Design investigation of a cost-effective dual-band (MWIR/LWIR) and a wide band optically athermalized application  
Fujian Ding*, Joe Washer, Daniel Morgen  
ISP OPTICS, 50 S. Buckhout St., Irvington, NY USA 10533

ABSTRACT

Dual-band and wide-band lenses covering both the MWIR and LWIR spectral bands are increasingly needed as dual-band MWIR/LWIR detectors have become prevalent and broadband applications have expanded. Currently in dual-band /wide-band applications, the use of more than three elements per lens group and the use of chalcogenide glass is common. This results in expensive systems. Also, many chalcogenides are available only in small diameters, which is a problem for large aperture broadband lenses.

In this paper an investigation of cost-effective designs for dual-band MWIR/LWIR lens using only widely available IR materials, specifically Ge, ZnSe and ZnS were performed. An athermalized dual-band MWIR/LWIR using these three materials is presented.

The performance analysis of this lens shows that this design form with these three common IR materials works well in certain applications. The required large size blanks of these materials can be easily obtained.

Traditional chromatic aberration correction without diffraction for either wide-band or dual-band application was employed. In addition, the methods of harmonic diffraction for dual-band applications, especially with one narrow band, were used for two different presented designs.

Keywords: IR Imaging, IR Wide-band Lens, Dual-band Lens, Athermalization, Chromatic Aberration Correction, Harmonic diffraction

1. INTRODUCTION

Today, the dual-band covering MWIR and LWIR and the wide band from 2 to 12μm has become increasingly important across different fields including: military and defense, homeland security, and academia. Dual band applications will significantly enhance target detection, identification, and tracking. The demand of dual-band lenses is also increased by the successful development of the MWIR/LWIR dual-band focal plane arrays [1].

Chromatic aberration in the wide wavelength range from 2 or 3 to 12μm presents a challenging issue that cannot be compensated with the typical chromatic aberration correction methods such as diffraction surfaces. Diffractive surfaces are commonly chosen for chromatic aberration correction to decrease the number of optical elements and to enable compact IR lens applications. The application of diffractive surface(s) in the IR region is a very important and effective method for normal waveband lenses of either LWIR, MWIR, or SWIR; however, when one design needs to cover two or more of these bands, conventional diffractive surfaces can no longer be used. The application of conventional diffractive surfaces result in some issues that affect optical performance. One issue induced by the application of the diffractive surface is the diffraction efficiency, which has relations with the spectral aspect and the geometrical aspect. A diffractive optical element is designed and manufactured based on a primary design wavelength. The diffraction efficiency, which is 100% at the primary design wavelength when the geometrical aspect is not considered, becomes significantly worse as the wavelength moves away from the primary design wavelength. The geometrical shape of the diffraction pattern has two manufacturing errors, the diffraction step depth control and the radius of the single point diamond-turning tool. These geometrical manufacturing errors cause an additional diffraction efficiency drop. The IR energy beyond the diffraction efficiency may be projected to the focal plane array as stray light. For these reasons and more, the method of a normal chromatic aberration correction with diffractive surfaces cannot be applied for such wide band applications covering both MWIR and LWIR, especially for a wide band application from 2 or 3 - 12μm.

*fding@ispoptics.com; phone 1 914 591-3070; www.ispoptics.com
The refractive indices of IR materials varies as the operating temperature changes. Some IR materials have very high thermal powers, such as $133\times10^6$ (Germanium), $63\times10^6$ (Silicon), $81\times10^6$ (GaAs), $33.5\times10^6$ (ZnSe), and $26.6\times10^6$ (ZnS\_broa)d in the wavelength range from 3 to 5μm. This will result in de-focus when the operating temperature is different from the calibrated/focused temperature. This de-focus is compensated with three different methods including manual refocus, active refocus, and passive mechanically athermalized refocus. The compensation efficiency, the application background, and the cost consideration limit these kinds of compensation. The manual refocus is not feasible for some applications while the active refocus will significantly increase the complexity of the assembly and the cost for a fixed focal length application. The mechanical athermalization is implemented by changing the axial position of the whole lens or some optical element(s) with the thermal expansion/contraction difference between a compensation material and the housing. The mechanical athermalization will have different compensation qualities in a wide operating temperature range and a long focal length may require a very long mechanical compensation part. Mechanical athermalization generally needs a plastic material of a high coefficient of thermal expansion when the housing is aluminum. Plastic materials can have a thermal expansion coefficient that changes compared to the IR material as the temperature changes (such as polynomial vs. linear). The plastic material may also have mechanical issues when the operating temperature is high. For most applications, the optically athermalized method demonstrates its advantages over other methods.

