Design and fabrication of low-cost thermal imaging optics using precision chalcogenide glass molding

George Curatu

LightPath Technologies, 2603 Challenger Tech Ct., Orlando, FL 32826

ABSTRACT

Aspheric and diffractive surfaces in infrared materials are traditionally fabricated by single point diamond turning, which is a high-cost, low-throughput process, not suitable for low-cost, high-volume applications. Precision molding of chalcogenide glasses is a novel process we developed to allow the efficient fabrication of quality infrared optics in large volumes. In this paper we present the advantages and particularities of designing thermal imaging lenses for high-volume applications using precision molded chalcogenide glasses. As an example, we present a compact 19 mm F/1.1 infrared lens design for a 320 × 240 uncooled detector array operating from 8 to 14 microns. The excellent image quality and transmission of tested prototypes prove that precision molding of chalcogenide glasses is an ideal optical fabrication technology for the high-volume production of infrared optics.

Keywords: infrared lens design, thermal imaging, precision glass molding, chalcogenide glasses, athermal design, diffractive optics.

1. INTRODUCTION

In the past years, developments in microbolometer fabrication technology reduced the pixel size and cost of uncooled focal plane arrays. Arrays with smaller pixels are driving thermal imaging applications towards more compact, faster (low F/#) lenses, with better image quality. Also, the lower cost of uncooled detector arrays is driving down the cost of the infrared (IR) optics, making thermal imaging more accessible to high-volume commercial applications.

Usually, the image quality of a lens can be improved by a more complex design, with more elements. However, in most commercial applications, where cost, size, and weight are important factors, compact lenses with minimal number of elements are preferred. Another important aspect in IR imaging applications is maximizing the amount of light falling onto the detector. Designs with a smaller number of elements will reduce transmission loss due to surface reflections and bulk absorption.

Using aspheric surfaces and diffractive optical elements (DOE) in a lens design can significantly reduce the number of elements without trading off performance. In IR optics, aspheric and diffractive surfaces can be fabricated by single-point diamond turning (SPDT), as most materials used in IR are relatively soft. However, optical fabrication by SPDT is an expensive, low-throughput process, not suitable for high volume commercial applications, where low cost is a critical factor.

We developed the precision molding of chalcogenide glasses (CG) as our unique optical fabrication process to reduce cost and increase throughput in high volume IR imaging applications. CG are ideal candidates for the molding technology, as they are moldable at low temperatures. CG also transmit very well the IR radiation, and have excellent thermal properties compared to other IR materials. In this paper we present the advantages, challenges, and particularities involved in typical lens design with molded CG.

2. PRECISION MOLDING OF CHALCOGENIDE GLASSES

CG are binary or ternary systems containing at least one element from the chalcogen series (Sulfur, Selenium, Tellurium). Typically, CG have low glass transition temperatures due to the low covalent coordination (8-n rule) associated with the chalcogen elements [1]. Most commercial CG used in IR optics are ternary systems that also contain Germanium (Ge). Ge is added to the composition to increase the glass transition temperature and durability, making them useful across a wider range of applications and environments. CG transmit well in both 3-5 µm and 8-12 µm IR spectral regions, and maintain good transmission up to 120°C and even higher, unlike Ge, which becomes opaque above 80°C. Our preferred CG are BD-1 (n = 2.498 at 10 µm) and BD-2 (n = 2.603 at 10 µm).

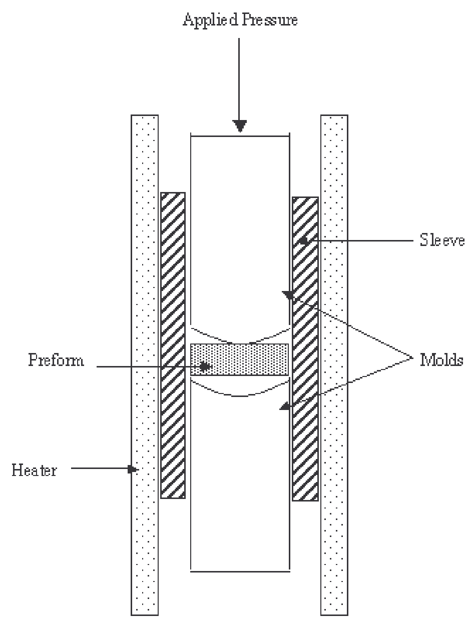

Figure 1: Schematic of the precision glass molding.

