Preliminary Scans of LIGO Quadrature Photodiode

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We aim to create a detection map of the FCI-InGaAs-Q3000 quadrature photodiode which is in use in the BOSEM assemblies in the LIGO Hanford and LIGO Livingston facilities. These photodiodes have so far been assumed to have perfectly uniform response across their surface within a certain percentage of error. Findings detailed below suggest that this may not be the case.

1 Introduction

To achieve the necessary levels of sensitivity required for the detection of gravitational waves, gravitational wave detectors require an incredible level of positional precision for their optics. For the current detectors in LIGO Livingston and LIGO Hanford, these tolerances are on the order of 10^{-13}m.[1] For future detectors like Einstein Telescope or Cosmic Explorer, it is likely that we will require even more precision.

A multitude of devices go into making sure that this level of positional stability is reached. The end test masses in LIGO use a series of four vertical pendulums for seismic isolation, and other optics use between two and four pendulum systems as well. Einstein Telescope is expected to have up to six pendulum systems. In LIGO, these pendulums have a system in place to actively stabilize after disturbances. A number of systems go into this active stabilization. One involves an accelerometer attached to a servo motor which is meant to actively correct and disturbance.

The detector we are concerned with involves a system where an LED points towards a photodetector. This is interrupted simply by a partial barrier between the two. When any swinging occurs, the photodetector observes a changing amount of light from the LED as either more or less of the diode becomes visible.[2] The photodetector used is a FCI-InGaAs-Q3000 quadrature photodiode (QPD).[3] A QPD is a circular photodiode divided into four quadrants. Both the Livingston and Hanford facilities employ a few hundred of these QPDs to aid in stabilizing their optics. So far, these devices have worked fairly well. The facilities are able to operate at a sensitivity such that over 100 gravitational wave events have been detected thus far. However, mechanical noise in the detectors remains an issue for both current and future detectors. It is assumed that the QPDs in use function uniformly across their detecting surface. This paper presents preliminary results of the verification of whether or not this is actually the case. If this is not the case, the QPD would misinterpret its own dead spots as a change in position, and the mirror would be moved to an incorrect location. This is a source of mechanical noise, and it is a constant goal to reduce the mechanical noise of the instrument.

2 Methods

In this project we completed a 2D scan across the surface of the QPD. To do this, a 950nm SLD source was focused from 1.8mm down to ∼38µm with the QPD positioned within the beam waist. The beam is normal to the QPD, which is mounted on a 2-axis manual translation stage. Wire leads were soldered at one end to each channel of the QPD, and at the other end crossed a 51.7Ω resistor. A Keysight DAQ970 was used to measure the voltage difference across all four resistors. Using a standard power supply, a baseline current of 3V was applied across the QPD. The Keysight allows us to take measurements from all 4 channels separately.

Using both axes of the translation stage in tandem, we are able to move the QPD over a square grid. For the full scan, we chose the spacing of this grid to be 20μm. The procedure involved moving the stage to a location on the grid, taking a measurement from the Keysight, and putting that into a Python array. The array could then be graphed on a heat map, showing the gradient of voltage detection by the QPD. Note that the Keysight takes 3125 measurements over a half second period and calulates their average. This is the value imported into the array. One array was collected from each channel on the Keysight which corresponds to each quadrant of the QPD. A fifth array was created as the sum of corresponding elements of the four previously mentioned arrays. This array becomes the full scan shown below.

3 Results

The initial scan was unable to show the full surface of the QPD due to a slip in one of the translation stages. However, one quadrant was able to be fully profiled. This allowed for a few key finds. An important note is that the blue horizontal line is believed to be an error in data collection and not an artifact of the detector itself.

