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

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***Abstract*—Recent work published in the cybersecurity research community demonstrated a surprising discovery: modulated, low-power lasers can reliably inject falsely-sensed acoustic signals in MEMS microphones. However, the work remained mute on the physics-based causality with only passing conjectures on why the technique works. Until the physics of the energy transfer is understood, it will be difficult to design defenses with convincing evidence of effectiveness and reliability. In this work, we provide a methodology to test the presence and contribution of the photoacoustic and photoelectric effects to laser signal injection in MEMS microphones. Our programmable, precise laser experiments on MEMS devices in a vacuum chamber creates conditions to sufficiently isolate photoacoustic effects from photoelectric effects in a diverse set of microphones. The results indicate a dominance of photoacoustic effects while also providing contraindications of photoelectric effects. This leads to profound implications on laser injection defenses as modern MEMS designs do not consider security requirements to protect against laser signal injection via photoacoustic phenomena.**

***Index Terms*—Lasers, Sensors, MEMS, Photoacoustics**

I. Introduction

In 2019, the Light Commands project [1] published a surprising result in the information security and privacy community: lasers could inject false acoustic sensations into MEMS microphones from hundreds of meters away, even through glass windows. The research reported that firing an amplitude-modulated laser into the acoustic port of a MEMS microphone produces a commensurate AC voltage signal on the output of the microphone, which is interpreted as an acoustic signal. This injection vulnerability poses substantial security risks to operational technologies that execute sensitive operations based on voice commands. A major shortcoming of the previous work was the insufficient investigation of the causality of the attack. Our work shines light on this unsolved problem, as we investigate the physical mechanisms of energy transfer that make the laser injection possible.

Without an understanding of the causality, it is difficult to generate new designs and methodologies to make these systems resistant to light signal injection. All previous works in laser fault injection attacks [2]–[4] exploit photoelectric effects, where light generates current within semiconductor circuits [5], [6]. This has lead manufacturers to use light-blocking epoxies in their devices, including MEMS microphones. But *Light Commands* found that the injection may be exploiting photoacoustic effects, where light causes vibrations due to a variety of thermomechanical and electromechanical phenomena [7]–[10]. Due to the black-box nature of these microphone designs, it is difficult to know which of the photoacoustic or photoelectric effects are the present in these laser injection attacks that affect many MEMS microphones present in consumer devices. That is why we sought to characterize the laser signal injection into MEMS microphones.

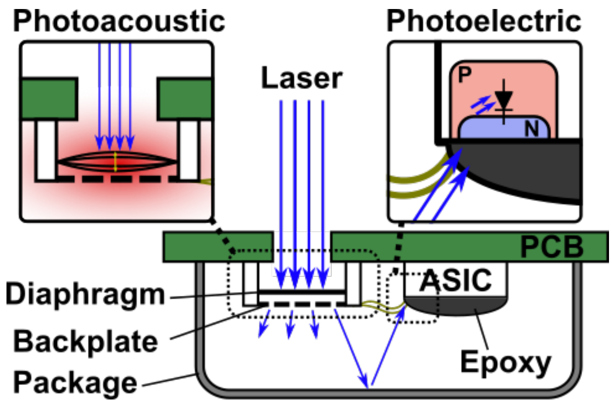

Fig. 1. The photoacoustic and photoelectric effects are the primary mechanisms of energy transfer in laser signal injection into MEMS microphones

Our contributions are as follows:

- Laser experiments on MEMS devices indicate photoacoustic effects are dominant while also finding contraindications of dominant photoelectric effects.
- Our setup and methodology enables others to replicate and characterize laser injection attacks to test further hypotheses on energy transfer effects in MEMS devices.
- Experiments on a diverse set of MEMS microphones show that our results apply to a large proportion of actively deployed products.
- The research uncovers complexities and other confounding factors for laser signal injection previously unexplored by the sensor research community.

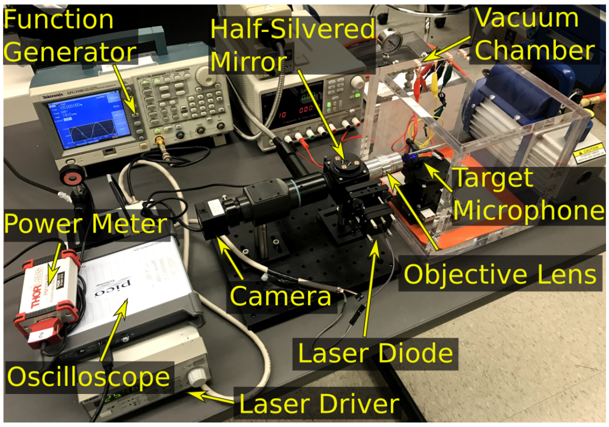

Fig. 2. Experimental setup to perform precision aiming and focusing.

