Reduction of optical cavity losses using actively-tunable adaptive optics

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(Dated: 2 August 2019)

Optical cavities play an important role in laser interferometer gravitational wave detection. To increase the interferometer's sensitivity, the operating power in the cavities needs to be proportionally increased. Nevertheless, due to point absorbers in the end mirrors, light is scattered into higher order modes limiting the amount of power that can be reached inside a cavity. Here, we propose an adaptive optics approach in reducing optical losses by residual aberration correction using focused heat. We use a spherical reflector and cartridge heater to focus radiant heat to a 1.5 cm spot near the center of the mirror. The reflector radius of curvature does not significantly affect the focus, however the distance of the heater from the mirror and the coating of the reflectors make a paramount difference. We will vary the distance from the mirror and use Aluminum foil and potentially, polished gold, to get as small of a focus as possible. Obtaining a good focus will allow better control in the projected heat pattern and can be used to actuate the coupling of different modes.

I. INTRODUCTION

One of the most exciting uses of optical cavities is in detecting gravitational waves (GWs) using large scale interferometers. When GWs pass through spacetime they cause a strain by stretching it in one direction and shrinking it in the other[1]. The Laser Interferometer Gravitational-Wave Observatory (LIGO) uses a setup similar to a Michelson interferometer (see Figure 1) to detect GWs[2]. The end mirrors used in LIGO and Advanced LIGO act as freely falling masses, hence they are displaced when a GW passes through. The change in the mirrors' position causes a phase shift in the optical cavities which is measured and related to the length change of the arm, providing information about the GW[3].

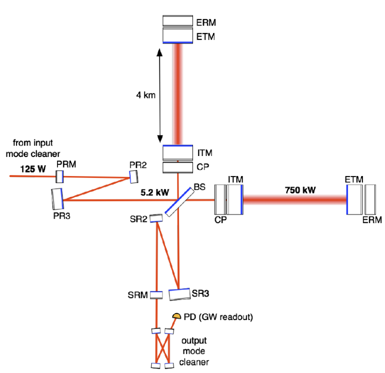
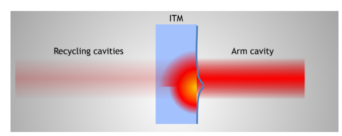


FIG. 1: (color online) LIGO's L-shaped interferometer with two 4 km long Fabry-Perrot cavities[2]

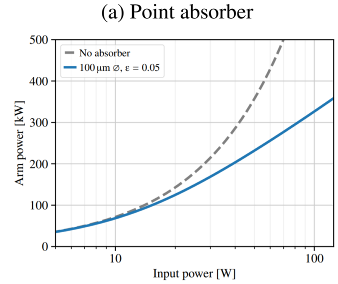
As seen in Figure 1, LIGO's interferometer includes two 4 km long Fabry-Perrot cavities and a power recycling mirror to account for optical losses and provide optimum power for coupling[3]. The cavities are created by adding a mirror near the beam-splitter that reflects light back to the farther mirror, increasing the effective path length of light to 1120 km[2]. To improve the resolution of the interferometer, a partly reflective mirror is added between the laser and the beam splitter, increasing the power from 200 W to 750 kW[2].

II. POINT ABSORBER DEFECTS IN THE ADVANCED LIGO MIRRORS

In theory, the power-recycling cavities should increase the effective power to 750 kW, however Advanced LIGO cavities can only reach 350 kW[4]. This is due to nonuniform surface absorption resulting in small bumps on the mirror's surface called point absorbers. These increase scattering into higher order modes with increasing input power, thereby limiting the maximum power that can be reached in the optical cavity. An absorber of $100\mu m$ diameter and just a few nanometers tall can significantly limit the operating power at 30W of input power[5].



