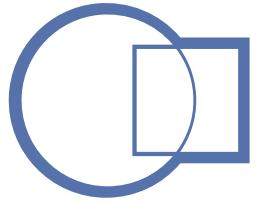


sensing, interaction & perception lab



Department of Computer Science, ETH Zürich

Semester Project

Discrete Photodetector Array Approach to High-Bandwidth Vibration Sensing

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January 6th, 2024

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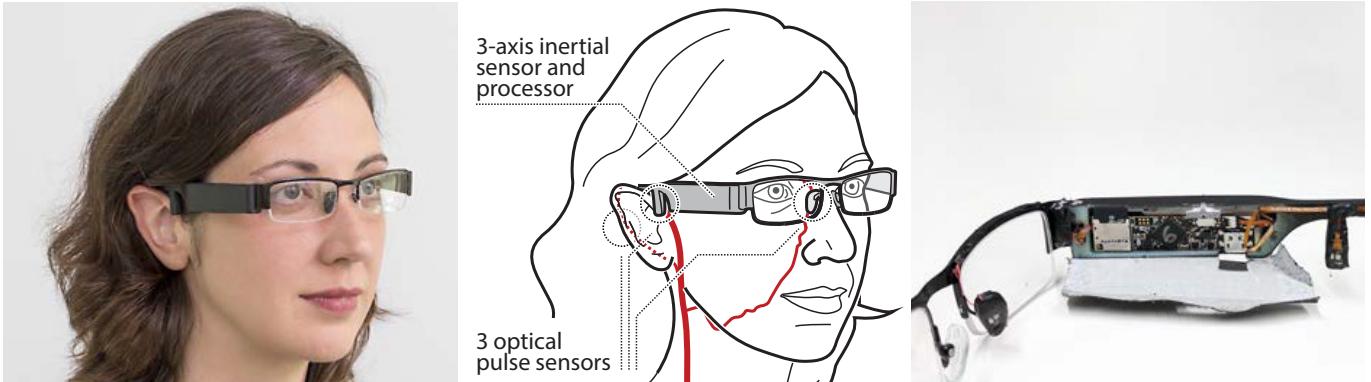


Figure 1. *Optional:* Consider including a teaser figure. Think of it as a visual abstract, illustrating the main contributions of your project. This could include photos, algorithms, results, etc. Oftentimes, this teaser contains multiple subfigures, such as (a) something, (b) something, and (c) something.

ABSTRACT

Camera imaging sensors - placed adjacent to a surface diffusing the collimated light of a laser - can be used to sense the resulting surface dependent speckle pattern. The pattern oscillates if the surface oscillates, leading to the possibility of remote vibrometry. While cameras are low cost, easy to use and highly sensitive, they have relatively low frame-rate and thus are thus a poor choice of sensor for high rate oscillations. The present work explore the creation of a device to increase the measurement bandwidth while maintaining the sensitivity an off the shelf imaging sensor can provide. To this end, a high gain low noise amplifier array has been designed with a bandwidth of 1 kHz. The array amplifies the currents of a grid of 3x3 photodiodes which is then low pass filtered and digitized using a high rate ADC. Tests were conducted to measure the ability of the device to detect laser speckles. Discrete IR lasers, with different beam patterns, and IR dot projectors were evaluated and a detection limit is defined.

Keywords

laser speckle; remote vibrometry; speckle detection; photodiode array

INTRODUCTION

Vibration sensing enables condition monitoring and predictive maintenance of industrial equipment by detecting mechanical faults before catastrophic failure occurs. Critical applications

include monitoring of rotating machinery, bearings, and industrial robots, where unexpected downtime can result in significant production losses. Higher frequency vibrations are of particular interest [?].

Typically, a vibration sensor is physically coupled to a designated surface of a machine using adhesive or glue. However, this brings the burden of cable management onto the user. Wireless sensors need their batteries replaced once in a while and require a receiving station. These limitations motivate the need for a vibration sensor that is easier to install and maintain and capable of monitoring many instances of equipment at once.

