Creation of flat-top and annulus beams for gravitational wave detectors using photothermal effects

Rachel Spreng[1,2], Muzammil Arain[2], and David Reitze[2]

[1] Department of Physics and Astronomy, Rowan University, Glassboro, NJ, USA

[2] Department of Physics, University of Florida, Gainesville, FL, USA

In the LIGO interferometers, one of the main noise sources in thermal Brownian noise in the coatings of the test masses. This noise is caused by random flow of heat in the system. Several methods have been proposed to reduce this noise. One of them is to use flat-top beams that enable better averaging over the beam size. This paper studies the use of CO_2 induced heating and electrical heating in the form of ring heaters to flatten the beam, thus reducing the thermal noise in the interferometer. Using this method, a Gaussian beam can be reshaped into either a flat-top beam or an annulus beam. Apart from application in LIGO, flat-top and annulus beams are desirable in laser material processing. This paper presents the results of this experiment, as well as a discussion of their significance to the LIGO project.

1. Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a scientific collaboration committed to the detection of gravitational waves. Gravitational waves are ripples in space-time, first predicted by Albert Einstein in 1917 in his general theory of relativity. They are produced by violent events in the distant universe, such as the collision of two black holes. Gravitational waves have not yet been directly detected, but their effects can be measured on astronomical objects. LIGO is only one of many organizations worldwide dedicated to the detection and harnessing of gravitational waves. It will ultimately be a tool in physics and astronomy, as well as a resource for understanding the nature of gravity.

As part of the LIGO group at UF, we are attempting to compensate for noise and aberrations of the system. Our group is part of Advanced LIGO, designing upgrades which will improve the functions of the LIGO interferometers. Typically, a Gaussian laser beam is used in gravitational wave interferometers, however, the thermal Brownian noise of the system can be reduced by using flat-top beams. D'Ambrosio et al. has proposed and studied the effects of flattening the beam by reshaping the mirrors in the optical cavity [1,2]. We propose the use of CO_2 induced heating and electrical heating in the form of ring heaters to produce flat-top and annulus beam shapes.

2. Theory and Experiment

In order to produce a flat-top beam, we propose the use of a beam shaping element, made of SF57 glass, with 4 heaters (on the top, bottom, left, and right), which creates thermal gradients in both the horizontal and vertical directions. SF57 used in this experiment is a 1 cm thick, 2.54 cm diameter cylindrical shaped element. Figure 1 shows a diagram of the SF57 with ring heaters (RHs), which was designed by members of the UF LIGO team.