(a) Point absorber



(b) Power Limit

FIG. 2: (color online) top: Non-uniform surface deformation of the mirror[4]; bottom: Operating arm power vs. input power[5]

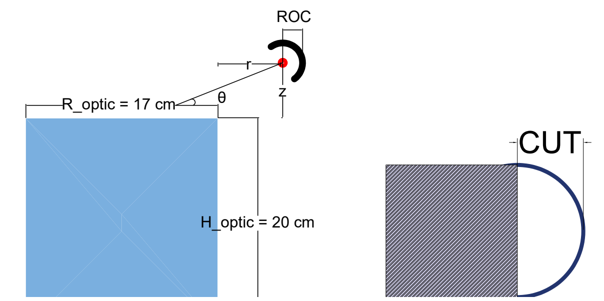
Different approaches have been taken to actuate the loss of power from the fundamental Gaussian mode (TEM_{00}) into higher order modes. The initial test mass (ITM) of LIGO's optical cavities was heated using a compensation plate[6], a heater array was projected onto a mirror using an in-vacuum ZnSe[7], and a CO_2 laser projector was used to produce a spatially-tunable heat distribution[7]. While these methods reduce scattering into higher order modes, the power inside the cavities is still far from the desired value. Here we present a new adaptive optics approach to reduce optical losses in the cavities by using a central heating residual aberration correction (CHRAC) technique.

III. ADAPTIVE OPTICS APPROACH

The primary objective of this experiment was to focus a source of radiant heat to a point near the center of a test optic. While initially we considered using horns and elliptic reflectors to get a better focus, we decided to work on a design for a spherical reflector due to easier manufacturing.

A. Finite-element analysis

Before setting up the experiment, we used COMSOL to simulate our design and obtain preliminary results. The simulation consists of a ring heater placed just outside the mirror's front surface at a few centimeters above. A spherical reflector is wrapped around it with an opening (θ) towards the center of the mirror (see Figure 3).



(a) Side view of heater and reflector setup (b) Reflector Geometry

FIG. 3: (color online)

The size of the test mass and the radius of the heater are fixed. The distance of the heater from the optic, the ROC and opening of the reflector are parameters that need to be optimized. Additionally, the geometry of the reflector is obtained by cutting the circle in half. The cut was varied from the center to the focal point in order to obtain a better focus given spherical aberrations and we found that a cut at the center focuses more energy. At 100W source power from the ring heater, there is a 3K difference between the peaks produced by reflectors cut at the focal length and center, respectively.

The distance of the heater from the reflector was determined using ABCD matrices[89]:

$$\begin{bmatrix} 1 & L_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{-2}{R} & 1 \end{bmatrix} \begin{bmatrix} 1 & L_1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} \frac{R-2L_2}{R} & \frac{L_1(R-2L_2)+RL_1}{R} \\ \frac{-2}{R} & \frac{-2L_1+R}{R} \end{bmatrix} \quad (1)$$

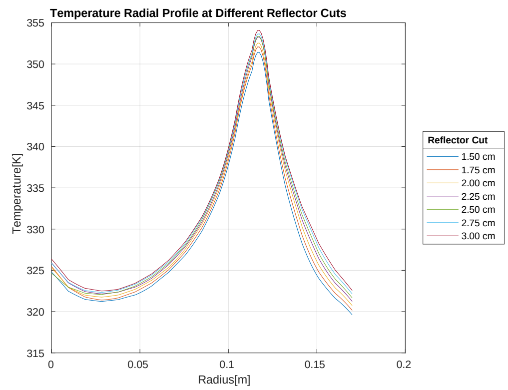


FIG. 4: Radial Temperature Profile at Different Reflector Cuts

where L_1 is the distance from the heater to the reflector and L_2 is the distance from the reflector to the test optic (at a point 5 cm away from the center). Setting $B = 0$ we can neglect the slope[10] and obtain an expression for L_2 depending on the position of the heater (L_1) and the ROC of the reflector:

$$L_2 = \frac{-RL_1}{R-2L_1} \quad (2)$$

In order to optimize the focus of the reflector we ran the model in MATLAB using different parameters. The best focus was achieved by ROC of 2.75 cm - 3.25 cm (see Figure 4) at a height of z = 3 cm rotated 30 degrees counter-clockwise. The COMSOL model assumes a gold-coated reflector and a heat source of 100W.

