Computer Analysis of Thermal Lensing in TGG and DKDP

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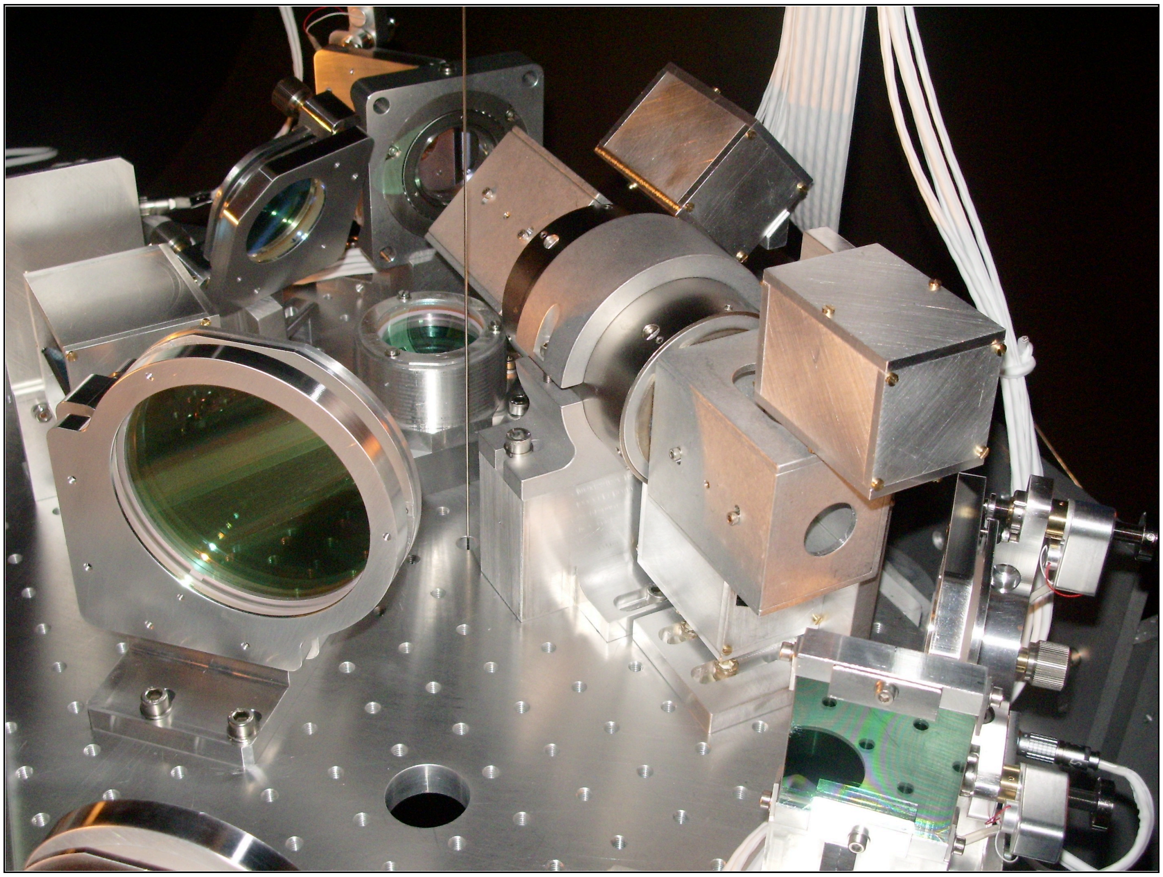

Photo Source: [6]

Introduction

Virgo is one of the largest ground based interferometric gravitational wave detectors in the world. Virgo first began searching the skies for gravitational waves in May 2007. After the initial run of 4 months of data gathering, the interferometer was closed in order to upgrade to the Virgo+ configuration in order to increase sensitivity. The primary difference between Virgo+ and the current Virgo will be an increase in power for the main laser. While the current Virgo set-up utilizes a 20W Nd:YAG (neodymium-yttrium-aluminum-garnet) input laser, the plans for Virgo+ include the use of a 50W Nd:YAG laser. This increased power in the laser results in a more visible change in the interference pattern in the Michelson interferometer, increasing the sensitivity of the instrument. Implementing this more powerful laser poses significant technical difficulties, however. The problem analyzed here is that of the induced thermal lensing in the Faraday Isolator (FI).

