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Exploring the Potential of Chalcogenide Lens Designs for Cost-effective LWIR Systems

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Abstract. The high cost of optical raw materials in the long wavelength infrared (LWIR) region necessitates the development of cost-effective solutions without compromising resolution. Chalcogenide glasses offer a faster and easier production process compared to growing single crystals of Germanium (Ge). Additionally, they can be molded into complex optical surfaces, reducing processing costs further for serial production. In this study, we explore the potential of chalcogenide lenses. Our comprehensive design study demonstrates that chalcogenide lens designs can achieve comparable or even superior optical performance with reasonable system complexity when compared to a wide-angle benchmark Ge design.

1 Introduction

The price of infrared devices has decreased due to advancements in cost-effective uncooled microbolometers, making them more accessible for consumer markets. However, the price of optical components for these systems remains high due to costly raw material Germanium (Ge) in long wavelength infrared (LWIR) applications. Chalcogenide glasses have great potential, as they are faster and easier to produce than growing single crystals of Ge. Additionally, their lower transformation temperature allows for molding complex optical surfaces into cost-effective high-volume optics.

This work compares a benchmark Ge design with different design concepts utilizing commercially available chalcogenide glasses to explore the possibility of cost-effective LWIR objectives.

2 LWIR material optical properties

Several vendors offer chalcogenide glasses with the same chemical composition but under different material names. For this design study, we use the chalcogenide glass catalogue from SCHOTT as our material database [1].

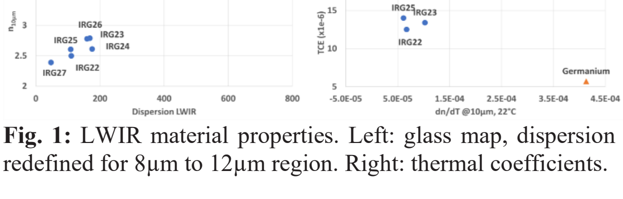

Fig. 1: LWIR material properties. Left: glass map, dispersion redefined for 8µm to 12µm region. Right: thermal coefficients.

An infrared glass map is shown in **Fig. 1**(left), with dispersion redefined as $(n_{10\mu m} - 1)/(n_{8\mu m} - n_{14\mu m})$ for LWIR. In general, Chalcogenide glass has a significantly smaller refractive index and larger dispersion than Ge, meaning more lenses are needed for the same system specification, or worse system performance is expected with the same lens count.

This can be understood easily with the help of lens maker formular $\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$ and surface contribution to Seidel aberrations [2-3].

$$Spherical\ aberration\ S_I = -\sum (n \cdot i)^2 \cdot B = -\sum A^2 B \qquad (1)$$

The reduction in refractive index requires increase in lens curvature to remain the original lens power. Surface contribution to primary spherical aberration is shown in (1) as an example to explain how quantity A, that is determined by multiplication of marginal ray paraxial incident angles with refractive index, is causing more aberration. A smaller surface curvature leads to a larger incident angle of the same paraxial ray, resulting in a higher amount of spherical aberration that must be addressed elsewhere in the system.

Aside from its deficiency in refracting power, chalcogenide glass exhibits more stable thermal behavior than Ge, as indicated in **Fig. 1** (right), with dn/dT being almost a magnitude smaller than that of Ge. Although its thermal coefficients of expansion (TCE) are larger, this geometrical thermal change typically has a less significant impact than the thermal change of refractive indices.

3 Design study

Replacing Ge with chalcogenide glasses while keeping the lens curvature will reduce the lens optical power by roughly half. This suggests that an original two-lens Ge design can be replaced by a four-lens chalcogenide design with comparable performance. To verify this simplified

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theory in a real design, we conduct a comprehensive design study to map the design complexity using chalcogenide glasses.

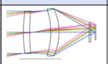
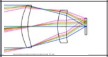
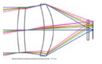
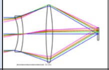
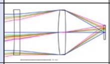
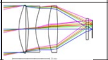
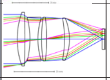
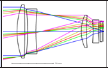
We use a state-of-the-art 12µm microbolometer with a resolution of 640x480 for the study. System focal length is fixed as 25mm. Given the 8 to 12µm working spectrum, a large system aperture of f/1 is required for maximum throughput and the best possible optical resolution.