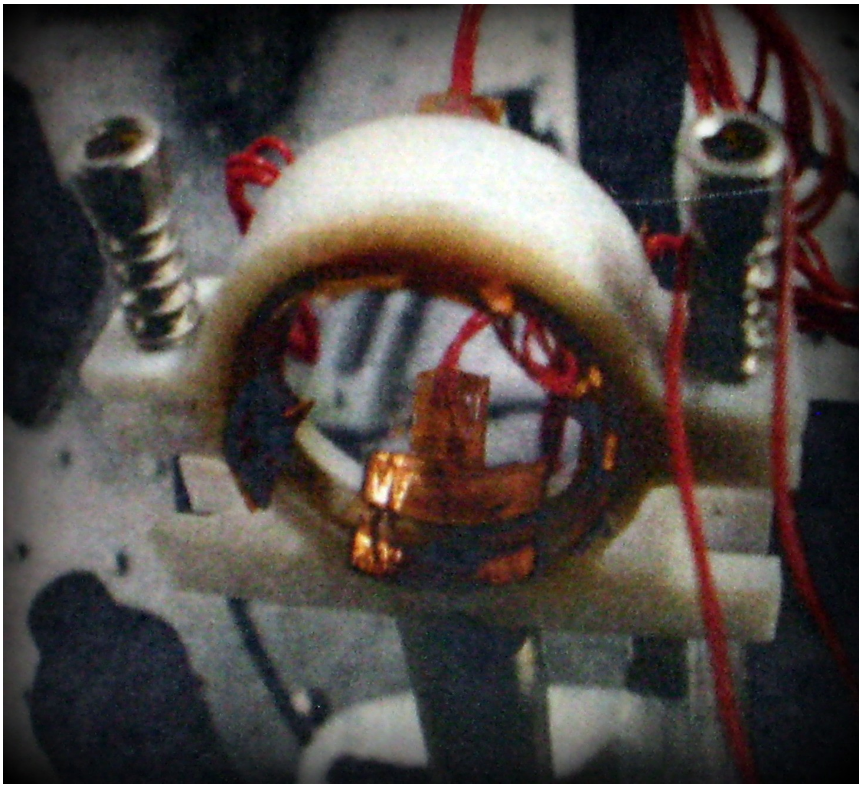

Figure 1: SF57 Glass with Ring Heaters

The proposed method is based upon using photothermal effect in optical elements. Photothermal effect is the change in physical properties of an optical element when it is heated. Specifically, heating an optical element produces change in refractive index of the material. Another effect is the thermal expansion of the material due to the coefficient of thermal expansion. Change in refractive index is proportional to the thermo-optic coefficient, dn/dT, of an optical element.

The optical path length of the material (OPL) can be defined as:

$$\mathrm{OPL} = \{n+dn/dT+\alpha(n-1)\}*d$$

where d is the thickness of the material, n is the refractive index at the room temperature, and α is the coefficient of thermal expansion. If we either heat the optical element at the center or from the edges, there will be a temperature gradient as shown in Fig 2a and 2b.

If we define S(x) as the optical path length difference between the beam passing through the center and the edge, we can write:

$$S(x) = \{dn/dT+\alpha(n-1)\}*\int_0^a T(x)dx$$

where a is the radius of the optical element. Thus we can create a positive or negative lens by heating the center or the edge of the optical element respectively. The optical material used in this experiment is SF57 which is a glass. The relevant properties are given in Table I.

Table I: Material properties of SF57

Property	Unit	SF57
Refractive Index *n* @ 1.06mm	-	1.81
d*n*/d*T*	10-6 K-1	6.8
Thermal Expansion	10-6 K-1	9.2

Figures 2a, 2b, and 2c demonstrate this effect. This causes the outer light rays to diverge differently than the central light rays, which changes the shape of the beam profile into a flattop or an annulus shape, depending on the strength of the positive lens (which is dependent on the power of the CO_2 beam). Figures 3a, 3b, and 3c shows the profiles for a Gaussian beam, a flat-top beam, and an annulus beam, respectively. These images are ideal beam profiles only.

