The Effect of High Intensity Laser Power on AlGaAs Coatings and the Implications for Thermal Noise Interferometers

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Abstract

We report on the damage threshold for crystalline coatings composed of alternating layers of gallium arsenide (GaAs) and aluminium gallium arsenide (AlGaAs). From this, we predict the lower limit of power that can be used on this AlGaAs coating without resulting in damage. We conclude that plans to use AlGaAs mirrors with small spot size lasers in the Thermal Noise Interferometer will not damage the coating.

PACS numbers:

I. INTRODUCTION

A. Gravitational Wave Detection

Experimental efforts to directly measure gravitational waves have progressed over the past 50 years [1]. Gravitational waves were predicted from Einstein's general theory of relativity, and are the events associated with the acceleration of mass. Any mass accelerating through space creates a spacial disturbance known as a gravitational wave, but they are small and often go unnoticed. Even events created by large and violent astronomical events have strain on the order of 10^{-21} so instruments need to be very sensitive. Gravitational waves are characterized by general relativity as fluctuating quadrupolar tidal strains in space, producing differential strains along perpendicular paths in space [10]. This strain can be measured by suspending mirrors some distance apart, and using laser interferometry to monitor their relative positions. LIGO achieves this with a Michelson interferometer, using a beam splitter, mirrors, and Fabry-Perot cavities in each arm. This setup is shown in Figure 1. LIGO interferometers have been taking data since the early 2000's, with the most sensitive displacement measuring devices in physics [2]. After years of planning improvements, the advanced interferometers began operating in September 2015 [6]. On September 14, 2015 at 09:50:45 UTC, the LIGO observatories in Hanford, WA and Livingston, LA, both observed the coincident signal GW150914 within minutes of data acquisition of the first Advanced LIGO science run [6]. On December 26, 2015, GW151226 was detected, and the third detection of GW170104 occurred on January 4, 2017 [7]. More are expected as observational runs continue. Estimates of strength and rate of gravitational wave events have been such that as improvements in sensitivity of components continue, so will the strength and rate of signals. Several detec-

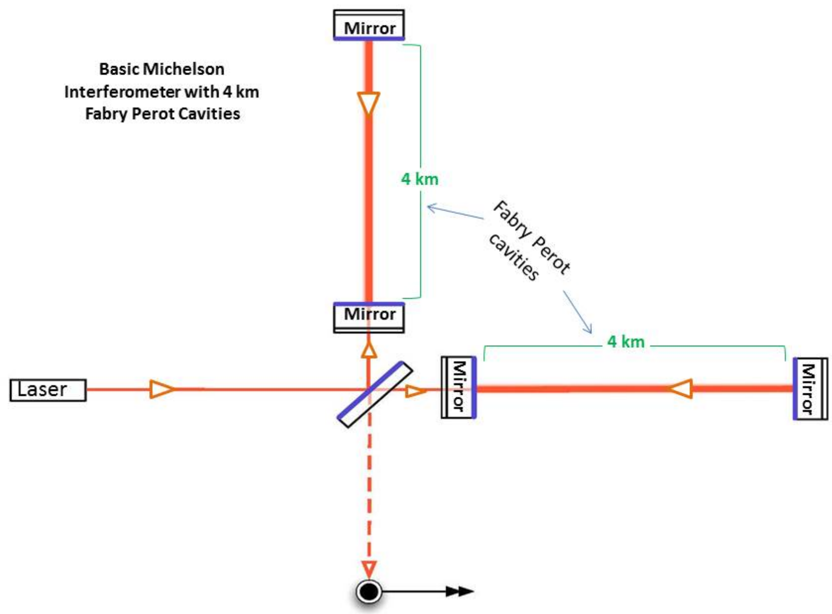

FIG. 1: A Michelson interferometer with Fabry-Perot cavities used to detect Gravitational Waves. When a Gravitational Wave passes through the interferometer, the stretching and compressing of the two arms create either a constructive or destructive interference pattern [14].

tions per year have already been recorded, and there still exists the possibility of multiple events per month [3].

While the sensitivity of detectors is limited by many factors, fundamental noise sources are the most limiting, as they are a property of the materials themselves and can not be removed from the system. The thermal noise from the mirrors and coatings set a limit at the frequency band of highest sensitivity [3]. The coating Brownian noise is the dominant of the various thermal noise sources on the test mass, which arises from mechanical dissipation in the coatings [5].

