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LIGO Laboratory / LIGO Scientific Collaboration

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A Note on Substrate Thermal Lensing Compensation using Negative Thermo-optic Coefficient Material

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1 Introduction

1.1 Purpose

This document proposes the use of optical material with negative thermo-optic coefficient (TOC) to compensate the substrate thermal lensing in the LIGO test masses. The idea is to use a combination of passive compensation due to the intrinsic power absorption in the compensation plate and active compensation through heating by a pump beam. Due to the identical nature of the proposed compensation scheme with the thermal lensing problem, it is expected that a high degree of compensation will be achieved. An initial study of the optical and physical properties of calcium fluoride (CaF_2) suggests that this material can be a viable option for thermal compensation in Advanced LIGO. Note that here only substrate thermal lensing compensation is discussed.

1.2 Scope

This document is prepared for the purpose of introducing thermal compensation techniques. Typical readers of this include people involved in designing core optics, alignment sensing, and material scientists.

1.3 Definitions

Thermo-optic Coefficient: Quantitative measure of the change in refractive index with temperature, represented by dn/dT.

α_t: Thermal expansion coefficient.

1.4 Acronyms

TOC: Thermo-optic coefficient

ROC: Radius of curvature

HV Theory: Hello-Vinet Theory

CaF_2: Calcium Fluoride

1.4.1 LIGO Documents

1. M. A. Arain et. al., "Thermal Compensation in Stable Recycling Cavity," in LIGO LSC Meeting, March 2006, LIGO-G060155-00.
2. K. Yamamoto et. al., "Mechanical loss of optical coating at low temperature," in Gravitational Wave Advanced Detector Workshop, Feb. 2003, Aspen, Colorado, U.S.A, LIGO-G030225-00-Z.

1.4.2 Non-LIGO Documents

3. UF LIGO Group, "A Note on Optimal Spherical Approximation to Thermal Lenses".
4. P.Hello and J. Vinet, "Analytical models of thermal aberrations in massive mirrors heated by high power laser beams," J. Phys. France **51**, 1267-1282, (1990).
5. P. Hello and J. Vinet, "Analytical models of transient thermoelastic deformations of mirrors heated by high power CW laser beams," J. Phys. France **51,** 2243-2261, (1990).
6. E. Khazanov et. al., "Compensation of Thermally Induced Modal Distortions in Faraday Isolators," IEEE J. of Quantum Electronics, **40**, 1500-1510, (2004).
7. V. Quetschke et. al., "Adaptive control of laser modal properties," Opt. Lett. **31**, 217-219 (2006).

8. Z. Yan et. al., “High mechanical quality factor of calcium fluoride (CaF_2) at room temperature,” Eur. Phys. J. Appl. Phys. **30**, 189-192 (2005).
9. STREGA, Joint Research Efforts, “Study of Thermal Noise Reduction for European Gravitational WaveDetectors,” http://www.ego-gw.it/ILIAS-GW/documents/J3_final.pdf.

2 General description

When a high power laser beam is reflected or transmitted through an optical material, a portion of the light power is absorbed in the coating or in the substrate depending upon the physical properties of the materials. This absorbed power creates a non-uniform temperature distribution on the surface and the substrate of the material. This results in surface deformation due to the coefficient of linear expansion (α_t) of the material. Furthermore, this temperature distribution also changes the refractive index of the material depending upon the TOC (dn/dT). These two effects create substantial thermal aberrations, i.e., position based optical path length change, in the reflected/transmitted optical beam.

In Advanced LIGO, the resonating power is expected to approach 850 kW in the arm cavities and 2.1 kW in the recycling cavity. This will create substantial deformation on the surface affecting the carrier arm cavity modes as well as thermal lensing in the substrate of test masses affecting the sideband build-up in the power recycling cavity and signal recycling cavity. In this document, we will concentrate on compensation of substrate thermal lensing. Surface thermal lensing compensation is not discussed here. Substrate thermal lensing in the substrate of input test masses (ITMs) due to its non-spherical nature will introduce approximately 10-15% higher order losses in the recycling cavity.[3] For feasible operation, these aberrations should be compensated. Depending upon the amount of power absorption in the ITMs the compensation required in the two arms of the interferometer can be different. Therefore, it is prudent to compensate the two arms separately. A number of options are available for substrate compensation including ring heaters employed on fused silica compensation plates or annular pump heating. These methods more or less work on the principle of trying to create a thermal profile similar to the one produced by absorption from an inverse Gaussian beam. Instead, here we propose to use negative TOC material to compensate the substrate thermal lensing. By carefully selecting the material properties and geometry, a very efficient scheme of thermal compensation can be achieved because the same fundamental mechanism of power absorption though a Gaussian beam is used to cancel this effect. The thermal profile being created is due to intrinsic beam and pump beam heating. Both these beams are Gaussian but the negative TOC creates a diverging lens thus compensating the converging thermal lens in the substrate. Details of such a compensation scheme using CaF_2 as the compensation plate material are presented next.

