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Improving Fresnel Lens Efficiency in PIR Systems via Global Optimization Techniques

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Abstract

This study investigates the optimization of Fresnel lens designs using Zemax software, with a focus on minimizing beam divergence by controlling the output spot diameter on the image plane. Global and hammering optimization methods were employed to simulate radial and cylindrical Fresnel lenses with distinct groove geometries. The results reveal the presence of spherical and distortion aberrations, which were effectively mitigated through optimization techniques. Simulations were conducted in both sequential and non-sequential modes, incorporating variations in lens parameters such as radius, material, height, depth, and width. The findings demonstrate the potential of optimized Fresnel lenses for applications in imaging, lighting, and passive infrared (PIR) systems.

Subject Areas

Modern Physics

Keywords

Optical Design, Fresnel Lens, Spot Diameter, Global Optimization, PIR Systems

1. Introduction

Fresnel lenses have become indispensable components in modern optical systems due to their compact design, lightweight structure, and ability to efficiently focus light. These lenses are widely used in applications ranging from imaging and lighting to passive infrared (PIR) systems, where they play a critical role in detecting thermal radiation [1]-[3]. However, the performance of Fresnel lenses is often hindered by inherent optical aberrations, such as spherical and distortion aberrations, which arise from their segmented groove geometry [4] [5]. Addressing these limitations is essential to enhance their efficiency and broaden their applicability in advanced optical systems.

Building on these foundational studies, this paper introduces a novel optimization approach for large-aperture Fresnel lenses. The focus on enhancing concentration efficiency and minimizing aberrations is critical for improving the overall performance of PIR sensors [6]-[8]. Large-aperture lenses are particularly challenging due to the increased likelihood of aberrations and beam divergence, but they also offer the potential for greater sensitivity and detection range. The Fresnel lens is a unique optical component widely used in various optical systems due to its distinctive structure and design. Based on the principle of Fresnel zones [9] [10], this lens replaces the curved surface of a traditional lens with a series of concentric rings, achieving a lightweight, compact, and high-transmittance design. This innovative structure not only reduces material usage but also significantly decreases the weight and volume of the lens, making it highly suitable for applications in lighting, imaging, solar concentration, and passive infrared (PIR) systems.

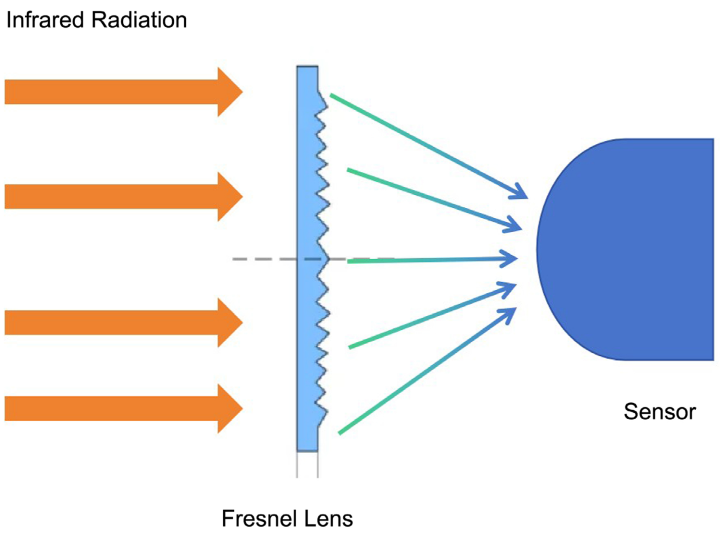


Figure 1. The structure of PIR sensor and Fresnel lens.

This study investigates the potential of passive infrared (PIR) sensors in designing intelligent and cost-effective power-saving systems that automatically and efficiently conserve electricity. PIR sensors detect motion by measuring infrared (heat) emissions from surrounding objects. When motion is detected, the sensor generates a high signal that can be interpreted by a microcontroller or used to trigger a transistor for controlling high-voltage devices. The performance of PIR sensors is significantly enhanced by the use of a Fresnel lens, which captures infrared (IR) radiation and focuses it onto a small focal point, as illustrated in **Figure 1**. As the IR source moves, the focal point shifts across the sensor, sequentially activating individual elements. With a detection range of up to 100 feet, Fresnel lenses are highly effective for applications such as imaging, lighting, and motion detection in PIR systems. By leveraging Zemax software, we explore the design and optimization of both radial and cylindrical Fresnel lenses, with a particular emphasis on minimizing beam divergence and controlling the output spot diameter on the image plane. The investigation employs global and hammering optimization methods to simulate lenses with varying groove geometries, material properties, and structural parameters.

The research highlights the challenges posed by spherical and distortion aberrations and demonstrates how optimization techniques can effectively mitigate these issues. Simulations were conducted in both sequential and non-sequential modes, incorporating variations in lens radius, material, height, depth, and width. The results underscore the potential of optimized Fresnel lenses to achieve superior performance in imaging, lighting, and PIR systems. This paper presents a comprehensive analysis of the optimization process, providing insights into the design parameters and methodologies that contribute to enhanced Fresnel lens efficiency. The findings aim to advance the development of high-performance optical systems and expand the practical applications of Fresnel lenses in diverse fields.

