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Advanced Lens Design and Analysis for Vascular Imaging in The MWIR Band

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Abstract

This study focuses on the design of a lens system operating in the Mid-Wave Infrared (MWIR) range (3.5–4.5 μm) for vascular imaging and blood flow analysis. The MWIR band offers significant advantages, including deeper tissue penetration, reduced scattering, and higher thermal contrast, particularly around body temperature (~37.5°C). These features make MWIR imaging an effective tool for visualizing vascular structures and detecting abnormalities in blood flow. A lens system was designed using ZEMAX and optimized to maximize resolution and contrast for thermal imaging applications. The design exploits the natural thermal emissions of the human body, eliminating the need for external illumination. Results indicate the lens system achieves high sensitivity and resolution, facilitating detailed imaging of small-diameter vessels and thermal anomalies. This innovative approach demonstrates the potential of MWIR-based optical systems for advancing medical imaging technologies, offering a non-invasive, high-contrast solution for cardiovascular diagnostics.

1. Introduction

Modern medical imaging technologies play a critical role in early diagnosis and treatment of diseases. Vascular imaging and blood flow analysis are vital for the diagnosis of cardiovascular diseases. When the rays are directed to the skin, they penetrate the subcutaneous tissue, where the deoxygenated hemoglobin in the vessels absorbs more than the surrounding tissues. Ultrasound is one of the methods used in vascular imaging, but it requires additional skills, and assistance, and is costly[1].

Another method for vascular imaging involves using an infrared light source to image the vessels. This allows the vascular patterns to be seen darker than other tissues using an infrared camera[2]. In the literature, the NIR wavelength is often used for vascular imaging[3,4]. The MWIR band is generally more logical for thermal imaging of blood and vessels. There are several reasons for this. MWIR rays penetrate deeper into the tissues compared to NIR rays, allowing for clearer and deeper imaging of the vessels. Thermal radiation emitted depending on body temperature is stronger in the MWIR band. Although the NIR band provides high resolution due to its short wavelengths, the MWIR band can penetrate deeper into the tissues. MWIR wavelengths are less scattered and absorbed by tissues, resulting in sharper images. While NIR usually requires active illumination (e.g. IR LEDs), MWIR operates by its thermal emission, meaning it provides vision even in the dark. This feature makes it easier to distinguish vessels from surrounding tissues and makes vascular anomalies more visible. Blood moving through vessels has a certain temperature that can be detected, making it suitable for designing a lens operating at the MWIR wavelength. We can notice that the contrast in MWIR bands at 300 K is 3.5-4% compared to 1.6% in the LWIR band. So, the LWIR band may have higher sensitivity for objects at ambient temperature while the MWIR band has more contrast[5].

For this reason, in this work, we focused on lens systems operating in the Mid-Wave Infrared (MWIR) range (3.5-4.5 μm), which offers high sensitivity and resolution for detailed examination of vascular structures and blood flow. The MWIR wavelength increases the thermal contrast between different tissue types. Another reason for designing a lens operating at the MWIR wavelength for high-contrast vascular imaging is shown in Figure 1. This shows how the

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thermal contrast at different wavelength ranges changes depending on the scene temperature (K). Especially around 310.65K (37.5°C), the thermal contrast obtained at the MWIR (3.5-4.5 µm) wavelength range appears to be approximately 2.5 times greater than at the LWIR (8.0- 12.0 µm) wavelength range. This high contrast allows clearer and more detailed visualization of both the vessels and the blood flow within them in the MWIR band. The study[6] corroborates this. The MWIR spectrum better matches the natural thermal emission characteristics of the human body, enabling more sensitive detection of subtle temperature differences in vascular structures. This offers a great advantage, especially in terms of imaging small-diameter vessels and detecting abnormalities in blood flow. In this work, a lens design capable of imaging in the MWIR range has been presented. The applicability of this lens design to vascular imaging and blood flow analysis has been discussed, and the results have been thoroughly analyzed using ZEMAX.

