Chalcogenide and Germanium Hybrid Optics

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Abstract

When choosing a material to design infrared optics, an optical designer has to decide which material properties are most important to what they are trying to achieve. Factors include; cost, optical performance, index of material, sensor format, manufacturability, mechanical mounting and others. This paper will present an optical design that is made for a 640x480, 17µm sensor and is athermalized by using the material properties of chalcogenide glass and Germanium (Ge). The optical design will be a 3-element, f1.0 optic with an EFL of 20mm at 10µm. It consists of two Ge spherical lenses and a middle chalcogenide aspheric element. By using Ge and chalcogenide, this design utilizes the high index of Ge and combines it with the lower dn/dt of chalcogenide glass to provide an athermalized design without the use of additional electro-optical compensation inside the assembly. This study will start from the optical design process and explain the mechanical and optical properties of the design, then show the manufacturing process of molding an aspheric chalcogenide element. After the three elements are manufactured, they will be assembled and tested throughout the temperature range of -40 to 85˚C to compare optical performance to design expectations. Ultimately, this paper will show that a high performance, athermalized optical assembly is possible to manufacture at a lower cost with the use of combining different infrared materials that allow for spherical Ge lenses and only one aspherical chalcogenide element which can be produced in higher volumes at lower costs through glass molding technology.

Keywords: Germanium, Chalcogenide glass, Precision Molded Optics, infrared, laser optics, athermalized, imaging assembly, large aperture infrared optics.

1. OPTICAL SPECIFICATIONS

The 640 x 480, 17µm uncooled IR sensor was chosen for this project as it is quickly becoming a popular sensor in the thermography sector. The optical specifications for this design are shown in Table 1.

Focal Length	20mm @10um; FOV = 40º
F/#	1
Working Spectrum	8~13 um
Working Distance	15.7mm w/0.67 Si window at Inf. Conj.
Glass Material	Germanium & BD2 ($Ge_{28}Sb_{12}Se_{60}$)
Focus	Fixed focus, manually adjusted
Focus range	1m to infinity
Design Detector	640x480(17um, 13.6mm)
Transmission	>90% (absolute across spectrum)
Operation Temperature	-40 to 85 deg C

Table 1: Infrared 3-element assembly specifications

2. OPTICAL DESIGN: MATERIAL SELECTION

The driving idea behind this project was to produce a high performance athermalized imaging system that utilized the benefits of different IR transmitting materials. In this project we used Germanium with its high index and low dispersion qualities, coupled with a molded BD2 chalcogenide glass element with higher dispersion and lower dn/dt. By combining these different materials, we were able to develop a lens system that would correct chromatic aberration without the use of a diffractive surface(s) and would be able to be passively athermalized. Table 2 shows the optical and mechanical properties of Germanium and BD2 chalcogenide glass.

	n@10µm	CTE (1/˚C)	dn/dt	Abbe (V)	Max Operating Temp
Germanium	**4.0052**	**6.1 E-6**	**600**	**942**	**80ºC**
BD2 (Ge,Sb,Se)	**2.4967**	**14 E-6**	**91**	**110**	**120ºC**

Table 2: Optical qualities of Germanium and BD2 (LWIR)

During the optical design phase of this project, time was spent in balancing the power of the lenses with their dispersion values of the elements to correct for the chromatic aberration. It was also important from a cost perspective to design the Germanium elements using either spherical or plano surfaces so they could be ground and polished versus having to use the more expensive method of Single Point Diamond Turning (SPDT). The middle element of the system is a bi-gullwing aspheric element. This lens has two complex surfaces used to balance the power of the Germanium lenses to correct for chromatic aberration without employing the use of one or more diffractive surfaces which can introduce ghosting and thermal rings onto the IR detector(2). The BD2 glass is a chalcogenide glass that can be molded using heat and pressure unlike other common IR glasses such as Germanium, ZnSe and ZnS. Lastly, and possibly the most attractive advantage to using chalcogenide glasses, is the material costs associated with BD2 glass and Germanium. Germanium has significantly increased in price within the past couple of years and while BD2 contains 28% of Ge, it is a generally accurate to estimate the raw material cost of BD2 glass to be 40% of Germanium. There are numerous chalcogenide glasses, some of which have no Ge in them. As the IR optics industry continues to demand higher volumes; research and lean manufacturing of chalcogenide glasses will once again become prevalent and costs will continue to decline.

