Using molded chalcogenide glass technology to reduce cost in a compact wide-angle thermal imaging lens

George Curatu[a], Brent Binkley[a], David Tinch[a], and Costin Curatu[b]

[a]LightPath Technologies, 2603 Challenger Tech Ct., Orlando, FL 32826
[b]University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816

ABSTRACT

This paper presents the design, analysis, and fabrication of a telecentric f/1.3 thermal imaging lens. The 14.8 mm wide-angle lens provides a 62° diagonal field-of-view, and was designed to operate over the 8-14 µm infrared spectral band. Focus can be manually adjusted from 0.5 m to infinity, maintaining constant image quality over the entire range. A compact air-spaced doublet design limits the overall length to 34 mm and the maximum diameter to 28 mm. Lens materials were chosen to minimize chromatic aberrations, reduce cost, and fit within the molded chalcogenide glass manufacturing capabilities. Combining a molded aspheric chalcogenide lens with a polished spherical Germanium lens eliminated the need for a diffractive surface to correct chromatic aberrations, and reduced the fabrication cost. Vignetting was purposely introduced at the extreme fields to compensate for the effects of aberrations on the relative illumination variation across the field-of-view. Athermalization of the lens was achieved mechanically over the entire operating temperature range (– 40 to + 80°C).

Keywords: infrared lens design, thermal imaging, molded chalcogenide optics, athermal design, wide-angle lenses.

1. INTRODUCTION

Recent developments in microbolometer technology improved the performance and cost of uncooled focal plane arrays. Larger arrays with smaller pixels are driving thermal imaging applications towards more compact, faster lenses, with better image quality. Also, the lower cost of uncooled detector arrays is driving down the cost of the infrared imaging optics.

Usually, the image quality of a lens can be improved by a more complex design, with more elements. However, in applications where size and weight are an important factor, compact lenses with minimal number of elements will be preferred. Another important aspect in most infrared applications is to maximize the amount of light falling onto the detector. The absorption of radiation through multiple thick elements may significantly reduce transmission. Furthermore, infrared materials tend to be much more expensive when compared to visible and near-infrared optical glasses.

Since most materials used in infrared optics are diamond-turnable, aspheric and diffractive surfaces can be used to reduce the number of elements in a lens design without giving up performance. However, the cost of diamond-turned aspheric optics is much higher than ground-and-polished spherical optics. An effective method to reduce cost in high volume applications is to use molded optics only where aspheric surfaces are needed, while limiting all other elements to ground-and-polished spherical surfaces. Good candidates for the infrared molding technology are chalcogenide glasses, because they have low glass transition temperatures (softening point) and transmit well in infrared.

2. MOLDED CHALCOGENIDE TECHNOLOGY

Commercial chalcogenide glasses are typically binary or ternary systems containing at least one element from the chalcogen series (Sulfur, Selenium, Tellurium). They have good transmission in both 3-5 μm and 8-12 μm infrared spectral regions. Another benefit of the chalcogenide glasses is their good transmission across a large temperature range. Unlike Germanium (Ge), which becomes opaque at 80°C, chalcogenide glasses are transparent up to 120°C. Typically, chalcogenides have low glass transition temperatures due to the low covalent coordination (8-n rule) associated with the chalcogen elements [1]. Therefore, chalcogenide glasses lend themselves well to press molding of spherical, aspheric, and diffractive elements. Many commercial chalcogenide glasses are ternary systems that contain Ge. This is usually done to increase the glass transition temperature and durability, making them useful across a wider range of applications and environments.

