# Quantitative comparison of the chalcogenide glass GASIR with Germanium and Silicon for use in LWIR sensor lens design

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## 1 Introduction

In recent years, improvements in sensor fabrication technology have allowed infrared imaging devices to penetrate the commercial market. Applications in non-contact thermal sensing, domotics and security and surveillance are becoming affordable to a wide range of end users.

As detector prices drop, the importance of the cost of the optical components increases. In a large part, this is determined by optical requirements such as resolution, focal length and f-number, which in practice translates into size and complexity of the lenses.

Another key determinant of both design and price is the material being used. Germanium lenses have long been a favourite of the infrared lens designer due to the high refractive index, but suffer from drawbacks such as thermal drift and price fluctuations. Chalcogenide glasses have been developed to overcome these limitations, albeit at a lower refractive index. Where resolution is not as critical (i.e. for detectors with few pixels), silicon lenses are widely used.

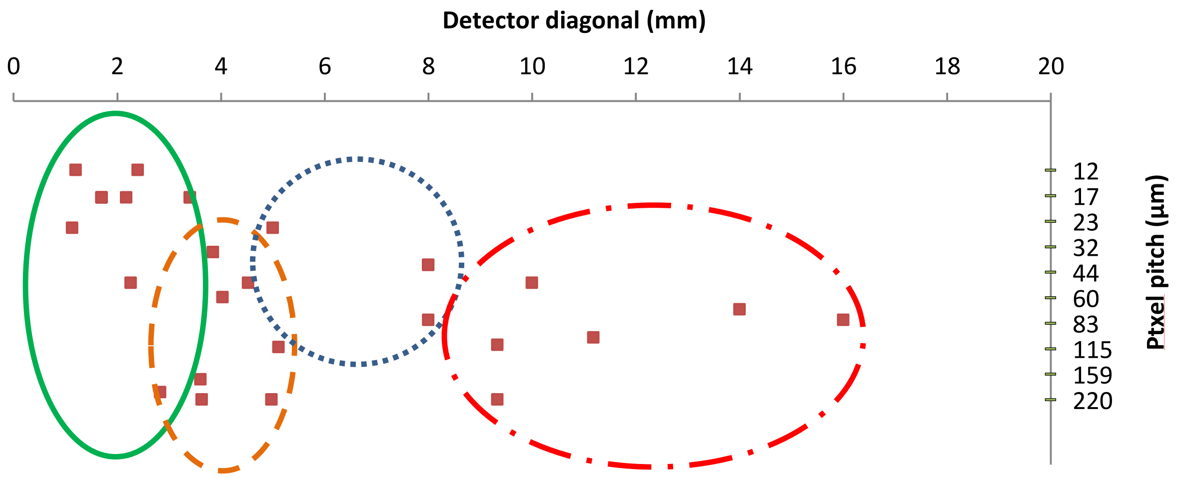



Figure 1: sensor diagonals plotted versus pixel pitch. The ranges used in this article are indicated and refer to range A: diagonal ≤ 3.5 mm (full line), 2.8 mm ≤ diagonal ≤ 5 mm (dashed line), 5 mm ≤ diagonal ≤ 8 mm (dotted line), diagonal > 8 mm (dash-dotted line). See text for more details.

However, the fact that even sensing detectors are now available with many more pixels is driving change.

In this work, we compare the performance and potential of three different LWIR lens materials, namely germanium, silicon, and GASIR. A quantitative analysis is made of several optical parameters. In addition, we demonstrate the potential of GASIR in designs tailored to a specific request.

## 2 Methods

We define a sensing lens by the following prime criteria: HFOV > 50° in combination with its detector, high energy throughput (a combination of high aperture (close to f/1.0 or better) and high transmission, see below) and an MTF > 40% at half the detector's Nyquist frequency. In this work, we focus on the 8-12 µm (LWIR) waveband.

As cost is driven by, amongst others, the number of optical elements and their size, we consider aspherical singlets for germanium and GASIR. As silicon is more difficult to machine into complex aspheric shapes [1], designs in this material feature two spherical lenses to allow a similar number of degrees of freedom.

