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Department of Computer Science, ETH Zürich

Semester Project

Discrete Photodetector Array Approach to High-Bandwidth Vibration Sensing

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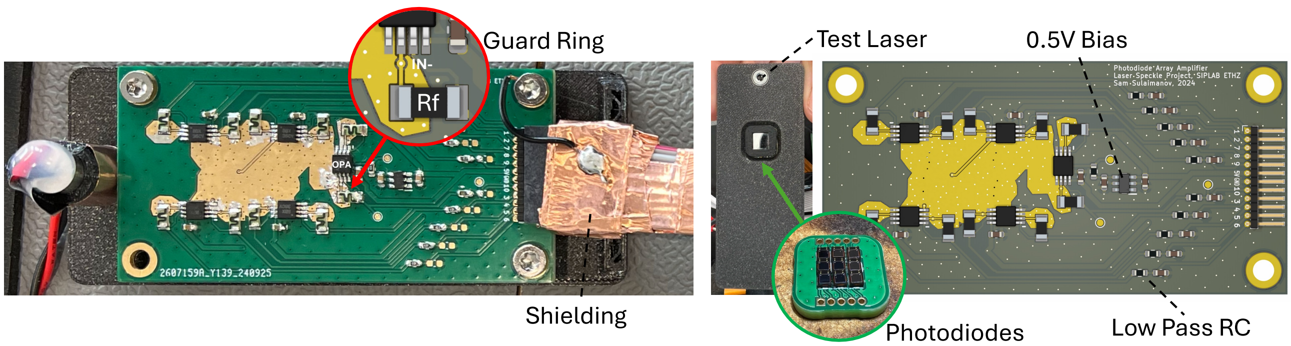

Figure 1. Left: the final assembled discrete photodetector in a test housing. Middle: Front view of the detector with IR bandpass filter. Right: Rendered PCB.

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 [3].

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 [6] 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 [2] 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. [5] 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. 13

Speckle size can be tuned without changing d or a by de-focused imaging, proposed by Heikkinen and Schajer [4]. 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. [10] 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. [1] 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 if proportional to the velocity [7]. 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 [7].

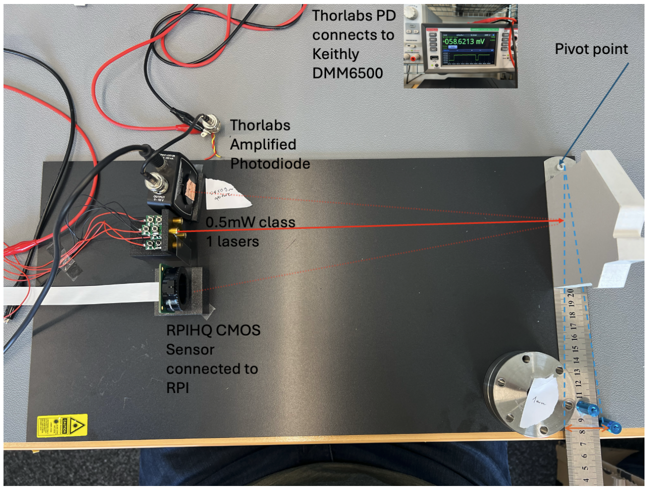

Figure 2. A laser is pointed at a painted wooden surface. A multimeter measured the current from a masked photodiode. A RPI HQ camera is used as a reference to visualise the speckle pattern.

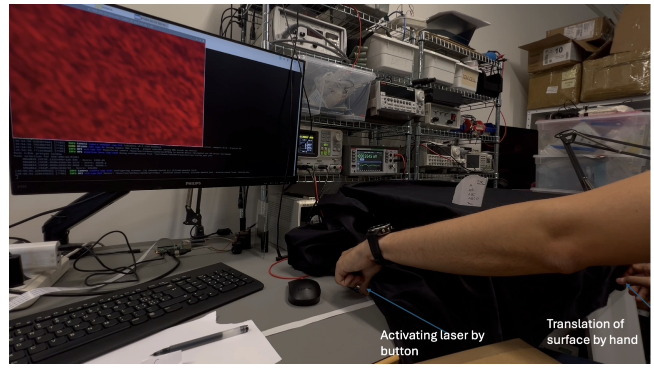

Figure 3. Speckle pattern visualised by RPI Cam HQ (from Setup in 2)