3. OPTO-MECHANICAL DESIGN

Shown in Figure 1 is the opto-mechanical design of the system with the optical ray fan file imported to ensure correct lens and aperture placement. The key optical and mechanical features of this design is achromatic aberration correction using different dispersion optical materials and utilizing the BD2's lower dn/dt value to minimize the required movement for athermalization. BD2 is a softer material, so Germanium was used as the outer-most element so the assembly could utilize DLC coating for a harder outside surface if this assembly were to be used in a more abrasive environment.

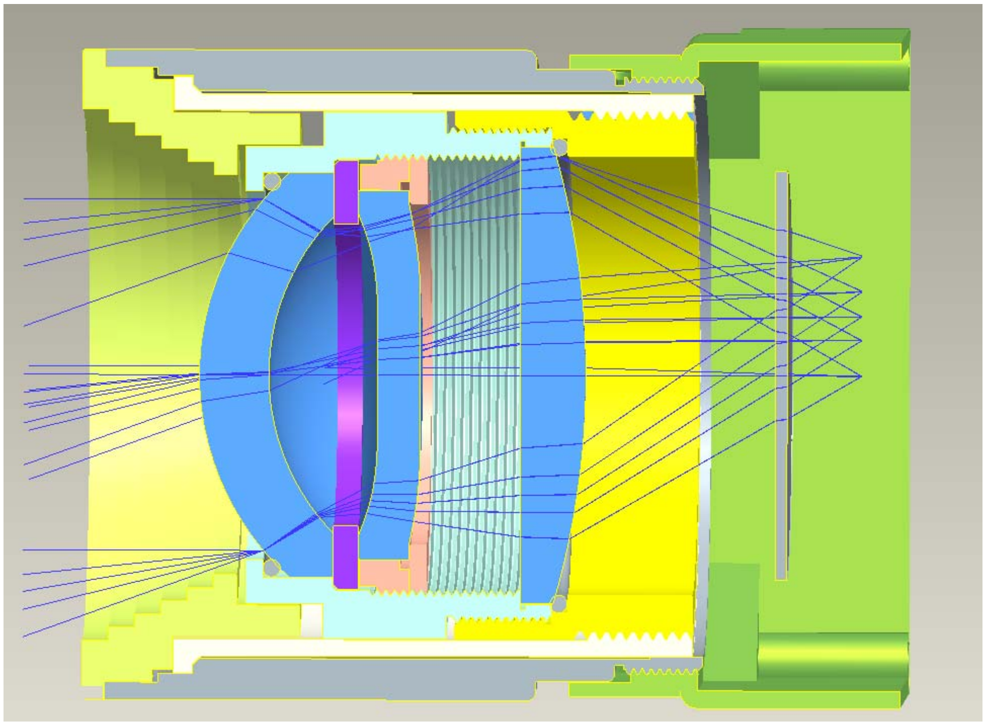

Figure 1: Opto-Mechanical Design of 20mm EFL, f1.0 System

An athermal analysis was modeled in Zemax and Figure 2 shows the needed optical package movement to maintain athermalization throughout the temperature range of -45˚C to +85˚C. The lenses are packaged in their own aluminum mount to isolate them from the outside lens barrel. A high temperature PTFE thermal compensator was thermally modeled to allow for the movement of the lenses with the lenses dn/dt values, and lens' and mount materials CTE values taken into account. Figure 2 shows the Z-position needed for athermalization (red/middle legend), the Z-position if all lenses were only mounted in 6061 Aluminum (blue/top legend) and the entire package calculated Z-position after all lenses, mounts and thermal compensator values through the temperature range are modeled(green/bottom legend). By adjusting different materials and lengths of mounting parts, passive athermalization was possible for this assembly.

