

Athermal and Achromatic Design for a Night Vision Camera Using Tolerable Housing Boundary on an Expanded Athermal Glass Map

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We propose a new graphical method for selecting a pair of optical and housing materials to simultaneously athermalize and achromatize an LWIR optical system. To have a much better opportunity to select the IR glasses and housing materials, an athermal glass map is expanded by introducing the DOE with negative chromatic power. Additionally, from the depth of focus in an LWIR optical system, the tolerable housing boundary is provided to realize an athermal and achromatic system even for not readily available housing material. Thus, we can effectively determine a pair of optical and housing materials by reducing the thermal shift to be less than the depth of focus. By applying this method to design a night vision camera lens, the chromatic and thermal defocuses are reduced to less than the depth of focus, over the specified waveband and temperature ranges.

Keywords : Athermalization, Achromatization, Diffractive optical element, Expanded athermal glass map
OCIS codes : (220.3620) Lens system design; (160.4670) Optical materials

I. INTRODUCTION

The demand for a night vision camera, to identify an object in nighttime driving, is gradually increasing, and a camera has actually been developed. Since the night vision system is used in night time and mounted outside the vehicle, its optical system generally suffers from chromatic and thermal defocuses due to wide changes in wavelength and temperature. In particular, because the optical IR glasses have large thermo-optic coefficients compared to the visible glasses, the optical system should be athermalized [1]. The chromatic and thermal defocuses caused by such changes significantly degrade the image quality. Therefore, a refractive lens system should be designed to have stable performance over the specified waveband and temperature ranges.

In the visible and infrared waveband, many design methods to reduce these defocuses have been reported [2-5]. Although these methods are good, they often lead to unworkable solutions: because of the limited availability of optical and housing materials in a long wave infrared (LWIR) optics, a suitable material combination for an athermal and achromatic design is not frequently obtained

using the previously proposed methods.

In order to solve these problems, this study suggests a new graphical method to obtain the material combination by providing the tolerable housing boundary on an expanded athermal glass map. We introduce the diffractive optical element (DOE) with negative chromatic power to expand an athermal glass map. In addition, using the depth of focus in an LWIR optical system, the tolerable housing boundary is provided. These expanded athermal glass map and tolerable housing boundary provide a much better opportunity to select the IR glasses and housing materials for athermal and achromatic design. Using this method to design a night vision camera lens with an F/1.1, a good solution having small chromatic shift and thermal defocus has been found.

II. THERMAL POWER AND CHROMATIC POWER OF A DOE

Figure 1 is a schematic diagram describing the surface

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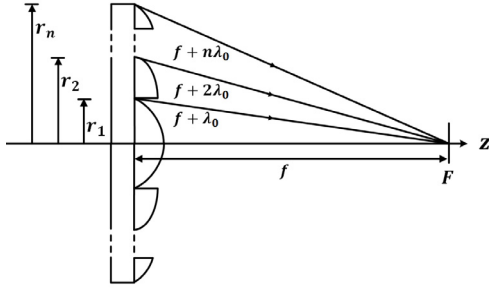


FIG. 1. Schematic diagram of a diffractive optical element.

profiles of a diffractive optical element (DOE). For each zone, the optical path length between the focal point F and the top of the zone is $(f + n\lambda_0)$. Therefore, the radius of each zone profile, r_n , is given by

$$r_n = \sqrt{2n\lambda_0 f} \quad (1)$$

where λ_0 is the design wavelength, f is the focal length of a diffractive element, and $n = 1, 2, \dots$, maximum zone number [6].

From the radial symmetry with respect to the optical axis, the phase function $\Phi(r)$ for a wavefront is expressed as

$$\Phi(r) = m \frac{2\pi}{\lambda_0} \sum_{n=1} C_n r^{2n} \quad (2)$$

where m is the diffraction order, and r is the distance from the optical axis to the point of a DOE. In Eq. (2), the coefficient (C_1) of the first term contributes the power of a DOE and higher order coefficients (C_2, C_3, \dots, C_n) control the wavefront of the light after diffraction. The power of a DOE, being used at design wavelength and the first order diffraction, is given by [7, 8]

$$\phi_{DOE} = -2C_1 \quad (3)$$

From the Sweat model [9], the Abbe number of the diffractive element, V_{DOE} , is given by

$$V_{DOE} = \frac{\lambda_0}{(\lambda_s - \lambda_l)} \quad (4)$$

where λ_s and λ_l are the shortest and the longest wavelengths in the spectral bandwidth. For LWIR waveband from 8 μm to 12 μm , V_{DOE} is about -2.5. Meanwhile, the Abbe number for a refractive element, V_{ref} , is

$$V_{ref} = \frac{n(\lambda_0) - 1}{n(\lambda_s) - n(\lambda_l)} \quad (5)$$

The main advantage is that the DOE has an excellent chromatic-aberration correction function. Because the diffractive element has a negative Abbe number whereas the refractive element has a positive one.

