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Design and research of a dual-band IR lens

Dimcho Pulov
Department of Mechanical and Precision Engineering
Technical University ogf Gabrovo
Gabrovo, Bulgaria
pulov@mail.bg

Abstract. **Infrared imaging systems are widely used in military and civilian applications. Acquiring IR images simultaneously in two spectral ranges provides additional and more detailed information about objects. Dual band IR systems are equipped with a lens that operates simultaneously in two ranges of the IR spectrum MWIR and LWIR. In the design of such a lens, a problem arises with the strong dependence of the refractive index on the wavelength, which requires the correction of chromatic aberration simultaneously in two spectral ranges.**

In this article, the possibilities for the synthesis of dual-band lenses in the MWIR and LWIR spectrum using different optical materials are analyzed. The possible combinations of such materials are determined. Dual band lenses are designed using different material combinations. Their optical characteristics are investigated and the possibility of creating relatively simple high-quality dual-band IR lenses is shown.

Keywords: MWIR and LWIR spectrum , dual-band IR lens, IR optical materials, optical design , achromatization.

I. Introduction

Infrared cameras were originally developed for military purposesSubsequently, with the reduction of their price, they have received a very large application in civilian fields such as: automotive industry, machine vision, technical diagnostics, metallurgy, chemistry, electronics and electrical engineering, ecology, medicine, protection from accidents and disasters, etc. Причина за това са свойствата и уникалните възможности, които те притежават. Thermal cameras visualize invisible IR radiation by converting invisible bright contrasts in the IR region to bright contrasts in the visible region [1].

Modern thermal cameras can work in two strictly defined sections of the infrared spectrum - MWIR (3÷5) μm and LWIR (8÷12) μm. The reasons for this are:

- the maximum radiation of most objects around us is located in these areas.
- these sections coincide with the so-called atmospheric windows beyond which the atmosphere is opaque to radiation of mid- and far-IR regions.

Images obtained in the MWIR and LWIR ranges of the spectrum carry different information about the observed object. When examining the thermal imaging characteristics, it was found that:

- for objects with a temperature of around (300÷310) K, both atmospheric windows can be used with equal success;
- for objects with a higher temperature, the range (3÷5) μm is preferable, and for objects with a lower temperature – (8÷12) μm;
- for relatively distant objects and a humid atmosphere, the range (3÷5) μm is preferable;
- for relatively distant objects and an atmosphere with reduced transparency (smoke, fog, dust, low drizzle) the range (8÷12) μm is preferable.

For this reason, there has been active work in recent years on the development of thermal cameras operating simultaneously in both MWIR and LWIR spectrum sections [2], including allowing the software reconciliation (overlay) of the obtained images [3],[4]. There are different schemes for realizing such a thermal camera - with an objective and an optical filter [5] , with an objective and a beamsplitter [6],[7], with an objective and a spectral splitter [5], with an objective and a sandwich photoreceiver [8]. Common to all these schemes is the lens, which must be dual band.

For an infrared objective in a wide range, there is a strong dependence of the refractive index of the optical materials used on the wavelength. A major problem in the design of a dual band IR lens is the need for the simultaneous correction of chromatic aberration in two relatively wide and distant from each other spectral ranges [9],[10]. The most common way to solve this problem is to use combinations of different optical materials and subsequent analysis and optimize the system using optical software.

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There are known such solutions. Combinations of optical materials for correcting axial color in the 3-12 μm range are shown in [11]. But these combinations are calculated for thin lenses and the degree of their correction is not shown. A dual band objective consisting of 5 lenses is described in the same publication.

In [12], a methodology for selecting optical materials for an achromatized objective composed of 6 lenses (Ge, Atmir, KCl, ZnSe) is shown.

In [13], an achromatized IR objective composed of 2 lenses with good correction is shown. In it, one lens is made of chalcogenide glass and the other – of ZnSe or ZnS. Here the chromatic correction is good, but according to [9] the use of chalcogenide glasses is preferably to be in the LWIR range of the spectrum.

In [14] the results of designing two-lens objectives with good correction of chromaticism and spherical aberration made of KRS5 (first lens) and GaAs or IKS32 (second lens) are reported. In [15] the design of the 3-lens IR objective (IKS25:ZnSe:IKS25) that operate with cooled detector in LWIR spectrum is shown. However, these optical materials are poisonous and harmful when processed. So for example, IKSxx chalcogenide glass contains sulfur, selenium and tellurium, and KRS5 - bromined and iodined thallium. Therefore, their toxicity limits their use in optical systems.

