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A DESIGN OF 4-LENS THERMAL IMAGING OBJECTIVE WORKING IN THE LWIR SPECTRAL REGION

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Abstract: This article presents a thermal imaging objective design with four lenses working in the LWIR (long-wave infrared) spectral region. The design solution combines passive heat removal and manual mechanical compensation. The optimization of the optical system quality is performed on ZEMAX optical software, taking into account the change in the operating temperature range of the optical system from -40 to +80 °C and the change in the image plane of the optical system compared to the detector. The change in the image plane of the optical system and the plane of the detector are then manually mechanically compensated. Considering criteria such as MTF (modulation transfer function), image spot size, energy function, the optical system has good image quality. Infrared materials are available on the market and the lens surfaces are completely spherical, so they are easy to manufacture and suitable for Vietnamese technology.

Keywords: Mechanical compensation; Optical compensation; Thermal infrared lens.

1 INTRODUCTION

Materials working in the 8-12 µm spectral region are characterized by high refractive index, low dispersion, and small amount. Aberrations common to infrared materials are corrected quite easily, except for the problem of thermal aberrations. Thermal aberration refers to the change in the image plane position of the optical system when the thermal imaging device works at different temperatures. The formula for determining the focal shift of a thin lens 1-element optical system according to temperature is calculated as follows [1, 3]:

$$\Delta f = \frac{f'}{(n-1)}\left(\frac{dn}{dt}\right)\Delta t, \tag{1}$$

where *f'* is the back focal length of the lens, *n* is the refractive index of the lens material, d*n*/d*t* is the change in refractive index with temperature, Δt is the working temperation difference of the lens. The focal shift increases proportionally to the change in refractive index. In addition, the wider the working temperature range, the larger the focal shift. There are many criteria to evaluate the quality of thermal imaging optical systems through evaluating the quality of the MTF (modulation transfer function), the RMS (root mean square) magnitude of the image spot, and the energy concentration function in an image pixel of the detector, Rayleigh standard of DOF (depth of focus),... In which, the magnitude of DOF is used to evaluate the quality of the optical system as expressed by the following expression [4, 6, 7]:

$$DOF = 4\lambda \cdot (f/\#)^2 = 4\lambda \cdot (f'/D)^2 \tag{2}$$

where *f/#* is the ratio of the back focal length to the clear aperture diameter, λ is the primary wavelength, D is the clear aperture diameter of the objective lens. The depth of focus is proportional to the wavelength and proportional to the square of *f/#*.

From formulas (1) and (2), it can be seen that, when the focus shift according to temperature exceeds the focus depth, the optical system does not satisfy the quality according to Rayleigh standards.

For example, for a lens of focal length $f' = 100$[mm], made from Germanium material with $n =$ 4,001 (at wavelength 10 [µm]), $dn/dt = 0.00039$, considering the temperature change range as from 0°C to +50°C, then $\Delta f' = 0.649$ [mm]. According to formula (2), considering the above lens when *f/#* = 3, $DOF = 0.36$ mm. Thus, the above lens does not meet Rayleigh standards of quality. If one wants the optical system to achieve quality when the temperature changes, it is necessary to remove heat from the optical system, called athermalization. That is, adjusting the focus shift according to temperature so that the focus shift value is as small as possible.

There are two main methods for heat removal: mechanical and optical. The mechanical method is divided into two: active mechanical and passive mechanical. Passive mechanical methods rely on the natural expansion or contraction of mechanical parts to compensate for image displacement due to changes in working temperature.

The mechanical method actively adjusts by hand or uses motors and heat sensors to move the position of lenses as well as mechanical details and assemblies in the system. This method is widely used in zoom camera systems that require many different temperature compensation movements.

Passive optical methods rely on choosing a combination of optical materials to minimize the focus shift over a given temperature range [5]. The characteristic of this method is that there is little choice of materials, when good heat removal is required, it is necessary to use aspherical refractive surfaces or hybrid refractor/diffraction.

This article introduces the design of a heat-reducing thermal imaging objective optical system using the passive optical method, combined with a manual mechanical adjustment solution to ensure that the image plane of the optical lens coincides with the detector plane. This combination allows the design and manufacture of thermal imaging lenses in accordance with Vietnam's technological capabilities.