Chalcogenide glasses are used in IR lenses due to their small thermal powers and their good transmission in a wide band covering SWIR, MWIR, and LWIR. IG6 and IG4 have such small thermal powers as low as $-0.89\times10^6$ and $-5.4\times10^6$, respectively. The chalcogenide glasses, however, are limited in the applications because of cost and size limitations in the supply.

Some designers used chalcogenide glasses in the design of wide band achromatic lenses and/or wide band achromatic and athermalized lenses. Cooper Erwin [2] used chalcogenide glass, germanium and cleartran in his design of a wide band color-correcting lens from 3.5 to 12μm. Max Amon [3] presented a design for one dual-band system for both 3-5μm and 8-12μm. John Tejada [4] performed a design of a MWIR/LWIR dual-band lens with molded chalcogenide glasses. Wilhelm Ulrich [5] used one front objective including one chalcogenide optical element and one ZnSe or Cleartran optical element and a relay including one chalcogenide optical element and another 2 or 3 optical elements of ZnSe or Cleartran in an achromatic and athermalized reimager covering 7.5 to 10.5μm.

An optically athermalized lens is designed with thermal power compensation in the operating temperature range among different optical elements of IR materials of different thermal powers. This method has neither moving parts nor plastic material in the assembly.

Here, an optically athermalized lens for a wide band or a dual-band covering MWIR and LWIR is investigated with three widely used IR materials including Germanium, ZnSe, and ZnS\_broa)d.

### 2. DESIGN OF ACHROMATIC AND ATERMLIZED WIDE BAND LENS

#### 2.1 Achromatic consideration

##### 2.1.1 Multi-order harmonic diffraction

First, we check the feasibility of the chromatic aberration correction through diffractive surfaces for dual-band applications. Two bands may have such a specific relationship and the shorter band so narrow that diffractive surfaces may work for the chromatic aberration correction of two bands with satisfactory performance. For the dual band (MWIR and LWIR) applications, the diffraction order in the band of LWIR needs to be 1 while the diffraction order in the band of MWIR is either 2 or 3. Diffraction efficiencies of 1st, 2nd, and 3rd diffraction orders in the band of MWIR with a diffraction peak at 3.873micron were shown in Figure 1. According to Figure 1, the diffraction efficiency drops of multi-orders are much more serious than that of the 1st diffraction order. Therefore, the bandwidth of multi-order application has to be narrower than the bandwidth of the 1st diffraction order to achieve the same average diffraction efficiency.

In order for the average diffraction efficiencies of 2nd and 3rd diffraction orders in narrower MWIR bands to be the same as the average diffraction efficiency of the 1st diffraction order in a band from 3 to 5micron, the band widths need to be
1micron and 0.68micron, respectively. The design wavelength of 1st diffraction order in LWIR needs to be 2x or 3x of the wavelength of the diffraction orders 2 and 3, respectively. These mentioned requirements make this kind of harmonic diffraction application for MWIR/LWIR two bands very limited. Williams [7] mentioned a MWIR/LWIR dual band QWIP detector with a MWIR band from 4.4 to 5.1micron and a LWIR band from 8.0 to 9.1micron. This kind of dual band detector may be a good application of multi-order diffraction because the band width of the MWIR of this detector is only 0.6micron. This detector can use a lens with a 2nd diffraction order in the MWIR band at 4.7micron that also is 1st diffraction order in the LWIR band at 9.4micron. The diffraction efficiency distribution of this MWIR band is shown in Figure 2 and the average diffraction efficiency in the band from 4.4 to 5.1micron is as high as 0.974 when the peak wavelength is 4.73micron. While multi-order diffraction may be feasible for some dual band applications with a narrow bandwidth for the MWIR band, it cannot work for many dual band applications because of the serious diffraction efficiency drop. Therefore, designs of chromatic correction based on material combination are still one effective solution to a dual-band or a very wide band application.

![Figure 1. Diffraction Efficiencies Curves of Different Orders with a Same Diffraction Peak at 3.873micron.](image1)

![Figure 2. Diffraction Efficiency Curve of 2nd Different Order with a Diffraction Peak at 4.73micron.](image2)

2.1.2 Chromatic aberration correction with material combination

Design of a lens with a very wide wavelength range meets the challenge of the chromatic aberration correction. First, the spectral refractive index changes in such a wide waveband are much bigger than those in either a MWIR band or a LWIR band. Second, the spectral chromatic powers of different IR materials show very different characteristics among such a wide band and this point results in very different partial chromatic powers in several partial bands of the whole band. Third, the normal diffraction surface cannot be used for chromatic aberration correction because of the significant drop of the diffraction efficiency. Fourth, the number of IR materials that are appropriate for such a wide band application are extremely limited.

