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Optimization-Based First-Order Synthesis of Infrared Triplet Systems for LWIR Imaging

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

***Abstract* — This paper presents an optimization-based approach for the first-order design of infrared triplet systems in the LWIR spectral range. The method is based on paraxial optical theory and formulates the design task as a multi-parameter optimization problem aimed at minimizing chromatic aberrations and Petzval curvature under given constraints. Numerical optimization techniques are applied to determine the optical powers and spacing between the lenses. The obtained results demonstrate stable and physically realizable first-order solutions, validated through convergence of the iterative optimization procedure. The proposed framework provides an efficient and extensible approach for preliminary infrared optical system design.**

Keywords—chromatic aberration correction, infrared optical systems, LWIR imaging, paraxial synthesis.

I. INTRODUCTION

The rapid advancement of infrared imaging technologies has significantly increased the demand for efficient and reliable optical design methodologies, particularly in the long-wavelength infrared (LWIR) spectral range (8–12 µm) [1] – [4]. Systems operating in this range are widely employed in applications such as thermal imaging, surveillance, environmental monitoring, laser material processing and industrial diagnostics, where high image quality and robust performance are essential [5] – [8].

Among classical optical configurations, triplet systems provide a compact and effective solution capable of correcting primary aberrations while maintaining moderate complexity [9] – [12]. Although originally developed for the visible spectrum, triplet-based designs remain highly relevant for infrared applications due to their favorable balance between performance, manufacturability, and system compactness [3], [5] , [13]. However, extending these configurations to the LWIR range introduces additional challenges, including limited material availability, wavelength-dependent refractive properties, and increased sensitivity to design parameters [13] – [14].

The first-order design stage plays a critical role in optical system development, as it establishes the initial distribution of optical power and element spacing, providing a foundation for subsequent high-order optimization [2], [15], [16]. In infrared optics, accurate determination of these parameters is particularly important due to the strong coupling between system geometry and optical performance.

Several studies have investigated LWIR optical systems, including thermally compensated triplets [17], diffractive–refractive configurations [18] – [20], and achromatic infrared optics [17], [21], [22]. However, many existing approaches remain application-specific, rely on complex optical elements, or lack a systematic optimization-based formulation at the first-order design level [14], [20], [21], [23]. This motivates the development of a computationally efficient framework for reproducible first-order infrared optical design.

The main contribution of this work is the formulation of the first-order design of infrared triplet systems as a constrained multi-parameter optimization problem. The proposed approach integrates paraxial optical modeling with numerical optimization techniques, enabling systematic determination of lens powers and spacing parameters while satisfying key optical requirements, including focal length, chromatic aberrations, and Petzval curvature.

The proposed framework provides a computationally efficient and physically consistent methodology suitable for preliminary optical design, serving as a reliable starting point for further refinement in advanced optical design environments.

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This underscores the current relevance of developing unified and computationally efficient methodologies for infrared optical system design. In this context, the aim of the present work is to develop a reduced-parameter optimization-based framework for the first-order synthesis of infrared triplet systems operating in the LWIR spectral range.

II. Materials and Methods

A. Problem formulation

The design of optical systems is inherently a complex and iterative process, requiring the application of successive approximations in order to converge toward a feasible optical configuration. A critical stage in this process is the determination of a reliable first-order (paraxial) solution, which provides the initial distribution of optical power and axial separations and serves as the basis for subsequent higher-order aberration correction and numerical refinement.

Due to the nonlinear coupling between optical powers, ray heights, ray angles, and axial separations, direct analytical determination of the first-order solution is generally difficult. In addition, the governing equations may produce mathematically valid but physically impractical solutions, characterized by unrealistic lens powers or excessive axial distances. Consequently, iterative numerical procedures are commonly employed in order to determine physically meaningful first-order configurations.