2 THEORETICAL CALCULATION BASIS AND SELECTION OF OBJECTIVE OPTICAL SYSTEM

2.1 Theoretical calculation basis

Select the objective lens focal length to be designed based on the parameters of the available detector, target size and required working distance. Then, the field of view of the objective lens is calculated according to the formula:

$$2\omega = \arctan\left(\frac{d}{f'}\right), \quad (3)$$

in which, f' is the back focal length of the objective lens, d is the diagonal of the detector matrix.

Select the parameter *f/#* according to the balance requirements of image illuminance, operating distance, and optical detail manufacturing technology. A value between 1.1 and 2.5 is reasonable. The optical clearance diameter of the objective lens is calculated according to the formula:

$$D = \frac{f'}{f\#}. \quad (4)$$

Next, calculate the optical power of components based on the conditions of total optical power, chromatic aberration removal, and heat removal [2].

$$\phi = \sum_{i=1}^{K} \phi_i, \quad (5)$$

$$\sum_{i=1}^{K} \frac{\phi_i}{v_i} = 0, \quad (6)$$

$$\sum_{i=1}^{K} T_i \phi_i = -\alpha_h \phi, \quad (7)$$

in which, $\emptyset_i$ is optical power, ν_i is the dispersion coefficient, T_i is thermal glass constant of the i-the component, respectively; ϕ is the total lens power, α_h is thermal expansion coefficient of the mounting base material; K is number of components.

2.2 Select the input criteria of the optical system

As mentioned in section 2.1, some basic parameters of the optical system are calculated and selected based on the working distance of the optical device, and also based on the features of the detector. It is assumed that the optical device can identify a human target at a distance up to 1500 meters, using a commercially available uncooled microbolometer detector. Table 1 shows the input parameters of the optical device.

Tab. 1 Table of optical input parameters of the objective lens

Parameter	Value
Detector dimensions, [μm×μm]	640 x 512
Pixel size, [μm]	17
Working spectral range, [μm]	8 -12
f', [mm]	100
2ω, [°]	8
$f/\#$	1.2
Optical system length, [mm]	120

Source: authors.

3 RESULTS OF DESIGN AND ANALYSIS

From the formulas established above, combined with the selected detector, the optical power distribution of the components can be calculated, and the starting optical system can be selected.

After calculating the dimensions and finding the starting system, the optical system is imported into Zemax software for optimization. Enter the appropriate objective functions. First, optimize the optical system at a standard temperature of 25°C. Then, set up the optical system configuration working at nearby temperatures, and add the linear expansion coefficient of the mechanical material to make the objective tube (choose 2024 grade aluminum material with expansion coefficient $\alpha = 22.9 \cdot 10^{-6}$[mm/(mm·°C)]) [4]. The resulting objective lens optical system has the following configuration:

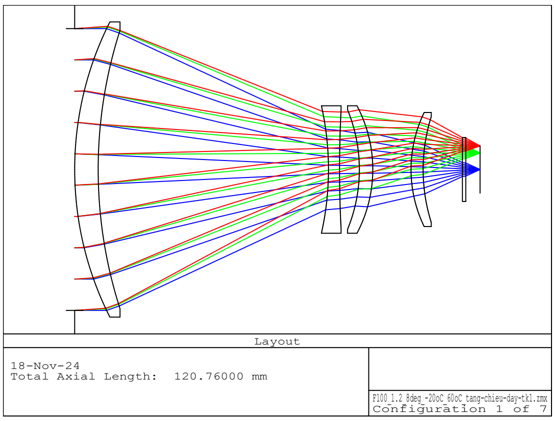

Fig. 1 Four-lens objective optical system
Source: authors.

The system consists of 4 lenses, of which the first and fourth lenses are made from germanium material, the second lens is made from ZnSe, and the third lens is made from ZnS. All above materials are popular and available on the market. To reserve a back focal length of the objective lens large enough for assembly, a 1 [mm] flat plate made of Germanium was added.

The specific parameters of the designed optical system after multi-configuration optimization with working temperature of 25 ℃ and working pressure of 1 atmosphere are given in Table 2.

