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Design of a Dual-Band Infrared Continuous Zoom Optical System with Chromatic Aberration Compensation for Room-Temperature Infrared Photoelectric Applications

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Abstract

Chromatic aberration correction remains a major challenge in dual-band infrared continuous zoom optical systems. To address this issue, an achromatic design method based on the equivalent refractive index and equivalent dispersion rate is proposed. Starting from a four-component continuous zoom model, chromatic compensation is introduced into the initial structural parameter calculation, and the initial structural parameters are obtained through an iterative procedure. To validate the proposed method, a MWIR/LWIR dual-band continuous zoom optical system is designed. The final system covers the MWIR (3.7–4.8 μm) and LWIR (8–10 μm) bands with a focal length range of 10–120 mm, and the chromatic focal shift is controlled within the depth of focus. Clear imaging is achieved in both bands over the entire zoom range. These results demonstrate the effectiveness of the proposed achromatic strategy and provide a practical approach for the design of wide-band achromatic zoom optical systems.

Keywords: dual-band zoom optical system; achromatic design; initial structure

1. Introduction

Infrared detection uses the radiance contrast between a target and its background for target identification. It requires no external illumination and offers strong immunity to environmental interference [1]. Medium-wave infrared (MWIR) is sensitive to high-temperature targets, while long-wave infrared (LWIR) provides good imaging performance in nighttime and complex background conditions. MWIR/LWIR dual-band sensing can make use of complementary information from different infrared bands, thereby improving target discrimination and recognition performance in complex backgrounds. Accordingly, dual-band continuous zoom optical systems are of interest for infrared observation and monitoring tasks that require both dual-band information and variable field of view [2–4]. However, infrared optical materials show great differences in dispersion characteristics over the MWIR/LWIR spectral range, which increases chromatic aberration and makes it difficult to maintain high imaging quality in both bands. In addition, the limited availability of infrared optical materials further increases the difficulty of system design [5]. As a result, realizing dual-band synchronous zoom imaging without introducing a secondary imaging



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group or an additional refocusing structure, while also achieving low aberration and a compact form, remains challenging.

Single-band zoom imaging optical systems can no longer meet increasingly diverse needs [6–9]. The widespread application of multiband optical systems can alleviate this dilemma. However, references on the design of dual-band continuous zoom optical systems remain relatively limited, primarily because chromatic aberration is difficult to correct. To achieve high-quality imaging across wide-band systems, Chen et al. employed particle swarm optimization (PSO) to obtain the optimal solution of the initial structure of the optical system and designed a common-aperture optical system in visible band (VIS), near-infrared (NIR) and mid-wave infrared band (MWIR) systems [10]. Li et al. designed a dual-band high-zoom-ratio continuous co-focal optical system. However, the system requires an additional focal length compensation group to correct the residual aberration of each band, making the system volume larger [11]. Zhang et al. studied the mathematical relationship between substrate material selection and polychromatic integral diffraction efficiency, employing multilayer diffractive optical elements to realize a MWIR/LWIR zoom system [12]. More recently, Geng et al. reported a cooled MWIR/LWIR zoom optical system with a large magnification ratio [13]. Lu et al. designed a dual-band co-aperture synchronous zoom system based on a beam-splitting prism, and Ma et al. introduced a dual-band continuous zoom hybrid system using a double-layer diffractive optical element [5,14]. These studies provide guidance for the design of dual-band zoom optical systems, but they often rely on additional compensation structures, diffractive elements, or relatively complex system configurations. In parallel, recent studies have also explored broadband achromatization from the perspectives of material screening and emerging optical elements. Qu et al. investigated wide-band continuous zoom design in the VIS–SWIR range and proposed an achromatic model for the zoom system, along with a set of equations for material selection and focal power distribution. However, the resulting formulation involves many coupled equations and variables, making the solution process difficult and time-consuming [15]. Salinas et al. studied infrared lens selection using a weighted dispersion derivative. Their work provides a useful recent reference for infrared achromatic material screening [16]. Qian et al. demonstrated a MWIR/LWIR dual-band imaging system based on hybrid refractive–diffractive–metasurface optics. However, the work focused on a fixed-focus architecture rather than a continuous zoom system [17]. Hao et al. employed an achromatic metalens in the design of a simplified see-through head-mounted display optical system, reflecting the increasing use of emerging phase-control elements in chromatic aberration correction for optical systems [18]. To simplify the design process of zoom systems, researchers have explored liquid lenses for dual-band continuous zoom systems. Liquid lenses have the characteristics of compact structure, low power consumption, and rapid focal tuning, but their working band is narrow, and achieving large zoom ratios typically requires multiple liquid lenses, which is costly. Li et al. designed a dual-band shared aperture zoom imaging system employing two liquid lenses per band. Due to the limited zoom capability and imaging spectrum of liquid lenses, the imaging spectrum only reached the NIR band, and the overall dual-band zoom ratio was only $4\times$ [19].

There are two traditional ways to obtain the initial structure of the zoom optical system. One is the PWC method, which is used to calculate the paraxial parameters of the lens. However, this procedure is highly complicated, and the resulting initial structural parameters do not always meet the design requirements. The other approach is to re-optimize existing patented designs with similar specifications, which is relatively faster. For single-band systems, both approaches are feasible to some extent. However, for infrared dual-band continuous zoom systems, few similar designs are available for reference because

broadband chromatic aberration is difficult to correct and the constraints of common optical path synchronous zoom are complex. Moreover, most existing dual-band zoom systems adopt large apertures, multiple lens elements, or additional compensation structures. These features are unfavorable for the miniaturization and compact design required in monitoring equipment. Therefore, it is necessary to explore a design approach that balances low chromatic aberration with system compactness, thereby providing a more reasonable basis for subsequent real-lens substitution and optimization.

Based on the four-component continuous zoom model and a broadband achromatization strategy, a chromatic aberration compensation method is introduced for the initial structural solution of a dual-band zoom optical system. The focal shift caused by material dispersion is incorporated into the optical path constraint. In this way, chromatic aberration is considered during the initial structure calculation rather than only in the subsequent optimization stage. A MWIR/LWIR dual-band continuous zoom optical system is taken as the design example to demonstrate the proposed method. The method is intended to alleviate the difficulty of chromatic correction in dual-band zoom systems while preserving structural compactness and avoiding additional compensation groups. It therefore provides a targeted achromatic design route for dual-band zoom optics intended for room-temperature infrared photoelectric imaging.

2. Chromatic Aberration Compensation Method for Dual-Band Infrared Continuous Zoom Optical System

2.1. Zoom Principle of Dual-Band Infrared Continuous Zoom Optical System

The dual-band continuous zoom optical system adopts a common aperture split-path structure and realizes zooming based on a mechanical four-component zoom model, as shown in Figure 1. The continuous zoom optical system consists of five parts: a front fixed group (S1), a zooming group (S2), a compensating group (S3), a beam splitter prism and a rear fixed group (S4). The focal lengths of S1, S2, S3 and S4 are f'_1 , f'_2 , f'_3 and f'_4 , respectively. The first three groups (S1~S3) constitute a public zoom group through which the MWIR and LWIR beams propagate together. The two bands are then separated by the beam splitter prism through a coated splitting interface inside the prism. The MWIR beam is transmitted through the prism and is finally imaged on focal plane 1, while the LWIR beam is reflected toward focal plane 2.

