An analytical study of thermal invariance of polymeric nanolayer gradient index optical components

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ABSTRACT

Specially formulated Gradient-Index polymeric optical materials offer capabilities not possible in conventional GRIN or homogenous optics. A novel technology that enables large scale processing of nanolayered polymer films into real, performance-enhancing lenses and other optical components for Defense-related optical systems is currently being employed.

Polymeric nanoLayer GRIN materials (LGRIN) offer the ability to design and fabricate optics with custom gradient refractive index profiles in optical components up to 90 mm in diameter and approaching 5 cm thick. High performance achromatic singlet lenses were designed using specially developed ZEMAX design tools and exceptionally high quality lenses were fabricated from the LGRIN materials. Optical performance of LGRIN optics is shown to be significantly better than with conventional monolithic optics while also significantly reducing optical system mass, volume, and optical element count.

Understanding the thermal behavior of such optical components is essential to their operational capability. An experimental study of the effects of elevated operational environments to validate the feasibility of deploying LGRIN optics into real-world operational environments was carried out. Interferometric and physical measurements of structure and optical performance of LGRIN lenses was completed over a 30° – 50°C temperature range. It is shown that nanolayered LGRIN optics and components exhibit no significant variation in optical performance with temperature as compared with commercial, homogenous acrylic optics in the designed operational thermal range.

Keywords: GRIN, polymeric GRIN, Nanolayer polymer, GRIN Optics, Polymer GRIN Optics

1. INTRODUCTION

Gradient index (GRIN) optical materials have enabled the fabrication of lenses whose capabilities far exceed those achievable by homogeneous optical materials [1, 2]. GRIN lenses can be fabricated to give significant corrections of classical Spherical, Chromatic, Astigmatic, and Comatic aberrations, as well as allowing exceptional optical performance to be achieved in concert with both spherical and aspherical surface forms. There are a number of well known methods of producing GRIN optics with axial, radial, and distributed GRIN profiles such as diffusion, sol-gel, stacked-glass-layer, and others[3]. These GRIN materials have always been constrained to a small subset of GRIN profile geometries, with small diameters, between some minimum and some maximum index value without allowing inflection. Revolutionary performance could be achieved if GRIN materials could be designed with a “custom tailored” approach as unconstrained with unlimited GRIN profile and inflection throughout the optical material volume to address specific optical performance parameters, and then be fabricated into lenses for real-world applications. If such optical lenses could also be made significantly lighter, then many advanced applications problems could be addressed and solved with real components.
Polymer nanolayer materials offer the ability to design and fabricate optics with exactly this kind of custom-tailored Gradient Index profiles and not be constrained to simple geometries. Polymeric Nanolayer GRIN materials (LGRIN) have been assembled into substrates up to 5 cm thickness composed of over $10^6$ layers of multiple polymer materials with parametric, unconstrained structural definition. Exceptionally high quality optical lenses have been designed and fabricated from these materials using a combination of unique thermoforming molding and current Optical Diamond Turning and/or grinding/polishing machining processes to achieve final optical surface geometries. The results are physical lenses that have demonstrated major advantages in addressing Spherical Aberration, Coma, Chromatic Aberration, and Astigmatism. Results are shown to be significantly better than what is achievable with singlet or multi-lens homogenous optics, with spherical or even aspherical surfaces, and particularly, with more classical Axial or Radial GRIN characteristics. LGRIN optics, while offering exceptional optical performance, have also demonstrated a capability to significantly reduce Vis-SWIR optical system mass/volume by replacing glass or homogenous plastic optics and reducing the required optical element count.

1.1 LGRIN Technology, Fabrication, and Applications overview

The key technology breakthrough is the large scale processing of nanolayered polymer films with a single, compositionally dependent refractive index. This is achieved through a unique process of Layer-Multiplication during film-extrusion of polymeric nanolayer films. This is accomplished employing unique, patented extrusion-layer-multiplier equipment which can produce thousands of feet of custom-defined polymer nanolayer films per day. Nanofilms of different polymer materials with thickness of approximately 8 nm are “multiplied” together and layered into ~50µ thick macroscopic sheets of nanolayer materials with varying index of refraction. These films are then stacked into full scale sheets of polymer material up to 5 cm thick with specifically tailored GRIN profiles, Figure 1. These materials are then molded and machined to final shape and performance with specially chosen GRIN contour which, with the GRIN profile, addresses and corrects well known optical aberrations with much lighter weight and smaller volume optical components. High performance achromatic singlet lenses were designed and fabricated using specially developed ZEMAX design tools[4].