Tab. 2 Optimized objective parameters

Surf	Radius	Thickness	Glass	Semi-Diameter
STO	Infinity	0.00		42.00
2	97.58	7.00	GERMANIUM	44.00
3	135.63	68.60		41.48
4	-86.90	3.30	ZNSE	19.00
5	344.57	5.90		17.60
6	-46.93	4.00	ZNS_IR	17.80
7	-40.69	11.40		19.00
8	38.95	3.60	GERMANIUM	17.00
9	52.68	11.70		15.78
10	Infinity	1.00	GERMANIUM	9.52
11	Infinity	4.26		9.41
IMA	Infinity			7.04

Source: authors.

In the extreme configurations with the operating temperature that differs the most from the standard operating temperature (the standard temperature is chosen to be 25 ℃), the image quality of the optical system is the worst. Therefore, the following figures will describe the image quality of the optical system in three main configurations: the standard configuration, two extreme configurations (operating temperature is -40 ℃, and +80 ℃).

The MTF curves of the optical system at different temperatures are shown in Figures 2-4.

The MTF value of the optical system at 25 ℃ is very good, the system quality is close to the diffraction limit.

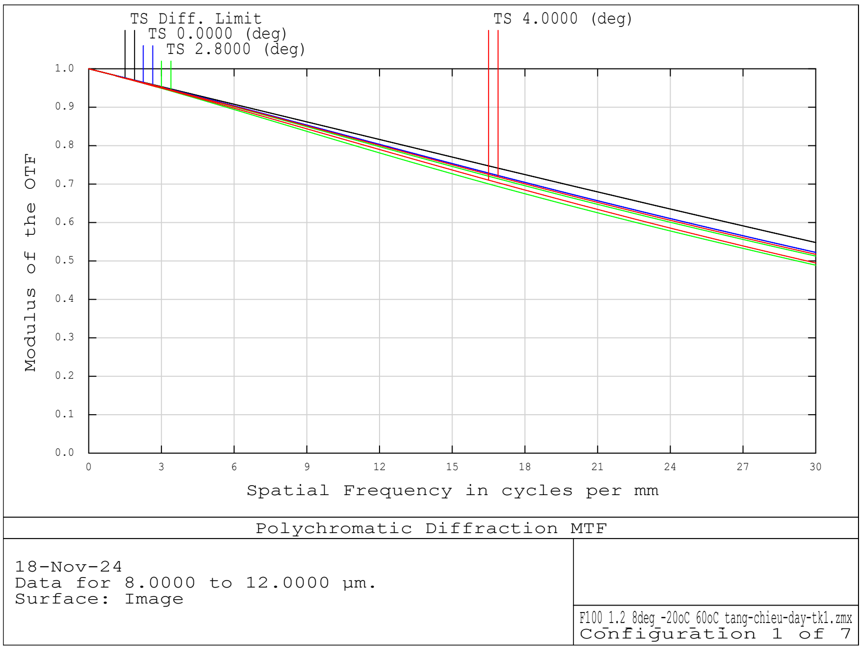

Fig. 2 MTF value of objective lens at 25 ℃
Source: authors.