Table 5 gives an overview of the detectors used in this study, ordered by increasing diagonal. In this collection, we define 4 ranges, for which one lens in each material shall be designed. These ranges are broadly defined as follows:

| | |
|---|---|
| Range A | Detector diagonal < 3.5 mm |
| Range B | 2.8 mm ≤ diagonal ≤ 5 mm |
| Range C | 5 mm ≤ diagonal ≤ 8 mm |
| Range D | Diagonal > 8 mm |

Note that these ranges do not say anything about the detector's pixel size and that the MTF requirements may thus differ, explaining the partial overlap.

Energy throughput ETP is defined as the transmission of the entire optical system scaled with the square of the reciprocal of the f-number:

$$ETP = \frac{\tau}{RF^2},$$

where RF is the aperture-based f-number. The transmission τ takes into account absorption and reflection losses and assumes the presence of an antireflective coating with reflectivity ρ < 1.5% on each surface.

## 3 Results

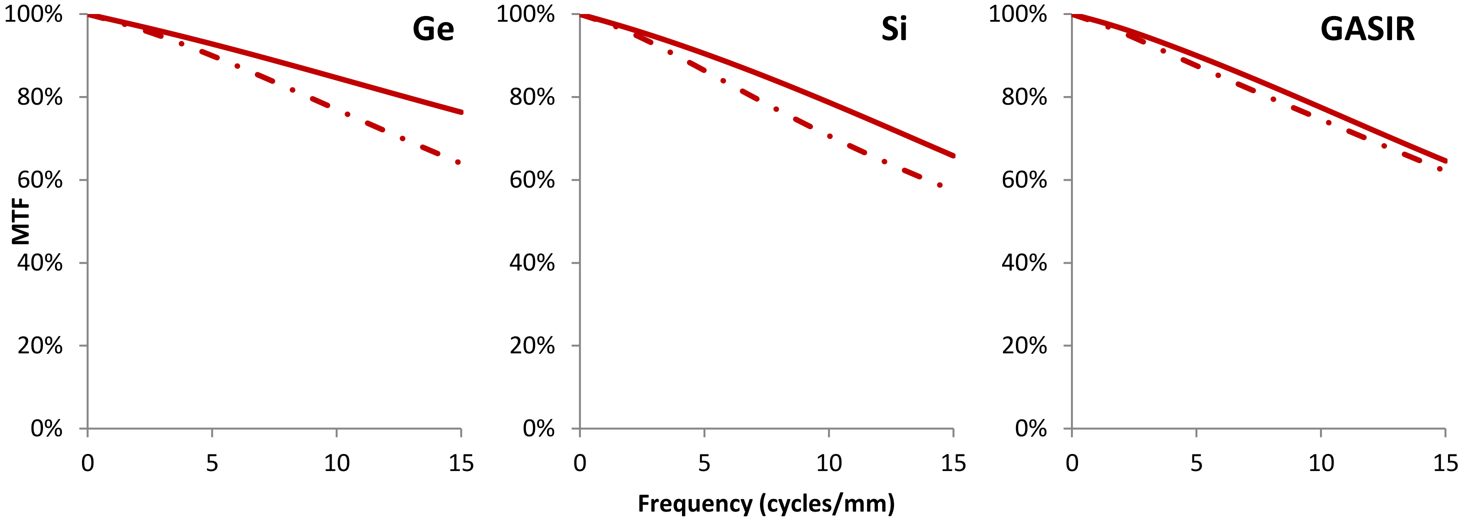
### *A: Detector diagonal < 3.5 mm*

To yield a diagonal field of view (DFOV) of 140° with a 160x120 17 µm detector, designs aimed for a focal length of approximately 1.7 mm and -60% distortion. The resulting optical and mechanical parameters are given in Table 1, as well as the corresponding MTF curves (Figure 2).