For a three-element infrared triplet system, the first-order optical configuration is described by a set of external parameters independent of the detailed lens geometry. These parameters include the optical powers of the individual lenses and the axial separations between consecutive elements. Accordingly, the first-order parameter space can be represented by:

$$x = [\Phi_a, \Phi_b, \Phi_c, t_1, t_2]^T \quad (1)$$

where:

- Φ_a, Φ_b, Φ_c denote the optical powers of the first, second, and third lenses, respectively;
- t_1, t_2 denote the axial air spaces between the optical elements.

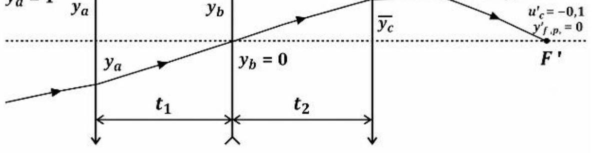

Fig. 1. Paraxial optical model of the infrared triplet

The principal paraxial quantities used in the first-order model are illustrated in Fig. 1, where y_i and $\bar{y}_i$ denote the heights of the axial and oblique paraxial rays, respectively; u_i' denotes the paraxial ray angle after the corresponding optical element.

These quantities represent the actual first-order design parameters of the optical system and define the physical configuration of the infrared triplet.

However, direct iterative optimization with respect to all components of the vector x is computationally inconvenient due to the strong interdependence between the parameters. In particular, the optical powers and axial separations are coupled through the paraxial ray-tracing equations and the chromatic and Petzval correction conditions.

For this reason, the optimization problem is reformulated using a reduced iterative parameterization [1], [2], [24], [25]. Instead of directly varying all first-order parameters, the iterative procedure is performed with respect to the axial ray angle after the first lens u_a' and the axial separation t_1. The remaining system parameters are then determined sequentially through paraxial ray tracing, geometrical relationships, and the imposed first-order conditions.

Thus, for a fixed configuration parameter R, the reduced iterative parameter vector is defined as

$$x_R = [u_a', t_1]^T \quad (2)$$

while the remaining quantities $\Phi_a, \Phi_b, \Phi_c, t_2$ are treated as dependent variables determined during the iterative solution process.

This reformulation significantly reduces the complexity of the optimization problem while preserving the physical interpretation of the first-order optical configuration. As a result, the proposed approach enables stable and efficient determination of physically realizable infrared triplet solutions in the LWIR spectral range.

B. Preliminary Conditions

The first-order model of the investigated infrared triplet system is formulated under a set of preliminary assumptions defining the physical and optical conditions of operation. These assumptions establish a consistent paraxial framework and simplify the initial design stage.

All optical elements are considered as thin lenses, while lens thicknesses and higher-order geometrical effects are neglected. The object is assumed to be located at infinity, corresponding to collimated incident radiation. The aperture stop is positioned at the second lens, defining the pupil configuration of the optical system.

The investigated optical system operates in the long-wavelength infrared (LWIR) spectral range $8–12\,\mu m$, which determines the relevant material properties and dispersion characteristics of the optical elements.

The effective focal length of the system is fixed at $f' = 10\,mm$.

The normalized height of the axial paraxial ray at the first lens is selected as $y_a = 1$.

The entrance angle of the axial ray is $u_a = 0$.

The focal length condition is imposed through the final angle of the axial paraxial ray after the third lens $u_c' = -0.1$.

The optical materials are selected according to their transmission properties in the LWIR spectral range. For the investigated triplet configuration, germanium (Ge) is used for the first and third lenses, while zinc selenide (ZnSe) is used for the middle lens.

C. Optical Constraints and Design Conditions

The first-order design of the investigated infrared triplet system is carried out under a prescribed set of optical constraints defining the required paraxial performance of the system.

The total optical power of the system must satisfy the effective focal length condition $\Phi_{sys} = {}^{1}/_{f'}$.

At the paraxial level, the primary chromatic aberrations are required to be corrected. Therefore, the lateral and axial chromatic aberration constraints are imposed as $PAC_{target} = 0$ and $PLC_{target} = 0$.

The field curvature is controlled through the prescribed Petzval condition $PTZ_{target} = -0.3\Phi_{sys}$.