Faraday Isolator

The FI is located in the Input Optics (IO) section of Virgo. The IO is responsible for preparing the beam for the Fabry-Perot cavities in the main interferometer, or Core Optics (CO). The laser initially passes through an input mode cleaner, which provides a clean, Gaussian wave. Once this has been achieved, the beam is sent to the IO, where sidebands are added and the size and position of the laser's waist matches those of the Fabry-Perot cavities in the CO. An additional role of the IO is to prevent the previous optics in the set-up from harmful back reflections, ensuring beam stability. This is the role of the FI. The FI functions as essentially as a one-way street for light: linearly polarized light can travel through it in the forward direction with no change in polarization. However, light is prevented from traveling through the FI in the backwards direction.

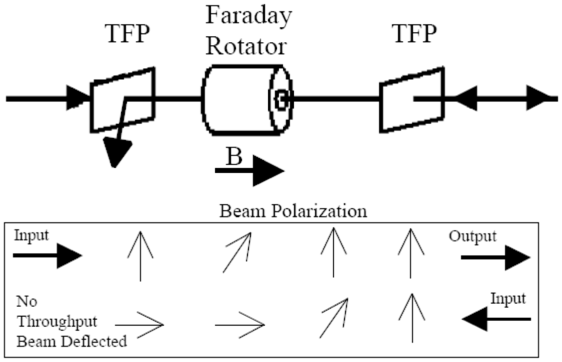

Figure 1: Faraday Isolator

Photo Source: [1]

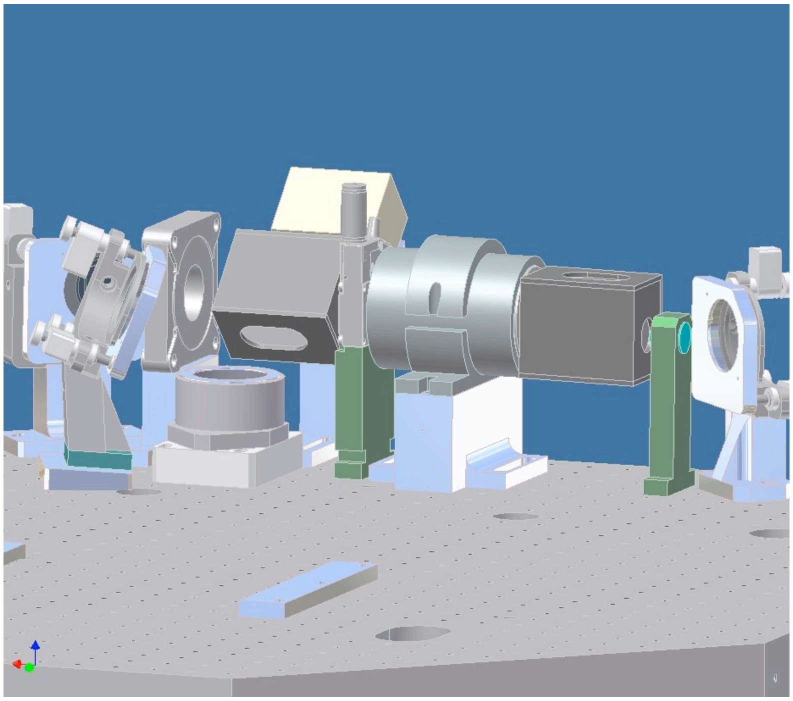

Figure 2: Digital image of Faraday Isolator
Photo Source: [5]

