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# PPKTP Crystal Degradation Study: preliminary result

Nutsinee Kijbunchoo, Terry McRae, Sheon Chua, Peter Veitch, Daniel Sigg

**California Institute of Technology**
**LIGO Project, MS 100-36**
**Pasadena, CA 91125**
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

**Massachusetts Institute of Technology**
**LIGO Project, NW22-295**
**Cambridge, MA 02139**
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

**LIGO Hanford Observatory**
**PO Box 159**
**Richland, WA 99352**
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

**LIGO Livingston Observatory**
**19100 LIGO Lane**
**Livingston, LA 70754**
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

# Contents

# 1 Introduction

The current aLIGO squeezer cannot meet the A# requirement of 10dB of realized squeezing, operational stability, and duty cycle. One of the main causes of the degradation of the squeezer over time is gray tracking in the periodically poled potassium titanyl phosphate PPKTP crystals used in both SHG and OPO. Gray tracking is a well-known, but not well understood, phenomenon and has been shown to cause losses in both 532 nm and 1064 nm [1, 2, 3, 4]. The existence of $Ti^{3+}$ impurities within the crystal lattice is believed to create a trapped energy state inside the band gap between the covalent and the conduction bands. Another cause associated with PPKTP crystals is GRIIRA (Green-Induced Infrared Absorption), where infrared loss occurs in the presence of green light [5, 6]. In T2300424 Dhruva and Vicky have shown evidence of long-term green degradations in both LHO and LLO. Although direct evidence of infrared loss has not been shown, both sites had to adjust the positions of the OPO crystal several times between O3-O4 in order to recover the amount of squeezed vacuum. T2300424 is a useful review of the literature on gray tracking and GRIIRA in KTP. I recommend reading it before continuing with this document.

As LIGO expects to use PPKTP in A#, we propose to investigate the gray tracking and GRIIRA mechanism using the diagnostic setup shown in Figure.1.

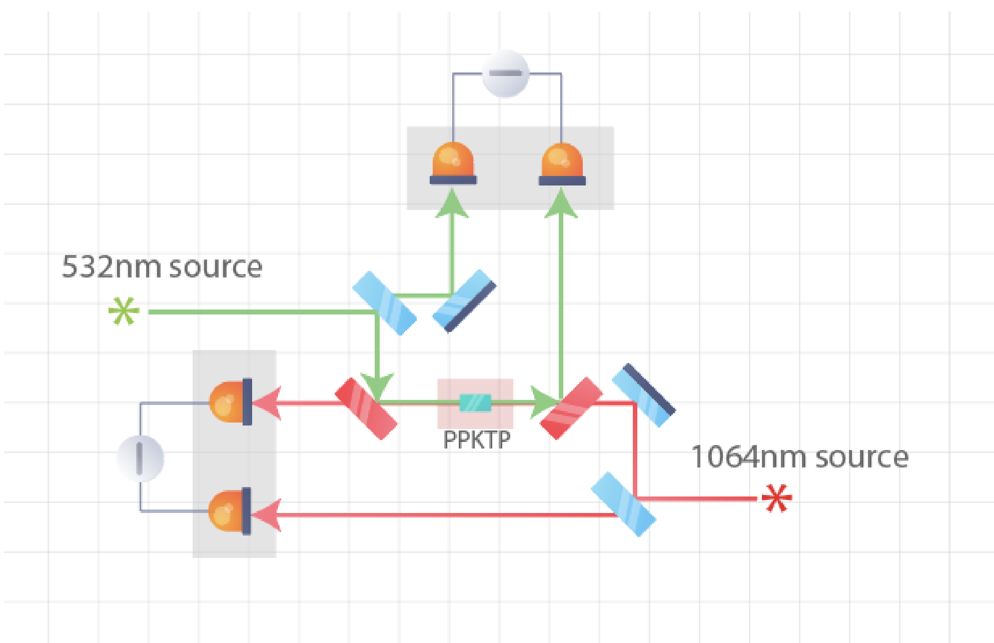


Figure 1: A simplified schematic of the PPKTP absorption experiment. The idea is to use a pump/probe technique to induce infrared loss using green light with an intensity equivalent to that inside the LIGO OPO. Counter-propagating the beam allows for easier separation between green and infrared light at the detectors.

Although the concept of using a probe and pump beam is not new (see [5]), co-propagating infrared and green beams outside the phase-matching temperature is. These preliminary results have no temperature control for the crystal. To our knowledge, we are also the first to utilize a balanced detector to enhance sensitivity in this context.

This project is part of the 2025 OzGrav Special Initiative and is a collaboration between the University of Adelaide and the Australian National University.