Figure 1 shows a simplified schematic cross-section of our press molding operation. The pressing apparatus consists of two molds that have been fabricated with the desired surfaces: aspheric, flat, kinoform diffractive. The molds are placed into a sleeve with a CG preform. Both heat and pressure are applied to the system to mold the chalcogenide glass preform into the desired shape. Precise tooling design and fabrication as well as precise process control are critical to the successful molding of high quality optics. Unlike in other molding technologies, our unique precision molding process allows the high-volume fabrication of IR optics with very tight tolerances of the surface profile. Aspheric optics with surface power/irregularity of less than 3/1 fringes (at 633 nm) or even tighter can be fabricated in high volumes up to 35 mm in diameter. We are currently working on expanding our process up to 50 mm diameter optics. Typical optical fabrication tolerances are listed in Table 1.

Center thickness [mm]	±0.025
Diameter [mm]	±0.015
Decentration [mm]	±0.020
Wedge [arcmin]	4
Power/Irregularity [fringes @ 633 nm]	3/1

Table 1: Typical fabrication tolerances for molded chalcogenide optics.

3. THERMAL PROPERTIES

A common requirement for IR lenses used in most commercial applications is to operate over a wide temperature range (typically from – 40°C to 80°C) without any significant change in the image quality. The main cause of image degradation with temperature is the focal shift, which is caused by the change in the glass refractive index with temperature $\mathrm{d}n/\mathrm{d}t$, and the thermal expansion of the glass and spacing materials. The refractive index usually increases with temperature, making the effective focal length (EFL) and back focal length (BFL) shorter. In addition, the spacing material between the last surface and the image plane will expand with temperature, increasing further the defocus of the lens.

Without compensation, the focal shift with temperature can have a major impact on the image quality of fast lenses, which are very sensitive to defocus. Active compensation based on temperature sensors and electrical actuators could be a simple solution to this problem, but adds to the cost, size, and weight of the lens, and can decrease the overall reliability of the imaging system. Generally, the preferred method is passive mechanical compensation, which is a low-cost solution, but it is only practical for small amounts of focal shift.

The advantage of designing IR optics with CG is that they have relatively low $\mathrm{d}n/\mathrm{d}t$ values. For example, at room temperature, the $\mathrm{d}n/\mathrm{d}t$ of BD-1 is 72 ppm/°C, which is more than five times lower than the $\mathrm{d}n/\mathrm{d}t$ of Ge (about 400 ppm/°C) [2]. If all the elements in a lens are made of CG, the focal shift with temperature will be small enough to be compensated passively using very few additional mechanical parts, or in some cases, mechanical compensation might not even be necessary.

4. CHROMATIC CORRECTION

In order to reduce cost in high-volume IR imaging applications, we have to design all the lens elements using molded CG. Another benefit of using an all-CG design is the small focal shift with temperature. However, CG have relatively large dispersion values (change of refractive index with wavelength), and chromatic aberrations can significantly lower the image quality. CG could be combined with Ge to construct an achromat, but since Ge is not a moldable material, the use of a Ge element will increase the cost of the lens. Also, a Ge element in the design would significantly increase the focal shift with temperature.

A kinoform DOE on one of the surfaces can be effectively used to correct chromatic aberrations in an all-CG design. The dispersion of the DOE will counteract the dispersion of the CG, reducing the chromatic aberrations. However, as the diffraction efficiency of kinoform DOE is wavelength dependent, the use of a DOE will slightly reduce the average transmission of the lens over the wavelength range of operation [3]. For example, the average diffraction efficiency of a kinoform DOE from 8 to 12 µm is about 95%. In spite of this slight loss in transmission, the DOE remains a powerful solution for low cost all-CG lenses.

5. LENS DESIGN

We designed a thermal imaging lens to be used with an uncooled microbolometer detector array following the requirements listed in Table 2. The size of the focal plane array (FPA) is 8 × 6 mm, so the focal length of the lens has to be about 19 mm in order to cover a horizontal field of view (HFOV) of 24 degrees. Our solution is a 2-element design in the inverted telephoto (or retrofocus) configuration. The retrofocus arrangement is formed by a front negative component followed by a rear positive component, and is characterized by a long BFL in relation to its EFL [4]. This construction is useful in lenses with a short focal length, when a long BFL is required to clear the FPA protective window and the shutter mechanism. The BFL in our design is 13.6 mm, allowing sufficient space for the protective window and the shutter. The total track of the system is 32.6 mm. The layout is shown in Figure 2 (a).

FPA resolution	320 × 240
Pixel pitch	25 µm
Wavelength range	8 – 14 µm
HFOV	24 degrees
Image space F/#	F/1.1
Operation temperature range	–40°C – 80°C

Table 2: Typical fabrication tolerances for molded chalcogenide optics.