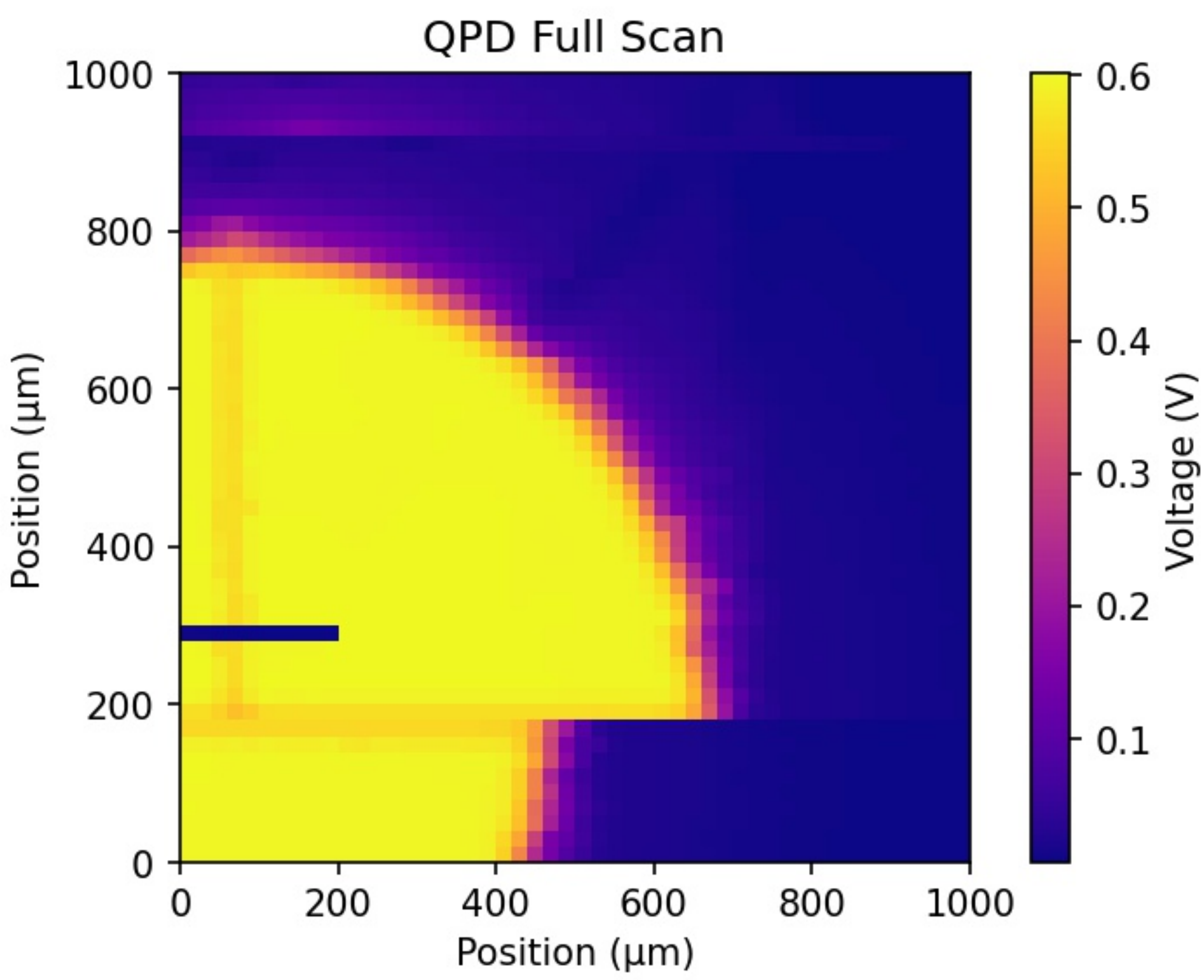

Figure 1: Attempted full scan of QPD surface

The first is that the primary detector surface of each quadrant of the QPD does not seem to have any aberrations larger than 50 micrometers. This was the assumed and expected result. Second, the crosshair has a dip in power at the 20-micron level, but not a full lack of voltage detected. This was expected as well. However, a further project should investigate the crosshair further and in finer detail.

The next point of notice in the image is the diagonal directed away from the photodiode surface. While it may be hard to see in the image, there is a small drop in voltage here. This is an interesting result as the outside of the photodetector should be perfectly uniform. However, we can see on the physical surface of the detector plate that there is a metallic line along this diagonal. This is discussed below in Section 3.1. The line is not well defined at this spacing and will require further research.