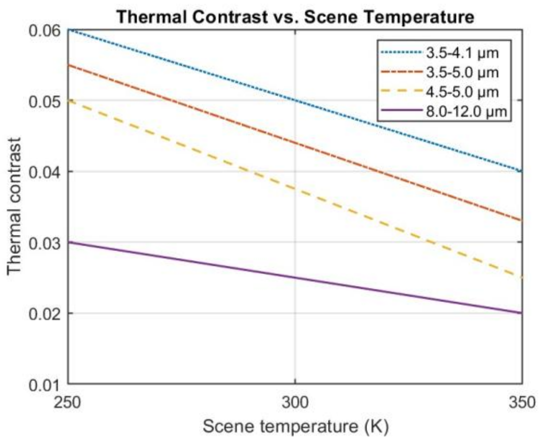

Figure1. Spectral photon contrast in the MWIR and LWIR bands.

2. Materials and Methods

The study was conducted using ZEMAX optical design software to develop a lens system optimized for the Mid-Wave Infrared (MWIR) range (3.5-4.5 µm). The selected lens materials are germanium and silicon due to their high transmittance and refractive properties in the MWIR spectrum.

The system is designed with an effective focal length (EFFL) of 5 mm and a total track length (TOTR) of 6.75 mm. These specifications aimed to achieve high resolution and contrast for thermal imaging of vascular structures. The optical design process included Hammer optimization in ZEMAX to improve imaging performance for thermal radiation emitted by blood vessels at body temperature (~37.5°C). Basic analysis included modulation transfer function (MTF)[7], Field of View (FOV), Spot diagram, Point Spread Function (PSF)[8], Field Curvature and Distortion, Seidel Diagram, Merit Function, Diffraction Image Analysis, Geometric Image Analysis, Optical Path Difference (OPD) and thermal contrast performance evaluation[5].

Simulations were performed to evaluate the imaging quality at different FOV angles (0°, 2° and 4°). Environmental conditions were simulated to ensure system performance in a realistic environment. The final design was validated by evaluating image quality metrics including contrast and resolution under MWIR operating conditions. The results were then analyzed by image analysis to determine the suitability of the lens system for vascular imaging and blood flow analysis.

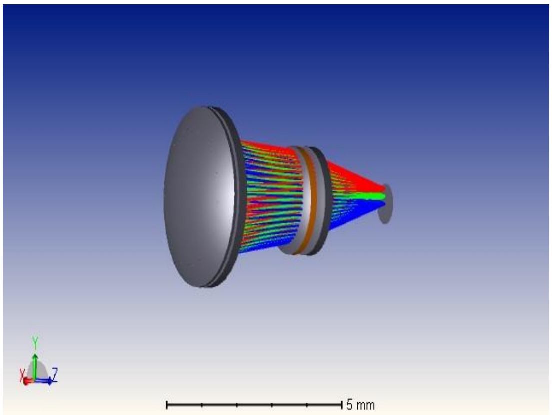

Figure 2. Shaded Model

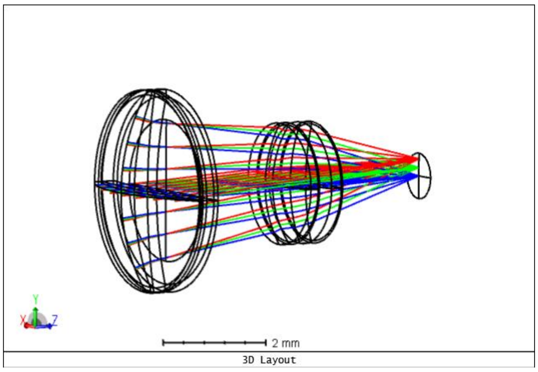

Figure 3. 3D Viewer

Figure 2, the shaded model of the design is presented, while Figure 3 displays the 3D model. The general structure and ray simulations of the lens design can be seen in these visuals. The designed lens system has a total length of 6,75 mm and an effective focal length (EFFL) of approximately 5 mm. This system provides high performance in the MWIR range.