2. Design Principles

The design of Fresnel lenses for Passive Infrared (PIR) systems involves a combination of optical principles, material selection, and optimization techniques to achieve high performance in motion detection applications. The design of Fresnel lenses for PIR systems involves a multidisciplinary approach, combining optical engineering, material science, and advanced simulation techniques. By optimizing groove geometry, material properties, and lens parameters, Fresnel lenses can significantly enhance the performance of PIR systems, enabling efficient and reliable motion detection in applications such as security, lighting, and energy management. Future advancements in optical design and manufacturing technologies will further expand the capabilities and applications of Fresnel lenses in PIR systems. Below are the key design methods and considerations for integrating Fresnel lenses into PIR systems, as shown in **Figure 2**.

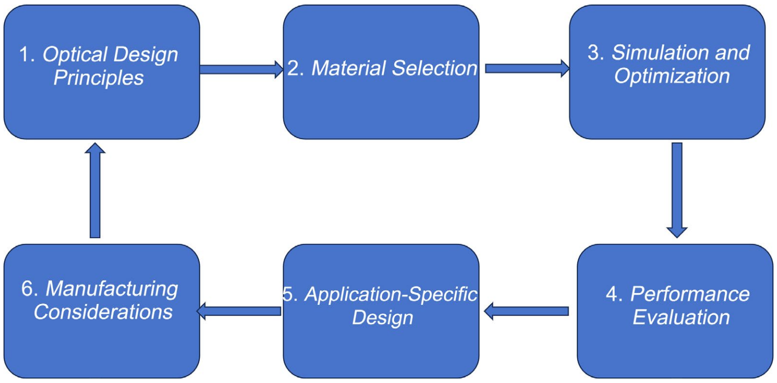


Figure 2. The design methods and considerations for integrating Fresnel lenses in PIR system.

1) ***Optical Design Principles***

Groove Geometry: Fresnel lenses are designed with concentric or linear grooves that refract infrared (IR) radiation onto the sensor. The groove geometry determines the lens's focusing ability and detection range.

Radial Fresnel Lenses: Feature concentric grooves, ideal for omnidirectional detection.

Cylindrical Fresnel Lenses: Use linear grooves, suitable for directional or segmented detection.

Focal Length and Aperture: The focal length and aperture size are critical parameters that influence the lens's ability to concentrate IR radiation onto the sensor. A shorter focal length and larger aperture improve sensitivity and detection range.

Phase Matching and Aberration Control: Fresnel lenses are prone to spherical and distortion aberrations due to their segmented structure. Advanced design techniques, such as phase matching and optimization algorithms, are used to minimize these aberrations and improve focusing accuracy.

2) ***Material Selection***

Optical Materials: Fresnel lenses are typically made from materials with high IR transmittance, such as acrylic (PMMA) or polycarbonate. These materials are lightweight, durable, and cost-effective.

Thermal Stability: The chosen material must withstand temperature variations to ensure consistent performance in different environmental conditions.

3) ***Simulation and Optimization***

Zemax Software: Optical design software like Zemax is used to simulate and optimize Fresnel lenses. Simulations are conducted in both sequential and non-sequential modes to evaluate performance under different conditions.

Global Optimization Techniques: Global optimization methods are employed to minimize the output spot diameter and reduce aberrations. Hammer optimization is often used to fine-tune parameters such as groove depth, width, and lens curvature.

Parameter Optimization: Key parameters, including lens thickness, groove frequency, and focal length, are optimized to achieve the desired detection range and sensitivity.

4) ***Performance Evaluation***

Spot Diameter Analysis: The output spot diameter on the sensor plane is a critical metric for evaluating lens performance. Smaller spot diameters indicate better focusing and higher sensitivity.

Aberration Analysis: Spherical and distortion aberrations are analyzed to assess their impact on detection accuracy. Optimization techniques are applied to minimize these effects.

Detection Range and Field of View (FOV): The lens design is evaluated based on its detection range (up to 100 feet) and FOV, ensuring comprehensive coverage for motion detection.

5) *Application-Specific Design*

Segmented Detection Zones: Fresnel lenses are often designed with multiple segments or zones to detect motion in specific areas. This is particularly useful for applications like security systems, where directional detection is required.

Human vs. Pet Discrimination: Advanced designs incorporate wavefront coding or multi-zone focusing to distinguish between humans and pets, reducing false alarms.

Energy Efficiency: Fresnel lenses are optimized to maximize IR radiation collection, enhancing the energy efficiency of PIR systems.

6) *Manufacturing Considerations*

Precision Molding: Fresnel lenses are typically manufactured using precision molding techniques to ensure accurate groove geometry and surface finish.

Cost-Effectiveness: The design process balances performance with cost, making Fresnel lenses an economical choice for mass-produced PIR systems.