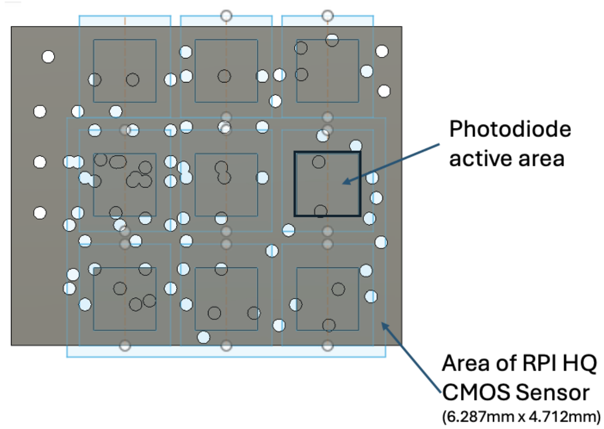

Figure 4. Emulated array for validation.

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. [9] 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, Streli et al. [8] 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 3.

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 $1.5\,\mathrm{mm}^2$.

We choose a 3x3 grid of photodiodes. We validate this choice by recording a video of the speckle pattern using a Raspberry Pi HQ camera. In the video, the speckle pattern translates back and forth. The sensor area of the RPI Cam is large enough to accomodate 9 VEMD2704 photodiodes as in 4. Using this emulation we can process the 9 area's average pixel intensity and create a 1d signal (coarsensess) 6.

Hardware Implementation

The system block system block diagram is given in 5 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.

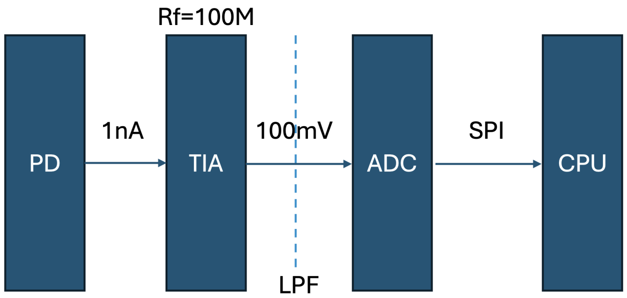

Figure 5. Block diagram

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.

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.

To convert the 9-channel photodiode array readings into a single vibrometry signal, we compute the inter-channel variance. First, we remove common-mode fluctuations by subtracting the instantaneous mean across all channels:

$$s_i(t) = r_i(t) - \frac{1}{n}\sum_{k=1}^{n} r_k(t) \tag{1}$$

where $r_i(t)$ is the raw intensity reading from channel i and $n = 9$ is the number of channels. We then compute the inter-channel variance:

$$V(t) = \frac{2}{n(n-1)}\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} |s_i(t) - s_j(t)| \tag{2}$$

This metric quantifies the average magnitude of pairwise intensity differences between spatial channels in the instantaneous speckle pattern. Changes in $V(t)$ over time indicate surface motion and vibration while being robust to common-mode noise.

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

The custom-designed PCB transmitted its analog signals to an 8-channel Digilent ADC MCC 128 DAQ Hat, which was powered by a 5V low-noise bench power supply. A piezo disc, positioned at a distance of approximately 30 cm, was excited using a signal generator set to produce a sine wave at 133 Hz with a peak-to-peak amplitude of 3 V. All lasers utilized in the setup operated at a wavelength of 850 nm.

For visual alignment of the lasers, one camera was employed, while another camera was used to monitor the presence of speckles. Both the cameras and the photodiode array were equipped with 8 × 8 × 1 mm bandpass filters at 850 nm with a 40 nm FWHM and a 90% transmission rate (manufacturer: Haian Subei Optical Glass Factory). Data acquisition was handled by a Raspberry Pi, which recorded the ADC data. Data processing was performed in real time during qualitative experiments or recorded for later post-processing.

Procedure

The initial steps of the evaluation involved SPICE simulations to analyze the Bode plot and transient response of the amplifier, as illustrated in Figures 9 and 8. These simulations provided the theoretical SNR and total noise values (Figures 10 and 11), demonstrating that the amplifier displayed stable behavior with high gain. Based on these results, the PCB was constructed.