For a diffractive lens of power ϕ_{DOE} and Abbe number V_{DOE} , the thermal power γ_{DOE} and chromatic power ω_{DOE} are given as follows [8]:

$$\text{Thermal power : } \gamma_{DOE} = 2\alpha_g \quad (6)$$

$$\text{Chromatic power : } \omega_{DOE} = 1/V_{DOE} = \Delta\lambda/\lambda_0 \quad (7)$$

where α_g is the DOE substrate's coefficient of thermal expansion (CTE), and $\Delta\lambda$ is the specified waveband. The chromatic power of a diffractive lens is a function of only wavelength, and does not depend on the material parameters unlike the case for refractive lenses. Also, the thermal power of a diffractive lens is a function of only α_g , i.e., CTE of the substrate. These are basic differences between the thermal behaviors of refractive and diffractive lenses.

III. ATHERMAL AND ACHROMATIC CONDITIONS USING AN EQUIVALENT LENS

In an optical system composed of k thin lenses separated by spacers, summing the refraction equations for paraxial rays over all surfaces yields the total power ϕ_T , as follows [10]:

$$\phi_T = \sum_{i=1}^k \left(\frac{h_i}{h_1} \right) \phi_i = \sum_{i=1}^k \phi'_i \quad (8)$$

where $\phi'_i = (h_i/h_1)\phi_i$, h_i is the paraxial ray height at the i th lens. By differentiating the total power ϕ_T of Eq. (8) with respect to the temperature T , the thermal aberration is given as [4]:

$$\frac{d\phi_T}{dT} = \frac{1}{h_1} \sum_{i=1}^k \left(\frac{\partial h_i}{\partial T} \phi_i + \frac{\partial \phi_i}{\partial T} h_i \right) \quad (9)$$

Here, we assume that the first summation is negligible compared to the second summation, because the change of lens power with the temperature has greater influence on the total power fluctuation than that of ray height in a refractive optical system. Thus, in order to have an athermal system with total power ϕ_T , Eq. (9) can be rewritten as [4]:

$$\frac{d\phi_T}{dT} \cong \sum_{i=1}^k \gamma_i \phi'_i = -\alpha_h \phi_T \quad (10)$$

where α_h is the CTE of a housing material, and γ_i is the thermal power of the i th lens element.

The axial color aberration can be expressed as the difference (Δf_b) of back focal lengths between both extreme wavelengths. Therefore, for the system to be achromatic, the system must also satisfy the following equation [11]:

$$\Delta f_b = \left(\frac{1}{\phi_T} \right)^2 \sum_{i=1}^k (\omega'_i \phi'_i) = 0 \quad (11)$$

where $\omega'_i = (h_i/h_1)\omega_i$. In Eqs. (8), (10), and (11), the i 'th lens power is weighted by the ratio of the paraxial ray heights, i.e., $\phi'_i = (h_i/h_1)\phi_i$, implying that the air spaces between lens elements are included in these equations.

An equivalent lens is useful to design the athermal and achromatic system with an arbitrary number of elements. The equivalent lens is defined as the lens that represents the optical properties of an original optical system, by use of the equivalent power (ϕ_e), equivalent chromatic power (ω'_e), and equivalent thermal power (γ_e). For the equivalent lens L_e consisting of N elements, these three quantities are given by [4, 5]:

$$\phi_e = \sum_{i=1}^N (\phi'_i) , \quad (12)$$

$$\omega'_e = \frac{\sum_{i=1}^N (\omega'_i \phi'_i)}{\phi_e} , \quad (13)$$

$$\gamma_e = \frac{\sum_{i=1}^N (\gamma_i \phi'_i)}{\phi_e} . \quad (14)$$

Assuming that a DOE has the optical power of Eq. (3) and no thickness, as Fig. 2, an optical system with three elements can be recomposed of the DOE (L_{DOE}) and the equivalent lens (L_e), similar to a doublet. Thus, from Eqs. (8), (10), and (11), the total power, athermal and achromatic conditions for this doublet system are given by

$$\text{Total power : } \phi_T = \phi'_{DOE} + \phi'_e , \quad (15)$$

$$\text{Athermal : } \gamma_{DOE} \phi'_{DOE} + \gamma_e \phi'_e = -\alpha_h \phi_T , \quad (16)$$