It can be noted that the most available, used and assimilated by the production materials for the MWIR and LWIR sections of the spectrum are Ge, ZnSe and ZnS. All this provides arguments for the development of this work, the goal of which is to design a relatively simple infrared dual band objective using technologically mastered and distributed optical materials.

II. Materials and Methods

A. Optical materials and a photoreceivers for the IR range of the spectrum

Optical system layout and the determination of characteristics of objective depend on the type of used photoreceiver [5],[16],[17]. The most common are cooled photoreceiver modules and uncooled microbolometric matrices. A very important advantage of cooled photoreceivers is their higher temperature sensitivity (lower value of NETD). However, due to the absence of cooling, microbolometric matrices have significant advantages such as:

- Significantly smaller mass and dimensions
- Much less electricity consumption
- Greater convenience for placement the optical system.

Because of these advantages the objective in the this article, will be designed to work with microbolometric matrices. Typical values of the main geometrical features of the VOx Microbolometer are: format (640x480) pixels and pixel size (17x17) μm. Therefore, it can be assumed that the image size (diagonal of the working sensitive surface) is ≈ 14 mm.

In [18], it is stated that in order to reduce NETD when using uncooled photorecpiervers in the IR range of the spectrum, the optical system should be fast lens with a small F/#. The minimum theoretical value of F/# according to the condition of Abbe sines condition is 0.5. In real objectives it is between 0.8 and 2. It can be accepted that the designed lens will be with F/2.

The opportunity to correct chromatic aberration is based on finding appropriate ratios between the refractive indixes and the average dispersion (Abbe number, V-number) of the optical materials used. The analysis shows that there are a relatively limited number of optical materials that are transparent in the infrared spectrum. They can be referred to two large groups [10]:

- infrared crystals – Ge, Si, GaAs, ZnSe, ZnS and some others;
- chalcogenide glasses - e.g. IRG22, IRG23,…,IRG26 from Schott's catalog.

TABLE 1 SPECIFICATIONS OF OPTICAL MATERIALS FOR THE MWIR AND LWIR RANGES

IR Material	n, average value	Abbe number		k
		ν_M	ν_L	
Ge	4,02	102.07	869.13	0,18
Si	3.42	242	1818	0.13
ZnSe	2,42	169,66	57,18	2,97
ZnS	2,24	109,67	25,46	4,31
KRS-5	2,37	232.80	164.90	1.41
Amtir1	2.61	195.54	114.48	1,71
GaAs	3,29	148,31	108,09	1.37
IRG26	2,77	169,42	160.2	1,06

The optical specifications of common infrared materials are shown in Table 1. In it, *n* is the refractive index and ν_M and ν_L are the Abbe numbers for ranges MWIR and LWIR respectively. The optical constants were calculated by dispersion formulas in the optical software OSLO (catalog Infrared). It can be seen from the Table 1 that most materials have a refractive index in the range of 2.2-2.8, and Ge, Si, GaAs own a higher one. The Abbe number has a high value in the LWIR range (ν>100). There is a large difference in Abbe number in the LWIR range (25<ν<700). ZnSe, ZnS have low Abbe number. Chalcogenide glasses own a relatively high Abbe number, the highest for Ge.

B. Methodology for Design of Dual Band Objective

The chromatic aberration of a objective composed of n number of thin lenses will be corrected if the optical forces of the individual lenses fulfill the condition

$$\begin{cases} \phi_{1,M} + \phi_{2,M} + \cdots + \phi_{n,M} = \phi_M \\ \frac{\phi_{1,M}}{\nu_{1,M}} + \frac{\phi_{2,M}}{\nu_{2,M}} + \cdots + \frac{\phi_{n,M}}{\nu_{n,M}} = 0 \\ \frac{\phi_{1,L}}{\nu_{1,L}} + \frac{\phi_{2,L}}{\nu_{2,L}} + \cdots + \frac{\phi_{n,L}}{\nu_{n,L}} = 0 \\ \phi_{1,L} + \phi_{2,L} + \cdots + \phi_{n,L} = \phi_L \end{cases} \quad (1)$$

where:

- ϕ_M and ϕ_L are the optical powers of the lens in MWIR and LWIR respectively;

- $\phi_{i,M}$ and $\nu_{i,M}$ are the optical powers and Abbe number of lens number *i* in the MWIR, $i = 1 \div n$;

- $\phi_{i,L}$ и $\nu_{i,L}$ are the optical powers and Abbe number of lens number *i* in the LWIR range of the spectrum.