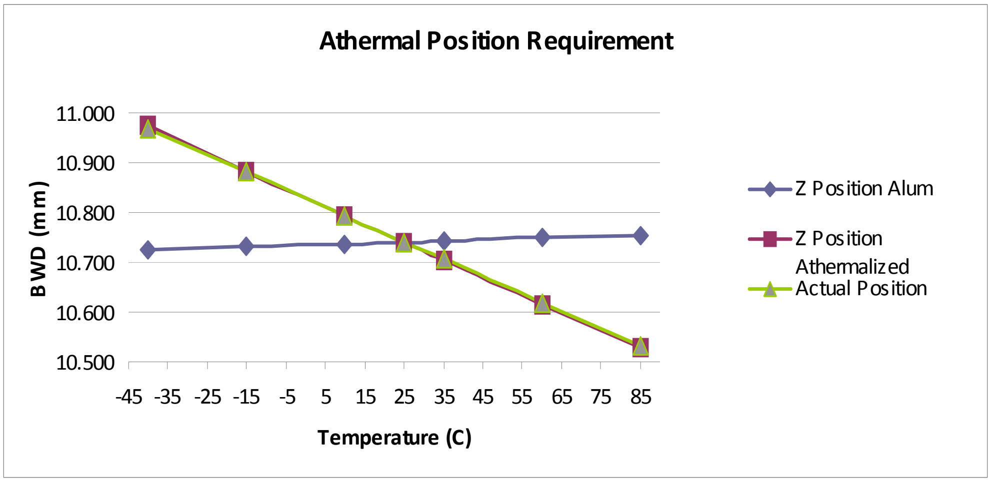

Figure 2: Required Z-Position for Athermalization

4. MOLDING: INTRODUCTION AND DESIGN CONSIDERATIONS

Molding offers the advantages in manufacturing optics that are geometrically consistent and cost effective in mid to high volumes. A basic tooling stack is shown below in Figure 3; it consists of two mold pins that represent the negative shape of the corresponding lens surface, a ring that controls the outside diameter (OD) of the lens and a sleeve to align all the tooling. The lens is molded from a preform of glass that is sized according to the finished lens mass. This ensures no post processing of the glass optic and once molded, the optic is ready for coating with the desired wavelength of anti-reflective (AR) coating.

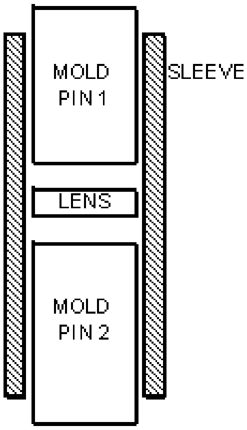

Figure 3: Mold Tooling

Because the molds are used to form multiple lenses without being replaced, the metrology of molded optics is repeatable without having the concern of diamond tool wear and other manufacturing variants associated with SPDT. The mold pins are measured using a profilometer and/or interferometer and once the molding process has been established, the lenses molded from that set of tooling need only be measured at a low sampling rate. The capital costs of molding equipment are a fraction of the cost of SPDT machines and operators do not require the same training and experience to operate them. The time to manufacture a molded optic, most notably those of larger diameters, aspheric surfaces and diffractive features; can be anywhere from a third to a fifth of the time required to produce the same optic using SPDT.

When designing lenses to be molded, certain considerations need to be considered pertaining to the manufacturability of the lens. LightPath has molded a ø45mm OD lens for a SBIR project, but currently ø25mm is the limit being produced in commercial volumes. Though not absolutely necessary, it is good practice to leave room in the optical packaging for the OD of the lens to grow by 10%. This and other considerations are shown in Figure 4.