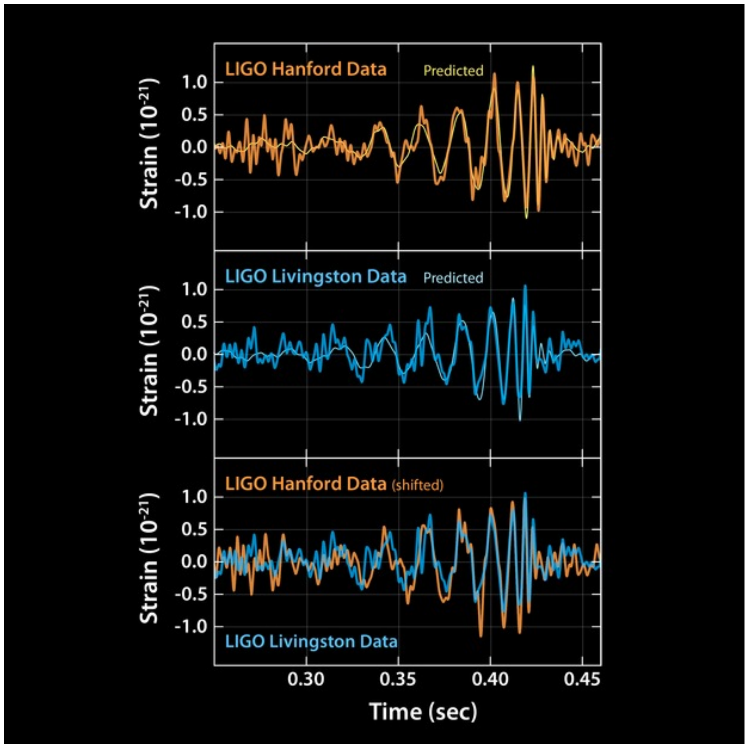

FIG. 2: First Gravitational Wave Detection by LIGO Observatories on September 14th, 2015 [14].

B. Reflective Coatings and Thermal Noise

To create the reflective test masses, optical coatings are applied to the surface. Multi-layer dielectric coatings are used to obtain high reflectivity. The alternating layers of dielectric materials have different refractive indices. The number and thickness of layers deposited onto the substrate determines its reflectivity [5]. The thermal noise amplitude of a substrate depends on several characteristics including the square root of the loss-thickness product and scaling inversely with the probing laser beam radius [10]. Brownian noise is therefore often limited by reducing the mechanical dissipation associated with mirror coatings, minimizing the required coating thickness, increasing the laser beam diameter, cryogenically cooling the system, or some combination [10].

While both generations of interferometers have used multi-layered mirror coatings with ion beam-sputtered amorphous silica and tantalum pentoxide, $Ta_2O_5$and SiO_2, because they give the necessary reflectivity and satisfy the limits on optical loss, future generations of detectors hope to use a coating with less Brownian noise. AlGaAs coatings, with gallium arsenide and aluminium gallium arsenide, show promising thermal noise and absorption properties, giving the necessary reflectivity and simultaneously satisfying the limits on optical loss required for the second generation interferometers [11]. These crystalline coatings are grown on bulk crystalline substrates with matching coating and substrate crystal structure and lattice parameters, then transferred to the Silica substrates. At 1064nm and at 1.5 micrometers, the coatings have a transmission of 15ppm, and a reduction in the Brownian thermal noise by a factor of three compared to currently used $Ta_2O_5$and SiO_2 coatings [11]. When used in detector conditions, with larger spot size, $Ta_2O_5$and SiO_2 coatings achieve 1ppm level total optical losses, and the AlGaAs coatings will reach a level below that [10].

Thermal noise is often studied indirectly in a laboratory by utilizing the fluctuation-dissipation theorem [4], as this is easier than the direct measurement of thermal noise. The fluctuation-dissipation theorem states that thermal noise depends on the loss of a system, characterized by the mechanical loss, ϕ, which also determines the Q of various resonant modes, where a higher Q is correlated with lower thermal noise. However, Thermal Noise Interferometers (TNI) exist to measure the thermal noise of a system directly. Built as cavities in suspension, these interferometers can measure thermal noise in a frequency band from 10Hz to 50kHz, limited from below by seismic noise and above by photon shot noise [12].