Our aspheric germanium singlet design provides the best resolution at a given temperature.

| | Germanium | Spherical silicon | GASIR |
|---|---|---|---|
| Focal length | 1.8 mm | 1.9 mm | 1.7 mm |
| Back focal length (w/ 1 mm Ge window) | 3.1 mm | 1.9 mm | 2.8 mm |
| Total track length | 7.5 mm | 9.6 mm | 5.4 mm |
| Aperture-based f-number RF | 1.00 | 1.25 | 1.03 |
| Relative illumination | >93% | > 77% | >80% |
| DFOV | 135° | 134° | 136° |
| Distortion | -60% | -62% | -60% |
| MTF | Thermal drift | Good | Good |
| Lens dimensions (thickness x diameter) | 4.4 mm x 4.4 mm | 3.2 mm x 3.2 mm<br>4.0 mm x 4.0 mm | 2.6 mm x 3.5 mm |
| Energy throughput on-axis | 0.94 | 0.40 | 0.86 |

**Table 1: Overview of lens parameters for lenses designed to cover range A.**




However, due to the large thermal expansion coefficient and large dn/dT, this performance shows considerable thermal drift. In addition, the lens is relatively large compared to the other solutions (see below) and hence more costly.

The two-lens spherical silicon solution displays good resolution. However, it has low energy throughput and large dimensions, making it less favourable in practice.

An aspherical GASIR singlet, on the other hand, shows temperature stable MTF performance. In addition, it is a compact solution with high energy throughput, ideal for sensing applications in this detector range.

### $B{:}\ 2.8\ mm \le diagonal \le 5\ mm$

To obtain a DFOV of 120° with a 113x113 32 µm detector, designs aimed at a focal length of approx. 3 mm with -50% distortion. The resulting lenses' optical and physical specifications are given in Table 2 along with corresponding MTF curves (Figure 3).

The germanium lens is again significantly bulkier than the other solutions. However, contrary to the solution from the previous section, it does not offer the best MTF performance. Coupled with the large thermal drift, this lens is a sub-optimal solution.

A design using two spherical silicon lenses shows slightly better resolution, but again does not have the high energy throughput required for sensing, making it less suited for these applications.

The GASIR solution shows the best resolution of all lenses in this range and has the widest DFOV

| | **Germanium** | **Spherical silicon** | **GASIR** |
|---|---|---|---|
| Focal length | 3 mm | 3.5 mm | 2.6 mm |
| Back focal length (w/ 1mm Ge window) | 4.5 mm | 2.0 mm | 3.8 mm |
| Total track | 11.8 mm | 19.8 mm | 7.8 mm |
| Aperture-based f-number RF | 0.98 | 1.12 | 1.01 |
| Relative illumination | > 91% | > 60% | > 78% |
| DFOV | 120° | 106° | 134° |
| Distortion | -50% | -45% | -60% |
| MTF | Thermal drift | Good | Good |
| Lens dimensions (thickness x diameter) | 7.1 mm x 7.5 mm | 4.4 mm x 5.9 mm<br>10.7 mm x 11.9 mm | 4.0 mm x 5.4 mm |
| Energy throughput on-axis | 1.00 | 0.14 | 0.90 |

