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Use of mesa beams to reduce thermal lensing effects inside the arm cavities

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Use of mesa beams to reduce thermal lensing effects inside the arm cavities

Jérôme Degallaix [1] (2006)

Abstract

In this report, thermal lensing effects for the arm cavities of advanced interferometers are simulated for both Gaussian and mesa beams. The use of mesa beams as cavity optical modes can slightly reduce the decrease of the circulating power due to thermal lensing compared to Gaussian beams. For both Gaussian and mesa beams, and for less than 1 MW of circulating power, the optical gain of the arm cavity decreases by less than 1.5% due the coating absorption from the input and end test masses, therefore we conclude that thermal lensing compensation is not necessary for thermal lensing generated inside the arm cavities.

1 Introduction

The use of mesa beams (also called flat beams) instead of Gaussian beams inside the arm cavities of interferometric gravitational wave detectors has been proposed to reduce the test mass thermoelastic noise [1]. For equivalent optical powers, mesa beams present a lower central energy density and wider radius compared to the classical Gaussian beams. Hence, the use of mesa beams allows a better spatial averaging of the test mass surface fluctuations due to thermal noise. Intuitively, we can also expect that the wavefront distortion induced by the residual optical absorption inside the substrate and coating of the test masses can also be reduced by using mesa beams instead of Gaussian beams. Indeed the relative low energy density of mesa beams can effectively reduce the gradient of temperature within the test mass due to the partial absorption of high optical power laser beams. By reducing the gradient of temperature, the wavefront distortion induced by the thermo-optic effect and the thermal expansion of the surface of the test mass can be attenuated. To confirm our intuition, we developed numerical simulations to demonstrate the superiority of mesa beams compared to Gaussian beams regarding the thermal lensing issue.

This report is organised as follow: first we present the parameters used to simulate the arm cavities and then we briefly explain our numerical tools. Second, thermal lensing effects for the arm cavities of the interferometer are described for both mesa and Gaussian beams. Then, we succinctly explore the possible advantage of using fused silica test mass at low temperature. Finally, some concluding remarks are made.

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2 Parameters of the simulations

Two steps are necessary to simulate the effects of thermal lensing in a Fabry Perot cavity. Firstly we used a finite element package to simulate the temperature distribution within the test mass substrate and the mechanical deformations of the test mass surfaces due to the partial absorption of the laser beam. Secondly, we load the mechanical deformations of the reflective coating of the test masses into an FFT optical code. The FFT code can calculate the circulating power inside the cavity as well as the resonant mode profile which is distorted due to the deformations of the mirror surfaces.

2.1 Parameters of the arm cavity

In our simulations, we used the parameters of the Advanced LIGO arm cavities. The cavity is 4 km long and the substrates of the two mirrors are in fused silica. The two mirrors have a diameter of 34 cm and are 20 cm thick. We suppose that the high reflective coating applied on the test mass has a diameter of 32.5 cm. The optical absorption of the coating is set to 0.5 ppm.

The ITM has a reflectivity of 0.995 and the ETM is considered to be totally reflective. The round trip loss inside the cavity, excluding the ITM transmission and the diffraction loss, is 70 ppm [2]. In theses conditions, the cavity gain is 771.6.

To have a Gaussian fundamental resonant mode inside the cavity, we used a spherical mirror profile for the reflective side of the test masses. The radius of curvature of the test mass is set to 2076 m. For the mesa beam, we use a near concentric mesa beam as described by Agresti et al. [3]. Using the same notation as Agresti, the radius of the mesa beam is $3.45w_0$. Both mesa and Gaussian beams resonant mode have the same diffraction loss of 2.2 ppm per round trip. The intensity profiles of both Gaussian and mesa beams on the cavity mirror are presented in figure 1.

During our simulations, the size and position of the waist of the input laser beam is kept constant and is coincident with the cold cavity waist.