Theoretically, a perfectly chromatically corrected lens means one that has the chromatic aberration correction of all partial bands that make up the entire wide design waveband. This requires the simplified spectral chromatic powers defined in equation 2 for the involved materials to be similar to each other in the design waveband. However, this point is impossible to achieve in practical applications. Therefore, one approach requires materials with highly similar spectral chromatic powers to be used for the chromatic correction in the design waveband. The second approach is that the chromatic aberration corrections in and among several bands need to be performed to an acceptable extent and the chromatic aberrations do not need to be perfectly corrected. The spectral chromatic powers of Ge, ZnSe and ZnS broad were calculated based on the related parameters in the refractive index formula from Zemax. Figures 3 shows the related
spectral chromatic powers of these three materials from 2 to 12 micron. According to these curves, Ge shows a steep curve in the short wavelength and a flat curve in the long wavelength.

\[ \varphi = \frac{n_{\text{min}} - n_{\text{max}}}{n_{\text{cen}} - 1} \]  
(1)

\[ \frac{d\varphi}{d\lambda} = \frac{-dn_{\lambda}/d\lambda}{n_{\lambda} - 1} \]  
(2)

\[ \psi = \frac{\partial n/\partial t}{n_{\text{cen}} - 1} - \alpha \]  
(3)

Where, \( \varphi, \psi, \alpha, \) and \( n_{\lambda} \) are the chromatic power, thermal power, CTE of the IR material, and the refractive index at wavelength \( \lambda \), respectively.

For a dual band application, the chromatic aberration corrections in two specific bands such as MWIR and LWIR can be implemented for two individual bands at one focus position. When selecting materials, we need to consider their partial chromatic aberration correction in two individual bands and across both bands. Three thermal maps of Ge, ZnSe, and ZnS_broad at different bands including MWIR (3-5 micron), LWIR (8-12 micron), and the whole band (4-10 micron) are shown in Figure 4 and all related chromatic powers are shown in Table 1.

<table>
<thead>
<tr>
<th>Band</th>
<th>Germanium</th>
<th>ZnSe</th>
<th>ZnS_broad</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWIR</td>
<td>9.32x10^{-3}</td>
<td>5.62x10^{-3}</td>
<td>8.83x10^{-3}</td>
</tr>
<tr>
<td>LWIR</td>
<td>0.87x10^{-3}</td>
<td>17.4x10^{-3}</td>
<td>43.7x10^{-3}</td>
</tr>
<tr>
<td>Wide</td>
<td>6.89x10^{-3}</td>
<td>18.7x10^{-3}</td>
<td>41.5x10^{-3}</td>
</tr>
</tbody>
</table>

Figure 3. Spectral chromatic powers of Ge, ZnSe, and ZnS_broad
According to the above curves, the simplified spectral derivatives of the chromatic powers of these materials show different features in different partial bands.

Therefore, in general, the designers need to consider some partial chromatic powers in some partial bands as well as the general chromatic power when performing a design of a wide band lens. For a dual band application including MWIR and LWIR, the partial chromatic aberration corrections for the MWIR band and the LWIR band and the general chromatic correction for the whole band are considered to determine the starting point of the design.

2.2 Athermalization consideration

Generally speaking, more than two materials will be involved into the design of an achromatic lens in wide band or dual band applications. More than two materials may give the designers the freedom of considering both the optically athermalized design and the chromatic correction. Therefore, we need to consider selecting the materials in terms of the thermal glass map including both the chromatic power and the thermal power. The related minimum wavelength, central wavelength, and maximum wavelength of MWIR are 3, 4, 5; of LWIR, 8, 10, 12; and of the general band 4, 6, 10 micron.

Seeing that the changes of absolute index of many IR materials with temperature are specified just with one linear constant of $D_0$ while all other non-linear constants are 0 in Equation 4, the changes of the thermal power among different bands can be ignored. The thermal powers of Ge, ZnSe, and ZnS_broad are 132.8x10^{-6}, 33.5x10^{-6}, and 26.59x10^{-6}, respectively, in the MWIR band and 132.9x10^{-6}, 33.6x10^{-6}, and 26.9x10^{-6}, respectively, in the LWIR band. Generally, these three materials, in particular Ge, have very large thermal powers, therefore, many designers prefer chalcogenide glasses to control the thermal issue of an IR imaging lens. However, the application of chalcogenide glasses is limited because of its available size and its cost.

$$\Delta n_{\text{abs}} = \frac{n^2 - 1}{2n} \left[ D_0 \Delta T + D_1 \Delta T^2 + D_2 \Delta T^3 + \frac{E_0 \Delta T + E_1 \Delta T^2}{r^2 - S_{ik} r_{ik}^2} \right]$$

Figure 4. Thermal maps: 4a), MWIR (3-5\(\mu\)); 4b), LWIR (8-12\(\mu\)); 4c), a wide band (4-10\(\mu\))
3. DESIGN SAMPLES