3 Thermal Lensing in ITM Substrates

Thermal lensing due to coating absorption on the high reflecting surface and bulk power absorption in the substrate can be modeled analytically through Hello-Vinet (HV) theory.[4,5] The HV theory provides an expression for the thermal aberrations in the substrate due to the two absorption mechanisms. The expression can then be evaluated numerically. The effect of surface absorption is the dominant contributing factor. Since the surface absorption is largely due to the coating power loss, therefore the thermal lensing in the two substrates can differ significantly from each other.

Fig. 1 shows the total substrate aberrations including the individual contributions from surface power absorption and bulk power absorption. Here 0.5 ppm coating absorption at 850 kW and 2 ppm/cm bulk absorption at 2.1 kW power is assumed.

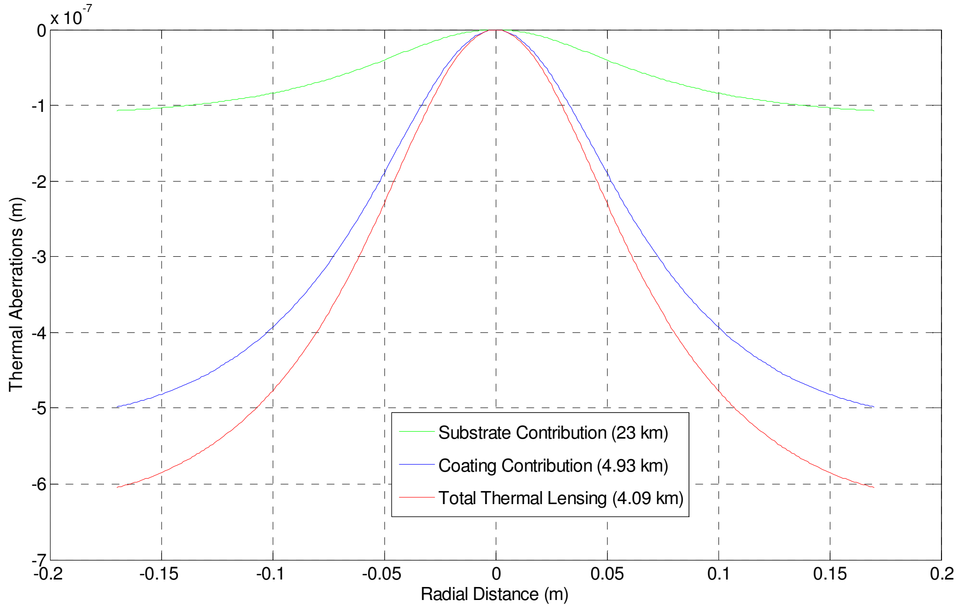


Fig. 1: Thermal lensing in ITM substrate for 0.5 ppm coating absorption at 850 kW and 2 ppm/cm bulk absorption at 2.1 kW. A 6 cm beam size is assumed at the ITM surface corresponding to 2076 hot ROC.

It is customary to associate a radius of curvature (ROC) value with the thermal lensing. However since the thermal lensing profile is not spherical therefore various ROCs can be associated with the thermal lensing. One approach is to fit a polynomial to the thermal aberration and use the coefficient of the quadratic term to estimate the ROC. A more precise approach is to use overlap-integral maximization to predict the correct ROC.[3] This approach also provides the amount of higher order losses due to the non-spherical nature of the thermal lensing. For example for the case of Fig. 2, the higher order losses are around 14%.