# 2 Experimental Layout

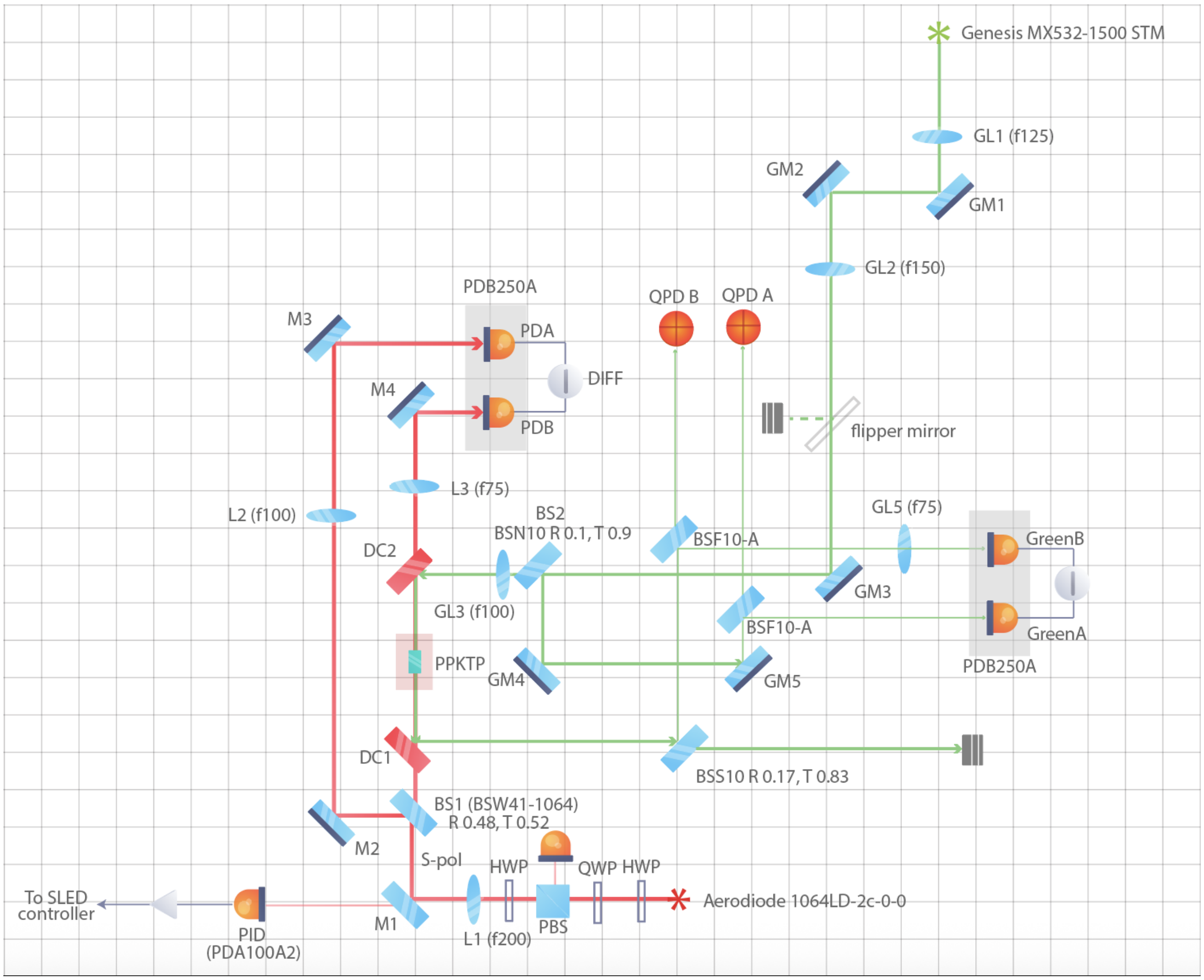


Figure 2: A detailed experimental layout as of July 14, 2025, drawn roughly to scale. Each square represents 2.5 cm of optical table spacing. The 1064 nm and 532 nm beams counter-propagate and are separated before and after the crystal using a dichroic mirror. Band-pass filters are installed in front of every photodiode (except the QPDs) to prevent cross-contamination between the infrared and green beams.

## 2.1 The setup

Figure.2 shows the experimental layout as of July 14, 2025. A single mode 532 nm laser that can go up to 1.5W in power (Genesis MX532-1500 STM) is used to pump the PPKTP crystal. To mimic the LIGO OPO circulating power condition, the beam waist at the crystal is designed to be $\sim$40$\mu$m. The power before the crystal is $\sim$800 mW. This gives an intensity of ~30 kW/cm$^2$. Compared to the circulating intensity of LHO O4 OPO of 25 kW/cm$^2$ and the LLO OPO intensity of 44 kW/cm$^2$ [7] (note that in this document the intensity calculation is missing a factor of 2). Recall:

$$I_0 = \frac{2P_0}{\pi\omega_0^2} \tag{1}$$

The 1064 beam waist at the crystal is ~70 $\mu$m. The nominal operating power is 1 mW through the crystal (2 mW before the beam splitter). Since we only use 1064 as a probe, the waist size does not need to be precise. Ideally, the beam should be large enough to interact with any gray track left behind by the 532 nm beam during the measurement.

We used a PDB250A balanced detector to enhance the sensitivity in both the infrared and green paths. The 'signal' diode detects changes caused by the PPKTP crystal, while the 'reference' diode remains unaffected. On the infrared path, we are able to detect differences as small as 0.1 $\mu$W between the signal and reference when the PID loop is engaged.