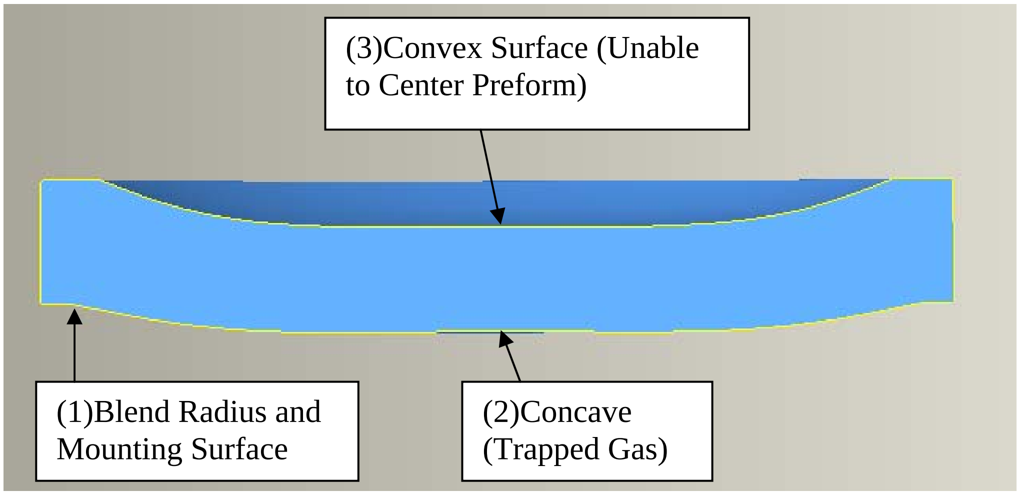

Figure 4: Design Considerations of Molded Optics

1. Blend Radius and Mounting Surface: Because glass shrinks in relation to its CTE, it is best to have room for the opto-mechanical packaging of the OD to grow 10% which allows room for molding process parameters to be altered while ensuring the clear aperture (CA) of the optic can be formed as intended.
2. For this lens, it was optically beneficial to have two gullwing surfaces. Typically, when designing an optic for molding, one surface needs to be convex in the center for two reasons.
   a. Centering the preform – Because there is no post processing of the molded optic, the preform must be centered before it is formed. This is generally accomplished by having a convex optic, which requires a concave optic mold pin that will center the preform through the force of gravity.
   b. Trapped Gas – The shape of the preform is generally a sphere, if the radius of the sphere is larger than that of the optic mold pin, gas can get caught between the optic and the mold pin which will not allow the optic to form completely or cause a bubble-like haze on the optic surface.

This lens, as illustrated in Figure 4, presented both of these concerns. The most prevalent being the centration of the preform. On the convex surface of the lens, the center is actually convex which does not allow the preform to self center itself to the center of the mold. Part of this project was to develop a process to mold a lens with this geometry. After considerable time spent experimenting with unconventional tool design and process engineering, we were able to repeatedly produce this lens with acceptable centration values within 15µm. Two lenses showing both surfaces fully formed are shown in Figure 5 below.

Figure 5: Both Surfaces of Aspheric bi-Gullwing Lens

Figure 4 shows all three lenses after manufacturing, the two outer lenses are coated spherical Germanium elements and the middle is a molded BD2 chalcogenide lens.