2.2 Finite element modeling simulations

The software ANSYS is used for our finite element simulations. The test mass is represented in 3 dimensions and with a 16000 nodes meshing. The mechanical deformations of the reflective side of the test mass due to the coating optical absorption are simulated for Gaussian and mesa beams. An example of the sagitta change of the mirror profile due to the optical absorption is shown in figure 3. This sagitta change along the optical axis can be compared with the sagitta of the cold mirror profiles shown in figure 2.

It is worth noting that the sagitta change due to the optical absorption is more than 3 orders of magnitude smaller than the initial sagitta of the cold mirror. Even if the change may seem negligible, it still induces some noticeable changes in the cavity gain or in the shape of the cavity mode as we will seen in the next section.

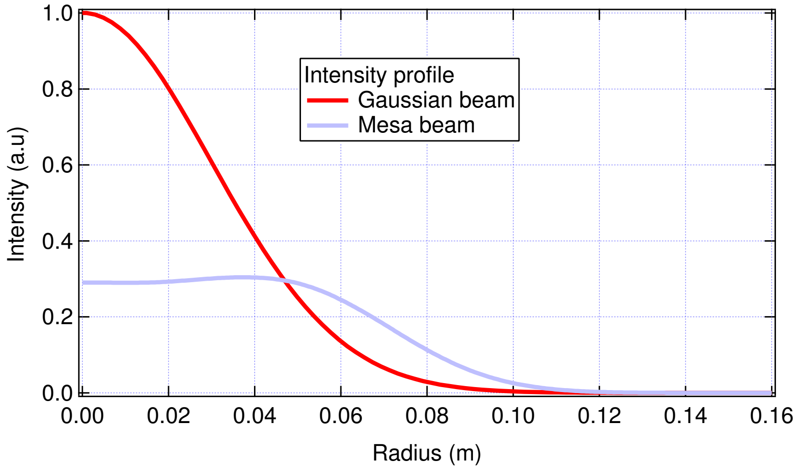

Figure 1: Comparison of the intensity profile between the Gaussian beam and the mesa beam. The intensity profile is calculated on the mirror surface. Both beams are normalised and have the same diffraction loss of 2.2 ppm per cavity round trip.

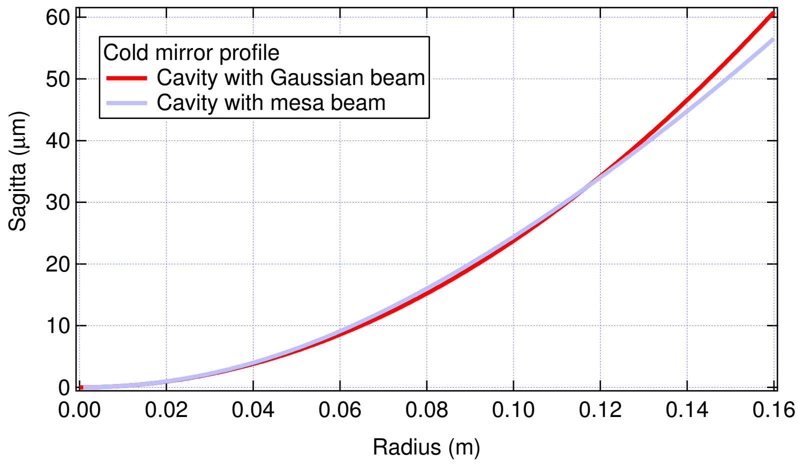

Figure 2: Profiles of the mirrors when a Gaussian beam and mesa beam are supported by the mirrors of the cavity.

