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Design of a Passive Heat-Rejecting Thermal Imaging Lens for Long-Wave Infrared (LWIR)

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Abstract:

The paper presents a method for calculating a thermal imaging objective lens working with an uncooled detector in the long-wave infrared (LWIR) spectral region with the ability to passively remove optical heat based on the selection of appropriate materials. The objective lens optical system consists of only 3 spherical lenses made from three types of infrared materials with different refractive indices and dispersions. The simulation results show that the thermal imaging objective lens optical system has good quality, fully meeting the requirements for image quality, with the ability to completely passively remove heat.

Keywords:

triplet, thermal infrared lens, athermalization

1 Introduction

Thermal imaging devices are increasingly used in civilian fields such as medicine, industry, agriculture, and aerospace. In the military, thermal imaging devices help increase the ability to observe and detect targets in low light or complete darkness. The most important component of a thermal imaging device is the thermal imaging objective. The characteristic of a thermal imaging objective is that it is made of materials with high refractive index and large thermal expansion coefficient. When operating in environmental conditions with temperature changes, the image quality of the objective is greatly affected due to the change of objective focal length and displacement of image plane. Therefore, when designing a thermal imaging objective, special attention must be paid to the ability to compensate for temperature changes. This paper focuses on the calculation of a thermal imager that self-compensates for

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image plane displacements operating with an uncooled detector in the LWIR spectral region, which can maintain good image quality within a certain temperature range.

Let us calculate the change in focal length due to temperature change:
Consider an infinitely thin single lens. The refractive index, thickness, and radius of curvature of the lens change with temperature as follows [1]:

$$n = n_0 + \beta\left(t - t_0\right) \tag{1}$$

$$d = d_0\left[1 + \alpha\left(t - t_0\right)\right] \tag{2}$$

$$r = r_0\left[1 + \alpha\left(t - t_0\right)\right] \tag{3}$$

where n_0, d_0, r_0 are the refractive index, thickness, radius of the lens at a given reference temperature t_0, respectively; n, d, r are the refractive index, thickness, radius of the lens at the temperature t, respectively; β is the temperature coefficient of the refractive index; α is the thermal expansion coefficient of the lens material.

Differentiate the formula to calculate the focal length of a thin lens $\frac{1}{f'} = \left(n-1\right)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$ according to the values n, r_1, r_2 to find the relationship between the change in focal length of a thin lens and the quantities α and β:

$$\frac{\mathrm{d}f'}{f'^2} = \mathrm{d}n\left(\frac{1}{r_2} - \frac{1}{r_1}\right) + \left(n-1\right)\left(\frac{\mathrm{d}r_1}{r_1^2} - \frac{\mathrm{d}r_2}{r_2^2}\right) \tag{4}$$

where r_1, r_2 are the radii of the thin lens; substitute $\mathrm{d}n = \beta\Delta t$; $\mathrm{d}r_1 = r_1\alpha\Delta t$; $\mathrm{d}r_2 = r_2\alpha\Delta t$ into Eq. (4) to get:

$$\frac{\mathrm{d}f'}{f'} = \left(\alpha - \frac{\beta}{n-1}\right)\Delta t \tag{5}$$

where $\Delta t = t - t_0$ is the temperature difference.

Relationship between chromatic aberration of infinitely thin lenses and change in focal length:

$$\frac{\mathrm{d}f'}{f'} = -\frac{1}{\nu} \tag{6}$$

where ν is Abbe number. Therefore, balance Eqs (5) and (6) to get:

$$\left(\alpha - \frac{\beta}{n-1}\right)\Delta t = -\frac{1}{\nu} \tag{7}$$

Let $V = \frac{\beta}{n-1} - \alpha$, which is the optothermal coefficient, then $\nu = \frac{1}{\left(\frac{\beta}{n-1} - \alpha\right)\Delta t}$.

Thus, to calculate the change in focal length of an infinitely thin lens system, it is possible to use the calculation formulas for chromatic aberration, in which the Abbe number is replaced by the quantity.

$$\frac{1}{\left(\dfrac{\beta}{n-1}-\alpha\right)\Delta t}$$

2 Calculation of Initial Optical System that Self-Compensate Temperature Change

2.1 Optical System Schematic Diagram

The optical system has a schematic diagram consisting of 3 lenses with optical powers φ_1, φ_2, φ_3 (corresponding focal lengths f'_1, f'_2, f'_3) placed at distances d_1 and d_2 apart (Fig. 1).

