THERMAL LENSING COMPENSATION OBJECTIVE FOR HIGH POWER LASERS

Michael Scaggs[1], Gil Haas[2]

[1] Neoteric Concepts, LLC, 1612 Eastlake Way, Weston, FL 33326
[2] Haas Laser Technologies, Inc. 37 Ironia Road, Flanders, NJ 07836

Abstract

Athermalization of focusing objectives is a common technique for optimizing imaging systems in the infrared where thermal effects are a major concern. The athermalization is generally done within the spectrum of interest and not generally applied to a single wavelength.   By applying athermalization techniques to a laser system, a significant reduction in thermal lensing of the laser system can be realized. We describe a passive method minimizing thermal lensing of high power lasers.

Introduction

The current state of the art of focusing high power fiber lasers in excess of 100 watts is to use one or more fused silica elements [1]. One or more of the high quality fused silica lenses is used to collimate the fiber laser which is emitted from a fiber ranging in diameter from single mode to over 300 microns. The light after it has been collimated is directed to a focusing lens assembly, again made of one or more fused silica lenses that focus the light on to a surface to be cut, drilled, marked or welded. Although the fused silica lens material is highly transmissive, there is still some radiation that is either absorbed or scattered within the lens which causes it to heat up. All optical glass materials have certain thermal properties which as they heat up changes the focus characteristics of a lens made from the glass.   In particular the thermal coefficient of expansion α and change in index of refraction n as a function of temperature dn/dT (temperature coefficient of refractive index) are the driving influences on the change of power within a lens.. The power of a lens is directly influenced by these two properties by what is called the thermal power of a lens:

$$\Psi_p = \left[\frac{dn/dT}{(n-1)} - \alpha \right]$$

The power of a lens is therefore altered as a function of temperature by the following equation:

$$\Delta\Phi = \Phi \left[\frac{dn/dT}{(n-1)} - \alpha \right],$$

where Φ is the power of the lens. The change in power then is the original power of the lens times the thermal power of the lens Ψ_p.
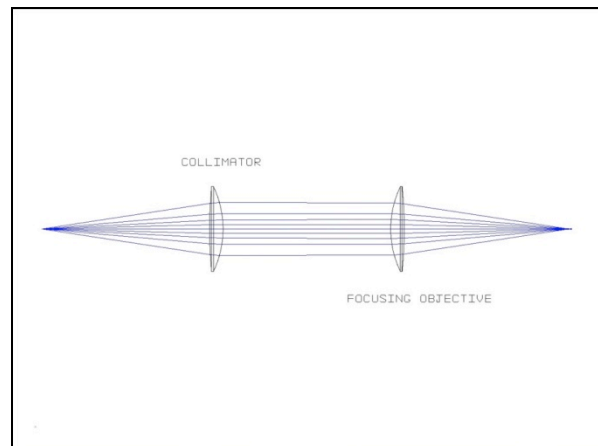

Figure 1: Typical method for delivering a high power fiber laser from the output of a fiber and then refocus onto a material to be cut, drilled, scribed, marked or welded.

Figure 1 shows the typical optical configuration for delivering the high power laser light from a fiber laser to a material to be processed. The light is delivered from a fiber to a collimation optic and then directed over some distance with mirrors to a focusing objective.   The most desirable glass for this configuration is high quality fused silica.   Upon inspection of the thermal properties of fused silica, it is found to have a very low coefficient of thermal expansion and has a very high transmission from the ultraviolet to near infrared, has low scattering and therefore the most logical and cost effective glass for the task.   Nevertheless, as can be seen from the equations above still susceptible to focal power changes as the temperature of the glass increases. Now that fiber lasers are reaching average powers of

more than 20 kW, this problem is even more troublesome.

The typical thermal coefficient of expansion (TCE) for fused silica is around 0.5×10^{-6}/K and has a dn/dT of ~ 10×10^{-6}/K. If a lens then that has a nominal focal length of 200 mm and made of fused silica, this lens will have a change in focus of more than 350 microns for a 100 °C temperature increase. Although this may not seem like a huge amount for such a long focal length lens, when used as a collimator for a fiber it has a dramatic impact on how the light is collimated from the fiber.