Thermal imagers are usually placed behind an external protective window, which should be as close as possible to the entrance pupil of the lens in order to minimize the impact of window obscurations (dirt, chips, bugs, etc.) on the image quality. Therefore, the pupil stop is located on the first surface. Placing the entrance pupil on the first surface also allows for a more image-telecentric design and reduces the size of the first element. All four surfaces are aspheric, with a kinoform DOE located on the last surface. The DOE has only 9 zones and corrects very efficiently the longitudinal chromatic aberrations. Its location on the last surface, far from the pupil stop, also allows the correction of the lateral color.

The modulation transfer function (MTF) curves at 20ºC are shown in Figure 2 (d) up to 20 lp/mm: on-axis (0.0 mm image height), at 70% field (3.5 mm image height), and corner (5.0 mm image height). In many commercial applications, IR imagers are required to operate from – 40°C to 80°C without any significant change in the image quality. In our design, the focal shift from – 40°C to 80°C is only about 70 µm, which was easily compensated mechanically. Figure 2 (e) and (f) show the MTF curves at – 40°C and at 80°C after mechanical compensation, and reveal no significant change in the image quality over the specified temperature range. The values for the MTF contrast at 20 lp/mm for 20°C, – 40°C, and 80°C are listed in Table 3.

Temperature	20°C	– 40°C	80°C
On-axis (0.0 mm image height)	0.69	0.65	0.66
At 70% field (3.5 mm image height)	0.62	0.58	0.59
At 100% field (5.0 mm image height)	0.53	0.49	0.51

Table 3: MTF contrast at 20 lp/mm.

In this retrofocus arrangement there is absolutely no symmetry about the aperture stop. Therefore, the correction of coma and distortion is difficult. In many other design configurations, these aberrations are reduced by an approximately symmetrical arrangement of the elements about the aperture stop. However, distortion is only a magnification error that varies with the field angle, and does not affect the MTF of the lens. If kept below a reasonable value, distortion can be calibrated and corrected at the firmware level without losing the image resolution. In our design, we have some slight barrel (negative) distortion, but it is less than 3% across the full field of view (FOV), and can be easily eliminated at the calibration stage.

In most lenses, the relative illumination tends to decrease towards the peripheral fields. One reason this happens is the cosine-fourth falloff rule: the illumination onto the image plane decreases proportionally with the cosine-fourth of the angle of incidence of the chief-ray to the image plane [4]. Although the relative illumination can be calibrated and flattened at the firmware level, the signal-to-noise ratio of the system will decrease with the relative illumination, therefore reducing the contrast of the imaging system towards the edge of the FOV. An image-space telecentric design solves the problem of the cosine-fourth falloff, but also makes the retrofocus design even more non-symmetrical about the stop, increasing distortion. This symmetry issue creates a design tradeoff between flattening the relative illumination and minimizing distortion. Another factor contributing to the drop of the relative illumination towards the edge of the FOV is the vignetting of the peripheral fields. In our design, the effect of cosine-fourth falloff is minimal, as the exit pupil is located 60 mm into the object-space from the first optical surface, and the incidence angle of the chief-ray to the image plane is only 5 degrees at the maximum field angle. Also, the vignetting in our design is not significant (less than 2%), resulting in a very uniform relative illumination: less than 4% drop across the full FOV.

