

Gingin High Optical Power Test Facility

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Abstract. The Australian Consortium for Gravitational Wave Astronomy (ACIGA) in collaboration with LIGO is developing a high optical power research facility at the AIGO site, Gingin, Western Australia. Research at the facility will provide solutions to the problems that advanced gravitational wave detectors will encounter with extremely high optical power. The problems include thermal lensing and parametric instabilities. This article will present the status of the facility and the plan for the future experiments.

1. Introduction

Gravitational wave detectors are the most sensitive instruments ever made. Current laser interferometers (LIGO, VIRGO, TAMA, GEO)^[1,2,3,4] operate at a displacement sensitivity $\sim 10^{-19}$ m/ $\sqrt{\text{Hz}}$ over a considerable bandwidth, and LIGO's performance, for example, is remarkably close to its design sensitivity. However an order of magnitude improvement in sensitivity is required for the detection of gravitational wave signals at practical rates.

The above sensitivity improvement requires an increase in the laser power in the interferometer arms of approximately 100-fold. This increase in stored optical power, combined with improved isolators, test masses and suspensions will give the detectors sufficient sensitivity to detect between 20 and 15,000 binary coalescence events per year (95% confidence interval, based on observations of neutron star binaries and stellar evolution modeling for black hole systems^[5]). There are also many other exciting target sources.

While high optical power is essential to increase the detector sensitivity it will also introduce the possibility of instabilities. Thus even small absorption of this high optical power in the test mass material or on the high reflection coatings will induce strong thermal lensing effects, which

can seriously degrade the interferometer sensitivity. Also the optical spring effects in the high optical power cavities can induce parametric instabilities^[6,7,8] in test masses and their suspensions.

ACIGA's High Optical Power Test Facility (HOPTF) at Gingin has been commissioned by LIGO to investigate the problems associated with harnessing high optical power to bring laser interferometer gravitational wave detectors to their next stage of sensitivity, known as Advanced Interferometer Sensitivity.

2. The Facility

The configuration of the facility is shown in figure 1. The injection locked high power laser, developed by ACIGA, will be frequency stabilized to a rigid reference cavity and mode matched to a 10-meter mode cleaner. The output beam from the mode cleaner will be mode matched to the Michelson interferometer with arm cavities. The eventual facility will be a high optical power interferometer with power recycling and resonant sideband extraction configuration. The signal extraction mirror is not shown in figure 1. The two 80 meter long vacuum pipes with vacuum tanks connected for suspended optics have been constructed and pumped down to better than 10^{-6} mbar.

The first stage experiment will use only the south arm for investigating the thermal lensing and compensation. A preliminary experiment using BK7 optics suspended from Small Optics Suspension (SOS) system provided by the LIGO laboratory has been completed. The aim was to gain experience in suspended optics systems. Longitudinal locking of a monolithic Nd:YAG master laser to the suspended cavity and auto alignment have been demonstrated [9]. The BK7 optics have now been replaced with sapphire optics with the substrate of the Input Test Mass (ITM) set up inside the cavity to increase the thermal lensing effect. The detailed experimental setup is described in section 3.

Assembly of the advanced vibration isolators for the east arm is in progress. This arm will contain a second sapphire cavity suspended from the advanced isolators with niobium ribbon test mass suspension. The first goal of the east arm experiment is to evaluate the performance of the advanced isolator developed by ACIGA. In the next stage, with the availability of a high power laser, high test mass internal Q-factor and high finesse cavity we will be able to test parametric instabilities at Gingin facility and demonstrate possible control schemes for it. In section 4, we will describe the planned parametric instability experiments.

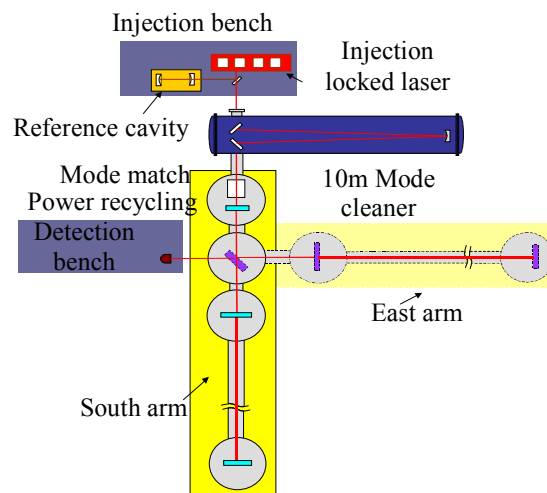


Figure 1: The HOPTF configuration.