Figure 6: 2 Germanium Lenses and 1 BD2 Chalcogenide Lens

5. SYSTEM PERFORMANCE

The mechanical assembly parts are in the manufacturing process at time of this publication, but this assembly should be assembled and thermally tested by the beginning of 2012. Modeled thermally dependent MTF values are shown in Figure 7. As a passively athermalized assembly, the systems performance is consistent throughout the temperature range with the only significant falloff occurring at the edge of the sensor the extreme temperature of 85˚C, which is mostly due to Germanium having a operating range of 80˚C and below

Location from Center

Temp C	0mm	2.04mm	3.4mm	4.8mm	6.8mm
-45	47	47	45	44	45
-15	54	54	52	50	47
0	59	58	55	52	45
60	54	54	52	50	38
85	48	47	46	46	30

Diffraction Limit = 60

Figure 7: MTF Values Throughout Temperature Range

As is many times equally important to IR system performance, the relative illumination shown in Figure 8 is rather consistent across the sensor. The average Relative Illumination is 98% and the delta from center to corner is 6% with the falloff occurring at the last 1mm of the sensor.

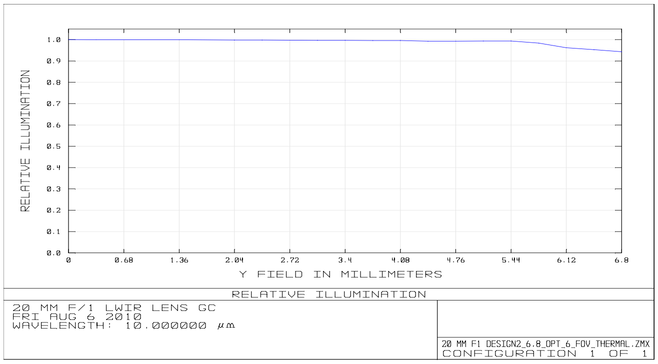

Figure 8: Relative Illumination of System

The assembled design is shown here in Figure 9 and in summary, by utilizing the different material properties of Germanium and BD2 chalcogenide glass we were able to model and design a high performance 20mm EFL, f1.0 passively athermlized assembly for a 640x480 17µm sensor that operates between the temperatures of -45˚C to 85˚C.

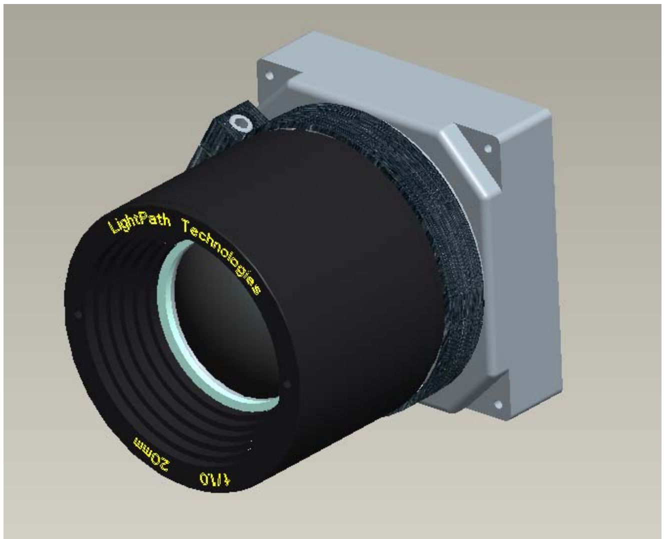

Figure 9: 20mm EFL, f1.0 Athermalized Assembly

I want to extend my special gratitude to the optical design, manufacturing and processing team at LightPath Technologies. Without their extraordinary efforts and contribution to this project, it would have not been possible.

6. SUMMARY

When designing a high performance athermalized infrared optic assembly, it is possible to maintain optical performance without incurring significant costs if appropriate optical materials are chosen and additional attention taken during the design process. Each additional aspheric surface, diffractive element and electro-optical or mechanical thermal compensator that is added to the design augments the assembly cost. This paper has discussed a f1.0, 20mm EFL, athermalized design for a 640x480, 17µm sensor from the optical design process through manufacturing and testing. Desired optical performance can be achieved while keeping the assembly cost manageable, by using appropriate material selection and opto-mechanical design to combine Germanium and other traditional IR material spherical optics with a molded aspherical Chalcogenide element(s).

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