

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Cavity-Enhanced Sum Frequency Generation First Interim Report		
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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is one of the most ambitious experiments in modern physics. In 1916, Einstein predicted the existence of gravitational waves as a consequence of General Relativity. More than a hundred years later, LIGO made the first direct detection of these waves. It does so using laser interferometry precise enough to measure changes in length smaller than one thousandth of the size of a proton.

The performance of gravitational-wave detectors is affected by several fundamental noise sources. Among these, thermal noise is expected to become a major limitation for future detectors, especially in the mid-frequency region. The proposed LIGO Voyager upgrade aims to reduce these effects using cryogenically cooled silicon test masses. However, silicon strongly absorbs at the currently used 1064 nm wavelength, making a shift to longer wavelengths necessary. Voyager is therefore designed to operate near 2050 nm, where silicon becomes nearly transparent. The challenge then shifts to photodetection, because 2 micron detection still falls short of the extremely low-loss requirements of GW detectors.

Sum frequency generation (SFG) offers a solution. In a nonlinear crystal, two input fields at frequencies ω_1 and ω_2 can interact to produce a third field at $\omega_3 = \omega_1 + \omega_2$. By mixing the 2050 nm signal light with a strong 1064 nm pump in a periodically poled lithium niobate (PPLN) crystal, the signal is upconverted to ~ 700 nm where silicon photodetectors can achieve quantum efficiencies exceeding 99%.

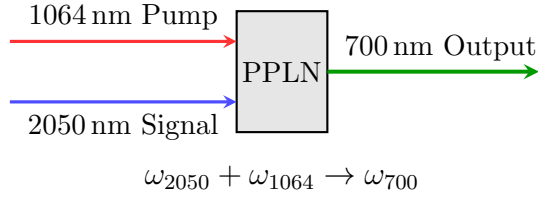


Figure 1: Illustration of optical upconversion via SFG.

Sufficiently high optical intensities are required for efficient nonlinear conversion inside the crystal. One way to achieve this is through cavity enhancement, in which the 1064 nm pump field is enhanced inside an optical bow-tie cavity in order to build up large circulating power. This project focuses on the development of a cavity-enhanced SFG system for upconversion of weak 2050 nm light to 700 nm using a resonantly enhanced 1064 nm pump field.

Previous efforts within the group have demonstrated single-pass upconversion [4] and initial development of the enhancement cavity [5]. Building on this, the work will involve locking and characterizing the bow-tie cavity, integrating the nonlinear crystal, mode matching the signal beam, and detection of the generated 700 nm output. We also aim to investigate thermal effects and evolution of cavity mode at high power.

2 Objectives

The primary goal of this project is to develop and characterize a cavity-enhanced sum frequency generation (SFG) system for upconversion of weak 2050 nm light to 700 nm. The specific objectives are:

- Lock the 1064 nm bow-tie cavity and build up resonant circulating power. Characterize cavity finesse, gain, round-trip loss, and circulating power enhancement in order to maximize pump intensity for efficient SFG.
- Introduce and align the nonlinear crystal within the cavity while maintaining stable resonance. Evaluate mode matching quality and crystal-induced losses from bulk absorption, surface reflections, and thermal effects.
- Mode-match the 2050 nm ECDL signal beam into the cavity and demonstrate generation and detection of the upconverted 700 nm light.
- Obtain a measured quantum conversion efficiency of the system and construct a loss budget spanning cavity, crystal, and detection path losses.
- Study the effect of thermal lensing in the crystal both theoretically and computationally to determine the pump power threshold at which it becomes significant, and if feasible, observe its effect on cavity mode experimentally.

3 Approach

3.1 Understanding Experimental Setup

Initial work will focus on understanding previous work, the existing optical setup and the theoretical framework underlying the experiment. Gaussian beam propagation, cavity stability, and mode matching using the ABCD matrix formalism will be studied in parallel with experimental beam profiling and cavity alignment.