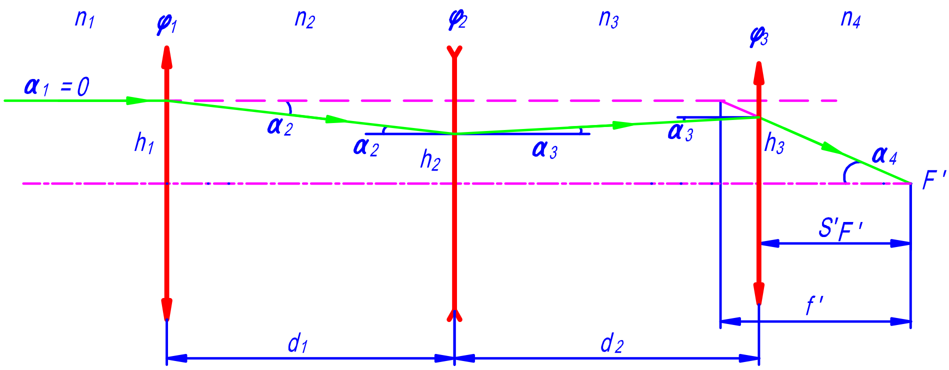

Fig. 1 Optical system schematic diagram

The angle of incidence of the first-order auxiliary ray meeting each thin lens is denoted by α_i, corresponding to the height of incidence h_i, i is the lens number with the values from 1 to 3. Considering the lenses to be infinitely thin, their optical power distribution is the solution of the following system of Eqs (8)-(10).

Total optical power equation:

$$\sum_{i=1}^{3} h_i \varphi_i = 1 \tag{8}$$

Equation for eliminating positional chromatic aberration:

$$\sum_{i=1}^{3} \frac{h_i^2 \varphi_i}{\nu_i} = 0 \tag{9}$$

Temperature compensation equation:

$$S'_{F',t_0} = S'_{F',t} \tag{10}$$

where S'_{F',t_0} is the back focal distance of the optical system at the initial temperature t_0 and $S'_{F',t}$ is the back focal distance of the optical system at the temperature t.

The back focal distance of the optical system at the initial temperature t_0 is calculated by the formula:

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$$S'_{F',t_0} = 1 - \varphi_1\left(d_1 + d_2\right) + \varphi_2 d_2\left(\varphi_1 d_1 - 1\right) \tag{11}$$

Optical power of lenses when temperature changes Δt:

$$\varphi_{1,t} = \varphi_{1,t_0}\left(1 + V_1\Delta t\right),\ \varphi_{2,t} = \varphi_{2,t_0}\left(1 + V_2\Delta t\right),\ \varphi_{3,t} = \varphi_{3,t_0}\left(1 + V_3\Delta t\right)$$

where V_1, V_2, V_3 are the optothermal coefficients of the materials of the lenses.

Assuming that the air gap between the lenses changes extremely small with changes in temperature, the back focal distance of the objective at the temperature t is given by [2]:

$$S'_{F',t_0} = \frac{h_3(t)}{\alpha_4(t)}$$

where $h_3(t) = 1 - \varphi_1\left(1 + V_1\right)\left(d_1 + d_2\right) + d_2\varphi_2\left(1 + V_2\Delta t\right)\left[d_1\varphi_1\left(1 + V_1 - 1\right)\right]$;

$$\left.\begin{aligned} \alpha_4(t) = \varphi_1\left(1+V_1\Delta t\right) + \varphi_2\left(1+V_2\Delta t\right) + \varphi_3\left(1+V_3\Delta t\right) - \\ - d_1\varphi_1\left(1+V_1\Delta t\right)\cdot\left[\varphi_2\left(1+V_2\Delta t\right) + \varphi_3\left(1+V_3\Delta t\right)\right] - \\ - d_2\varphi_3\left(1+V_3\Delta t\right)\left[\varphi_1\left(1+V_1\Delta t\right) + \varphi_2\left(1+V_2\Delta t\right) - \right. \\ \left. - d_1\varphi_1\left(1+V_1\Delta t\right)\varphi_2\left(1+V_2\Delta t\right)\right] \end{aligned}\right\}$$