Some monitoring approaches use microphones installed centrally in the room, using sound as a proxy for vibration. Many microphones are required to distinguish sounds coming from different sources.

Remote video cameras can be used to record vibrations [?] when aimed at a fiducial marking. Many objects can fit in the field of view of a camera and can thus be monitored.

While cameras offer a non-contact and simple method for vibration sensing, they're limited to detecting macroscopic (resolution limited) and low-frequency (frame-rate limited) vibrations.

In order to measure microscopic vibrations, we can exploit the speckle patterns that an optically rough surface produces

(surface height variations on the order of laser wavelength) when laser light (like from a laser pointer) hits it.

When the laser light is reflected and scattered by the optically rough surface, it produces a locally unique and stationary interference pattern. This pattern, known as a speckle pattern, results from the superposition of coherent light waves with different path lengths due to the surface's microscopic imperfections. The resulting speckle pattern can be observed on any imaging plane at a distance from the surface. To capture this pattern one can expose the bare image sensor (without lens) of any camera to the reflected and scattered light.

When the surface is mechanically deformed, the imperfections are altered, causing the pattern to change as well. If the surface is translated under the laser light, the pattern appears to shift.

In this work, we exploit this phenomenon for high speed remote vibration sensing. Our approach exceeds the bandwidth limitations of camera-based vibration sensing by capturing speckle patterns with an array of discrete high-speed photo-detectors arranged in a 3x3 grid - essentially a discrete image sensor.

The novel discrete image sensor combines the advantages of remote, non-contact sensing with the ability to capture vibrations at a higher sampling rate than conventional cameras.

To implement this concept, we designed and built the analog photo-detectors on a custom printed circuit board (PCB).

The performance of the hardware was assessed in experiments using laser modules and a laser dot projector at 850 nm, with surface reflectivity being a critical factor in detection quality. A key finding was that multiple aligned laser sources could be used simultaneously without degrading the signal quality, enabling easier aiming from a distance.

Hardware design parameters like pixel size and sensitivity were empirically deduced by using a reference the Raspberry Pi™ HQ camera 12.3 MP (IR filter and objective lens removed) as a reference image sensor.

Detection of genuine speckle patterns was verified through comparative testing against non-coherent LED illumination, which produced no detectable vibration signal.

Our discrete sensor has a bandwidth of 1 kHz exceeding the maximum sampling rate of conventional cameras by an order of magnitude. Our sensor has a comparable sensitivity to the reference sensor.

Contributions

The work in this semester project makes the following contributions.

- High-bandwidth discrete sensor. Developed 1 kHz single-supply bandwidth sensor, surpassing conventional cameras by order of magnitude.
- Sensitivity optimization. Achieved comparable sensitivity to reference sensor while maintaining high bandwidth.

RELATED WORK

The work in this thesis is related to Laser Speckle Imaging, Laser Doppler Vibrometry and Laser Speckle Vibrometry.

Laser Speckle Imaging

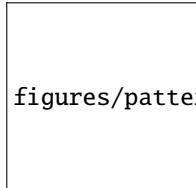
Laser speckle imaging analyses the interference patterns generated when coherent light from a laser, scatters off an optically rough surface. These "speckles" can be captured by any photosensitive surface - and most commonly - a camera image sensor. The mean speckle size is an important parameter, as the pixels of the image sensor must be smaller in order to resolve a pattern. The speckle size is a statistical property of the interference pattern and depends on the laser wavelength, sensor-to-surface distance and illuminated area. Cloud [?] defines the speckle size as "the center-to-center spacing of adjacent dark or adjacent light spots in the speckle pattern". It can be expressed approximately:

$$\text{Mean speckle size} \approx \lambda \cdot \frac{d}{a}$$

where:

- λ is the wavelength of the laser light,
- d is the distance from the scattering surface to the observation plane,
- a is the diameter or size of the illuminated area (e.g. laser spot area).