The QPDs, on loan from ANU, were recently introduced to investigate the possibility that the green beam deflects as the crystal heats up. We suspect this may be the cause of SHG output power variations observed at LHO—and likely at LLO as well. The QPDs have also proven useful for restoring alignment when inserting or removing the Rochon prism to change the green polarization.

The 1064 source is a fiber SLED and is a mix of s- and p-polarization. To ensure that mostly s-polarized light passes through, a half-wave plate, a quarter-wave plate, and a polarizing beam splitter (PBS) were installed. First, we optimize transmission through the PBS using p-polarization. Then, another half-wave plate is used to rotate the polarization back to s-polarization.

The green laser is composed of mostly s-pol and its power can be controlled remotely from outside the lab. When the green laser is turned on, it still emits an idle power of 0.5 mW even when the requested power is set to 0 mW. To fully block the green light when needed, we installed a flipper mirror in the beam path.

### 2.2 Controller

We used a Moku:Lab PID instrument to stabilize the laser output. The signal from the PID diode (located at the bottom left of Figure.2) was sent to the Moku PID input (In1), as shown in Figure.3. The controller was configured as a simple 1/f integrator with an upper frequency gain (UFG) around 25Hz. Since we did not have access to an SR785 and the Moku spectral analyzer is slow at low frequencies, minimal effort was put into optimizing the control loop shape. Further improvements could have been made in the 100 Hz to 1 kHz range. The output of the Moku PID was connected to a Thorlabs LDC220C diode controller. Measurements were recorded using a Keysight DAQ970A. The SLED was mounted on a butterfly mount and temperature-controlled using a Thorlabs TED200C.

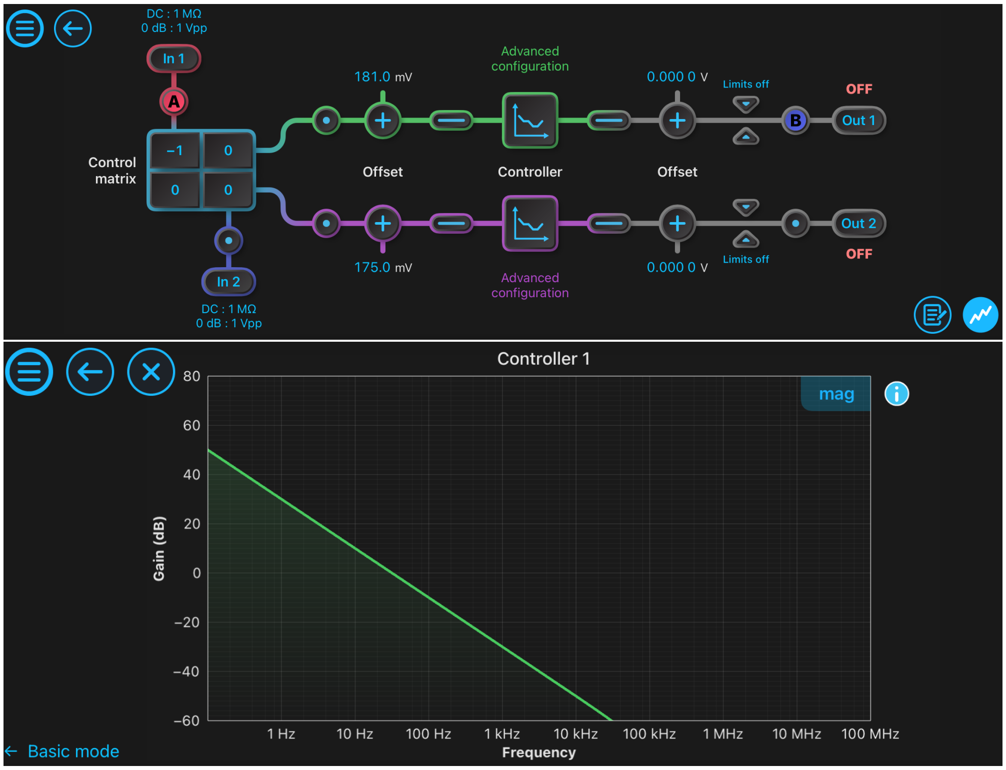


Figure 3: Top: Moku PID interface. Bottom: An integrator

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### 2.3 PPKTP crystal

We have been using ANU preloved crystal to test the set up. This crystal is known to have poor nonlinear gain. Measurements through the crystal in multiple places have given a nonlinear gain of approximately 2 under conditions where a value of at least 10 would have been expected. The dimension is 1mm x 5mm x 11.2mm with a 1.15 degree wedge. See T1500350 for more details.

## 3 Preliminary result

### 3.1 Gray Track

Figure 5 shows some of the green degradations observed over the course of this experiment. The exponential decay is consistent with the gray tracking behavior reported in [4] and [8]. With this crystal, we started seeing the gray-tracking behavior at 300 W/cm$^2$ (7.5 mW, 40 $\mu$m waist at the crystal). To find out at what intensity the gray track starts to manifest, I recommend performing this experiment on a new crystal. This number would determine whether the green power in the OPO can be reduced enough to prevent gray-tracking.