Substitute h_1, h_2, h_3, $h_3(t)$ and $\alpha_4(t)$ into the system of Eqs (8)-(10) to find the optical power of the components:

$$\left.\begin{aligned} &\varphi_1 + \left(1 - d_1\varphi_1\right)\varphi_2 + \left[1 - \varphi_1\left(d_1 + d_2\right) + d_2\varphi_2\left(d_1\varphi_1 - 1\right)\right]\varphi_3 = 1 \\ &\frac{\varphi_1}{v_1} + \frac{\left(1 - d_1\varphi_1\right)^2\varphi_2}{v_2} + \frac{\left[1 - \varphi_1\left(d_1 + d_2\right) + d_2\varphi_2\left(d_1\varphi_1 - 1\right)\right]\varphi_3}{v_3} = 0 \end{aligned}\right\}$$

$$\left.\begin{aligned} &1 - \varphi_1\left(d_1 + d_2\right) + \varphi_2 d_2\left(\varphi_1 d_1 - 1\right) - \\ &- \frac{1 - \varphi_1\left(d_1 + d_2\right)k_1 + d_2\varphi_2 k_2\left(d_1\varphi_1 k_1 - 1\right)}{\varphi_1 k_1 + \varphi_2 k_2 + \varphi_3 k_3 - d_1\varphi_1 k_1\left(k_2\varphi_2 + k_3\varphi_3\right) - d_2\varphi_3 k_3\left(\varphi_1 k_1 + \varphi_2 k_2 - d_1\varphi_1 k_1\varphi_2 k_2\right)} = 0 \end{aligned}\right\}$$

where $k_1 = 1 + V_1\Delta t$, $k_2 = 1 + V_2\Delta t$, $k_3 = 1 + V_3\Delta t$.

Because the number of the unknowns in the above equation system is more than three, it is necessary to select the material in advance.

The selection of material combination should be based on the properties of the materials as shown in Tab. 1 [3, 4] and also based on the graph in Fig. 2 so that the three selected materials form a triangle with the largest area possible.

The graph in Fig. 2 has the horizontal axis representing the Abbe number and the vertical axis representing the product of the optothermal coefficient and the Abbe number. Germanium material is quite far on the graph compared to the remaining materials, so Ge can always be chosen reasonably in the material combination.

From the graph in Fig. 2, the combination of materials IKS25-ZnSe-Ge is selected.

2.2 Selection of the Detector and Main Parameters of the Objective Lens

Select an uncooled microbolometer detector with the following features: working spectrum 8-12 μm ; detector size: 640 × 540 pixels; and pixel size 25 μm.

Tab. 1 Commonly used materials for longwave thermal imaging

Material	n at $\lambda = 10$ µm	v	$\beta = \frac{\mathrm{d}n}{\mathrm{d}t}$ $\left[10^{-6}\ \mathrm{K}^{-1}\right]$	α CTE $\left[10^{-6}\ \mathrm{K}^{-1}\right]$	$V = \frac{\beta}{n-1} - \alpha$ $\left[10^{-6}\ \mathrm{K}^{-1}\right]$
AgCl	1.98	53.84	−61.00	32.40	−94.62
Amtir1	2.50	109.35	72.00	12.00	36.06
Amtir2	2.77	162.30	30.70	22.40	−5.05
Amtir3	2.60	110.00	91.00	14.00	42.78
CdTe	2.65	164.90	50.00	4.50	25.82
CsBr	1.66	132.24	−79.00	47.90	−167.14
GaAs	3.28	105.00	185.00	5.00	76.19
Gasir-1	2.49	119.55	55.00	17.00	19.80
Ge	4.00	750.75	396.00	5.70	126.17
KBr	1.52	64.72	−40.83	43.00	−120.89
KCL	1.46	27.02	−33.20	36.00	−108.71
KRS5	2.37	165.14	−23.50	58.00	−75.14
NaCl	1.49	18.59	−25.00	44.00	−94.54
SchottIG2	2.50	110.87	60.00	12.10	27.99
SchottIG6	2.78	158.76	41.00	20.70	2.36
ZnS	2.20	24.00	39.00	6.60	25.90
ZnSe	2.41	52.46	61.00	7.10	36.29
IKS25	2.77	152.37	46.00	22.00	4.03
IKS 28	2.69	111.02	40.00	22.00	1.70
IKS 29	2.60	122.18	44.00	22.00	5.49

For example, choose a thermal imaging objective that can identify human targets at a distance of 200 m, so reasonably choose an objective focal length of 100 mm and a f-number of 1.2.