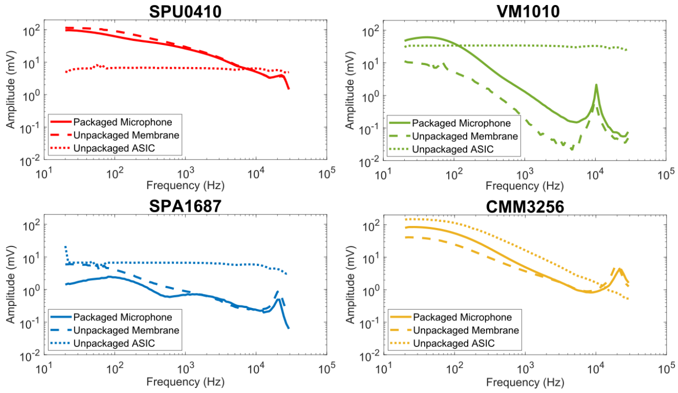

Fig. 3. The frequency response of the microphones to a 0.5mW amplitude, 5mW offset, 450nm laser signal injection attack at different injection locations.

II. Experimental Setup

To perform our investigation, we first made a precise and flexible setup to perform the laser signal injection on MEMS microphones. Figure 2 shows and overview of the setup.

The setup consists of a laser diode being driven with a Thorlabs LDC205C laser driver and a Tektronix AFG3102 function generator to enable precise optical power control. A Thorlabs PM100USB power meter with a S121C head was used to measure the power accurately. We developed a setup to control the aiming and focus of the laser beam using a camera, a Thorlabs LDH56-P2 laser collimation cage, a half-silvered mirror, and a Mitutoyo 5x objective lens. This setup allowed us to visually see the focus and position of the laser beam. A Thorlabs 3-Axis manual stage with rotation was used for precise control on the aiming, and the target microphones were placed inside a BVV acrylic-wall vacuum chamber to have control over the pressure of the air around the microphone.

We selected four target microphones of similar size and use case, but with a diversity in the design of the MEMS structures. Two of the microphones, the Knowles SPU0410 (M_{SPU}) and the CUI Devices CMM3526 (M_{CMM}), are capacitive-sensing microphones with a single diaphragm-backplate pair. The Knowles SPA1687 (M_{SPA}) is another capacitive-sensing microphone, but using two diaphragm-backplate pairs in a differential-capacitive-sensing scheme, neither of which are directly in line with the acoustic port. Finally, the Vesper VM1010 (M_{VM}) microphone is a piezoelectric-sensing microphone, measuring piezoresistors placed on the edges of a single diaphragm structure. All four microphones were manufactured with light-blocking epoxy applied to the ASICs. All the microphones were powered with a Siglent SPD3303C power supply set to +3 volts, and measured using a Picoscope 5444D oscilloscope.

III. Experimental Methodology

Based on the theoretical understanding of the photoacoustic and photoelectric effects, we identified three different variables that can be used to isolate between the two classes of phenomena. These variables are the frequency of the signal injection, the color of the injection laser, and the air pressure of the surrounding environment.

A. Signal Frequency

The first variable is the frequency of amplitude-modulated laser injection; photoacoustic effects should have a very strong low-frequency bias and show the resonant frequencies of the vibrating diaphragm, while photoelectric effects should have a flat frequency response [7].

Using a blue (450 nm) laser diode, a calibrated optical signal with a power offset of 5 mW and an amplitude of 0.5 mW was fired into the microphone. A frequency sweep was performed to measure the response. To test that our assumptions were correct, we also depackaged the microphones to prevent reflections from hitting the ASIC and repeated the frequency sweep two more times: once by aiming on the membrane and once aiming at the ASIC. We then compared the frequency responses of firing at each of the locations.

The results of the frequency sweeps at the different microphone locations are showed in Figure 3. In the M_{SPU}, M_{VM}, and M_{SPA}, the ASIC injection attack had a nearly flat frequency response, revealing that there is very little frequency bias within the electronics affected by the photoelectric injection. In contrast, when the laser was fired at the membrane (both when packaged and depackaged), there was a strong low frequency bias, as predicted by the photoacoustic models. Beyond this, every injection on the membrane revealed a resonant frequency peak between 10–20 kHz. The frequency of these peaks are close to the mechanical resonant frequencies of the membrane structures, indicating the presence of a photoacoustic vibration.

B. Laser Color

The second variable is the color of injected light with the same optical power; photoacoustic effects should be stronger in bluer light with higher diaphragm absorption coefficients, while photoelectric effects should be stronger in redder light with higher concentrations of photons.

We designed the second experiment to measure the laser signal injection into the target microphones using three different colors of light: red (638 nm), green (532 nm), and

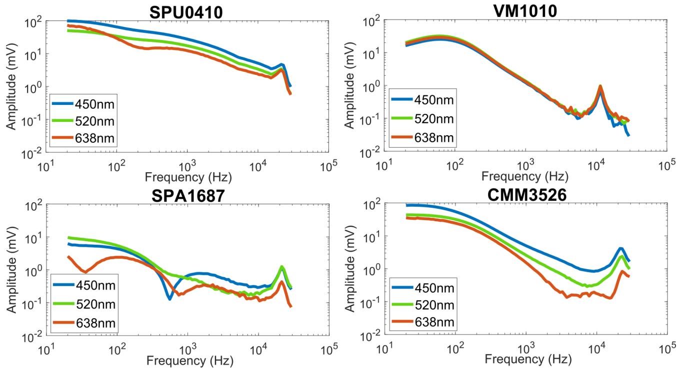

Fig. 4. The frequency response of the microphones to a 1mW amplitude, 5mW offset signal injection attack with different colors of laser.

blue (450 nm). Each of the lasers were calibrated to the same optical power offset (5 mW) with the same signal amplitude (1 mW). We performed a frequency sweep on each of the microphones with the three lasers and compared the response.