Following the PCB assembly, it was meticulously cleaned using isopropyl alcohol (IPA) and compressed air, particularly

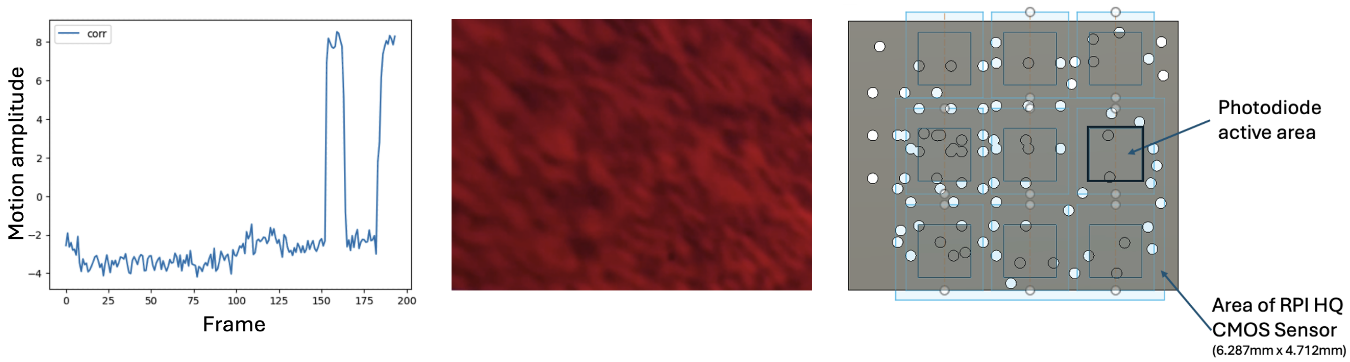

Figure 6. Emulation captures translations of the speckle. Peaks show motion.

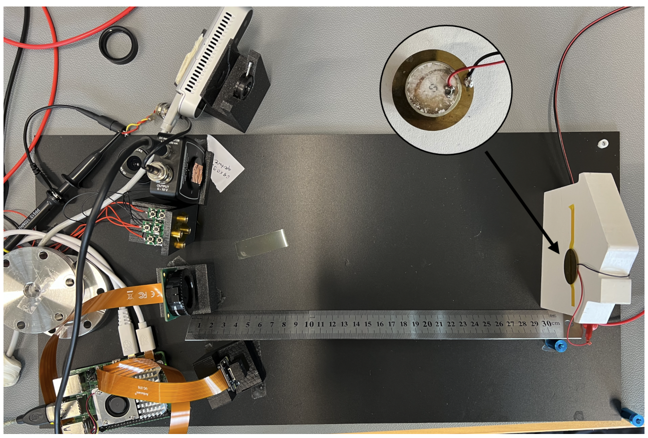

Figure 7. Photo of the experimental configuration with the piezo disc.

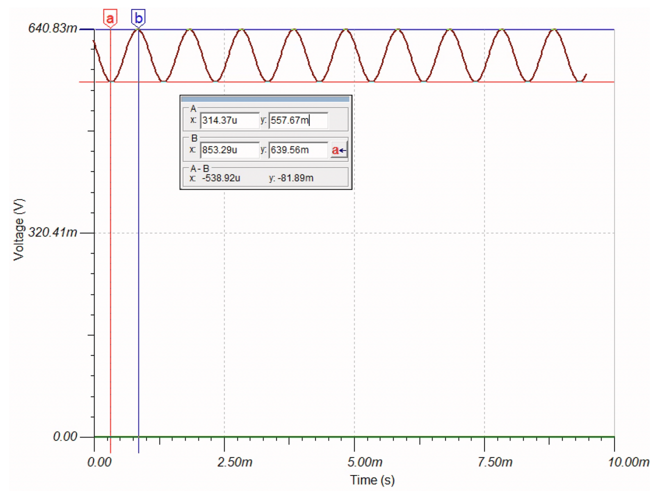

Figure 8. Transient response captured during SPICE simulation, highlighting amplifier dynamics and stability.

under the pads of the amplifier section. Removing all flux residue from the PCB was deemed critical to ensure accurate operation. All measurements were conducted in a light-controlled environment to minimize interference from external light sources.

To assess the influence of multiple laser sources, a controlled surface vibration of the piezo disc at 133 Hz was measured while lasers in the square array were activated incrementally (Figure 14). For each configuration, the power spectral density of the inter-channel variance signal was calculated, and the SNR was analyzed. The spectral analysis, shown in Figure 15, established a positive correlation ($R^2 = 0.60$) between the number of active lasers and the detection SNR. A control measurement with all lasers switched off confirmed that the recorded signals originated from laser speckle patterns.

Additionally, time-domain signals captured by multiple photodiodes were compared to verify that each photodiode detected phase-shifted signals, which indicated the presence of a moving speckle pattern. An infrared (IR) LED was integrated into the setup to validate that the observed vibrations were dependent on coherent light.