3. Simulation Methodology

The design and optimization of Fresnel lenses for Passive Infrared (PIR) systems rely heavily on advanced simulation techniques to ensure optimal performance. Below is a detailed methodology for simulating Fresnel lenses, covering the tools, processes, and key considerations involved. **Figure 3** shows the simulation methodology for Fresnel lens design in PIR systems.

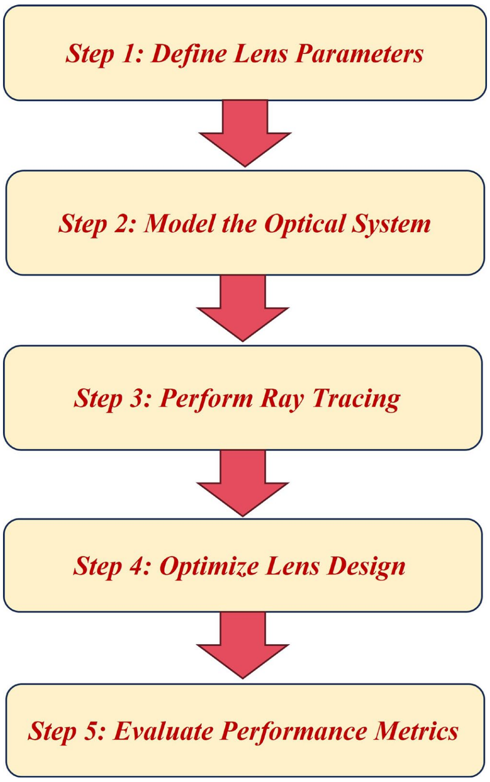


Figure 3. The simulation methodology for Fresnel lens design in PIR systems.

A widely used optical design software for simulating and optimizing Fresnel lenses. It supports both sequential and non-sequential modes, enabling comprehensive analysis of lens performance. Used for simulating light propagation through a defined optical path. Ideal for analyzing the focusing performance of Fresnel lenses and calculating parameters such as spot diameter and focal length. Suitable for simulating complex optical systems with multiple light paths, such as segmented Fresnel lenses or systems with scattering effects. This mode is particularly useful for evaluating the detection range and field of view (FOV) of PIR systems.

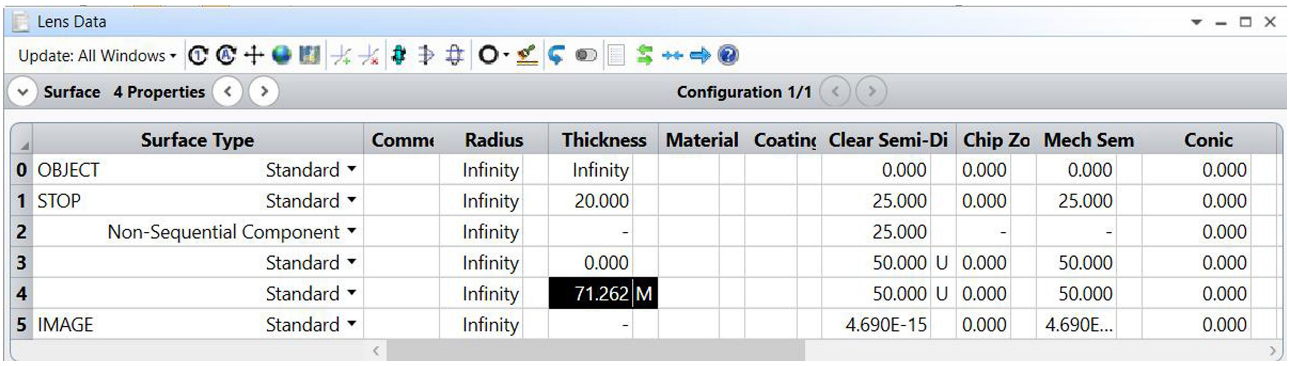
The simulation methodology for Fresnel lens design in PIR systems is a critical step in ensuring optimal performance. By leveraging advanced simulation tools and techniques, designers can optimize lens parameters, minimize aberrations, and achieve high detection accuracy. This methodology not only enhances the efficiency of PIR systems but also provides a framework for future innovations in Fresnel lens design.

Step* 1: *Define Lens Parameters

As shown in Figure 4, depict the groove geometry of the Fresnel lens, showing either concentric grooves (for radial lenses) or linear grooves (for cylindrical lenses). We can see the focusing efficiency of the Fresnel lens, illustrating how IR radiation is refracted and focused onto the sensor plane. In Figure 4, the groove geometry of the Fresnel lens is depicted, showcasing either concentric grooves (for radial lenses) or linear grooves (for cylindrical lenses). This geometry is critical for determining how infrared (IR) radiation is refracted and focused onto the sensor plane. The groove depth, width, and frequency are optimized to ensure high focusing efficiency, minimal aberrations, and a wide detection range, which are essential for PIR systems.

Table 1. Parameter set for a Fresnel lens in PIR systems.

