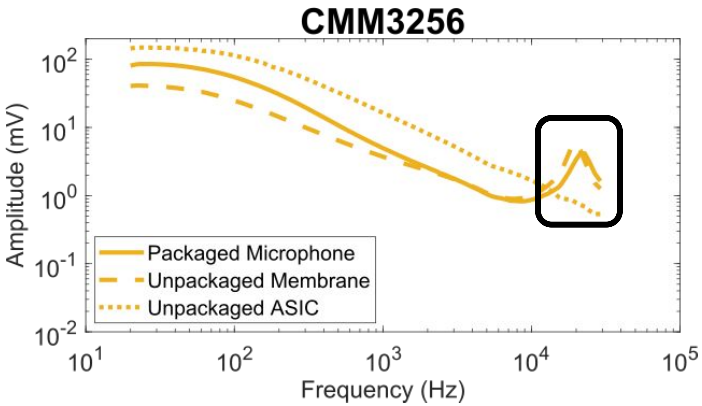


+ Mechanical Resonance









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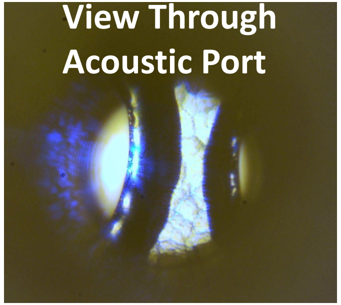
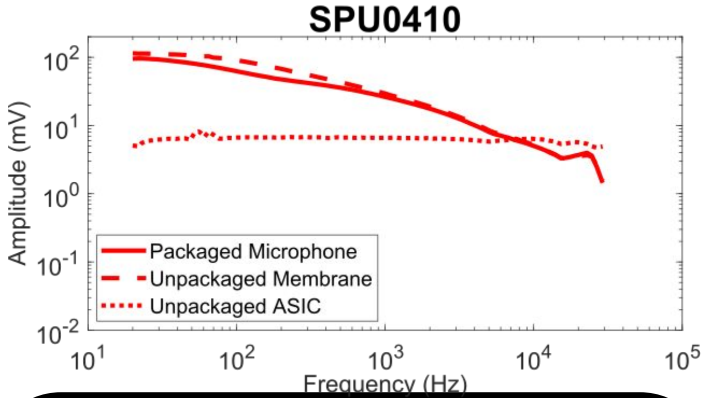
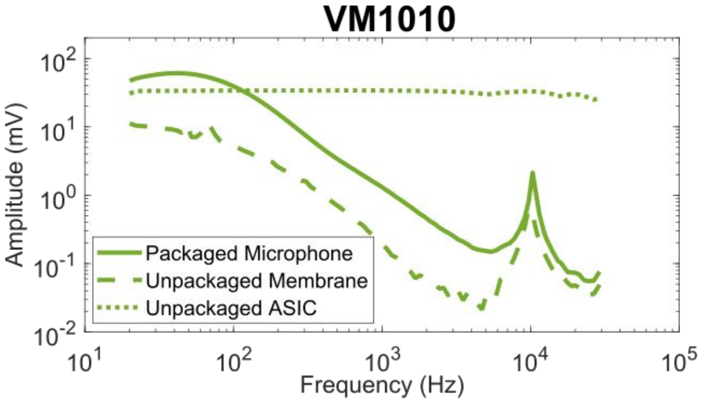
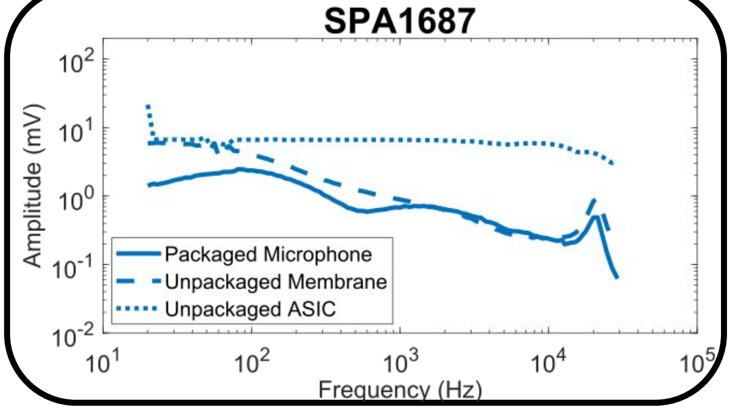
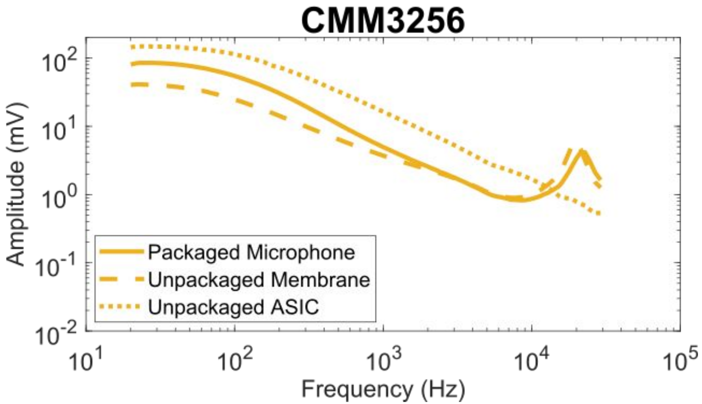