Unlike the chromatic aberration constraints, the Petzval sum is intentionally not forced to zero. A prescribed negative Petzval value is retained in order to provide controlled first-order field curvature, which can subsequently support balancing of higher-order aberrations during further optical refinement.

In addition, the geometrical constraints $t_1 > 0$ and $t_2 > 0$ must be satisfied in order to ensure physically realizable optical configurations.

These constraints define the admissible first-order solution space used in the subsequent iterative optimization procedure.

D. Mathematical Model

The first-order mathematical model describes the nonlinear relationships between the optical powers, axial separations, and paraxial ray parameters of the infrared triplet system.

The first-order design problem requires determination of physically admissible values of $\Phi_a, \Phi_b, \Phi_c, t_1, t_2$ satisfying the imposed optical constraints.

$$\begin{cases} \Phi_{\text{sys}} = \dfrac{1}{f'} = 0.1 \\ PLC(\text{x}) = PLC_{\text{target}} = 0 \\ PAC(\text{x}) = PAC_{\text{target}} = 0 \\ PTZ(\text{x}) = PTZ_{\text{target}} = -0.3\,\Phi_{\text{sys}} \end{cases} \tag{3}$$

Here x is a physical first-order parameter vector, not an iterative optimization vector. The reduced iterative parameterization used in the numerical procedure is introduced separately in Section E.

The total optical power of the system is given by:

$$\Phi_{sys} = \Phi_a + \Phi_b + \Phi_c - t_1\Phi_a\Phi_b -$$
$$-t_2\Phi_b\Phi_c - (t_1 + t_2)\Phi_a\Phi_c + t_1 t_2\Phi_a\Phi_b\Phi_c \tag{4}$$

The Petzval sum is defined as

$$PTZ = -\sum_{i=a}^{c} \frac{\Phi_i}{n_i} \tag{5}$$

The chromatic correction conditions are defined as

$$PLC = \sum_{i=a}^{c} \frac{\Phi_i}{V_i} \tag{6}$$

$$PAC = \sum_{i=a}^{c} \frac{y_i\Phi_i}{V_i} \tag{7}$$

Equations (4)–(7) define the nonlinear algebraic system governing the first-order design problem

$$\begin{cases} \Phi_{sys} = \Phi_a + \Phi_b + \Phi_c - t_1\Phi_a\Phi_b - t_2\Phi_b\Phi_c - \\ \quad -(t_1 + t_2)\Phi_a\Phi_c + t_1 t_2\Phi_a\Phi_b\Phi_c = 0.1 \\ PLC(x) = \sum_{i=a}^{c} \frac{\Phi_i}{V_i} = 0 \\ PAC(\text{x}) = \sum_{i=a}^{c} \frac{y_i\Phi_i}{V_i} = 0 \\ PTZ(\text{x}) = -\sum_{i=a}^{c} \frac{\Phi_i}{n_i} = -0.3\Phi_{sys} \end{cases} \tag{8}$$

System (8) represents a nonlinear algebraic system with respect to the unknown parameters $\Phi_a, \Phi_b, \Phi_c, t_1, t_2$, defining the feasible first-order configurations of the optical system under the imposed constraints.

E. Methodology

The determination of the first-order solution for the investigated infrared triplet system is performed through a constrained iterative optimization procedure based on paraxial optical theory. The proposed methodology combines a reduced parameterization of the design problem with sequential paraxial ray tracing and aberration evaluation.

Unlike conventional approaches based on direct optimization of all first-order parameters, the present method employs a reduced iterative parameter vector (2) for a fixed spacing ratio $R = t_2/t_1$.

The remaining first-order parameters $\Phi_a, \Phi_b, \Phi_c, t_2$ are determined sequentially during the iterative process through the paraxial governing equations and the imposed optical constraints.

The optimization problem is formulated through the objective function:

$$F(u'_a, t_1; R) = w_1 PAC^2 + w_2(PTZ - PTZ_{target})^2 \tag{9}$$

where:

- w_1 and w_2 are weighting coefficients;
- $PTZ_{target} = -0.3\Phi_{sys}$.