![Fig. 1. LGRIN optics fabrication process overview showing stacking, thermoforming, and final diamond machining steps](image-url)
1.2 Applications and Technology

An example of real-world application of the LGRIN technology is the improvements made to an eyepiece of a US Military AN/PVS-14 Night-Vision monocular. LGRIN achromatic optics were designed and fabricated that significantly improved Chromatic, Spherical, Comatic, and astigmatic aberrations for a series of test eyepieces of identical external physical form-factor, Figure 2, which also resulted in significant improvement of optical performance (wavefront transmission error) over the full Clear-Aperture, on axis in the image plane, compared to current glass-eyepiece in use, Figure 3.

LGRIN optics also offer a very significant ~7X weight savings in the optics (Glass eyepiece has 6 elements with 81g weight compared to the LGRIN eyepiece comprised of 4 elements with 11g weight), resulting in a 25% overall system weight savings. The most current work has resulted in successful manufacture of High-performance LGRIN achromatic singlet objective lenses with diameters up to 90mm with 80% weight savings over current purpose-designed glass achromatic doublets.

Fig. 2. GRIN optics NVG-14 Night-Vision eyepiece example

Fig. 3. RMS wavefront error comparing serial production prototype LGRIN eyepieces to current GLASS eyepiece.
1.3 Scope and Objectives of the program
The goals of this work included Quantification of the thermo-optical behavior of polymeric nanolayered GRIN lens materials at elevated, DOD relevant temperatures.

Custom designed and fabricated LGRIN optics were subjected to a regimen of stringent analysis in order to characterize their behavior under carefully controlled and understood varying thermal loads in the range of nominal room-temperature 30°C to 50°C. Characterizing analysis included Interferometric wavefront (reflected-surface and transmitted) and Focal Length measurements.

Information collected on the thermo-optical behavior of the LGRIN optics is important for incorporation into LGRIN optical design tools to simulate “in-the-field” performance of the technology for accurate and well understood design.

The goal of investigating temperature variant LGRIN optical characterization is primarily to evaluate paths to reduce the thermally dependent performance of polymer LGRIN optics.

2.0 TECHNICAL APPROACH AND METHODS
Comparisons were made of two distinct types of optical components at Thermal conditions ranging from Room-Temperature (~22°C) to 50°C maximum at increments of 5°C. The first is a commercial 25mm Diameter, f/4 (100 mm Focal length), Uncoated, Molded Acrylic Aspheric Lens (Edmund Optics Molded Acrylic Asphere PCX lens – 48712). The second is a Peak Nano designed 25mm Dia., f/4 (100 mm Focal Length), uncoated LGRIN PCX singlet GRIN lens.

The components were analyzed under the designated thermal loads employing a Zygo VeriFire interferometer. Measurements of Temperature VS Radius, optical Figure, and Transmission wavefront geometry (both Peak-to-Valley and RMS) as well as defining three primary measured parameters: Astigmatism, Spherical, and Coma at the 0.6328 micron wavelength. Measurements of focal length and focal length change were also made.

2.1 Optical characteristics of lenses to be tested
The optical performance characteristics as designed of the lenses tested were compared as a baseline for understanding both the significant differences in performance between a good quality homogeneous, aspheric polymer lens and the Peak Nano LGRIN lens. The as-designed performance characteristics for the commercial polymer aspheric PCX lens are shown, Figure 4 and 5.

Figure 4. Commercial high quality polymer asphere PCX lens layout and geometric MTF curve
2.2 Peak Nano polymeric LGRIN PCX lens

This lens was fabricated from an existing “Preform mold” which accommodated the design for a 25.4 mm diameter, f/4 LGRIN lens and defines that the GRIN contour radius will be 19.80mm.