The present method for handling the problem is to let the system thermally stabilize which can take in excess of 3 to 4 minutes and then readjust the focus of the collimation optics and the focusing optic. This, of course, in a production environment is a very undesirable and expensive delay.
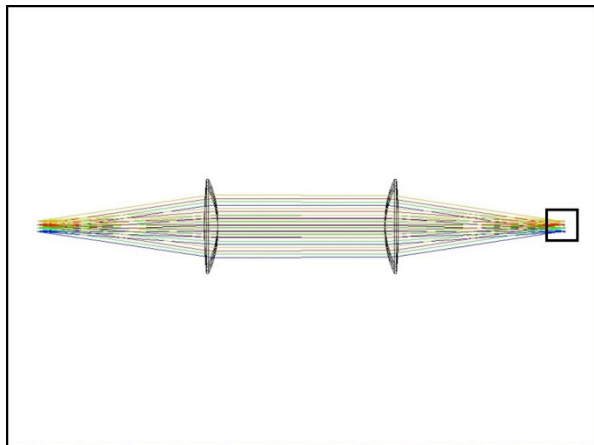

Figure 2: The same set of lenses shown in figure 1 but a multi-thermal configuration has been setup where the lower lens is at ambient temperature of 25°C, followed by increase to 50°C, 75°C and 125°C respectively.

Figure 2 shows the lens system in figure one where a multi-thermal configuration has been simulated to show the thermal lensing over a temperature gradient of 105 °C. Figure 3 shows a close up of the focus without the vertical offset, i.e., collinear on the optical axis, and the best focus is shifted towards the left, i.e., the focal length is reduced as the temperature of the system increases. The amount of focus shift in this system for a temperature gradient of 100° C is 644 microns. As the fused silica has a positive *dn/dT*, the index of refraction increases as the temperature of the glass increase which naturally results in a shorter focal length.

Athermalization is commonly applied to mid infrared optical systems but not specifically applied to high power lasers [4],[5]. These systems are adapted to compensate thermal changes over a broad spectrum within the infrared. Optical design techniques teach to achromatize and athermalize by solving three simultaneous equations:

$$\Phi = \Phi_a + \Phi_b$$

$$\Delta\Phi = \varphi_a \Phi_a + \varphi_a \Phi_b$$

$$\frac{d\Phi}{dT} = \Psi_a \Phi_a + \Psi_b \Phi_b$$

Where Φ is the power of the lens system , Φ_a and Φ_b are the powers of the individual lens elements; φ_a and φ_b are the chromatic powers of each element and Ψ_a and Ψ_b are the thermal powers of the lenses. The chromatic power of a lens is the inverse of its abbe value v.
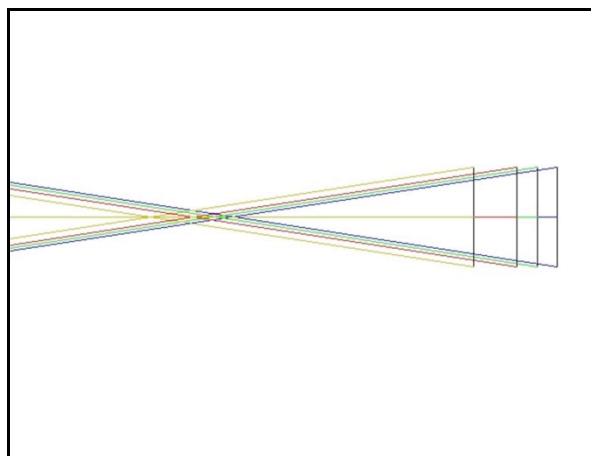

Figure 3: Close up of the thermal lensing shown in figure 2.

The present work improves the thermal lensing by using the well known thermal advantages of fused silica and offsetting the temperature coefficient of refractive index with a second material that has a negative *dn/dT*. While most glasses exhibit a positive change in temperature coefficient of refractive index as the material increases in temperature, some glasses, like CaF_2, BaF_2, LiF_2, NaCl, KCl, have negative *dn/dT*s. By balancing the power of the lenses in the system with an offsetting *dn/dT*, the optical system can maintain its focus over a wide temperature range.