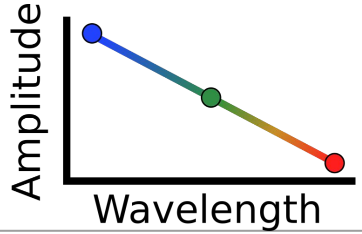
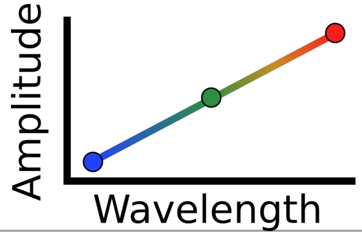
Much lower amplitude than other microphones



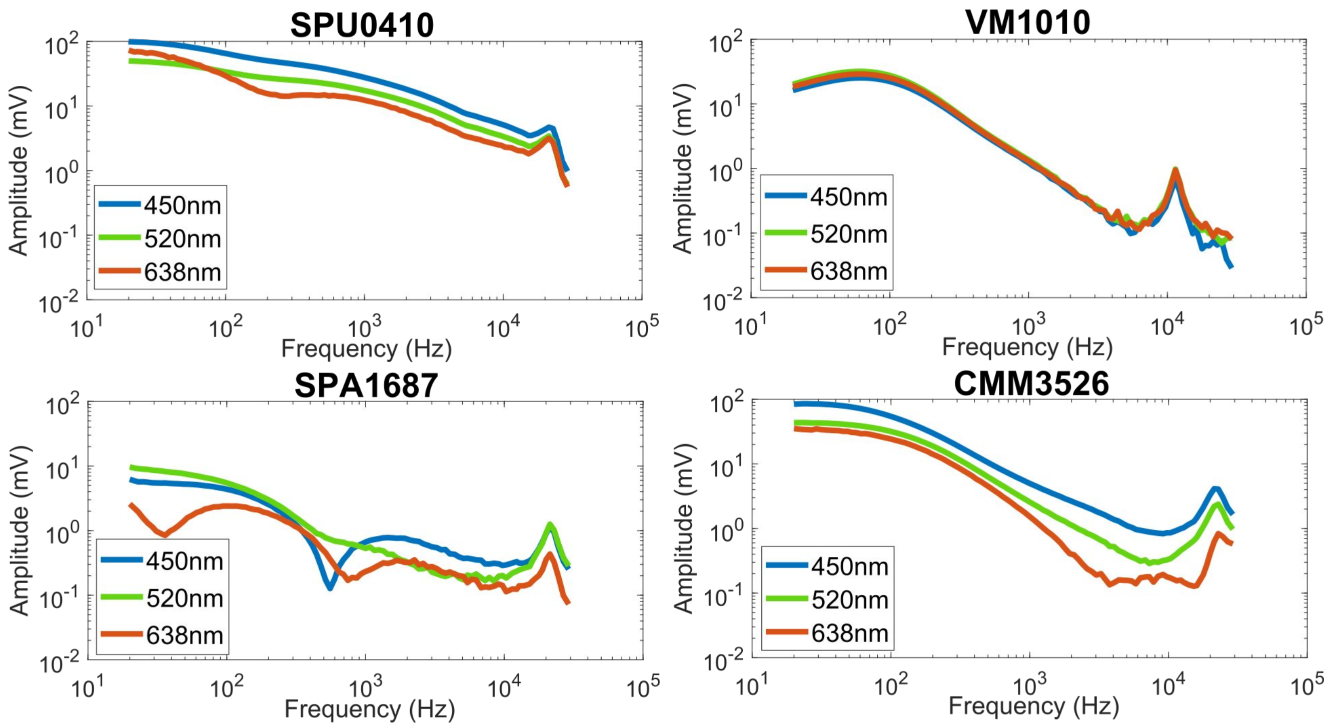


Experiment #2: Laser Color

- Measure signal response to different laser colors
  - Silicon membrane absorbs more **blue** light as heat