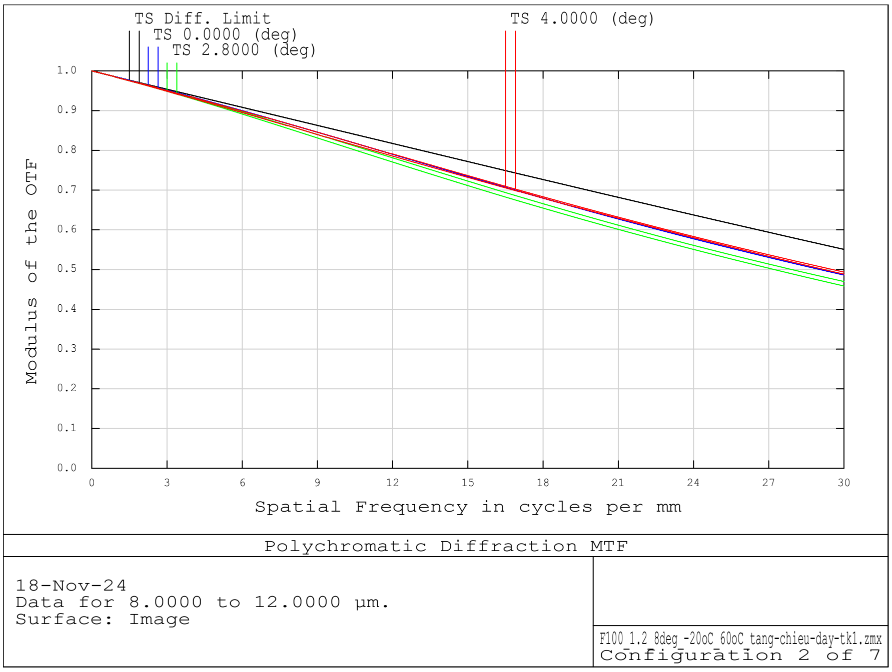

Fig. 3 MTF value of objective lens at -40 ℃
Source: authors.

The MTF value of the optical system at -40 ℃ is lower than the MTF value at 25 ℃, but is still quite good. Similarly, the MTF value of the optical system at +80 ℃ also decreases.

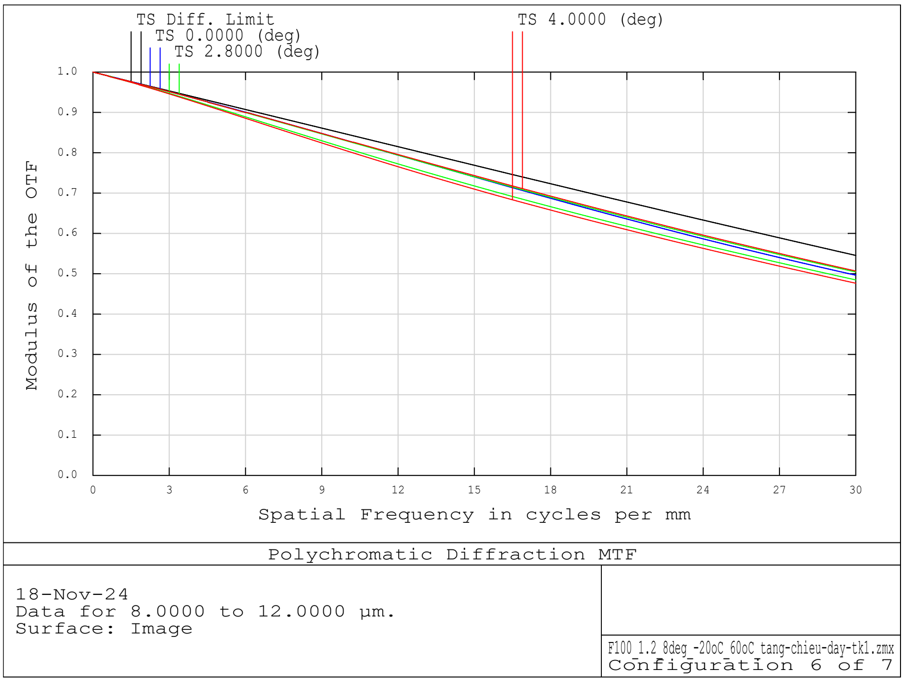

Fig. 4 MTF value of objective lens at 80 ℃
Source: authors.

The image quality of the optical system is quite good, as shown by the MTF values being quite uniform throughout the entire working temperature range (-40 ℃ to +80 ℃), all greater than 0.473 at the cutoff frequency of 30 $[mm^{-1}]$. The worst value is 0.458 at -40 ℃ (Figure 3).

The next pictures (Figures 5-7) show the shape and size of the image spot created by the objective optical system at different temperatures, the largest RMS image spot radius size is still smaller than the radius of the Airy disk, thus meeting the requirements for image spot quality.