The power of a two lens system is given by:

$$\Phi = \Phi_a + \Phi_b$$

Where Φ_a is the power of the first element and Φ_b is the power of the second element. If the lens system is put under a temperature change its power will be changed by:

$$\Delta\Phi = \Psi_a\Phi_a + \Psi_b\Phi_b$$

Which is the sum of the power of each element times its thermal power Ψ. In order to get a zero shift in focus, the powers of the two lens must balance as follows:

$$\Psi_a\Phi_a = -\Psi_b\Phi_b$$

Glass	dn/dT (10^{-6}/°C)	α (10^{-6}/°C)
BaF$_2$	-15.2	18.1
CaF$_2$	-10.6	18.85
LiF$_2$	-12.7	37
KBr	-40.83	43
KCl	-33.2	36
AgCl	-61	30
NaCl	-36	44
NaF	-36.2	36
SrF$_2$	-12	19.2
N-PSK53A	-4.3	9.6
N-PK51	-8.4	12.4
N-PK52A	-8.0	13
N-FK51A	-7.3	12.7
P-PK53	-6.9	13.3
N-FK5	-2.6	9.2

Table 1: Glasses with Negative Temperature Coefficient of Refractive Index and Corresponding Thermal Coefficient of Expansion.

Since we are dealing with a monochromatic light source, we don't need to concerned about the chromatic

power of the lens and the above equations are all that is needed to athermalize a laser focusing lens. An ideal situation is where the coefficient of expansion α of each glass is identical and the dn/dT of one material is the exact negative for the other. Unfortunately nature is not that generous but the deferential can be minimized by varying the thickness and curvatures of the elements to help compensate for the offsets in α and the *dn/dT*.

Glass	dn/dT (10^{-6}/°C)	α (10^{-6}/°C)
Fused Silica	10	0.52
Sapphire	13	8.4
BK7	2.4	7.1
MgF$_2$	2.3 & 1.7	13.7 & 8.5
ZnS	38.7	6.5
ZnSe	61	7.8
Si	160	4.15
Ge	396	5.7

Table 2: Common Glasses used with High Power Laser and the Corresponding Temperature Coefficient of Refractive Index and Thermal Coefficient of Expansion.

The basic requirement is that at least one of the elements that make up the multielement lens have a negative dn/dT value and the other lens be of a positive dn/dT value. The best material match of available glasses to date is that of a fused silica element and a N-PSK53A (Schott) element. The N-PSK53A glass is a moldable glass which is advantageous for fabricating an aspheric surface which helps reduce spherical aberration. N-PSK53A being a moldable glass may restrict the level of laser power used as it has > 2 times softening point compared to fused silica. In view of the potential power limitations of the N-PSK53A glass, we choose an alternate design using a CaF$_2$ element and a fused silica element. CaF$_2$ and fused silica are both good materials for high power lasers ranging form the UV through the near infrared [3]. Nevertheless, the possibilities are not limited to just these two materials.

Table 1 shows useable glasses with negative *dn/dT* values and the corresponding α values. Table 2 lists glasses typically used with high power lasers and their corresponding *dn/dT* and α values.

Since the tables show that it is hard to get a perfect match of *dn/dT* and comparable TCEs, that the thickness of the lens elements and their corresponding curvatures are variables that will assist in achieving best athermalization for a high power laser. This is accomplished by building a suitable merit function in today's optical design software programs to optimize the lens thickness, curvatures and spacing to keep the focus shift under the nominal Rayleigh range value for the lens system. Nevertheless, it is clear to see from the tables that a combination of glasses can be configured to accommodate athermalization for high power lasers ranging from the UV to the far infrared which includes but is not limited to excimer lasers, Nd:YAG lasers, fiber lasers and CO_2 lasers.
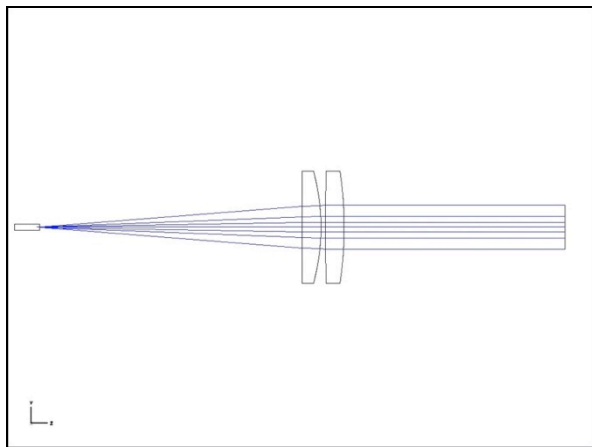

Figure 4: Fused Silica Collimation Doublet.