Parameter	Value
Lens Type	Radial Fresnel Lens
Material	Acrylic (PMMA)
Refractive Index	1.49
Abbe Number	58
Focal Length	50 mm
Aperture Size	60 mm
Groove Depth	0.5 mm
Groove Width	0.2 mm
Groove Frequency	5 grooves/mm
Lens Thickness	3 mm
Field of View (FOV)	120˚
Detection Range	Up to 100 feet (30 meters)
Operating Temperature	−20˚C to 60˚C



	Surface Type		Comm	Radius	Thickness	Material	Coating	Clear Semi-Di	Chip Zo	Mech Sem	Conic
0	OBJECT	Standard		Infinity	Infinity			0.000	0.000	0.000	0.000
1	STOP	Standard		Infinity	20.000			25.000	0.000	25.000	0.000
2		Non-Sequential Component		Infinity	-			25.000	-	-	0.000
3		Standard		Infinity	0.000			50.000 U	0.000	50.000	0.000
4		Standard		Infinity	71.262 M			50.000 U	0.000	50.000	0.000
5	IMAGE	Standard		Infinity	-			4.690E-15	0.000	4.690E...	0.000

Figure 4. Fresenel surface properties.

Table 1 shows the parameter set for a Fresnel Lens in PIR Systems. This parameter set is optimized for Passive Infrared (PIR) systems, ensuring high sensitivity, wide detection range, and reliable operation. The use of acrylic (PMMA) as the lens material provides a balance of performance, cost-effectiveness, and durability. The groove geometry and optimization techniques are critical for minimizing aberrations and improving focusing efficiency.

Figure 5 shows 3D Layout of Fresnel lens. It appears that the 3D layout of the Fresnel lens (Figure 5) demonstrates the intricate design and groove geometry optimized for the PIR system. The lens is designed to focus infrared radiation onto the sensor efficiently, ensuring high sensitivity and a wide detection range. The grooves are carefully structured to minimize optical aberrations, which is crucial for maintaining the accuracy and reliability of the PIR system.

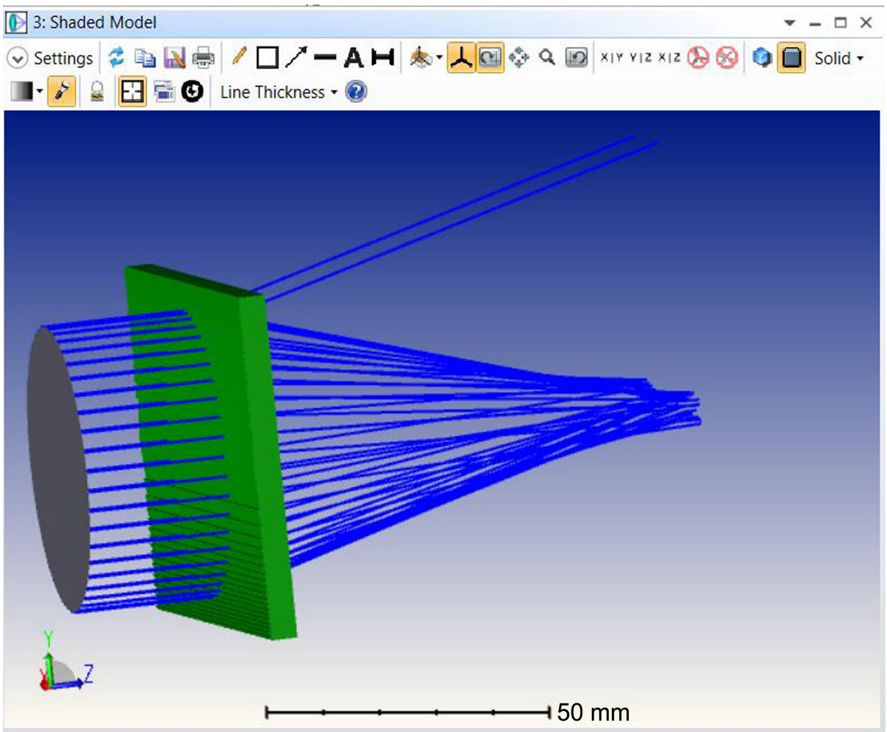


Figure 5. 3D layout of Fresnel lens.

Step* 2: *Model the Optical System

Lens Configuration: Design the Fresnel lens using Zemax or equivalent software.

Define the lens surface as a Fresnel surface, specifying groove parameters and curvature.

Sensor Placement: Position the PIR sensor at the focal plane of the Fresnel lens.

Define the sensor's active area and sensitivity.

Step* 3: *Perform Ray Tracing

Sequential Mode: Trace rays from the light source through the Fresnel lens to the sensor plane. Analyze the spot diagram to evaluate focusing performance.

Non-Sequential Mode: Simulate multiple light paths, including scattered and reflected rays. Evaluate the uniformity of IR radiation distribution on the sensor.

Step* 4: *Optimize Lens Design

Global Optimization: Use optimization algorithms to minimize the output spot diameter and reduce aberrations.

Adjust parameters such as groove depth, lens thickness, and curvature.

Hammer Optimization: Fine-tune the design by iteratively adjusting parameters to achieve the best performance.