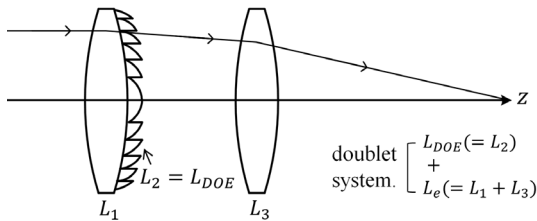


FIG. 2. Doublet system composed of a DOE (L_{DOE}) and an equivalent lens $L_e (=L_1+L_3)$.

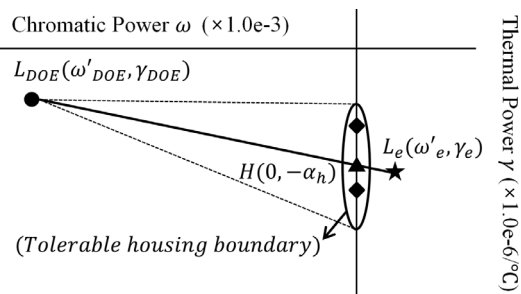


FIG. 3. Tolerable housing boundary on an expanded athermal glass map.

$$\text{Achromatic : } \omega'_{DOE} \phi'_{DOE} + \omega'_e \phi'_e = 0 . \quad (17)$$

For a doublet system to be achromatic, each element must have the power given in Eq. (18) by solving Eqs. (15) and (17), as follows:

$$\phi'_{DOE} = -\frac{\omega'_e}{(\omega'_{DOE}-\omega'_e)} \phi_T, \quad \phi'_e = \frac{\omega'_{DOE}}{(\omega'_{DOE}-\omega'_e)} \phi_T . \quad (18)$$

Inserting Eq. (18) into Eq. (16) results in an expression for the athermal and achromatic conditions for a doublet system:

$$-\gamma_{DOE} \frac{\omega'_e}{(\omega'_{DOE}-\omega'_e)} + \gamma_e \frac{\omega'_{DOE}}{(\omega'_{DOE}-\omega'_e)} = -\alpha_h . \quad (19)$$

Rearranging Eq. (19) to solve for γ_e yields the following expression:

$$\gamma_e = \frac{\gamma_e - \gamma_{DOE}}{\omega'_e - \omega'_{DOE}} \omega'_e - \alpha_h . \quad (20)$$

To graphically obtain a pair of materials that satisfy Eq. (20) in a doublet system, we plot the athermal glass map, as shown in Fig. 3 [4]. This figure includes the coordinates of the DOE $L_{DOE}(\omega'_{DOE}, \gamma_{DOE})$, equivalent lens $L_e(\omega'_e, \gamma_e)$, and housing material $H(0, -\alpha_h)$.

If L_{DOE} , L_e , and H are on the line given by Eq. (20), then these materials simultaneously satisfy the athermal and achromatic conditions. For a doublet system composed of L_{DOE} and L_e with a housing H , rearranging Eq. (20) to solve for α_h yields the expression:

$$\alpha_h = \frac{\gamma_e \omega'_{DOE} - \gamma_{DOE} \omega'_e}{\omega'_e - \omega'_{DOE}} . \quad (21)$$

IV. TOLERABLE HOUSING BOUNDARY ON AN EXPANDED ATHERMAL GLASS MAP

If $L_{DOE}(\omega'_{DOE}, \gamma_{DOE})$, $L_e(\omega'_e, \gamma_e)$, and housing material $H(0, -\alpha_h)$ are on the line given by Eq. (20), then these materials satisfy the athermal and achromatic conditions, as shown in Fig. 3. For these lens glasses, however, the housing material on this line frequently does not happen in an athermal glass map. In this case, the optical glasses should be changed to have available housing materials, like previous studies [2-5].