Figure 4 represents the current state of the art fiber collimator used in conjunction with a high power fiber laser based on a fused silica doublet that produces the best level of collimation and wavefront error.
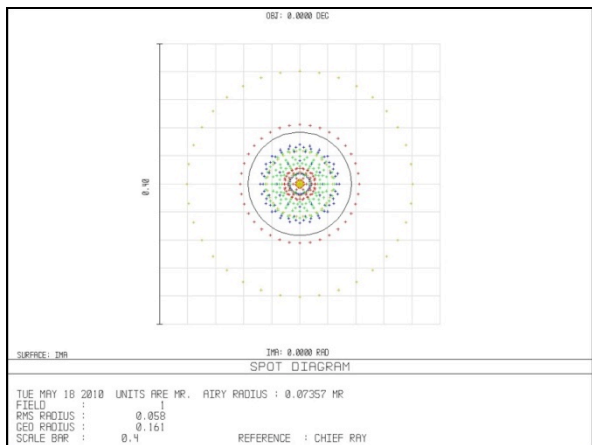

Figure 5: Spot Diagram of Fused Silica Collimation Doublet Over a Temperature Gradient of 100 °C.

Figure 5 is a spot diagram of the collimation lens doublet in figure 4. The airy disk radius (diffraction limited divergence) for this lens system is 0.074 mradians and the temperature values of less 40°C and the most outer sets of rays extend to 0.161 mradians at 125°C.
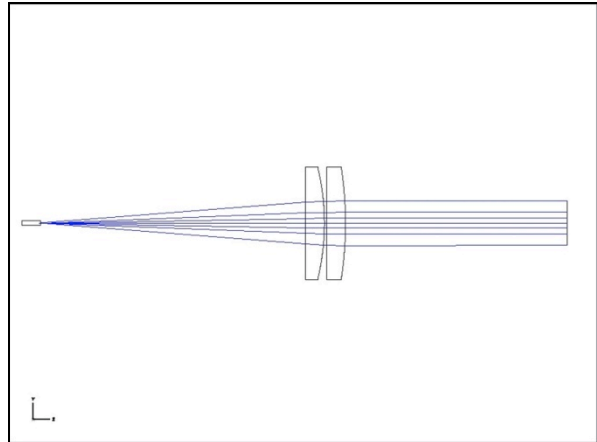

Figure 6: N-PSK53A and SiO$_2$ Collimation Doublet.

Figure 6 is a representation of the thermal lensing compensations objective as a fiber collimator for a high power fiber laser. Here the first lens is a fused silica lens and the second lens is made from N-PSK53A.
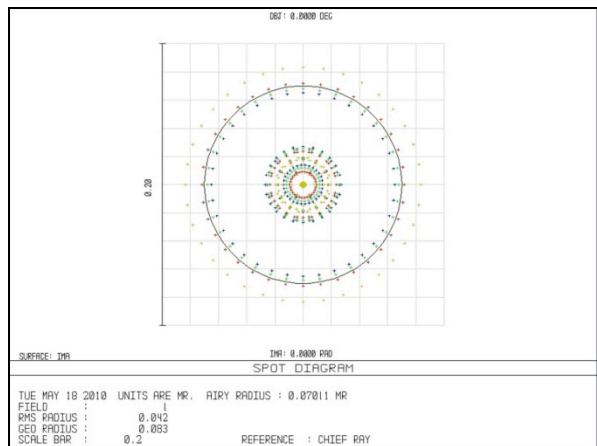

Figure 7 Spot Diagram of N-PSK53A & Fused Silica Collimation Doublet Over a Temperature Gradient of 100 °C.

Figure 7 is the spot diagram for the collimator in figure 6. The divergence of the system at the higher temperature has been reduced to 0.083 mradians which is very close to the diffraction limit of 0.0701 mradians but most importantly the divergence as a function of

temperature is much more constant in contrast to the fused silica doublet.

Figure 8 is a representation of the thermal lensing compensation focussing objective for a high power fiber laser. Here the first lens is a fused silica lens and the second lens is made from N-PSK53A. Each color of the ray trace represents a temperature configuration starting from ambient (25° C) blue, to green (50° C), red (75° C) and gold (125° C). There is no discernable change in the position of the geometrical ray trace focus over this range of temperatures.
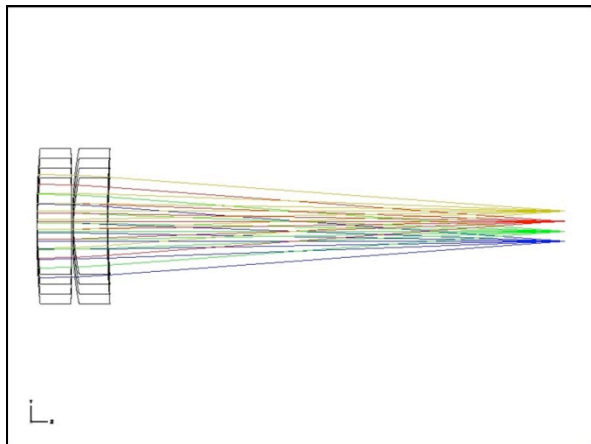

Figure 8: SiO2 and N-PSK53A Thermal Lensing Compensation Objective.