The lens is a PCX designed to most highly correct Achromatic and Spherical aberrations and achieve the highest MTF for F, d, C visible wavelengths across a 1 degree FOV. This design was accomplished using the custom Zemax code for designing with Peak Nano LGRIN materials specially developed by the Naval Research Laboratory and Peak Nano.

The final design can easily be compared against Zemax models, shown previously, for the commercial polymer aspheric PCX lens for baseline evaluation and was optimized for superior optical performance.

The final design of LGRIN PCX singlet lens was translated to fabrication and several were made for the thermal analysis effort in the project.

The as-designed performance characteristics for the Peak Nano LGRIN PCX lens are shown, Figure 6.
The Gradient Index Contour molded into the volume of the lens shows how the GRIN contour is decoupled from the lens surfaces and the unique LGRIN profile through the z-axis of the lens shows a custom design to achieve very high optical performance not possible with even highly corrected aspheric singlet PCX optics, Figure 7.

2.3 Thermal system and interferometer

Thermal testing was accomplished using a specially designed thermal control system consisting of 2 major components: A custom designed “thermal block” for housing and supporting the optical components in an unconstrained mount so as to not induce artificial stress into the lenses being tested, and a specially designed thermal heating and sensor system with heating control and measurement accurate to ±1ºC.

The thermal sensor system has 4 miniature thermocouple inputs to simultaneously measure temperature of the lens under test, and thermal block, and other parts as determined was designed and fabricated. The thermal control system was then tested in the interior of the Zygo VeriFire Interferometer and it was determined that the heat source does not introduce any deleterious thermal effects in the air-volume or measurement capability of the instrument. This result gave a very high confidence that all planned Interferometric measurements would be real and not adulterated by spurious thermal effects in the interferometry.
The thermal block with integrated heater-coil/control sensor is shown under construction and completed for use, Figure 9. The lens mounting recess is clearly seen and entire block is wrapped in thermal-insulating silicone tape before being mounted in the interferometer or for other testing.

![Figure 9. Thermal block assembly showing heater sensor/coil and thermocouple lead.]

A series of redundant measurements were made to understand the actual thermal behavior, thermal loading, thermal-time-lag, and relationship between set instrument temperature, Thermal mounting block temperature, and actual lens temperature. Prior to testing the lenses for the analytical comparisons this first set of measurements were set up to measure Heater/Sensor setting, Thermal Block Setting, Control lens temperature at edge, and Control lens temperature at center. The goal was to determine the time for the lens to come to actual desired, stable temperature, and what actual setting for temperature of heater/sensor and thermal mounting block were required to achieve that goal. It turned out conveniently, that one hour was sufficient for the lens to come to stable temperature and that the results of the measurements gave a clear set of temperature settings to bring the lenses to actual desired temperatures.

The thermal block and thermal control system are shown fully instrumented and mounted in Zygo VeriFire interferometer, Figure 10. This is the configuration for measurement of surface characteristics and for transmitted wavefront vs temperature.

![Figure 10. Thermal block assembly and control system mounted in Zygo interferometer as employed with test lens in place.]

The thermal block assembly and control system mounted in Zygo interferometer as employed with test lens in place.
The thermal block is mounted in the vertical interferometer to enable measurements of both surface interferometry and wavefront transmission interferometry, Figure 11.

![Figure 11. Thermal block and all control and sensor leads mounted in place for testing in the interferometer](image)

It is important to note that the thermal convective effects in the air mass (thermal column) between differentially heated optical components in the interferometer can introduce a significant source of error to measurements. In order to obviate these effects it is necessary to change the laminar convective layer at the radiating lens surface, which is composed of a large thermal cell to a turbulent convective layer, which is composed of very small thermal cells. This is a well-known and understood method that will negate the effects of thermal convection in the air column and allow only the true wavefront to be shown by the interferogram.

This was accomplished by using a small fan turned on and off to match the image-capture cycle of the interferometer. This is the same method typically used in compensation in large reflecting astronomical telescopes, and was very successful for these measurements.