Figure 4: A container of ANU preloved crystal. Note crystal was subsequently polished by Photon Laseroptik, with a wedge added to one end and then AR coated by Laseroptik.

### 3.2 GRIIRA

Figure 6a shows the differential infrared output overlaid on the green transmission. The infrared output decreases as the green beam is turned on, and recovers once the green is turned off. The total power incident on the balanced detector was 2 mW. The change in the differential (DIFF) readout with and without the green beam was 0.5 $\mu$W. This corresponds to a 1064 nm loss due to GRIIRA in the ANU crystal of 0.025%.

Figure 6b focuses in around the time the infrared output recovered as green light was turned off. An exponential fit suggests a time constant of 0.16 seconds. Figure 6c shows the data collected from PDA and PDB separately. The dip only presents in PDB data, which confirms that the observed GRIIRA was real.

### 3.3 Annealing with 1064

Figure 8a shows the green power transmission through the crystal over a 10-hour period on May 9, 2025. The intensity at the crystal is $\approx 30kW/cm^2$. The green beam was cycled on for 20 minutes and off for two hours to test whether the crystal exhibited any signs of self-annealing. No measurements were taken during the 3rd and 6th hours. During the 6th hour is when we observed GRIIRA for the first time, coincides with the significant drop in green power. Figure 8b plot shows a measurement taken six days later, indicating that even after a week at room temperature the crystal exhibited no signs of self-annealing. Finally, figure7c shows the green power recovering to nearly 1.2 V after 50 hours of continuous exposure to 60 mW of 1064 nm light with no exposjure to green light.

This experiment has only been performed once, so more evidence is needed before conclusions can be drawn.

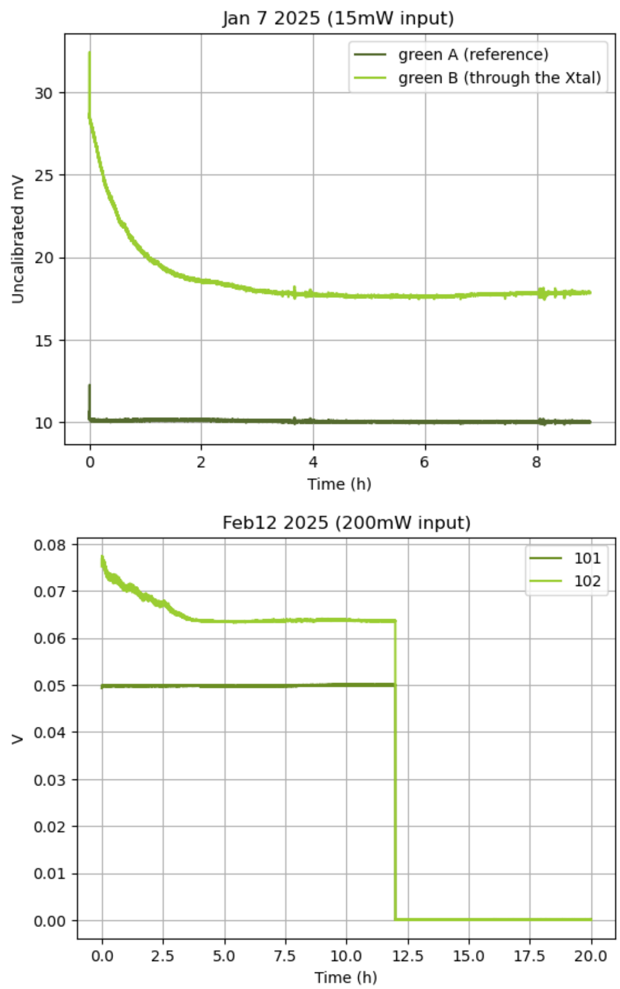
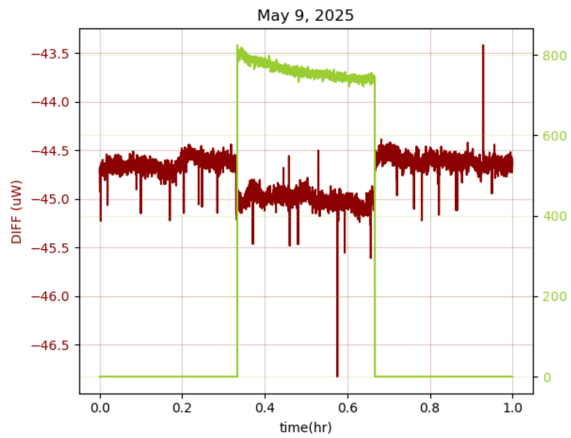



Figure 5: A couple of examples where gray-track were observed on different days. Light green trace measures the 532nm power through the crystal while dark green serves as a reference. The y-axes are uncalibrated mV and V. The 'input' power is an estimated power before the crystal. 15 mW and 200 mW at 40$\mu$m beam waist ($w_0$) correspond to 600 W/cm$^2$ and 8 kW/cm$^2$ intensity. At the time of these measurements the diodes DET36A2 were used. Ignore the inconsistent plot labels. Green A and Green V is what I should have called them. 101 and 102 correspond to DAC channel used at the time.