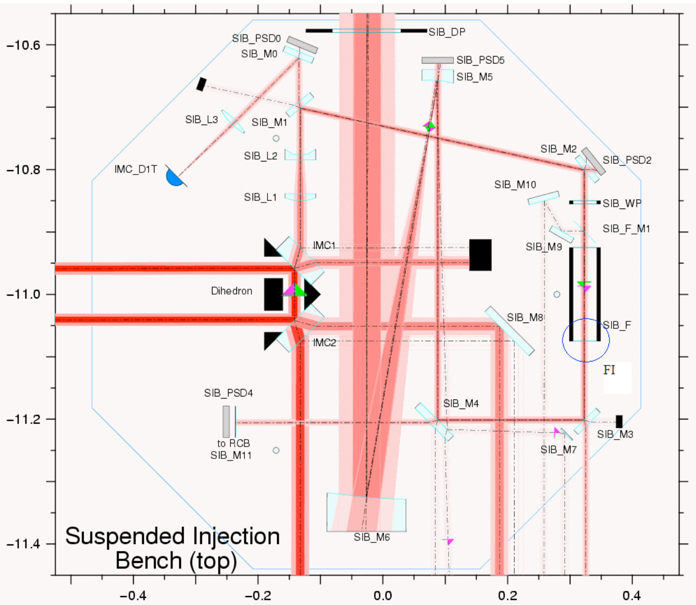

Figure 3: Location of FI in the optical schematic of the Injection Bench
Photo Source: [6]

The FI is composed of a thin film polarizer (TFP), a Faraday isolator, and another TFP. The key component of the FI is the Faraday rotator, which is a device that rotates linearly polarized light's polarization by an angle θ. This is achieved by placing an isotropic dielectric material in a magnetic field. The Faraday rotator in the Virgo apparatus uses a terbidium gallium garnet (TGG) crystal as the isotropic dielectric material. The angle through which the polarization is rotated is given by

$$\Theta = VBl$$

where l is the length of the crystal, V is the Verdet constant for TGG, and B is the magnetic field strength in the direction of light propagation [1],[3].

Induced Thermal Lensing

For low power lasers, the laser itself has no effect on the TGG crystal as it passes through. However, as the power of the incoming laser increases, more power is absorbed by the TGG crystal. As we increase the power, the crystal will naturally heat due to the increased energy passing through, and partially absorbed by, the crystal itself. This heating effect will have a number of effects on the TGG crystal, as discussed extensively in [2]. The primary issue that we aim to address is the induced thermal lensing in the TGG crystal. The heating of the TGG crystal will cause its index of refraction to change, with TGG having a positive dn/dT (as the temperature T increases, so does the index of refraction, n). As the beam passing through the crystal has a Gaussian profile, it is clear that the thermally induced change in refractive index will also have a roughly Gaussian (or parabolic) profile (it will not be exact, as heat dissipates through the crystal, thus not heating all areas exactly proportionately to the amount of power being passed through them). This gradient in the index of refraction causes the crystal to behave very much like a normal biconvex lens, as shown:

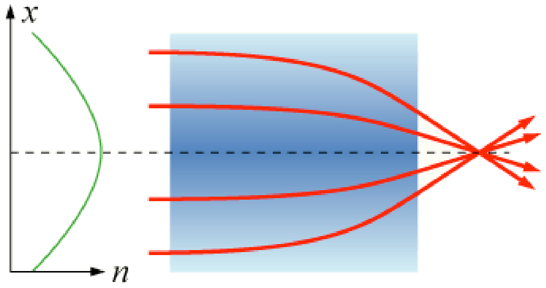

Figure 2: A gradient index of refraction (shown in blue) acting as a lens.
Photo Source: [7]

With the 20W laser, the 13W of power that reaches the FI has a minimal effect on the crystal. However, at 50W, around 40W of power will reach the FI, and the effect becomes too much to ignore. The heating of the crystal essentially adds a new lens into the already precisely balanced optical set-up, as well as giving shifting the phase of the laser. This new lens then causes mode-mismatch and unwanted interference.

To correct for this effect, we can introduce a material with a –dn/dT which, when heated, will create a biconcave lens to cancel the effects of the thermally induced biconvex lens in the TGG crystal. That material chosen for this is deuterated potassium phosphate, or DKDP.