Figure 9 is the spot diagram for the focusing objective in figure 8. The rms spot radius is 2.129 microns and the geometric radius is 3.936 microns which is well below the diffraction limit of 8.737 microns.
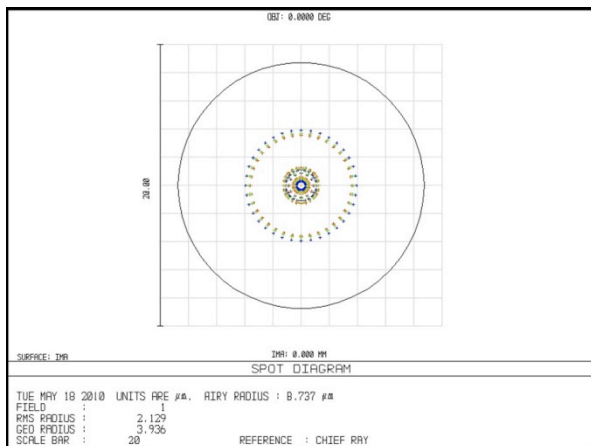

Figure 9: Spot Diagram of the Thermal Lensing Compensation Objective in Figure 8.

Figure 10 is a spot diagram of a fused silica and CaF_2 doublet that have been thermally optimized for minimal focal shift variation. Here we can see that the design is still diffraction limited and that the rays are very closely together over the temperature 105 °C gradient. It is important to note that the negative dn/dT of CaF_2 causes the focal length of the system to increase slightly but as can be seen in the spot diagram the higher temperature rays are actually focusing a bit more tightly so this seems to help improve the overall performance of the system as the temperature increases.
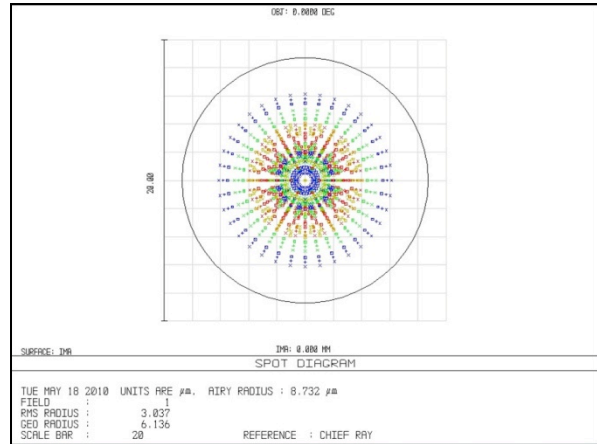

Figure 10: SiO$_2$ and CaF2 Thermal Lensing Compensation Objective Spot Diagram.

Table 3 shows the optical prescription and thermal setting for a fused silica lens with a nominal effective focal length of 100mm focusing light at 1.075 µm. The back focal length is given for each temperature variation and the then the corresponding difference of the focus shift to the nominal temperature is given as the "Delta" values. A positive "Delta" represents a decrease of the focus by the value given in millimeters.

Operand	Surface	CONF1	CONF2	CONF3	CONF4
TEMP	1	25	50	75	125
CRVT	1	0.018	0.018	0.018	0.018
THIC	1	7.000	7.000	7.000	7.000
CRVT	2	-.004	-0.004	-0.004	-0.004
TEMP	2	25	25	25	25
BFL		95.695	95.642	95.596	95.497
	Delta	**0.000**	**0.052**	**0.098**	**0.197**

Table 3: Prescription of Fused Silica Singlet (TEMP in °C all other values in mm)

Table 4 shows the optical prescription for a fused silica doublet at 1.075 µm.

Table 5 provides the prescription of the best matched glass for a doublet focusing a fiber laser at 1.075 microns.