However, since the available optical and housing materials are limited in an LWIR optics, it is difficult to get available housing materials by changing the optical glass only. To solve this problem, this study suggests a new graphical method to obtain material combinations by providing the tolerable housing boundary which uses the depth of focus in an LWIR optics.

In non-diffraction limited system, the allowable depth of focus (DOF) is given by [12]:

$$DOF = \pm \Delta(F/\#) , \tag{22}$$

where Δ is an acceptable image blur diameter, and $F/\#$ is an F-number. Also, the thermal defocus (Δf) due to temperature change (ΔT) is expressed as [13]:

$$\Delta f = -f \left[f \sum_{i=1}^k (\gamma_i \phi_i') + \alpha_h \right] \Delta T . \tag{23}$$

Now, substituting Eq. (22) in Eq. (23) yields an expression for α_h as, satisfying the athermal and achromatic conditions:

$$\alpha_h = - \left[\frac{\Delta(F/\#)}{f \Delta T} + f \sum_{i=1}^k (\gamma_i \phi_i') \right] \sim \left[\frac{\Delta(F/\#)}{f \Delta T} - f \sum_{i=1}^k (\gamma_i \phi_i') \right] . \tag{24}$$

Thus, selecting the housing materials within the boundary given by Eq. (24) reasonably identifies a pair of optical and housing materials that simultaneously satisfies athermal and achromatic conditions, as shown in Fig. 3. This is a key point of this study.

V. ATHERMAL AND ACHROMATIC DESIGN EXAMPLE USING A TOLERABLE HOUSING BOUNDARY

As a design example, a patented lens operating in the LWIR waveband from -40°C to 80°C is presented in Fig. 4 [14]. An initial patented lens consists of two Germanium (Ge) elements, and its specification is listed in Table 1. The optical properties of the elements are illustrated in Table 2.

By replacing γ_{DOE} , γ_e , ω'_{DOE} , ω'_e within γ_1 , γ_2 , ω'_1 , ω'_2 in Eq. (21), respectively and using Table 2, the CTE of housing material should be $\alpha_h = -125.76 \times 10^{-6}/^\circ\text{C}$ to satisfy both athermal and achromatic conditions. However, there is actually no housing material available with this CTE, as shown in Fig. 5(a). Figure 5 shows the expanded athermal glass map plotted for a DOE and IR glasses, including housing materials. Among the housing materials, SS416 with $\alpha_h = 9.9 \times 10^{-6}/^\circ\text{C}$ is selected to mount the lenses and then evaluate the optical performances, because its CTE is nearest to the required CTE of housing.

The effective focal length and the back focal length of this system are thermally unstable from -40°C to 80°C , as shown in Fig. 6. In that figure, housing material length (HML) and flange back distance (FBD) are the lengths of the housings, which correspond to EFL and BFL, respectively. The thermal defocus expressed as $\Delta = \text{EFL} - \text{HML}$ ranges from $+179.1 \mu\text{m}$ to $-178.6 \mu\text{m}$ at both extreme temperatures, which is greater than the depth of focus

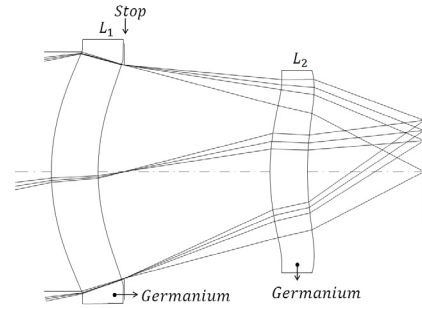


FIG. 4. Layout of a patented lens for a night vision camera.

TABLE 1. Specification of a patented lens

Parameters	Values
EFL	28.3 mm
BFL	12.8 mm
FOV	22.4°
F-number	1.1
Depth of focus	$\pm 26.4 \mu\text{m}$
Wavelength	$8\sim 10\sim 12 \mu\text{m}$
Temperature	$-40^\circ\text{C}\sim 20^\circ\text{C}\sim 80^\circ\text{C}$
Housing material (α_h)	SS416 ($9.9 \times 10^{-6}/^\circ\text{C}$)

TABLE 2. Optical properties of the elements in a patented lens

Element	Material	Index at $10 \mu\text{m}$	Abbe number	ω' ($\times 10^{-3}$)	γ ($\times 10^{-6}/^\circ\text{C}$)
1	Ge	4.00	942.38	1.06	125.76
2	Ge	4.00	942.38	0.61	125.76