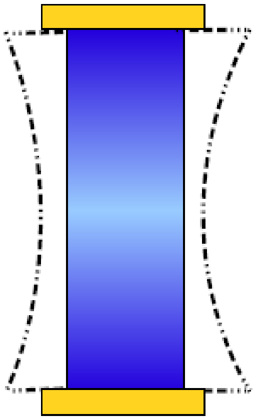

Figure 2a: Lensing effect of the ring heaters

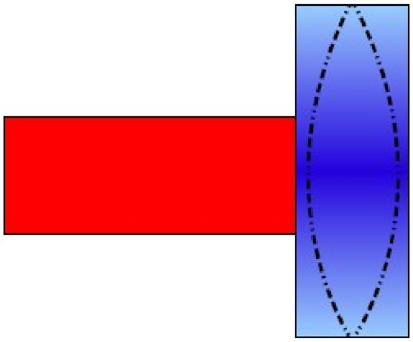

Figure 2b: Lensing effect of the CO_2 beam

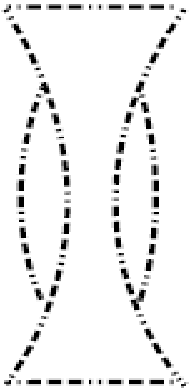

Figure 2c: Combined lensing effect

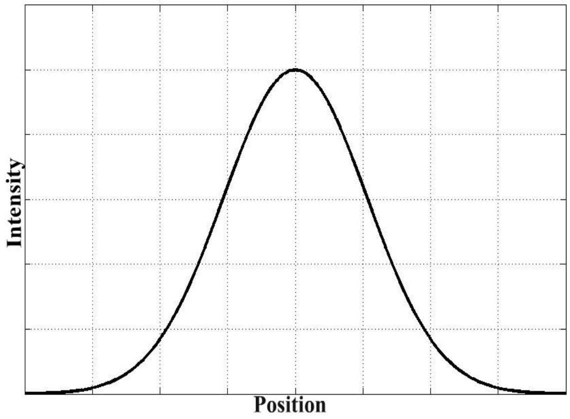

Figure 3a: Gaussian beam profile

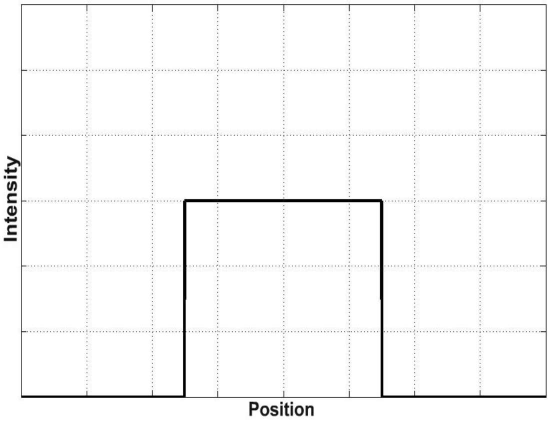

Figure 3b: Flat-top beam profile

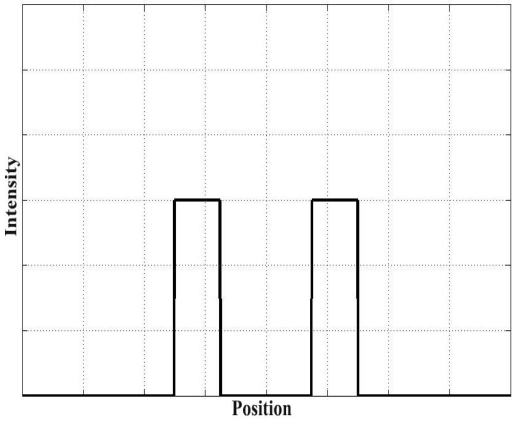

Figure 3c: Annulus beam profile

Before it can be reshaped, our probe beam must first be expanded through the use of lenses. The beam size hitting the SF57 is about 1 cm in radius. Here the beam is heated with RHs as well as using CO_2 beam. We selected CO_2 beam for heating because almost all the CO_2 power is absorbed in SF57. Next, the probe beam goes through a series of mirrors and other optical components. Finally, the beam is focused on a CCD camera using a lens. The lens creates a far field pattern at the CCD. We use CCD that allows us to observe the shape and quality of the beam. Figure 4 shows the setup of our experiment. The red and blue lines represent the paths of the CO_2 beam and the probe beam, respectively. Distances are not to scale.