Figure 4 shows the results of the laser color experiment. Two of the microphones, the $\mathrm{M_{SPU}}$ and the $\mathrm{M_{CMM}}$, have an increase in the output signal as the light wavelength decreases. This suggests a dominant photoacoustic component to the output signal for these devices. The output of the $\mathrm{M_{VM}}$ stays roughly constant in all three cases, which may indicate that the diaphragm structure is thicker and the majority of all three colors are absorbed by the diaphragm. Finally, the $\mathrm{M_{SPA}}$ does not follow an obvious trend, though the differences in the frequency responses between the colors suggests a complex combination of multiple physical phenomena.

C. Air Pressure

The third variable is the air pressure in and around the microphone; photoacoustic effects should be strongly affected, as removing air would reduce air-dependent photoacoustic effects [7] and squeeze-film damping around the diaphragm, while photoelectric effects should remain unaffected.

To test this variable, we included a vacuum chamber in our experimental setup. In our experiment, we used the blue (450 nm) laser to inject a 100 Hz signal into each microphone. The optical power offset was set to 5mW with a signal amplitude of 1 mW. We then used a vacuum pump to reduce the air pressure to 0.1 atm, then let air slowly back into the chamber, measuring the output signal at every step of 0.1 atm until back at 1.0 atm.

Figure 5 shows that all four microphones are affected by air pressure, indicating the presence of photoacoustic effects. As air is pulled from the system, the output signal is reduced for three of the microphones: the $\mathrm{M_{CMM}}$, $\mathrm{M_{VM}}$, and $\mathrm{M_{SPA}}$. This suggests that the air-dependent photoacoustic effects account for a large part of the signal, as it is the only effect that decreases as air is removed. The $\mathrm{M_{CMM}}$ and $\mathrm{M_{SPA}}$ also see an increase in the output amplitude a pressures below 0.3 atm, suggesting a secondary mechanism that is out-of-phase with the air-dependent photoacoustics. This could be photoelectric effects or another air-independent photoacoustic effect that is

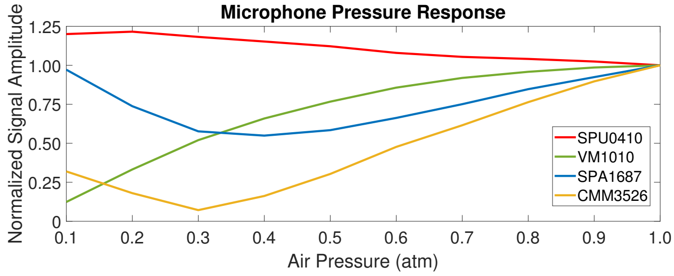

Fig. 5. The response to changes in air pressure when injecting a 100 Hz, 1mW amplitude, 5mW offset signal with a 450nm laser.

benefitting from the reduced squeeze-film damping. Finally, the $\mathrm{M_{SPU}}$'s signal increases as air is removed, indicating that the reduced damping is changing the amplitude of a photoacoustic vibration.

IV. Discussion

In all the experiments we performed, the results suggested a dominance of photoacoustic effects contributing to the laser signal injection on MEMS microphones. This is an important fact to consider when manufacturing new sensor designs that are resistant to light signal injection.

This leads us to provide recommendations to microphone manufacturers and system designers to protect future systems from laser signal injection attacks. First, a layer of light-absorbing epoxy alone is insufficient to prevent laser signal injection attacks. Despite the light-blocking epoxy in all of these devices, each microphone was vulnerable to injection via photoacustic and even photoelectric effects. Second, the most effective way to resist the laser signal injection is to avoid microphone designs with an external direct line-of-sight to the diaphragm. This is exemplified by the $\mathrm{M_{SPA}}$, where the injected signal was an order of magnitude lower than the other microphones because there is no direct line-of-sight to the center of the diaphragm. Finally, it is possible to detect the presence of a light signal injection with the low frequency bias of the photoacoustic effect. This distinctive feature of the signal injection would allow current devices to detect anomalies in microphone signals and prevent these attacks.

There are still many questions to be investigated surrounding the physical causality of these signal injection attacks. Future work should be focused on discovering which of the several potential photoacoustic phenomena provides the strongest contribution to the output signal, as this may indicate why some microphone designs are more resistant to laser injection. Future research should investigate other new capabilities that photoacoustics can present, both to protect future devices and to potentially create entirely new physical mechanisms to use in MEMS designs.

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