Since the lateral chromatic aberration condition $PLC = 0$ is imposed structurally through the adopted parameterization and material assignment, it is not included explicitly in the objective function.

The proposed iterative methodology consists of the following computational steps.

Step 1 — Selection of the Spacing Ratio

A value of the spacing ratio $R = t_2/t_1$ is prescribed.

This parameter determines the proportional relationship between the axial separations and, through the lateral chromatic correction condition, establishes a functional dependency between the optical powers of lenses $a$and c.

Step 2 — Initialization of the Iterative Variables

An initial approximation of the reduced parameter vector is selected

$$\mathrm{x}_R^{(0)} = [u_a'^{(0)}, t_1^{(0)}]^T \tag{10}$$

The initialization is guided by first-order optical design heuristics $t_1^{(0)} \approx 0.3f'$ while $y_a = 1$ and $u_a = 0$ are preserved during the entire iterative process.

The second axial separation is determined from

$$t_2 = Rt_1 \tag{11}$$

Step 3 — Material Assignment

The optical materials are fixed according to their transmission properties in the LWIR spectral range:

- first lens a: Germanium (Ge);
- second lens b: Zinc Selenide (ZnSe);
- third lens c: Germanium (Ge).

Thus $V_a = V_c$ which enables structural implementation of the lateral chromatic correction condition.

The optical properties of the selected LWIR materials are:

$$Ge\begin{pmatrix} V_a = V_c = 869.13 \\ n_a = n_c = 4.02 \end{pmatrix} \text{ and } ZnSe\begin{pmatrix} V_b = 57.18 \\ n_b = 2.42 \end{pmatrix}$$

Step 4 — Structural Chromatic Constraint

The lateral chromatic aberration condition $PLC = 0$ is imposed directly as a structural condition.

Using $PLC = \sum_{i=a}^{c} \frac{\Phi_i}{V_i} = 0$ and the identical material assignment for lenses a and c, a functional relationship is obtained between the optical powers of the first and third lenses.

Step 5 — Paraxial Ray Tracing

For the current iterative state

$$\mathrm{x}_R^{(k)} = [u_a'^{(k)}, t_1^{(k)}]^T \tag{12}$$

the paraxial ray tracing procedure is performed sequentially through the optical system

$$y_{i+1} = y_i + t_i u_i' \text{ and } u_i' = u_i - y_i\Phi_i \tag{13}$$

These relations provide the ray geometry required for evaluation of the first-order aberrations.

Step 6 — Determination of the Optical Powers

Using the paraxial propagation equations together with the imposed constraints $\Phi_{sys} = \frac{1}{f'}$ and $PLC = 0$ the optical powers Φ_a, Φ_b, Φ_c are determined sequentially for the current iterative state.

Step 7 — Aberration Evaluation

The first-order aberrations are evaluated for the current configuration $PAC^{(k)}$ and $PTZ^{(k)}$ using the governing equations of the mathematical model.

Step 8 — Objective Function Evaluation

The objective function value is computed.

$$F^{(k)} = w_1(PAC^{(k)})^2 + w_2(PTZ^{(k)} - PTZ_{target})^2 \tag{14}$$

It provides a scalar measure of deviation from the required optical performance.

Step 9 — Iterative Update

The reduced parameter vector is updated iteratively

$$\mathrm{x}_R^{(k+1)} = \mathrm{x}_R^{(k)} + \Delta\mathrm{x}_R^{(k)} \tag{15}$$

corresponding to directed modification of u_a' and t_1 in order to minimize the objective function. The iterative corrections $\Delta x_R^{(k)}$are selected adaptively according to the current deviation from the imposed first-order constraints. At each iteration, the update direction is chosen so as to reduce the objective function value, while the step magnitude is adjusted empirically in order to ensure stable numerical convergence and preservation of physically realizable optical configurations.

Step 10 — Convergence Criterion

The iterative process continues until convergence is achieved

$$| F^{(k+1)} - F^{(k)} | < \varepsilon \tag{16}$$

or equivalently $PAC \approx 0$ and $PTZ \approx PTZ_{target}$, where $\varepsilon = 10^{-6}$. The convergence tolerance was selected sufficiently small to ensure numerical stability and accurate satisfaction of the imposed paraxial constraints.