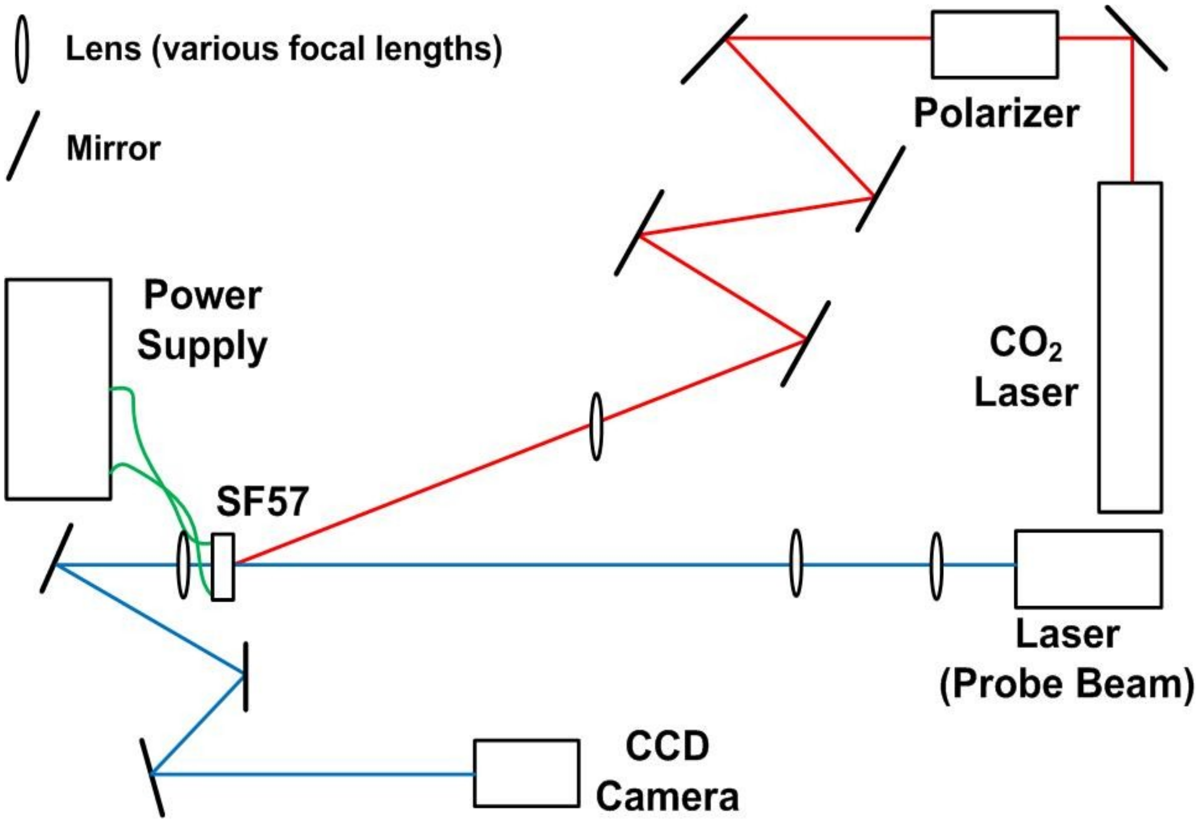

Figure 4: Experiment Setup

Once the optical setup was optimal, the first step in our experiment was to apply maximum power to the RH (~10 W). Using a thermal imaging camera, we then adjusted the power to each RH so that the heat was symmetrical. Then, we applied the CO_2 beam to heat the center. We then looked at images of the beam using a CCD camera, and used these images to find the optimal power of the CO_2 beam needed to create each beam shape. Figure 6a shows thermal images of the SF57 lens with power only to the RHs, while Figures 6b – 6e show thermal images with power to the RHs and the CO_2 beam. They look asymmetrical because we need to take the images from above so that the laser does not damage the camera. As the power to the CO_2 beam increases, you can start to see a red dot in the middle where the CO_2 beam is heating the lens.

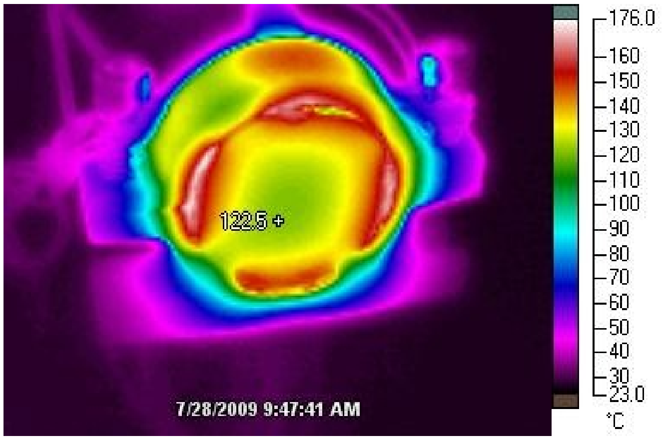

Figure 5a: Thermal image of SF57 with 10 W of power to RHs and no heat to CO_2 beam