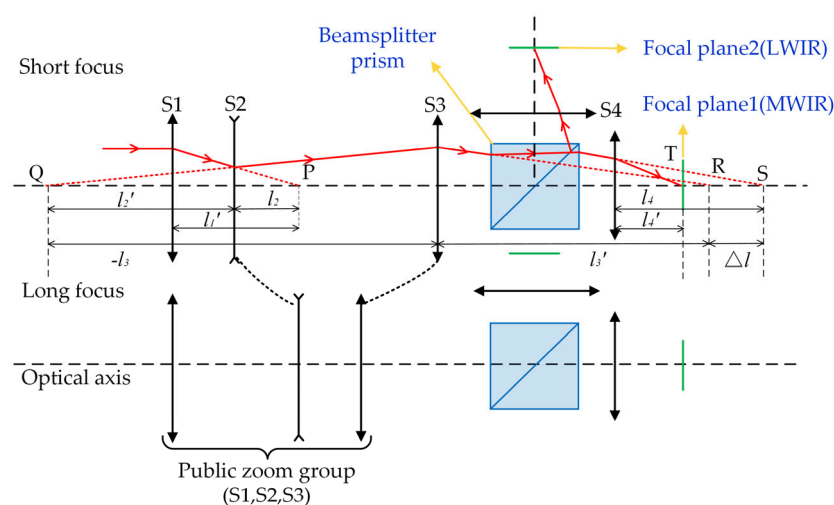


Figure 1. The structure of a dual-band infrared continuous zoom optical system.

Two moving groups, S2 and S3, are used to achieve continuous zooming of the optical system. Compared with a negative compensation zoom optical system, a positive

compensation zoom optical system typically offers a smaller aperture and shorter total length. It also offers stronger correction of chromatic and spherical aberrations. Specifically, the focal power of S1 is positive and is used to collect the light entering the optical system. The focal power of S2 is negative; it organizes the beam from S1 to reduce the incident angle on the stop. The focal power of S3 is positive, which helps reduce the overall aperture of the system and enables a larger zoom ratio. When the power of S4 is also positive, the power of S1 can be kept lower. A lower-power S1 generally leads to reduced chromatic aberration. Therefore, the focal power of the four lens groups is selected as “+, −, +, +” [20,21]. The positions of S1, S4, and the beam splitter prism remain fixed. Continuous zoom is achieved by varying the relative positions of S2 and S3 during the zoom process.

2.2. Chromatic Aberration Compensation Method for Dual-Band Infrared Continuous Zoom Optical System

To address both chromatic aberration correction and the miniaturization requirements of dual-band infrared continuous zoom optical systems, a chromatic aberration compensation method based on the equivalent refractive index and equivalent dispersion rate is proposed. Chromatic aberration is estimated under the assumption that the focal power and thickness of individual lenses are unknown, while the overall lens group selection of the system is completed. Based on the focal power and functions of S1~S4, and with reference to related infrared optical system designs, the initial number of lenses in each group was determined independently rather than by directly adopting the overall configuration of an existing dual-band continuous zoom system. For the intended application, a common aperture split-path configuration is adopted. The proposed dual-band chromatic aberration compensation model can also be extended to the achromatic design of other zoom optical systems. Initial materials were selected by first narrowing the candidate range and then refining the selection iteratively. Materials with higher dispersion coefficients are generally used as negative elements in positive groups and as positive elements in negative groups, whereas materials with lower dispersion coefficients have opposite uses. The initial materials were selected according to these principles. Optional infrared optical materials and their key properties are shown in Table 1.

Table 1. Optional infrared optical materials.

Material	Spectral Range/ μm	Refractive Index		$\partial n/\partial \lambda \text{ } \mu\text{m}^{-1}$	
		4 μm	10 μm	4 μm	10 μm
Ge	2.0~17	4.0250	4.0043	−0.0122	−0.0009
ZNS_BROAD	0.37~14	2.2524	2.1999	−0.0056	−0.0130
ZNSE	0.55~20	2.4331	2.4064	−0.0038	−0.0061
GASIR1	1.0~14	2.5116	2.4959	−0.0035	−0.0031
AMTIR-1	0.75~14	2.5136	2.4970	−0.0035	−0.0033
AMTIR-2	1.0~14	2.7867	2.7700	−0.0050	−0.0027
AMTIR-3	1.0~14	2.6210	2.6022	−0.0044	−0.0036
IG2	0.75~14	2.5133	2.4967	−0.0035	−0.0034
IG4	0.8~14	2.6220	2.6090	−0.0037	−0.0022
IG5	0.85~14	2.6221	2.6032	−0.0043	−0.0036
IG6	0.85~14	2.7945	2.7775	−0.0058	−0.0027

For observation zoom optical systems, axial chromatic aberration is primarily concerned [22]. Chromatic aberration arises from differences in the refractive indices of optical materials at different wavelengths, which cause shifts in the image position. This effect disrupts the synchronization of a dual-band zoom optical system and can be regarded as a shift in focal length, equivalent to an increase or decrease in optical path. To correct the

focal mismatch caused by chromatic aberration, this shift is incorporated into the total optical path length constraint. After passing through the four groups of the zoom optical system, the dual-band beams exhibit a focal offset caused by chromatic aberration. This effect is modeled and compensated by introducing a chromatic aberration compensation term ($\Delta_{chromatic}$), which can be expressed as

$$\Delta_{chromatic} = \sum_{i=1}^n \left[\frac{\partial f_i}{\partial \lambda} \cdot \Delta \lambda \right] \quad (1)$$

$$\frac{\partial f_i}{\partial \lambda} = -f_i \frac{1}{n_i - 1} \cdot \frac{\partial n_i}{\partial \lambda} \quad (2)$$

where n_i is the refractive index of the material of the i -th lens ($i = 1, \dots, n$); f_i is the focal length of the i -th lens; $\partial f_i / \partial \lambda$ is the rate of change in the lens focal length with wavelength, determined by the dispersion rate $\partial n_i / \partial \lambda$; and $\Delta \lambda$ is the difference between the center wavelengths of the MWIR and LWIR bands.