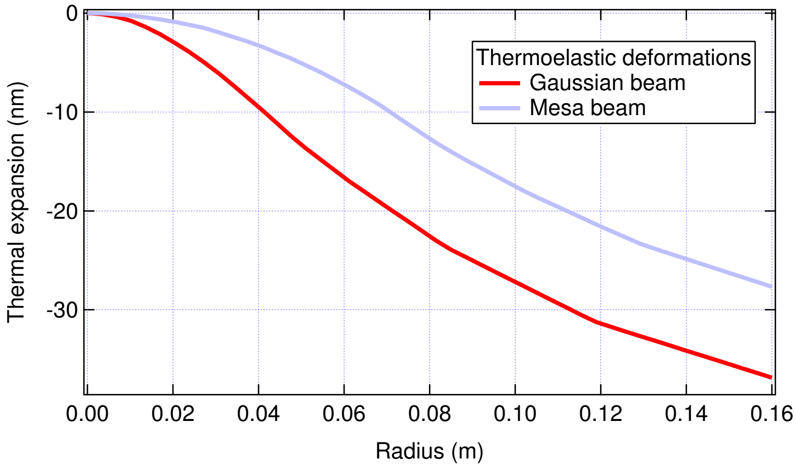

Figure 3: Sagitta change of the reflective side of the test mass due to the absorption of a laser beam. The vertical scale of this figure is 3 order of magnitude smaller than that of figure 2. The optical power absorbed is equal to 0.4 W per test mass for both beam profiles. The use of mesa beams can reduce the sagitta change induced by the optical absorption by more than 30%.

2.3 Optical FFT simulations

We used the FFT code developed in the ACIGA lab in UWA. A detail description of the code can be found in Degallaix thesis [4]. For the simulations presented here, a 256×256 grid is used representing a portion of space of 50 cm by 50 cm. The code is adapted to calculate the diffraction loss of the cavity as well as the coupling loss between the input laser beam and the fundamental cavity mode (distorted due to thermal lensing).

3 Simulation results

When 800 kW of optical power is circulating inside the arm cavity, the cavity gain decrease due to thermal lensing is around 1% when mesa beams or Gaussian beams are used as shown in the figure 4. Since the use mesa beams induces lower deformations of the mirror profile, the cavity gain for the mesa beam is always slightly higher than that for Gaussian beams in presence of thermal lensing.

The decrease of the cavity gain as the circulating power increase is mainly due to the increase in the injection loss. Indeed when the mirror profiles are distorted, the resonant mode of the cavity is also distorted and no longer perfectly match the input laser mode. This loss can be simply calculated by an overlap integral between the cavity mode and the input laser mode. The injection loss due to thermal lensing is more than 30% smaller for mesa beams than for Gaussian beams as shown in figure 5.

Interestingly, thermal lensing decreases the diffraction loss of the beam. Indeed, the thermal expansion of the central part of the mirrors is equivalent to an increase of the mirror radius of curvature. As the result of this increase, since the cavity is near concentric, the radius of the fundamental cavity mode becomes smaller, decreasing the diffraction loss of this mode. For example at low circulating power, the radius of the Gaussian beam on the mirror is 6.0 cm. For 800 kW of cavity circulating power, the radius of the Gaussian beam becomes 5.5 cm. The decrease in the beam radius reduces the diffraction loss per round trip from 2.2 ppm to 1.8 ppm. Because of the round trip loss in the cavity due to scattering at the mirror surface is around 70 ppm per round trip, the diffraction loss is usually negligible.

Even if the thermal expansion of the mirrors due to the coating absorption induces a relatively small change in the mirror sagitta, the shape of the cavity resonant mode may be quite affected. The profile of the resonant mode inside the hot cavity is presented in figure 6 and figure 7 for both Gaussian and mesa beam respectively. Despite the thermoelastic deformations of the mirrors, the resonant mode of the Gaussian hot cavity has still a Gaussian profile. However, the mesa beam tends to suffer greater changes in its profile as shown in figure 7. It is not as tragic as it seems since the overlap integral between the cold initial mesa beam and the hot distorted one is still quite small as demonstrated by the calculation of the injection loss.