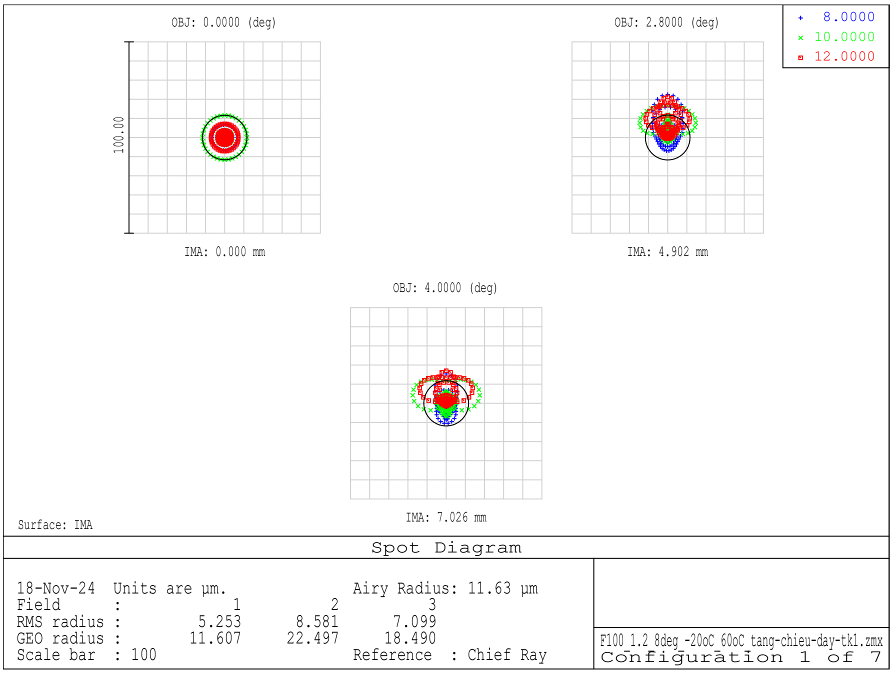

Fig. 5 RMS image spot size at 25 °C
Source: authors.

In Figure 5, the RMS radius of the image spot at the second field is the largest (=8.581 µm) and much smaller than the Airy disk radius, which proves that the image quality of the system at 25℃ at the focal plane is very good.

In Figure 6, the RMS radius of the image spot at the third field is the largest (=11.358 µm) but is still smaller than the Airy disk radius (=11.56 µm).

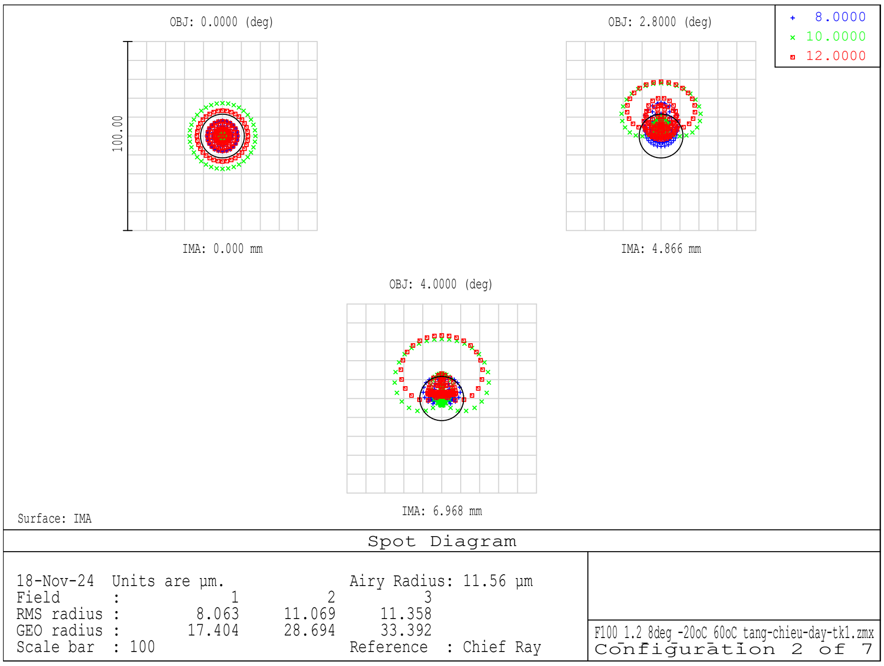

Fig. 6 RMS image spot size at -40 °C
Source: authors.