LIGO observatories and the 10m prototype use beams with large spot sizes in their tests, and therefore do not worry about the breakdown of AlGaAs coatings. However, in order to measure the thermal noise of the coating, the TNI will use a small spot size with a high power laser, creating a small spot of high power density on the coating. Concern was expressed that the maximum power density with a small spot size would damage the AlGaAs coatings.

The Thermal Noise Interferometer will be using the AlGaAs coating to test thermal noise in the test mass mirrors, suspension systems, and control electronics [12]. A TNI is built by suspending two masses in order to isolate them from seismic noise. These suspended masses are used to create an optical resonating cavity. Once the cavity is locked, the movement detected in the cavity is a direct result of thermal noise [12].

C. AEI 10m Prototype

The Albert Einstein Institute in Hannover, Germany, is currently building a 10 meter prototype interferometer [9]. The AEI facility will use advanced techniques to perform research for future gravitational wave detectors. Advanced gravitational wave detectors are incredibly sensitive, but because their sole purpose is to detect gravitational waves from space, their incredible sensitivity is not available for quantum mechanical research. Prototypes, like the AEI 10m prototype, has been designed to further increase the detectors' sensitivities, while focusing on both technical advancements and quantum mechanical questions [9].

Designed for easy vacuum pump down and access to multiple experiments at once, the AEI prototype has an ultra-high vacuum system. There are seven crucial components to the prototype, with the major goals of designing and building an apparatus able to reach the standard quantum limit and conduct a wide range of tests using sensitive interferometry [9].

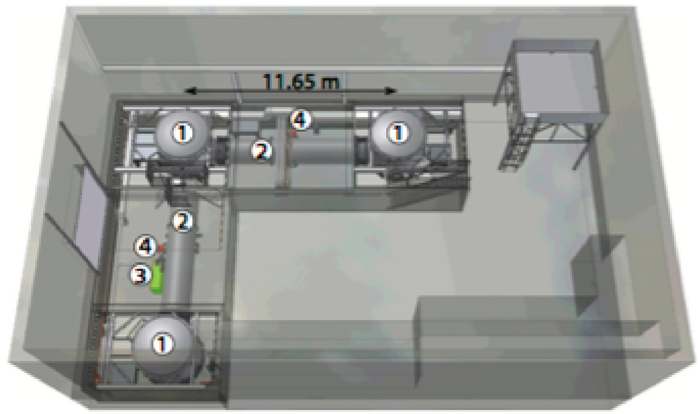

FIG. 3: A diagram of the AEI 10m prototype, where 1 denotes the "walk-in" tanks, 2 denotes the 1.5m diameter tubes in an L-shaped configuration of 11.65m arms, 3 denotes the screw pumps for fast pumpdown and 4 denotes the turbo-pumps [9].

A large, ultra-high vacuum system is set up with the same geometrical design as LIGO observatories, three tanks 3.4 meters high and 3 meters in diameter are connected by 1.5 meter diameter tubes create a large L-shape. This system is then able to be pumped down to 5Pa within two hours, followed by a pump down to $10^{-}6$hPa within 10 hours. While this vacuum is enough to conduct most tests, the prototype can be pumped down to less than or equal to $10^{-}7$hPa within a week if needed. A diagram of the prototype can be found in Figure 3. The tables that reside within the tanks are designed to be isolated from the seismic noise of the ground. This happens with optical benches in each tank, with local sensors and Suspension Platform Interferometers, which create additional active isolation at low frequencies [9]. Noise is limited with isolation for both the pitch and yaw directions of motion. A Suspension Platform Interferometer forms a virtual connection between the center table and the two end tables, which actively controls the positions and angles of the tables in the low frequency range [9].

The system is controlled digitally through a Control and Data System (CDS), which offers more flexibility of control over each component while the system works together. The system is orchestrated by a digital CDS developed at California Technical Institute to operate the Advanced LIGO detectors [9].

Laser power is often a limitation on the sensitivity of high precision interferometry called shot noise. In order to limit this noise, the prototype uses a highly stable, high power laser and a monolithic non-planar ring oscillator [9]. While this design is stable, a frequency reference is needed. This is created with a triangular optical cavity, formed between the three mirrors. This yields a round trip length of 21.2 meters and a finesse of the cavity of 7300, illuminated with 130mW of input power [9]. The Pound-Drever-Hall sensing scheme is used to match the laser frequency to the cavity length, which maintains the resonance and subsequently full sensitivity. The optics are a crucial aspect of any interferometric detector, and therefore also with the prototype. The interferometer is designed on a 10m scale, optimized to be dominated by quantum noise in the measurement band around 200Hz, which makes it possible to conduct macroscopic quantum mechanical experiments [9]. For more details about the construction of the AEI 10m prototype and the subsystems involved, see the paper Design of the 10m prototype facility for interferometry studies by Westphal *et al.*