The final find is the most interesting. At roughly y=47, there is a noticeable voltage detection. This behavior is entirely unexpected, and the most likely artifact to affect accuracy of the actual stabilization systems. While this looks like an error, it is not. This is detailed further below.

3.1 Edge Scan

The off-detector voltage detection was observed to occur at the metallic border around the plastic surrounding the QPD surface. As the most unexpected feature of the wider scan, this feature had the most importance for a further examination. The two figures below show these localized scans.

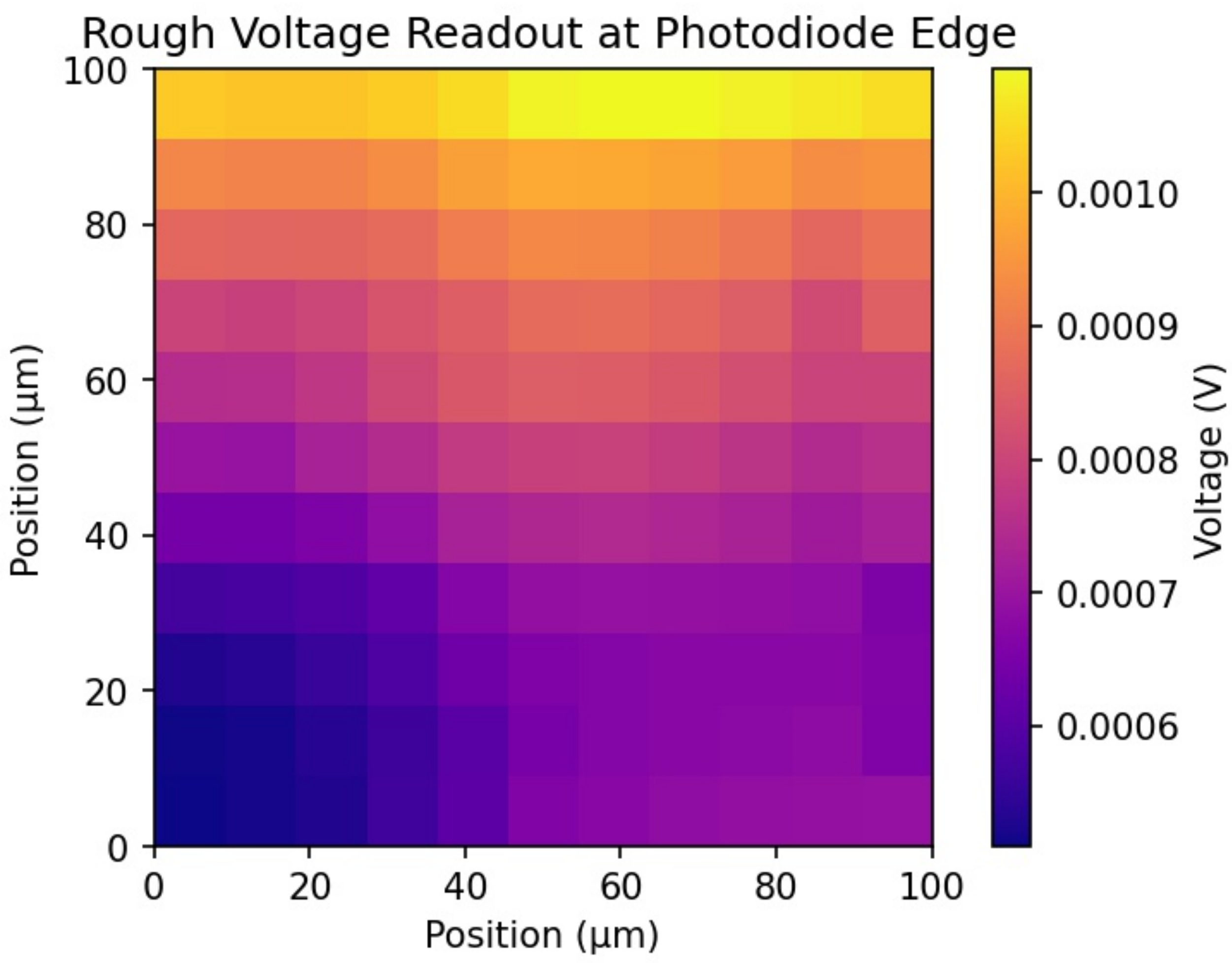