  - **Red** light has more photons per unit optical power, and generates more charge carriers in ASIC

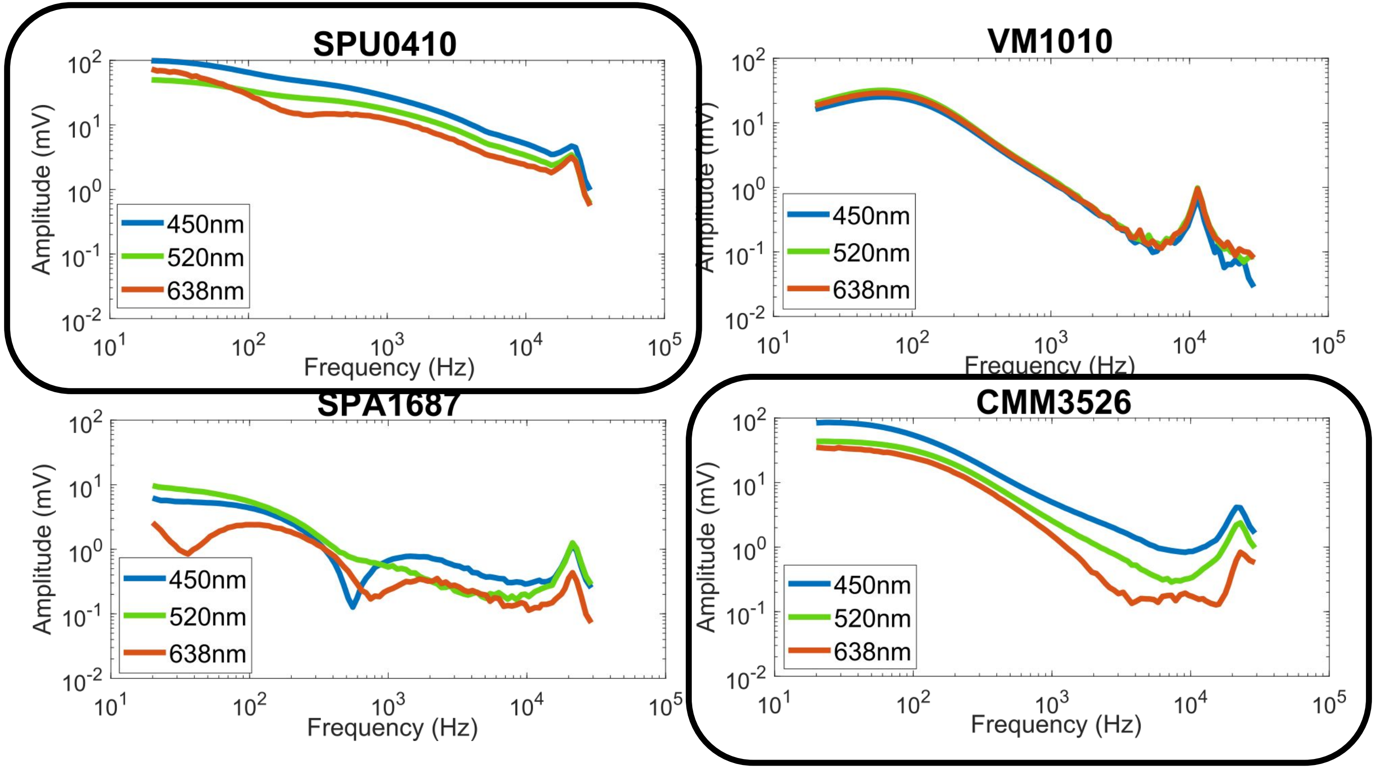
Photoacoustics: Shorter Wavelength (bluer) light stronger	Photoelectricity: Longer Wavelength (redder) light stronger
	