C. Two lenses. Two materials.

For convenience, the objective can be scaled so that $\phi = \phi_M = \phi_L = 1$. Then, for a two-lens objective expression (1) converts

$$\begin{cases} \phi_{1,M} + \phi_{2,M} = 1 \\ \frac{\phi_{1,M}}{\nu_{1,M}} + \frac{\phi_{2,M}}{\nu_{2,M}} = 0 \\ \frac{\phi_{1,L}}{\nu_{1,L}} + \frac{\phi_{2,L}}{\nu_{2,L}} = 0 \\ \phi_{1,L} + \phi_{2,L} = 1 \end{cases} \quad (2)$$

Separate solutions of this system in the MWIR and LWIR ranges give the corresponding values of the optical powers of the two lenses:

$$\begin{cases} \phi_{1,M} = \frac{\nu_{1,M}}{\nu_{1,M}-\nu_{2,M}} \quad \phi_{2,M} = \frac{\nu_{2,M}}{\nu_{2,M}-\nu_{1,M}} \\ \phi_{1,L} = \frac{\nu_{1,L}}{\nu_{1,L}-\nu_{2,L}} \quad \phi_{2,L} = \frac{\nu_{2,L}}{\nu_{2,L}-\nu_{1,L}} \end{cases} \quad (3)$$

As can be seen,, the optical forces in expression (3) depend in a specific way on the Abbe numbers of the two materials, which in turn have certain discrete values shown in the Table 1. Therefore, not for every combination of optical materials there exists a solution of (3) corresponding to system (2). From (2) and (3), it follows that a correct solution can be found only for those combinations that simultaneously satisfy the conditions:

$$\begin{cases} \frac{\nu_{1,M}}{\nu_{1,L}} \cong \frac{\nu_{2,M}}{\nu_{2,L}} \cong k \\ \text{significant diference of } \nu_M \text{ and } \nu_L \end{cases} \quad (4)$$

Let $k = 1$. This means that the Abbe numbers in both spectral ranges are the same for both materials. It can be seen from Table 1 that for the considered materials there is no such combination that meets conditions (4).

The values of coefficient *k* calculated by expression (4) are shown in Table 1. From Table 1, the combinations consisting of the technologically adopted and widespread optical materials Ge, ZnSe, ZnS are selected. Three combinations of two lenses each are made from the three selected materials. For them, the optical powers of individual lenses in the MWIR and LWIR ranges were calculated using expressions (3) and (1). The obtained results are shown in table 2. It can be seen from it that the combinations Ge:ZnSe and Ge:ZnS are not suitable, because the coefficients k of the lenses composing them are very different. This results in very different optical powers of the lenses in the two ranges.

TABLE 2 OPTICAL POWERS OF LENSES FOR DIFFERENT MATERIAL COMBINATIONS

Combinations		**k**		**Optical power**			
				MWIR		**LWIR**	
L1	L2	L1	L2	$\phi_{1,M}$	$\phi_{2,M}$	$\phi_{1,L}$	$\phi_{2,L}$
Ge	ZnSe	0,18	2,97	-1,51	2,51	1,07	-0,07
Ge	ZnS	0,18	4,31	-13,43	14,43	1,03	-0,03
ZnSe	ZnS	2,97	4,31	2.82	-1,82	1,67	-0,67

The ZnSe:ZnS combination can be realized in two variants: with optical powers ($\phi_{1,M}$; $\phi_{2,M}$) and ($\phi_{1,L}$; $\phi_{2,L}$). The axial color for these variants is shown in Table 3.