D. Optical Resonating Cavity

We investigated the effect of directing a high power laser with a small spot size onto an AlGaAs coating. We did this by directing laser power through a resonator cavity and lens system to create a small spot size onto the coating. Linear optical resonators, called cavities, are formed by two partially-

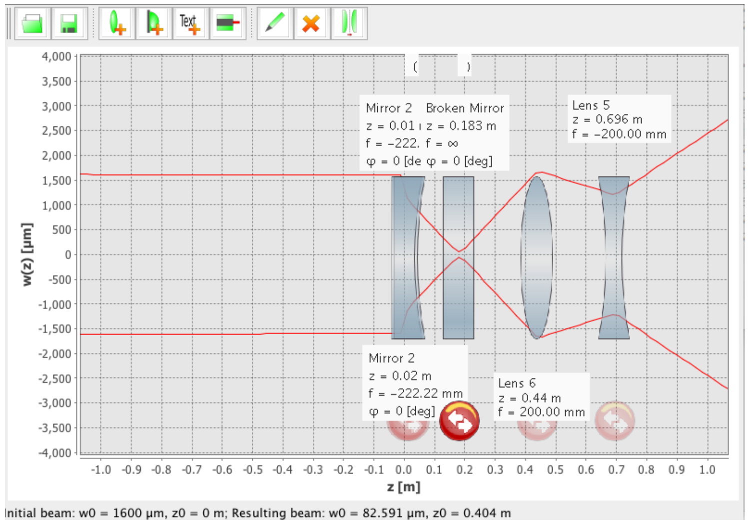

FIG. 4: An example of a JAMMT cavity model, with two mode matching lenses.

transparent mirrors arranged in series [8]. This allows for the laser power to build in the cavity until it is high enough to burn the test coating.

A cavity is considered stable if the focal points of the mirrors and the distance between the mirrors are such that the internal beam does not grow in size as it is continually reflected. When a cavity is stable, the beam will remain entirely between the mirrors [15]. The stability of a cavity depends on the length of the cavity, which is dictated by the radii of curvature of each mirror. We used a hemispherical cavity to be able to focus down the laser to a the smallest beam size possible on the flat mirror.

We used the computing tool Just Another Mode Matching Tool (JAMMT) to model the size of the cavity before constructing it. We used this program to calculate the mode matching of the cavity. Mode matching is used to ensure cavity stability, using lenses to shape the beam before it enters the cavity so that it may be ideal for resonance. We designed a model that provided the smallest spot size within the cavity.

II. BACKGROUND

A. Theory

Lasers are a useful tool in the study of optical coatings and small measurements. LIGO uses lasers to observe very small changes in the fabric of spacetime. GEO600, a smaller observatory in Germany uses optical resonating cavities to increase the power of their laser [18]. Damage Threshold testing is a common way to determine the point at which a coating will begin to break down. ThorLabs conducts damage threshold tests on their reflective coatings to give an upper limit where they begin to breakdown [13]. AlGaAs degradation tests have previously been conducted with a wide beam laser. Tests done on AlGaAs coatings with a small spot size, and therefore a small, high intensity beam, are limited. General damage Threshold testing on AlGaAs coatings is also limited, and tests on these coatings in the past have not produced consistent results. AlGaAs damage tests with beam waists on the order of micrometers are limited because at this size dust is often burned by the laser and mistaken for coating damage. Therefore, these tests need to be conducted in clean-room conditions.

Optical resonating cavities reflect the laser off of a second mirror, so that the laser is reflected between two lasers several times before reaching the final mirror at full power. Optical resonators are defined by the propagation length between the two mirrors, D, the amplitudes of reflectivity of the mirrors, $r1$ and $r2$, and the amplitude of transmittance of the mirrors, $t1$ and $t2$. A basic layout of a cavity is the Fabry-Perot interferometer. The behavior of the cavity is determined by the wavelength of the laser lambda, the reflectivity of the mirrors, and the length of the cavity L. The maximum power of the cavity is obtained when the cavity is at resonance. Cavity resonance occurs when the total length the laser travels is an integer multiple of the wavelength injected into the cavity. The resonance for laser frequencies is reached when