Hu et al. [?] show that the size of the speckle is not impacted by the structure of the laser beam. Using multiple lasers increases the illuminated area and reduces the speckle size.



`figures/pattern_laser_progression.png`

Speckle size can be tuned without changing d or a by de-focused imaging, proposed by Heikkinen and Schajer [?]. They use a de-focused telephoto lens to optically change d and show that the resulting speckle pattern is comparable if d was changed physically. The method has an additional advantage of sampling a larger speckle field and capturing more light, important for weaker signals.

Laser speckle imaging is simple to implement and does not require significant hardware, which motivates this semester project. Yan et al. [?] developed "LaserShoes," a system using a USB webcam and Raspberry Pi mounted on shoes to classify ground textures based on speckle patterns. They evaluated different laser wavelengths and achieved accurate surface recognition with a compact, low-cost system. Chan et al. [?] measured liquid characteristics (e.g., milk fat content) using smartphone LIDAR to image speckles, though many frames were needed due to the low power of the LIDAR laser.

Laser Doppler Vibrometry

Laser Doppler Vibrometry (LDV) measures an objects velocity by detecting the Doppler shift in the frequency of reflected

coherent light. The measurement setup required is more complex as it involves mixing the emitted and back scattered laser light to detect a beat frequency, which is proportional to the velocity [?]. LDV offers high precision and can measure large vibrations, but the complex setup makes it costly and challenging to scale. Speckle noise is a known limitation in LDV, caused by random phase shifts in scattered light due to surface roughness. Addressing this noise often requires advanced signal processing [?].

Laser Speckle Vibrometry

Laser Speckle Vibrometry detects vibrations from changes in the speckle pattern over time. Unlike LDV, it is much simpler, requiring only at least 1 photodiode or camera to capture intensity changes.

Veber et al. [?] used a single photodiode with a spatial mask and telephoto lens. Their system was able to measure vibrations at distances up to 50 m using a high power (1.5 W) laser. It detected oscillations of a sheet of paper exposed to sound pressure at 50 dB up to 5 kHz. On the other hand, Strelík et al. [?] demonstrated a camera-based method using a 200 FPS camera with laser pointer modules to detect finger taps on a surface. However, the limitations of camera frame rates restrict detection to lower frequencies.

Speckle vibrometry is effective for small-amplitude vibrations (including translation and pitch) but struggles with vibrations parallel to the laser beam (where LDV excels). Its simplicity and cost-effectiveness make it an attractive alternative to LDV for lower-cost applications.

IMPLEMENTATION

System Design

Backscattered photocurrents from lasers are typically very low in intensity. How low depends on the situation. A low noise and high gain first stage amplifier is necessary to achieve the required output signal. We gain intuition of the current required by measuring the induced photocurrent from the backscattered light of a laser pointer.

Camera Sensor Proof of Concept

A Thorlabs Amplified Photodiode is used as the detector and a Keithley High Precision Multimeter measures its output as in ??.

A typical store-bought class 1 red laser pointer has an output power under 0.5mW. Using this laser pointer we find that the amount of photocurrent produced by the masked (0.9mm x 0.9mm pinhole) photodiode is on the order of 1 nA. This means that we need to at least be able to measure currents on this order of magnitude.

The active area of the photodiode determines the capacitance but also the current sensitivity. The capacitance directly influences possible bandwidth. Ideally, we want a small photodiode area and we find this in the VEMD2704 with 1.5mm^2 active area.