The parameters of the selected objective and detector are summarized in the following table (Tab. 2).

After selecting the material composition, continue to select the distance d_1 and d_2. Solving the above system calculates φ_i. Entering the data just found into the Zemax program will calculate the bright diameter of each lens.

To simply find the radius of curvature of the starting lens system, let the lenses have a plane surface. The radius of curvature of the lens is found using the thin lens formula [5]:

$$\varphi_i = (n-1)\left(C_{1i} - C_{2i}\right) \tag{12}$$

where C_{1i}, C_{2i} are reciprocal of radii of i-th lens.

Tab. 2 Optical input parameters of the objective lens

Detector size [pixels]	640 × 480
Pixel size [μm]	25
Working spectrum range [μm]	8-12
f' [mm]	100
2ω [°]	8
f/#	1.2
Optical system length [mm]	< 180

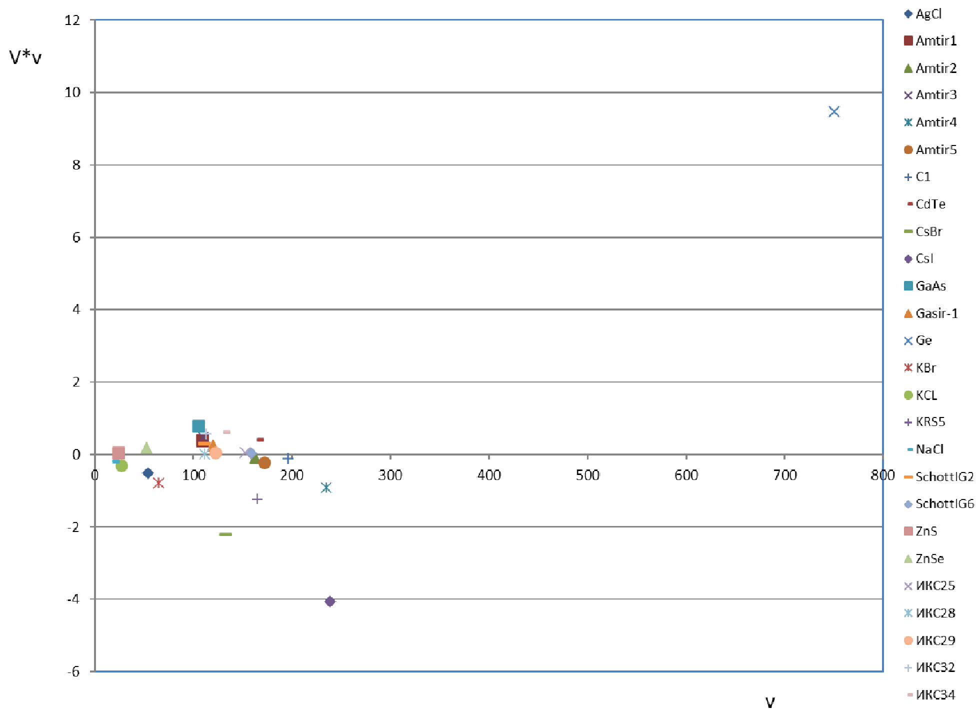

Fig. 2 LWIR band material distribution graph

3 Results of LWIR Objective Design and Analysis

The starting optical system is always of poor quality because the calculations are only first-order approximations. Use Zemax's multi-configuration optimization capability to optimize the optical system at selected temperature ranges from 10 °C to 50 °C, in which the standard configuration is at 20 °C. Note that IKS25 material is not available in ZEMAX, so IKS must be entered in Model form (entering the refractive index and dispersion coefficient at the main wavelength). In addition, the values of refractive index, dispersion coefficient, curvature, and first lens thickness (IKS material) must be calculated manually. The triplet objective lens optical system after optimization is shown in Fig. 3 [6].