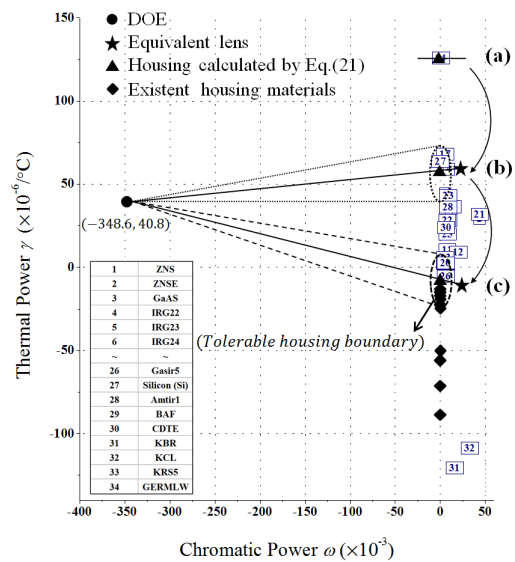


FIG. 5. Athermal and achromatic design processes using tolerable housing boundary on an expanded athermal glass map.

given in Table 1. Note that the distance between two image planes, expressed as $\Delta' = \text{BFL} - \text{FBD}$, is also longer than the depth of focus. These great thermal defocuses lead to the unstable modulation transfer function (MTF) at the Nyquist frequency, as shown in Fig. 7. For an LWIR image sensor having the pixel size of $12 \mu\text{m}$, the Nyquist frequency is about 40 lp/mm [15].

Thus, for the optical system composed of two Ge elements in Fig. 4 it is found to be hard to correct the thermal aberration. To solve this problem, we try to design the lens system by changing the material and power of each element. The crystalline materials such as Ge and ZnS are fabricated with a CVD method and ground by single diamond turning to make an IR lens. Therefore, there is a limit to expanding application of these IR glasses with aspherical geometries because of complex fabrication

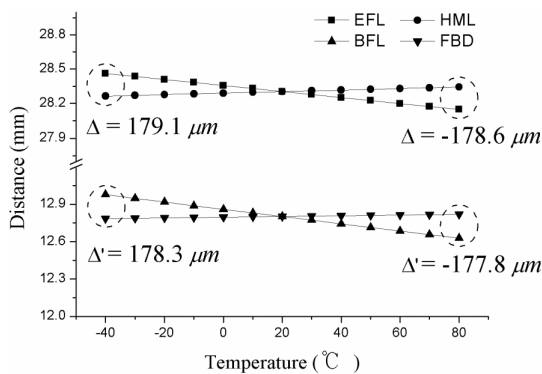


FIG. 6. Thermal shifts of a patented lens with temperature for effective focal length (EFL), back focal length (BFL), housing material length (HML), and flange back distance (FBD).

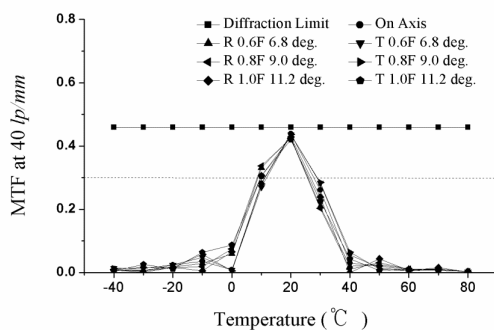


FIG. 7. MTF graphs of a patented lens with temperature.

TABLE 3. Optical properties of the elements in a temporary lens for an LWIR night vision camera

Element	Material	Index at $10 \mu\text{m}$	Abbe number	ω' ($\times 10^{-3}$)	γ ($\times 10^{-6}/^\circ\text{C}$)
1	IRG24	2.61	177.38	5.63	-8.03
2	DOE	-	-2.50	-351.82	40.80
3	Ge	4.00	942.38	0.67	125.76

process and high cost.

In this study, the Ge glass is replaced with the chalcogenide glass of which the surface can easily be aspherized by a mold press method. The molding method enables us to get the mass production so that the chalcogenide glasses are useful in civilian demand for a night vision camera [16]. Among them, the glass of L_1 is replaced with IRG24 ($\gamma = -8.03 \times 10^{-6}/^\circ\text{C}$) of Schott. Here, to reduce the thermal aberration, the new glass for L_1 should hopefully be selected to have small thermal power.