Operand	Surface	CONF1	CONF2	CONF3	CONF4
TEMP	1	25	50	75	125
CRVT	1	0.009	0.009	0.009	0.009
THIC	1	7.000	7.000	7.000	7.000
CRVT	2	-.002	-.002	-.002	-.002
THIC	2	0.250	0.250	0.250	0.250
CRVT	3	0.016	0.016	0.016	0.016
THIC	3	7.000	7.000	7.000	7.000
CRVT	4	0.005	0.005	0.005	0.005
TEMP	4	25	25	25	25
BFL		91.958	91.915	91.869	91.771
	Delta	0.000	0.044	0.090	0.188

Table 4: Prescription of Fused Silica Doublet (TEMP in °C all other values in mm)

Operand	Surface	CONF1	CONF2	CONF3	CONF4
TEMP	1	25	50	75	125
CRVT	1	0.008	0.008	0.008	0.008
THIC	1	7.000	7.000	7.000	7.000
GLSS	1	FS	FS	FS	FS
CRVT	2	-.002	-.002	-.002	-.002
THIC	2	0.250	0.250	0.250	0.250
CRVT	3	0.015	0.015	0.015	0.015
THIC	3	6.993	6.995	6.997	7.000
GLSS	3	N-PSK53A	N-PSK53A	N-PSK53A	N-PSK53A
CRVT	4	0.006	0.006	0.006	0.006
TEMP	4	25	25	25	25
BFL		92.341	92.344	92.345	92.344
	Delta	0.000	-0.003	-0.004	-0.003

Table 5: Prescription of Fused Silica and N-PSK53A Doublet (TEMP in °C all other values in mm)

Operand	Surface	CONF1	CONF2	CONF3	CONF4
TEMP	1	25	50	75	125
CRVT	1	0.011	0.011	0.011	0.011
THIC	1	7.000	7.000	7.000	7.000
GLSS	1	FS	FS	FS	FS
CRVT	2	-.002	-.002	-.002	-.002
THIC	2	0.250	0.250	0.250	0.250
CRVT	3	0.016	0.016	0.016	0.016
THIC	3	6.987	6.990	6.994	7.000
GLSS	3	CaF_2	CaF_2	CaF_2	CaF_2
CRVT	4	0.007	0.007	0.007	0.007
TEMP	4	25	25	25	25
BFL		91.111	91.125	91.139	91.164
	Delta	0.000	-0.014	-0.028	-0.053

Table 6: Prescription of Fused Silica and CaF_2 Doublet (TEMP in °C all other values in mm)

Given that N-PSK53A glass may be a questionable material for extremely high laser powers, table 6 shows a prescription where fused silica is use in conjunction with CaF_2.

Results

If fused silica is solely used as the glass for a focusing objective, the focal length decreases by 197 microns and 188 microns for the singlet and doublet respectively referring to tables 3 and 4 for the nominal effective focal length of 100 mm over the 100 °C temperature gradient. In contrast the focus shift over the 25 to 125 °C temperature range is only about 3 to 4 microns for the fused silica/N-PSK53A glass combination. This is an improvement of 47 times over the fused silica doublet for the BFL values (see tables 4 and 5).

The use of CaF_2 causes the focal length of the system to increase by 53 microns for the highest temperature configuration which is indicated by the negative sign in contrast to the positive value for the fused silica doublet. Nevertheless, the focal shift is a 3.5 times improvement over the fused silica doublet and the optics can be used at very high average power levels.

A close inspection of the spot diagram in figure 10 shows that the more the lens system heats up the smaller the spot is actually becoming so that even though the focal length is slightly increasing, it is further reducing aberrations and improving performance of the lens system and thereby making if more diffraction limited.

Conclusion

This work shows that it is theoretically possible to manage thermal lensing of high power laser optics using a completely passive approach. Given the multi-element nature of the design, there is the added benefit of the ability to manage aberrations in addition to the thermal lensing.

Presently under development is actual laser testing of both a collimation and focusing objective thermal lensing compensation system; where we will compare the theoretical Zemax data with field data with a high power laser setup.

References

[1] Abt et al, *Focusing High-Power, Single Mode Laser Beams*, Photonics Spectra Magazine, May 2008

[2] Steele et at describe a similar behavior with a CO_2 laser in *Spot Size and Effective Focal Length Measurements for a Fast Axial Flow CO2 Laser*, in a paper released by the Department of Energy

[3] Klein in *Materials for High-Energy Laser Windows: How thermal Lensing and Thermal Stress Control Performance*, SPIE Proceedings Vol. 6666, 66660Z1 (2007)

[4] Smith, *Modern Optical Engineering*, McGraw Hill 2000 and in *Practical Optical System Layout and Use of Stock Lenses*, McGraw Hill, 1997

[5] Fishcer et al in *Optical System Design*, McGraw Hill, 2008