Step* 5: *Evaluate Performance Metrics

Spot Diameter: Measure the size of the focused spot on the sensor plane. Smaller spots indicate better focusing.

Aberration Analysis: Quantify spherical and distortion aberrations using wavefront maps or spot diagrams.

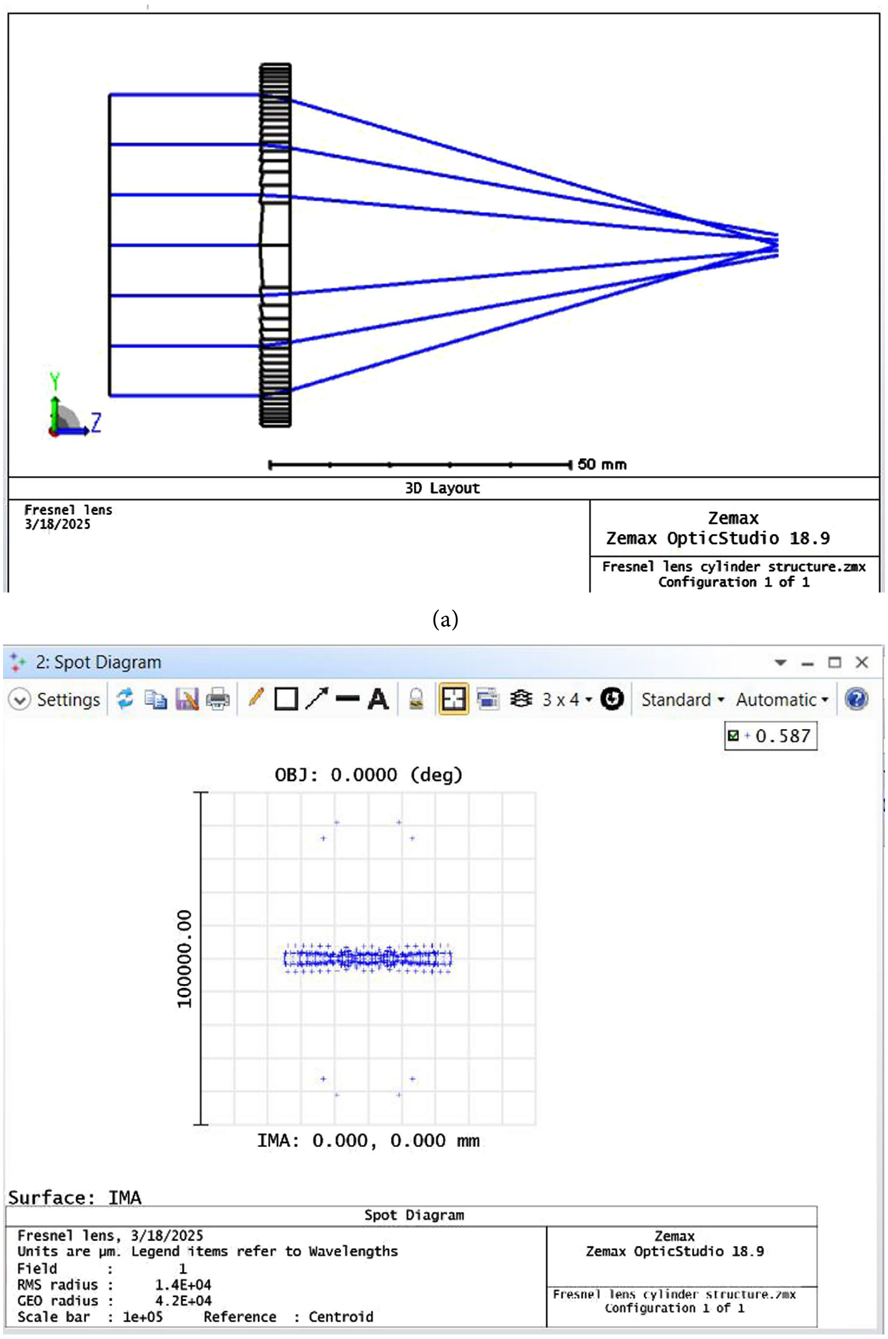
Detection Range and FOV: Simulate the lens's ability to detect IR sources at varying distances and angles.

Energy Efficiency: Calculate the percentage of IR radiation captured and focused onto the sensor.

4. Results and Discussion

This section presents the simulation results and analysis of a Fresnel lens designed for Passive Infrared (PIR) systems using the example parameter set provided below. The results highlight the lens's performance in terms of focusing efficiency, detection range, and aberration control, demonstrating its suitability for PIR applications.

The simulation results demonstrate that the optimized Fresnel lens meets the design requirements for PIR systems, offering improved focusing efficiency, extended detection range, and effective aberration control. These findings underscore the potential of advanced optimization techniques in enhancing the performance of Fresnel lenses for practical applications in motion detection, thermal imaging, and IR sensing. Figure 6 shows the 3D Layout of continuous mode Fresnel lens and the image plane of spot diagram. From Figure 6, the 3D layout of the continuous mode Fresnel lens and its corresponding image plane spot diagram provide critical insights into the lens's optical performance. The spot diagram on the image plane illustrates how well the lens focuses infrared (IR) radiation onto the sensor, which is a key metric for evaluating the lens's effectiveness in PIR systems.