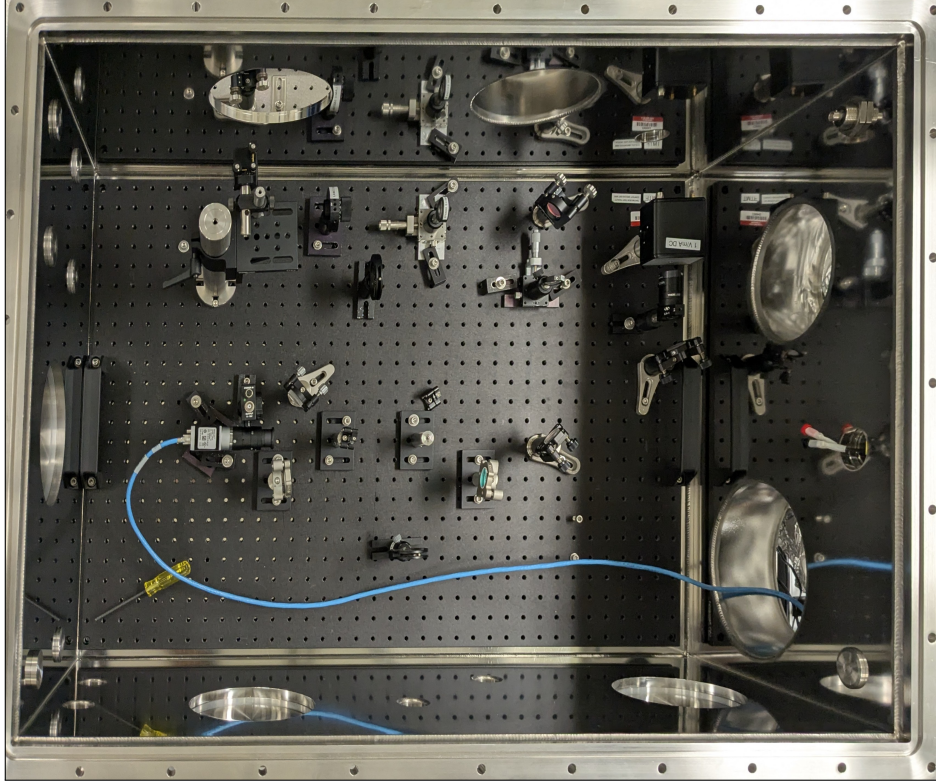


Figure 2: Current experimental setup for the cavity-enhanced SFG system.

3.2 Cavity locking and Characterization

Before introducing the nonlinear crystal or the 2050 nm signal beam, the first experimental phase will focus entirely on building resonant 1064nm power inside the bow-tie cavity. This is important because in the undepleted pump regime, SFG efficiency depends primarily on the circulating 1064 nm pump intensity.

Stable cavity locking will be implemented using the Pound–Drever–Hall (PDH) technique with RF phase modulation and feedback derived from the reflection PD signal. The cavity will then be characterized through measurements of beam waist size, free spectral range (FSR), linewidth, finesse, power enhancement, and round-trip loss. Coupling behaviour in the context of undercoupled, overcoupled, and critically coupled operation will also be studied.

3.3 Crystal Integration and Mode Matching

Once stable cavity operation with the crystal is achieved, the nonlinear crystal will be introduced into the bow-tie cavity. Crystal alignment will be optimized while maintaining stable cavity resonance and mode matching. Since the crystal modifies the optical path and mode evolution, the cavity alignment and mode matching conditions need to be re-optimized after inserting the crystal. The effect of the crystal on cavity performance including losses from bulk absorption and surface reflections will also be investigated.

3.4 Signal Beam Integration and 700 nm Detection

After the stable cavity locking with crystal is achieved, the 2050 nm ECDL signal beam will be introduced into the cavity.

The 2 micron light will be mode matched to the cavity and aligned to achieve efficient spatial overlap with the pump field within the nonlinear interaction region of the crystal.

The generated 700 nm output will then be sought and characterized. Conversion efficiency will be measured under different cavity configurations and circulating pump powers.

3.5 Thermal Lensing and Cavity Stability

At high circulating pump powers, absorption within the nonlinear crystal can lead to thermal lensing and modification of the cavity mode. The resulting change in beam focusing can further increase the intensity within the crystal, leading to self-reinforcing changes in cavity mode structure.

The evolution of the cavity mode under thermal loading will therefore be studied theoretically and computationally using Gaussian beam propagation and equivalent lens models. If feasible, the observed cavity behaviour will also be compared with finite element or numerical simulations of thermal lensing within the crystal.

4 Progress

During the first three weeks, work focused on learning the setup, aligning the cavity, and measuring the properties of the 1064 nm pump laser. While attempting to obtain a PDH error signal, it became clear that the laser beam had significant distortions in spatial profile. This led to an investigation of the laser beam profile and possible sources of distortion. The following sections summarize the methods used, observations made and conclusions drawn from them.