TABLE 3 AXIAL COLOR FOR TWO VARIANTS OF OBJECTIVES

Variants	**PAC_M**	**PAC_L**	**PAC_M/PAC_L**
$\phi_{1,M}$; $\phi_{2,M}$	$-4{,}55.10^{-5}$	$3.63.10^{-4}$	0,16
$\phi_{1,L}$; $\phi_{2,L}$	$-1.91.10^{-4}$	$1.81.10^{-4}$	-1,05

From Table 3, it can be seen that due to the approximate fulfillment of condition (4), the chromatic aberration is not zero. However, it is very small, and the PAC_M/PAC_L ratio of the second variant is close to 1. Furthermore, the optical powers of the second variant are smaller, resulting in smaller lens curvatures and smaller monochromatic aberrations. Therefore, it can be assumed that this variant is suitable for design of objective for MWIR and LWIR ranges.

A dual band objective has four refracting surfaces with radii r_j ($j = 1 \div 4$). These radii are determined by the expression

$$r_j = \frac{n_{j+1}-n_j}{u_{j+1}n_{j+1}-u_j n_j} \quad (5)$$

where:

- n_j and n_{j+1} are refractive index before and after the surface j;
- u_j and u_{j+1} are the paraxial angles before and after the surface j.

Paraxial angles are defined as follows:

- u_1 and u_5 from the conditions: $u_1 = 0$ and $u_5 = 1$;
- $u_3 = \phi_1$ from an expression (2);
- u_2 and u_4 from an expression (6);

According to expressions (5) and (6), an objective with thin lenses in the paraxial region was calculated, which will be the starting point for the design of a two-lens dual band objective.

$$\begin{cases} Du_2^2 + Eu_2 + F = 0 \\ D = u_3 b^2(2a+3) + \\ \quad +a^2(2b+3)(1-u_3) \\ E = 2ABa^2(2b+3)(1-u_3) - \\ \quad -u_3^2 b^2(a+3) + \\ \quad +Aa^2(b+3)(u_3^2-1) \\ F = B^2a^2(2b+3)(1-u_3) + \\ \quad +Ba^2(b+3)(u_3^2-1) + \\ \quad +u_3^3(b^2-a^2) + a^2 \\ A = \frac{u_3 b(a+2)}{a(b+2)(u_3-1)} \\ B = \frac{u_3^2(b-a)+a}{a(b+2)(1-u_3)} \\ a = \frac{1}{n_2} - 1 \\ b = \frac{1}{n_4} - 1 \\ u_4 = Au_2 + B \end{cases} \tag{6}$$

D. Three lenses. Three materials

A two-lens objective may not give good aberration correction at large focal numbers due to higher-order aberrations. That is why it is useful to analyze the dual band objective consisting of three lenses according to the above methodology.

Correctly the solution of system (1) for n=3 can be found by setting a relationship between the optical powers of two of the lenses, e.g. $\phi_1 = m\phi_2$. Then, with known optical materials and laying $\phi = 1$, the values of the optical forces are found from the expressions:

$$\begin{cases} G = \frac{\nu_1 \nu_2}{\nu_3(m\nu_2+\nu_1)} \\ \phi_3 = \frac{1}{1-G(m+1)} \\ \phi_2 = -G\phi_3 \\ \phi_1 = m\phi_2 \end{cases} \tag{7}$$

The curvature of the field of the objective is determined by the expression

$$\mathrm{PTZ3} = \frac{\phi_1}{n_1} + \frac{\phi_2}{n_2} + \frac{\phi_3}{n_3}$$

The optical powers and field curvature for the Ge:ZnS:ZnSe combination for different values of *m* are shown in Table 4

TABLE 4 OPTICAL POWERS OF LENSES FOR DIFFERENT MATERIAL COMBINATIONS

m	Optical power			PTZ3
	ϕ_1	ϕ_2	ϕ_3	
0,1	-0,0868	-0,8678	1,9545	0,0629
0,2	-0,1889	-0,9443	2,1331	0,0308
0,3	-0.3107	-1,0356	2,3463	$-7{,}05.10^{-3}$
0,4	-0,4586	-1,1465	2,6051	-0,0533
0,5	-0,6421	-1,2843	2,9261	-0,11
0,6	-0,8755	-1,4592	3,3345	-0,1837
0,7	-1,1823	-1,689	3,872	-0,2794
0,8	-1,6049	-2,006	4,6108	-0,4117
0,9	-2,2216	-2,4685	5,6903	-0,6045
1	-3,2086	-3,2086	7,4171	-0,9132

The dependence $\mathrm{PTZ3} = f(m)$ is drawn in Fig. 1.