Figure 2: Rough voltage scan taken at bottom half of photodiode edge

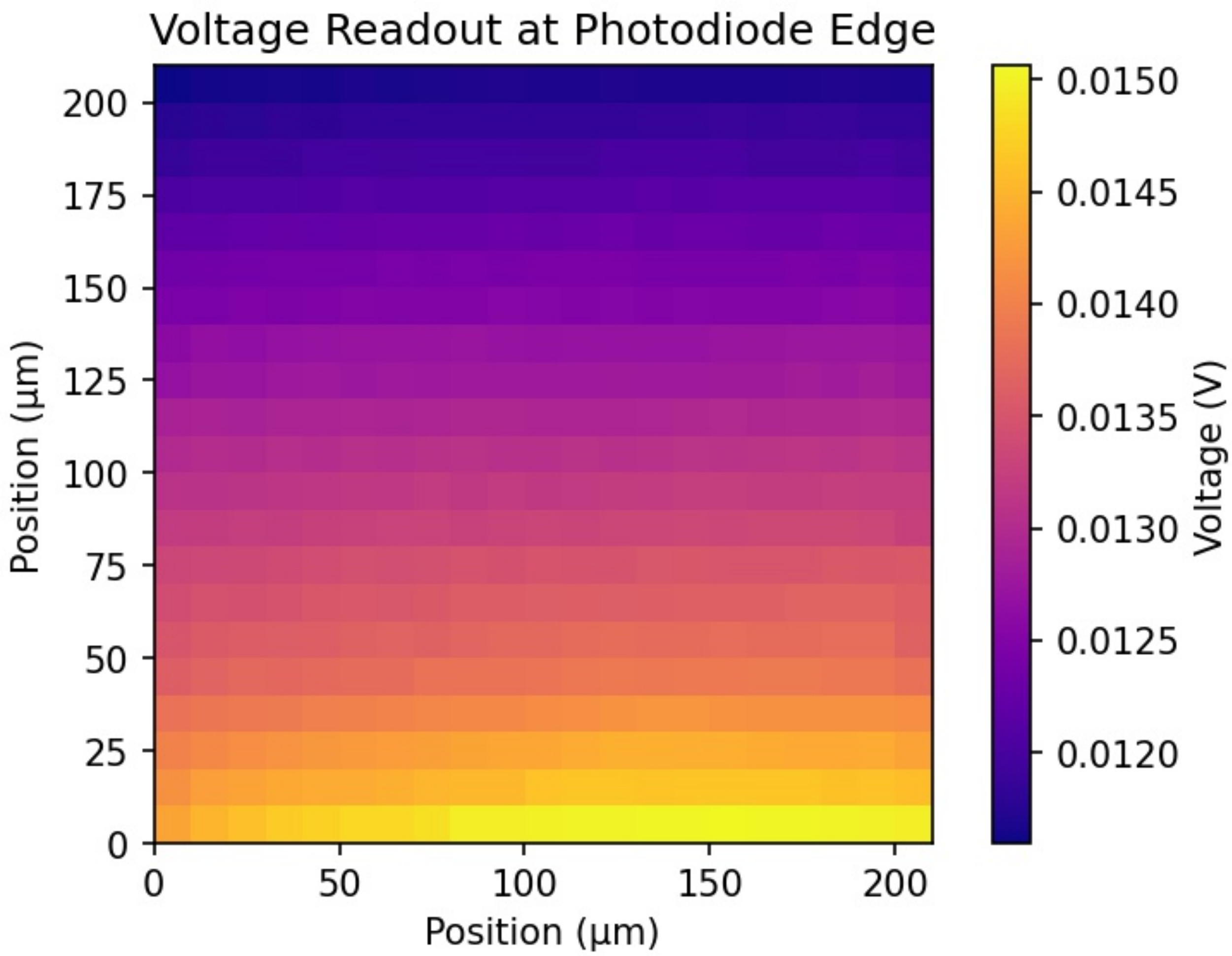

Figure 3: Voltage scan taken from top half of photodiode edge

The first scan shows the underside of this feature at 50-micron spacing, and the second scan shows the top side of the feature at 10-micron spacing. In the second scan, the maximum voltage is observed to be 0.015V. The maximum total power is 0.6V, so this represents roughly 2.5% of the maximum. This is certainly an appreciable amount, and significant enough to be noted, especially considering that this feature is not something that is expected to exist.