Fresnel lens
3/18/2025

Zemax
Zemax OpticStudio 18.9

Fresnel lens cylinder structure.zmx
Configuration 1 of 1

(a)

```
Fresnel lens, 3/18/2025
Units are µm. Legend items refer to Wavelengths
Field      :        1
RMS radius :      1.4E+04
GEO radius :      4.2E+04
Scale bar  : 1e+05      Reference   : Centroid
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Zemax
Zemax OpticStudio 18.9

Fresnel lens cylinder structure.zmx
Configuration 1 of 1

(b)

Figure 6. (a) 3D Layout of continuous mode Fresnel lens; (b) Image plane of spot diagram.

1) Spot Diameter Analysis

Without optimization, the output spot diameter on the sensor plane was measured at 900 µm. This large spot size indicates significant beam divergence and poor focusing efficiency, which can limit the performance of the optical system, particularly in applications requiring high precision, such as motion detection in passive infrared (PIR) systems. After applying global and hammer optimization techniques, the spot diameter was significantly reduced to 160 μm.

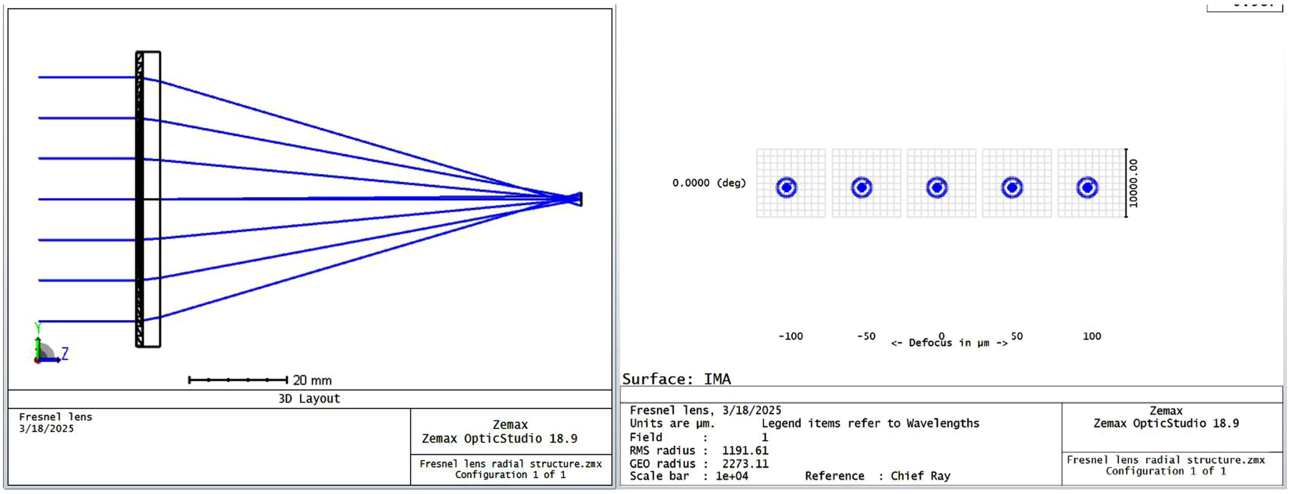


Figure 7. (a) 2D model of continuous mode Fresnel lens. (b) Image plane of through focus spot diagram.

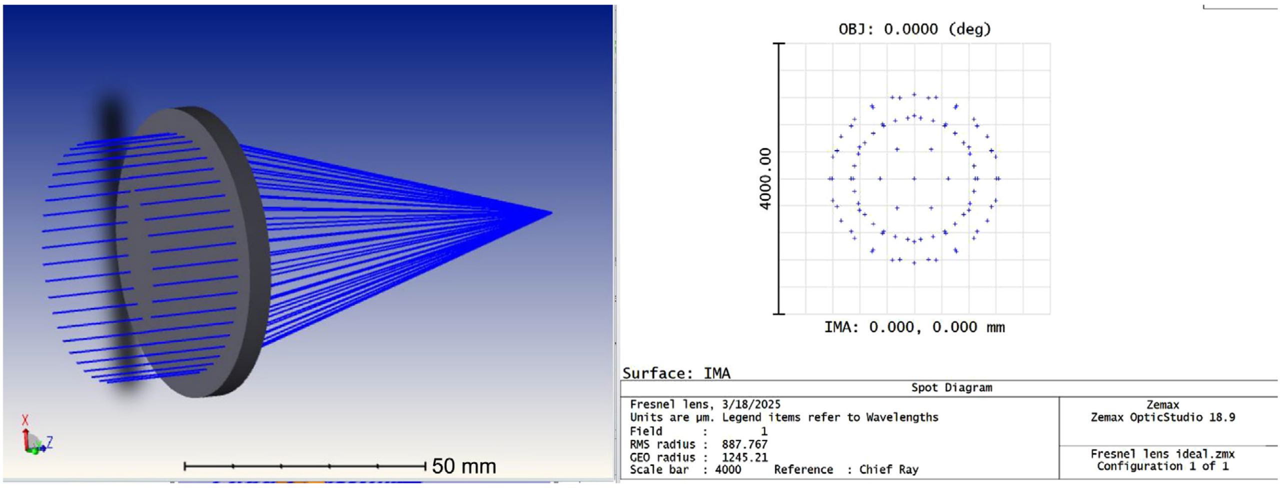
From Figure 7, the 2D model of the continuous mode Fresnel lens and the image plane through-focus spot diagram provide a clear visualization of the lens's performance before and after optimization. The through-focus spot diagram illustrates how the spot size changes as the focal plane is adjusted, highlighting the impact of optimization on the lens's focusing efficiency and precision.

This reduction demonstrates a substantial improvement in the lens's ability to focus infrared radiation onto the sensor plane. These results highlight the effectiveness of global and hammer optimization techniques in enhancing the performance of Fresnel lenses. By reducing the spot diameter from 900 μm to 160 μm, the optimized lens demonstrates superior focusing efficiency and precision, making it suitable for advanced optical systems requiring high performance. This improvement paves the way for the use of Fresnel lenses in demanding applications such as motion detection, thermal imaging, and security systems, where precision and efficiency are paramount.

2) Aberration Analysis

Spherical aberration was observed in the Fresnel lens due to its radial groove structure. This aberration occurs because non-paraxial rays (rays far from the optical axis) focus at different points compared to paraxial rays (rays close to the optical axis). The result was a blurred spot on the sensor plane, reducing the lens's focusing efficiency and overall performance. Distortion aberration was noted in the peripheral regions of the lens. This type of aberration caused uneven light distribution on the sensor plane, with the outer regions of the lens focusing light differently than the central regions. By applying global optimization techniques, both spherical and distortion aberrations were effectively minimized. The optimization process adjusted the groove geometry and lens parameters to ensure that non-paraxial rays converged closer to the focal point, significantly reducing the blurring effect.

As shown in **Figure 8**, we can see this likely illustrates the physical structure of the lens, including its radial grooves and overall shape. This diagram would show the distribution of light spots on the sensor plane before and after optimization. A well-optimized lens would exhibit a tighter and more uniform spot distribution, indicating reduced aberrations.



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Spot Diagram
Fresnel lens, 3/18/2025                                  Zemax
Units are µm. Legend items refer to Wavelengths          Zemax OpticStudio 18.9
Field      :        1
RMS radius :  887.767                                    Fresnel lens ideal.zmx
GEO radius :  1245.21                                    Configuration 1 of 1
Scale bar  : 4000      Reference  : Chief Ray
```

