Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 16th International Scientific and Practical Conference. 2025. Volume IV, 329-335

Passive Athermalization of Lenses for LWIR Spectral Range

Dimcho Pulov
Department of Mechanical and Precision Engineering
Technical University of Gabrovo
National Center of Excellence Mechatronics and Clean Tecnologies
Gabrovo, Bulgaria
pulov@tugab.bg

Petar Tsvyatkov
Department of Mechanical and Precision Engineering
Technical University of Gabrovo
Gabrovo, Bulgaria
p.cviatkov@tugab.bg

***Abstract*— This paper investigates the possibility of passive athermalization of objectives for the long-wave infrared (LWIR) region of the spectrum. The main scientific problem is the difficulty in designing an athermalized objectives without the use of aspherical and diffractive surfaces and with the availability of a limited number of optical materials. A design methodology is applied, the focus of which is the use of materials with a negative thermal coefficient of refractive index and with specific values of the refractive index and Abbe number. The results obtained show that the designed objectives are thermally stable in a wide temperature range and have the ability to work with medium-format FPA microbolometric arrays.**

Keywords—LWIR spectrum, optical design, passive athermalization, IR optical materials

I. INTRODUCTION

In can order to fulfill their intended purpose, modern IR thermal cameras must meet high requirements in terms of their resolution, sensitivity and reliability when operating in various environmental conditions. The propagation medium of the radiation can strongly affect the optical radiation by generally weakening the optical radiation and reducing the contrast in the image. Most often, this environment is the Earth's atmosphere, and its optical characteristics depend on such factors as pressure, humidity, and temperature. Modern thermal imaging cameras must be able to operate with ambient temperature variations from -40 to +60 degrees. Moreover, the quality of performance of such IR systems must be stable across the entire temperature range [1], [2].

When the temperature changes, the design parameters of the optical system change. As a result, the path of the rays and the focal length of the lens change, which leads to an increase in the geometrical spot and a shift of the focusing plane from the plane of the photoreceiver matrix. It is obtained temperature defocusing of the image, deterioration of image quality, and instability in the operation of the entire IR system [3], [4].

Temperature defocusing is particularly important for lenses operating in the LWIR spectrum because optical materials for the LWIR spectrum have a higher refractive index n and a higher gradient of the refractive index with respect to temperature change ${dn}/{dt}$ compared to materials for the visible region of the spectrum [5] - [8]. For this reason, it is necessary for such lenses to be athermalized, i.e. to compensate for the influence of temperature on the stability of its operation. For this reason, it is necessary for such lenses to be athermalized, i.e. to be compensated for the influence of temperature on the stability of its operation.

Several methods exist for athermalizing lenses:

- Passive optical method. It consists of a suitable selection of optical materials for the lenses (matched to the housing material) and subsequent optimization of the optical scheme [9] - [11]. A separate variation of this method is the use of diffractive optical elements and diffractive and aspherical surfaces [12] - [15]. With this method, the lenses construction is simple, lightweight, and reliable because it has no additional moving elements. However, it implies the use of diverse and expensive optical materials and technologies.
- Passive mechanical method. It consists of adding to the objective structure several movable mechanical elements (spacer rings), which are made of different materials and have a linear expansion coefficient respectively greater and smaller than that of the lenses [2], [5]. Moving these elements

Online ISSN 2256-070X
https://doi.org/10.17770/etr2025vol4.8448

compensates for thermal defocusing [16] - [18]. With this method, high focusing accuracy is possible due to the wide range of linear expansion coefficients of different materials. However, the application of this method leads to an increase in the mass and dimensions of the lenses, sealing problems may arise, and their reliability is lower.

- Active electromechanical method. It consists of adding to the design of the lens an electromechanical drive system that moves one or several optical elements longitudinally [1], [2]. Due to the high accuracy of the servomotors used, this method is the most precise for compensating for thermal defocusing under all existing temperature gradients [19] - [21]. The need to use servomotor and moving mechanical elements determines the complexity, increase in mass and dimensions, and lower reliability of this method. This method is justified for application only for complex multi-lens lenses, in which there is already an integrated electric drive for moving the components (e.g. zoom lenses).

A comparison has been made between the different athermalization methods and the most important characteristics of the lenses in Table 1.