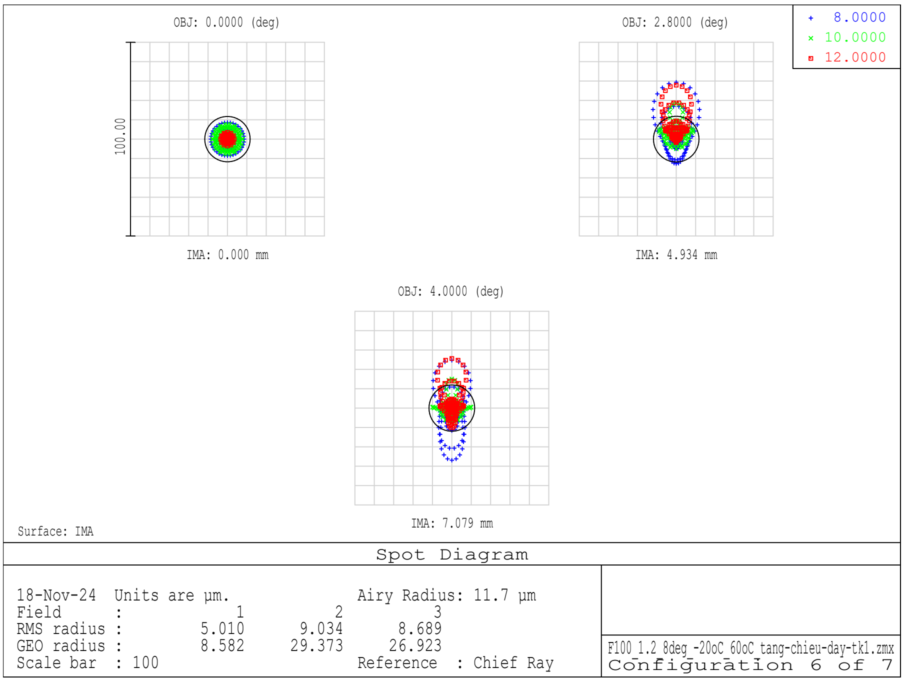

Fig. 7 RMS image spot size at 80 °C
Source: authors.

The graph representing the energy concentration function of the objective lens at different temperatures is shown in Figures 8-10, showing that the energy concentration function values are all greater than 0.6 in a circle of radius 8.5 µm. Thus, about 60 % of the energy of the imaging beam lies entirely in one pixel of the detector.

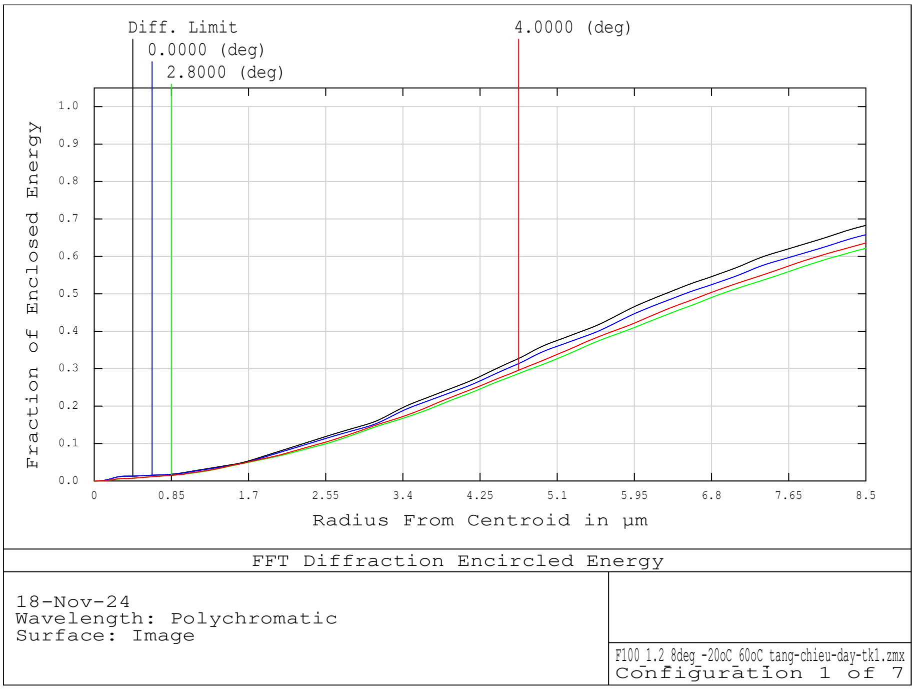

Fig. 8 Energy concentration function at 25 °C
Source: authors.