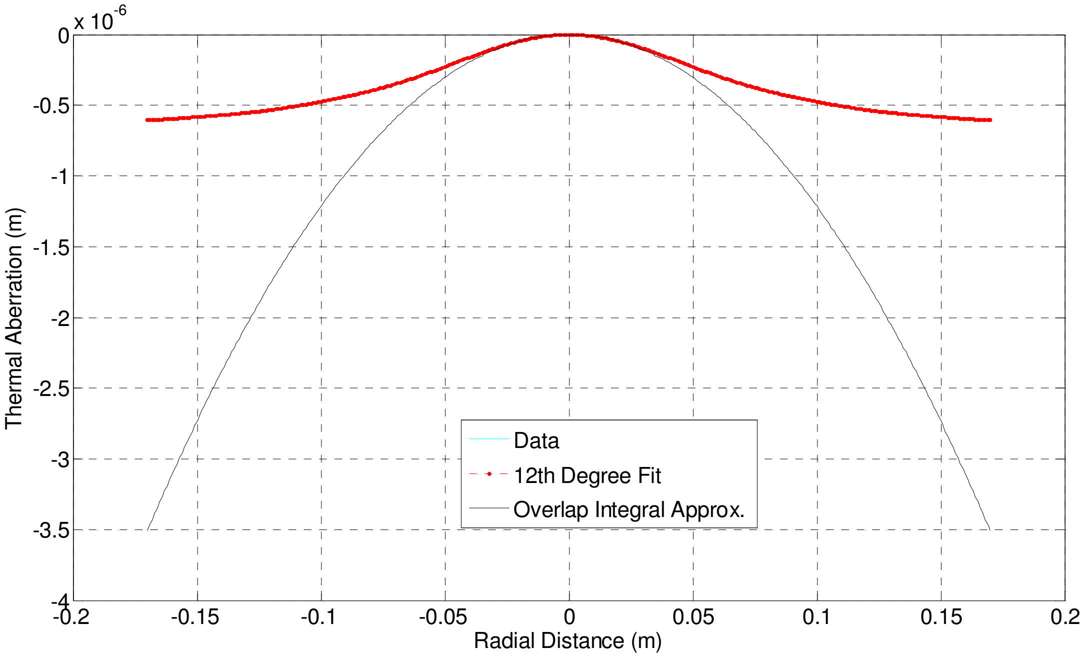


Fig. 2: Over-lap integral approximation to the substrate thermal lensing.

4 Compensation of Thermal Lensing using Compensation Plate

Compensation of the thermal lensing profile requires both the ROC correction and higher-order losses compensation. One obvious way is to create an inverse (negative) thermal profile of the substrate aberrations. The resulting profile obtained by adding these two phase aberrations should give a constant phase across the whole cross-section of the beam. The compensation thus achieved can be quantitatively represented by the overlap integral of the resultant phase with a constant phase front.

If a material with negative TOC is heated by any means, the region in which more power is absorbed gets hotter than the other regions. The hotter regions exhibit a lower refractive index as compared to the cooler regions. If the heating source is a Gaussian beam, the resultant temperature profile will create a lower refractive index at the central region as compared to the outer regions. This is like creating a negative or diverging lens in the substrate of the material as shown in Fig. 3. However, due to the heating, the material will expand based upon the thermal expansion coefficient. The expansion will be more at the center as compared to the outer regions thus offsetting the effect of negative lens creation. For realizing a negative lens, following condition should hold true:

$$\alpha_t (n-1) < \left| \frac{dn}{dT} \right| . \quad (1)$$

Here α_t is the thermal expansion coefficient, *n* is the refractive index, and *T* is the temperature. As long as expression 1 is satisfied, the plate will act as a diverging lens. The exact expression for the thermal aberrations in this plate can be calculated by using HV theory.