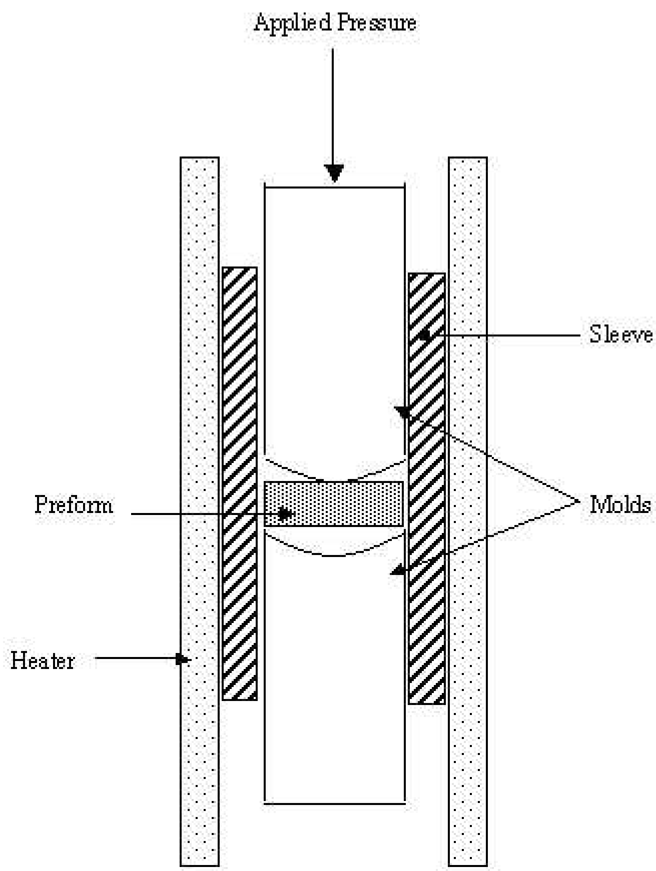

Figure 1: Schematic of chalcogenide glass pressing apparatus.

Figure 1 shows a generalized schematic cross-section of the press molding operation. The pressing apparatus consists of two molds that have been fabricated with the desired surfaces (spherical, aspheric, plano, diffractive, etc). The molds are placed into a sleeve with a chalcogenide glass preform. Both heat and pressure are applied to the system to mold the chalcogenide glass preform into the desired shape. The mechanical design and thermal analysis of the molds, sleeves, and preforms are critical to the successful molding of a high quality lens. Lens fabrication tolerances on wedge, decenter, center thickness, and surface figure, strongly depend on the fabrication tolerances of the molds and sleeves, as well as the tolerance on the preform volume. So far, we have developed tooling and processes to mold precision infrared optics with diameters up to 25 mm in two different chalcogenide glasses: BD-1 and BD-2. Currently, we are developing processes that will allow the molding of larger chalcogenide optics up to 40 mm.

3. LENS DESIGN AND OPTICAL PERFORMANCE

Molded chalcogenide elements must be used wisely in the lens design in order to maintain good image quality while staying cost effective. The choice of materials and the power of each element are important factors in reducing chromatic aberrations and thermal effects. Another important aspect in the lens design is the location of the aspheric surfaces to effectively reduce geometrical aberrations. Not every design can benefit from using molded aspheric chalcogenide optics. However, in many cases, a clever lens design can leverage the advantages of molded chalcogenide optics.

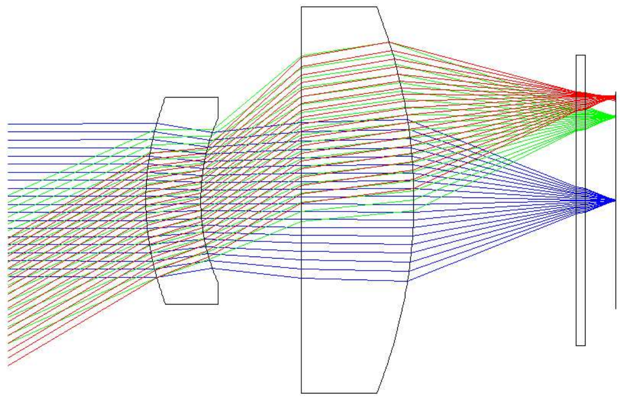

Figure 2: Layout.