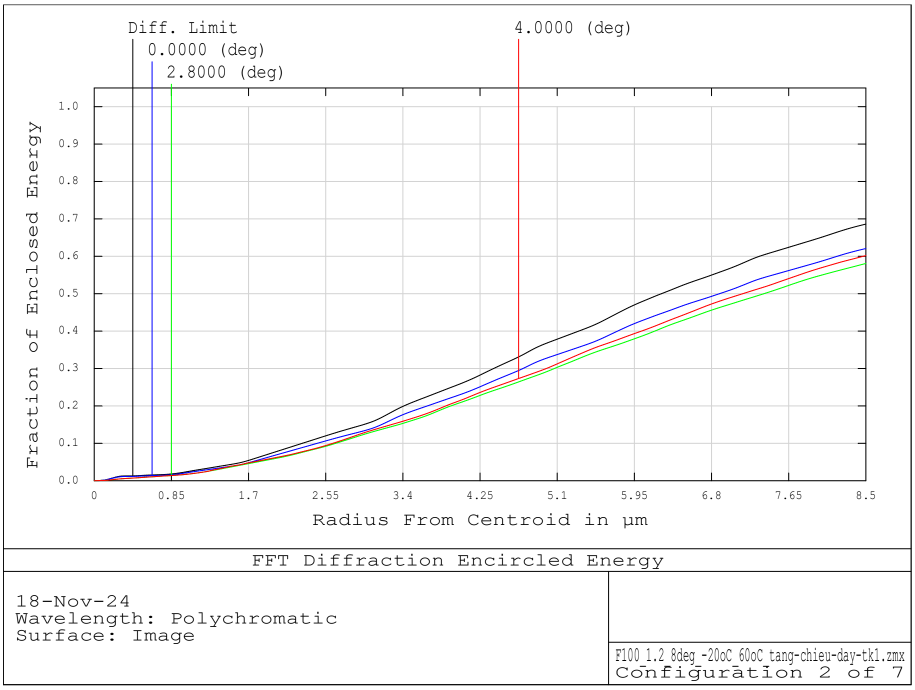

Fig. 9 Energy concentration function at -40 °C
Source: authors.

In Figure 9, the energy concentration function value at the second field (2.8 degrees) reaches 0.581 corresponding to 58.1 % of the light energy concentrated in one pixel. This is the lowest energy concentration value of the optical system in the entire operating temperature range.