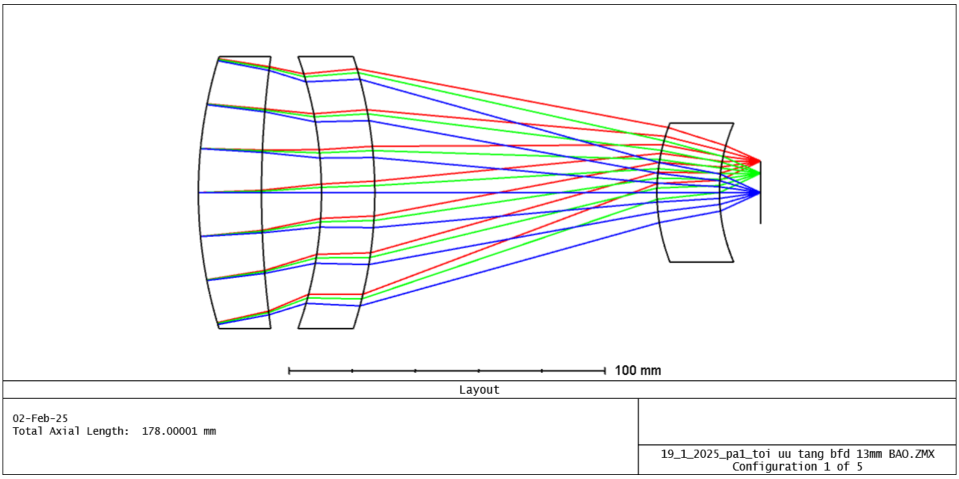

Fig. 3 Triplet objective optical system

The optimized triplet lens radius, axial thickness and half-diameter parameters are given in Tab. 3 [6].

The system consists of only three spherical lenses with large curvature radii, making it easy to process and assemble.

Tab. 3 Optimized objective parameters from Fig. 3

No	Radius	Thickness	Glass/Air	Semi-Diameter	Shape
1	144.195	19.999	IKS25	43	U
2	315.629	19.980	Air	43	U
3	−128.237	16.885	ZnSe	43	U
4	−139.060	89.327	Air	43	U
5	60.637	19.773	Germanium	22	U
6	55.334	13.047	Air	22	U
IMA	-	-	Air	9.973	

The Modulation Transfer Function (MTF) value is quite excellent throughout the entire working temperature range (10 °C to 50 °C), all approximately greater than 0.5 at the cutoff frequency of 20 mm^{-1} (see Fig. 4a-4c).

After obtaining the MTF value of the objective, the MTF graph of the system consisting of the detector and the objective is plotted as shown in Fig. 5. The blue curve represents the MTF of the objective at the standard temperature configuration (20 °C) for the image points on the axis, the gray curve represents the MTF of the used detector (25 μm). The red curve is the MTF of the detector + objective system.