Most chalcogenide glasses including IRG24 have small refractive index and low Abbe number compared to Ge, as listed in Table 3. Therefore, replacing Ge with a chalcogenide glass leads to bad performance due to color aberration. To correct the chromatic aberrations, the DOE is introduced on the back surface of the first lens L_1 . Introducing the DOE with negative chromatic power enables an athermal glass map to be expanded. This expanded athermal glass map provides the glass map with a much better opportunity to select the materials, rather than any of the refractive elements themselves. We use the first order diffraction ($m=1$) and the first term coefficient (C_1) of Eq. (2) to specify the optical power of a DOE, as in Eq. (3).

When we set up a doublet system using three elements in the temporary lens of Table 3, there are three combinations for an equivalent lens. To have the expanded athermal glass map, the configuration of a DOE (L_2) plus an equivalent lens composed of two refractive lenses (L_1 , L_3) is selected: the other two combinations for equivalent lens contain one refractive lens plus one DOE, which is not proper to realize an expanded athermal glass map. Thus, two elements of L_1 (IRG24) and L_3 (Ge) are chosen such that they create an equivalent lens. While the specifications given in Table 1 are not changed, the power of each element is reconfigured to satisfy Eq. (18) by using the design program Code-V. Table 3 lists the optical properties of the elements in the lens system designed from this process.

The chromatic and thermal powers of an equivalent lens, calculated from Eqs. (13) and (14), are $\omega'_e = 3.18 \times 10^{-3}$, $\gamma_e = 58.12 \times 10^{-6}/^\circ\text{C}$ and they are located at Fig. 5(b). From Eq. (21) and Table 3, the CTE of housing material should be $\alpha_h = -57.97 \times 10^{-3}/^\circ\text{C}$ to satisfy both achromatic and athermal conditions. However, there is actually no housing material having this CTE. The tolerable housing boundary, calculated from Eq. (24), ranges from $\alpha_h = -73.5 \times 10^{-6}/^\circ\text{C}$ to $-42.5 \times 10^{-6}/^\circ\text{C}$. Because there is no available housing material within this tolerable housing boundary, the third lens glass is additionally changed into GASIR5 manufactured by Umicore. Combining the third lens of GASIR5 with the first lens of IRG24 yields small equivalent thermal power γ_e .

After replacing Ge glass with chalcogenide glass of GASIR5, keeping the specifications of the system intact, the power of each element is changed to satisfy Eq. (18)

by using the design program. The optical properties of the elements are listed in Table 4. Figure 8 shows the finally designed athermal and achromatic lens for a night vision camera.

Here, the chromatic and thermal powers of an equivalent lens are $\omega'_e = 4.96 \times 10^{-3}$, $\gamma_e = -7.01 \times 10^{-6}/^\circ\text{C}$, and they are located at Fig. 5(c). From Eq. (21) and Table 4, the CTE of housing material should be $\alpha_h = 6.36 \times 10^{-6}/^\circ\text{C}$ to realize an athermal and achromatic system. However, there is actually no housing material having this CTE. But, the tolerable housing boundary ranges from $\alpha_h = -9.1 \times 10^{-6}/^\circ\text{C}$ to $+21.9 \times 10^{-6}/^\circ\text{C}$. Among the available housing materials within tolerable housing boundary, SS416 with $\alpha_h = 9.9 \times 10^{-6}/^\circ\text{C}$ is selected to mount the lenses and then evaluate the optical performances, because its CTE is closer to the required CTE of $\alpha_h = 6.36 \times 10^{-6}/^\circ\text{C}$.

The thermal shifts of this lens are significantly reduced,

TABLE 4. Optical properties of the elements after replacing Ge glasses with chalcogenide glasses

Element	Material	Index at 10 μm	Abbe number	ω' ($\times 10^{-3}$)	γ ($\times 10^{-6}/^\circ\text{C}$)
1	IRG24	2.61	177.38	5.63	-8.03
2	DOE	-	-2.50	-351.82	40.80
3	GASIR5	2.77	160.09	3.91	-5.49

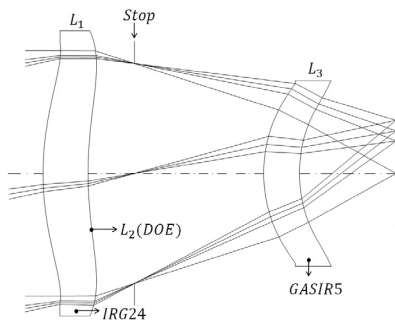


FIG. 8. Layout of an athermal and achromatic lens for an LWIR night vision camera.