4.1 Beam Profiling using He-Ne Laser

Before profiling the 1064 nm laser, a practice beam profile was taken using a He-Ne laser to become familiar with the DataRay Beam'R2 profiler. The beam width was measured along several longitudinal positions along propagation axis and fitted to the standard Gaussian propagation formula:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z - z_0}{z_R} \right)^2}, \quad (1)$$

where w_0 is the $1/e^2$ beam waist radius, z_0 is the waist location, and $z_R = \pi w_0^2 / \lambda$ is the Rayleigh range.

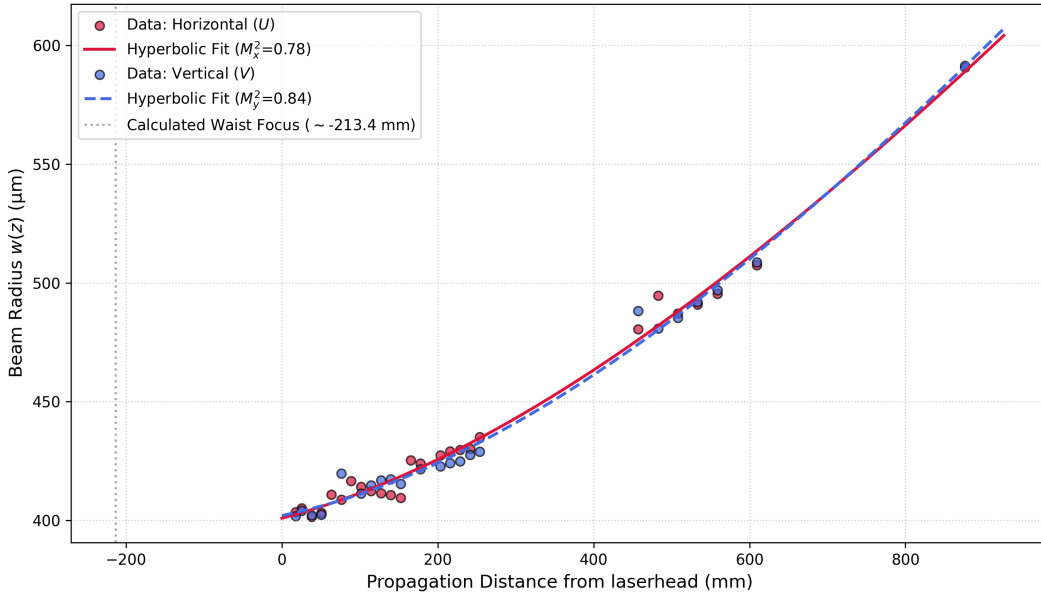


Figure 3: Helium-Neon Laser Profile

This exercise helped understand the profiling technique before applying it to the main laser. Uncertainty errors are not accounted for in the widths because the data was extracted from static DataRay screens at each location. For later measurements, I used a script to record 100 samples in real-time at each position to account for and average out fluctuations.

4.2 Cavity Alignment and Flashing

Coarse alignment of the bow-tie cavity was done using the existing setup. Beam height and pointing were adjusted using irises, and the beam was centered on optical components within the vacuum chamber. Input coupler was temporarily removed to allow the beam to be walked through the round-trip path, centering the spot on each cavity optic. The input coupler was then reinserted and its orientation was adjusted until the prompt reflection and the round-trip beam overlapped with each other.

Reflection photodiode signal was monitored during the alignment process to guide fine adjustment. Cavity flashing was successfully observed on the transmission camera. Higher-order transverse cavity modes were also observed on the camera.

Despite obtaining cavity flashing, a PDH error signal of a magnitude that was expected could not be obtained. Temperature actuation at 25 mHz, 50 mV_{pp} and PZT actuation at 5 Hz, 300 mV_{pp} into a 15x driver were both attempted but did not yield a usable error signal. This led us to further investigate the quality of mode matching. The first step towards this was a more careful characterisation of the input beam.

4.3 Characterization of 1064 nm NPRO Laser

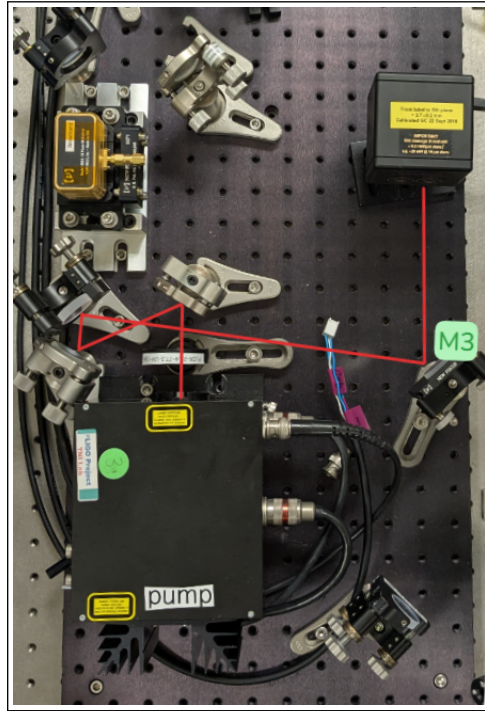


Figure 4: Setup for direct profiling of the beam before the EOM.