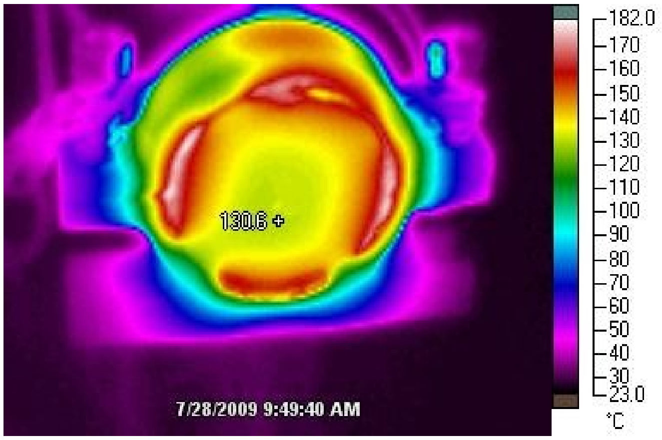

Figure 5b: Thermal image of SF57 with 10 W of power to RHs and 25 mW to CO_2 beam

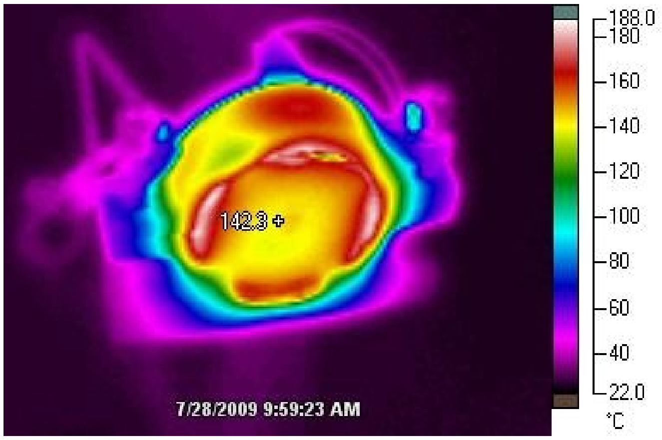

Figure 5c: Thermal image of SF57 with 10 W of power to RHs and 100 mW to CO_2 beam

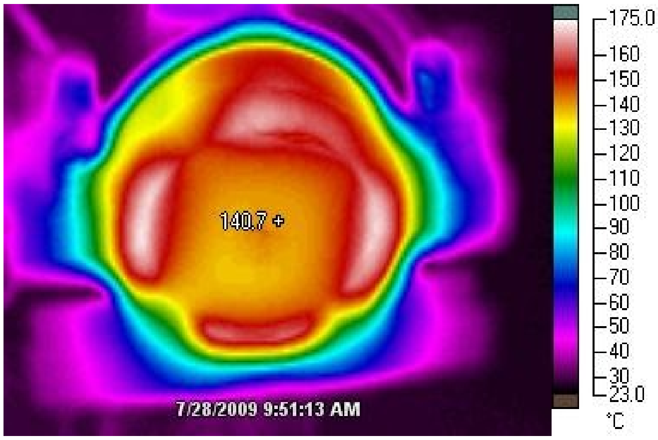

Figure 5d: Thermal image of SF57 with 10 W of power to RHs and 200 mW to CO_2 beam

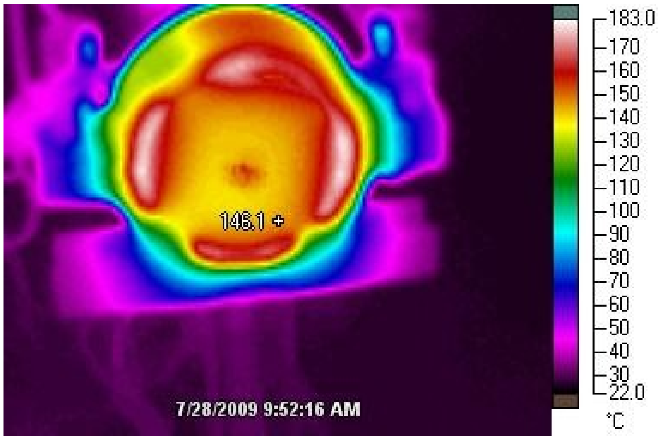

Figure 5e: Thermal image of SF57 with 10 W of power to RHs

and 400 mW to CO_2 beam

3. Results

Using this setup, we attained both a flat-top beam and an annulus beam. In order to get quantitative results, we measured the amount of power being supplied by the CO_2 beam. Figures 6a – 6f show beam profiles at several different CO_2 power levels. These power measurements were taken directly before the SF57. The numbers on the y axis have little meaning, the important thing is the relative levels of intensity and the overall profile shapes at different power levels.