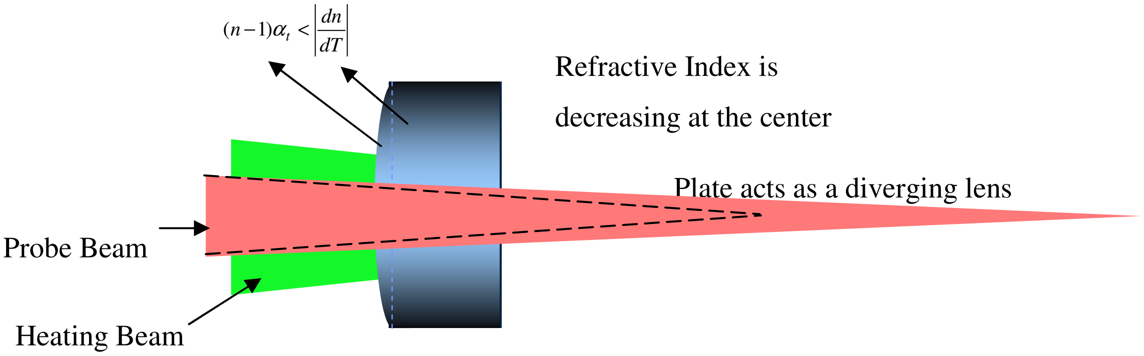


Fig. 3: Hybrid compensation scheme involving both active and passive compensation through probe beam heating and external beam heating respectively.

4.1 Hybrid Compensation Scheme[1]

To use this plate as a compensation plate, one has two options.

1. Intrinsic heat absorption in the bulk material
2. External heating through a heating beam at the surface

In theory, one can compensate for the thermal lensing in the ITM substrate by carefully choosing the right thickness of the compensation plate. The amount of power absorbed in the compensation plate due to the passage of optical beam will create a diverging thermal lens.[6] However, this requires an exact estimate of the thermal lensing in the substrate. This thermal lensing will always be a poorly estimated figure because of the variations possible in the coating absorption. Also, any change in the material properties from the nominal value can degrade the compensation process. Hence an alternative approach is to design the compensation plate in such a way that it under-compensates the thermal lensing in the ITM substrate in all situations. For example, the thickness of the plate can be chosen to be 90% of the required thickness to fully compensate the thermal lensing. The remaining compensation can be achieved my heating the plate through external beam. This heating can be achieved by using a laser as a heating beam as demonstrated in the adaptive compensation for input optics system.[7] This will require a moderate amount of heating beam power. The control of beam diameter and power of the heating beam gives an enormous amount of flexibility in the compensation process.

The proposed place for the compensation plates is right before the ITMs as shown in Fig. 4. Each compensation plate, independently operating, will cancel the thermal aberrations in the respective ITMs. This takes care of both the common mode and differential thermal lensing effects in the ITMs.

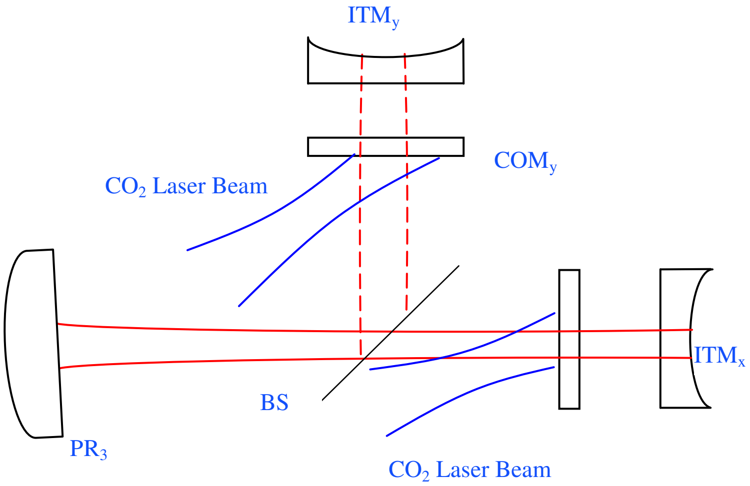


Fig. 4: Layout of the compensation scheme for Asvanced LIGO

4.2 Material Considerations

To realize such a compensation scheme, the key element is to find an appropriate material. The position of these plates, i.e., before the ITMs, places very stringent requirement on the physical and optical properties of the material. This material has to be compatible with the ITM substrate material. Some of the most important material properties are as follows.

1. Sufficient negative TOC to offset the effect of thermal expansion
2. Availability in large sizes
3. Homogeneity
4. Ability to be polished to the requirements similar to recycling mirror
5. Appropriate absorption at 1.064 µm
6. Thermally stable

An initial survey of the available negative TOC materials shows following choices.