Step 11 — Final First-Order Solution

Upon convergence, the obtained values $\Phi_a^*, \Phi_b^*, \Phi_c^*, t_1^*, t_2^*$ represent the optimized first-order solution of the infrared triplet system.

The resulting configuration provides a physically realizable paraxial starting point suitable for subsequent higher-order optical refinement and detailed numerical optimization.

The flowchart of the proposed iterative optimization algorithm is presented in Fig. 2.

III. RESULTS AND DISCUSSION

A. *Iterative Optimization Results*

The proposed optimization-based methodology was applied to the first-order design of an infrared triplet system operating in the LWIR spectral range 8–12 μm. The investigated optical configuration consisted of a positive–negative–positive triplet using germanium (Ge) for the first and third lenses and zinc selenide (ZnSe) for the middle lens.

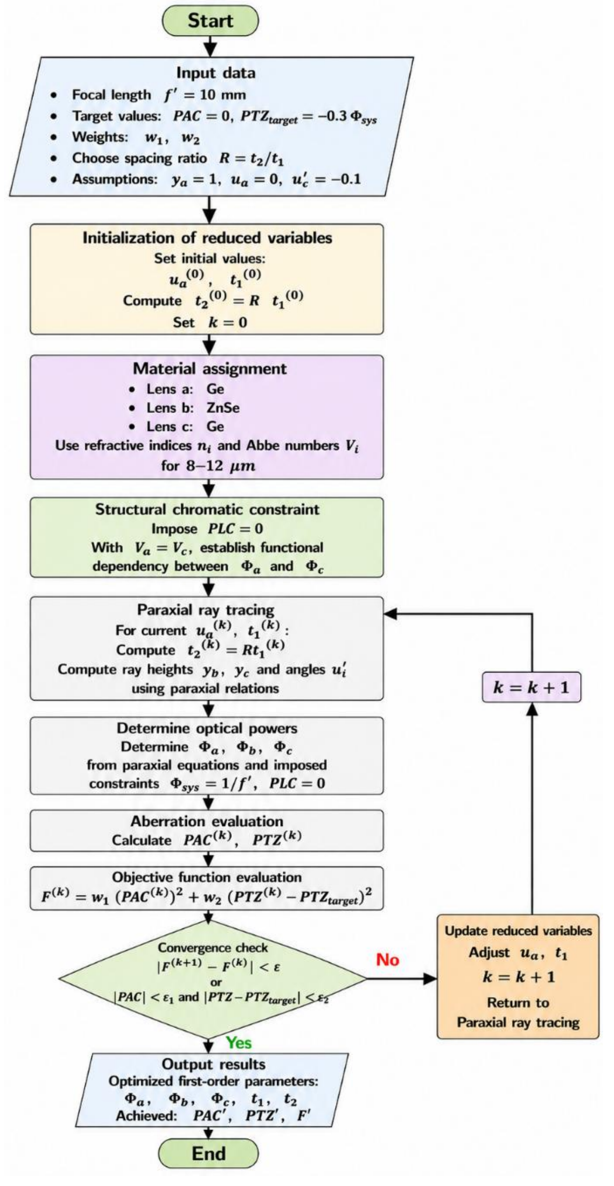

Fig. 2. Flowchart of the proposed optimization-based methodology illustrating the reduced-parameter iterative optimization procedure

The optimization procedure was performed for several prescribed values of the spacing ratio R. For each selected value of R, the reduced iterative parameter vector $x_R = [u_a', t_1]^T$ was iteratively updated until convergence of the objective function was achieved. During the iterative process, the optical powers Φ_a, Φ_b, and Φ_c, together with the axial separation t_2, were determined sequentially through the paraxial governing equations and the imposed first-order constraints.

The optimization process converged successfully for all investigated configurations, producing physically realizable first-order solutions satisfying the imposed optical conditions (3).