This 14.85 mm F/1.3 lens was specifically designed for a 320 × 240 uncooled microbolometer array, with 38 µm pixels. The lens covers a 62° diagonal field-of-view (FOV), and operates over 8-14 µm. The inverted-telephoto design uses a molded BD-1 negative element and a ground-and-polished positive Ge element (Figure 2). The design takes into account the Silicon cover window in front of the detector. The stop of the system is located on the first surface, which is also the entrance pupil. The only aspheric surface is located at the pupil (on the BD-1 element). To keep the fabrication and assembly cost low, the polished Ge element was designed to be plano-convex. The overall length from the first optical surface to the image plane is 34 mm and the maximum diameter of the optics is 28 mm.

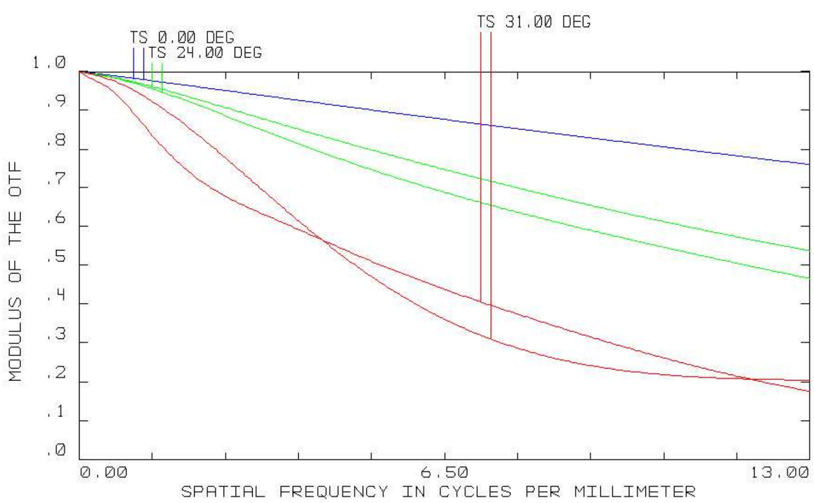

Figure 3: Polychromatic MTF plots on-axis, at 24°, and at 31°.

A 38 µm pixel pitch implies a Nyquist spatial frequency of 13 lp/mm. Figure 3 shows the polychromatic nominal modulation transfer function (MTF) plots on-axis, at the horizontal field (24°), and at the diagonal corner (31°). At 13 lp/mm, the nominal MTF is 76% on-axis, 50% at the horizontal field, and 20% at the diagonal corner. Focus can be adjusted manually and locked at the desired working distance. The MTF performance is maintained constant over the entire focus range (0.5 m to infinity).

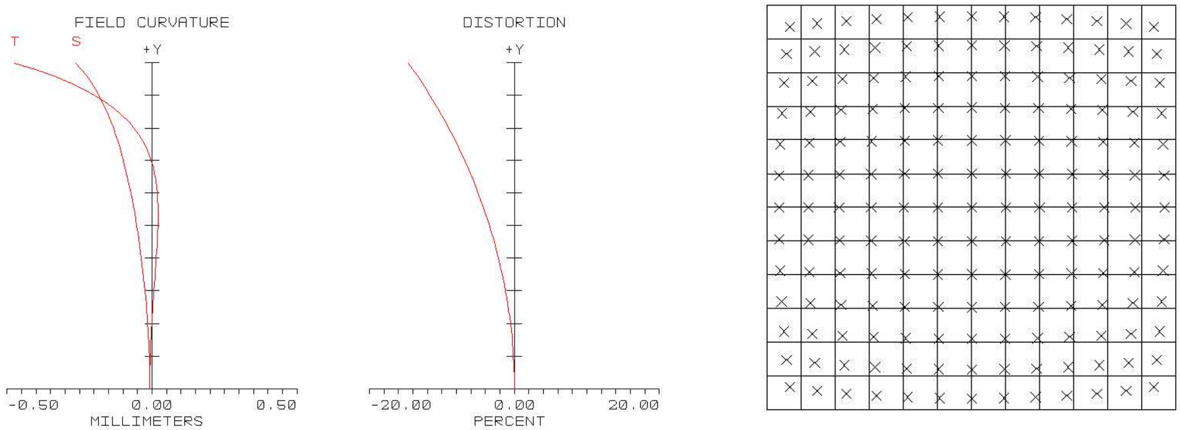

Figure 4: Left: field curvature and distortion plots (vertical axis is the field angle 0 to 31°). Right: grid distortion.