3. Thermal Lensing and Compensation

The first stage HOPTF experiments will be thermal lensing and compensation on the south arm. This arm cavity consists of a 77 meter long Fabry Perot cavity with sapphire test masses. The Input Test Mass (ITM) is flat and the End Test Mass (ETM) has a radius of curvature of 720 m, leading to a cavity g-factor of ~ 0.89 . As shown in figure 2, the substrate of the ITM has been placed inside the cavity for the first test. Hence, the high optical power circulating inside the cavity will also circulate through the ITM substrate, creating a strong thermal lens comparable to that in the Advanced LIGO power recycling cavity. A fused silica plate mounted in an aluminum mount with direct conduction heating has been installed inside the cavity for testing thermal compensation^[10]. The end mirror is almost totally reflective (power transmission of < 50 ppm) to increase the cavity finesse. The sapphire test mass absorptions are expected to be 50 ppm/cm for the substrate and 1 ppm for the coating. An off-axis Hartmann sensor^[11], has also been installed for monitoring the thermal effects in both the ITM and compensation plate.

Long term locking of the master laser to this cavity has been achieved. The measured finesse of the cavity is ~ 1000 and power build up factor is ~ 200 . A 10W injection locked laser developed by ACIGA^[12] has been installed and mode matched to the cavity. A preliminary lock of this laser to the cavity has been achieved using reduced power (~ 200 mW) as the high power phase modulator was not yet available.

After the compensation plate was installed inside the cavity, preliminary tests were conducted by locking the master laser to the cavity and measuring the transmitted beam profile. When heated, the compensation plate can dynamically change the radius of curvature resulting in a change in size of the transmitted beam from the cavity as shown in figure 3. The top of the graph shows the heating power switched on and off. The dots in the bottom graph are the measured results and the squares are the results from a simulation using Finite Element Modeling (FEM). The beam passes through a reversed beam expander to demagnify the size to fit the CCD camera.

Preliminary conclusions are as follows. First, the principle of the compensation plate works: the cavity modes can be tuned by heating the plate. Second, an estimated 7% of the heat generated in the aluminum heating mount is not transmitted to the plate (additional to the heat loss due by radiation). Third, a non negligible astigmatism (30%) seems to be induced by the heated plate, most probably due to imperfect alignment of the beam with the plate centre.

In the next step we will use the Hartmann sensor installed to detect the wavefront distortion induced by the heated plate, to verify its heating profile. Then, by operating the 10 W laser at full power we will investigate the thermal lensing inside the ITM and the thermal compensation of the plate.

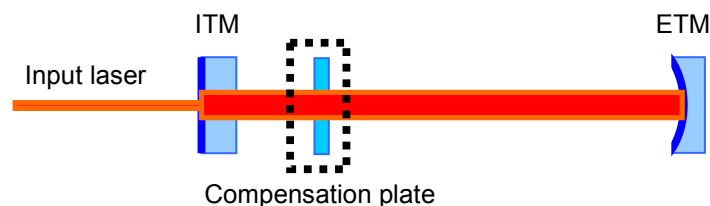


Figure 2: the schematic of the south arm cavity with thermal compensation plate.