**Table 2: Overview of lens parameters for lenses designed to cover range B.**

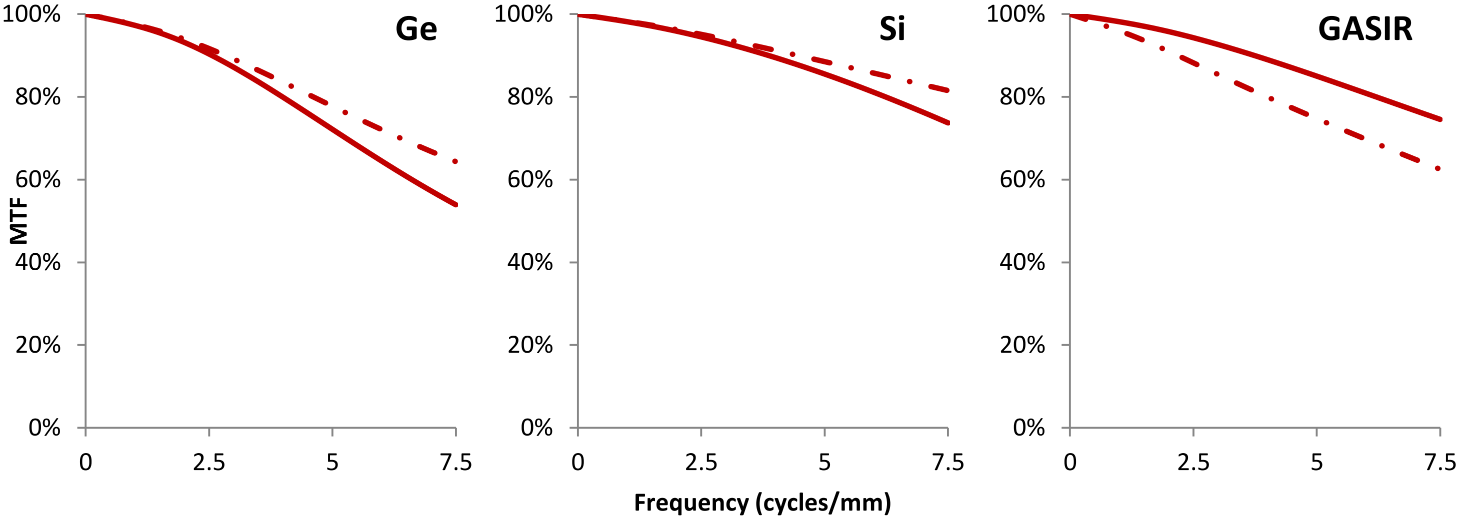



**Figure 3: MTF curves for designs for range B. Full lines indicate the on-axis MTF, dashed lines the MTF at 70% of the maximum field. The x-axis cutoff is half the Nyquist frequency of the detector with the smallest pixels.**

(134°). In addition, its compact dimensions and high energy throughput make it very well suited for sensing applications, where size and speed are important factors.

## *C: 5 mm ≤ diagonal ≤ 8 mm*

Designs aimed for a focal length of 4.5 mm and a distortion of -40%, resulting in a DFOV around 125° with an 80x80 80 µm detector. Specifications are given in Table 3, MTF curves in Figure 4.

The aspheric germanium singlet here again shows the best performance at any given temperature but fails to perform stably over the temperature range. As for the other germanium lenses, this is again a rather bulky lens.

A setup with two spherical silicon lenses yields a resolution that just passes the MTF specifications at the Nyquist frequency (data not shown). However, the lenses are too large to be practical, making the whole system quite cumbersome as well as reducing energy throughput through absorption losses.

The GASIR singlet design has more stable resolution over the image field, despite the MTF being lower on-axis. However, MTF values are insufficient compared to the specification, whereas energy throughput is the highest of all the lenses.

While GASIR does not suffer from the same thermal drift as germanium, a more performant solution might be found in a germanium lens that

| | Germanium | Spherical silicon | GASIR |
|---|---|---|---|
| Focal length | 4.5 mm | 4.5 mm | 4.6 mm |
| Back focal length (w/ 1mm Ge window) | 7.3 mm | 2.4 mm | 5.4 mm |
| Total track | 17.6 mm | 28.7 mm | 12.9 mm |
| Aperture-based f-number RF | 1.03 | 1.09 | 1.00 |
| Relative illumination | > 93% | > 57% | > 83% |
| DFOV | 117° | 156° | 123° |
| Distortion | -45% | -81% | -50% |
| MTF | Thermal drift | Borderline | Below spec |
| Lens dimensions (thickness x diameter) | 10.4 mm x 10.8 mm | 10.8 mm x 11.2 mm<br>15.0 mm x 15.2 mm | 7.6 mm x 9.4 mm |
| Energy throughput on-axis | 0.90 | 0.05 | 0.91 |