$$f_r = N \times FSR \tag{1}$$

where FSR is the free-spectral range of the cavity, the distance between the resonances of the cavity, and N is an integer. Another important calculation is the finesse of the cavity, which can be calculated by

$$F = \frac{FSR}{FWHM} \tag{2}$$

where FWHM is the full width at half maximum of the cavity. Finesse can also be calculated as such

$$F = \frac{2\pi}{1-\rho} \tag{3}$$

where ρ is the fraction of power left after the laser travels once through the cavity. For more detailed proofs of these equation derivations, see the paper Interferometer Techniques for Gravitational-Wave Detection by Freise *et al* [8]. The finesse of the cavity can then be used to calculate the power, and subsequently, the intensity on the coating.

There are five types of stable cavities, as seen in Figure 5 [15]. In this experiment we built a hemispherical cavity, with the AlGaAs coated flat mirror and curved 10 cm mirror, in order to create the smallest possible beam waist inside the cavity.

The waist of a beam is the smallest point in the beam. This can be calculated by using Equation.

$$\omega^2(x) = \omega_0^2[1 + \frac{\lambda x}{\pi\omega_0^2}]^2 \tag{4}$$

where ω_0 is the beam radius at $x = 0$, and λ is the wavelength.

The divergence of a Gaussian beam is calculated by

$$\theta = \frac{\lambda}{\pi\omega_0} \tag{5}$$

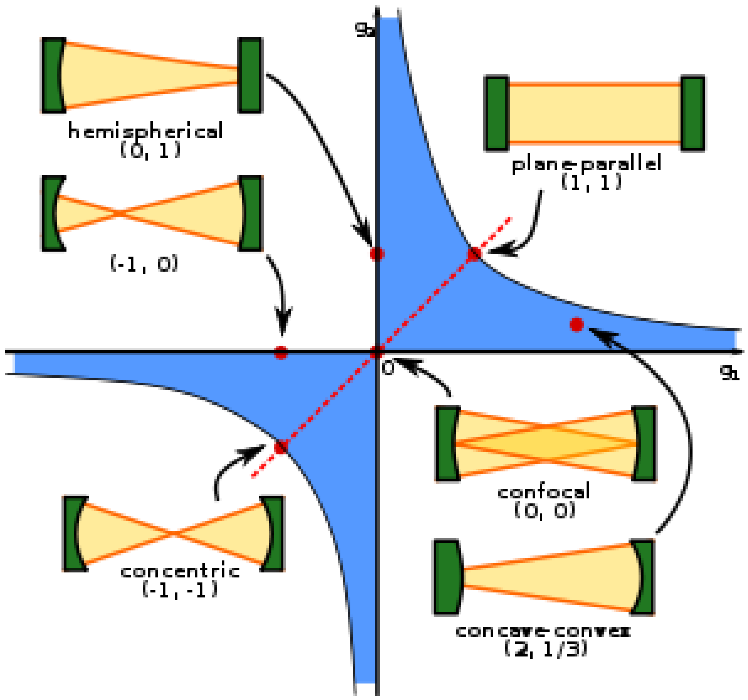

FIG. 5: Five possibilities for a stable cavity [16].

which can be rearranged in order to calculate waist size

$$\omega_0 = \frac{\theta\pi}{\lambda} \tag{6}$$

where

$$\theta = \frac{d_2 - d_1}{z_2 - z_1} \tag{7}$$

as seen in Figure 6.

The peak intensity of a Gaussian beam is calculated by

$$I_0 = \frac{2P}{\pi\omega_0^2} \tag{8}$$

where P is the total power within the cavity and ω_0 is the waist size of the Gaussian beam. The effective diameter of a Gaussian beam is given by

$$d_0 = \frac{2f\lambda}{D} \tag{9}$$

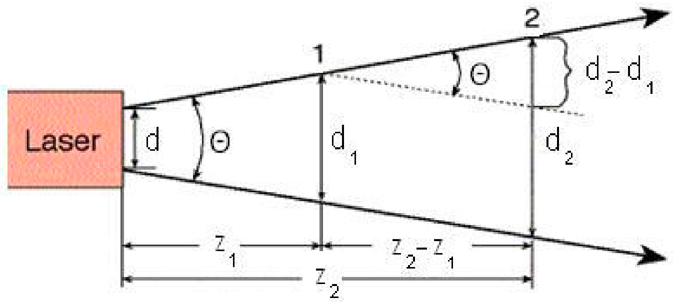

FIG. 6: Divergence of a Gaussian Laser Beam [17].