Since each of the groups S1~S4 in the zoom optical system comprises multiple lenses, direct calculation of $\Delta_{chromatic}$ using Equations (1) and (2) would require single-lens parameters n_i , f_i and $\partial n_i / \partial \lambda$ for every lens. However, these parameters are unknown at the initial design stage. Therefore, it is impractical to calculate the chromatic aberration contribution of each lens individually; a comprehensive characterization of the chromatic aberration effects across multiple lenses is required. To make the evaluation of $\Delta_{chromatic}$ feasible, the concept of equivalent group parameters is introduced. The equivalent refractive index n_{eff} and equivalent dispersion rate $\partial n_{eff} / \partial \lambda$ are used for lens groups S1~S4 to approximate the overall dispersion behavior of each group, thereby estimating the chromatic aberration compensation values required for each lens group. By substituting n_{eff} and $\partial n_{eff} / \partial \lambda$ for n_i and $\partial n_i / \partial \lambda$ in Equation (1) and then substituting Equation (2) into Equation (1), the equivalent chromatic aberration compensation term can be written as Equation (3).

$$\Delta_{chromatic} = - \sum_{k=1}^4 \left[-f'_k \frac{1}{n_{eff,k} - 1} \cdot \frac{\partial n_{eff,k}}{\partial \lambda} \cdot \Delta \lambda \right] \quad (3)$$

where f'_k is the focal length of group Sk ($k = 1, 2, 3, 4$), and n_{eff} and $\partial n_{eff} / \partial \lambda$ represent the overall chromatic aberration behavior of the corresponding lens group. Since the refractive index n reflects differences in focal power most effectively, it is adopted as the weighting factor. The weighted averages of n_i and $\partial n_i / \partial \lambda$ are then calculated over all lenses in each group. Accordingly, n_{eff} and $\partial n_{eff} / \partial \lambda$ are given by Equations (4) and (5).

$$n_{eff,k} = \frac{\sum_j^N (w_j n_j)}{\sum_j^N w_j}, w_j = n_j \quad (4)$$

$$\frac{\partial n_{eff,k}}{\partial \lambda} = \frac{\sum_j^N (w_j \cdot \frac{\partial n_j}{\partial \lambda})}{\sum_j^N w_j}, w_j = n_j \quad (5)$$

where w_j is the weight of the j -th lens in group Sk ($k = 1, 2, 3, 4$), and N is the number of lenses in group Sk . The weight assigned to each lens is defined as $w_j = n_j$.

The magnitude of chromatic aberration in a zoom optical system depends strongly on material parameters and the focal power distribution among lens groups. The chromatic aberration compensation term $\Delta_{chromatic}$ is calculated from the group focal lengths (f'_1, f'_2, f'_3, f'_4) together with $n_{eff,k}$ and $\partial n_{eff,k} / \partial \lambda$. It is then incorporated into the zoom equation. The proposed method enables targeted control of chromatic aberration during the calculation of the initial structural parameters and provides a high-accuracy starting point for subsequent optical optimization.

Since the parameters required to calculate $\Delta chromatic$ are obtained by solving the initial structure of the zoom optical system, $\Delta chromatic$ cannot be determined until the initial structural parameters (f'_1, f'_2, f'_3, f'_4) have been obtained. However, since the goal is to obtain initial structural parameters that inherently incorporate chromatic aberration compensation, an iterative scheme is adopted to reduce chromatic aberration. First, set $\Delta chromatic = 0$, and an initial set of structural parameters is solved. Then $\Delta chromatic$ is calculated from the first-round results, and the structural parameters of the optical system are updated accordingly. In this way, an iterative optimization process is established.

2.3. Calculation Method for Initial Structural Parameters with Chromatic Aberration Compensation

In the dual-band infrared continuous zoom optical system, S1, the beam splitter prism and S4 are fixed, which means that the total length of the optical system remains constant. Continuous zooming is achieved by varying the relative positions of the zooming group (S2) and the compensating group (S3). When S2 is close to S1 and S3 is close to the beam splitter prism, the system operates at a short focal length. Conversely, when S2 moves away from S1 and S3 moves away from the beam splitter prism, the system operates at a long focal length. As shown in Figure 1, light parallel to the optical axis is imaged at point P after passing through S1, at point R after passing through S2 and S3, at point S after passing through the beam splitter prism, and finally at point T on the focal plane after passing through S4. Therefore, regardless of the relative motions of S2 and S3 during continuous zooming, the distance between the object point P of S2 and the image point S of the beam splitter prism ($\overline{PS}$) remains constant [23,24], which leads to Equation (6).

$$\overline{PS} = (l'_3 - l_3) - (-l'_2 + l_2) + \Delta l \quad (6)$$

where l_2 and l'_2 denote the object distance and image distance of S2, respectively; l_3 and l'_3 denote the object distance and image distance of S3, respectively.

The relationship between the focal length f' , object distance l , image distance l' , and magnification m of an optical system is given by Equation (7).

$$\begin{cases} l = \frac{1-m}{m}f' \\ l' = (1-m)f' \end{cases} \quad (7)$$

The lateral displacement Δl introduced by the beam splitter prism can be expressed in terms of the prism thickness d and refractive index n [23]. By combining Equations (6) and (7), the zoom equation is obtained as Equation (8).

$$\overline{PS} = 2(f'_2 + f'_3) - f'_2 \left(m_2 + \frac{1}{m_2} \right) - f'_3 \left(m_3 + \frac{1}{m_3} \right) + d \left(1 + \frac{1}{n} \right) \quad (8)$$

The zoom equation, Equation (8), is based on the paraxial approximation in geometrical optics. For systems with a wide spectral span, large chromatic aberration prevents different wavelengths from focusing on the same point and thus degrades image quality. To account for this effect, a dual-band chromatic aberration compensation term $\Delta chromatic$ is introduced into Equation (8). This term covers both the fixed groups and the multi-piece moving groups, so the displacement caused by chromatic aberration is incorporated into the total optical path length constraint. After this displacement is quantified and compensated, a revised zoom equation is obtained.

$$\overline{PS} = 2(f'_2 + f'_3) - f'_2 \left(m_2 + \frac{1}{m_2} \right) - f'_3 \left(m_3 + \frac{1}{m_3} \right) + d \left(1 + \frac{1}{n} \right) + \Delta chromatic \quad (9)$$

Since the distance between point P and point S is a constant, and since the material, position, and thickness of the beam splitter prism are fixed, $\Delta chromatic$ is determined by f'_k , n_{eff} , and $\partial n_{eff} / \partial \lambda$, and is therefore also constant. Accordingly, the zoom equation for the dual-band continuous zoom optical system can be written as Equation (10).

$$2(f'_2 + f'_3) - f'_2 \left(m_2 + \frac{1}{m_2} \right) - f'_3 \left(m_3 + \frac{1}{m_3} \right) = constant \quad (10)$$

From Equation (10), the relationship between the magnification for each group at short focal lengths (m_{2s}, m_{3s}, m_{4s}) and those at long focal lengths (m_{2l}, m_{3l}, m_{4l}) is obtained as Equation (11).

$$f'_2 \left(m_{2s} + \frac{1}{m_{2s}} \right) + f'_3 \left(m_{3s} + \frac{1}{m_{3s}} \right) = f'_2 \left(m_{2l} + \frac{1}{m_{2l}} \right) + f'_3 \left(m_{3l} + \frac{1}{m_{3l}} \right) \quad (11)$$

$$m_{4s} = m_{4l}$$

Based on the geometric relationships in Figure 1, the total length of the optical system can be expressed as Equation (12).