By installing a DKDP crystal of the proper dimensions in line with the TGG crystal in the FI, we can compensate for the thermally induced lensing in the TGG crystal. If you have two lenses in line with focal lengths f_1 and f_2 and separated by a distance D, then the effective focal length of the two lenses is given by:

$$1/f = 1/f_1 + 1/f_2 - D/(f_1 f_2)$$

For the crystals involved here, the product of the focal lengths will be considerably more than the distance separating them (the two crystals will probably be roughly 10 cm apart, whereas the focal length of the TGG and DKDP crystals at 40W will be roughly 68 meters), so as long as $f_1 = -f_2$, we will get nearly complete cancellation of the thermally induced lensing in the TGG crystal. This is a well known procedure, and has been implemented successfully before [1].

Matching DKDP and TGG

The difficulty lies in determining the proper dimensions for the DKDP crystal. The size of the crystal determines the effective focal length, which must be matched with high precision with the focal length of the TGG crystal. The proposal for this project is to utilize a computer simulation program recently developed by scientists in the Virgo Collaboration to model the effects of thermal lensing in optical crystals of varying properties.

The program is run through Matlab via a central header file. In this file one can access and modify a vast array of properties of the crystal which is being simulated. Once the specific characteristics of the crystal under study have been inputted (as well as the power of the incoming laser and the amount of time to study the heating, among various parameters), the program essentially slices the crystal (which we are assuming to be cylindrical) into small sections:

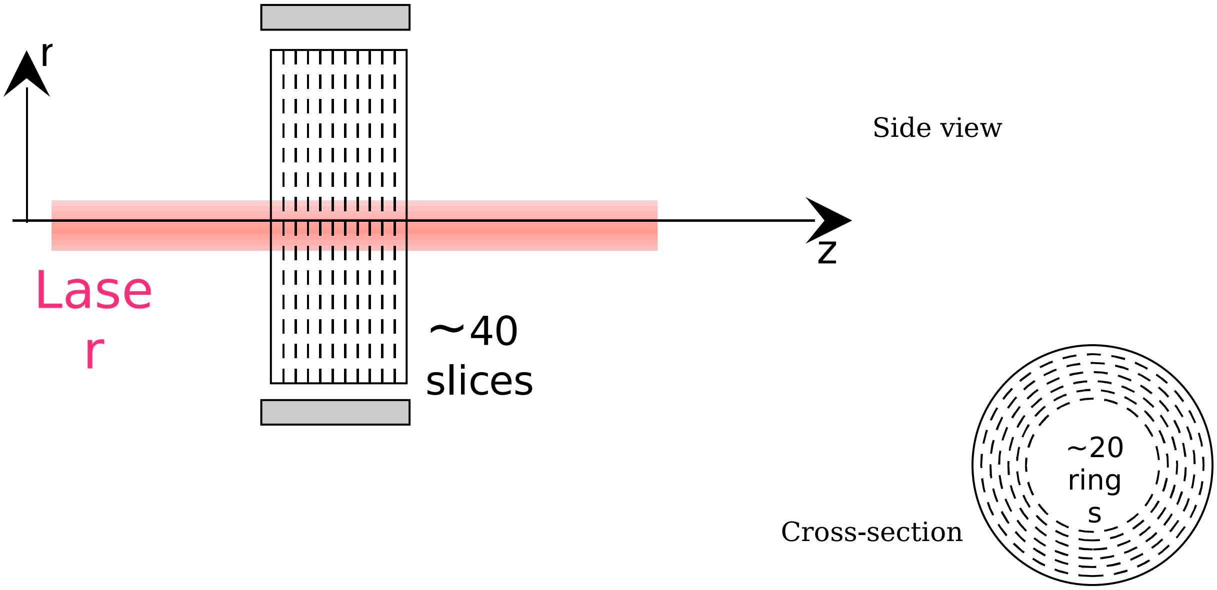

Photo source: [4]