The total power reached in the cavity, P, is calculated by multiplying the transmitted power through the cavity and the transmission of the mirror.

We detected the transmitted power through the cavity on the photodiode, having calibrated it to power using the power meter.

B. Cavity Lock

In order to take effective damage measurements, we need to be able to lock the cavity. This is another way to describe the stability of a cavity. In order to check for lock, we used a feedback loop. The components of this loop were an oscilloscope, an SR560, an offset box, and the laser. The oscilloscope has two channels and is used for viewing the feedback. The SR560 has channels A and B, calculates A-B and can be used adjust filtering and gain. The offset box was used to find the initial TEM_{00} mode before using the SR560 for locking. See figure 7 for the feedback loop schematic.

Before locking with the feedback loop, the TEM_{00} must be in the system. An optical cavity will have many different TEM modes, as seen in Figure 8, and fine tuning can amplify the TEM_{00}.

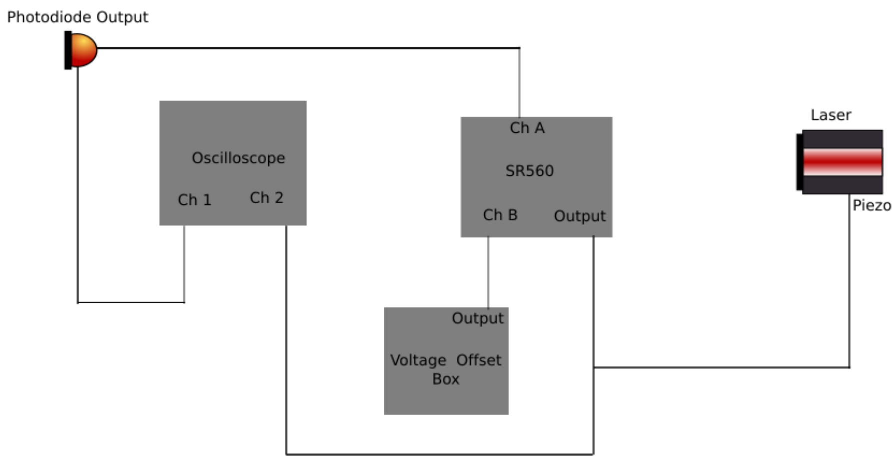

FIG. 7: The output of the photodiode is connected to both channel 1 of the oscilloscope and channel A of the SR560. The voltage offset box connects to channel B of the SR560, channel 2 of the oscilloscope, and the piezo of the laser. The oscilloscope is used as a display of the system.

III. EXPERIMENTS

A. Method

We tested the damage threshold of the AlGaAs coating by creating a optical resonating cavity. The resonating cavity was set up with a 98 percent reflective mirror with a 10cm radius of curvature and a flat mirror coated with AlGaAs. This cavity created a finesse of roughly 200. The laser beam was collimated over a 2 meter length by a lens of 500mm focal length, resulting in a beam of 1.6 micrometers. We then sent this beam through two quarter and two half wave plates, a Faraday Isolator, and a beam splitter, as shown in Figure 9. A Faraday Isolator was used to allow the laser light to pass through in only one direction. The rotator of the Faraday Isolator sits between two prisms