TABLE 1 ATHERMALIZATION METHODS

	Optical passive	**Mechanical passive**	**Electro mechanical active**
Constant FOV	yes	yes	yes
Variable FOV	no	yes	yes
Zoom	no	yes	yes
Reliability	Very good	Good	Depends on components used
Mass and dimensions	Small	Medium	Big
Stability to external influences	Very good	Good	Affected by vibrations
Power supply	no	no	yes
Price	Low	Medium	High

It can be seen from Table 1 that when designing compact IR lenses, the passive optical method for athermalization is the most preferred.

There are known solutions related to the application of the passive optical method. Most often these are graphoanalytic solutions. It is proposed in [22] that optical materials for individual lenses should be chosen so that their Abbe number ν and Thermal glass constant T are proportional. This method is convenient and suitable in the presence of a large number of optical materials which to choose from. With a limited number of optical materials available, this method is difficult to realising and does not always lead to result. In [23] - [28], methods for passive athermalization of lenses are proposed, based on the use of various nomograms for the selection of suitable optical materials. For all of them, a graph is drawn, on the axes of which different combinations of the dependencies between Abbe number ν and Thermal glass constant T for different optical materials are plotted. Different authors give different geometric criteria for the correct choice. These are convenient and relatively simple solutions. Their common disadvantage is that they give one specific solution and do not take into account all possible combinations of optical materials. Furthermore, a solution for a multi-component optical system cannot be found by this method.

In [29] - [33], lenses for thermal cameras are considered, the optical scheme of which includes diffractive optical elements or diffractive and aspherical surfaces. These are very promising methods that allow the development of high-quality objectives composed of a small number of individual lenses, even with a limited number of optical materials. Their common disadvantage is that these are technologically more difficult and expensive solutions. Furthermore, the energy transmission at the end of the diffractive optical element decreases.

It can be summarized that the issue of correcting defocusing caused by (arising as a consequence of) temperature gradients during the operation of IR imaging devices is a relevant issue, especially in cases of a limited number of optical materials and without the use of complex electromechanical moving devices. All of this argues the development of this work, the goal of which is to design a passively athermalized LWIR lens for the thermal region of the spectrum.

II. MATERIALS AND METHODS

A. Temperature defocusing and conditions of athermalization

Let the optical system be given with its design parameters *r, t, n* (Fig. 1). When the temperature changes by a value of Δt, they change as follows:

- the refractive indexn_i n of the element with number i becomes $n_i + dn_i = n_i + \beta\Delta t$, where $\beta = \frac{dn_i}{dt}$ is thermal coefficient of refractive index;

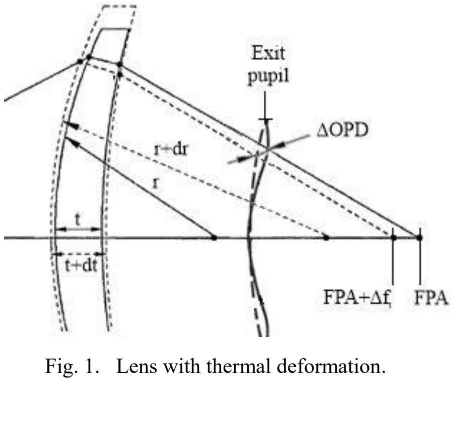


Fig. 1. Lens with thermal deformation.

- the radius r_i of the surface with number i becomes $r_i + dr_i = r_i + \alpha_{L_i}\,\Delta t$, where α_{L_i} is thermal expansion coefficient of lens material;
- the thickness t_i of the optical element with number i becomes $t_i + dt_i = t_i + \alpha_{L_i}\,\Delta t$;
- size of airspase with number i becomes $t_i + dt_i = t_i + \alpha_H\,\Delta t$, where α_H e thermal expansion coefficient of housing material.

As a result of these changes in the design parameters, a temperature defocusing Δf_t occurs, which for a objective composed of m thin lenses can be determined by the expression:

$$\Delta f_t = -f\left(\frac{\sum_{i=1}^{m} T_i\phi_i}{\phi} + \alpha_H\right)\Delta t \qquad (1)$$

where:

- f is the focal length of the entire objective;
- ϕ_i is the optical power of the element with number i, $i = 1 \div m$;
- ϕ is the optical power of the entire objective;
- $T_i = \frac{dn_i/dt}{n_i - 1} - \alpha_{L_i}$ is thermal glass constant.