Results #2: Laser Color



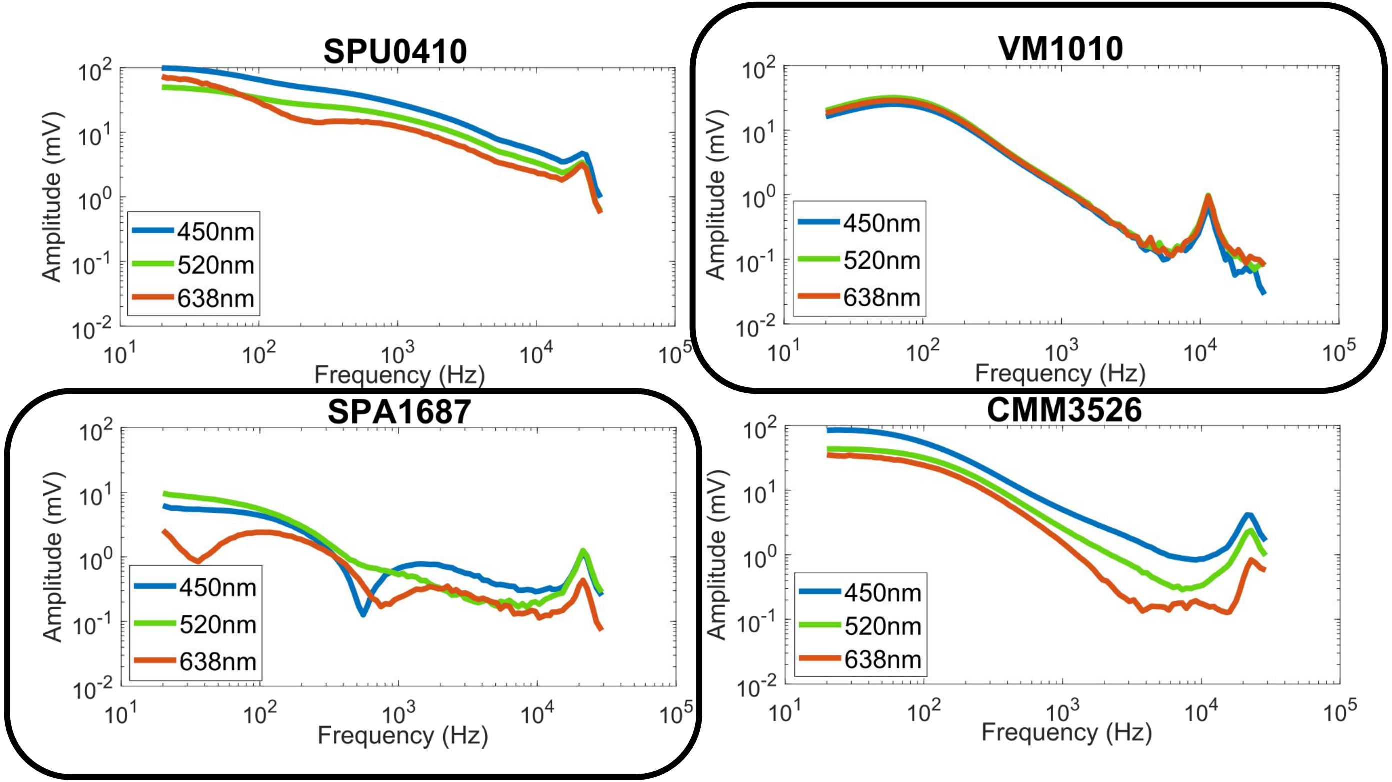
Results #2: Laser Color

Blue Light has strongest response



Red Light has weakest response

Results #2: Laser Color