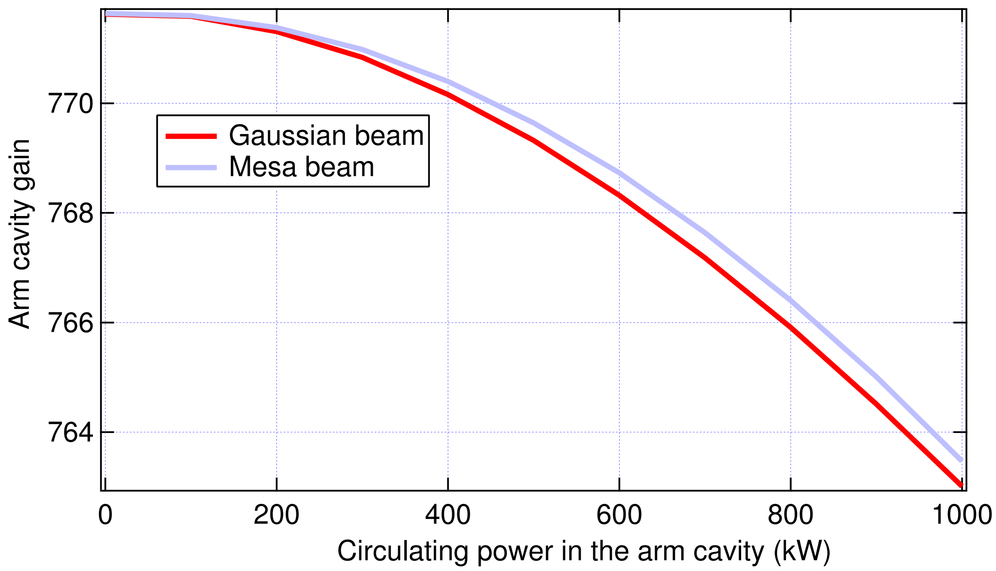

Figure 4: Decrease in the cavity gain of the arm cavity as a function of the circulating power inside the cavity.

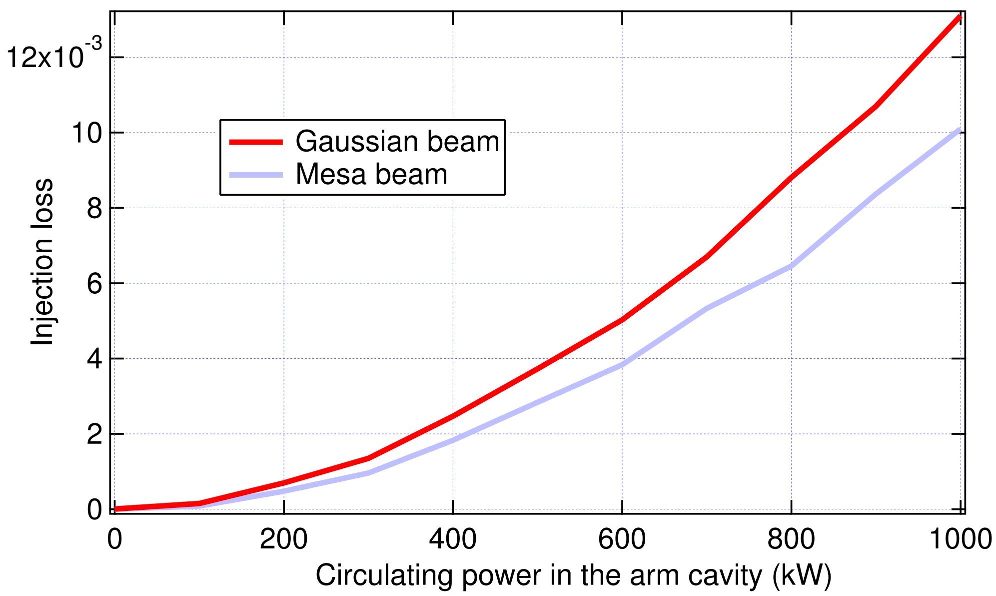

Figure 5: Injection loss of the input beam as a function of the circulating power inside the cavity. For 0 W of circulating power inside the cavity, since the input laser mode is perfectly matched to the cavity fundamental mode, the injection loss is equal to zero.