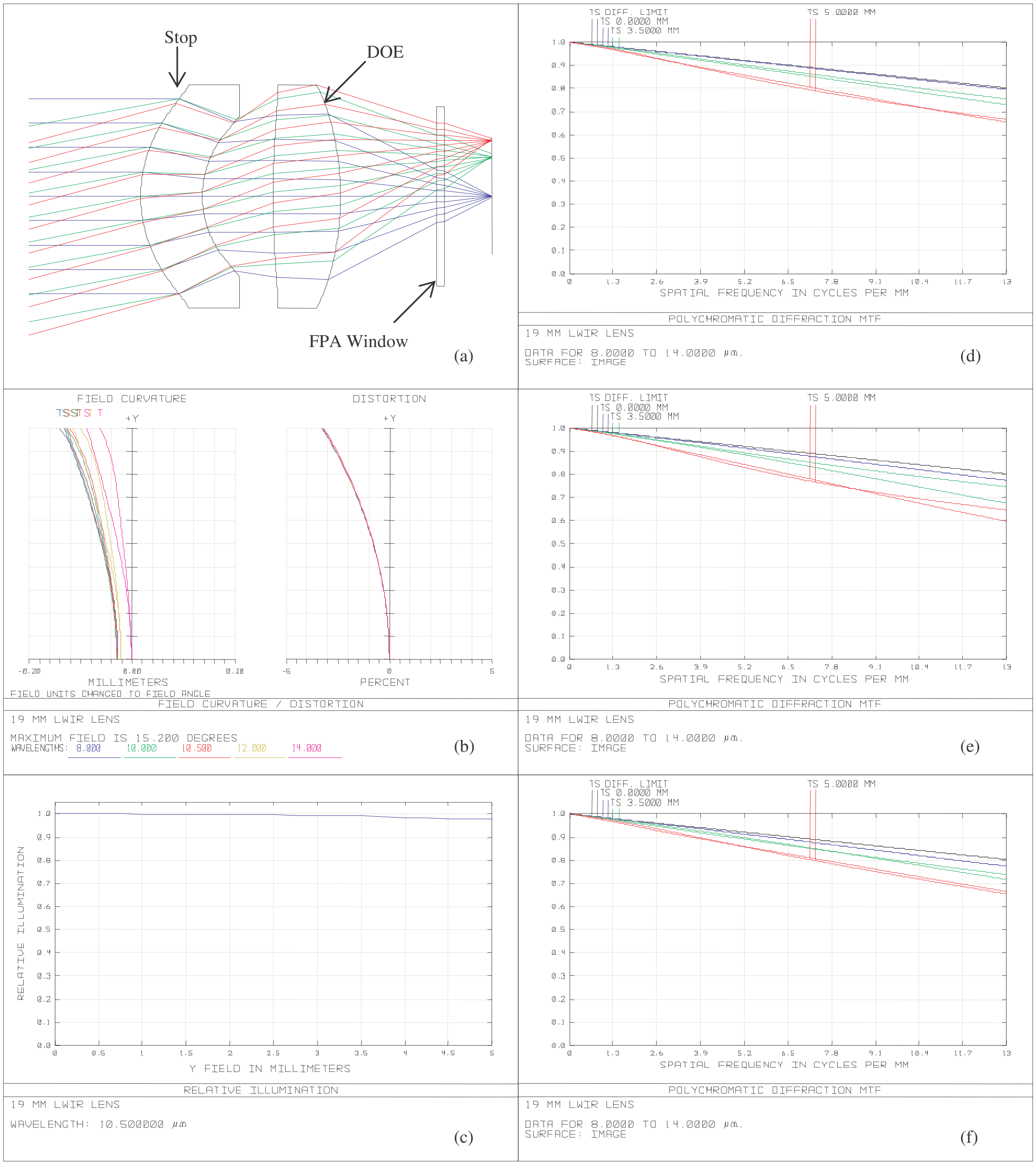

Figure 2: (a) Layout (b) Distortion (c) Relative illumination (d) MTF at 20ºC (e) MTF at -40ºC (f) MTF at 80ºC.

6. TOLERANCING

The sensitivity of an optical system to the fabrication and assembly errors depends primarily on the F/#, wavelength, and design. In general, faster lenses (lower F/#) and systems operating at shorter wavelengths will be more sensitive to these errors. Also, designs with relatively large refraction angles at an optical surface are generally sensitive to the errors on that particular surface. In IR the operation wavelength is long, so IR lenses are relatively less sensitive to fabrication errors compared to lenses in the visible wavelength range. However, most commercial thermal imaging applications use very fast lenses (F/1.4 down to F/0.8) in order to gather as much light as possible onto the uncooled microbolometer FPA. The small F/# makes these lenses very sensitive to fabrication and assembly errors.

Establishing tolerances for the fabrication and assembly errors is a critical step in the lens design, as tolerances can significantly affect the MTF and also determine the manufacturability, assembly method, and cost of the optics. The possible optical fabrication errors are power/irregularity, glass center thickness (CT), surface tilt, surface decenter, and the refractive index. The possible optical assembly errors are air CT, element tilt, and element centration. Tighter tolerances will increase the cost of the optics, so the tolerances must be loosened as much as possible while still satisfying the performance requirements of the application with a reasonable yield. A tolerance sensitivity analysis can determine which errors have the most significant impact on the MTF. A Monte Carlo tolerance analysis can be run to estimate the yield and the worst-case MTF.

7. TESTING

We fabricated the chalcogenide optics by precision glass molding with the tolerances shown in Table 1 and applied an anti-reflective coating to all the optical surfaces (< 2% reflection from 8 to 12 µm). We assembled several lenses with an element centration tolerance of 20 µm. A picture of a finished lens assembly is shown in
Figure 3.