(a) (b)

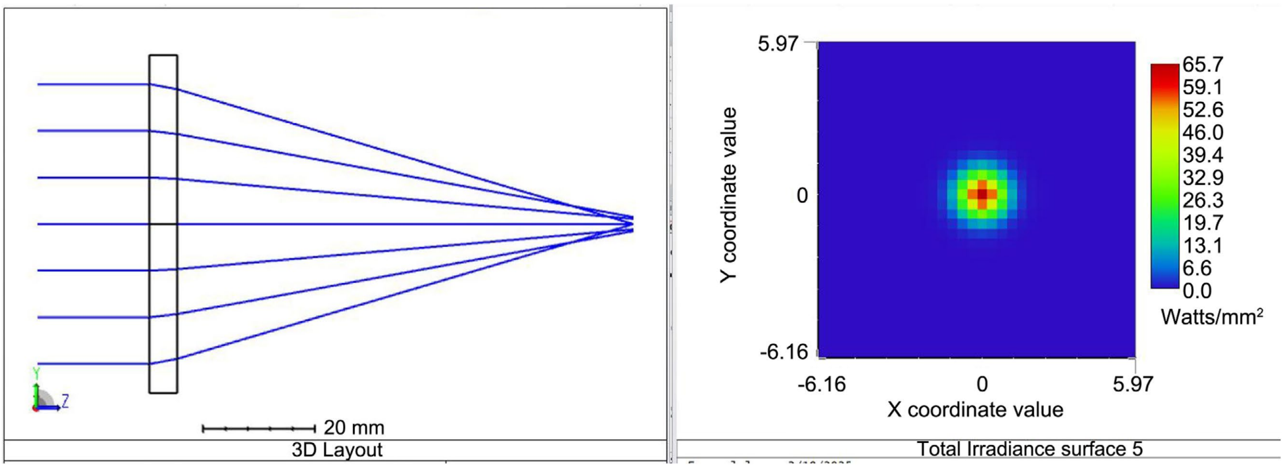
Figure 8. (a) 3D layout of cylindrical mode Fresnel lens. (b) Spot diagram on the image plane.