An IR lens, in addition to being athermalized, must have constant optical power and small chromatic aberrations in the working spectral range. In such a case, the condition for athermalization can be written as:

$$\begin{cases} \phi_1 + \phi_2 + \cdots + \phi_m = \phi \\ \frac{\phi_1}{\nu_1} + \frac{\phi_2}{\nu_2} + \cdots + \frac{\phi_m}{\nu_m} = 0 \\ T_1\phi_1 + T_2\phi_2 + \cdots + T_m\phi_m = -\alpha_H\phi \end{cases} \qquad (2)$$

where: ν_i is the Abbe number in the spectral range $(8 \div 12)$ µm of the lens with number i , $i = 1 \div m$.

B. Optical materials and photoreceivers for LWIR range of the spectrum

There are a relatively limited number of optical materials that are transparent in the infrared spectrum. They can be classified into three groups:

• infrared semiconductor crystals and optical ceramics – Ge, Si, GaAs, ZnSe, ZnS etc.;

• chalcogenide glasses – Amtir, Gasir, IRG, IKS, IG etc.;

• alkali metal halides – e.g. KRS-5, AgCl, CsBr, NaCl, KBr, CsI etc.

For correcting temperature aberrations, the most important meaning are the temperature and optical characteristics of optical and non-optical materials: thermal glass constant T_i ; thermal coefficient of refractive index β ; thermal expansion coefficient α_{L_i}, thermal expansion coefficient of housing material α_H.

The analysis of IR materials shows that the coefficient α_{L_i} varies from 5 [K^{-1}] for GaAs to 61 [K^{-1}] for KRS5. The β coefficient varies from -236 [K^{-1}] for GaAs to 396 [K^{-1}] for KRS5 [2], [4], [6], [11]. These high values of α_{L_i} and β imply high and unacceptable values of the temperature defocusing in non-thermalized lenses. There is a group of IR materials with a negative value of β coefficient. This means that when the temperature changes, the refractive index will change in the opposite direction compared to the change in the physical parameters of the corresponding optical element. In such a case, it is possible to design a lens in which the temperature defocusing caused by the change in the radii and thicknesses of the optical elements will be compensated by an opposing temperature defocusing caused by the change in the refractive index of the material. Thermal expansion coefficient of the most common housing materials changes from 1,3.10^{-6} [K^{-1}] for Invar to 23,6.10^{-6} [K^{-1}] for Aluminum.

The dimensional characteristics of the lens (focal length and angular field) depend on the physical dimensions of the photoreceivers used. Furthermore, image quality requirements depend on the pixel size of the photoreceiver. Modern uncooled microbolometric matrix have a format from 120 × 160 to 768 × 1024 pixels and a pixel size 17 µm or 25 µm.

C. Passively athermalized lens design methodology

Passive athermalization of a lens implies the selection of optical materials in which temperature defocusing is minimized and the resulting deterioration in image quality is permissible. Optical path difference (OPD) is used as a criterion for evaluating the quality of the lens. The change in temperature by Δt causes change in OPD, which is determined by the expression

$$\Delta OPD = -\frac{Tf'}{(2F/\#)^2}\Delta t \qquad (3)$$

The Strehl ratio for diffraction limited lenses should be $Str. \geq$ 0,8 and then according to the Marechal criterion

$$\Delta OPD \leq 0{,}071\lambda \qquad (4)$$

Good athermalization of a lens in the LWIR range of the spectrum will be obtained when using a combination of the following types of optical materials:

- materials with both a high refractive index and a high Abbe number;
- materials with $\beta < 0$
- materials with low Abbe number.

The analysis conducted so far allows us to propose the following methodology for selecting materials for passive athermalization of a refractive objective (Fig. 2). It is possible to achieve good athermalization with 3 lenses (triplet) for relatively simpler optical systems. If to the objective has higher requirements for its geometric and energy resolution and 3 lenses are not sufficient to correct its field aberrations, then additional lenses need to be added to correct them.