The obtained results demonstrate that the proposed reduced-parameter formulation provides stable convergence behavior while preserving the physical consistency of the infrared triplet configuration.

Table I summarizes the optimized first-order solutions obtained for different values of the spacing ratio R.

TABLE I OPTIMIZED FIRST-ORDER SOLUTION FOR DIFFERENT VALUES OF THE SPACING RATIO R

R	u'a	t_1 [mm]	t_2 [mm]	Φa [mm⁻¹]	Φb [mm⁻¹]	Φc [mm⁻¹]
0.5	-0.03942	5.313	2.657	0.03942	-0.00891	0.09598
1.0	-0.06374	3.286	3.286	0.06374	-0.00891	0.07166
1.5	-0.07814	2.680	4.020	0.07814	-0.00891	0.05725
2.0	-0.08771	2.388	4.775	0.08771	-0.00891	0.04768
2.5	-0.09454	2.215	5.538	0.09454	-0.00891	0.04086
3.0	-0.09965	2.101	6.304	0.09965	-0.00891	0.03574
3.5	-0.10363	2.021	7.073	0.10363	-0.00891	0.03177
4.0	-0.10681	1.961	7.843	0.10681	-0.00891	0.02859
4.5	-0.10941	1.914	8.613	0.10941	-0.00891	0.02599
5.0	-0.11158	1.877	9.384	0.11158	-0.00891	0.02382

Fig. 3 illustrates the variation of the optical powers of the three triplet elements as a function of the spacing ratio R. The obtained results demonstrate redistribution of optical power between the first and third lenses with increasing values of R, while the optical power of the negative middle lens remained nearly constant throughout the investigated range. This behavior confirms the stability of the proposed reduced-parameter optimization framework and preserves the classical positive–negative–positive triplet configuration.

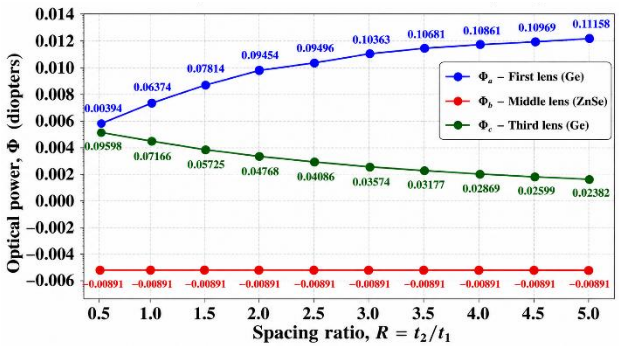

Fig. 3. Variation of optical powers as a function of the spacing ratio $R = t_2/t_1$.

The results indicate that the lateral chromatic aberration remained structurally corrected throughout the optimization process due to the adopted material configuration and parameterization strategy. Consequently, the iterative optimization was primarily focused on minimization of the axial chromatic aberration and control of the Petzval curvature.

It was observed that increasing the spacing ratio Rmodifies both the distribution of optical powers and the axial geometry of the system. Larger values of Rgenerally resulted in increased axial separation t_2, accompanied by redistribution of optical power between the first and third lenses in order to preserve the imposed first-order constraints.

B. *Convergence Behavior of the Iterative Procedure*

The obtained numerical results demonstrated stable convergence behavior for all investigated configurations. In all examined cases, the objective function decreased monotonically during the iterative process, indicating stable numerical performance of the proposed optimization framework.

Table II presents a representative convergence sequence obtained for $R = 1$.

TABLE II REPRESENTATIVE CONVERGENCE SEQUENCE FOR $R = 1$

k	u′a	t1 [mm]	PAC	u′c	F
0	-0.05000	3.000	-3.88×10^{-6}	-0.10415	1.72×10^{-5}
1	-0.07030	2.971	2.82×10^{-6}	-0.10252	6.37×10^{-6}
2	-0.06379	3.254	2.67×10^{-8}	-0.10026	6.57×10^{-8}
3	-0.06374	3.286	-2.40×10^{-10}	-0.10000	3.24×10^{-17}
4	-0.06374	3.286	2.30×10^{-15}	-0.10000	4.93×10^{-24}

The convergence sequence confirms rapid reduction of the objective function and stabilization of the iterative variables after a limited number of iterations. The axial chromatic aberration converged toward zero, while the Petzval condition approached the prescribed target value with high numerical accuracy.