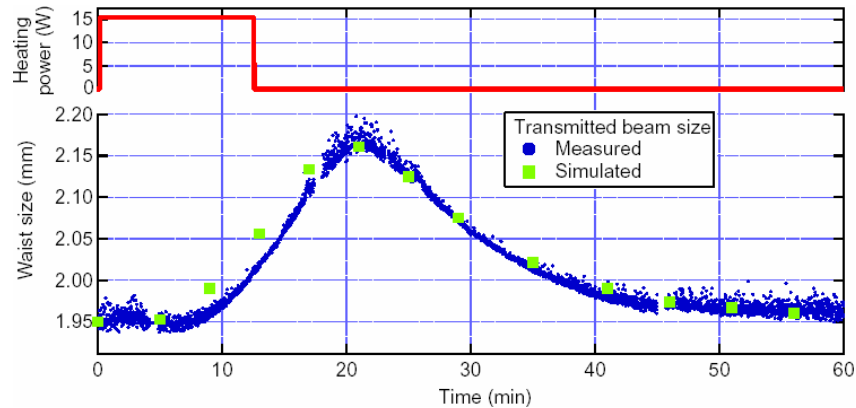


Figure 3: Evolution of the beam size transmitted by the Fabry Perot cavity when the compensation plate is heated. The focal length of the plate has been simulated using FEM. The presence of gaps in the measurement is due to the temporary loss of lock of the cavity

4. Parametric instability

Parametric instabilities themselves occur in two ways, depending on whether the instability occurs at frequencies smaller or higher than the optical cavity bandwidth. Low frequency parametric instabilities^[13] occur through the creation of a negative spring by the length dependence of the radiation pressure inside an optical cavity. Such optical spring effects can drive instabilities in the interferometer suspension system. Preliminary simulation results of locking the HOPTF arm cavity in the presence of radiation pressure effects have been summarized in an article by Y. Fan et al^[14]. The simulation shows that the cavity can be locked with 100 W input power by locking the cavity first at low power and then slowly increasing the input power to the required one. This will avoid abrupt changes of the radiation pressure force applied to the suspended test masses that can drive the cavity out of its position bandwidth thereby losing control.

High frequency parametric instabilities^[6] occur due to optical modes interacting with test mass acoustic modes to excite ultrasonic ringing. In the case of high power optical cavities, the acoustic modes of the test mass can scatter the fundamental optical mode into higher order modes, mediated by the radiation pressure force of the optical modes acting on the acoustic modes. The phenomenon can occur only if two conditions are met: a) the acoustic mode frequency is equal to the difference frequency between the fundamental TEM₀₀ mode and a higher order mode TEM_{mn}. b) Secondly the mode shape of the higher order optical mode must overlap the mode shape of the acoustic modes. Our research^[7,8] has shown that such instabilities can be significant in second generation laser interferometer GW detectors. They will need to be reduced or eliminated by a combination of tuning, damping and feedback.

Using Finite Element Modeling (FEM), we have modeled the HOPTF sapphire test mass acoustic modes. One of the acoustic modes with frequency of ~162 kHz has relatively high overlap factor of 0.174 with an optical high order mode, LG41. The modes are shown in figure 4. Figure 5 shows the highest parametric gain factor of all acoustic modes as a function of the ETM radius of curvature with 30 W input power. Thus the HOPTF arm cavity should observe high frequency parametric instabilities. Even with lower input power and lower test mass Q-factor we may still detect the parametric effects at HOPTF by measuring the test mass Q-factor variations resulting from the parametric effects. Figure 6 shows the test mass Q-factor as a function of the input power if the initial Q-factor is 107. The figure 7 shows the proposed experimental setup for measuring the test mass Q-factor variation due to the parametric effects. The capacitor actuator has been installed to excite resonantly the test mass acoustic modes. The PDH frequency locking error signal should detect the acoustic mode frequency signal. After band pass filtering, we can record the ring down of the acoustic mode after the actuator is switched off.

5. Conclusions

The HOPTF south arm cavity with sapphire test masses has been locked to the 10 W injection locked laser. It is ready to start the first stage thermal lensing and compensation experiments. Preliminary experiments with the thermal compensation plate demonstrate that the compensation plate works as expected.

Using FEM modeling we have predicted that high frequency parametric instability should be observed on HOPTF. Even with lower input power and lower test mass mechanical Q-factor we should be able to detect parametric effects by measuring changes in the apparent acoustic loss of a particular acoustic mode, which results from the parametric effects.