$$L = f'_1 + \overline{PS} - (l_4 - l'_4) = f'_1 + 2(f'_2 + f'_3 + f'_4) - f'_2 \left(m_2 + \frac{1}{m_2} \right) - f'_3 \left(m_3 + \frac{1}{m_3} \right) - f'_4 \left(m_4 + \frac{1}{m_4} \right) + d \left(1 + \frac{1}{n} \right) + \Delta chromatic \quad (12)$$

Once the magnification of each group at short focal length has been determined, the corresponding magnification at long focal length can be obtained in different combinations according to Equation (11). The interval between the four groups of the zoom optical system is then given by Equation (13).

$$\begin{cases} d_{12} = f'_1 - \frac{1 - m_2}{m_2} f'_2 \\ d_{23} = -\frac{1 - m_3}{m_3} f'_3 + (1 - m_2) f'_2 \\ d_{34} = (1 - m_3) f'_3 + d \left(1 + \frac{1}{n} \right) - \frac{1 - m_4}{m_4} f'_4 \\ d_{4f} = (1 - m_4) f'_4 \end{cases} \quad (13)$$

Among these, the intervals at short focal lengths are $d_{12s} \sim d_{4fs}$, where d_{12s} , d_{23s} and d_{34s} denote the distances between S1~S2, S2~S3, and S3~S4, respectively, and d_{4fs} denotes the distance between S4 and the focal plane. Similarly, the intervals at long focal lengths are $d_{12l} \sim d_{4fl}$, where d_{12l} , d_{23l} , d_{34l} , and d_{4fl} denote the distances between each group. Since $m_{4s} = m_{4l}$, it follows that $d_{4fs} = d_{4fl}$.

During continuous zooming, the zooming group (S2) and compensating group (S3) of the optical system have two extreme configurations corresponding to the shortest and longest focal lengths. At the shortest focal length, the distances d_{12s} (between S1 and S2) and d_{34s} (between S3 and S4) reach their minimum values, and a sufficient width d must be reserved between S3 and S4 for the beam splitter prism. At the longest focal length, the distance d_{23l} between S2 and S3 reaches its minimum value. To avoid mechanical interference among lens groups during zooming and to satisfy the installation requirements of mechanical components such as detectors, constraints are imposed on component spacing. Here, d_{4fs} denotes the back focus length of the optical system, leaving an installation space of more than 10 mm. Therefore, the following conditions must be satisfied: $d_{12s} > 0$, $d_{23l} > 0$, $d_{34s} > d$, $d_{4fs} > 15$ mm.

The calculated value of the chromatic aberration compensation term ($\Delta chromatic$) depends on the group focal length f'_k , which is itself obtained by solving the zoom equation

containing $\Delta chromatic$. To address this coupling, an iterative scheme is adopted to solve the initial structural parameters of the optical system. In this scheme, chromatic aberration is reduced by progressively adjusting the material parameters, focal power, and assumed magnification values.

First, set $\Delta chromatic = 0$, and an initial set of structural parameters is obtained from the zoom equation. The corresponding initial $\Delta chromatic$ is then calculated and substituted back into the zoom equation for chromatic aberration correction. The structural parameters are then re-solved, and this iterative process is repeated until $\Delta chromatic$ falls below a specified threshold. The cyclic iterative process for solving the initial structure parameters is illustrated in Figure 2. The detailed steps are as follows:

1. First, set $\Delta chromatic = 0$ and solve for a set of initial structural parameters. The solutions include $(f'_1 \sim f'_4)$, $(d_{12} \sim d_{4f})$ and $(m_2 \sim m_4)$.
2. Based on the first-round solution obtained in step (1), the lens count and initial material of each group are assigned according to group function. Then, n_{eff} and $\partial n_{eff} / \partial \lambda$ are calculated from the properties of the selected materials. By substituting the initial structural parameters from step (1) into Equation (3), the first-round value of $\Delta chromatic$ is obtained.
3. The updated $\Delta chromatic$ is substituted back into the zoom equation to form a coupled equation set. An infrared glass library satisfying the dual-band requirements is then established, and a material substitution search is performed in Zemax 2022R2.01. The assumed focal powers, magnifications, and material combinations are then adjusted jointly. The iteration continues until $\Delta chromatic < 0.01$ mm, yielding an initial low chromatic aberration structure. Finally, the constraints are checked to ensure $d_{12s} > 0$, $d_{23l} > 0$, $d_{34s} > d$, $d_{4fs} > 15$ mm, and they confirm that no mechanical interference occurs during zooming.

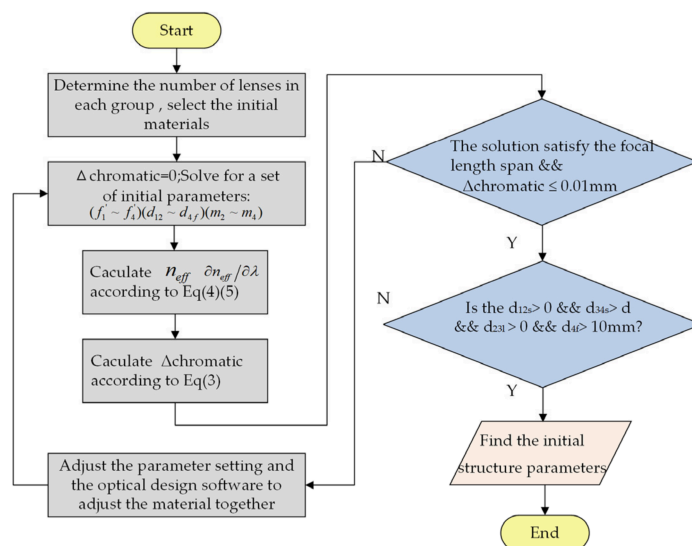


Figure 2. Iterative process for solving the initial structural parameters.

3. Design Example of an Achromatic Dual-Band Infrared Continuous Zoom Optical System

3.1. Design Index

For the room-temperature infrared photoelectric application considered here, the optical system is designed to provide continuous zoom capability while satisfying the chromatic aberration tolerance requirement. The system has a $12\times$ zoom ratio with a focal length range of 10–120 mm, and the total length is less than 190 mm. The working bands

are selected as MWIR and LWIR. After beam splitting, the MWIR and LWIR channels are imaged onto two independent detectors respectively, and uncooled detectors are adopted in both channels. The pixel size of each detector is $25\ \mu\text{m} \times 25\ \mu\text{m}$. The design index is detailed in Table 2.

Table 2. Design index of the infrared optical system.