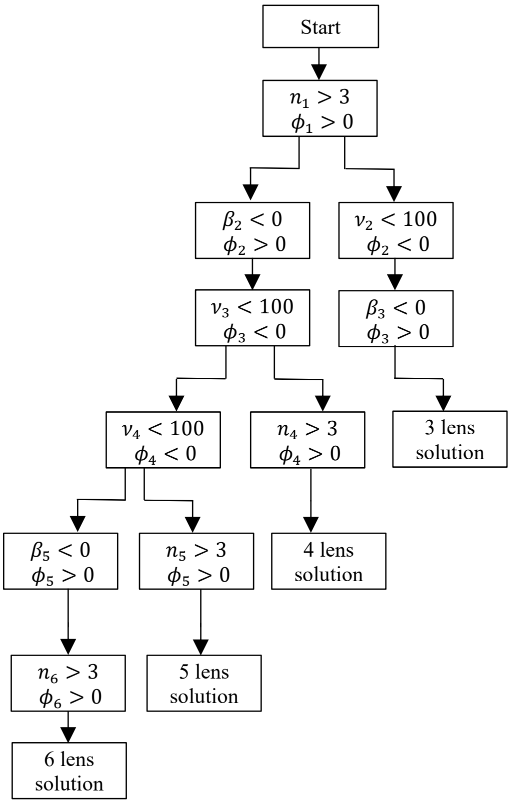


Fig. 2. Block diagram for selection of materials for passive athermalization of an IR lens.

For objective of 3-lens.

- The first lens is positive and made of a material with a higher refractive index.
- The second lens is negative and made of a material with a low Abbe number.
- The third lens is positive and is made of a material with $\beta < 0$.

For a objective of more than 3 lenses.

- The first lens is positive and made of a material with a higher refractive index.
- The second lens is positive and made of a material with $\beta < 0$.
- The third lens is negative and is made of a material with a relatively lower Abbe number.
- The fourth lens can be positive or negative. If it is positive, it is made of a material with a high refractive index. If it is negative, it is made of a material with a relatively lower Abbe number.
- The fifth lens is positive and is made of a material with $\beta < 0$ or a material with a higher refractive index.
- The sixth lens is positive and is made of a material with a high refractive index.
- Lenses with high optical power must be made of a material in which the influence on the temperature defocusing of the β coefficient is greater.

In the proposed methodology, the second and third lenses work as optical compensators of temperature deformation. The second lens – at the expense of the negative value of the coefficient β, and the third lens – at the expense of the negative optical power. The other lenses serve to maintain the set focal length f and to fulfil the condition for image quality.

Lens variants are shown for which the selection of materials was made according to the proposed methodology in Table 2.

TABLE 2 ATHERMALIZED LENS VARIANTS

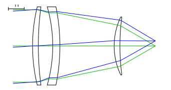
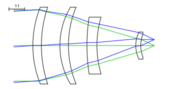
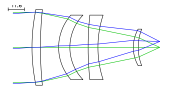
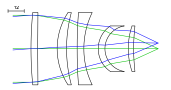
Lenses and optical materials	**Optical powers**	**Optical system layout**
Lens 1 Ge/ZnSe/KRS5	+/-/+	
Lens 2 Ge/KRS5/ZnSe/Ge	+/+/-/+	
Lens 3 GaAs/KRS5/ZnS/GaAs	+/+/-/+	
Lens 4 GaAs/AgCl/ZnS/ZnS/GaAs	+/+/-/-/+	

Table 3 shows the optical and thermo-optical characteristics of the materials used.

III. RESULTS AND DISCUSSION

The dimensional characteristics of the lens were determined: 60 mm, focal length F/1.2 and angular field 8°. Using the methodology proposed in item II, five athermal objectives consisting of 3, 4 and 5 lenses were designed. All lenses are spherical and have no diffractive surfaces. The housing material is aluminum. Optics software for layout and optimization OSLO was used and the lenses were optimized using the Marechal criterion for the root mean square of the wave aberration. To evaluate the image quality of the designed lenses, the root mean square of OPD_{RMS} was determined within the entire field of view using the expression

$$OPD_{RMS} = \sqrt{\frac{\sum_{i=1}^{m}(OPD_i - \overline{OPD})^2}{m-1}} \quad (5)$$

where:

- OPD_i is the optical path difference between the off-axial ray number i and the axial ray;

- $\overline{OPD}$ is the arithmetic mean of the optical path difference between the off-axis rays and the on-axis ray; the optical power of the element i, $i = 1 \div m$;

- m is the number of off-axis rays.