Field curvature and distortion plots are shown in Figure 4. Distortion is negative (barrel), and is 11% at the maximum diagonal field, which is common for a 62° FOV lens. By making the fourth surface aspheric, distortion could have been reduced further by a couple of percentages. However, considering distortion can be corrected electronically without compromising the image quality, a slight improvement in distortion does not justify the cost of diamond-turning the Ge element.

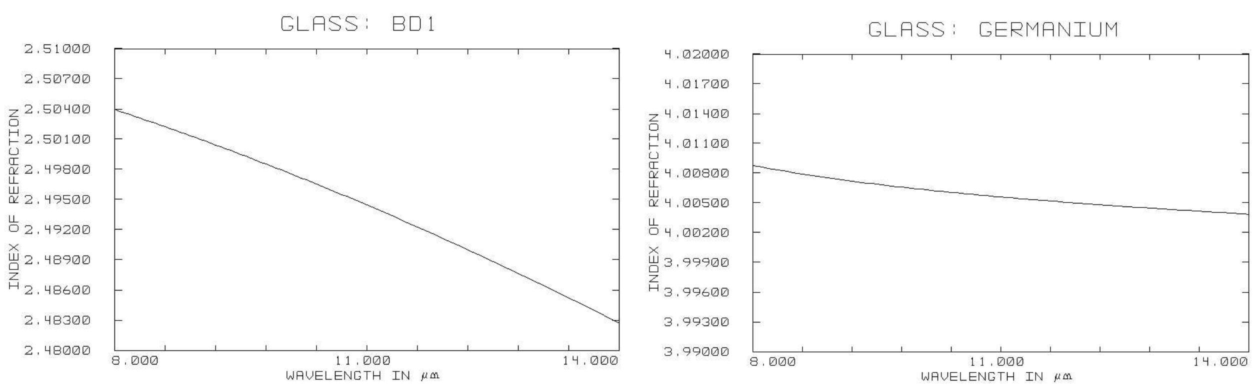

Figure 5: Dispersion curves of BD-1 and Germanium.

The dispersion curves of BD-1 and Ge are shown in Figure 5. The refractive index of BD-1 is 2.50 and for Ge is 4.00 around 10 µm. For the wavelength range of 8-14 µm, the change in index for BD-1 is 0.021, and 0.005 for Ge. Chromatic aberration was corrected by using the right combination of BD-1 (which has a lower index and higher dispersion, and therefore a lower Abbe number – $\nu_{BD\text{-}1} \approx 70$) and Ge (which has a higher index and a lower dispersion, and therefore a larger Abbe number – $\nu_{Ge} \approx 600$). This eliminated the need for a diffractive element, which would have lowered the average transmission by at least an additional 6% [2].

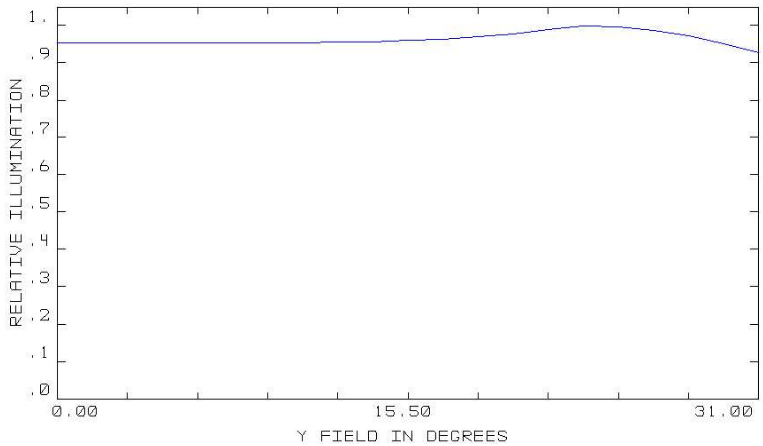

Figure 6: Relative illumination.