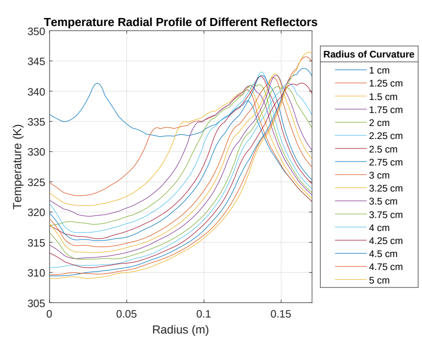


FIG. 5: (color online) Radial temperature profile obtained by using different ROCs for the reflectors

B. Experimental Setup

In order to analyze the surface deformation of a test optic cause by focused heating, we set up a 2-lens system which collimates a laser beam to a radius of 2.5 cm, goes through the test optic (10 cm diameter) and is focused to a spot of r = 0.6 cm in order to fit the CCD aperture of the Hartmann Wavefront Sensor (HWS). A neutral density filter (NDF) was used to account for the saturated pixels of the sensor. The beam's angle of divergence, $\theta = 0.125$ rad was calculated by measuring the beam radius at 2 different points on the propagation axis. The focal length of the lenses and their position were chosen using paraxial ray approximation (see Eq. 3,4).

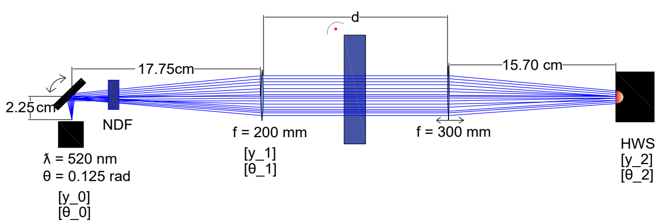


FIG. 6: (color online) Experimental setup

$$\begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} y_0 \\ \theta_0 \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} y_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} 1 & d_2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_2} & 1 \end{bmatrix} \begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix} \tag{4}$$

Solving for $y_0 = 0$ and $\theta_0 = 0.125$ rad, in order to collimate the beam ($\theta_1 = 0$), the distance of the first lens from the beam source must equal its focal length ($f_1 = d_1$).

$$\begin{bmatrix} y_1 \\ \theta_1 \end{bmatrix} = \begin{bmatrix} d_1 \theta_0 \\ \frac{\theta_0 (f_1 - d_1)}{f1} \end{bmatrix} \tag{5}$$

The beam's divergence angle and the desired radius of the collimated beam (y = 2.5 cm) determine the focal length of the first lens (f_1 = 200 mm). Similarly, we determine the focal length of the second lens (f_2 = 300 mm) to focus the beam to a radius of y_2 = 0.6 cm. To heat the test optic, we used a 31 mm long cartridge heater of 3 mm diameter. We powered it with a DC power supply of 120 V, running 180 mA of current through it. We will be using a 120V AC power supply for future measurements. The reflectors are semi-cylindrical with a height of 31 mm to fit the heater inside. We will test different ROCs for the reflector: 2.54 cm, 3.175 cm, and 3.81 cm. The reflectors are currently coated with Al foil, however we will try using polished Al and potentially polished Au for an even better focus.

The Hartmann Wavefront Sensor will be used to measure the optical path distance of the wavefront, providing information about the surface deformation of the test optic[11]. This data will then be used to calculate the overlap integrals of higher order modes to determine how much power is being lost through scattering[12]. If there is enough time in the end, we will create point absorbers on the test optic and use the heater to reduce optical losses into higher order modes.

IV. NEXT STEPS

In the next two weeks, we will take data using the HWS and analyze it to see if our approach was successful and suggest ways in which it can be improved. The semi-cylindrical design worked well in focusing the heat to about a 2 cm diameter, however we will try different ROCs and z-displacement values to get a better focus. The heater seems to have the heat concentrated in the center, which is causing a slightly non-uniform profile in the HWS, so we will account for this in the analysis and will wait for the heater to reach equilibrium for a longer time.

ACKNOWLEDGMENTS

I would like to thank my mentors Dr. Rana Adhikari, Dr. Aidan Brooks, and Dr. Jonathan Richardson for their help and guidance through all parts of the project.

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