RESULTS

Speckle Motion Detection

The results confirmed that the motion of speckle patterns was successfully detected using the discrete photodiode array. Phase-shifted signals were observed across multiple photodiodes, indicating the presence of a moving speckle pattern. This phase information confirmed that the photodiode array could effectively visualize the dynamic speckle motion. The use of an IR LED further validated that the detected signals originated from laser speckle patterns and not from external light interference.

Signal-to-Noise Ratio (SNR) Analysis

The SNR analysis demonstrated a positive correlation between the number of active lasers in the square array and the measurement quality. Incremental activation of the lasers resulted in an improvement in SNR, as shown in Figure 15. The power spectral density analysis highlighted the 133 Hz vibration component of the piezo disc, with an R^2 value of 0.60 indicating a moderately strong relationship between the number of lasers and SNR enhancement.

Control experiments with all lasers turned off verified that the observed signals originated from the laser speckle patterns and

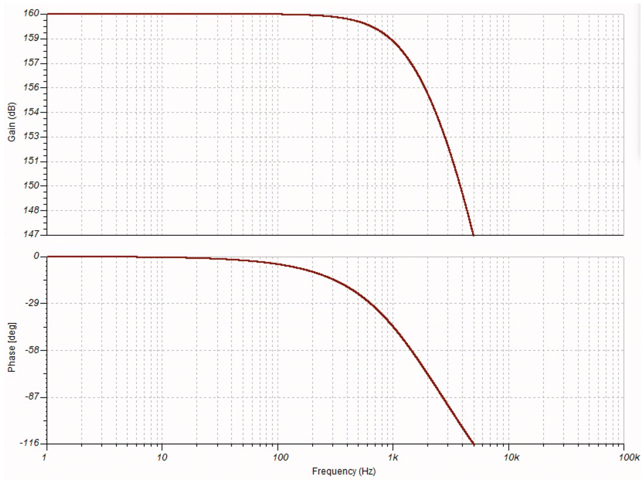

Figure 9. Amplifier frequency and phase response.

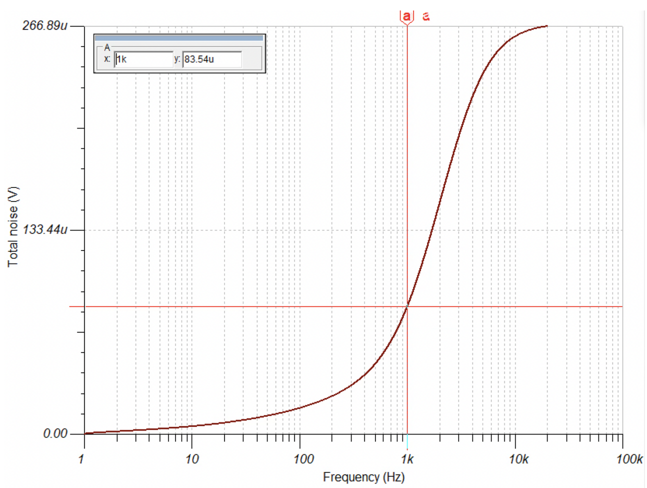

Figure 10. Total noise of the amplifier vs frequency.

not from other sources. These results support the hypothesis that the use of multiple lasers enhances the SNR, improving the sensitivity of the system.

Circuit Performance

The custom-designed PCB and amplifier circuit were validated using SPICE simulations and experimental measurements. The Bode plot in Figure 9 demonstrated a stable frequency response with high gain, while the transient response shown in Figure 8 confirmed system stability. Noise measurements (Figure 10) indicated a low total noise level, making the circuit suitable for laser speckle detection.

Impact of Experimental Parameters

The experiments revealed several critical factors impacting the measurement results. The PCB required thorough cleaning with IPA and compressed air to eliminate flux residue, as any remaining contaminants introduced noise. Additionally, conducting experiments in a light-controlled environment was essential to prevent saturation of the opamp and ensure reliable data capture. Dot projector alignment, facilitated by cameras, is critical for ensuring consistent speckle patterns and uniform distribution across the photodiode array.