We choose a 3x3 grid of photodiodes. We validate this choice by recording a video of the speckle pattern using a Raspberry

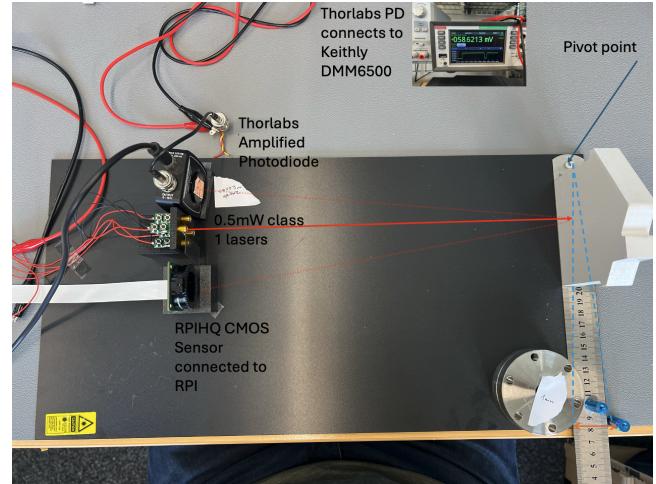


Figure 2. A laser is pointed at a painted wooden surface. A multimeter measured the current from a masked photodiode. A RPI HQ camera is used as a reference to visualise the speckle pattern).

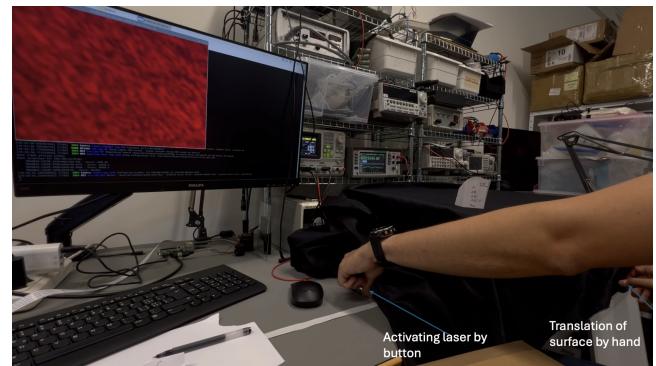


Figure 3. Speckle pattern visualised by RPI Cam HQ (from Setup in ??)

Pi HQ camera. In the video, the speckle pattern translates back and forth. The sensor area of the RPI Cam is large enough to accommodate 9 VEMD2704 photodiodes as in ???. Using this emulation we can process the 9 area's average pixel intensity and create a 1d signal (coarseness) ??.

Hardware Implementation

The system block diagram is given in ?? using the order of magnitude values devised in the emulation.

Photodiodes are commonly amplified using a transimpedance amplifier (TIA), although alternative options exist, such as current integrators like the DDC118. This application focuses on capturing high-frequency signals of up to 1 kHz, necessitating specific requirements for the operational amplifiers (op-amps) used.

The essential requirements for the op-amps include:

- A minimum of two op-amps in a single package.
- A target price of approximately \$5 per chip.
- JFET input with low input capacitance.
- Capability to operate on a single power supply.

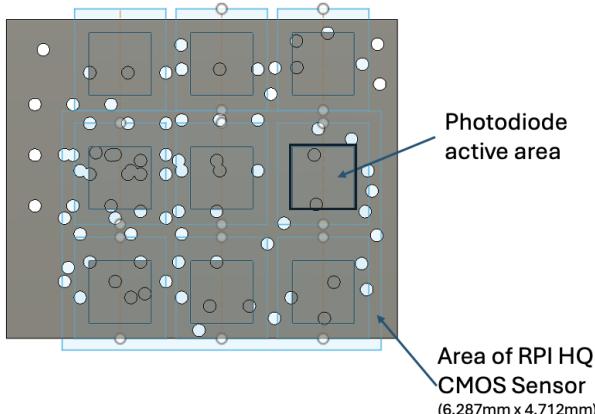


Figure 4. Emulated array for validation.



Figure 5. Emulation captures translations of the speckle

The OPA2380 fulfilled these requirements and a PCB was designed and built according to the datasheet recommendations. Particular attention to leakage currents was taken, like the implementation of a guard ring. The guard ring is a low impedance path for any stray AC that might want to make its way into the feedback path of the amp. The PCB is shown in ?? and contains a modular photodiode array with bandpass filter.

The bandpass filter is chosen to be at 850nm as that is where silicon photodiodes are most efficient. Lasers are 850nm are common and we are able to filter out a lot of environmental light.

