Improving the Sensitivity of Gravitational Wave Interferometers

Mesa Beams & Mexican Hat Mirrors

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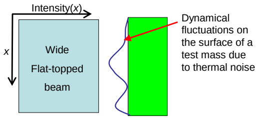
We aim to reduce the effects of test mass and coating thermal noise in interferometric gravitational wave detectors by reshaping the light beams and mirrors in the arm cavities.

1. Motivation and expectation

Considering thermal noise, a Gaussian profile is non-optimal.

Gaussian beams provide a poor spatial average of dynamical thermal fluctuations.



Intensity(x)

x

Wide

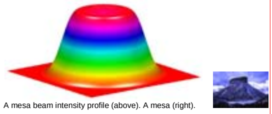
Flat-topped

beam

Dynamical fluctuations on the surface of a test mass due to thermal noise

A wide, uniform intensity beam better averages thermal fluctuations.

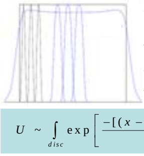
Intuitively one might expect a wider, flat intensity profile, beam to better average these fluctuations, thus reducing noise. This turns out to be the case.



A mesa beam intensity profile (above). A mesa (right).

The mesa beam (so called due to its similarity to mesa land forms in the south-western United States) may be thought of as a superposition of narrow Gaussian fields.

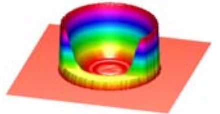
The width of the Gaussian functions used represents a compromise between flatness of top and diffraction losses.



One can think of a flat-intensity beam (black) as being composed of a superposition of infinitely narrow Gaussian beams. Increasing the waist of these beams we reduce both diffraction loss and uniformity of intensity. The mesa beam (blue) is given by using a waist size which gives a reasonable compromise between these effects. The mesa field at a cavity mirror is given below.

$$U \sim \int_{disc} \exp\left[\frac{-[(x-x_0)^2+(y-y_0)^2][1+i]}{2w_0}\right] dx_0\,dy_0$$

The mesa beam is supported by a non-spherical mirror, commonly known as a Mexican hat mirror due to its central bump and steep 'brim'.



An experimental map of our 'Mexican hat' mirror with cutaway.

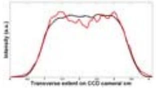
We expect the impact of total thermal displacement noise to be reduced by a factor of ~2 for a single test mass, without increased diffraction loss.

Noise source	**Fused Silica (34x20cm)**
Coating Brownian	~1.9
Substrate Brownian	~1.6
Coating Thermoelastic	~1.9
Substrate Thermoelastic	~2.2

Reduction in displacement noise relative to a Gaussian beam (in m/(Hz)$^{1/2}$) for a single fused silica test mass.

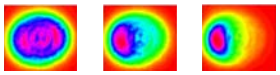
2. Experimental work

Representation of experimental apparatus. We are interested in how a standard Gaussian input beam transforms into a mesa mode.



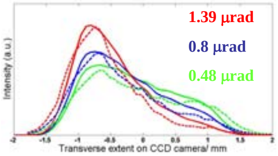
Left: Experimentally obtained intensity map. Above: A comparison of obtained (red) and expected (black) profiles.

Above we show the intensity profile routinely achievable with current set-up (red). We believe that deviations from the expected profile (black) are principally due to non-optimal cavity alignment and the imperfect optics currently in use.



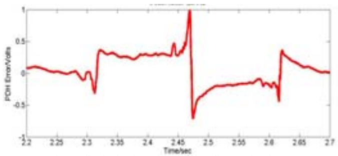
Experimentally obtained intensity maps as a function of mirror tilt.

As the response of mesa beams to mirror tilts differs from that of a standard Gaussian beam (which remains Gaussian for small tilts) we investigated the mesa beam tilt sensitivity.



Comparison of FFT simulated (solid) beam profiles and experimental data (dashed) for three values of Mexican Hat mirror tilt.

The above shows the good agreement between experimental data and intensity profiles obtained via Fox-Li FFT simulations.



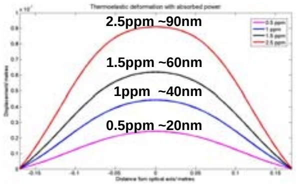
Experimentally obtained Pound-Drever-Hall error signal.

Future work will continue to test techniques which are well-known for Gaussian beams. For instance, Pound-Drever-Hall locking (experimental error signal above) has recently been implemented.

3. Thermal effects and thermal noise

Thermoelastic deformation

We are interested in the deformation of the resonant mesa mode as the test masses change shape thermoelastically due to absorbed optical power. A Gaussian beam maintains its Gaussian profile under a thermal load.



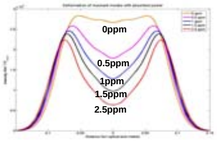
Thermoelastic deformations for various absorbed powers have been found (above). Peak deformation is significantly reduced with respect to the equivalent Gaussian beam.

Thermal Compensation System

An idealised thermal compensation system might involve depositing a mirror coating which counteracts the above deformation, only taking the correct profile under heating. This heating could come from an external source during lock acquisition or the circulating arm power during science mode. This technique is equally applicable to spherical mirrors.

Resultant arm cavity mode

If no compensation is employed the arm cavity mode will deform as shown below.



The arm cavity mode resulting from the above thermal deformations

Thermal noise

Absorption/ ppm	Equivalent strain noise x10^{21} (Hz)$^{1/2}$/m
0 Gaussian	4.38
0	2.41
0.5	2.28
1	2.21
1.5	2.16
2.5	2.09

Mirror thermal noise for mesa beams as a function of absorbed power. Gaussian beam included as a reference.

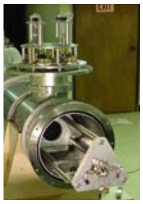
In contrast to a Gaussian beam, preliminary results show that the thermal noise of the thermally deformed mesa beam is reduced. Although not intuitive, similar effects have been seen with Bessel and high order Laguerre-Gauss beams. However these deformed beams have a poor overlap with the Gaussian beams outside the interferometer's arms.

4. Conclusions & Future Outlook

We have transformed a TEM_{00} Gaussian input beam into predominantly flat topped beam by means of a non-spherical Fabry-Pérot optical resonator.

The tilt sensitivity of the mesa mode has been experimentally studied. Results are in accord with simulation.

Thermal effects have been modelled. The intensity profiles in an arm cavity with thermoelastically deformed mirrors have been found. The thermal noise of these beams, in all its forms, has been found to be lower than that of the non perturbed eigenmode, at the cost of higher diffraction losses.



End view of current cavity.

Present cavity structure.

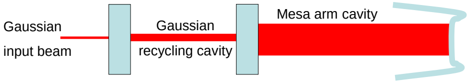
The natural progression of this work is to add some of the complexity found in modern interferometers

The next experimental steps will involve

-wavefront sensing – current apparatus

-recycling (three-mirror coupled cavity) – enhancement of existing cavity

-Investigations into concentric cavities – ~100m cavity required



Gaussian input beam

Gaussian recycling cavity

Mesa arm cavity

Schematic of future power recycling cavity. Here we look at a coupled cavity system where the fundamental mode of each cavity is different.

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