**Table 3: Overview of lens parameters for lenses designed to cover range C.**

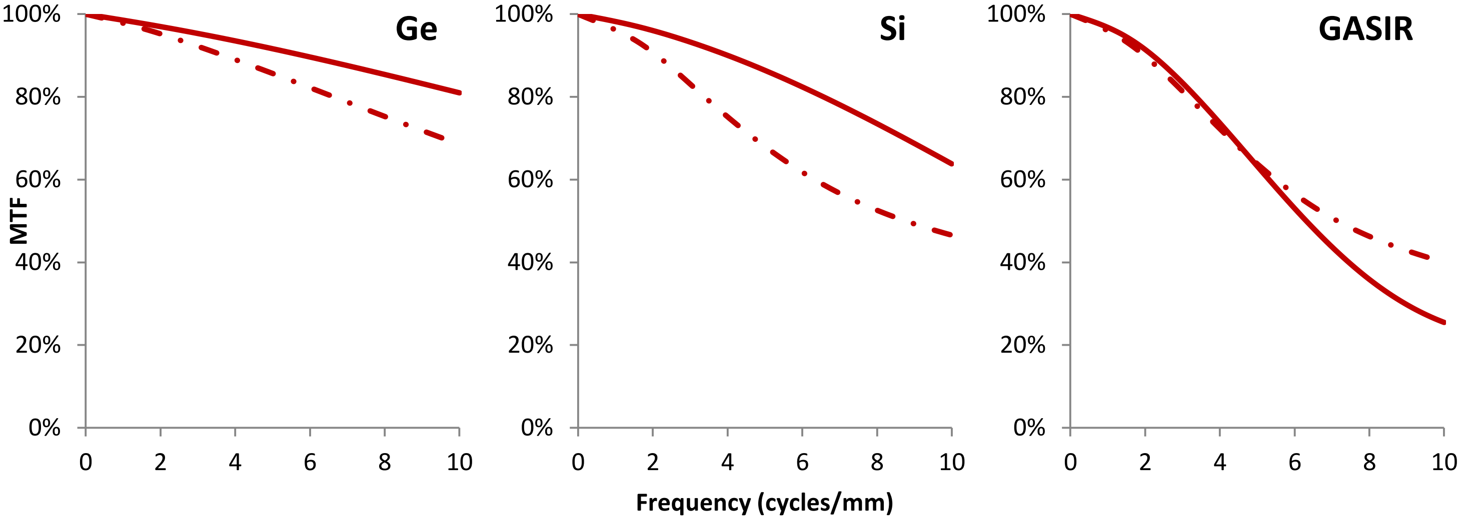



Figure 4: MTF curves for designs for range C. Full lines indicate the on-axis MTF, dashed lines the MTF at 70% of the maximum field. The x-axis cutoff is half the Nyquist frequency of the detector with the smallest pixels.

has been passively mechanically athermalised (PMA) [2], i.e. using no powered components. These types of lenses are already commercially available (e.g. from Umicore Infrared Optics).

### *D: Diagonal > 8 mm*

To achieve a DFOV of 130° with a 160x120 70 µm detector, designs aimed for a focal length of about 8.5 mm with -50% distortion. The resulting lens parameters are listed in Table 4, with corresponding MTF graphs in Figure 5.

The germanium lens shows good resolution over the entire field but, as in the previous sections, suffers from thermal drift and rather large physical dimensions.

Despite the MTF at half the Nyquist frequency being acceptable, the size of the lenses causes low energy throughput. Therefore, this solution is not suited for sensing applications.

An aspherical singlet made in GASIR performs comparably to the silicon solution, while retaining a smaller space envelope and performing significantly better on other criteria, thus making it the most promising candidate for this sensor range.

## 4 Potential of tailored designs

While a one-lens-fits-all solution as described above is interesting from a commercial and production perspective, it is rarely possible to ensure optimal performance and cost for the

| | Germanium | Spherical silicon | GASIR |
|---|---|---|---|
| Focal length | 8.3 mm | 8.9 mm | 8.7 mm |
| Back focal length (w/ 1mm Ge window) | 12.6 mm | 7.2 mm | 11.7 mm |
| Total track | 30.1 mm | 39.6 mm | 22.8 mm |
| Aperture-based f-number RF | 1.02 | 1.24 | 1.07 |
| Relative illumination | > 85% | > 65% | > 76% |
| DFOV | 136° | 153° | 123° |
| Distortion | -61% | -78% | -49% |
| MTF | Thermal drift | Acceptable | Acceptable |
| Lens dimensions (thickness x diameter) | 17.5 mm x 19.2 mm | 15.3 mm x 17.0 mm<br>15.0 mm x 26.3 mm | 11.1 mm x 16 mm |
| Energy throughput on-axis | 0.91 | 0.03 | 0.79 |

Table 4: Overview of lens parameters for lenses designed to cover range D.