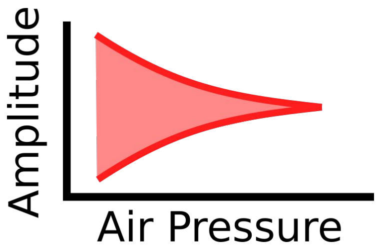
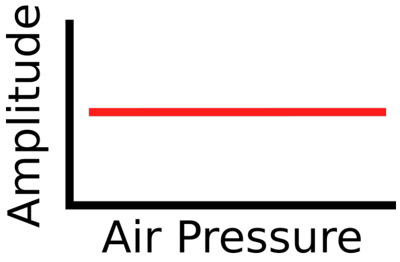


Roughly the same response

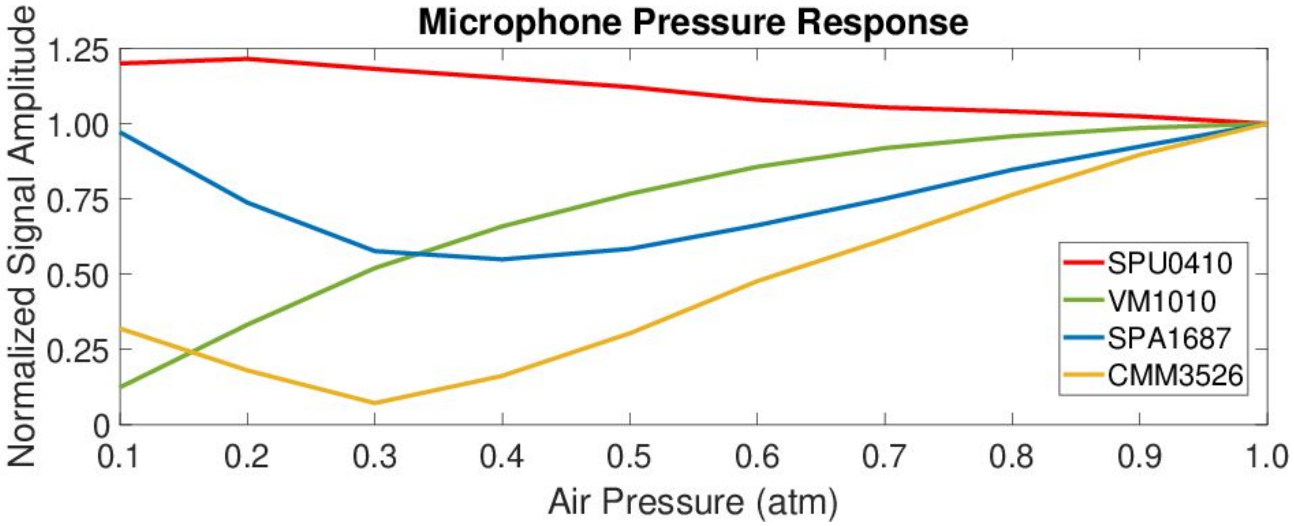
Complex interaction of different effects