Signal Processing

In this project, a Raspberry Pi 5 (RPI) was used with two types of Analog-to-Digital Converters (ADC).

The first ADC was unable to sample at high enough frequencies. Although it utilized a multiplexer (MUX), the channel switching was controlled via SPI, making it challenging to manage the switching delay. This limitation introduced a significant amount of noise, which was also noted in several GitHub issues reported by users.

A second ADC was then tested, featuring a higher sample rate and advertised synchronous sample readout capability. This ADC is designed as a Raspberry Pi HAT and uses the Pi's 5V supply as its analog reference. However, this reference is very noisy, with peak-to-peak noise in the millivolt range. To mitigate this issue, a bench power supply was used to power the ADC externally.

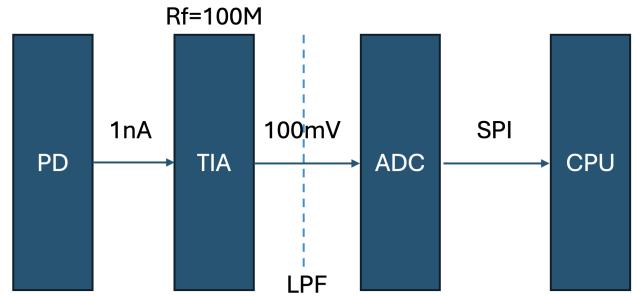


Figure 6. Block diagram

Raw data from the ADC was recorded and observed in real-time or processed post-capture. Real-time observations were conducted while simultaneously monitoring the speckle camera and the infrared (IR) camera.

EVALUATION

Hypotheses

The primary hypothesis is that the motion of speckle patterns can be effectively visualized using a photodiode array. Additionally, it is hypothesized that the use of multiple lasers will influence the signal-to-noise ratio (SNR) of the measurements.

Apparatus

In setting up the evaluation, crucial parameters were carefully selected based on the technology utilized. The experimental setup involved the identification of dependent variables, with the use of a precision vibration table to facilitate controlled testing conditions.

Procedure

The experimental procedure was designed to validate the performance of the printed circuit board (PCB) using a combination of detectors and lasers. We employed SPICE simulations to observe the Bode plot and transient response of the system, as illustrated in Figures ?? and ?? . The independent variables and experiment duration were rigorously controlled, with all measurements conducted in a light-controlled environment to mitigate external light interference. A comparative analysis was performed on the time-domain signals captured by multiple photodiodes. An infrared (IR) LED was incorporated to validate the hypothesis by ensuring that observed vibrations were not merely due to light interference.

RESULTS

By aiming the laser beam at the oscillating surface sequentially, multiple vibration sources could be sampled and distinguished from each other within the same environment. *In this section, you report the results of your evaluation and your work in a structured manner. In addition to raw values, charts, graphs, tables, use aggregates and statistical methods to evaluate the statistical significance of your results.*

Note: Even though you report your results in this section, refrain from judging them at this point. Although this section should be independent of your judgment, it should not be a mere dump of values. Define subsections when appropriate and try to tell a story using these numbers.