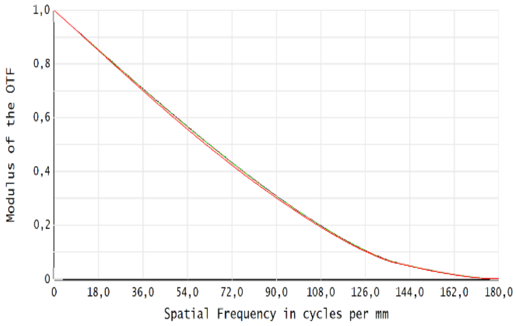

Figure 4. Modulation Transfer Function (MTF) graph of the proposed lens design. This analysis illustrates the lens's ability to resolve spatial frequencies, providing a quantitative assessment of its imaging performance and contrast reproduction across the field of view.

One of the analyses obtained, as shown in Figure 4, shows the MTF (Modulation Transfer Function) of the lens system. The MTF plot illustrates the system's ability to transmit structures at spatial frequencies exceeding the Nyquist frequency with sharpness[9]. This analysis shows the modulation transfer function of the lens against spatial frequencies. The results show that the lens performs well even at high spatial frequencies and shows excellent image quality. In the range of 0-75 cycles/mm, the MTF values of the lens are quite high (about 0.4).

This shows that the optical system achieves high contrast and sharp images at low and medium frequencies. Low frequencies usually represent large and distinct details. Therefore, the designed lens will effectively capture the details that improve the overall image quality. In the range of 75-100 cycles/mm, although the MTF value decreases, it still transmits some details. This shows that the lens continues to capture sufficient details at medium levels and provides satisfactory image quality in this frequency range. In the range of 150-180 cycles/mm, the MTF value starts to approach zero, making contrast transfer quite difficult. However, this decrease at high frequencies is common in all designs. The performance in this range will still be sufficient for applications requiring high resolution. In the figure, results very close to the diffraction limit were obtained in both tangential and sagittal directions at 1024*1024 sampling. This shows that the lens can produce high-quality images and that optical aberrations are minimal. MTF analysis strongly supports the suitability of the designed lens for vascular imaging and blood flow analysis. The lens provides high contrast transfer at low and medium frequencies, allowing clear and detailed imaging of vascular structures.

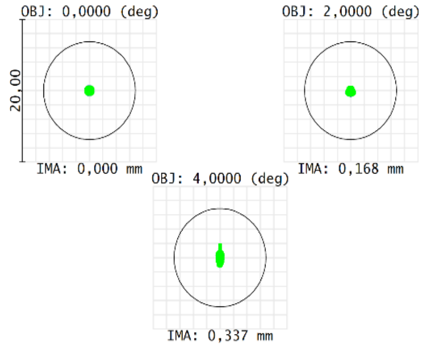

Figure 5. Spot Diagram

In Figure 5, spot diagrams of the lens system are presented. These diagrams show the focusing ability of the optical system and the aberrations in the image. The obtained results show that the lens successfully focuses the rays coming from different angles to the specified points at the design stage and provides high accuracy with low aberration values.

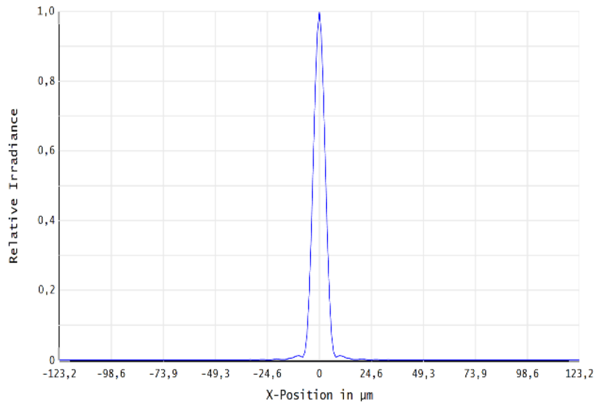

Figure 6. Point Spread Function

Figure 6 presents the PSF (Point Spread Function) analysis of the lens system. This analysis shows how the optical system spreads point sources. The results show that the lens focuses point sources with minimum spread and provides high resolution.

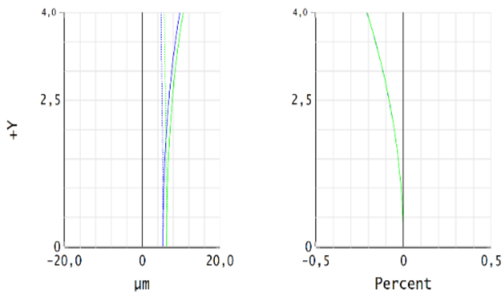

Figure 7. Field Curvative and Distortion

Figure 7 presents the field curvature and distortion analysis of the lens system. The maximum distortion value obtained is 0.2074%. This analysis shows that the lens operates with minimal distortion and field curvature and supports high image accuracy. Field curvature and distortion can cause both degraded image quality and positional inaccuracies for moving targets, and can also negatively affect the smooth merging of component images[10].