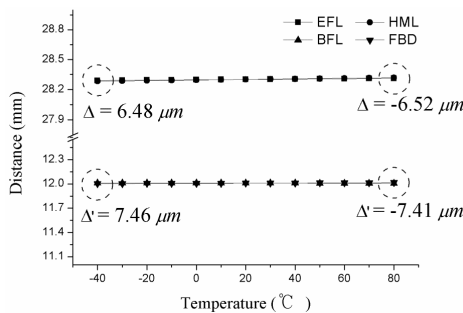


FIG. 9. Thermal shifts of an athermal and achromatic lens with temperature.

as illustrated in Fig. 9. The thermal defocus ($\Delta = \text{EFL} - \text{HML}$) and image plane shift ($\Delta' = \text{BFL} - \text{FBD}$) from -40°C to 80°C are less than $7.46 \mu\text{m}$. Note that here the sign of ΔEFL is the same as that of ΔHML , which effectively reduces this thermal defocus over the entire temperature range. Thus, all thermal defocuses are less than the depth of focus of $\pm 26.4 \mu\text{m}$. In addition, the chromatic focal shift between both extreme wavelengths is reduced to $7.0 \mu\text{m}$, which is also less than the depth of focus.

Figure 10 shows the modulation transfer functions (MTFs) at the Nyquist frequency of 40 lp/mm with temperature. The MTF of the lens designed from the athermal and achromatic process is much more stable than that of the starting patented lens over the specified temperature ranges. In addition, the MTF at the Nyquist frequency is greater than 30% over all fields. The finally designed lens has an F-number of 1.1, focal length of 28.3 mm, and stable chromatic and thermal focusings. In conclusion, the designed lens is achromatic in LWIR waveband and passively athermalized from -40°C to 80°C .

We can also realize other athermal and achromatic systems by selecting the materials being in tolerable housing boundary. To prove it, five housing materials within this boundary are used to mount the lens elements and evaluate the MTF properties at margin field. The MTFs of these systems mounted in five different housings are very stable over the specified temperature ranges. In Fig. 11, all MTFs at the Nyquist frequency are greater than 30% at 1.0 field from -40°C to 80°C . Although the AL6061 housing ($\alpha_h = 23.4 \times 10^{-6}/^\circ\text{C}$) is slightly deviated from the tolerable

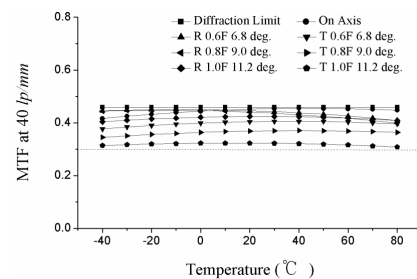


FIG. 10. MTF graphs of an athermal and achromatic lens with temperature.

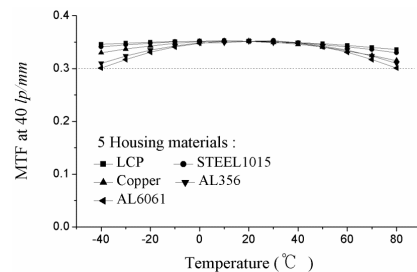


FIG. 11. MTF graphs at 1.0 field of an athermal and achromatic lens system mounted in housings within tolerable housing boundary.

housing boundary, but it is sufficiently available to this system. In conclusion, the expanded athermal glass map and the tolerable housing boundary enable us to easily get the material combinations for an athermal and achromatic design.

VI. CONCLUSION

To design an athermal and achromatic LWIR lens, this study suggests a new graphical method to obtain the material combinations by providing the tolerable housing boundary on an expanded athermal glass map. By introducing the DOE, an athermal glass map is expanded. This expanded athermal glass map provides a much better opportunity to select the IR glasses and housing materials, rather than glass map composed of the refractive elements only. Thus, we can easily identify a pair of optical and housing materials that satisfy both the achromatic and athermal conditions.

Even if the material combination is not readily available in an LWIR system, the proposed method effectively serves the athermal and achromatic solutions. By utilizing this method to design a night vision camera lens, a solution having small chromatic shift and thermal defocus has been obtained. In conclusion, this proposed design method is expected to serve as a useful way to find design solutions in an IR optical system.

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