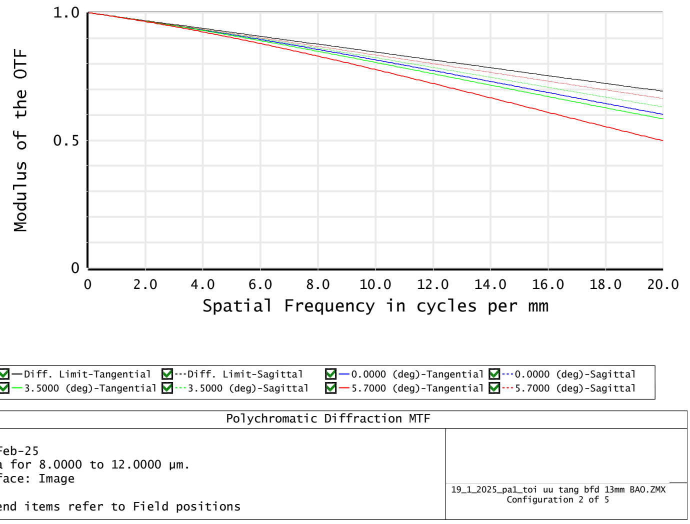

Fig. 4a MTF value of the objective at a temperature of 10 °C

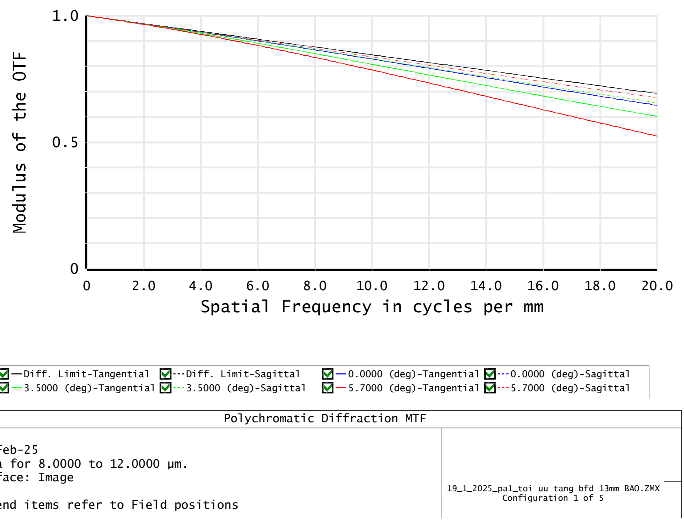

Fig. 4b MTF value of the objective at a temperature of 20 °C

According to Johnson standard, to identify human target, 8 pixels are needed across 0.5 m of the target [7]. Therefore, one cycle will occupy 0.125 m.

From the MTF graph of the system (see Fig. 5), the MTF function value is 0.1 at frequency $f_{0.1}$ = 25 LP/mm, corresponding to the cycle $T_{0.1}$ =1/25 (mm). The human target identification distance of the system is:

$$S = \frac{p \times f'}{T_{0.1}} = \frac{0.125 \times 100}{(1/25)} = 312.5 \text{ [m]} \tag{13}$$

where S is the human target identification distance of the system; p is the width of a cycle across the target for identification; f' is the back focal length of the objective; $T_{0.1}$ is the period when the MTF function of the system reaches the value 0.1. Thus, the target identification distance of the designed system satisfies the initial requirements.

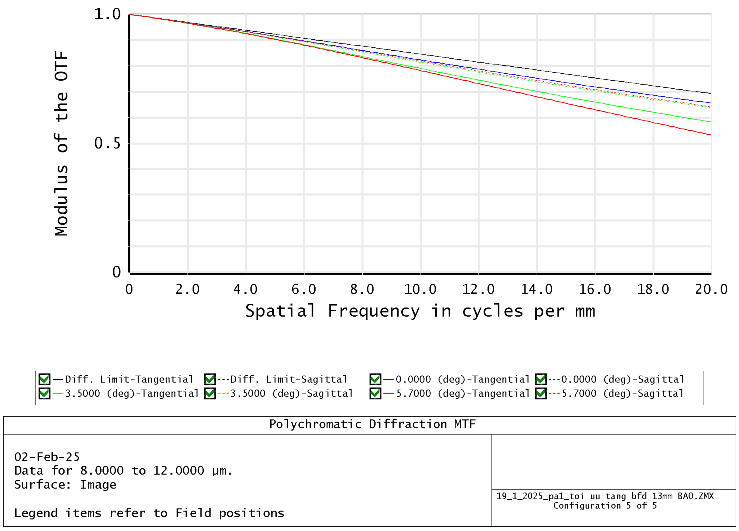

Fig. 4c MTF value of the objective at a temperature of 50 °C

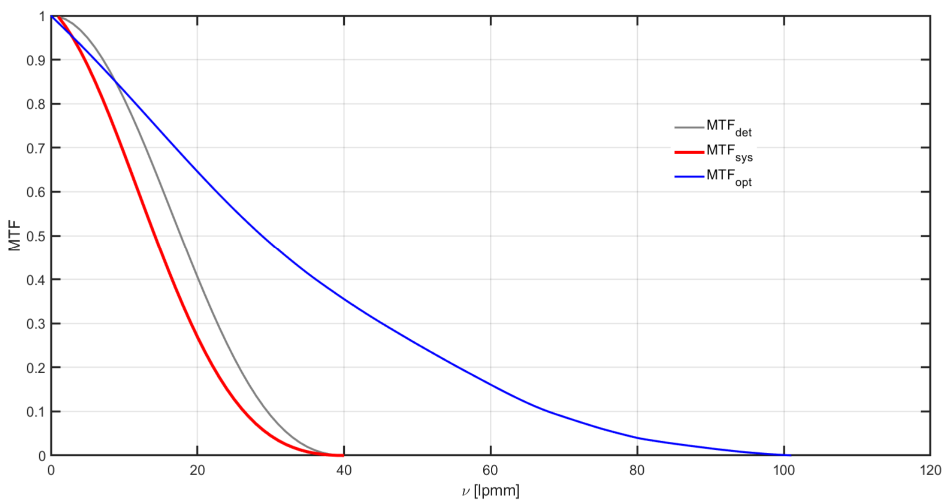

Fig. 5 MTF graphs of the detector, objective and of the system consisting of detector + objective