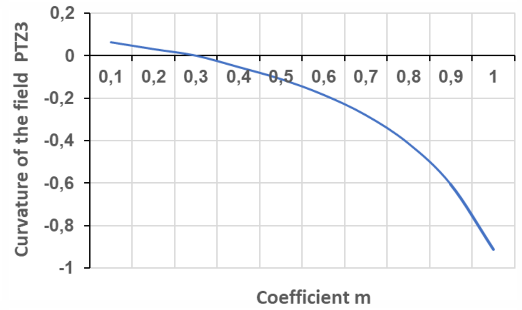

Fig. 1. Dependence on curvature of the field on the coefficient *m*

Fig. 1 shows that $\mathrm{PTZ3} = 0$ at $m \cong 0{,}25$. In this case, the optical powers of the individual lenses are determined from (7)

$$\phi_1 = 2{,}2346 \quad \phi_2 = -0{,}9877 \quad \phi_3 = -0{,}2469$$

This combination of optical powers of the individual lenses can be taken as a starting point for designing a triple lens dual band objective.

III. RESULTS AND DISCUSSION

Based on the analysis carried out in item II, the major optical characteristics of the designed dual band objective have been determined:

- focal length 100 mm,
- focal number F/2 (for triplet) and F/4 (for doudlet),
- angular field 8 degrees.

The thickness of the lenses and the distances between them were specified. Variable parameters were selected and the starting schemes were optimized with the specialized optical software OSLO. The root mean square value of the wavefront error was used as optimization criterion [10],[14],[19]. The design parameters of optimized two-lens and three-lens IR objectives are shown in Table 5 and Table 6. The corresponding optical system layout is shown in Fig. 2 and Fig. 3.

TABLE 5 THE DESIGN PARAMETERS OF THE IR DOUBLET

Surface №	Radius (mm)	Thickness (mm)	Aperture Radius (mm)	Glass type
1	94,16	3,5	12,50	ZnSe
2	-247,94	3	12,22	
3	-146,80	2,5	11,40	ZnS
4	360,93	89,68	11,22	

TABLE 6 THE DESIGN PARAMETERS OF THE IR TRIPLET

Surface №	Radius (mm)	Thickness (mm)	Aperture Radius (mm)	Glass type
1	107,28	6,5	25	Ge
2	153,55	49,5	23,98	
3	-295,53	5	15,94	ZnS
4	-683,19	20,2	15,72	
5	17,98	4,5	9,49	ZnSe
6	17,61	3,83	7,90	

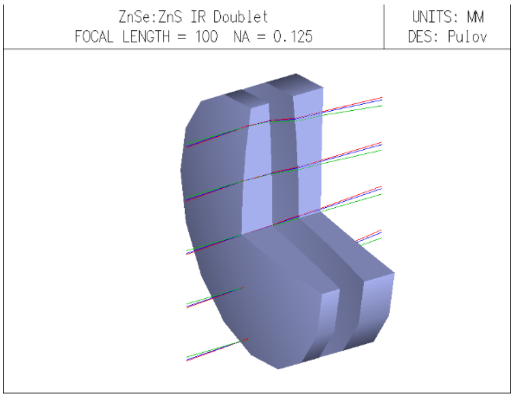

Fig. 2. Optical system layout of the IR doublet

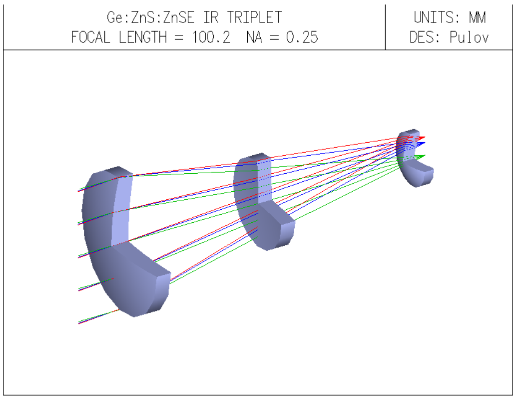

Fig. 3. Optical system layout of the IR triplet

An evaluation and analysis of the image quality of the IR objectives was made using wave and geometric criteria [20],[21],[22]. The most commonly used are the following:

- Rayleigh criterion $W_{P-V} \leq \frac{\lambda}{4}$
- Marechal criterion $W_{RMS} \leq \frac{\lambda}{14}$
- Airy disc criterion $R_{RMS} << R_{Airy}$

In the Table 7 and Table 8 the maximum peak-valley value and RMS value of the wavefront in the MWIR and LWIR ranges for doublet and triplet are shown. The RMS of the geometric spot size, the size of the Airy disc, Strehl ratio and ensquared energy distribution in area (17x17) µm are shown in the same Tables.