Parameters	Value
Working band	MWIR 3.7~4.8 μm LWIR 8~10 μm
Focal length	10~120 mm
Distortion	$\leq 3\%$
Chromatic focal shift	$\leq \text{DOF}$
Zoom ratio	12 $\times$
Pixel size	25 μm
Back focal length	$\geq 10\ \text{mm}$

3.2. Calculating the Initial Structure of the Optical System

The steps to solve the initial structural parameters of the dual-band infrared continuous zoom optical system with dual-band chromatic aberration compensation are as follows:

1. The short focal length $f'_s = 10\ \text{mm}$, long focal length $f'_L = 120\ \text{mm}$, and total length $L = 150\ \text{mm}$ are known parameters. The focal lengths ($f'_1 \sim f'_4$) of four groups; the intervals at the short and long focal lengths, namely ($d_{12s} \sim d_{4fs}$) and ($d_{12l} \sim d_{4fl}$); and the magnification ($m_{2s} \sim m_{4s}$), ($m_{2l} \sim m_{4l}$) are the unknown parameters to be solved. The design must avoid mechanical interference at the extreme zoom positions and reserve sufficient back focal length for the detector. Accordingly, a system of equations is established to solve the initial structural parameters.

$$\begin{cases} L = f'_1 + 2(f'_2 + f'_3 + f'_4) - f'_2\left(m_2 + \frac{1}{m_2}\right) - f'_3\left(m_3 + \frac{1}{m_3}\right) \\ \quad - f'_4\left(m_4 + \frac{1}{m_4}\right) + d\left(1 + \frac{1}{n}\right) + \Delta\text{chromatic} \\ f'_s = f'_1 \times m_{2s} \times m_{3s} \times m_{4s}; f'_l = f'_1 \times m_{2l} \times m_{3l} \times m_{4l} \\ d_{12} = f'_1 - \frac{1-m_2}{m_2} f'_2 \\ d_{4f} = (1-m_4) f'_4 \end{cases} \quad (14)$$

Including d_{12s} and d_{4f} in the set of equations both prevents mechanical interference during zooming and simplifies the calculation. The beam splitter prism is modeled using ZNS_BROAD as the substrate material, with a refractive index of 2.25 and a thickness of 16 mm. ZNS_BROAD was selected because it covers both the MWIR and LWIR bands and is suitable for use in infrared beam-splitting components.

2. Solve for the short-focus parameters. Equation (14) comprises four equations with seven variables, with constraints $d_{12s} > 10\ \text{mm}$ and $d_{4fs} > 15\ \text{mm}$. Set the focal length of S1 and the magnification of S4, assuming $m_{4s} = 0.5$. Set f'_2 to approximately 15% of the total length and initially set $\Delta\text{chromatic} = 0$. Based on the first-round solution, $\Delta\text{chromatic}$ is evaluated and substituted back into the equations to iteratively update the initial structural parameters until the stopping criterion is met. The resulting short-focus structural parameters are then substituted into Equation (13) to calculate the corresponding group spacings, d_{23s} and d_{34s} . The solutions may vary with different parameter settings, which are only used as one set of trial solutions.
3. After the short-focus parameters ($f'_1 \sim f'_4$) and ($m_{2s} \sim m_{4s}$) are obtained, the long-focus parameters can be calculated. Substitute the unknown long-focus parameters

($m_{2l} \sim m_{4l}$) into Equation (14) to express the total length L and the long focal length f_l' . Together with Equation (11), solve for ($m_{2l} \sim m_{4l}$). Then, substitute these results into Equation (13) to obtain the interval (d_{12l}, d_{4fl}) at long focus.

4. The obtained parameters are imported into Zemax OpticStudio to build the continuous zoom optical model. Then, optimize the model by writing an evaluation merit function until the MTF, distortion, and chromatic aberration satisfy the application requirements.

Based on the above calculation steps, the initial structural parameters and lens material combination of the dual-band infrared continuous zoom optical system are obtained. The final focal lengths of S1~S4 are listed in Table 3. The intervals between each group at short and long focus are given in Table 4. An ideal model constructed from the initial structural results is shown in Figure 3.

Table 3. Initial focal length of each group of the dual-band infrared optical system.

	S1	S2	S3	S4
EFL/mm	85.000	−22.500	40.637	40.000

Table 4. Initial interval between each group of the dual-band infrared optical system.

	d_{12}	d_{23}	d_{34}	d_{4f}
Short focus $f_s = 10$ mm	13.000	86.524	30.535	20.000
Long focus $f_L = 120$ mm	49.368	4.231	76.401	20.000

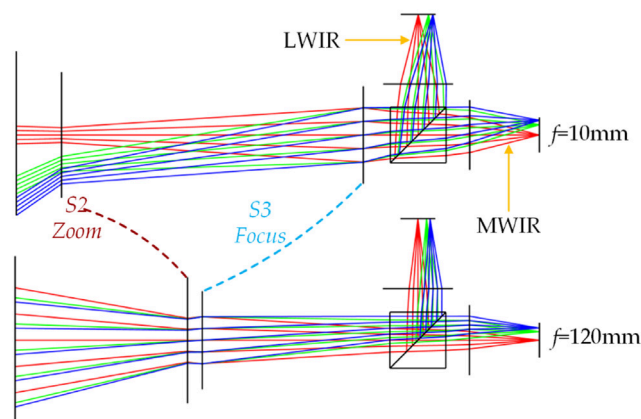


Figure 3. The ideal model of the initial structure.

S1 adopts a two-element lens positive configuration to provide preliminary correction of axial chromatic aberration of the incident light. The chromatic aberration in S1 should be minimized as much as possible [22]. S2 adopts a typical positive–negative lens combination. Chalcogenide glasses, which have a high refractive index and moderate dispersion, are preferred in S2 to reduce chromatic aberration between the two bands. S3 employs a positive–negative–positive triple-lens configuration, while S4 uses three lenses to correct the residual aberrations. The lens counts are chosen as follows: front fixed group S1: two lenses; zooming group S2: two lenses; compensating group S3: three lenses; and rear fixed group S4: three lenses. These configurations satisfy the basic imaging requirements.

After iterative chromatic aberration calculations are performed to optimize the focal power distribution and material combinations within each group, the final material configurations are as follows: S1: IG4/ZNS_BROAD; S2: GASIR1/IG6; S3: IG6/GERMANIUM/ZNSE; and S4: ZNS_BROAD/GASIR1/IG4. The stop moves with S3 throughout the zoom operation. As shown in Figure 3, S2 and S3 move progressively closer as the system focal length increases from short to long. The zoom process exhibits no inflection points.

4. Optimized Design and Performance Evaluation of Optical System

4.1. Optimization Strategy and Design Results

After the initial structural parameters are calculated, the data in Tables 2 and 3 are imported into the optical design software, and the ideal single-lens model is replaced with real lens groups. During this conversion, the basic surface properties are first defined, and it is ensured that each lens possesses sufficient thickness and aperture while avoiding excessively small curvature radius.

The final structure of the optimized achromatic dual-band infrared continuous zoom optical system is shown in Figure 4. Both the MWIR and LWIR subsystems consist of ten lenses and one beam splitter prism each. The system field of view ranges from 2.46° to 27.60° . Neglecting element thickness, the designed total lens length is 150 mm; including element thickness would exceed this value. After optimization, the final zoom system has a total length of 188 mm and a maximum manufacturable lens diameter of 50 mm. The system provides a focal length range of 10–120 mm in the MWIR and LWIR bands. Imaging quality is evaluated at three focal lengths: 10 mm, 70 mm, and 120 mm. A total of six multiple structures are used to analyze the imaging quality of the zoom optical system.