Experiment #3: Air Pressure

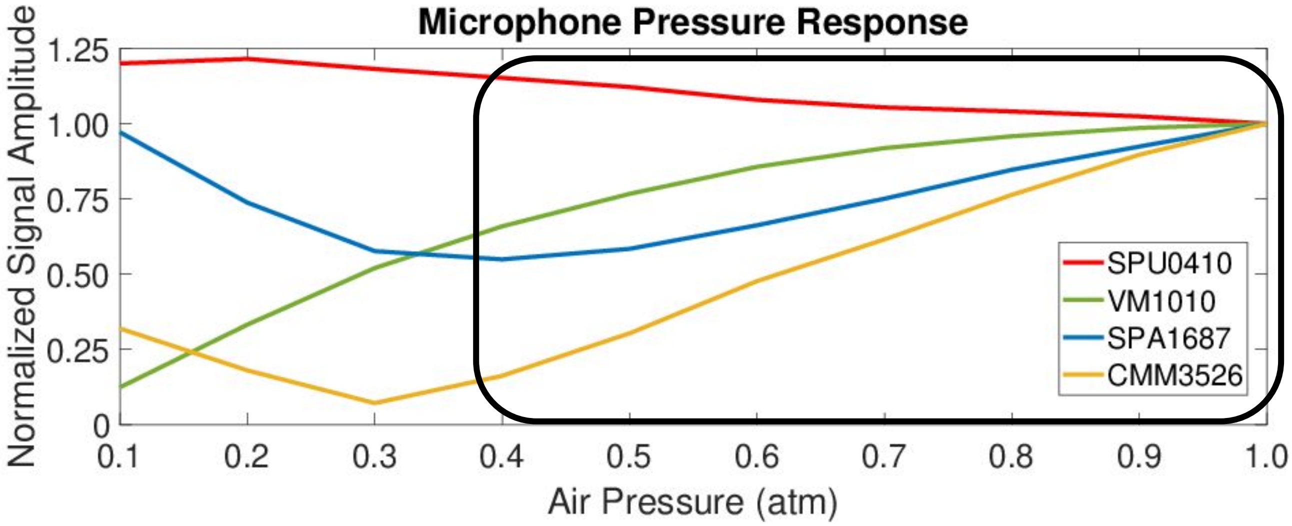
- Photoacoustics are **affected greatly** by changes in air pressure
  - Air causes **squeeze-film damping** in moving membrane
  - Air is the primary component in **Thermal-Piston Model**
- Air pressure has **very little effect** on photoelectricity

Photoacoustics: Significant Air Pressure Response	Photoelectricity: Flat Air Pressure Response
	