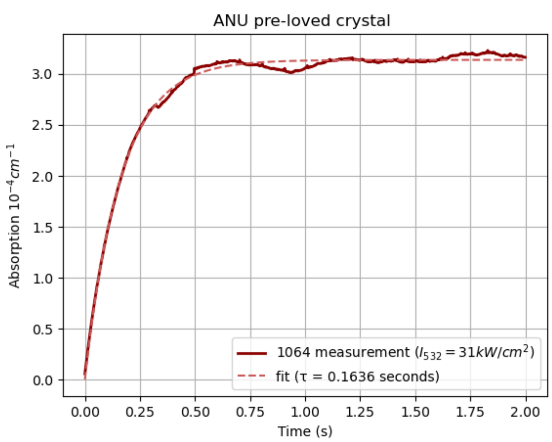
### 3.4 Running on p-pol 532

The idea is to test whether GRIIRA is truly associated with material energy traps; if so, polarization should not matter. To change the green polarization with minimal disruption to the setup, we installed a Rochon prism and a half-wave plate at the beginning of the green path.

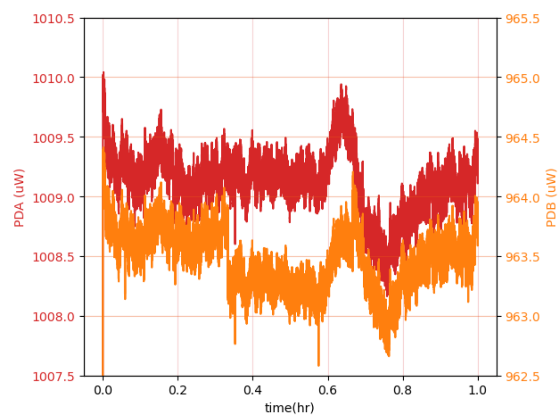
Unfortunately, there wasn't enough time to collect sufficient data to confirm whether GRIIRA occurs in p-polarization. After a week of alignment adjustments, I was unable to observe any evidence of GRIIRA. If this result is confirmed, it would suggest that the origin of GRIIRA lies in the nonlinear conversion process rather than the impurities within the PPKTP crystal. To investigate this further, one should first observe GRIIRA in s polarization and




(a) The differential 1064 output is overlaid on the 532 transmission. The 1064 signal is calibrated and low-pass filtered for clarity, while the 532 signal is uncalibrated..




(b) Zoom-in around the time when the 1064 signal recovered. The plot is comparable to Fig. 2 of [5].