At all temperature configurations, the RMS spot radius is smaller than the Airy disk radius, indicating that the objective can produce a sharp target image on the corresponding detector. The worst RMS spot radius (= 11.286 μm) is at configuration 2 (at 10 °C) but it is still within the allowable tolerance (Fig. 6).

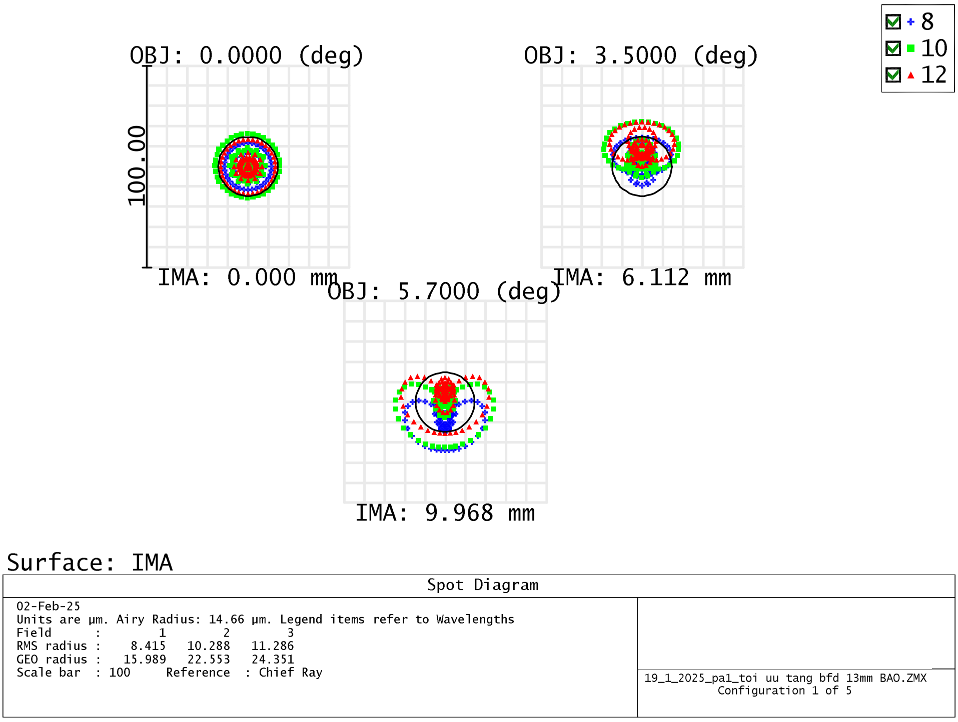

Fig. 6 The worst RMS spot radius of the objective at a temperature of 10 °C

From the Lens Editor parameter, the back focal distance of each configuration is extracted (Tab. 4).

Tab. 4 Value of back focal distance of objective lens according to temperature

Configuration	1	2	3	4	5
Temperature [°]	20	10	30	40	50
$S'_{F'}$ [mm]	13.047	13.047	13.046	13.046	13.046

It is clear that when the temperature changes from 10 °C to 50 °C, the focal length of the objective lens almost does not change. The amount of the deviation is:

$$\frac{13.047-13.046}{13.047}\times 100\ \% \approx 0.008\ \%$$

This value shows that the objective optical system is designed for complete passive heat rejection and it is also much smaller in depth of focus (DOF) [8].

4 Conclusions

The paper has presented quite a complete method of calculating the design of the starting system of the objective lens with the ability of passive optical heat reduction. The optimized design results show that the passive thermal compensation objective lens is extremely good. The image quality of the optimized objective lens meets the requirements. It can be used in thermal imaging devices working with uncooled microbolometer detectors, the operating temperature range is optimized from 10 °C to 50 °C without any additional means to adjust the thermal defocus. Therefore, this passive thermal compensation triplet objective lens can have many applications in the future.

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