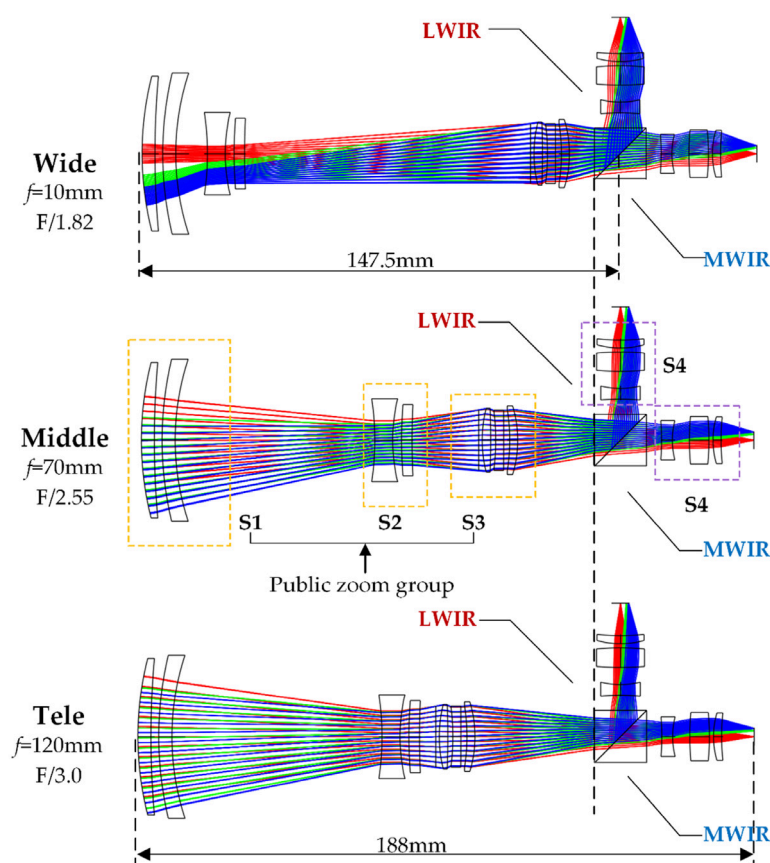


Figure 4. The design result of the achromatic dual-band infrared continuous zoom optical system.

During optimization, sufficient space is reserved between S3 and S4 to accommodate the beam splitter prism. The final distance between the beam splitter prism and S4 is 4.655 mm, and the distance from S4 to the image plane is 11.226 mm. During continuous zooming from a wide to a narrow field of view, the F-number changes approximately linearly from 1.82 to 3.00. The structural parameters of the optical system are given in Table 5, in which surfaces 16 to 20 correspond to the beam splitter prism.

Table 5. The structural parameters of the optical system.

	Surface	Radius/mm	Thickness/mm	Material
S1	1	97.73	3.98	IG4
	2	271.25	2.39	ZNS_BROAD
	3	106.87	4.03	
	4	80.11	9.80–64.29	
S2	5	−85.58	5.49	GASIR1_M
	6	45.92	2.73	IG6
	7	108.34	3.26	
	8	251.33	88.33–4.98	
stop	9	Infinity	1.00	
S3	10	42.74	2.62	IG6
	11	−240.99	1.51	GERMANIUM
	12	−84.92	2.48	
	13	−1300.01	1.84	
	14	−60.10	2.46	ZNSE
	15	−36.98	7.74–36.60	
S4	21	−74.44	3.33	ZNS_BROAD
	22	24.58	5.26	GASIR2
	23	87.22	6.02	
	24	−75.00	1.24	
	25	25.69	2.49	IG4
	25	75.151	11.23	

As shown in Figure 4, when the focal length increases continuously from 10 mm to 120 mm, S2 gradually moves away from S1, while S3 moves toward S2. No mechanical interference occurs, and no inflection point appears during the zoom process. The initial structural calculations assume that S1 and the beam splitter prism remain fixed. In the evaluation merit function, the ZTHI operand is used to control the fixed distance between S1 and the beam splitter prism for all six multiple structures while keeping the image plane fixed.

When an aspherical lens is located near the stop, it can be used to correct aperture-related aberrations; when it is placed far from the stop, it is more effective for correcting field-related aberrations [25]. The Seidel aberration plots obtained during optimization indicate pronounced spherical aberration. Therefore, an even aspheric surface is introduced near the stop to correct this aberration. In addition, guided by the Seidel aberration analysis during the optimization process, surfaces contributing the largest residual aberrations were selected and set as aspheric surfaces for optimization. The final zoom system contains seven even aspheric surfaces, with their locations and parameters detailed in Table 6.

Table 6. Higher-order coefficients of even aspheric surfaces.

Surface No.	Conic	4th-Order Term	6th-Order Term	8th-Order Term
3	−0.776	-1.308×10^{-7}	5.858×10^{-10}	-1.075×10^{-12}
6	−9.317	-8.887×10^{-6}	5.712×10^{-8}	-9.078×10^{-10}
7	−1.499	-9.386×10^{-6}	1.953×10^{-8}	-2.091×10^{-10}
10	2.354	7.484×10^{-6}	-1.124×10^{-8}	-4.164×10^{-10}
12	32.480	-9.154×10^{-6}	9.677×10^{-8}	-2.545×10^{-10}
15	0.762	-3.298×10^{-6}	3.030×10^{-8}	-1.456×10^{-10}
21	39.9998	-1.388×10^{-5}	1.555×10^{-6}	-6.814×10^{-8}

4.2. Image Quality Evaluation

The Modulation Transfer Function (MTF) quantifies the ability of an optical system to transfer contrast over spatial frequency, relating both to its aberrations and diffraction effects. Therefore, MTF curves provide a comprehensive evaluation of image quality and effective resolution. With a pixel pitch of 25 μm , the corresponding Nyquist frequency is 20 lp/mm. The MWIR MTF curves of the dual-band zoom system are shown in Figure 5a–c. At focal lengths of 10 mm, 70 mm, and 120 mm, the MTF of the central FOV at 20 lp/mm exceeds 0.572, while that of the edge FOV exceeds 0.504. The LWIR MTF curves are shown in Figure 5d–f; at the same focal lengths, the MTF of the central FOV at 20 lp/mm exceeds 0.266, while that of the edge FOV exceeds 0.296. Overall, the polychromatic MTF curves at all focal lengths and field positions are relatively concentrated and remain close to the diffraction limit, with no obvious deterioration in imaging performance at any particular field or focal length. This suggests that the system maintains stable image quality indicating effective overall suppression of spherical aberration, astigmatism, and other monochromatic aberrations during optimization.