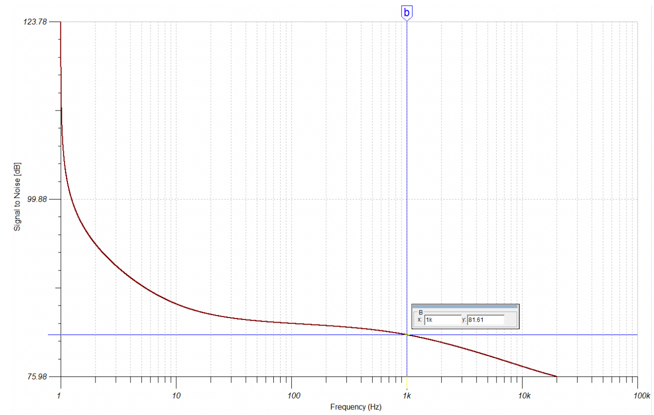

Figure 11. SNR for an output value of approximately 80 mV (corresponding to a 1 nA photocurrent at 1000 kHz).

Figure 12. Setup of the photodiode array used for detection.

Limitations

The opamp saturated in sunlight, rendering the signal irrecoverable in such conditions. Dot projectors cannot be effectively used as the reflected light is too weak. Furthermore, the bandwidth of the system is limited to 1kHz.

Future Work

To address the identified limitations and improve the system, several avenues for future work are proposed:

- **Higher Bandwidth**: Replace the current opamp with one that has a higher gain-bandwidth product (GBW) to increase the system bandwidth and enable detection of faster speckle movements.
- **Current to Digital Amp**: Integrate a current-to-digital amplifier chip, such as the DDC118, to enhance system integration and make the PCB smaller.
- **Sensor Vibration Compensation**: Mitigate the influence of vibrations from the sensor itself by incorporating an

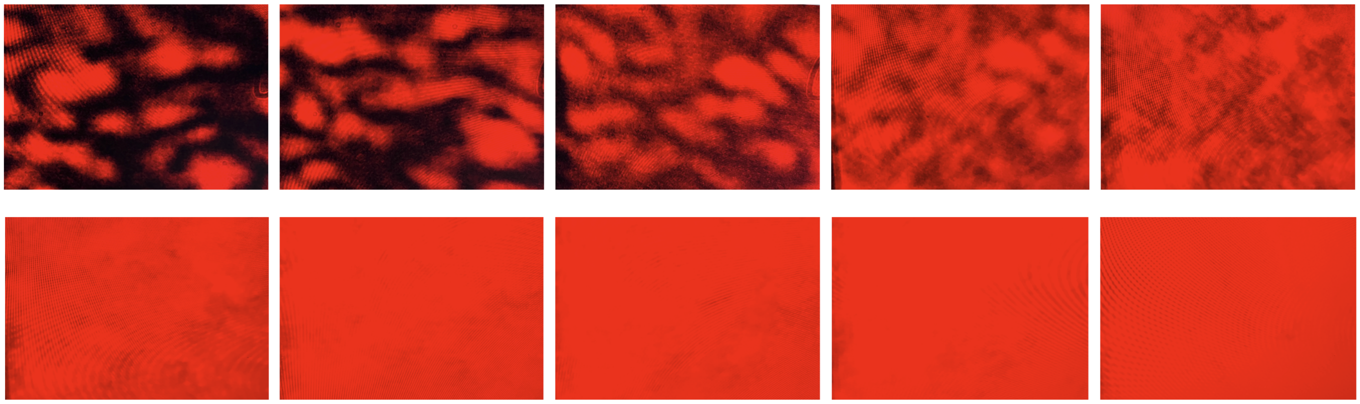

Figure 13. Visualization of speckle patterns under different 1 mW IR laser configurations using the square laser array from Figure 14. Top left: 1 laser. Bottom right: 10 lasers.