1. Potassium Chloride
2. Potassium Bromide
3. KDP (or DKDP)
4. Calcium Fluoride

Out of these materials Calcium Fluoride (CaF_2) seems to be the most appropriate choice. CaF_2 has been considered for test mass materials by the European, Australian, and Japanese gravitational wave community.[2,8,9] A number of tests has already been done to access the viability of using CaF_2 as the test mass material. An active collaboration with those groups involved in such an effort can reduce the amount of material research needed. Appendix A shows some properties of commercially available CaF_2 from Crystran Ltd. Table 1 compares basic properties with fused silica. The numbers are based on various inquires to the companies around the world who supply CaF_2.

CaF_2 is a crystalline material that has a widespread IR application as spectroscopic windows, prisms and lenses. Especially pure grades find useful application in the UV and as UV Eximer laser windows. CaF_2 is grown by vacuum Stockbarger technique in diameters up to about 300 mm. Material for IR use is grown using naturally mined fluorite, in large quantities at relatively low cost. For normal UV applications chemically prepared raw material is generally used and for high precision applications the highest grade of specially selected material and crystal is used.

Table 2: Comparison of material properties of CaF_2 with fused silica

Property	**Unit**	**Fused Silica**	**CaF_2**	**Ref.**
Refractive Index @ 1μm	-	1.45	1.4	App. A
Bulk absorption @ 1μm	$ppm\text{-}cm^{-1}$	< 3	2-1000	*
TOC	$10^{-6}\,K^{-1}$	8.7	-10.7	App. A
Thermal Conductivity	$W\,m^{-1}\,K^{-1}$	1.37	9.71	App. A
Heat capacity	$J\,kg^{-1}\,K^{-1}$	739	854	App. A
Thermal Expansion	$10^{-6}\,K^{-1}$	55	18.85	App. A
Homogeneity @ 0.63 μm	ppm	=< 0.5	5	#
Strain Birefringence	nm/cm	1	5	#
Mechanical Q factor	-	$>10^7$	10^7	Ref. 8

* : The absorption value widely differs from source to source. A value of 2 ppm is quoted in Ref. 2 while 1000 ppm is quoted by Bright Crystal Inc.

: Personal communication with Crytran Ltd.

5 Compensation Plate Design Exercise

Here a typical scenario is considered for the Advanced LIGO thermal lensing compensation. Fig. 1 is used as the thermal aberrations that have to be compensated by using a CaF_2 compensation plate. Important features of the compensation plate are shown in Table 2.

The design thickness is selected to provide around 92% compensation through self heating of the beam. Fig. 5 shows the resultant compensation. The remaining aberrations are shown as a blue curve.

Table 2: Design considerations for a specific Advanced LIGO thermal lensing compensation scenario

Property	**Unit**	**CaF$_2$**
Refractive Index @ 1µm	-	1.4
Bulk absorption @ 1µm	ppm-cm^{-1}	500
Plate Diameter	cm	34
Thickness	cm	6.5
Intrinsic beam power	kW	2.1
Intrinsic beam size	cm	6.0
Power Absorbed @ 1µm	W	6.8
Heating Beam Diameter	cm	4
Heating beam power @ 10.6 µm	W	1

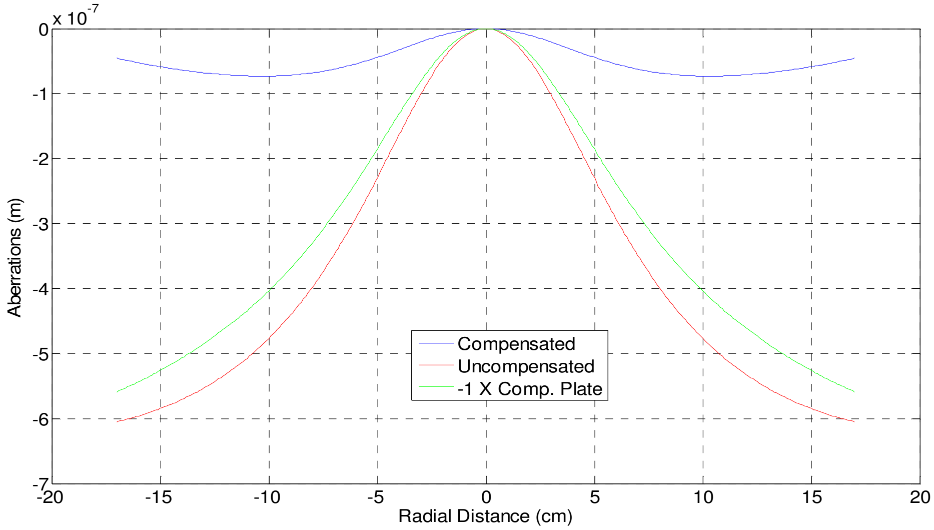


Fig. 5: 92% compensation through passive compensation by the plate.