These small slices are then analyzed, charting the mean focal length, mean temperature, phase shift (dephasage), and a temperature map for the whole crystal over a period of time. After a finite amount of time the crystal will reach equilibrium, and thus stop heating and its optical properties will stabilize. Once the simulation is complete, the program outputs graphs of the preceding quantities. A sample program output looks like:

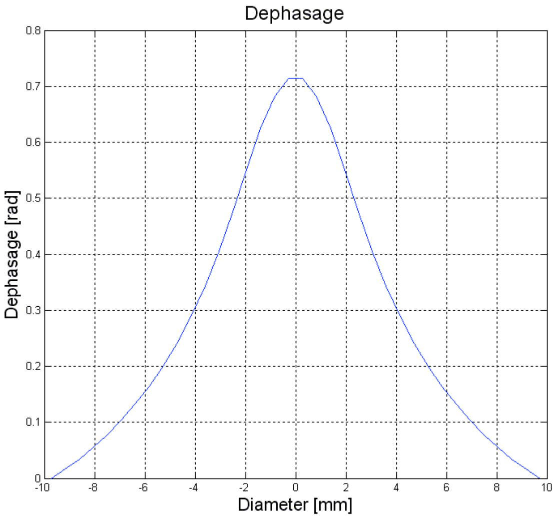

Figure 3: Dephasage plot for TGG crystal and 40W laser

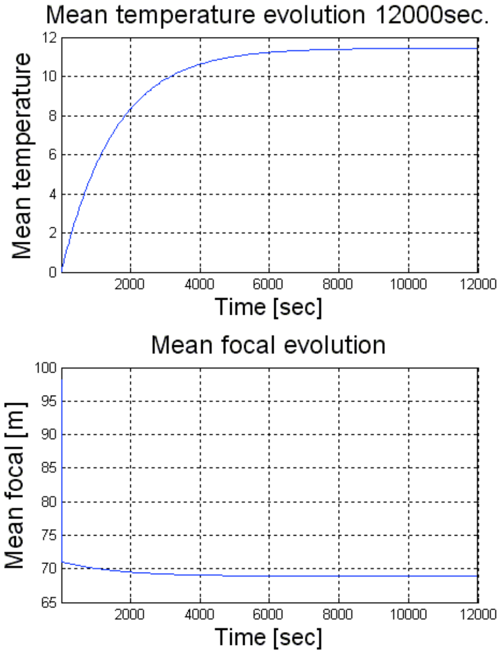

Figure 4: Mean temperature and mean focal length time evolution plots for TGG crystal and 40W laser