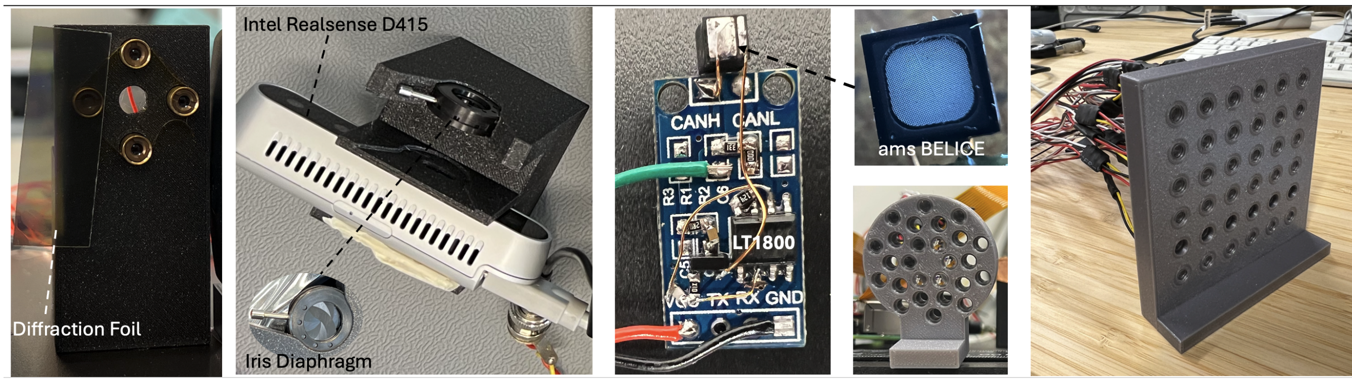

Figure 14. The different laser setups used from left to right: Red laser for initial emulation experiments, Realsense 415 dot projector with iris, reverse engineered Realsense dot projector and driver circuit, discrete circular and square IR laser arrays.

accelerometer to subtract self-induced motion artifacts from the measurements.

- **Synchrous Detection**: Modulate the laser light with a known reference signal to perform synchronous detection (aka lock-in amplifier) for more robustness against daylight.

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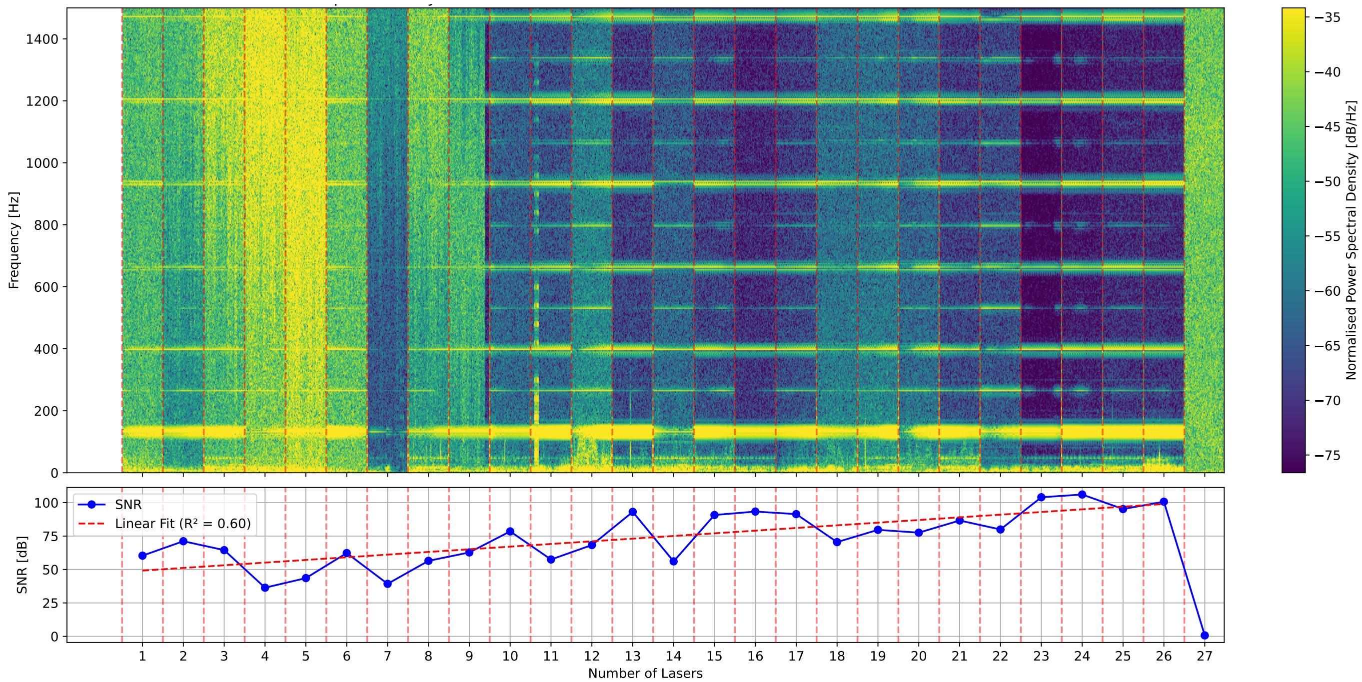

Figure 15. Spectral analysis of a 133 Hz surface vibration under different laser configurations. Top: Power spectral density showing the target frequency component. Bottom: SNR improvement with increasing number of active lasers.

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