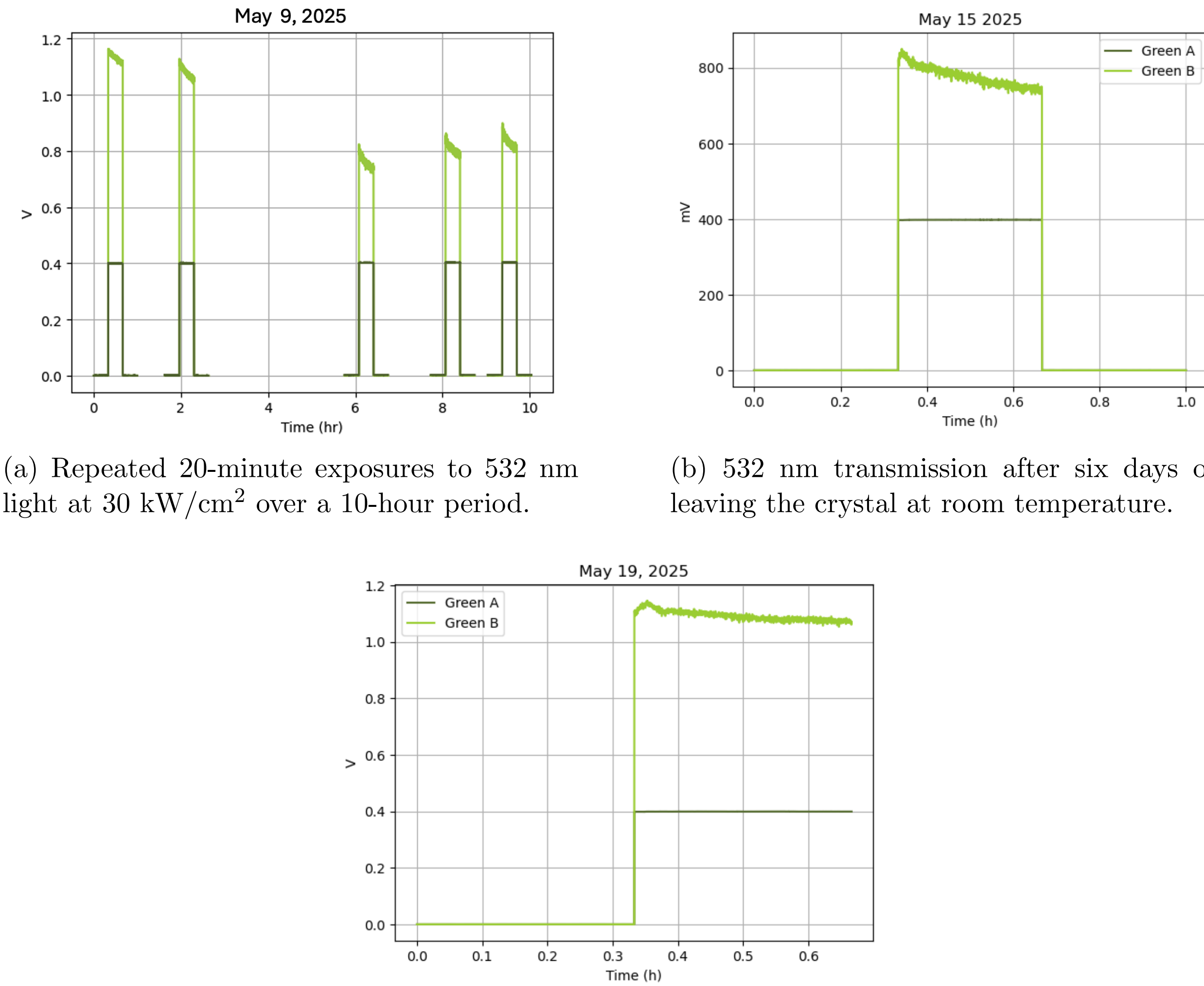

(c) Examining each diode separately, the dip appears only in the PDB, indicating that the observed dip is caused by the crystal.

Figure 6

then switch to p polarization with minimal alignment changes - ideally by utilizing the QPDs to maintain beam overlap.

# 4 Green-ish/Near IR Fluorescence

Fluorescence has been observed during the experiment. The fluorescence can be seen through goggles with 190-534 OD 6.5+ and 850-1070 OD5+ specification, putting its wavelength between 535 nm - 849 nm. A photomultiplier tube is required to determine the exact wavelength of the fluorescence. Fluorescence is reported in [9] and believed to be associated with the $Ti^{3+}$ complexes in place of $Ti^{4+}$ responsible for gray-tracking in KTP. Therefore, determining the strength of the fluorescence could be used to distinguish good crystals from




(a) Repeated 20-minute exposures to 532 nm light at 30 kW/cm$^2$ over a 10-hour period.

(b) 532 nm transmission after six days of leaving the crystal at room temperature.

(c) 532 nm transmission after 50 hours of 60mW 1064 nm annealing.

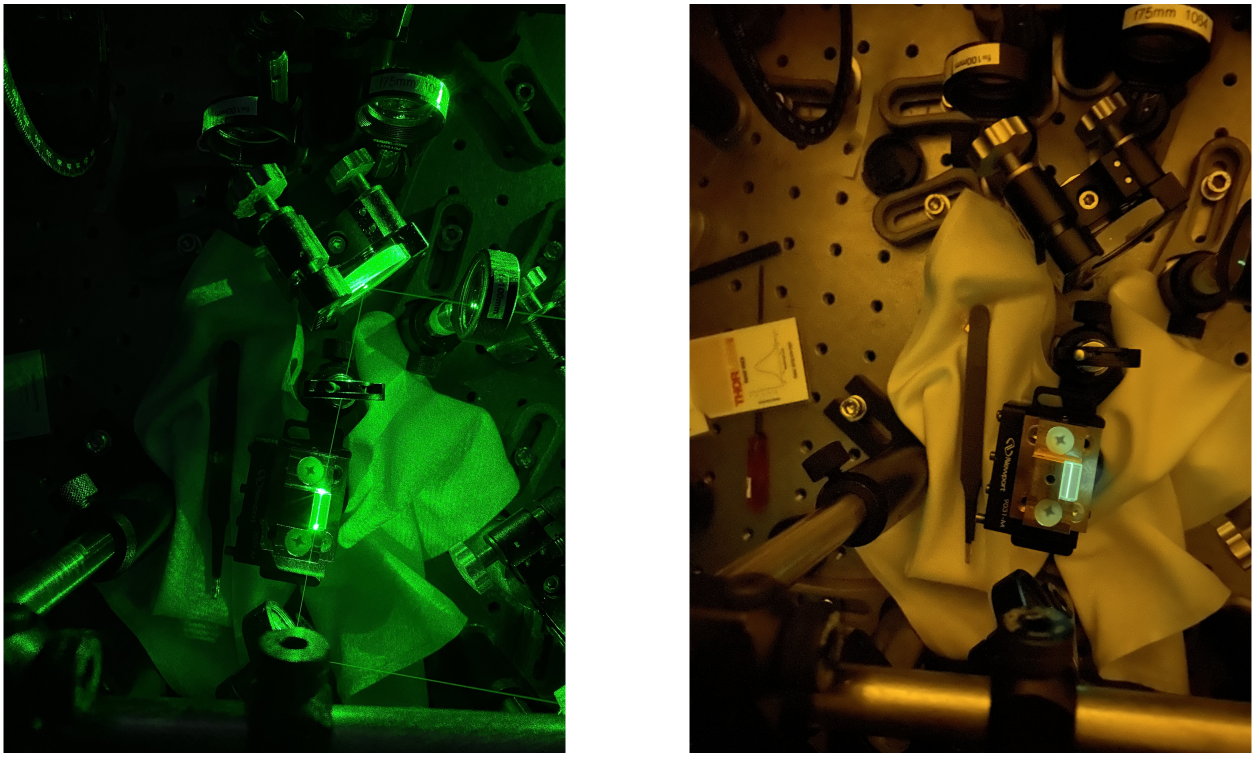
Figure 7: A closer look at the 532 nm behavior as the crystal is repeatedly pumped. The dark green trace shows the reference (beam without the crystal), while the light green trace shows the transmission through the crystal.

bad ones.