The exact reason for this area of detection is not known. One possibility is that the metallic surface reflects a small amount of light towards the photodetecting surface. This seems to be on a reasonable order of maximum power ($\sim$2.5%) as a reflection would cause only a small amount of the normal detection. However, this idea is contrasted by the behavior along the diagonal. Both the diagonal and the edge appear to be materially the same, so we would expect that if the edge reflects light towards the diode, that the diagonal would as well. However, not only is there not an increase in the detection along the diagonal, but there exists the reverse.

A second possibility is the photoelectric effect. It is possible that the electromagnetic radiation from the SLD is enough to excite electrons along this metal edge. The wire leads coming from the photodetector appear to make physical contact with this line, so it is possible that current is transferred in this way. If this is the cause, the discrepancy between the diagonal and the edge makes sense since the metal on the diagonal does not appear to contact the leads in the same way. There is an argument against this however, which is evidenced in the figures below:

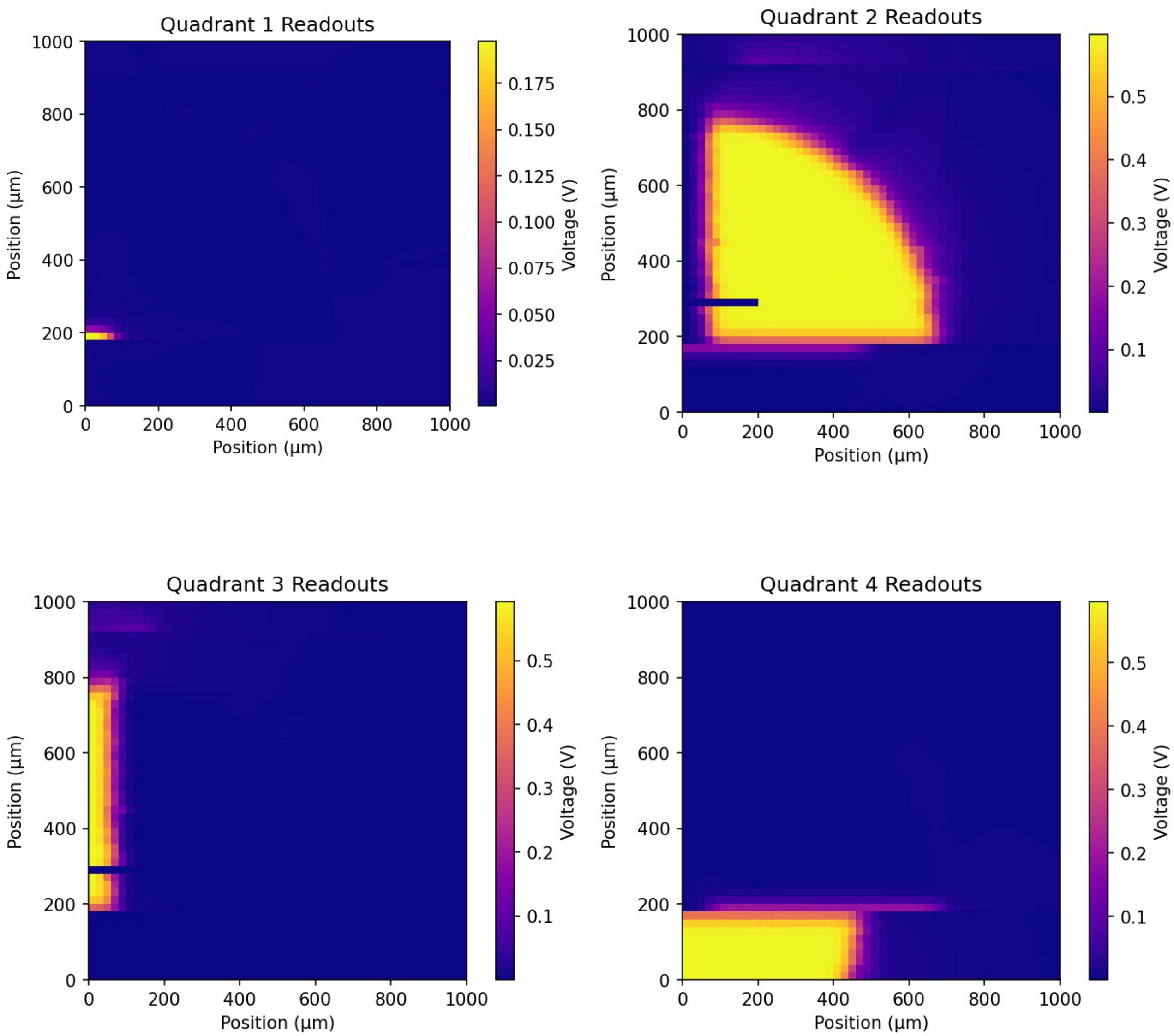

Figure 4: Voltage readouts from each of the four quadrants

If photoelectric effect were the cause, we would expect to see roughly similar readouts across all 4 channels. As evidenced above, this is not the case. Really only channel 2 shows current in this area, which would be more indicative that reflection is a more likely cause.

An interesting note here: quadrant 3 also has a small voltage detection in the neighboring region. However, we can see that the voltage detection at the edge for quadrants 2 and 3 does not align with the division on the QPD itself. Additionally, this isn't a symmetrical overlap. Even with the assumption of detection at the edge, we would expect one of two things. The first (and more likely option) is that the edge voltage should stop where the detector gap is, instead of crossing over to the other region. If reflection is the cause, then we would maybe expect that this would not be the caes and that there would be overlap. However, that leads us to our second expectation which is that if there is overlap, it should be symmetrical i.e. quadrant 3 detects some voltage in an edge region belonging to