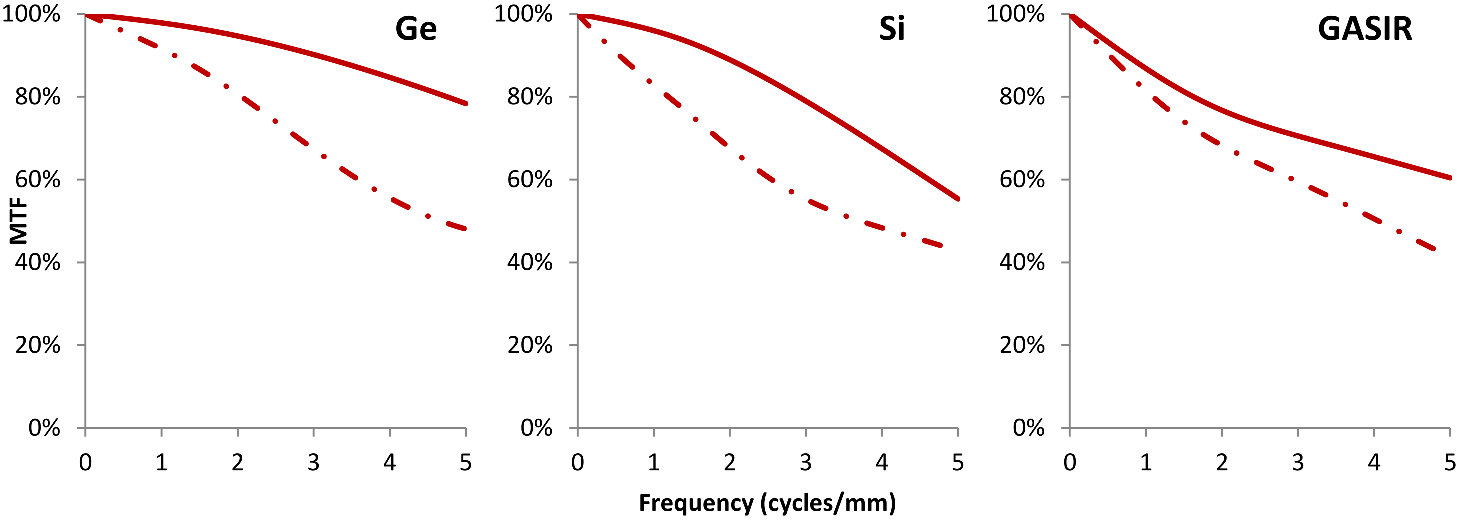



Figure 6: MTF curves for designs for range D. Full lines indicate the on-axis MTF, dashed lines the MTF at 70% of the maximum field. The x-axis cutoff is half the Nyquist frequency of the detector with the smallest pixels.

entire subset of detectors in a given range. To demonstrate the potential of a detector-specific approach, we elaborate on a lens designed for use with a 160x120 70 µm detector (Figure 6).

This 11.3 mm f/1.0 singlet features a DFOV of 75°, high energy throughput and relatively low distortion compared to the designs described above. In addition, it has good, temperature-stable resolution over the entire field with perfect passive optical athermalisation (i.e. no special mechanism is necessary to keep the lens focused). Its mechanical parameters as well as the inherent moldability of the material make this an attractive solution from both a production and a commercial point of view.

# 5 Conclusion

In the previous sections, we have quantitatively compared the performance and potential of several different materials with respect to sensor lens design. In these comparisons, several trends can be noticed. Germanium lenses tend to have good resolution, but this decreases considerably with temperature and the lenses are quite large and thus costly.