3.1 Chalcogenide systems and comparison

Different chalcogenide designs are explored ranging from the simplest 2-lens designs to more complex 4-lens designs with the goal of matching benchmark system's performance. Main results are listed in **Table 1**, where key performance metrics like MTF, distortion, axial color are given for each system including the number of aspheric lenses used.

System 1 is the benchmark Ge design, while system 2 to 8 use chalcogenide lenses with varying levels of system complexity. System 2 is the simplest one-glass chalcogenide design using IRG26. As predicted by the aberration theory, this simple design fails to deliver comparable MTF to that of our benchmark and fails to provide comparable color correction due to the inherent stronger dispersion of chalcogenide glass.

Table 1: Summary of investigated systems. System 1 is the benchmark system composed of two Ge lenses. MTF values are calculated at half Nyquist frequencies of 20lp/mm. The number of aspheres used for each system is listed along with their respective paraxial axial color (color 1) and axial color calculated with the marginal ray (color 2).

System	Layout	MTF on axis	MTFs max. FOV	MTFt max. FOV	Distortion	Asphere	Color 1	Color 2	Notes
1		0.688	0.453	0.543	0.65%	2	29µm	54µm	2 Ge
2		0.371	0.255	0.147	1.12%	2	116µm	119µm	2 chalc
3		0.714	0.135	0.411	0.74%	2	141µm	-17µm	2 chalc w/ DOE
4		0.732	0.567	0.603	2.33%	2	15µm	12µm	1 chalc +1 Ge
5		0.701	0.214	0.621	2.34%	2	24µm	25µm	1 chalc +1 Ge, v2
6		0.706	0.44	0.579	0.80%	3	47µm	5µm	3 chalc
7		0.672	0.494	0.518	0.43%	1	37µm	45µm	4 chalc w/ 1 asphere
8		0.608	0.563	0.504	0.91%	0	63µm	66µm	4 chalc w/o asphere

To address the color issue, one possibility is to add one diffractive optical element (DOE) surface to the rear surface of L1, as shown in system 3. Better color correction is achieved with higher order diffractive surface, lifting the on-axis MTF to a comparable level. Another possibility is to combine chalcogenide with Ge, using their differentiation in dispersion to create an achromatic design, as demonstrated in system 4. With color aberration remains to be of low order, axial color is well corrected through the whole pupil, leading to the best on-axis MTF amongst all investigated systems, as well as outstanding field performance.

To reduce cost by controlling the size of the second Ge lens, it is possible to shift the stop position from the first lens to the second. System 5 demonstrates a more cost-effective design version of system 4, albeit with some compromise in field astigmatism.

The potentials of a pure chalcogenide design without special optical surfaces are further explored in systems 6 to 8. The performance of these three systems shows that at least three chalcogenide lenses made with two different glasses are required to reach the benchmark system level (system 6). In a low-quantity production scenario where spherical lenses are preferred over aspheres, at least four chalcogenide lenses are needed (system 8).

3.2 Thermal performance

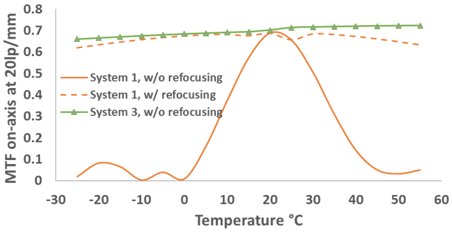


Fig. 2: On-axis MTF vs. temperature for the benchmark Ge design (system 1) and the two-element chalcogenide design (system 3). Refocusing of the image plane is necessary for system 1 to regain contrast.

The inherent stability of chalcogenide glasses leads to an athermalized system without the need for passive mechanical athermalization. **Fig. 2** takes one chalcogenide system as example and compares its thermal behavior represented as on-axis MTF at 20lp/mm, to that of the benchmark Ge design. The chalcogenide design demonstrates superior thermal stability without additional refocusing.

4 Conclusion

Our design study utilizing chalcogenide glasses provides alternative system solutions that can achieve similar or even higher levels of optical performance at the cost of increased system complexity. Although the final cost of optical components can be supplier dependent, the lower raw material and processing costs of chalcogenide glass still present great potential for cost-effective LWIR designs.

References

1. https://www.schott.com/en-se/products/infrared-glasses-and-materials-P1000261/downloads
2. H. Gross, Handbook of Optical Systems: Vol **1**, 29, (2005)
3. H. Gross, H. Zügge, M. Peschka, F. Blechinger, Handbook of Optical Systems: Vol **3**, 30, (2007)