TABLE 3 OPTICAL AND THERMO-OPTICAL CHARACTERISTICS OF THE MATERIALS USED

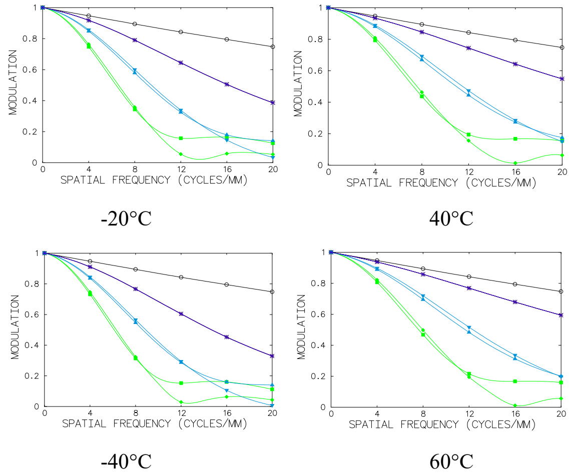
IR Materials	**n, average value**	**Abbe number ν**	**Thermal refractive index coefficient β.10^{-6}, [K^{-1}]**	**Thermal expansion coefficient α$_L$.10^{-6}, [K^{-1}]**
lens materials				
Ge	4,02	869,13	398,3	5,7
GaAs	3,29	108,09	186	5
ZnSe	2,42	57,18	61,6	7,1
ZnS	2,24	25,46	40,3	6,6
KRS-5	2,37	164,90	-236	61
AgCl	1,98	168,5	-61	32,4
CsBr	1,66	132,6	-78,4	47.2
housing materials				
Aluminum	housing material			23,6

Table 4 shows the values of OPD_{RMS} the designed lenses. As can be seen, all lenses except Lens1 fulfil condition (1). The reason for this is that Lens1 is a lens composed of 3 lenses, the materials of which are such that the temperature defocusing is minimal. Due to the small number of variable parameters, simultaneous correction of temperature and field aberrations for the entire field of view is not possible. All other lenses are composed of more lenses (3 or 4). They are athermalized and their image quality is close to diffraction.

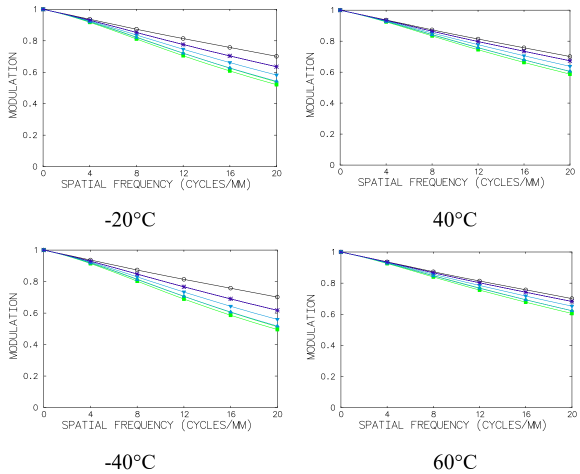
TABLE 4 ANALYSIS ON THE DESIGNED LENSES

Lenses	**OPD_{RMS}**	**Ensquared Energy (25x25) µm, % on axis/full field**			
		Temperature, °C			
		-40	**-20**	**40**	**60**
Lens 1 Ge/ZnSe/KRS5	0,074λ	49 8	54 8	68 10	72 12
Lens 2 Ge/KRS5/ZnSe/Ge	0,065λ	75 64	77 67	80 75	81 75
Lens 3 GaAs/KRS5/ZnS/GaAs	0,072λ	67 75	70 76	77 73	77 71
Lens 4 GaAs/AgCl/ZnS/ZnS/GaAs	0,046λ	58 59	57 59	57 58	56 58