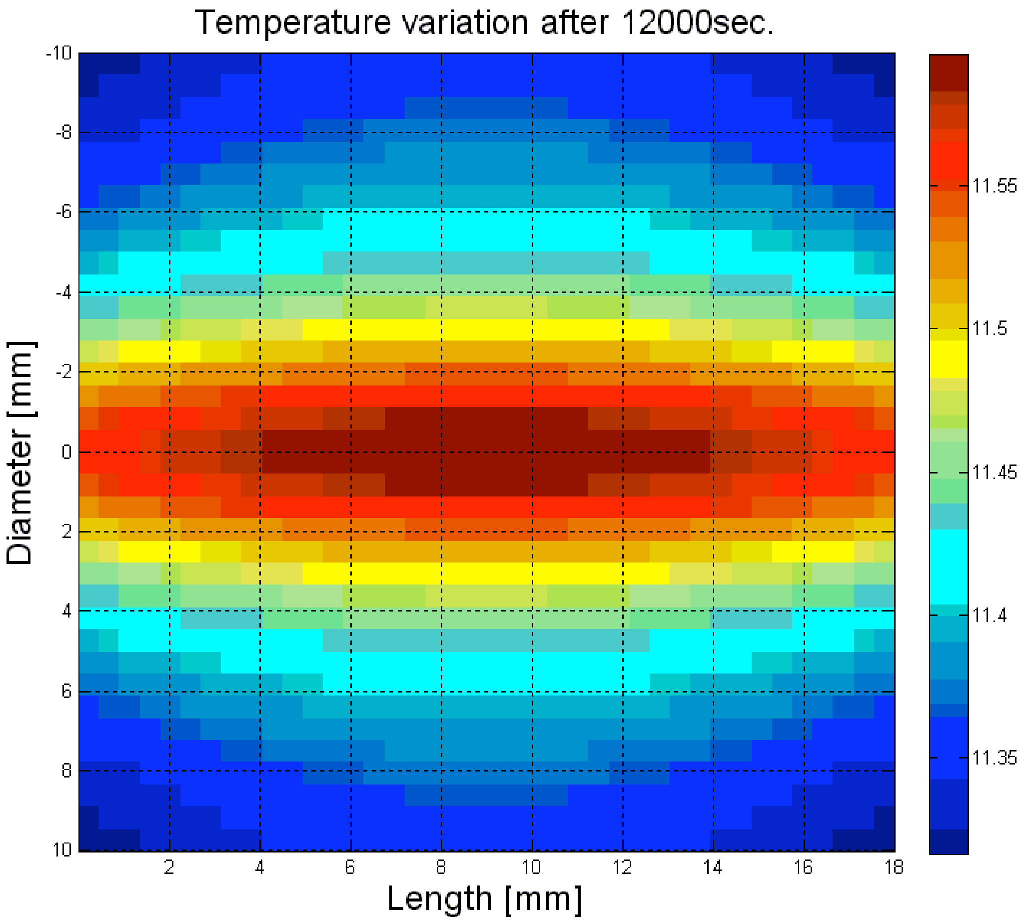

Figure 5: Temperature cross-section of TGG crystal with 40W laser

Though not part of the main output, the program can also calculate the focal length of the crystal after it has been heated.

This simulation allows us to simulate the focal lengths of heated TGG and DKDP crystals, allowing us to be able to determine the precise length of the DKDP crystal that is needed to properly compensate for the TGG thermal lensing. However, because the simulation was only developed recently, it still remained relatively untested. Thus the first objective is to make sure the simulation gives meaningful results. This was done by calculating the focal length of the TGG crystal (of the same dimensions as that being used in the Virgo experiment) after having been heated by lasers of 5W to 90W, and then comparing with experimentally obtained data:

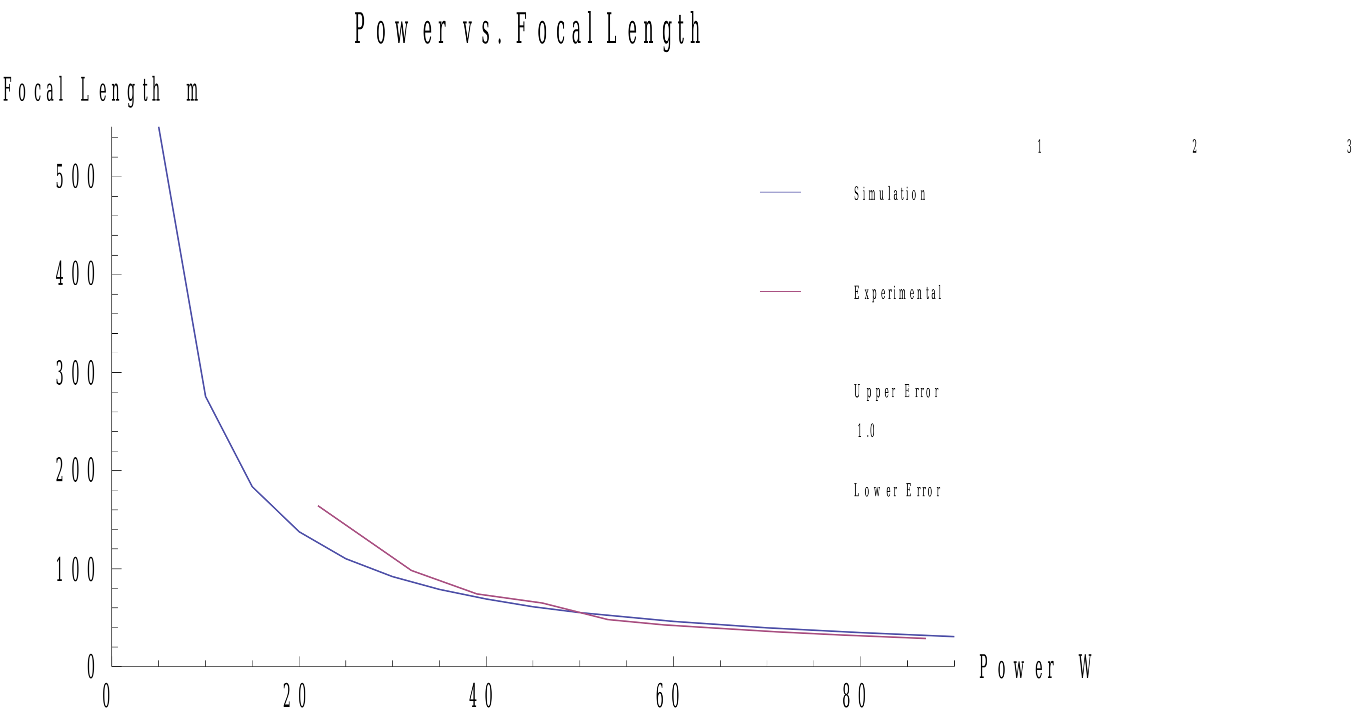

Figure 6: Power of incident laser vs. thermally induced focal length of crystal after equilibirum has been achieved.

In general, the two plots fit well together. With 40W being our area of primary interest, the results indicate that the simulation is with a 7% error, which is acceptable.

Results

Having now determined the validity of the simulation, the next step was to utilize the simulation to determine appropriate parameters for the DKDP focal length to properly match that of the TGG. The easiest characteristic to modify of the crystal is its length, which will give us a high degree of control on the focal length of the crystal. I ran the simulation for the TGG crystal at 40W using the exact specifications of the TGG crystal in the Virgo apparatus. I then ran the simulation for the DKDP crystal of varying lengths until I was able to find a length that matched that of the TGG. The two characteristics we wished to match were phase shift and focal length. In matching the phase shift, an acceptable match in the focal length was obtained, so a phase shift check was the primary result necessary. The accuracy I sought in matching the DKDP and TGG results was determined by how precise the DKDP crystal can be machined. Once the DKDP was of the proper length, the results looked like:

1.0
0.5
1 2 3 4

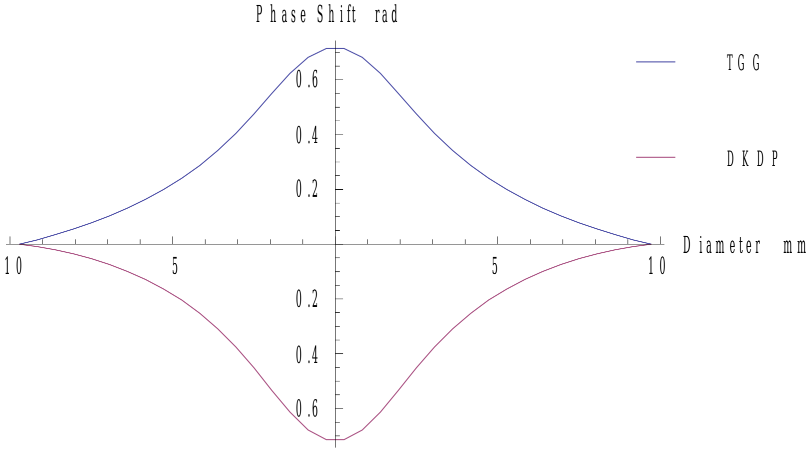

Figure 7a: Phase shift due to induced thermal lensing in TGG and DKDP crystals at 40W. This graph is for a DKDP crystal with substrate losses of 1900 ppm, which required a 3.52 mm crystal in order to compensate