Results #3: Air Pressure



Results #3: Air Pressure

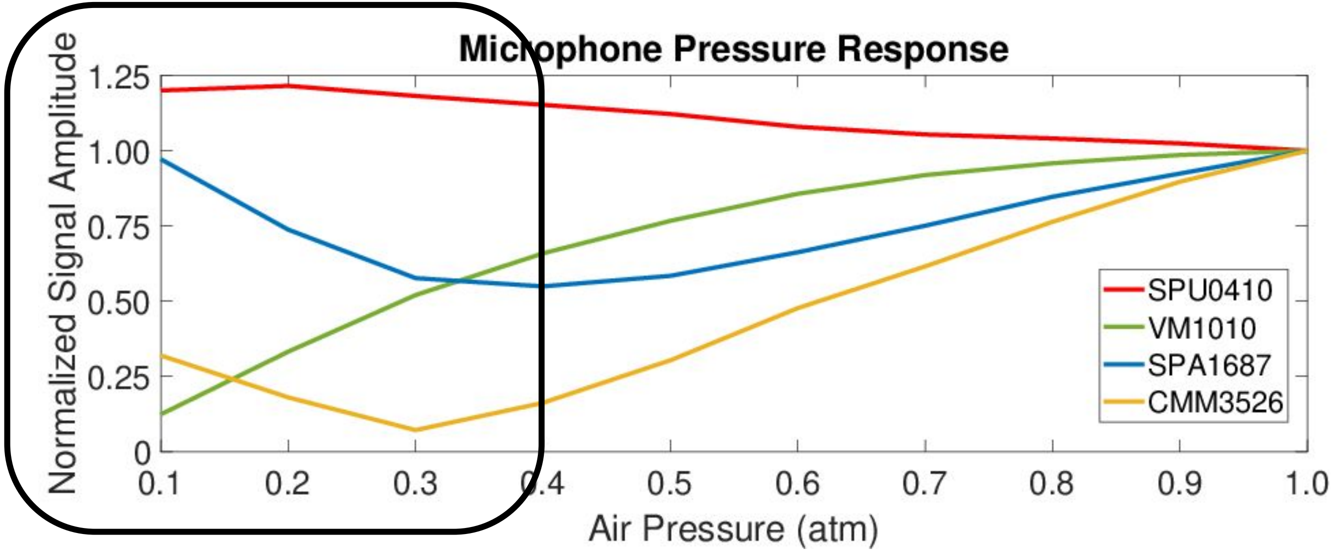


All have significant change

Results #3: Air Pressure

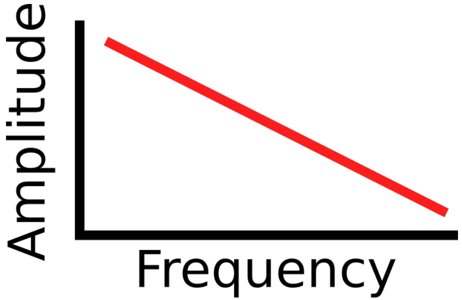
SPA and CMM reverse directions

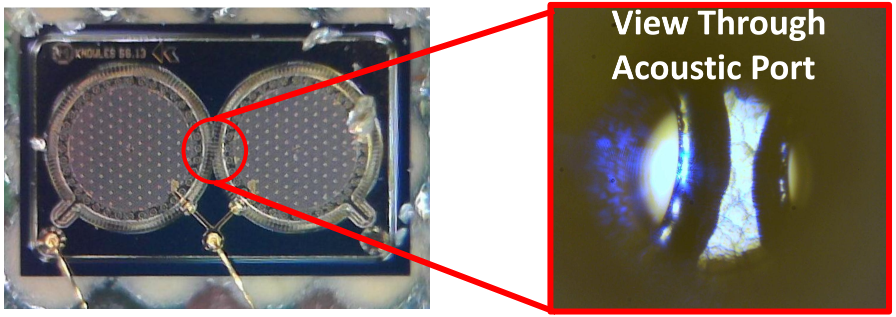
Indicates multiple effects



Discussion

- Results reveal a dominant photoacoustic effect
- Future defenses should consider photoacoustics:
  1. Light-blocking epoxy on ASIC is not enough
  2. Low-frequency bias can be a recognizable feature
  3. The most effective defense was a design that prevented line-of-sight to the membrane (see SPA1687)





Conclusion

- Experiments indicate the photoacoustic effect is the primary transduction mechanism in Light Commands
  - Unclear how multiple photoacoustic mechanisms are interacting

- A physical model of the injection should be further developed
  - To better understand the attacks and defenses

- **How can photoacoustics be used in future sensor designs?**

Related Work

Laser fault injection exploiting photoelectricity:

- J. L. Wirth and S. C. Rogers, “The transient response of transistors and diodes to ionizing radiation,” IEEE Transactions on Nuclear Science 1964
- D. H. Habing, “The use of lasers to simulate radiation-induced transients in semiconductor devices and circuits,” IEEE Transactions on Nuclear Science 1965
- S. P. Skorobogatov and R. J. Anderson, “Optical fault induction attacks”, CHES 2002
- M. Agoyan et. al., “Single-bit DFA using multiple-byte laser fault injection,” IEEE HST 2010
- J.-M. Dutertre et. al., “Review of fault injection mechanisms and consequences on countermeasures design,” IEEE DTIS 2011

Photoacoustic theory and models:

- A. Rosencwaig and A. Gersho, “Theory of the photoacoustic effect with solids,” Journal of Applied Physics 1976
- F. A. McDonald and G. C. Wetsel, “Generalized theory of the photoacoustic effect,” Journal of Applied Physics 1978
- G. Rousset et. al., “Influence of thermoelastic bending on photoacoustic experiments related to measurements of thermal diffusivity of metals,” Journal of Applied Physics 1983
- N. G. C. Astrath et. al., “Surface deformation effects induced by radiation pressure and electrostriction forces in dielectric solids,” Applied Physics Letters, 2013

Thank You!

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Questions?

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