### 2.4 Thermal system and Foucault Tester

A full characterization of the thermal effects on the lenses required that focal length relative to the radius of curvature of each lens be measured as accurately as possible. The method used to test the lenses is derived from the Foucault method of focal length measurement of mirror optics. The concept and application is identical to that of mirror measurement for lens measurement. This is well known (invented by Leon Foucault in 1858) and very sensitive for the precise measurement of focal length related to radius of curvature. It is still a high-precision method of simple, direct measurement of focal length and radius and especially useful for measuring focal length change. It is typically possible to visually measure absolute focal position with accuracies of better than 0.5%. With this in mind, a modified Foucault Test device integrating the thermal block to make quantitative measurements was designed and tested successfully.
The Foucault method very accurately locates the focal point as the center of radius of curvature using a sharp knife-edge to precisely cut the focal spot producing a diffraction pattern. We have been able to measure focal length changes over the temperature range of our experiments to ±50µ.

Foucault Test setup for measuring focal length change of lenses vs temperature is shown fully instrumented with the thermal block and control assembly at the Peak Nano Metrology Lab, Figure 12.

Figure 12. Foucault tester thermal block assembly

The Foucault method of focal length measurement for a lens requires a collimated light source, which we have generated using a laser and precision collimator. The test apparatus is built of opto-mechanical components which maintain ortho-normality and allow precise movement of the knife edge both along the optical axis and perpendicular to it. The lens under test is mounted in the same thermal block as used in the interferometric testing and the light path turned 90 degrees using a precision optical periscope mirror to direct the beam toward the knife-edge and a white screen upon which the diffraction pattern is projected.

The Foucault test uses the diffraction pattern formed by the knife-edge which is adjusted in position both along the optical path, and orthogonally to it, to cut the smallest point of the focal spot. The diffraction pattern is projected on a screen “downstream” and observed visually to make the adjustments and find the exact focal point in space. This method is particularly sensitive to measuring changes in the focal point.

The focal point is determined to be the location most nearly halfway between the points where the diffraction fringes form and are seen visually to reverse field from left to right. The characteristic “donut” shape of the projected focal spot lies between the diffraction fringe fields and gives a very accurate positional measurement of the focal point. The actual diffraction pattern produced clearly shows the inside-focus and outside-focus, and at-focus patterns, Figure 13.

Figure 13. Foucault tester diffraction patterns projected on screen.
Measurements of change in focal length with temperature of all lenses were made at each temperature and the simple average taken. Measurements were made at Room Temperature (30°C) and 50°C since the total change in focal length over the entire range was so small (on the order of ~300µ maximum for the polymer lenses). Since the change in focal length is small, finer resolution (5°C steps as in the interferometric measurements, or even 10°C steps) in temperature did not allow easily resolved change in focal length but the changes over the full 20°C range were easily measured confidently.

### 3.0 BASELINE ACRYLIC PCX LENS MEASUREMENTS, DATA, AND ANALYSIS

#### 3.1 Change of lens surface radius with temperature

Measurements of change in Radius with temperature were then made for 3 acrylic asphere control lenses. Three measurements were made for each lens at each temperature. Temperature range and settings for the lenses were room temperature (~30°C) to 50°C in 5°C increments. Data was tabulated to chart the change in Radius for each lens and compare the three samples. Data was also compared to a ZEMAX model of the control lens with thermal characteristics included in order to determine if the actual lens behavior was as expected. Data was tabulated and charted for 3 lenses designated ASP1, 2, 3 for temperatures as defined. The values are radius (mm) for each measurement. Three measurements were made for each lens at each temperature. Also, the average of the three radius measurements at each temperature for each lens were tabulated and charted as well. This data is shown in a comparative chart, Figure 14. The nominal design radius of the lens is 50.0 mm. The range of radius with temperature is as expected with respect to thermal coefficient of the acrylic material. The total change in radius from ~30°C to 50°C in 5°C increments is ~0.2mm. This is ~0.4% change. This would represent similar change in focal length, across the entire temperature range of ~0.4% (~.4mm total from ~30°C to 50°C).

![RADIUS VS TEMPERATURE](image)

**Figure 14.** Charted data showing change of convex lens radius with temperature for 3 acrylic PCX asphere reference lenses

#### 3.2 Change of transmitted wavefront with temperature
Measurements of change in transmitted wavefront with temperature were then made for 3 acrylic asphere control lenses. Three measurements were made for each lens at each temperature. Data was tabulated to chart the change in transmitted wavefront for each lens and compare the three samples. Temperature range and settings for the lenses were Room Temperature (-30ºC) to 50ºC in 5ºC increments.