Fig. 4 illustrates the convergence behavior of the objective function during the iterative optimization process.

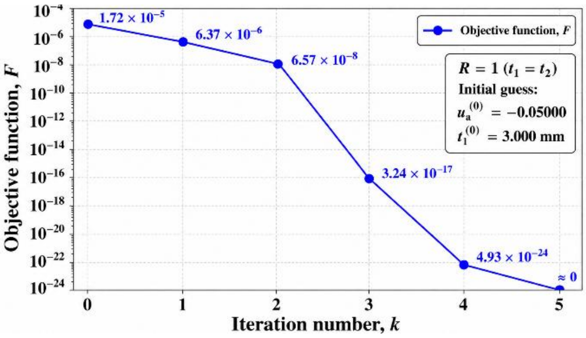

Fig. 4. Convergence of the objective function during the iterative optimization procedure for $R = 1$.

The obtained convergence characteristics indicate stable numerical behavior and physically consistent first-order solutions throughout the investigated range of spacing ratios R.

C. *Influence of the Spacing Ratio R*

The obtained results demonstrate that the spacing ratio R acts as an effective first-order control parameter governing both the optical power distribution and the axial geometry of the infrared triplet system. Increasing values of R lead to redistribution of positive optical power from the third lens toward the first lens, while preserving physically realizable positive–negative–positive triplet configurations.

D. *Physical Interpretation of the Obtained Solutions*

The obtained first-order solutions preserve the classical positive–negative–positive triplet structure characteristic of Cooke-type optical systems. The selected Ge/ZnSe/Ge material combination enables simultaneous satisfaction of the imposed chromatic and Petzval constraints while maintaining physically realizable optical configurations suitable for subsequent higher-order refinement.

IV. CONCLUSIONS

A first-order methodology for the design of infrared triplet optical systems operating in the LWIR spectral range (8–12 μm) has been presented. The proposed approach formulates the paraxial synthesis problem as a constrained multi-parameter optimization task in which the optical powers of the three lenses and the axial separations between them are determined simultaneously under predefined first-order conditions. The design procedure combines paraxial ray tracing with iterative numerical optimization in order to satisfy the imposed constraints related to system optical power, chromatic correction, and Petzval balance.

The obtained results demonstrate that physically meaningful infrared triplet configurations can be achieved for a wide range of spacing ratios $R = t_2/t_1$. The performed analysis shows that the parameter Racts as an effective first-order control variable governing both the axial geometry and the optical power distribution within the system. Increasing values of R lead to systematic redistribution of positive optical power toward the first lens, accompanied by a corresponding reduction of the optical power of the third lens. Simultaneously, the axial geometry of the system changes in a predictable manner while preserving the required first-order aberration conditions.

The study further demonstrates that the imposed paraxial constraints $PLC = 0$, $PAC = 0$ and $PTZ = -0.3\Phi_{sys}$ can be satisfied simultaneously through appropriate selection of the optical powers and air gaps. The obtained solutions confirm the strong coupling between chromatic correction, Petzval compensation, and axial spacing in infrared triplet systems. Consequently, the spacing ratio should not be interpreted merely as a geometrical parameter, but rather as a governing variable influencing the global first-order balance of the optical system.

The proposed methodology is based on a paraxial thin-lens approximation and therefore does not include higher-order aberrations, real lens geometries, diffraction effects, or thermo-optical influences. Nevertheless, the obtained first-order solutions provide a stable and physically consistent initial configuration suitable for subsequent detailed optical optimization.

Future work will include extension of the proposed methodology toward real optical surfaces, incorporation of higher-order aberration correction, thermo-optical analysis for infrared materials, and numerical validation using professional optical design software environments such as Zemax Optic Studio, CODE V and OSLO.

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