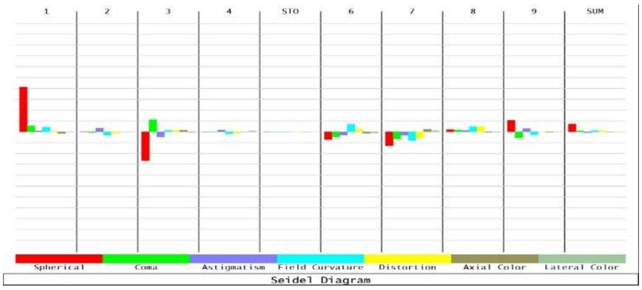

Figure 8. Seidel Diagram

Figure 8 is a diagram showing the optical defects found in the designed lenses according to individual surfaces. It is shown by the analysis that these defects are reduced to a very minimal level with the optimizations made in the SUM section at the end of the diagram.

The Merit Function is a mathematical expression that depends on the optical system parameters, including the radii of curvature of the lenses, lens thicknesses, the geometric positions of the elements, and the refractive indices[11]. This function is an error measure that shows how well the design complies with the targeted optical performance. It is usually used to minimize deviations from the targeted values.

The closer the merit function value is to zero, the more ideal the design is and the closer it is to the targeted parameters. The merit function value obtained for our design reached 0.0845531. This value shows that our design is very close to the targeted performance criteria and that design errors are kept at a minimum level. A low merit function value indicates that the optical system has high resolution and provides the desired optical quality. This result shows that the design is quite successful in terms of optical performance and is optimized according to the targeted vascular imaging features.

Figure 9 shows the Extended Diffraction Image Analysis graph. This analysis shows how the optical system processes an image by diffraction. In the image, a large letter "F" is represented by different intensity levels. These intensities represent the frequency and image sharpness of the lens system.

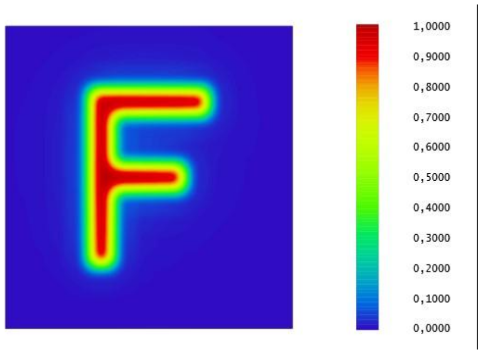

Figure 9. Diffraction Image Analysis. This figure illustrates the diffraction-limited performance of the lens system, demonstrating the quality and sharpness of the image formed.

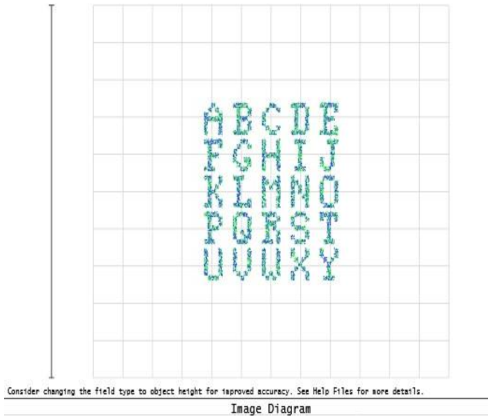

Figure 10. Geometric Image Analysis

The details of the letter are quite clearly visible. This shows that the system works with sufficient resolution. The spread caused by diffraction can cause some blurring at the edges of the image. However, the edges of the letter are still quite clearly visible here. This shows that the diffraction effect is minimal and that the details of the veins can be well preserved. Another image analysis is shown in Figure 10. This analysis is Geometric Image Analysis. It shows how the optical system is displayed geometrically. The first 25 letters of the alphabet are shown in the image and each letter is clearly recognized. This shows that the system is not affected by geometric distortions. The 100.00% information given in the image shows that the system uses energy very efficiently and that all energy contributes to the image creation process.