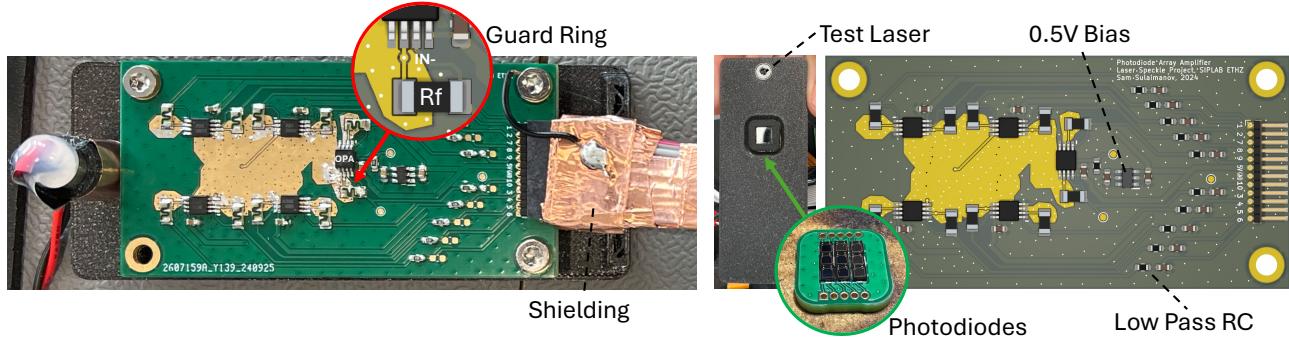


Figure 7. maxwidth cap



Figure 8. Photo of the standard experimental configuration.

DISCUSSION

What was surprising? unexpected? intriguing?

Were any hypotheses confirmed or rejected?

Were the predictions of any theory upheld or refuted?

What is important and worthy of again being called to the reader's attention?

What are the implications of your results?

What do they mean for this topic and your field?

Did you fulfill the promises you set out in the Introduction via the claims you made about your work?

What worked and what did not work?

CONCLUSION

research question answer: it is possible to detect a speckle pattern in motion using a discrete photodiode array

limitations: - in sunlight, the opamp saturates and the signal is unrecoverable - Bandwidth should be increased for

Future work

- use an opamp with higher GBW for higher Bandwidth - use a current to digital amplifier chip like the DDC118 for higher

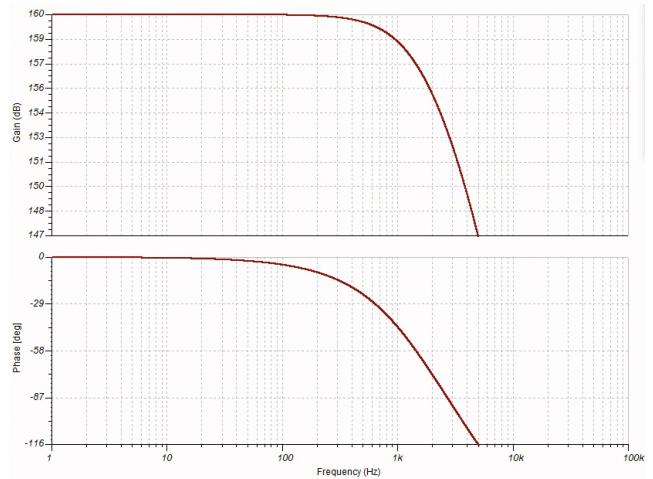


Figure 9. The Bode plot demonstrates the frequency response of the evaluated circuit.

integration - subtract the vibrations of the sensor itself using an accelerometer

ACKNOWLEDGMENTS

Optional space to thank people. If you include this section, make sure to mention people you collaborated with.

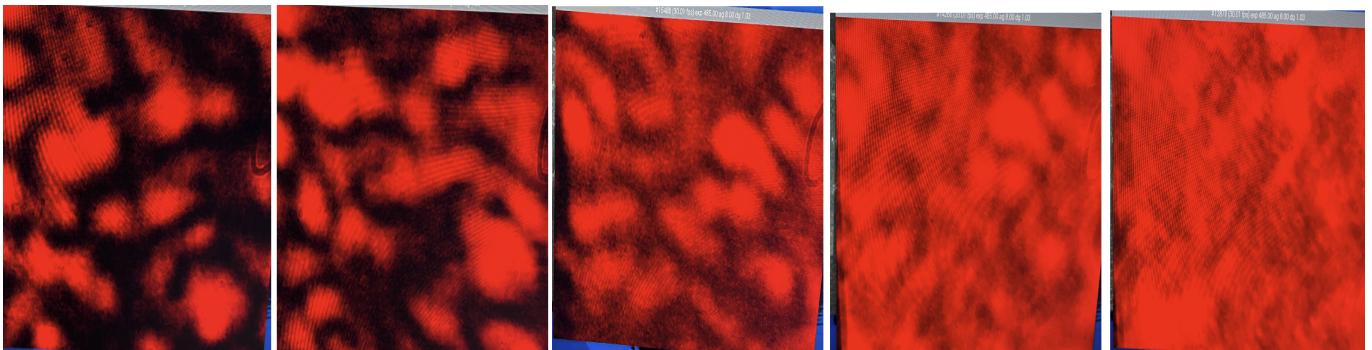


Figure 11. Visualization of speckle patterns under different laser configurations.

