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

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Light Commands

DEMO #3
THROUGH A WINDOW

Injecting “OK Google, open the garage door” to a Google Home by shining a laser from another building.
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

- Function Generator
- Half-Silvered Mirror
- Vacuum Chamber
- Target Microphone
- Objective Lens
- Power Meter
- Camera
- Laser Diode
- Oscilloscope
- Laser Driver
Target Microphones

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

<table>
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<tr>
<th>Photoacoustics: Low Frequency Bias</th>
<th>Photoelectricity: Flat Frequency Response</th>
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<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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1. Measure frequency response of laser injection on both the membrane and the ASIC.
2. Photoacoustics (based on thermal effects) have a slower response.
3. Photoelectricity is mainly affected by the circuit frequency response, designed to have a flat response in audio frequencies.
Results #1: Signal Frequency

- **SPU0410**
  - Amplitude vs. Frequency for Packaged Microphone, Unpackaged Membrane, Unpackaged ASIC.

- **VM1010**
  - Amplitude vs. Frequency for Packaged Microphone, Unpackaged Membrane, Unpackaged ASIC.

- **SPA1687**
  - Amplitude vs. Frequency for Packaged Microphone, Unpackaged Membrane, Unpackaged ASIC.

- **CMM3256**
  - Amplitude vs. Frequency for Packaged Microphone, Unpackaged Membrane, Unpackaged ASIC.
Results #1: Signal Frequency

Flat Frequency Response on ASIC
Results #1: Signal Frequency

Low-Frequency Bias on Membrane

+ Mechanical Resonance
Results #1: Signal Frequency

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

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<th>Photoacoustics:</th>
<th>Photoelectricity:</th>
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<td>Shorter Wavelength (bluer) light stronger</td>
<td>Longer Wavelength (redder) light stronger</td>
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![Diagram showing amplitude vs. wavelength for Photoacoustics and Photoelectricity.](image-url)
Results #2: Laser Color
Results #2: Laser Color

Blue Light has strongest response

Red Light has weakest response
Results #2: Laser Color

Complex interaction of different effects

Roughly the same response
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

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<th>Photoacoustics: Significant Air Pressure Response</th>
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- **Amplitude** vs **Air Pressure**
- **Amplitude** vs **Air Pressure**
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:


Photoacoustic theory and models:

Thank You!

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Questions?
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