TABLE 7 EVALUATION OF THE IMAGE QUALITY OF THE IR DOUBLET

ZnSe:ZnS	MWIR (3÷5) µm	LWIR (8÷12) µm
RMS Wavefront	0,044.λ	0,025.λ
P-V Wavefront	0.166.λ	0,087.λ
RMS Spot size, mm	0,016	0,015
Difraction limit, mm	0,0196	0,0491
Strehl ratio	0,926	0,976
Ensquared Energy (17x17) µm, %	45	42

TABLE 8 EVALUATION OF THE IMAGE QUALITY OF THE IR TRIPLET

Ge:ZnS:ZnSe	MWIR (3÷5) µm	LWIR (8÷12) µm
RMS Wavefront	0,016.λ	0,0128.λ
P-V Wavefront	0,048.λ	0,039.λ
RMS Spot size, mm	0,068	0,014
Difraction limit, mm	0,0098	0,0244
Strehl ratio	0,989	0,993
Ensquared Energy (17x17) µm, %	35	70

From table 7 and table 8 it can be seen that for the doublet and triplet the Rayleigh and Marechal wave criteria are fulfilled simultaneously in the MWIR and LWIR ranges. The geometric Airy disc criterion for the doublet is fulfilled in both ranges and for the triplet – only in the LWIR. Strehl's number is high enough for both ranges. The energy concentration is similar for both lenses, with it is highest for the triplet in the LWIR.

The doublet and triplet are of similar quality in both spectral ranges, however, the doublet has a focal number of F/4 and the triplet has a focal number of F/2. Due to the small number of lenses (correction parameters), the doublet cannot give a good aberrations correction for F/2. The image quality of the triplet in the LWIR range is better because of the longer wavelength there.

The wavefront of the IR triplet for three angular fields are shown in Fig. 4 and Fig. 5. From these it can be seen that the wave criteria are fulfilled within the full angular field simultaneously in the MWIR and LWIR ranges.

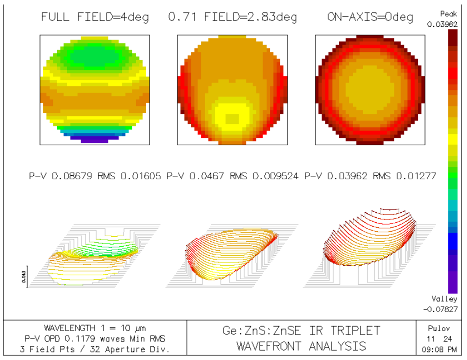

Fig. 4. Wavefront of the IR triplet in the LWIR ranges

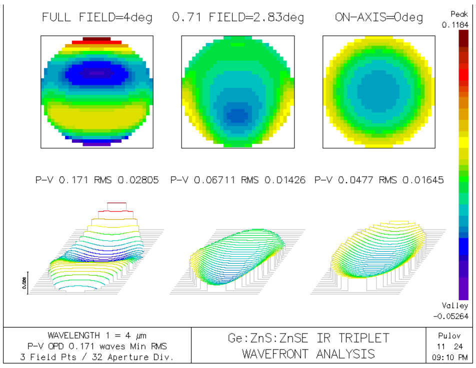

Fig. 5. Wavefront of the IR triplet in the MWIR ranges

IV. Conclusions

The possibility of designing doublet and triplet lenses operating simultaneously in the MWIR and LWIR ranges has been investigated. The parameters of very common IR photodetectors have been analyzed and the major optical characteristics of IR lenses have been determined. The optical parameters of the materials that are transparent in these ranges have been analyzed.

A methodology for dual band doublet and triplet design was developed. Combinations of optical materials composed of the technologically mastered and widespread optical materials (Ge, ZnSe, ZnS) were selected and studied. Lens variants using different combinations of these materials have been calculated.

Dual band doublet and triplet are designed, which according to a combination of wave and geometric criteria give good image quality when working with FPA microbolometric matrices with pixel size (17x17) µm and diagonal ≈ 14 mm.

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