quadrant 2, and vice versa. We can see that this isn't the case either. Quadrant 3 detects some voltage in region 2, but quadrant 2 detects nothing in quadrant 3. Not only this, but it actually has a region in quadrant 2 where it does NOT detect, but quadrant 3 does. It is possible that if reflection is found to be the cause that the reflection is occurring at an angle, but it is impossible to say at this time.

Both possibilities have solid arguments against them and only loose arguments in their support. There isn't enough evidence to say that either one of these is the cause, and it definitely warrants a more in-depth look.

4 Future Work

This project has produced a few interesting finds that warrant looking further at this photodiode. Most projects of importance would require an automatic 2-stage system for precise and faster measurements. The Xeryon XLS1-40 series[4] would be an excellent choice due to its 100nm precision and incredible speed.

Firstly, a full scan of the QPD would be beneficial as there are possible even more interesting features that are not captured in this scan. As for the known issues, a higher resolution (preferably 20µm) scan of the central crosshairs would be one of the first priorities. We had previously known that there would be a dead zone here, and it is reflected in the scan. However, the exact shape of it is a bit fuzzy due to its small size. A higher resolution scan about the center of the QPD would be necessary to predict its behavior in this central region. The diagonal aberrations should be looked into as well. It is likely that these might disappear during a full scan, so it may be beneficial to scan only these areas. Finally, the edge voltage detection should be looked into further. The main concerns are whether it is uniform around the entire edge or only in certain parts, as well as looking into why this phenomenon occurs. Possibly a separate project involving a material analysis of the QPD would be beneficial to determine the cause of the voltage.

5 Conclusions

In terms of finding whether or not the LIGO photodetectors should be replaced for a different model, the project was inconclusive. We have found however a number of interesting features that were not expected to be displayed. Further study on these features using a piezo-electric stage with micrometer accuracy is warranted.

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