4.3.1 Initial Profiling

We observed an elongation in the transverse profile of the beam at the Faraday isolator. To investigate whether the EOM was introducing clipping or astigmatism, power measurements were taken before and after the EOM. The measured power decreased from 25.7 mW at the input to 19.3 mW at the output, which corresponds to a transmission of 75.1%.

This raised the possibility that the beam was not properly centered through the EOM. The centering of the upstream optics and the EOM alignment were therefore checked and improved. After these adjustments, the transmitted power increased to 20.9 mW and the beam profile showed some improvement. However, the beam remained highly non-Gaussian.

By adding a pickoff mirror before the EOM, the laser beam was characterized directly before influence of the downstream optics. The profiler was aligned normal to the beam before every measurement and centered using DataRay bull's eye reference.

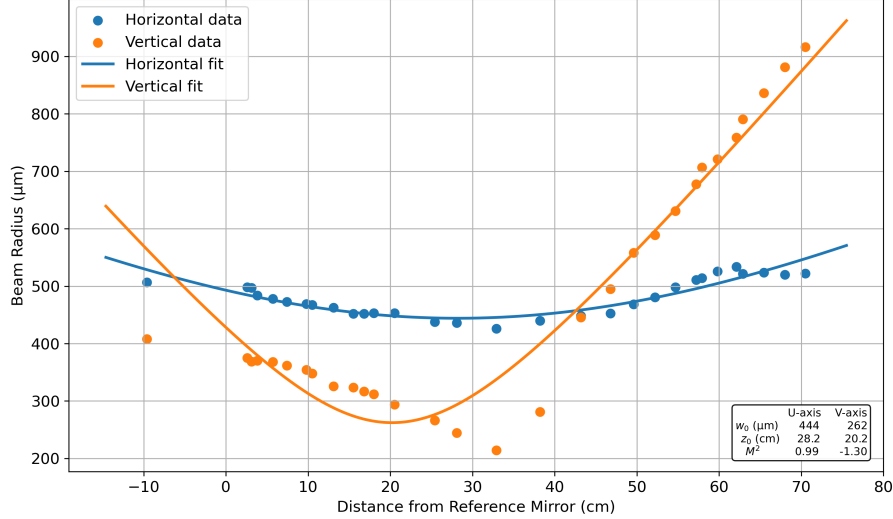


Figure 5: Measured beam profile for the NPRO laser before the EOM.

The results show signs of strong astigmatism. The horizontal and vertical waist positions differ by approximately 8 cm. The horizontal axis fits well as a cleaner TEM_{00} beam, while the vertical axis is not well described by a Gaussian mode. More interestingly, the beam evolution showed complex multi-lobed features as shown in the following figure.

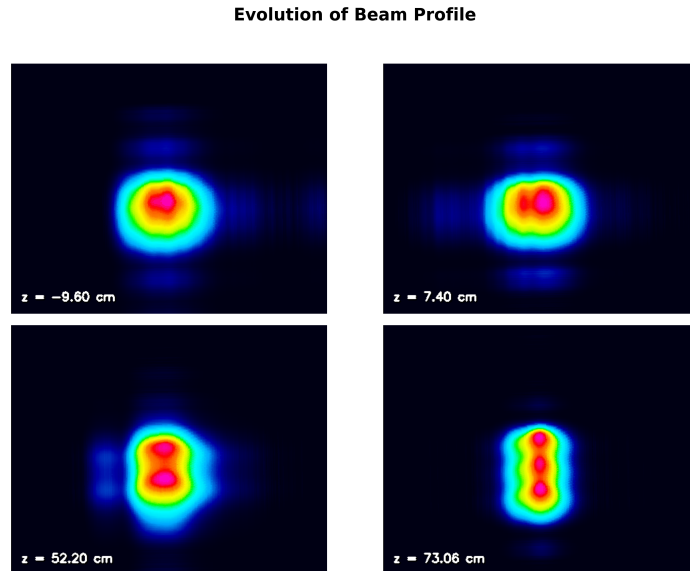


Figure 6: Frames showing higher-order features. Distances are with reference to M3.