There are 5 plots for transmitted wavefront effects vs temperature changes of the acrylic asphere control lenses. The plot for wavefront focus shows the deviation from focus expressed in mm, Figure 15. All measurements were made as close to focus as was possible to adjust the interferometer. There are a couple of outliers that can be obviously attributed to being at the extreme outside focus point (~0.1mm), however. The data for spherical aberration, Figure 16, coma, Figure 17, astigmatism, Figure 18, and tilt, Figure 19, are expressed in waves.

Figure 15. Data showing change of position of wavefront focus with temperature for 3 acrylic PCX asphere reference lenses

Figure 16. Data showing change of wavefront spherical aberration with temperature for 3 acrylic PCX asphere reference lenses
Figure 17. Data showing change of wavefront coma with temperature for 3 acrylic PCX asphere reference lenses

Figure 18. Data showing change of wavefront astigmatism with temperature for 3 acrylic PCX asphere reference lenses

Figure 19. Data showing change of wavefront tilt with temperature for 3 acrylic PCX asphere reference lenses
3.3 Analysis of baseline acrylic PCX lens wavefront transmission data

1) The four aberrations do show some effects during these measurements.
2) Focus position was maintained as closely as possible zero-position for all measurements but some of the variation in aberrations can be obviously attributed to variations in focus position.
3) Spherical Aberration is very well controlled over the entire temperature range from ~30ºC to 50ºC, showing generally less than 0.5 wave variation.
4) Comatic aberration is also very well controlled over the entire temperature range from ~30ºC to 50ºC, showing generally ~1 wave variation.
5) Astigmatic aberration is also very well controlled over the entire temperature range from ~30ºC to 50ºC, showing generally ~0.3 wave variation.
6) Tilt aberration is well controlled over the entire temperature range from ~30ºC to 50ºC, showing generally ~0.5 wave variation for one lens and ~1.0 to ~1.5 wave variation for the other two.

This data shows that the wavefront transmission as a reference for optical performance remains very well controlled and variations with temperature of key aberrations is minimal. This gives a clear indication of the sort of baseline behavior that can be expected from the LGRIN polymer lens when it is tested as well.

3.4 Change of baseline acrylic asphere PCX lens focal length with temperature

Measurements of change in focal length with temperature were then made for 3 baseline acrylic polymer asphere lenses. Three measurements were made for each lens at each temperature and the simple average taken. All measurements were made at focus position ~±0.1 wave. This data was charted, Figure 20.

![Figure 20](image)

Figure 20. Data showing change of focal length with temperature (waves).

3.5 Analysis of baseline acrylic PCX lens focal length change data

Focal length changed consistently for each lens tested as expected.

4.0 PEAK NANO LGRIN LENS MEASUREMENTS, DATA, AND ANALYSIS
4.1 Change of LGRIN lens surface radius with temperature

Measurements of change in radius with temperature were made for 2 asphere lenses designed by Peak Nano using the LGRIN design tools with ZEMAX-15 Optics Studio. Three measurements were made for each lens at each temperature. Temperature range and settings for the lenses were room temperature (~30ºC) to 50ºC in 5ºC increments. Data was tabulated to chart the change in radius for each lens and compare the two samples. Data was also compared to a ZEMAX model of the control lens with thermal characteristics included in order to determine if the actual lens behavior was as expected.

Data is tabulated and charted for 2 lenses designated 3-9-1 and 3-10-1 for temperatures as defined. The values are radius (mm) for each measurement. Three measurements were made for each lens at each temperature and, the average of the three radius measurements at each temperature for each lens is plotted, Figure 21.