Most thermal sensing and imaging cameras are electronically calibrated to account for the variation in the relative illumination across the image plane. Typically however, the relative illumination should not vary more than 15% in order to be corrected effectively. In wide-angle lenses, relative illumination tends to decrease towards the peripheral fields. One reason this happens is the $\cos^4$ falloff rule: the illumination onto the image plane decreases proportionally with the $\cos^4$ of the angle of incidence of the chief-ray to the image plane. Another factor that contributes to the drop in the relative illumination towards the edge of the FOV is the decrease in size of the effective entrance pupil with the field angle: the light collected by the lens decreases proportionally with the cosine of the angle of incidence of the chief-ray to the pupil plane. An image-space telecentric design would eliminate the effect of the $\cos^4$ falloff. In image-space telecentric systems, the exit pupil is located at infinity (or very far) in the object-space, and all the chief-rays fall perpendicular onto the image plane. In our design, the exit pupil is located 100 mm into the object-space, and the incidence angle of the chief-ray to the image plane is only 4° at the diagonal corner field. Because our lens is almost telecentric, the effect of $\cos^4$ falloff is negligible. Furthermore, the effect of negative distortion combined with blur caused by other aberrations overcompensates the decrease of the effective pupil with field angle, causing the relative illumination to actually increase towards the edge of the FOV. This is a common effect seen in wide-angle lenses with large distortion. To flatten the relative illumination curve, we introduced just the right amount of vignetting at the peripheral fields. Figure 6 shows only a 7% variation across the entire FOV.

4. FABRICATION TOLERANCES FOR MOLDED CHALCOGENIDE OPTICS

Fabrication and assembly tolerances were carefully specified in order to minimize cost while maintaining the required image quality. Tolerances, relative cost, and limitations are well known factors for ground-and-polished optics and opto-mechanical assemblies. However, fabrication tolerances for molded chalcogenide optics depend strongly on the press technology as well as the good understanding and characterization of the chalcogenide material. A summary of typical tolerances for molded glass lenses is given in Table 1.

Center thickness [mm]	±0.025
Diameter [mm]	±0.010
Decentration [mm]	±0.005
Wedge [arcmin]	±1
Power/Irregularity [fringes @ 633 nm]	1/0.5 – 0.5/0.25
Surface roughness [nm]	10
Surface quality [scratch-dig]	60-40 – 40-20

Table 1: Fabrication tolerances for molded chalcogenide optics.

Tolerances in Table 1 are comparable or in some cases better than fabrication tolerances for ground-and-polished or diamond-turned optics. Manufacturing limitations and feasibility depend on the size, shape, and aspect ratio of the molded lens. Currently, the largest diameter we can mold with our technology is 25 mm, and larger diameters are in development.