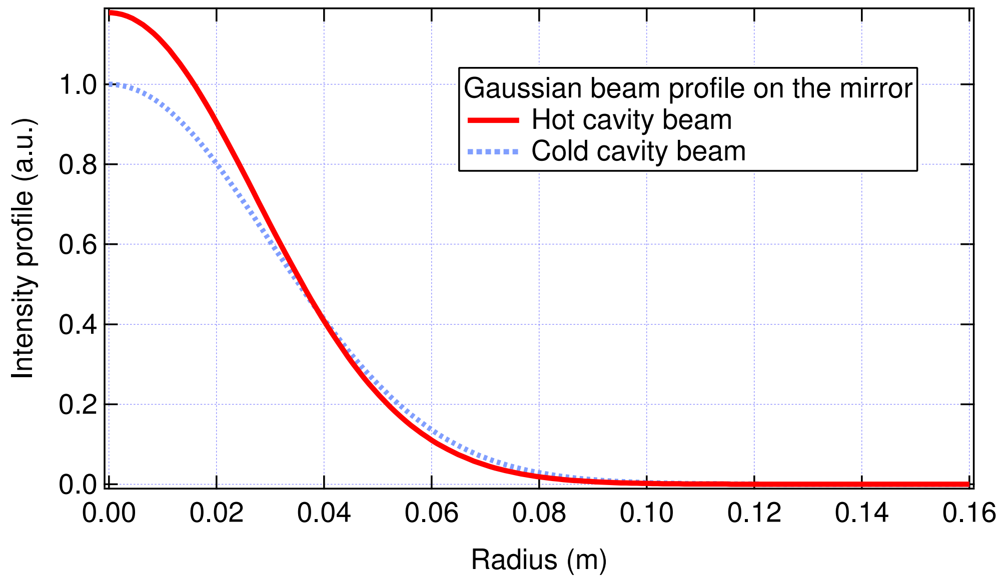

Figure 6: Comparison of the profile of the laser beam on the test mass between cold and hot cavity. The cold cavity refers to the a cavity without thermal lensing (or with very low circulating power inside). The hot cavity term is used when 800 kW is circulating inside the cavity and 0.4 W is absorbed in each mirror coating.