4.3.2 Investigating Possible Causes

Several experiments were performed to determine the origin of the observed beam distortions.

Lens Alignment

The focusing lens ($f = 7.73$ cm) placed after the laser output was found to be sitting low causing the beam to pass below the centre. The height and horizontal position of the lens were adjusted to improve centering in both axes while monitoring the beam shape downstream. Neither of these adjustments produced a measurable improvement in the beam profile.

Temperature Sweep

The laser temperature was varied for two reasons. Temperature directly affects the frequency of light lasing from the NPRO crystal. For our laser, the oscillating frequency shifts with crystal temperature at approximately 3 GHz/K. Secondly, the operating temperature determines the thermal lensing and mode structure within the NPRO crystal itself. If the distortions were caused by thermal effects inside the laser at the setpoint of 45.5°C, we might expect an improvement in beam quality operating at certain temperatures .

The laser temperature was varied in two ways. First, a slow temperature actuation was applied using a signal generator. The temperature was swept by approximately $\pm 1^\circ\text{C}$ about the nominal setpoint of 45.5°C using a 100 mHz, 1.2 V pp.

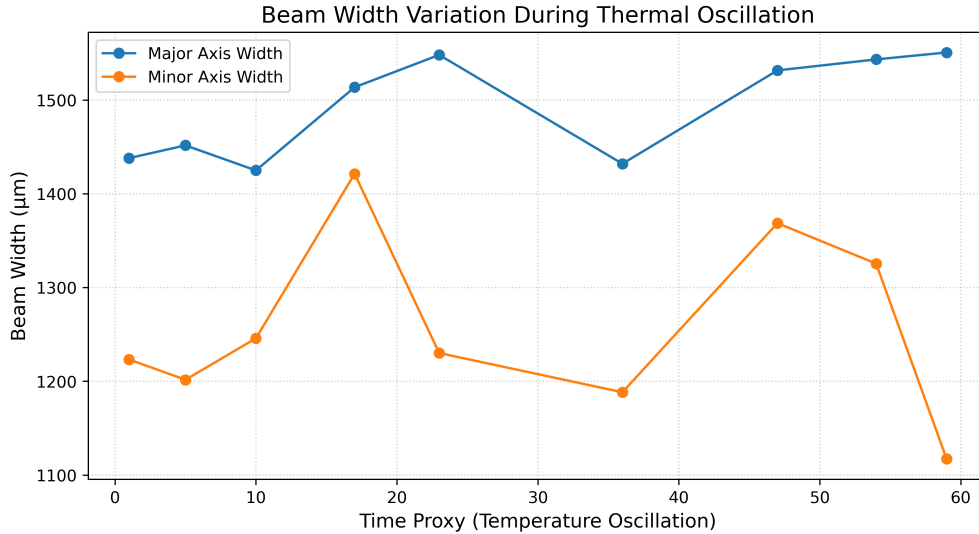


Figure 7: Effect of Temperature Sweep on Beam Width

Result: The central spot of the beam remained largely unchanged, but the outer concentric ring features expanded and contracted periodically with the sweep.

This observation suggested an interference between the main beam and a weak parasitic reflection somewhere in the beam path. As the laser frequency shifts with temperature, the interference condition changes, causing the fringes to move in and out. The circular fringe shape and its periodic response to temperature support this interpretation.

Operating Current

Beam width was measured at a fixed propagation distance as the laser current was varied from 0.85 to 0.95 A. Since the power output reduces with reduction in current, the ND filters were adjusted accordingly to avoid under-exposure.

Result: At lower currents, some higher-order features became less pronounced and the beam appeared more Gaussian on the camera. The beam width remained approximately constant below ~ 0.92 A, then rose sharply at higher currents. This threshold observation suggests a physical effect at play in the laser at higher currents; however, further tests showed no significant measurable dependence. The beam is better behaved below threshold but non-Gaussian features persist even at the lowest measurable current of 0.88 A.