Attempts in spherical silicon yielded no practical results. Resolution was often only moderate, but with thick lenses leading to reduced transmission and smaller apertures, these comparatively slow lenses are not a contender for the wide-angle

| | GASIR |
|---|---|
| Focal length | 11.3 mm |
| Back focal length (w/ 1mm Ge window) | 14.5 mm |
| Total track | 30.5 mm |
| RF | 1.03 |
| Relative illumination | > 94% |
| DFOV | 75.4° |
| Distortion | -18% |
| MTF | Very good |
| Lens dimensions (thickness x diameter) | 16 mm x 20 mm |
| Energy throughput on-axis | 0.85 |

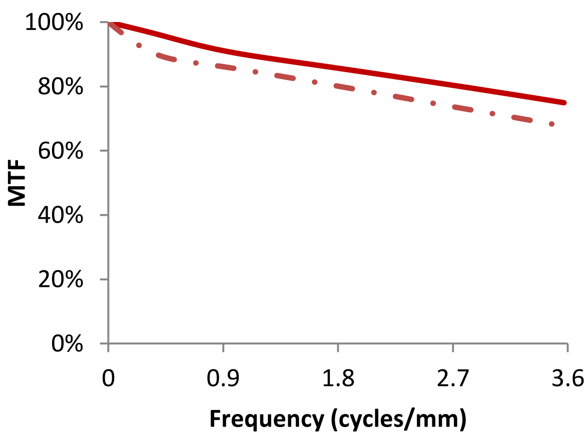



Figure 5: Left: overview of lens parameters for dedicated 160x120 70 µm design. Energy throughput is the transmission of the entire system scaled with the square of the reciprocal of the f-number. Right: On-axis MTF (full line) and MTF at 70% of the maximum field (dash-dotted line) for this lens. X-axis cutoff is half the detector's Nyquist frequency.

LWIR sensing applications covered in this article.

Lenses in GASIR tend to trade off increased compactness for slightly lower resolution. This drop is not always present, as in some cases GASIR lenses offer better resolution than both germanium and silicon lenses. This together with a more compact design as well as intrinsic material properties such as moldability allow for a cost-effective solution with superior performance.

Notwithstanding the above, we have also demonstrated that a universal design fitting many detectors is generally a sub-optimal solution, as a dedicated design can optimise both cost and performance.

# 6 Bibliography

[1] V. Venkatesh, “Precision manufacture of spherical and aspheric surfaces on plastics, glass, silicon and germanium,” *Current Science,* vol. 84, no. 9, pp. 1211-1219, 2003.

[2] N. Schuster, “Quantify Passive Athermalization in Infrared Imaging Lens Systems,” in *Proc. SPIE 8550, Optical Systems Design 2012, 85500E*, 2012.

| Resolution | | | Pixel pitch | Example of manufacturers |
|---|---|---|---|---|
| 32 | x | 32 | 25 µm | Korea Photonics Technology Institute |
| 80 | x | 60 | 12 µm | FLIR |
| 80 | x | 60 | 17 µm | SATIR, Ulis, FLIR |
| 100 | x | 80 | 17 µm | SATIR |
| 32 | x | 32 | 50 µm | MikroSens |
| 160 | x | 120 | 12 µm | RTN, FLIR |
| 10 | x | 10 | 200 µm | Nicera |
| 160 | x | 120 | 17 µm | SATIR, Ulis |
| 15 | x | 15 | 170 µm | IRISYS |
| 16 | x | 4 | 220 µm | Heimann |
| 80 | x | 80 | 34 µm | ULIS |
| 48 | x | 47 | 60 µm | Lapis Semiconductor Japan |
| 64 | x | 64 | 50 µm | MikroSens |
| 16 | x | 16 | 220 µm | Omron |
| 160 | x | 120 | 25 µm | Testo |
| 32 | x | 32 | 113 µm | Pelco |
| 160 | x | 120 | 40 µm | MikroSens, Magnity |
| 80 | x | 60 | 80 µm | Magnity |
| 30 | x | 30 | 220 µm | Heimann |
| 60 | x | 60 | 110 µm | Heimann |
| 160 | x | 120 | 50 µm | MikroSens |
| 100 | x | 50 | 100 µm | Bosch |
| 160 | x | 120 | 70 µm | MikroSens |
| 160 | x | 120 | 80 µm | Melexis |

Table 5: Detectors used in this study with examples of manufacturers.