Figure 3: Finished lens assembly.

We randomly chose a lens and measured the MTF at 20ºC and the total average transmission from 8 to 12 µm. The MTF curves at 20ºC on-axis, at 70% field, and 100% field are shown in Figure 4 (average between sagittal and tangential). Table 4 compares the measured MTF contrast values at 20 lp/mm to the nominal values. The drop in the MTF contrast due to fabrication and assembly errors is very small: 0.09 on-axis and 0.04 at the corner. The total average transmission from 8 to 12 µm was measured on the full aperture of the lens, to include all the possible fabrication imperfections of the diffractive rings. Total transmission was 91%, which is very good, considering that the theoretical average diffraction efficiency from 8 to 12 µm alone is 95%.

	Nominal	Measured	Drop
On-axis (0.0 mm image height)	0.69	0.60	0.09
At 70% field (3.5 mm image height)	0.62	0.55	0.07
At 100% field (5.0 mm image height)	0.53	0.49	0.04

Table 4: Measured MTF contrast at 20 lp/mm versus nominal values.

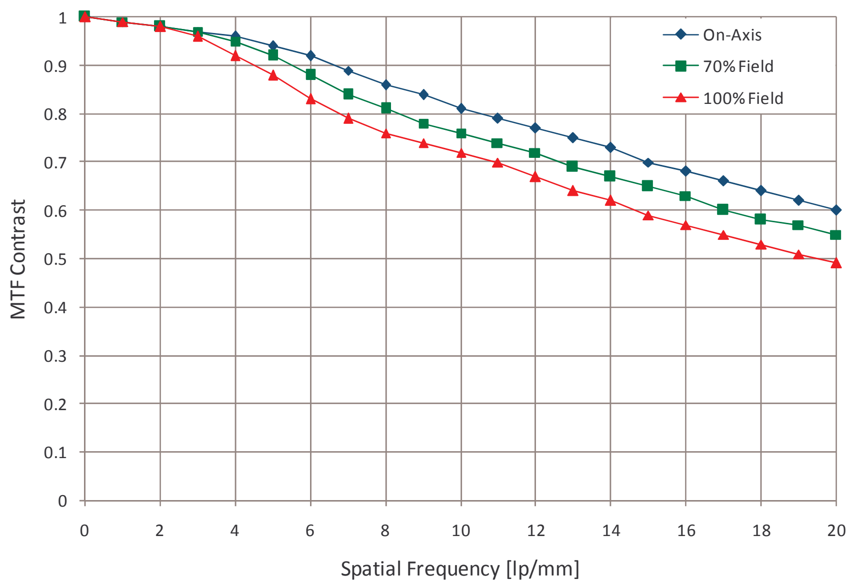

Figure 4: Measured MTF curves.

8. CONCLUSIONS

We have successfully demonstrated a compact 19 mm F/1.1 athermalized IR lens design for a 320 × 240 FPA with a 10 mm diagonal. Our design was intended specifically for high-volume commercial applications, so it was limited to only two elements, both made of chalcogenide glass. The main advantage of using chalcogenide glasses in the design of IR lenses is that aspheric and diffractive elements can be fabricated by precision glass molding, which is a low-cost optical fabrication process we developed for high-volume production of IR optics. In our design, all four surfaces are aspheric, with a DOE on one of the surfaces, resulting in a very compact lens with an exceptional optical performance in terms of MTF, distortion, and relative illumination. Another advantage of chalcogenide glasses is their relatively low $\mathrm{d}n/\mathrm{d}t$, which makes them an ideal material choice for athermalized lenses used in IR imaging applications requiring operation over a wide temperature range.

We fabricated the chalcogenide optical elements by precision glass molding and assembled several lenses. We measured the MTF and transmission for one of the lenses and obtained excellent results, proving that precision molding of chalcogenide glasses is an ideal optical fabrication technology for high-volume production of IR optics.

REFERENCES

1. A.K. Varshneya, *Fundamentals of inorganic glasses*, Academic Press, pp.131-136, 1994.
2. R.E. Fischer and B. Tadic-Galeb, *Optical system design*, McGraw-Hill, pp. 233-240, 2000.
3. M.J. Riedl, *Optical design fundamentals for infrared systems*, Second Edition, SPIE Press, pp.114-115, 2001.
4. W.J. Smith, *Modern lens design*, McGraw-Hill, pp. 147-167, 1992.