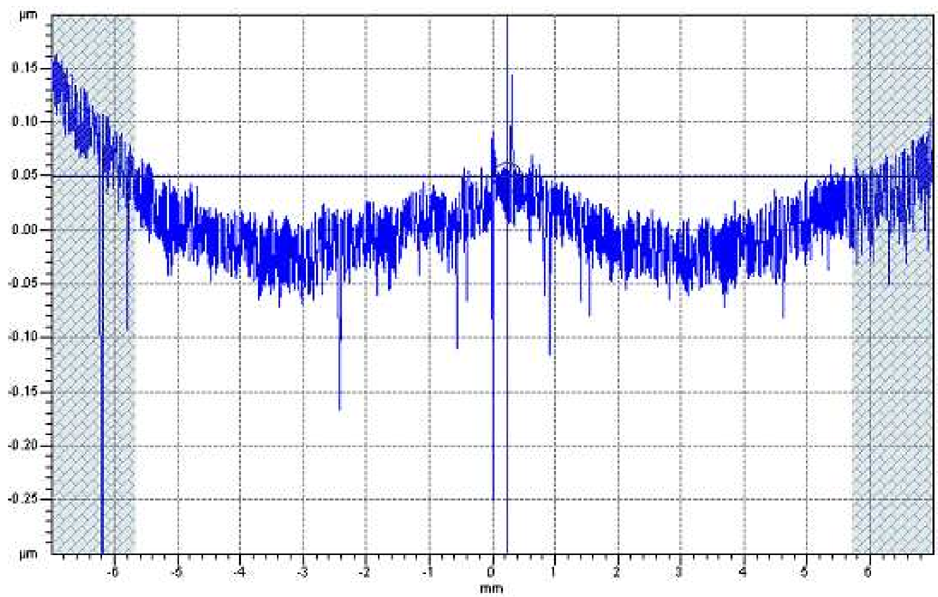

Figure 7: Aspheric surface profile error (with adjusted radius).

Figure 7 shows the profile error of the aspheric convex surface of our BD1 meniscus lens. The measurement was done using a high-precision profilometer, and data was analyzed over a clear aperture of 11.5 mm. The error on the radius of curvature is 0.02% (or 0.5 fringes of power). In Figure 7, the profile error is shown with the adjusted best-fit radius. The surface irregularity is 0.25 fringes, with a roughness of 10 nm. These tight surface tolerances exceed by far the requirements for this particular lens design, and they are only intended to demonstrate the manufacturing capabilities of our molded chalcogenide technology.

5. ATHERMALIZATION

The shift of the focal plane position with temperature is a significant issue in refractive infrared systems that operate over a broad temperature range [3]. Two separate thermal aspects cause this effect: the change in refractive index with temperature $\left(\frac{dn}{dt}\right)$, and the change in curvatures and thicknesses with temperature $\left(\frac{dl}{dt}\right)$. In some cases, passive optical athermalization can be achieved with careful design and the right choice of materials. However, due to many other constraints in our design, passive optical athermalization was not achievable.

A straightforward athermalization method is to mechanically move the lens to keep it in focus over the entire temperature range (-40˚C to 80˚C). First, we determined the focal shift over the required temperature range (Figure 8). The doublet has to move linearly with temperature towards the image plane to maintain the MTF performance constant as temperature changes. The two elements were mounted in a cell that allows them to slide together within the main barrel. The travel required over the entire temperature range is more than 300 µm. To achieve this long and precise movement, we used liquid-filled hydraulic pistons to push the spring-loaded cell as the liquid in the pistons expands with temperature.