To compensate the remaining thermal aberrations, a number of heating beam diameter and power combinations can be used. One set can be a 1 W heating beam of 4 cm diameter. All the energy in the heating beam is assumed to be absorbed at the surface. The resultant thermal profile can be calculated by using HV theory expressions for thermal aberration due to the coating absorbance on the surface. The sum of the thermal aberrations due to substrate heating and surface heating is subtracted from the Fig. 1 thermal aberrations. The result is plotted in Fig. 6. The total compensation achieved in this case is better than 99.99%.

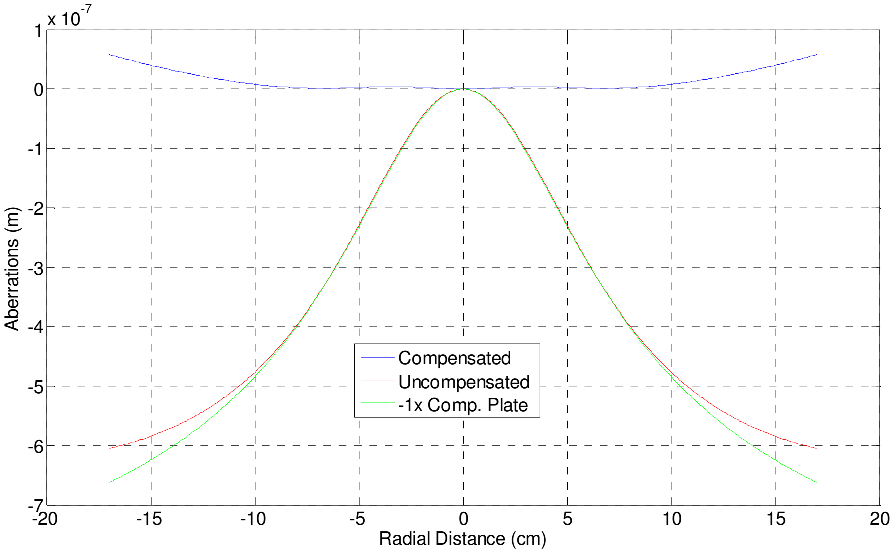


Fig. 6: 99.992 % compensation through hybrid control employing intrinsic and external heating of the compensation plate.

Here, a 6.8 W of power is absorbed from the intrinsic beam at 1µm means that this value is around 3300 ppm out of 2.1 kW power resonating in the recycling cavity. This value will lower the recycling cavity gain. However, the compensation scheme proposed in table 3, is only one of the possible scenarios. The amount of power absorbed at 1µm can be reduced by reducing the thickness, or by using material of lower absorption. This however will increase the amount of power required for the CO_2 heating beam. An upper limit on the amount of intrinsic compensation should be applied based upon the cavity gain factors and temperature increase allowed in the substrate.