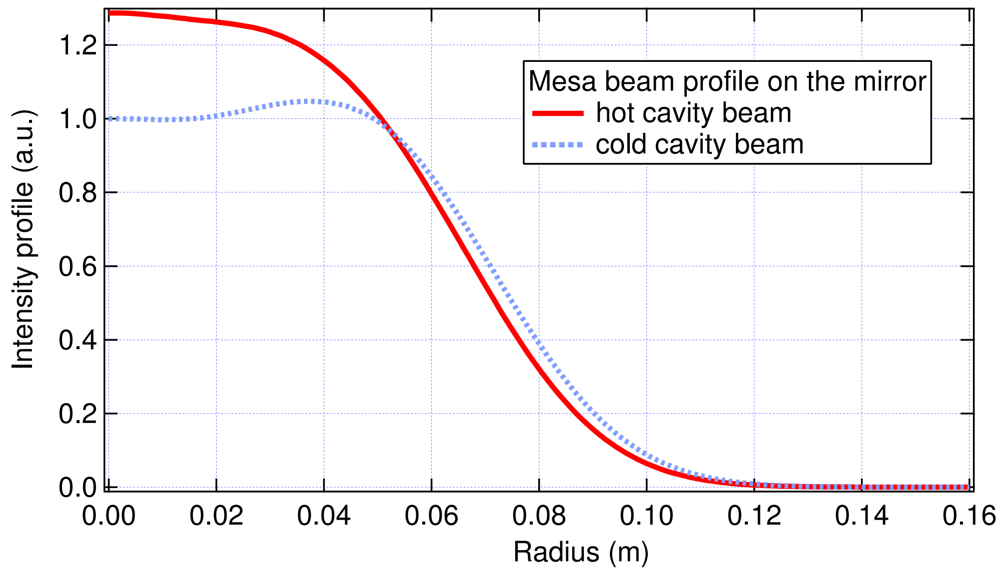

Figure 7: Same as figure 6 but for mesa beam.

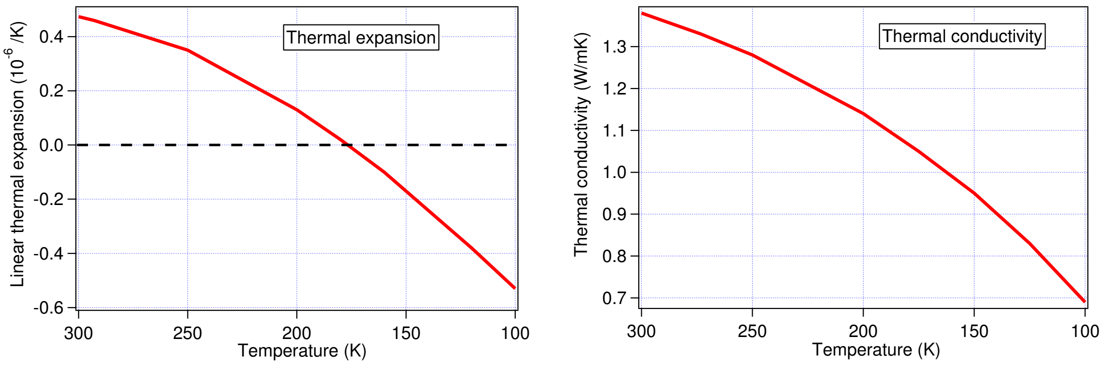

Figure 8: Temperature dependence of the thermal expansion (left) and thermal conductivity (right) of fused silica between 300 K and 100 K. These data are from the Touloukian's book [5]

4 Influence of the temperature

The previous simulations were done at room temperature (300 K). In this section, we will study the benefit of lowering the temperature of the test mass regarding thermal lensing. One particular temperature of interest is around 180 K when the thermal expansion of fused silica is nil as shown in the figure 8. Around this temperature, we can already expect the thermoelastic deformations to be very small and so the cavity gain to be maxima. A plot of the cavity gain as a function of the temperature is presented in figure 9 for a Gaussian beam. By cooling the mirror at 180 K, we can restore the cold cavity gain. At this temperature, the cavity gain is independent of the heating power absorbed by the coating.

For temperature lower than 170 K, the cavity gain dramatically drops as the temperature decreases. This is the result of the increase in the magnitude of the thermal expansion coefficient as well as a decrease in the thermal conductivity.

Another benefit of low temperature is the reduction of the different thermal noises which are proportional to the temperature. For example, the amplitude of the coating structural damping noise can be reduced by 20% from 300 K to 180 K. The thermoelastic noise whose power spectral density is proportional to the squared of the temperature can be reduced by 40% in amplitude from 300 K to 180 K.

Unfortunately, fused silica has a major disadvantage for its use at low temperature, its thermal conductivity decreases with the temperature (at the opposite of sapphire or silicon). That means the magnitude of the thermal lens in ITM substrate increases as the temperature decreases.

