Structural Optimization Design of Auxiliary Objective Lens (Postprint)

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Abstract

To facilitate the selection of an appropriate auxiliary objective lens, structural optimization design was conducted on commonly employed doublet-form auxiliary objective lenses from both theoretical derivation and experimental simulation perspectives, based on the working principle of such lenses. According to the design specifications, the initial structure of the auxiliary objective lens was judiciously selected, and various aberrations were theoretically derived. Building upon the initial structure and optimization objectives, structural optimization and aberration analysis were performed on two forms of auxiliary objective lenses using the optical design software OSLO. Subsequently, design optimization was implemented for an innovative doublet-thick meniscus auxiliary objective lens, utilizing structural parameters of similar lenses from existing literature as the initial design configuration, and leveraging OSLO optical software combined with design expertise to execute structural optimization, aberration analysis, and correction. Comparative analysis of the two auxiliary objective lens configurations demonstrates that after optimization, the parameters of both structural forms can meet the design requirements, but the doublet-thick meniscus auxiliary objective lens is more suitable for large-image-plane optical systems.

Full Text

Structural Optimization Design of Auxiliary Objective Lenses

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Abstract

In infinite image distance optical systems, the object is placed at the front focal plane of the objective lens, producing parallel emergent rays that must be converged by an auxiliary objective lens to form an image at its focal plane. The imaging quality of the auxiliary objective critically affects the overall system performance. This paper presents a structural optimization design for auxiliary objective lenses based on both theoretical aberration analysis and experimental simulation using OSLO optical design software. Two structural forms are investigated: a conventional double-cemented design and an innovative thick-meniscus hybrid design. Theoretical derivations of various aberrations are performed for both configurations. Comparative analysis demonstrates that the double-cemented thick-meniscus auxiliary objective is better suited for large-image-plane optical systems. After optimization, both designs meet all specified requirements, with the hybrid structure exhibiting superior aberration correction capability.

1. Introduction

In infinite image distance microscopy systems, placing the object at the object-side focal point yields parallel emergent rays, which facilitates confocal operation and lateral scanning capabilities [1-3]. However, these parallel beams require convergence by an auxiliary objective lens to form a final image. The optical quality of this auxiliary component significantly impacts the overall imaging performance. While previous studies have incorporated auxiliary objectives into confocal and infrared microscope designs [2,3], detailed structural design and optimization methodologies for these components remain underdeveloped. This work addresses this gap by presenting a comprehensive optimization approach for auxiliary objective lenses.

The primary optical specifications for auxiliary objectives include entrance pupil diameter, focal length, field of view, and relative aperture—all of which directly influence imaging quality. Aberrations arise from wavefront deformation due to non-uniform refractive index distribution, though proper lens selection and optimization can substantially reduce or eliminate these errors. This study employs OSLO (Optics Software for Layout and Optimization), a specialized optical design software developed by Lambda Research Corporation in the 1990s, known for its simple interface and fast optimization capabilities [4-6].

2. Design Methodology

The optimization process follows a systematic approach: (1) determination of initial structural parameters using primary aberration theory, (2) establishment of the optical model in OSLO, (3) automated optimization using variable parameters, and (4) manual fine-tuning based on design experience to achieve optimal image quality.

2.1 Double-Cemented Auxiliary Objective Design Initial Structure Calculation

The double-cemented lens group represents the simplest auxiliary objective structure capable of simultaneously correcting axial spherical aberration and sine difference. Figure 1 shows the optical path diagram for a double-cemented lens group, where d represents the separation between lens groups, n' and u' denote the refractive index and angle in image space, y' is the image height, and hz represents external parameters of the lens group. The Lagrange invariant is given by $n' \; u' \; y'$.

For this design, the primary aberration targets are: $m = 0.04$, sine difference S' $FC = 0.05$, and axial spherical aberration within specified limits. Initial structural parameters can be derived from primary aberration formulas or adapted from existing systems with similar optical characteristics [7-9].

Optimization Process

The initial system exhibits poor imaging quality, necessitating parameter optimization. In OSLO, six spherical surface curvature radii are set as variables for automatic optimization, while thicknesses and glass types are typically held constant due to their minor influence on aberrations in this configuration. The optimization function minimizes an error function across multiple variables, though this process may converge to local minima rather than the global optimum. When automated iteration fails to meet requirements, manual adjustment of critical parameters—particularly small curvature radii—is performed while preserving glass types to avoid destabilizing previous optimization efforts.

Optimization Results

After extensive iterative optimization, an ideal parameter set is obtained (Figure 2). The geometric aberration plot (Figure 3) and point spread function (Figure 4) demonstrate excellent correction. Key performance metrics include: MTF ≥ 0.2 at critical frequencies, well-corrected field curvature, and relative distortion of 0.75%. According to the Rayleigh criterion, when the maximum wave aberration is less than λ, the central bright spot contains $ $68% of the total energy, confirming that the optimized double-cemented objective meets all design specifications.

2.2 Double-Cemented Thick-Menisus Auxiliary Objective Design Design Rationale

While double-cemented objectives offer simplicity and compactness, their aberration correction capability is limited, particularly for large-field applications where edge aberrations become significant. The thick-meniscus hybrid structure provides an innovative solution with enhanced correction of axial spherical aberration, astigmatism, and field curvature, making it more suitable for large-image-plane infinite image distance systems.

Initial Parameters and Optimization

Based on design requirements similar to the double-cemented form, key technical specifications include an aperture diameter D and focal length $f' = 200$ mm. The initial structure (Figure 5) is derived from literature sources with comparable optical characteristics. The field of view is set to 3.7°.

The optimization process for this complex structure presents additional challenges. OSLO’ s automatic optimization may encounter multiple local minima, where minimizing one aberration inadvertently increases another. This necessitates extensive design experience and manual intervention to navigate the multi-variable solution space effectively. The optimization strategy involves: (1) automatic error function minimization, (2) manual parameter adjustment based on aberration theory, and (3) fine-tuning through iterative practice to identify efficient optimization paths.

Optimization Results

The optimized hybrid structure parameters are shown in Figure 6. Performance evaluation (Figures 7-9) reveals: MTF ≥ 0.15, well-corrected full-field curvature, relative distortion of 0.08%, and wave aberration distribution that satisfies the Rayleigh criterion across the entire field of view. The point spread function confirms that the central bright spot energy exceeds the 68% threshold, validating the design’ s effectiveness.

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3. Discussion and Comparison

Based on aberration theory and OSLO simulations, both design approaches achieve the required performance after optimization. The double-cemented auxiliary objective offers advantages in structural simplicity and compactness but exhibits limited aberration correction capability. In contrast, the double-cemented thick-meniscus hybrid structure, though more complex, demonstrates superior aberration correction performance [17-21] and is particularly well-suited for large-image-plane systems.

The choice between these configurations depends on specific application requirements. For systems prioritizing compactness and moderate performance, the double-cemented design suffices. For high-performance applications requiring large fields of view and minimal aberrations, the thick-meniscus hybrid is the preferred solution.

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4. Conclusion

This study presents a systematic optimization methodology for auxiliary objective lenses in infinite image distance systems. Through theoretical analysis and OSLO-based simulation, two structural forms are developed and validated.

The double-cemented thick-meniscus hybrid design emerges as a superior solution for large-image-plane applications, offering enhanced aberration correction while meeting all specified optical performance criteria. The proposed approach provides a valuable reference for optical designers developing advanced imaging systems.

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Note: Figure translations are in progress. See original paper for figures.