6 To Probe Further

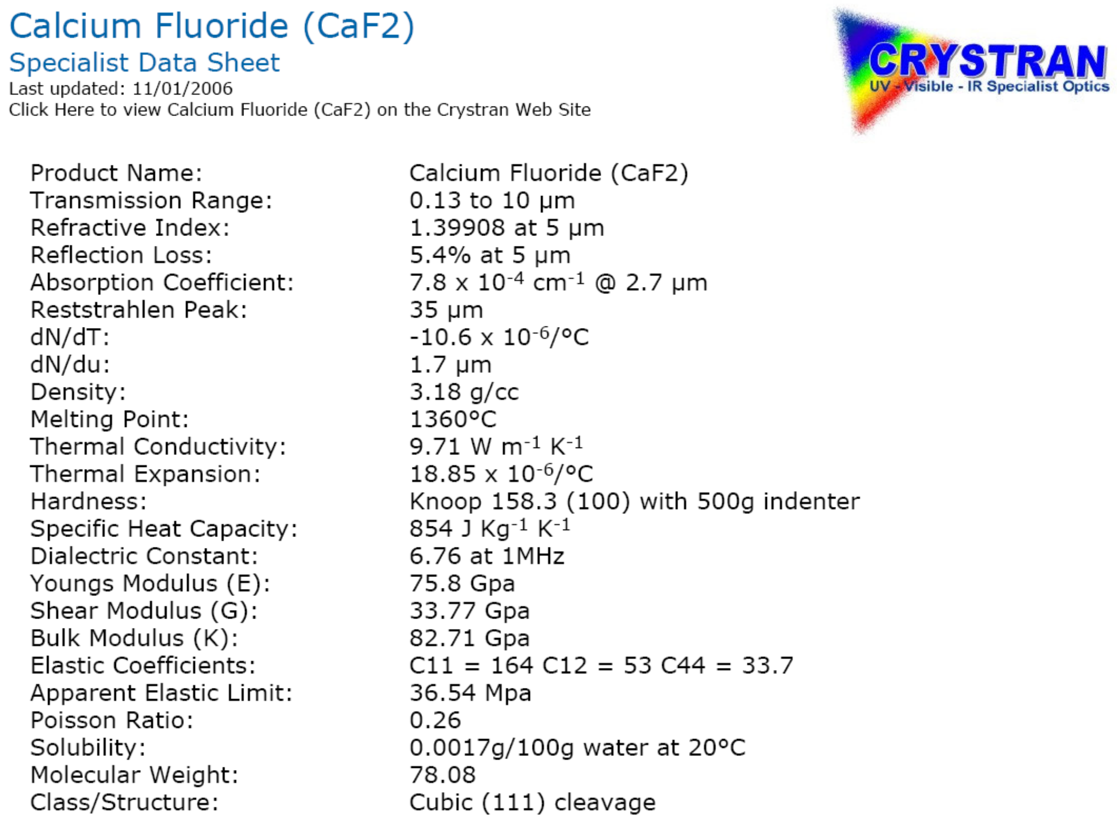
A number of aspects of the proposed scheme needs to be addressed.

1. Layout considerations
2. Availability of feasible CO_2 laser system without power fluctuations
3. Availability of CaF_2 in the required sizes
4. Comparison of the proposed scheme with other alternatives
5. Reliability of the available data
6. Testing of the material properties
7. Availability of high precision polishing
8. Availability of appropriate coatings on CaF_2 substrate
9. Effect on PRC, SRC gain

7 Conclusion

In conclusion, an alternative scheme for thermal lensing compensation in Advanced LIGO is proposed. The scheme is based upon using negative TOC material for the compensation plate. Based on initial research, CaF_2 has been found to be a reasonable choice for the compensation plate material. Apparently, the scheme has the potential to compensate thermal lensing upto 100%. Though initial results are encouraging, a lot of research on material side and comparison with the other alternatives is required.

Appendix A Material properties of CaF_2



Calcium Fluoride (CaF2)

Specialist Data Sheet

Last updated: 11/01/2006

Click Here to view Calcium Fluoride (CaF2) on the Crystran Web Site

Product Name:	Calcium Fluoride (CaF2)
Transmission Range:	0.13 to 10 µm
Refractive Index:	1.39908 at 5 µm
Reflection Loss:	5.4% at 5 µm
Absorption Coefficient:	7.8×10^{-4} cm^{-1} @ 2.7 µm
Reststrahlen Peak:	35 µm
dN/dT:	-10.6×10^{-6}/°C
dN/du:	1.7 µm
Density:	3.18 g/cc
Melting Point:	1360°C
Thermal Conductivity:	9.71 W m^{-1} K^{-1}
Thermal Expansion:	18.85×10^{-6}/°C
Hardness:	Knoop 158.3 (100) with 500g indenter
Specific Heat Capacity:	854 J Kg^{-1} K^{-1}
Dialectric Constant:	6.76 at 1MHz
Youngs Modulus (E):	75.8 Gpa
Shear Modulus (G):	33.77 Gpa
Bulk Modulus (K):	82.71 Gpa
Elastic Coefficients:	C11 = 164 C12 = 53 C44 = 33.7
Apparent Elastic Limit:	36.54 Mpa
Poisson Ratio:	0.26
Solubility:	0.0017g/100g water at 20°C
Molecular Weight:	78.08
Class/Structure:	Cubic (111) cleavage