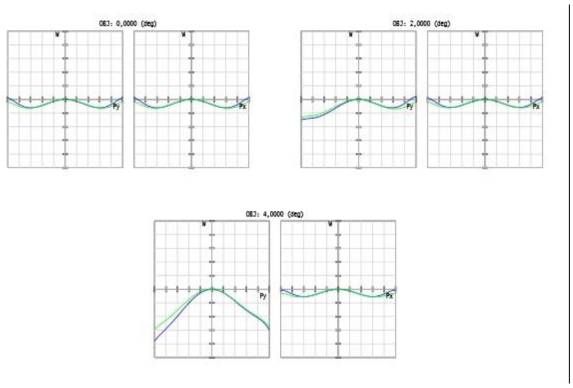

Figure 11. Optical Path Difference (OPD)

The OPD Fan is a metric utilized to quantify deviations of light waves from the ideal wavefront within an optical system [12]. The wavefront, in an ideal scenario, is a surface on which the light waves are in phase, indicating that the optical paths of the waves are identical. In practice, however, this ideality is unattainable due to inherent material properties and design limitations, leading to deviations from the ideal wavefront. In Figure 11, the OPD Fan graph for our optical system is presented. The analysis reveals that the OPD deviations are constrained within ±0.1 waves, demonstrating the system's superior optical performance, with minimal aberrations. Such low levels of deviation are crucial for the efficacy of thermal imaging systems, where precise wavefront control is essential for maintaining image quality. The OPD Fan graph further indicates that the Px and Py curves exhibit a generally flat and consistent profile, suggesting that the system’s astigmatism and field curvature are well-corrected and maintained at minimal levels. Moreover, the consistent profiles of OPD values at varying field angles (0°, 2°, 4°) underscore the system's ability to maintain robust performance across a wide field of view. In conclusion, the OPD Fan analysis confirms that the optical deviations within the system are exceptionally low. This indicates that the proposed optical system can achieve high-contrast, high-resolution thermal imaging while maintaining consistent and superior image quality across a wide range of viewing angles.

3. Results and Discussion

The results of all analyses confirm that the designed optical system is highly suitable for vascular imaging. The MTF analysis demonstrates sufficient contrast transfer, while the PSF analysis verifies that the lens achieves high resolution by focusing point shifts with minimal spread. The point diagram indicates that the lens accurately focuses rays from different angles onto the specified points with low deviation, ensuring high precision. The Seidel diagram shows that optical aberrations on the lens surfaces are minimized. The maximum distortion value is a low 0.2074%, confirming that the design delivers high resolution and minimal distortion. The Extended Diffraction Image Analysis highlights the system's ability to maintain high-resolution details with minimal diffraction effects. Geometric image analysis reveals that the optical system operates efficiently and without geometric distortions.

The system’s effective focal length (EFFL) is approximately 5 mm, and the total optical path (TOTR) is around 6.75 mm, reflecting its compactness and optimized dimensions. The high MTF values indicate that the design meets the required contrast levels for vascular imaging, providing sharp and clear images for accurate target detection. The low merit function value further confirms the system’s high resolution and optical quality. Optical path difference (OPD) analysis demonstrates excellent optical performance with minimal aberrations, while consistent OPD profiles verify the system’s robust performance across a wide field of view. These findings collectively establish that the designed optical system delivers exceptional performance for vascular imaging applications.

4. Conclusions

The compact design with an effective focal length (EFFL) of approximately 5 mm and a total optical path (TOTR) of 6.75 mm ensures the adaptability of the system to biomedical applications. Operating in the MWIR range, the lens system benefits from the enhanced thermal contrast of body temperature emissions and offers significant advantages over traditional methods such as ultrasound or NIR imaging in terms of high resolution without the use of an external light source.

Future work could focus on integrating this optical system into a complete imaging setup for real-time vascular imaging. Further improvements could explore broader medical applications such as detecting vascular anomalies or assisting in noninvasive diagnostics. This work contributes to the advancement of optical systems for thermal imaging in the biomedical field.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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