![Charted data showing change of LGRIN lens radius with temperature](image)

Figure 21. Charted data showing change of LGRIN lens radius with temperature

The nominal, performance-based design radius of the convex surface of the Peak Nano LGRIN lens is 44.05 mm. The change of radius with temperature is as expected with respect to thermal coefficient of the acrylic material. The total change in radius from ~30ºC to 50ºC in 5ºC increments is ~0.140mm. This is ~0.3% change, and would represent similar change in focal length, across the entire temperature range of ~0.3% (~.3mm total from ~30ºC to 50ºC). This variation is entirely consistent with the data observed for the previously tested monolithic acrylic asphere lens.

4.2 Change of LGRIN lens transmitted wavefront with temperature

Measurements of change in transmitted wavefront with temperature were then made for 2 asphere lenses designed by Peak Nano using the LGRIN design tools with ZEMAX-15 Optics Studio. Three measurements were made for each lens at each temperature. Data was tabulated to chart the change in transmitted wavefront for each lens and compare the three samples. Temperature range and settings for the lenses were room temperature (~30ºC) to 50ºC in 5ºC increments. There are 5 plots. The plot for focus shows the deviation from focus expressed in waves, Figure 22. Those for spherical, Figure 23, coma, Figure 24, astigmatism, Figure 25, and tilt, Figure 26, show the aberrations expressed in waves. All measurements were made as close to focus as was possible to adjust the interferometer. Chosen accuracy was ±0.1 wave. There are a couple of outliers that can be obviously attributed to being at the extreme outside focus point (~0.1mm), however.
Figure 22. Data showing change of position of LGRIN lens wavefront focus with temperature. All measurements made at focus position ~±0.1 wave

Figure 23. Data showing change of LGRIN lens wavefront spherical aberration (waves)

Figure 24. Data showing change of LGRIN lens wavefront coma with temperature (waves)
4.3 Analysis of Peak Nano LGRIN lens wavefront transmission data

1) The four aberrations do show some effects during these measurements.
2) Focus position was maintained as closely as possible zero-position for all measurements but some of the variation in aberrations can be obviously attributed to variations in focus position.
3) Spherical aberration is very well controlled over the entire temperature range from ~30°C to 50°C, showing generally less than 0.5 wave variation.
4) Comatic aberration is very well controlled over the entire temperature range from ~30°C to 50°C, showing generally <~1 wave variation.
5) Astigmatic aberration is also very well controlled over the entire temperature range from ~30°C to 50°C, showing generally <~ 0.5 - 1.0 wave variation.
6) Tilt aberration is well controlled over the entire temperature range from ~30°C to 50°C, showing generally ~1.0 to ~0.0-1.5 wave variation.
The immediate conclusion to draw from this data is that the wavefront transmission as a reference for optical performance remains well controlled and variations with temperature of key aberrations is minimal. This is a significantly important empirical conclusion in that it shows the optical performance of the LGRIN structure and material is NOT dependent on temperature.

4.4 Change of LGRIN lens focal length with temperature

Measurements of change in focal length with temperature were then made for 2 Peak Nano LGRIN lenses. Three measurements were made for each lens at each temperature and the simple average taken. All measurements were made at focus position ±0.1 wave. This data was charted, Figure 27.

![Figure 27. Charted data showing change of LGRIN lens focal length with temperature](image)

4.5 Analysis of baseline acrylic PCX lens focal length change data

1) Focal length changed for each lens tested as expected.

2) Data shows the comparisons between the commercial lenses and the Peak Nano LGRIN lenses to be entirely consistent.

The best conclusion to draw from this data is that the focal length of Peak Nano LGRIN polymer lenses changes exactly as that expected of a homogenous polymer lens.

Focal length change is well controlled and predictable with temperature change

This gives a clear indication that the LGRIN polymer lenses behave as expected and are consistently equivalent to the commercial control acrylic asphere lens behavior.
5.0 CONCLUSIONS TO BE DRAWN FROM THIS WORK

The simplest conclusion is the most important: optical aberrations measured in terms of wavefront transmission of Peak Nano polymeric nanolayer gradient index optical components does not change with temperature. Focal length changes are as expected and entirely consistent with homogenous acrylic lenses throughout the temperature range. The optical performance of the GRIN lenses was consistent throughout the test temperature range and a very high level of confidence is given to the performance of designs and fabricated optical systems that employ Peak Nano polymeric nanolayer gradient index optical components throughout a wide operational temperature envelope.

REFERENCES