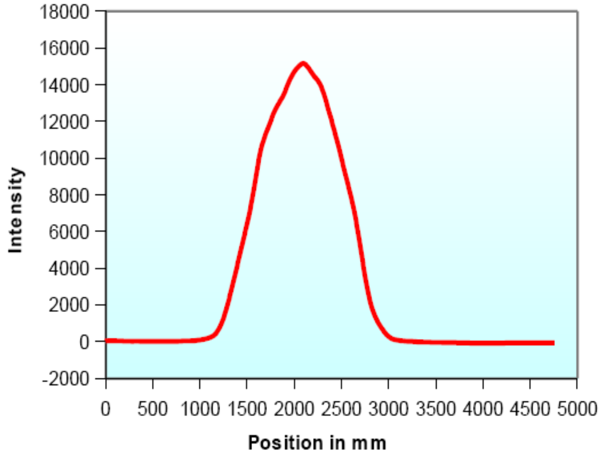

Figure 6a: No power

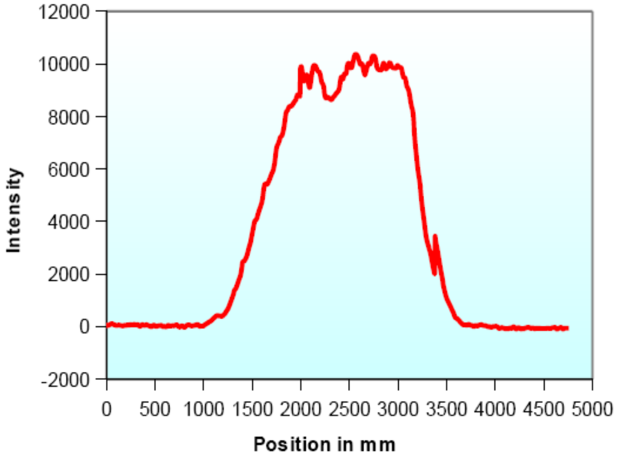

Figure 6b: 25 mW

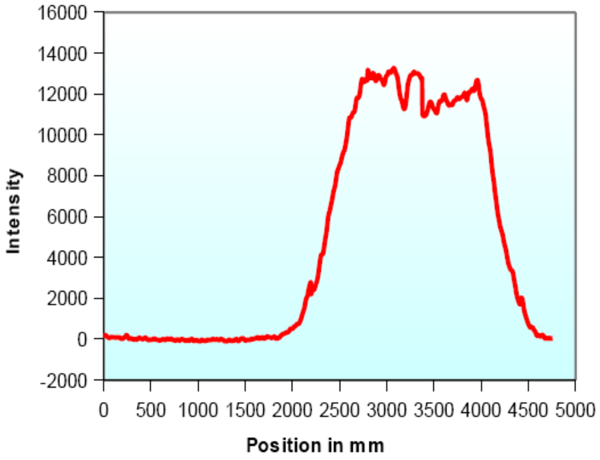

Figure 6c: 50 mW

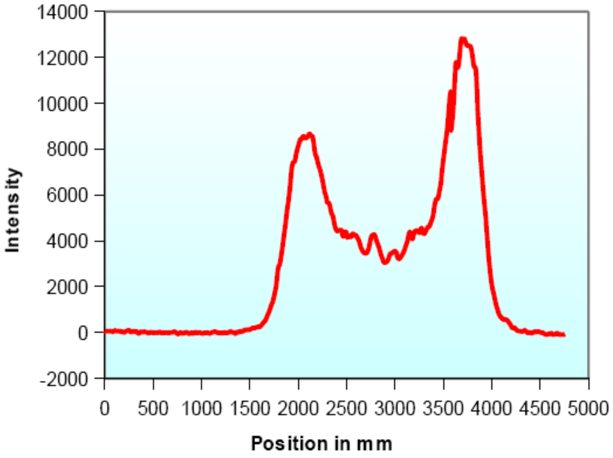

Figure 6d: 75 mW

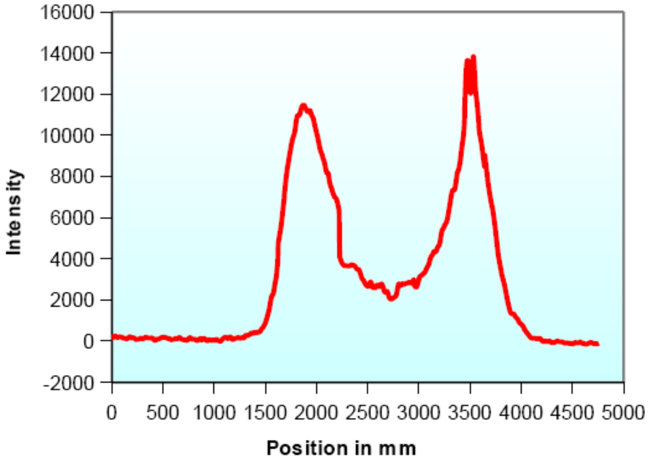

Figure 6e: 100 mW

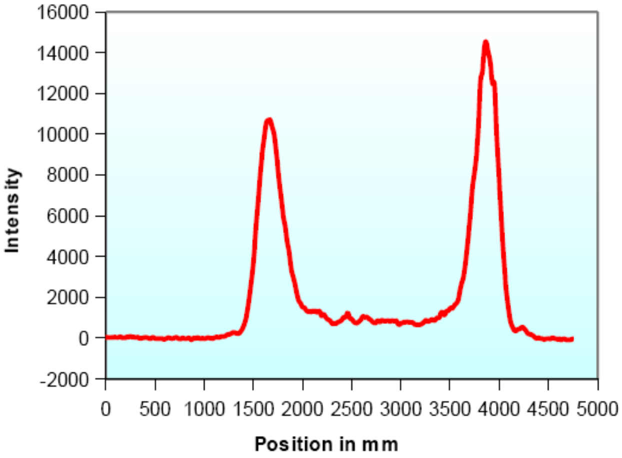

Figure 6f: 125 mW

4. Summary

This experiment used CO_2 induced heating and electrical heating to produce flat-top and annulus beams. Using this method, we obtained both flat-top and annulus beams by varying the power supplied by the CO_2 beam. We propose the technique of beam shaping presented in this paper as a method to reduce Brownian thermal noise in gravitational wave detectors such as LIGO. However, these beams have many applications in physics, because their intensity is more evenly distributed than a Gaussian beam. Laser material processing where the laser beams are used to drill or cut various materials is another important application where flat-top and annulus beams are helpful.

Acknowledgments

I would like to thank Prof. David Reitze, Dr. Muzammil Arain, and the rest of the UF-LIGO group for their support and guidance. I would also like to thank Prof. Selman Hershfield and Prof. Kevin Ingersent for running the REU program and the NSF for funding the program.

References

[1] E. D'Ambrosio, R. O'Shaughnessy, S. Strigin, K.S. Thorne, and S. Vyatchanin. “Reducing thermoelastic noise in gravitational-wave interferometers by flattening the light beams,” *arXiv.org e-Print archive,* gr-qc/0409075, 20 September 2004.

http://arxiv.org/abs/gr-qc/0409075

[2] Marco G. Tarallo, John Miller, J. Agresti, E. D'Ambrosio, R. DeSalvo, D. Forest, B. Lagrange, J. M. Mackowsky, C. Michel, J. L. Montorio, N. Morgado, L. Pinard, A. Remilleux, B. Simoni, and P. Willems, "Generation of a flat-top laser beam for gravitational wave detectors by means of a nonspherical Fabry-Perot resonator," Appl. Opt. **46**, 6648-6654 (2007).

http://www.opticsinfobase.org/abstract.cfm?URI=ao-46-26-6648