# 5 Results from QPDs

One hypothesis for the intensity drift of the 532 nm light as it exits the LHO SHG is that the beam is deflected by changes in the crystal temperature [**ref Daniel Sigg private communication**].

To test this, ANU loaned us a couple of QPDs. Figure 9 shows preliminary results recording 20 minutes of 532 nm light passing through the crystal compared against the QPD readings. Although GreenB shows the usual signature of GRIIRA, the QPDs did not record significant



(a) Phone picture of the crystal as it's pumped with 532nm.

(b) Phone picture through 532nm laser goggles.

Figure 8: Phone pictures of the crystal with and without goggles.

changes in the beam position.

# 6 ANU crystal loss

Before concluding, I measured the 1064 nm transmission with and without the crystal. The differential signal without the crystal was –8.84 $\mu$W, and with the crystal it was –14.34 $\mu$W. The total power incident on the balanced detector was 1.82 mW, corresponding to a crystal loss of 0.3%.

# 7 Issues

## 7.1 Contamination to the PID diode

When the green power increases, the PID diode sometimes detects a small amount of 1064 nm light that is unintentionally down-converted from the 532 nm beam. The good news is that this likely means the green and infrared beams are well overlapped. The bad news is that it confuses the results. When the PID loop is engaged, the PID diode sees this increased signal and sends the opposite response to the laser controller, requesting less power. Because the power is not perfectly balanced at the beam splitter, this results in the DIFF signal showing