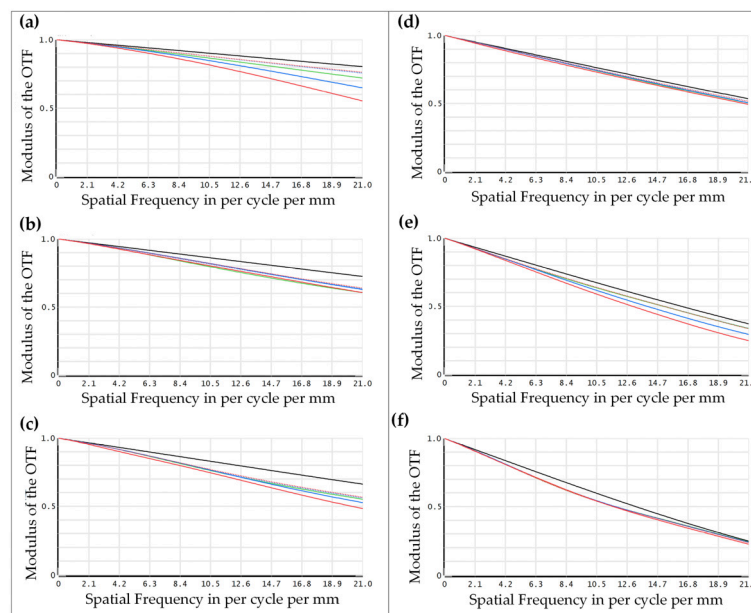


Figure 5. MTF curves of optical system. (a) MWIR $f = 10$ mm; (b) MWIR $f = 70$ mm; (c) MWIR $f = 120$ mm; (d) LWIR $f = 10$ mm; (e) LWIR $f = 70$ mm; and (f) LWIR $f = 120$ mm.

Distortion causes the image positions of off-axis field points on the ideal image plane to shift, thereby changing the image shape without directly degrading image sharpness. Figure 6 shows the distortion performance of the dual-band continuous zoom optical system. The MWIR distortion curves are shown in Figure 6a–c. At focal lengths of 10 mm, 70 mm, and 120 mm, the full-field distortion of the zoom optical system is less than 0.53%, 0.26%, and 0.75%, respectively. The LWIR distortion curves are shown in Figure 6d–f. At the same three focal lengths, the full-field distortion is less than 0.74%, 0.15%, and 0.45%, respectively, which is well below the design limit of 3%.

Chromatic focal shift describes the variation in the focal position with wavelength. By comparing the best-focus positions at different wavelengths, the effect of chromatic aberration on imaging performance across the full operating band can be evaluated. The longitudinal variation in the chromatic focal shift curve directly indicates the magnitude of axial chromatic aberration in the optical system. Figure 7 shows the axial chromatic aberration performance of the dual-band continuous zoom optical system at three representative focal lengths over the 3.7–10 μm spectral range (MWIR to LWIR). With 7 μm

taken as the reference wavelength, the fluctuations in the chromatic focal shift curves at each focal length remain within the depth of focus range ($DOF = 4\lambda F^2$), indicating that the chromatic aberration tolerance requirement is satisfied and that chromatic aberration is effectively corrected.

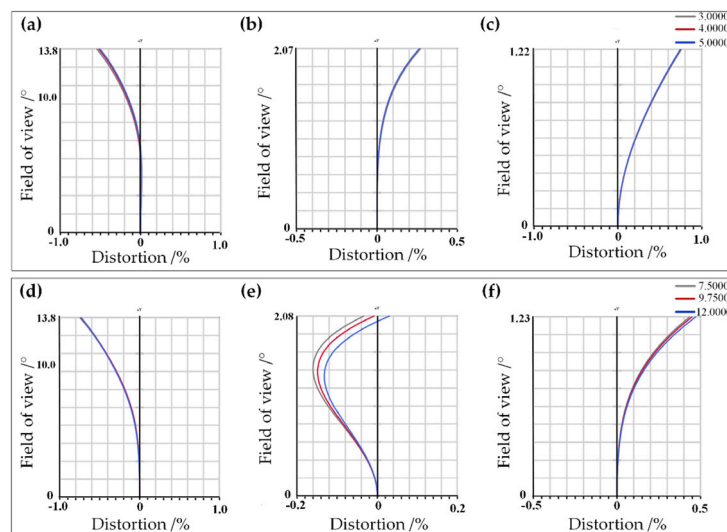


Figure 6. Distortion curves of optical system. (a) MWIR $f = 10$ mm; (b) MWIR $f = 70$ mm; (c) MWIR $f = 120$ mm; (d) LWIR $f = 10$ mm; (e) LWIR $f = 70$ mm; and (f) LWIR $f = 120$ mm.

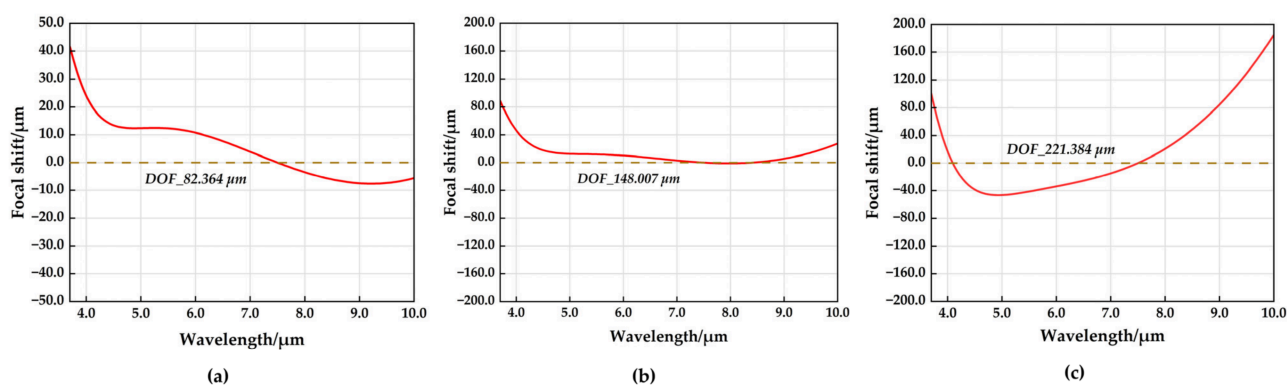


Figure 7. Chromatic focal shift curve of optical system (short to long focal point). (a) MWIR-LWIR $f = 10$ mm; (b) MWIR-LWIR $f = 70$ mm; and (c) MWIR-LWIR $f = 120$ mm.

4.3. Motion Curve and Full Zoom Image Quality Consistency Analysis

To ensure smooth zooming of the optical system, the motion curves should be as free of inflection points as possible. Accordingly, the continuous zoom process is sampled at a series of focal length positions. The axial displacements of the S2 and S3 relative to S1 are recorded as q_1 and q_2 , together with the corresponding focal lengths. The sampled data are then fitted to obtain the motion curves over the full zoom range, as shown in Figure 8. Here, q_1 denotes the displacement of S2 relative to S1, and q_2 denotes the displacement of S3 relative to S1. It can be seen that both S2 and S3 move smoothly during continuous zooming, and no inflection point is observed.

To evaluate the image quality consistency of the dual-band continuous zoom optical system over the full zoom range, 12 focal length positions from 10 mm to 120 mm are selected, and the MTF distributions of the MWIR and LWIR subsystems at 20 lp/mm are analyzed, as shown in Figure 9. The results indicate that the MTF values of both subsystems remain at a relatively high level throughout the full zoom range, and no abrupt degradation

in image quality is observed at any zoom position. Stable imaging performance and good image quality consistency during continuous zooming are thus demonstrated.