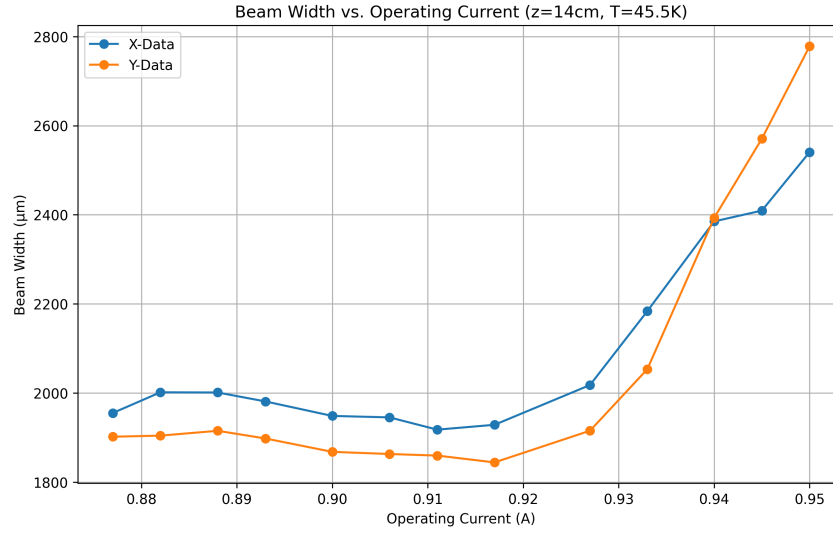


Figure 8: Beam width vs. laser current at $z = 14$ cm, $T = 45.5^\circ\text{C}$. Widths remain roughly constant below 0.92 A, then rise sharply. This coincides with appearance of a ring structure.

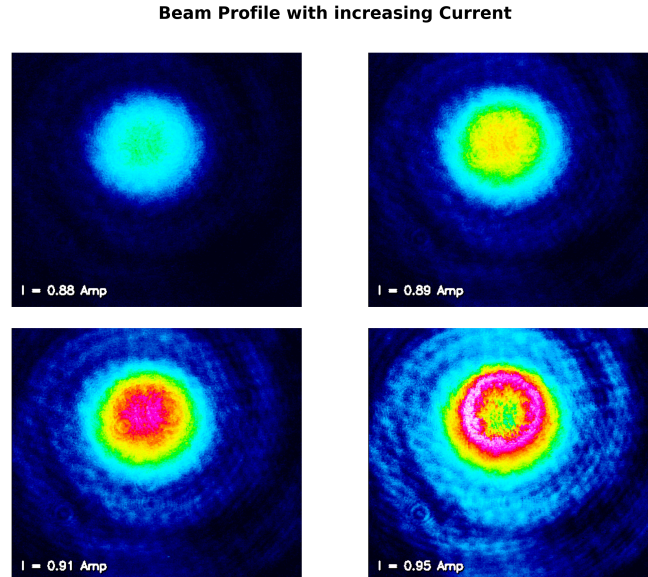


Figure 9: Beam profile evolution with laser current showing an annular ring gradually emerge.

Camera Saturation

To test whether the observed modes were artifacts due to saturation of the detector, measurements were repeated using different combinations of neutral density filters and with both the WinCam and Beam'R2 profiler. The Beam'R2 profiler is rated to be used below 1 W. Measured power at 40 cm from the laser was 24.25 mW, well within the instrument's operating range. The three-lobe structure was observed on both the Beam'R2 and the WinCam (with a net ND filter OD of 4.15), ruling out camera saturation as a cause.

Downstream Optics

The lens was replaced by a flat mirror to profile the beam directly out of the laser and rule out any unwanted effect that could be arising from the lens or beam splitter. Despite this, the profile remained effectively the same. This was by far the most direct evidence that the distortions are not introduced by any downstream optics.

5 Summary & Next Steps

The tests performed rule out lens misalignment, camera saturation, temperature, downstream optics, and operating current as possible causes of the features of the beam. These distortions could therefore be attributed intrinsic to the laser source itself. This result is not unexpected given that the NPRO laser is approximately 25 years old and does not have a previous characterization on record.

Since beam quality directly affects cavity coupling and mode matching, in view of these findings, it was decided to proceed with a fibre-coupled laser source as an alternative which can provide a clean output and allow the experiment to proceed toward cavity locking and mode matching.

In parallel, the cavity eigenmode q parameter is known to be $(-0.05025 + 0.1299i)$, and the mode matching calculation to design a lens telescope will be done soon. This will be one of the immediate focus of the next phase of work alongside setting up the optics and cavity with the fibre-coupled laser.

The planned steps after laser replacement are as follows:

- Mode-matching input laser beam to the bow-tie cavity
- PDH cavity locking and cavity characterization
- Nonlinear crystal integration and cavity re-optimization
- 2050 nm beam integration, 700 nm detection, and measurement of conversion efficiency

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