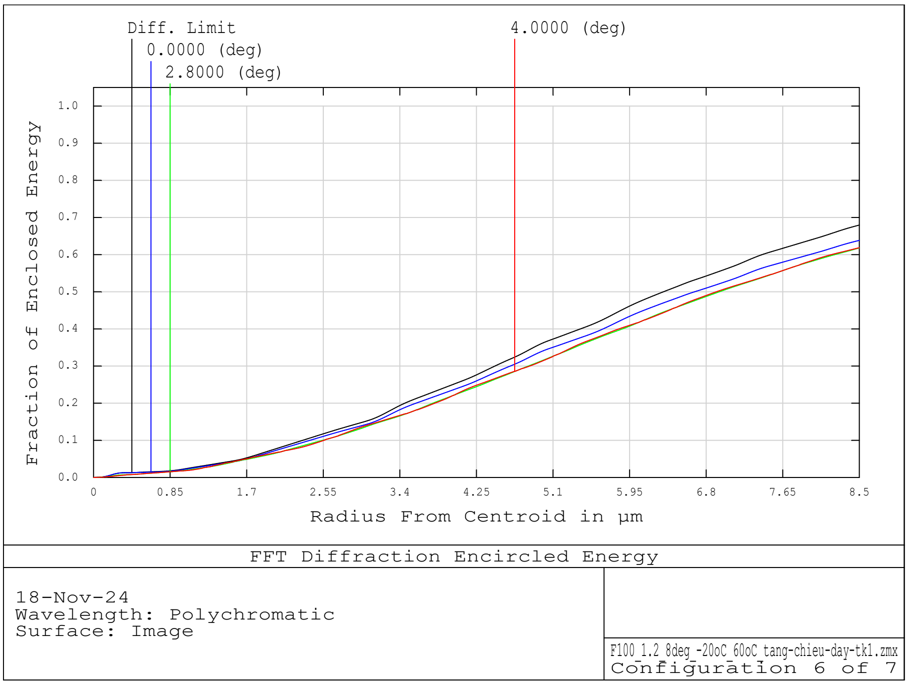

Fig. 10 Energy concentration function at 80 °C
Source: authors.

It is easy to see that at the extreme temperature of -40 °C, the optical system has the worst quality but is still acceptable (see Figures 3, 6, 9). Meanwhile, the optical system quality is best at the temperature of 25°C (see Figures 2, 5, 8). The optical system quality at the remaining temperatures is better than at -40°C. Therefore, the system is capable of working in the temperature range from -40 °C to +80 °C.

The 3D drawing of the optimised objetive lens optical system is shown in Figure 11.

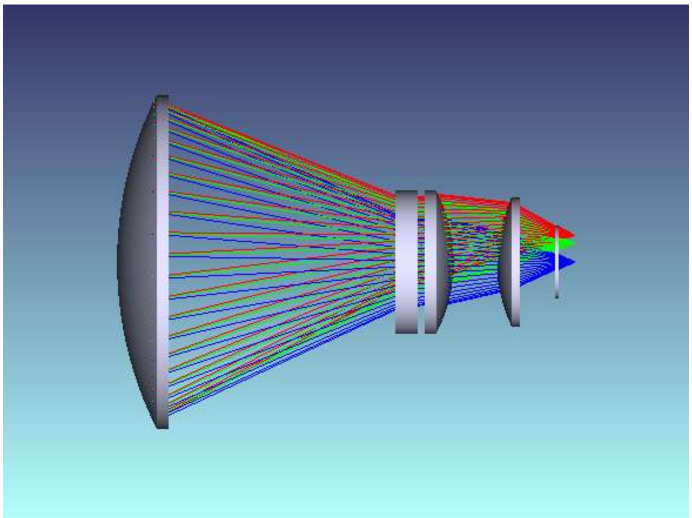

Fig. 11 3D drawing of the optimized objective lens optical system
Source: authors.

Consider one more criterion: the change in the image plane position of the objective lens. From the Lens Editor parameter table, extract the back focal length of the objective lens in the entire working temperature range that has been optimized.

Tab. 3 Values of the back focal length of the objective lens according to the temperature

Configuration	1	2	3	4	5	6
Temperature	25 ℃	−40 ℃	−20 ℃	0 ℃	50 ℃	80 ℃
Back focal length	16.960	17.980	17.666	17.355	16.570	16.094

Source: authors.

Considering the temperature range from -20 ℃ to 80 ℃, the largest back focal length value is 17,980 [mm] (at -40 ℃) and the smallest is 16,094 [mm] (at 80℃). The difference in the back focal length value later is equal to 17,980-16,094=1,570 [mm]. The value is greater than the depth of focus, so to use this objective, it is necessary to re-calibrate the coincidence of the image plane with the detector plane. This is easily accomplished by an active mechanical solution when connecting the objective tube to the detector housing with a fine-pitch thread. The entire objective tube will be manually moved relative to the detector to coincide with the image plane of the objective lens and with the detector plane. This is a viable and cheap solution.

4 CONCLUSION

This article presents a method for designing a lens thermal imaging objective that takes into account the passive heat suppression that can work in the LWIR region. The optical system consists of four lenses that are completely spherical, convenient for processing. The materials used are commercially available. Active mechanical adjustment to coincide the image plane with the detector plane is completely feasible, so this type of objective lens can be designed and manufactured to serve the needs of observation, detection, and identification. thermal target. To increase the quality of the optical system, it is necessary to continue to perform optimization with specialized optical software and it takes time.

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