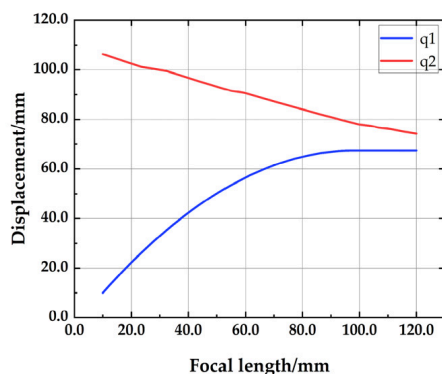


Figure 8. Motion curves of optical system.

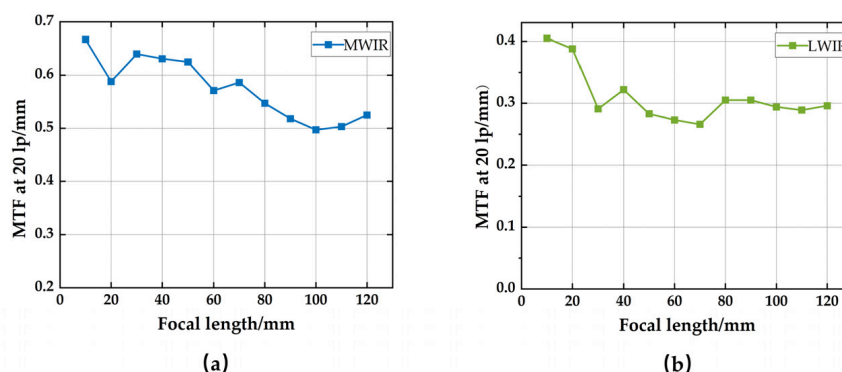


Figure 9. MTF distribution curves of optical system. (a) MWIR subsystems; (b) LWIR subsystems.

4.4. Tolerance Analysis

Tolerance analysis is performed to assess the feasibility of the optical system for fabrication. The axial position of the image plane is used as the assembly compensator. The tolerance allocation of the zoom optical system is shown in Table 7. A sensitivity analysis was conducted using the average diffraction MTF at 20 lp/mm as the performance metric. First, a sensitivity analysis is carried out and the worst-case tolerances are scaled; once the worst-case deviations fall within acceptable range, 400 Monte Carlo trials are performed. The resulting cumulative probability distributions of the average diffraction MTF at 20 lp/mm are shown in Figure 10a–f.

Table 7. Tolerance distribution.

Tolerance	Items	Values
Thickness	Thickness/mm	± 0.025
Surface quality	Radius (fringe)	± 1
	Irregularity (fringe)	± 0.2
	Abbe number (%)	± 1
Material	Refraction index	± 0.001
Surface tolerances	Decenter/mm	± 0.01
	Tilt (')	± 0.01
	Decenter/mm	± 0.03
Element	Tilt (')	± 0.03

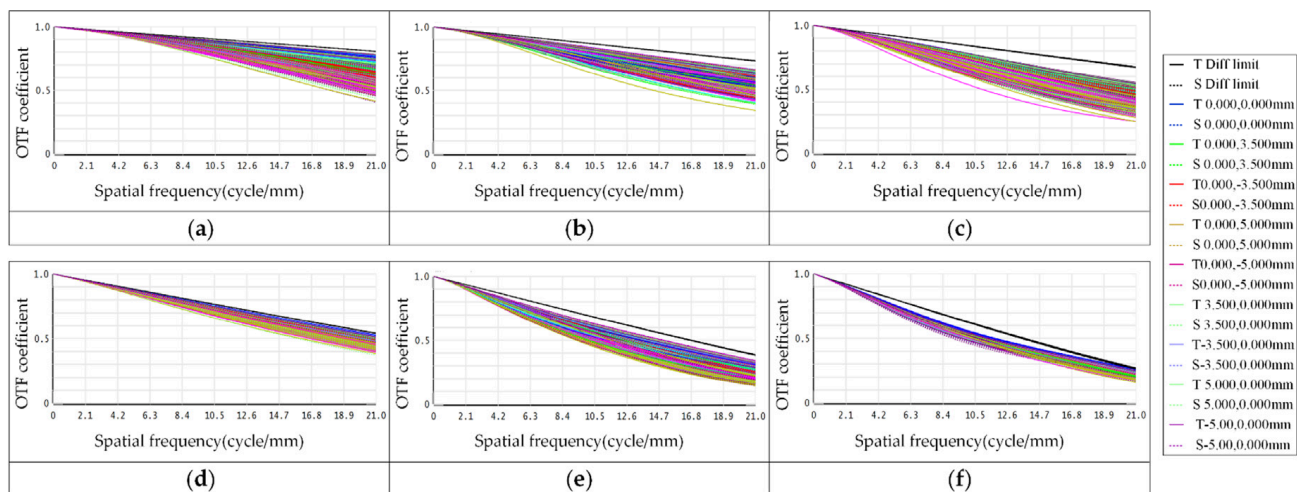


Figure 10. Monte Carlo MTF tolerance analysis results of dual-band infrared continuous zoom optical system. (a) MWIR $f = 10$ mm; (b) MWIR $f = 70$ mm; (c) MWIR $f = 120$ mm; (d) LWIR $f = 10$ mm; (e) LWIR $f = 70$ mm; and (f) LWIR $f = 120$ mm.

The results indicate that image quality remains relatively stable in both bands. As shown in Figure 10a–c, in the MWIR band, there is a 90% probability that the MTF exceeds 0.468 across the full zoom range for each field of view, and a 50% probability that the MTF exceeds 0.515. As shown in Figure 10d–f, in the LWIR band there is a 90% probability that the MTF exceeds 0.244 across the full zoom range for each field of view, and a 50% probability that the MTF exceeds 0.254. These results suggest that, within the specified tolerances, the system maintains the expected imaging performance with acceptable degradation, confirming the validity of the proposed optical design.

5. Conclusions

This paper proposes a chromatic aberration compensation method for a dual-band infrared continuous zoom optical system and verifies it through a MWIR/LWIR design example. By introducing chromatic aberration compensation into the initial structural parameter solving process, a new route is provided for constructing a dual-band achromatic zoom configuration. The final optical system achieves a focal length range of 10–120 mm over the MWIR and LWIR bands. The chromatic focal shift is controlled within the depth of focus. The distortion remains below the design requirement, and stable image quality is maintained over the full zoom range. These results demonstrate the effectiveness of the proposed achromatic strategy and confirm the optical feasibility of the dual-band zoom configuration for room-temperature infrared photoelectric applications. For applications with higher performance requirements, cooled infrared detectors may be further considered to improve the detection capability of the system. In such cases, further optimization would be required in terms of detector selection, and cold stop matching is needed to meet more demanding engineering requirements. In addition, for applications over a wider temperature range, athermalization design remains a topic for future work.

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