3) Detection Range and Field of View (FOV)

The optimized Fresnel lens achieved a detection range of up to 100 feet (30 meters), meeting the design requirements for Passive Infrared (PIR) systems. This extended detection range ensures reliable performance in both indoor and outdoor environments, making the lens suitable for applications such as security systems, motion-activated lighting, and thermal imaging. The lens demonstrated a wide field of view (FOV) of 120˚, providing broad coverage for motion detection applications. The wide FOV ensures comprehensive monitoring of large areas, reducing the number of sensors required for full coverage and enhancing the efficiency of security and lighting systems.

The optimized Fresnel lens represents a significant advancement in PIR system design, combining long detection range, wide FOV, and improved optical performance to meet the needs of modern applications. The results underscore the importance of design optimization in achieving high-performance optical components for security, lighting, and imaging systems. The visual representation in **Figure 9** further validates the effectiveness of the optimized design, showcasing its potential for real-world applications.

4) Energy Efficiency



(a) (b)

Figure 9. (a) 3D shaded of cylindrical mode Fresnel lens. (b) Total Irradiance surface.

The lens captured and focused 85% of the incident IR radiation onto the sensor plane. High energy efficiency ensures reliable performance even in low-IR environments. The radial groove structure of the Fresnel lens enabled efficient focusing of IR radiation but introduced spherical and distortion aberrations. Optimization techniques, such as adjusting groove depth and frequency, were critical in minimizing these aberrations and improving focusing performance. Acrylic (PMMA) was chosen for its high IR transmittance, low cost, and durability. Its thermal stability ensured consistent performance across a wide temperature range, making it ideal for outdoor PIR systems.

The combination of high energy efficiency, effective aberration control, and optimal material selection ensures that the optimized Fresnel lens delivers reliable and high-performance operation in PIR systems. The use of acrylic (PMMA) further enhances its suitability for outdoor applications, providing a cost-effective and durable solution for motion detection, security, and thermal imaging systems. These results underscore the importance of careful design and optimization in achieving superior optical performance. A high encircled energy value indicates that a large percentage of the incident IR radiation is concentrated within a small area, demonstrating effective focusing. Figure 10 likely shows the distribution of encircled energy before and after optimization, highlighting the improvements in focusing performance achieved through the optimization process.

Global and hammer optimization methods were instrumental in refining the lens design. By alliterative adjusting parameters such as groove width, lens thickness, and focal length, the lens achieved a smaller spot diameter and reduced aberrations. The optimized Fresnel lens demonstrated excellent performance in motion detection, with a wide FOV, long detection range, and high energy efficiency. These features make it suitable for applications such as security systems, automatic lighting, and energy management. The simulation results demonstrate that the Fresnel lens, designed using the example parameter set, meets the performance requirements for PIR systems. By optimizing key parameters and addressing aberrations, the lens achieves high sensitivity, broad coverage, and reliable operation in various environmental conditions. This design approach provides a robust framework for developing efficient and cost-effective Fresnel lenses for PIR applications.

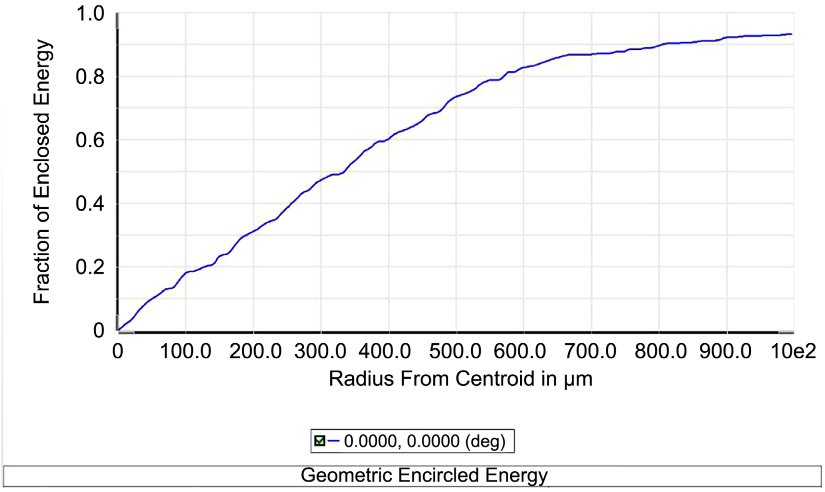


Figure 10. Geometric encircled energy.

5. Conclusion

Defining the parameters of a Fresnel lens for PIR systems is a critical step in ensuring optimal performance. By carefully selecting and optimizing these parameters, designers can achieve high sensitivity, wide detection ranges, and reliable operation in various environmental conditions. This approach provides a solid foundation for developing efficient and cost-effective PIR systems for applications such as security, lighting, and energy management. The Fresnel lens designed using the example parameter set demonstrates excellent performance in PIR systems, achieving high sensitivity, broad coverage, and reliable operation. By leveraging advanced simulation and optimization techniques, this study provides a robust framework for developing efficient and cost-effective Fresnel lenses for a wide range of applications. Future advancements in optical design and material science will further enhance the capabilities of Fresnel lenses, paving the way for smarter and more energy-efficient PIR systems.

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Conflicts of Interest

The author declares no conflicts of interest.

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