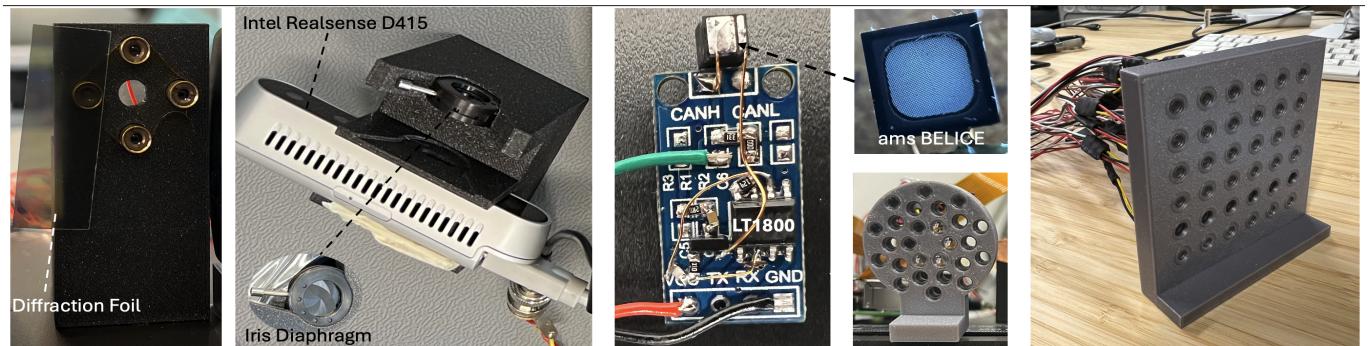


Figure 12. Impact of multiple laser sources on SNR in the experimental setup.

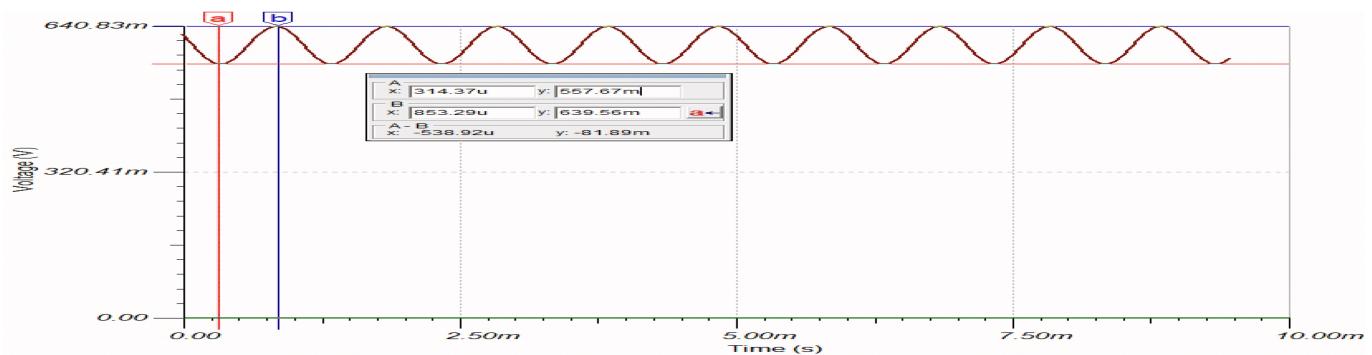


Figure 13. Transient response captured during SPICE simulation, highlighting system dynamics.