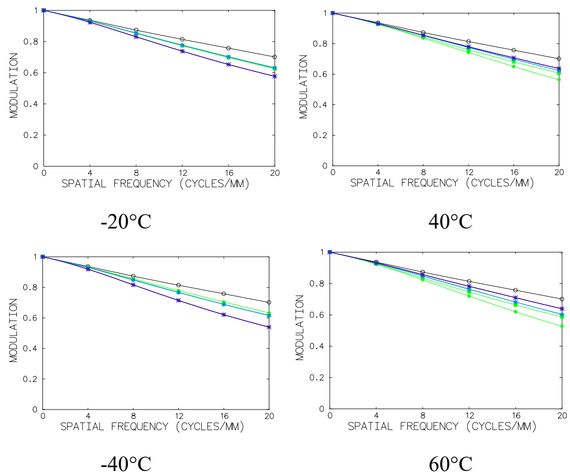
To assess the degree of correction of the temperature defocusing, the energy concentration function and the Modulation Transfer Function (MTF) of the lenses at different operating temperatures and angular fields were used. Fig. 3 shows the MTF graphs of the designed lenses for four temperatures $(-40, -20, +40, +60)°C$. The maximum spatial frequency for which the MTF is determined is20 mm^{-1}, which corresponds to the Nyquist frequency for a microbolometric matrix with a pixel size of $25\mu m$. Table 4 shows the values of the energy concentration in a square of size $(25x25)\mu m$ for these 4 operating temperatures.



Lens 1



Lens 2



Lens 3

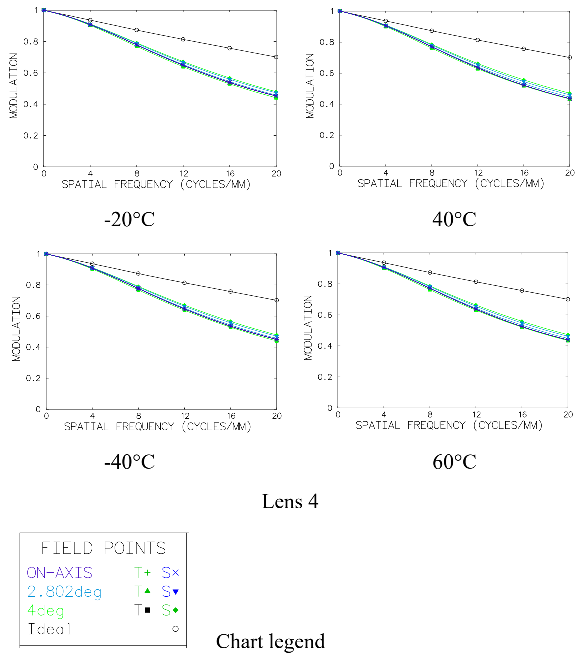


Fig. 3. MTF of lenses for different temperatures.

From Table 4 it can be seen that:

- for all lenses (except Lens 1) the energy concentration on the pixel of the microbolometric matrix is high – from about 50% to slightly over 70%;
- for all lenses the energy concentration is relatively constant for all operating temperatures;
- the operation of Lens 4 from the point of view of temperature change is the most stable, because in it the energy concentration is constant both with temperature change and for the entire field of view (deviations no more than 3%).

From Fig. 3 it can be seen that the MTF for the Nyquist frequency of most lenses is between 0.5 and 0.6, which means that they are diffraction-limited systems. The exceptions are Lens 1 for off-axis rays and partially Lens 4. The MTF of the lenses for different temperatures are very close, which indicates their high degree of athermalization.

The results obtained allow the use of the designed lenses with medium format microbolometric matrix at temperatures from -40 to +60 degrees.

IV. Conclusions

The influence of temperature on the design and optical parameters of IR lenses has been analyzed. The conditions for correcting the temperature defocusing have been formulated.

A methodology for the design of a passively athermalized LWIR objective has been developed. The essence of the methodology is the use of optical materials with different values of the refractive index and Abbe number. A mandatory condition is that at least one of the materials has a negative thermal coefficient of refractive index, i.e., it must be an alkali halide.

Optical schemes have been developed and the optical powers of objectives with 3, 4 and 5 lenses have been determined. Athermal diffraction-limited objectives for the LWIR region of the spectrum have been designed, which have subsequently been optimized using the Marechal criterion. The image quality has been assessed by the root-mean-square value of the OPD. The degree of correction of the temperature defocus has been assessed using the energy concentration function and MTF.

It has been found that an objective composed of 3 lenses cannot be simultaneously athermalized and meet the requirements for image quality over the entire field of view. The objectives with 4 and 5 lenses are diffraction-limited and athermalized over the entire field of view. They have stable characteristics when working with FPA microbolometric matrix with a pixel size of $(25x25)\mu m$ and a format of (320x240).