Upon the inversion of the DKDP plot, it is clear that the two cancel each other out:

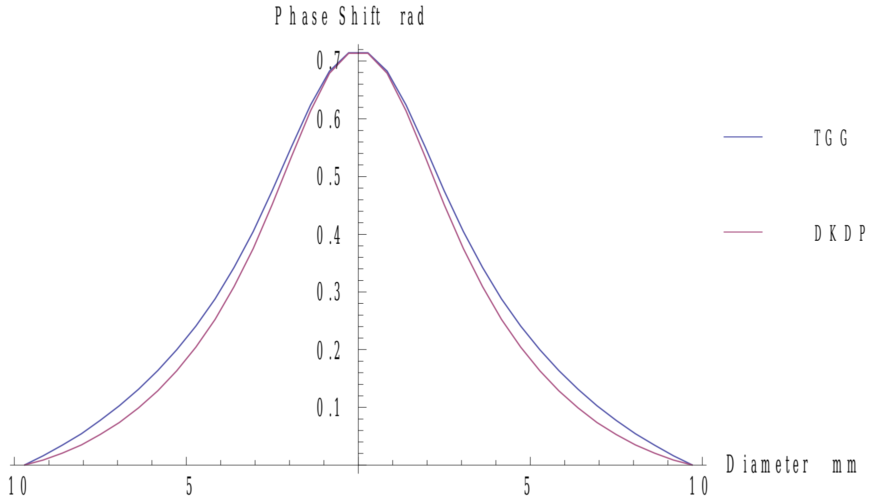

Figure 7b: Phase shift matching for DKDP and TGG crystals at 40W, highlighting the similarity of the DKDP and TGG phase shifts.

For the above example, the length of the DKDP crystal that properly compensated for the phase shift had a focal length of approximately -62 m, which combined with the roughly 68 m focal length of the TGG crystal gave the TGG-DKDP system an effective focal length of over 700 m, which is far too large to induce mode-mismatch.

I also had to take into account the possible variations in DKDP crystals. The substrate losses (per parts per million) of the crystal will vary form crystal to crystal and also have a large impact on the crystals reaction to heat. I therefore determined the appropriate length for the DKDP crystal at substrate losses ranging from 1500 to 2500 ppm.

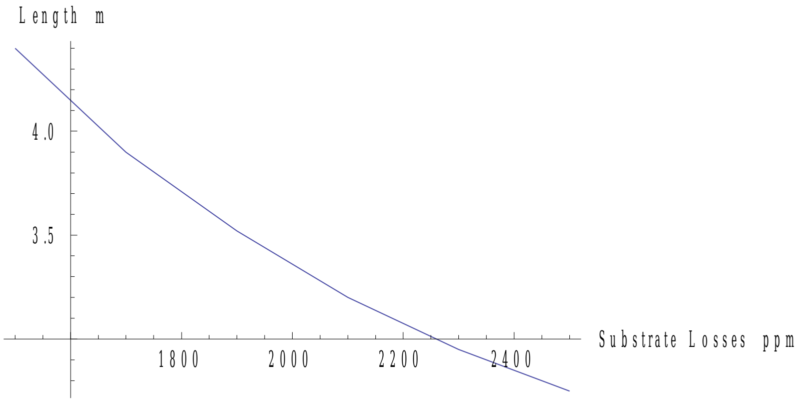

Figure 8: Substrate losses of DKDP crystal vs. appropriate length of compensator

When the DKDP crystal to be used in Virgo+ is purchased, its substrate losses will need to be determined experimentally. Once the substrate losses are known, the crystal can be machined to the proper length, as determined by the above plot. If the length suggested by the simulation proves to be effective in reducing the effect of thermal lensing in the TGG crystal, then this method will have proven its worth as effective and quick.

References

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[7] *Gradient-index Lens,* http://en.wikipedia.org/wiki/Gradient-index_lens