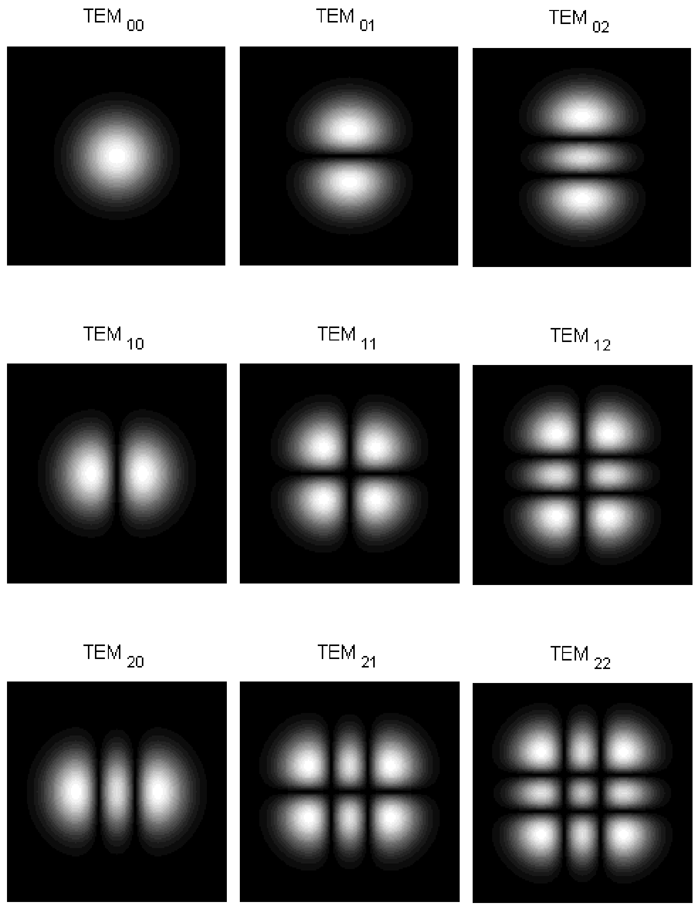

FIG. 8: The possible TEM modes of an optical resonating cavity [19].

at 45 degrees, which successfully protects against back-reflections of the laser light. Quarter and half wave plates were used to ensure that the correct polarization of light entered the Faraday Isolator and no laser power was lost. The polarized beam splitter has an AR coating idealized for 1064nm light, and is used to separate the s- and p-polarizations of the laser beam, reflecting the S component and allowing the P component to pass. This ensured that a the laser beam was fully characterized at maximal power at the end of the setup. The cavity was mode matched by JAMMT to create a final beam waist size

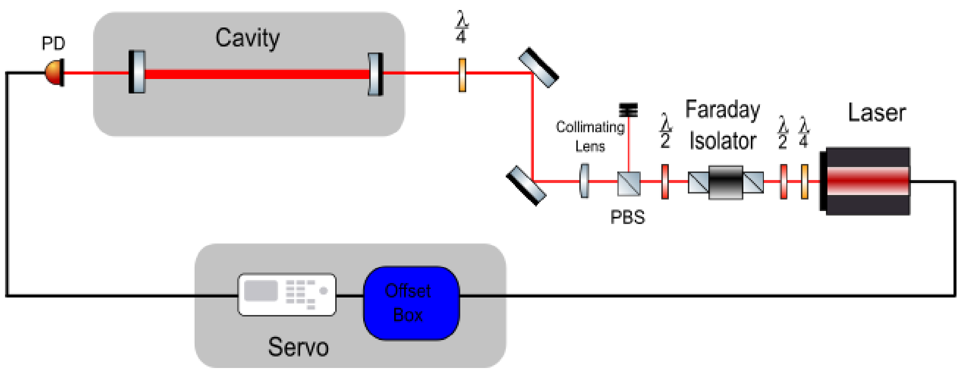

FIG. 9: The optical resonator used to conduct damage threshold tests on AlGaAs coatings.

of 20 micrometers, with a cavity length of 10.6cm.

We calibrated the photodiode using the power meter. We found that when .42mW was transmitted through the cavity, the oscilloscope read 2.2V. This meant that the oscilloscope read .19mW per volt in transmission.

When full power was directed into the cavity and it reached stability, 1V, or .19mW in transmission, was recorded on the oscilloscope.

We determined the precise waist size of the beam in the locked cavity by using a WinCam. A WinCam is a sensitive camera that is easily placed in the laser path. We used a WinCam to characterize the beam 15.4cm after the cavity, 21.4cm after the cavity, and 41.4cm after the cavity. Figure 10 shows the images from the WinCam. We plotted these values against the diameter of the beams at each location, see Figure 11.

The slope value of this plot is the divergence of our Gaussian beam.

B. Results

The divergence of the beam was found from the slope of the plot, θ=.0143. Using equation 6 and the divergence, we calculated the waist of the beam