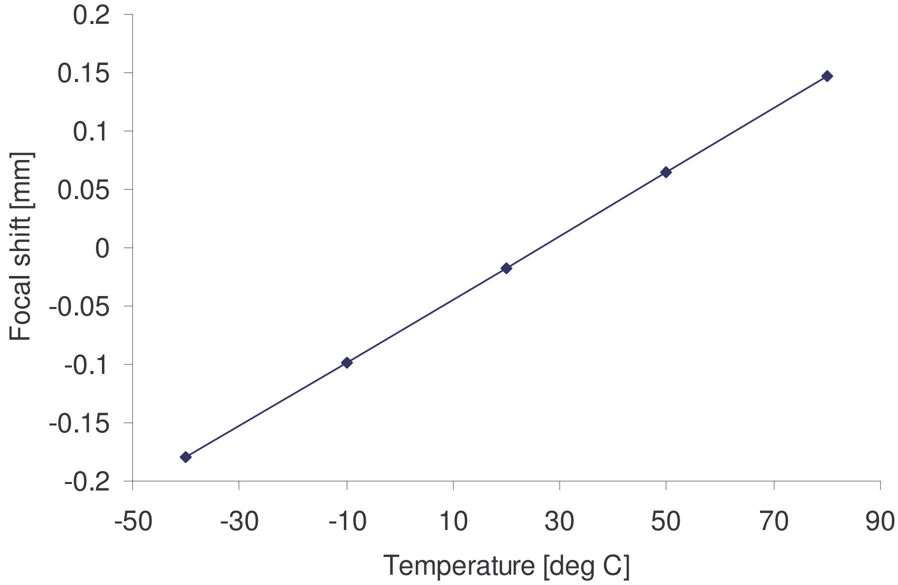

Figure 8: Focal shift versus temperature.

6. PROTOTYPE EVALUATION

We built, assembled and tested a few prototypes. MTF was measured in the sagittal and tangential planes up to 13 lp/mm on-axis, at 24˚, and at 31˚ (Figure 9). At a given field angle, astigmatism in the lens results in the sagittal MTF curve to be different than the tangential MTF. The on-axis astigmatism is caused by fabrication and assembly errors. Table 2 compares the measured average MTF values (sagittal and tangential combined) at 13 lp/mm with the nominal design values.

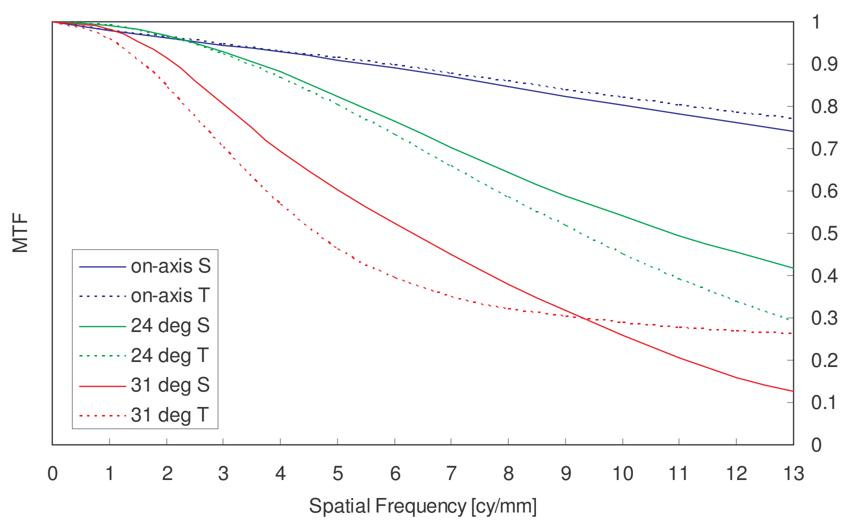

Figure 9: Measured MTF on-axis, at 24°, and at 31° (solid-sagittal, dashed-tangential).

MTF at 13 lp/mm	**Nominal**	**Measured**
On-axis	76%	75%
Horizontal (24˚)	50%	36%
Diagonal corner (31˚)	20%	19%

Table 2: Measured MTF compared to nominal values.

7. CONCLUSIONS

We have successfully designed, built, and tested a high quality f/1.3 wide-angle infrared lens using molded chalcogenide technology. The demanding specifications and the good image quality of the prototypes have proven that chalcogenide lens molding is a viable technology for high-end infrared applications.

ACKNOWLEDGEMENT

The authors are grateful to Dr. Eugene Curatu for insightful discussions on the lens design aspects.

REFERENCES

1. A.K. Varshneya, *Fundamentals of inorganic glasses*, Academic Press, pp131-136, 1994.
2. M.J. Riedl, *Optical design fundamentals for infrared systems*, Second Edition, SPIE Press, pp114-115, 2001.
3. V. Povey, "Athermalization technique in infrared systems", SPIE Vol. 655, *Optical System Design, Analysis and Production for Advanced Technology Systems*, pp. 142-153, 1986.