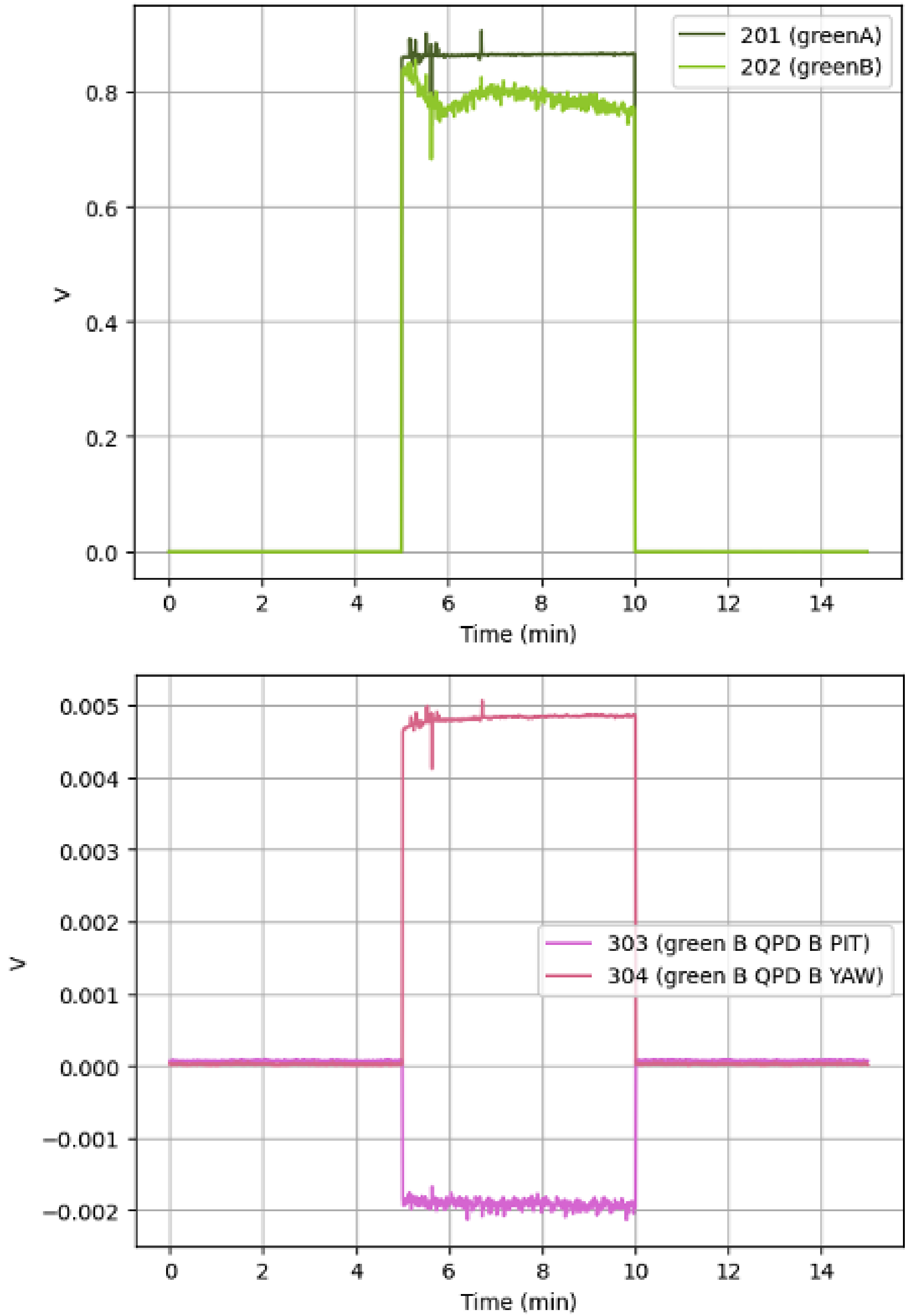



Figure 9: (Top) Green power measured by the two diodes of the homodyne detector. (Bottom) Green power measured by the QPD monitoring the transmitted green power.

a small correlation with the green power. This effect is easy to spot, as DIFF moves in the wrong direction—up with the green, instead of down, as expected in the case of GRIIRA. The change in power can also be observed in both PDA and PDB, which wouldn't be the case for GRIIRA. A Faraday isolator could be added in the future to help mitigate this issue.

### 7.2 GRIIRA is elusive

Once the right combination of alignments is found, GRIIRA can be repeated. However, getting to that point is not trivial. Without a cavity to define the beam path, the alignment of the infrared and green beams through the crystal has to be done by eye.

### 7.3 Ground loop problem

There are glitches observed in PDA and PDB channels associated with the green laser power being turned up and down, even when the diodes are blocked. The green laser and the 1064 balanced detector sharing the same power board. The effects on the PDA and PDB due to ground loop are on the order of a few nanovolts, resulting in a few tens of nanovolts on the DIFF channel.

## 8 Future

### 8.1 Suggested upgrade

Having gone through this exercise, here are a few suggestions:

- To ease alignment, a straight-cut crystal would have been helpful, though it would not be suitable for the OPO. An alternative is to place a cavity around the crystal or direct both 1064 and 532 beams to a reference cavity to mitigate alignment issues.
- For improved 1064 stability, use an NPRO.
- Expand the setup to include Faraday isolators.
- Add a photomultiplier tube to collect fluorescence data — likely the least invasive way to investigate sample impurities before installing the crystal in an OPO.
- Add a microscope to help visualize gray-tracking in the crystal, as it is unclear whether it can be observed with the naked eye simply because the crystal is so small.

# A Appendix

# References


[1] A. Bocchini, C. Eigner, C. Silberhorn, W. G. Schmidt, and U. Gerstmann. Understanding gray track formation in ktp: ti$^{3+}$ centers studied from first principles. *Phys. Rev. Mater.*, 4:124402, Dec 2020.

[2] S. Motokoshi, T. Jitsuno, Y. Izawa, and M. Nakatsuka. Control of gray-tracking formation for ktp and lbo crystals. In *Technical Digest. CLEO/Pacific Rim 2001. 4th Pacific Rim Conference on Lasers and Electro-Optics (Cat. No.01TH8557)*, volume 2, pages II–II, 2001.

[3] B. Boulanger, M. M. Fejer, R. Blachman, and P. F. Bordui. Study of KTiOPO4 gray-tracking at 1064, 532, and 355 nm. *Applied Physics Letters*, 65(19):2401–2403, 11 1994.

[4] Zhi M. Liao, Stephen A. Payne, Jay Dawson, Alex Drobshoff, Chris Ebbers, Dee Pennington, and Luke Taylor. Thermally induced dephasing in periodically poled ktp frequency-doubling crystals. *J. Opt. Soc. Am. B*, 21(12):2191–2196, Dec 2004.

[5] S. Wang, V. Pasiskevicius, and F. Laurell. Peculiarities of green light-induced infrared absorption dynamics in PPKTP. In *Advanced Solid-State Photonics (TOPS)*, page 461. Optica Publishing Group, 2004.

[6] Shaoping Shi, Yajun Wang, Wenhai Yang, Yaohui Zheng, and Kunchi Peng. Detection and perfect fitting of 13.2  db squeezed vacuum states by considering green-light-induced infrared absorption. *Opt. Lett.*, 43(21):5411–5414, Nov 2018.

[7] Team squeezing Dhruva Hanapathy, Victory Xu. OPO Crystal Degradation. *https://dcc.ligo.org/LIGO-T2300424*.

[8] Larry E. Halliburton and Michael P. Scripsick. Mechanisms and point defects responsible for the formation of gray tracks in KTP. In Gregory J. Quarles, Leon Esterowitz, and Lap Kin Cheng, editors, *Solid State Lasers and Nonlinear Crystals*, volume 2379, pages 235 – 244. International Society for Optics and Photonics, SPIE, 1995.

[9] K. L. Hegde, S. M.and Schepler, R. D. Peterson, and D. E.. Zelmon. Room-temperature, near ir fluorescence of high optical quality ktp. *proc. of SPIE*, 6552, April 2007.