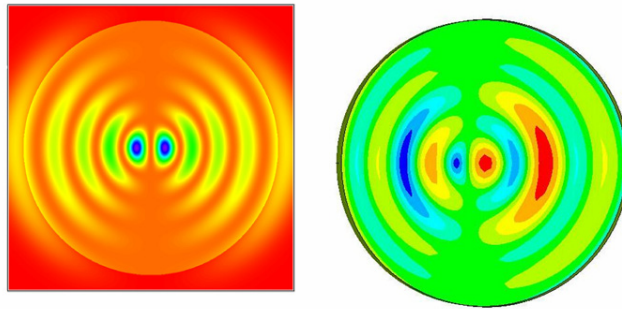


Figure 4: the HOPTF cavity optical mode shape of LG41 and the sapphire test mass acoustic mode shape with frequency of 162 kHz

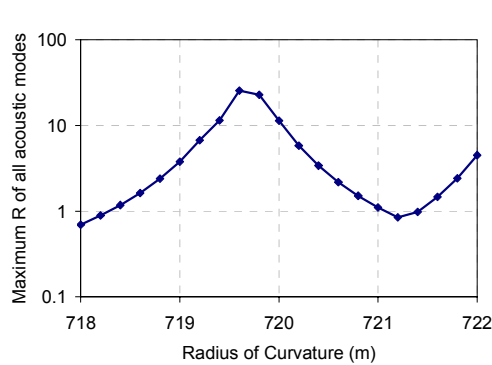


Figure 5: The calculated maximum parametric gain as a function of the ETM radius of curvature (cavity finesse: 3000, optical power inside the cavity: 50kW, Mechanical Q: 2×10^8 , acoustic mode frequency: 162 kHz)

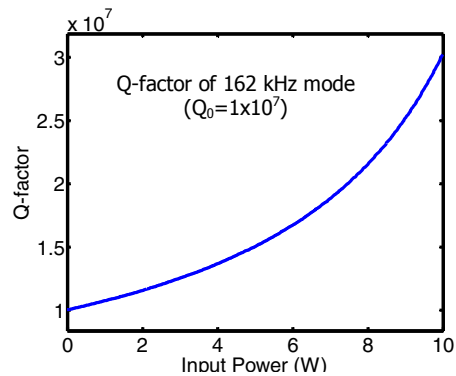


Figure 6: the measured test mass Q-factor as a function of the input power with initial Q-factor of 10^7

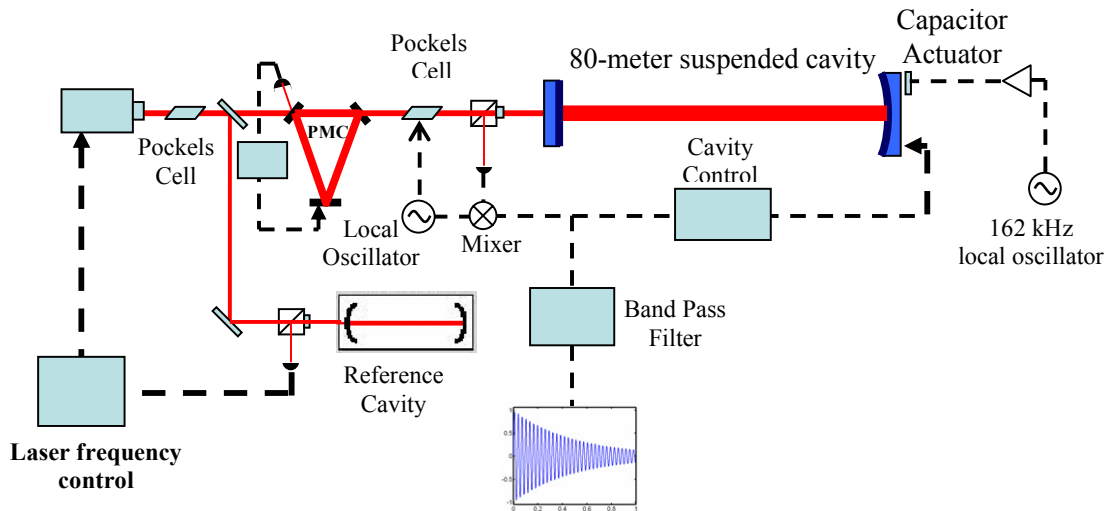


Figure 7: The schematic diagram of measuring the test mass Q-factor variation due to the parametric effects.

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