To have an idea of the problem, we can calculate a quick estimate for the change in the thermal lens as the temperature decreases. The focal length of the ITM thermal lens is proportional to the thermal conductivity and inversely proportional to the thermo-optic coefficient (we just consider the temperature

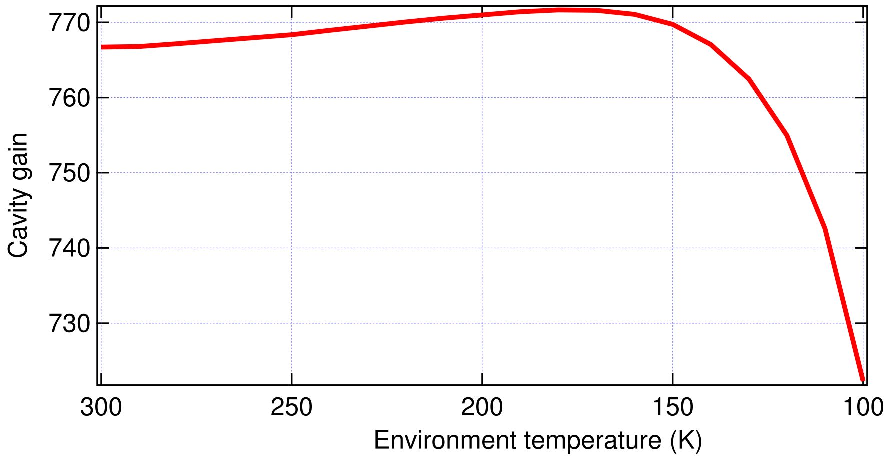

Figure 9: Cavity gain as a function of the room temperature. As expected the gain is maxima around 180 K where the coefficient of thermal expansion is nil. The cavity gain is plotted for a cavity supporting Gaussian beams.

Table 1: Evolution of the temperature of the test mass as the temperature decreases. The gradient of temperature inside the test mass represents the difference of temperature between the hottest and the coolest point of the test mass. The heating power absorbed by the test mass is 0.4 W.

Room temperature (K)	Average temperature of the test mass (K)	Gradient of temperature inside the test mass (K)
300	300.24	1.39
180	180.86	2.04
100	104.32	3.17

dependent parameters). From 300 K to 175 K, the thermal conductivity of fused silica decreases by 25%, and the thermo-optic coefficient by 10% [6]. So the magnitude of the thermal lens in the ITM substrate will increase by 20%. This can surely by compensated by the TCS but at which other price ?

For our simulations, we suppose that the heat absorbed by the test mass only escapes by radiation. At low temperature, this process becomes inefficient. For the same amount of heat to escape, the temperature difference between the test mass and its surrounding environment increases as the temperature decreases. This effect can observed in table 1. The difference between the test mass and the room temperature is less than 5 K for a room temperature of 100 K. So for the temperature range considered here, this effect is not a worry thanks to the large surface area of the test mass and the small heating power absorbed (0.4 W).

5 Conclusion

Using numerical simulations, we have shown the advantage of using mesa beams over Gaussian beams to reduce thermal lensing effects in the arm cavities of interferometers. Even for Gaussian beams, thermal lensing inside the arm cavities is relatively mild compared to thermal lensing in the power recycling cavity. The cavity gain decreases by less than 1 % when 800 kW is circulating inside the cavity. Therefore we do not think it is necessary to compensate thermal lensing in the arm cavities.

In advanced interferometer, the main thermal lensing problem resides in the power recycling cavity. We did not (yet) simulate the thermal lensing within the ITM substrate, however we can extrapolate that the use of mesa beams can also reduce thermal lensing effects inside the power recycling cavity. We estimated that the heating power of the thermal lensing compensation system can be reduced by at least 20% if mesa beams are used.

In this report we simulated fused silica test masses, however we can easily estimate the same thermal lensing effects with sapphire test masses. For the same power absorbed by the coating, the deformations of sapphire mirrors are 3 times smaller than that of fused silica mirrors. So we can scale our simulation results for the case of sapphire test masses. For example, from the thermal lensing point of view, 800 kW of circulating power inside a cavity with sapphire test masses is equivalent to 270 kW of circulating power inside a cavity with fused silica test masses.

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