Below, three design samples for a cooled detector are presented for different fields of view and different F-numbers. The related technical specifications of these three design samples are shown in Table 2. An image relay may be considered, especially for an application of a cooled detector in a wide band or dual-band system to control the sizes of the optical elements, the total dimensions and/or weight of the whole lens, and the total cost. The number of optical elements in a lens system with an image relay will be significantly increased causing the average transmission of the lens to be significantly decreased, especially for a wide or dual-band lens. Overall, the final optical configuration of a lens is a trade-off among all related considerations. These three design samples did not use any image relay and they have 4, 6, and 6 optical elements. Table 2 lists the technical specifications/features of these designs. Figure 5 shows the MTF curves of different bands at different temperatures of the dual-band lens, ISP_MWLWDualBand-150mm-F4. Similarly, Figures 6 and 7 show MTF curves of different bands at different temperatures of two wide band lenses, ISP_MWLWWideBand-50mm-2.3 and ISP_MWLWWideBand-58mm-F2.5, respectively. The lens, ISP_MWLWWideBand-58mm-F2.5mm, is working with a very short object distance of 800mm.

Lens, ISP_MWLWDualBand_150mm-F4, was tested for the LWIR band using a collimator with a primary reflector of a focal length of 1778mm, a 1951 Air Force Resolution Test Target with Group 0 and 1, a LWIR bandpass filter, and a FLIR camera detector of 640x512x15micron. Figure 8 shows one image of the target. Notice that this image was taken through holding the camera and the lens by hands. The spatial resolutions of Elements 1 to 6 of Group 0 and their related spatial resolutions at the detector of the LWIR camera were listed in Table 3. According to Figure 8, all elements of Group 0 can be identified with this configuration. The image shows the lens of 150mm achieved the expected spatial resolution.

These figures clearly show that the theoretical MTF curves of these lenses are close to the diffraction limit at all bands and at different temperatures. Such a result implies the lenses are athermalized and achromatic. This is achieved with common materials such as Germanium, Zinc Selenide, and Zinc Sulfide. Figure 8 shows the lens of 150mm achieved the expected spatial resolution.

Table 2. Technical specifications of three design samples.

<table>
<thead>
<tr>
<th>Item</th>
<th>ISP_MWLWDualBand-150mm-F4</th>
<th>ISP_MWLWWideband-50mm-F2.3</th>
<th>ISP_MWLWWideband-58mm-F2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveband</td>
<td>MWIR: 3-5μ + LWIR: 7-10μ</td>
<td>MWIR: 3-5μ + LWIR: 8-12μ + Wideband: 3-12μ</td>
<td>Wideband: 2.5-12μ</td>
</tr>
<tr>
<td>Focal length</td>
<td>150mm</td>
<td>50mm</td>
<td>58mm</td>
</tr>
<tr>
<td>F#</td>
<td>4.0</td>
<td>2.3</td>
<td>2.5</td>
</tr>
<tr>
<td>FOV</td>
<td>9.4°</td>
<td>18.4°</td>
<td>23.7°</td>
</tr>
<tr>
<td>Cold Shield Height</td>
<td>40.64mm</td>
<td>22.68mm</td>
<td>28.69mm</td>
</tr>
<tr>
<td>Minimum object distance</td>
<td></td>
<td></td>
<td>800mm</td>
</tr>
</tbody>
</table>

Table 3. Spatial resolutions of target and related spatial resolutions at detector.

<table>
<thead>
<tr>
<th>Element</th>
<th>Spatial Resolution of Target, lp/mm</th>
<th>Spatial Resolution at the Detector, lp/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
<td>11.85</td>
</tr>
<tr>
<td>2</td>
<td>1.1225</td>
<td>13.30</td>
</tr>
</tbody>
</table>
Figure 5. MTF Curves of ISP_MWLWWDualBand_150mm-F4, 5a), LWIR band at 20°C; 5b), MWIR band at 20°C; 5c), LWIR band at -25°C; 5d), LWIR band at 60°C; 5e), MWIR band at -25°C; 5f), MWIR band at 60°C.
Figure 6. MTF Curves of ISP_MWLGWideBand_50mm-F2.3; 6a), LWIR band at 20°C; 6b), MWIR band at 20°C; 6c), Wide band at 20°C; 6d), LWIR band at -25°C; 6e), LWIR band at 65°C; 6f), MWIR band at -25°C; 6g), MWIR band at -65°C; 6h), Wide band at -25°C; 6i), Wide band at 65°C;
Figure 7. MTF Curves of ISP_MWLLWideBand_58mm-F2.5, 7a), 1.4 meter at 20°C; 7b), 2.5 meter at 20°C; 7c), 0.9 meter at 20°C; 7d), 1.4 meter at -20°C; 7e), 1.4 meter at 60°C; 7f), 2.5 meter at -20°C; 7g), 2.5 meter at 60°C; 7h), 0.9 meter at -20°C; 7i), 0.9 meter at 60°C;
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