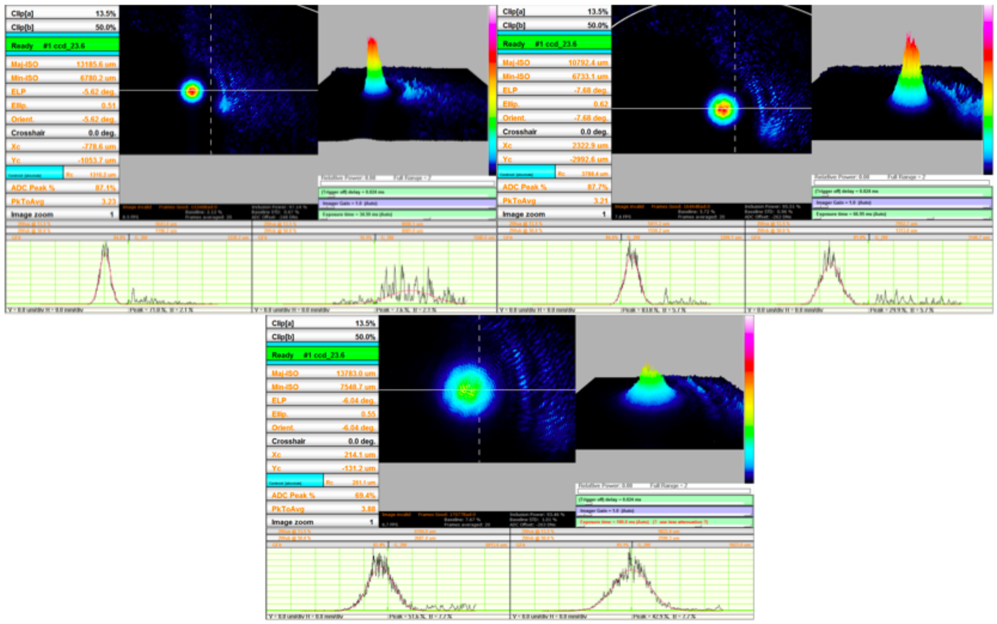

FIG. 10: Images from the WinCam at 15.4cm (left), 21.4cm (right), and 41.4cm (center). Under each beam image is the Gaussian fit to the beam profile.

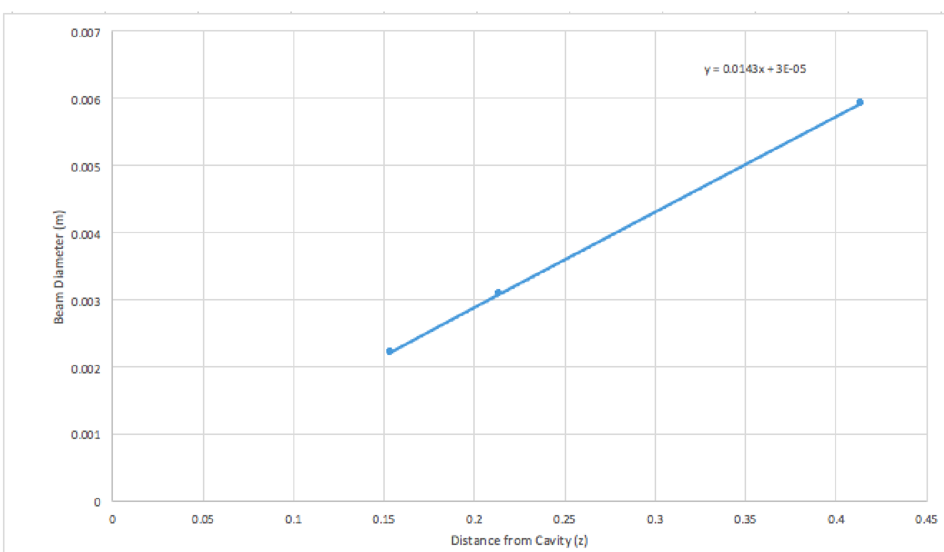

FIG. 11: The diameter of the beam versus the distance from the optical cavity.

ω_0=42.22 micrometers. The power within a cavity can be calculated by multiplying the transmitted power through the cavity and the transmission of the mirror. With the recorded transmitted power of.19mW and transmission of the mirror as 15ppm, the total power within our cavity was calculated to be P=28.5W. We then used this value to find the total power density on the AlGaAs coating using equation 8, which resulted in I_0=4.07 MW/cm^2 intensity. The cavity did not break from lock at this intensity. However, to confirm that this meant the coating was not damaged, we examined the coating under microscope. The mirror was not damaged at this intensity.

IV. IMPLICATIONS

The TNI is still under construction, and because it has not been finalized, there are no exact calculations on the characterization of the cavity that will be created. However, it is unlikely that it will create a power density higher than what we tested. A lower limit for AlGaAs coatings has therefore been tested and the AlGaAs coatings will not be damaged during use in the TNI. Future work may be done to set an upper limit for AlGaAs damage.

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