Acknowledgment

This research was funded by the European Regional Development Fund within the OP "Research, Innovation and Digitalization Programme for Intelligent Transformation 2021-2027", Project No. BG16RFPR002-1.014-0006 National Center of Excellence Mechatronics and Clean Tecnologies.

REFERENCES

[1] P. Rogers, "Athermalization of IR Optical Systems", Proc. of SPIE, Vol.10260, 1991. doi: 10.1117/12.48455

[2] T. H. Jamison, "Athermalization of optical instruments from the optomechanical viewpoint", Optical Design, Vol. CR43, pp. 131—159, 1992, doi: 10.1117/12.61105

[3] J. Tejada, "Passive Athermalization: Maintaining Uniform Temperature Fluctuations", Photonics Handbook, Optical Design, 2006, pp. 341–345, May 2006.

[4] J. Rayces and L. Lebich, "Thermal compensation of infrared achromatic objectives with three optical materials", Proc. of SPIE, Vol. 1354, pp. 752 – 759, 1990.

[5] V. Povey, "Athermalisation Techniques in Infra Red Systems", Proc. of SPIE, Vol. 0655, pp. 142–153, 1986, doi: 10.1117/12.938420

[6] A.R. Hilton, Chalcogenide glasses for infrared optics. NY: The McGraw-Hill Education; 2009.

[7] H.M, Hassan, TA-E Eldessouky and M. Medhat, "Compact athermalized LWIR objective lens", J Opt 2023, 52(1), pp. 261-268. doi: 10.1007/s12596-022-00892-2.

[8] O. N. Balatsenko and L. N. Arkhipova, "Environmentally stabilized thermal-imaging optical systems," Journal of Optical Technology. 90(9), pp. 491-497, 2023, doi: 10.1364/JOT.90.000491

[9] G.E. Romanova and G. Pyś, "Research of aberration properties and passive athermalization of optical systems for infrared region", Pro SPIE 2015, 9626: 96260H. doi: 10.1117/12.2191119.

[10] V. M. Tiagur, O. K. Kucherenko and A. V. Muraviov, "Passive optical athermalization of an IR three-lens achromat", J. Opt. Technol, Vol. 81, pp. 199–203, 2014, doi: 10.1364/JOT.81.000199

[11] K. Schwertz, A. Bublitz and S. W. Sparrold, "Advantages of using engineered chalcogenide glass for color corrected, passively athermalized LWIR imaging systems", Proc. of SPIE, Vol. 8353, 2012, doi: 10.1117/12.919430

[12] I.A. Levin, "Thermo-optical aberrations of radially symmetric diffractive optical elements", Computer Optics 2016, 40(1): 51-6. doi: 10.18287/2412-6179-2016-40-1-51-56

[13] G.I, Greisukh, S.T. Bobrov and S.A. Stepanov, "Optics of diffractive and gradient-index elements and systems", Bellingham: SPIE Press; 1997.

[14] G.P. Behrmann and J.P. Bowen, "Influence of temperature on diffractive lens performance", Applied Optics 1993, 32(14): 2483-2489.

[15] Liu Rui-qi, Chen Xing-ming and Zhao Jia-qi, "Applied Research of Diffractive Optical Elements in IR Imaging Systems",[J]. Infrared Technology, 31(6), pp. 327-330, 2009. doi: 10.3969/j.issn.1001-8891.2009.06.005

[16] D. Dichev, D. Diakov, I. Zhelezarov, S. Valkov, M. Ormanova, R. Dicheva and O. Kupriyanov, "A method for correction of dynamic errors when measuring flat surfaces", Sensors, volume 24, issue 16, 2024. doi: 10.3390/s24165154

[17] D. Dichev, D. Diakov, R. Dicheva, I. Zhelezarov and O. Kupriyanov, "Analysis of instrumental errors influence on the accuracy of instruments for measuring parameters of moving objects", 31st International Scientific Symposium Metrology and Metrology Assurance, MMA 2021, September, 2021, Sozopol, Bulgaria. doi: 10.1109/MMA52675.2021.9610855

[18] B. Georgiev and Ts. Karadzhov, "Investigating the repeatability of 3d printers using a multi-sensor measurement system", Environment. Technologies. Resources. Proceedings of the International Scientific and Practical Conference, Rezekne, Latvia, v. 3, p. 65–69, 2024. doi: 10.17770/etr2024vol3.8114.

[19] B. Georgiev and Ts. Karadzhov, "Comparative analysis of geometric deviations in contact measuring instruments for control and laser contactless scanning", Environment. Technologies. Resources. Proceedings of the International Scientific and Practical Conference, Rezekne, Latvia, v. 3, p. 306–310, 2024. doi: 10.17770/etr2023vol3.7182.

[20] D. Dichev, H. Koev, D. Diakov, N. Panchev, R. Miteva and H. Nikolova, "Automated System for Calibrating Instruments Measuring Parameters of Moving Objects", 59th International Symposium ELMAR, September 18-20 th, 2017, Zadar, Croatia, pp. 219-224. doi: 10.23919/ELMAR.2017.8124472

[21] D. Dichev, H. Koev, T. Bakalova and P. Louda, "A Gyro-Free System for Measuring the Parameters of Moving Objects", Measurement Science Review, volume 14, issue 5, 2014, pp. 263-269. doi: 10.2478/msr-2014-0036

[22] D.S. Volosov, "Photographic Optics. Theory, Principles of Design, Optical Characteristics". Moscow, Iskusstvo Publ., 1978, 543 p.

[23] Y. Tamagava, S. Wakabayashi and T. Tajime, "New design method for athermalized optical systems", Proc. SPIE, V. 1752, pp. 232–238, 1992, doi: 10.1117/12.130734

[24] K. Schwertz, D. Dillon and S. W. Sparrold, "Graphically selecting optical components and housing material for color correction and passive athermalization", Proc. of SPIE, Vol. 8486, 2012, doi: 10.1117/12.930968

[25] Y. Tamagava, "Multilens system design with an athermal chart", Applied Optics, V. 33., pp. 8009–8013, 1994, doi: 10.1364/ao.33.008009

[26] L. Lazov, E. Teirumnieks, N. Angelov and E. Teirumnieka, "Methodology for automatic determination of contrast of laser marking for different materials", Environment. Technology. Resources. Rezekne, Latvia, Proceedings of the 12th International Scientific and Practical Conference, 2019, Volume III, 134-136, doi: 10.17770/etr2019vol3.4143

[27] S.E. Ivanov and G.E. Romanova, "Calculation of heat-stabilized achromatic IR-lenses using a graphic method for choice of optical materials", Journal of Instrument Engineering, Vol. 60, issue 3, pp. 256–262, 2017, doi: 10.17586/0021-3454-2017-60-3-256-262

[28] S.E. Ivanov and G.E. Romanova, "Optical material selection method for an apochromatic athermalized optical system," Journal of Optical Technology. 83(12), 729-733 (2016). doi: 10.1364/JOT.83.000729

[29] G.I. Greisukh, I.A. Levin and O.A. Zakharov, "Diffractive elements in thermal imaging monofocal dual-band objectives: design and technological aspects", Computer Optics, 48(2), pp. 210- 21, 2024. doi: 10.18287/2412-6179-CO-1336.

[30] V. Laborde, J. Loicq, J. Hastanin and S. Habraken, "Multilayer diffractive optical element material selection method based on transmission, total internal reflection, and thickness", Appl Opt, 61(25), pp. 7415-7423, 2022. doi: 10.1364/AO.465999

[31] I. Draganov, L. Lazov, E. Teirumnieks and N. Angelov, "Numerical modeling and simulation for laser beam welding of ultrafine-grained aluminium", Published, 2021, Laser Physics, Volume 31, 066001 IOP Publishing, doi:10.1088/1555-6611/abf5d3

[32] A.S. Garshin and K.A. Andreev, "Design of athermalized infrared lenses involving diffractive optical elements", Scientific and Technical Journal of Information Technologies, Mechanics and Optics, 2018, vol. 18, no. 6, pp. 961–967 (in Russian). doi: 10.17586/2226-1494-2018-18-6-961-967

[33] J. Wang and C. Vue, "Athermalization and thermal characteristics of multilayer diffractive optical elements", Applied Optics, vol. 54, no 33, pp. 9665–9670, 2015. doi: 10.1364/AO.54.009665