OCAK 2024 M.Sc. in Optical Engineering MUSTAFA CÜNEYT MEMİŞ

REPUBLIC OF TÜRKİYE

GAZİANTEP UNIVERSITY

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

STATIC LOGO PROJECTION LAMP OPTICAL DESIGN FOR AUTOMOTIVE LIGHTING APPLICATIONS

M.Sc. THESIS

IN

OPTICAL ENGINEERING

BY

MUSTAFA CÜNEYT MEMİŞ

JANUARY 2024

STATIC LOGO PROJECTION LAMP OPTICAL DESIGN FOR AUTOMOTIVE LIGHTING APPLICATIONS

M.Sc. Thesis

in

Optical Engineering

Gaziantep University

Supervisor

Prof. Dr. Ahmet BİNGÜL

by

Mustafa Cüneyt MEMİŞ

January 2024

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Mustafa Cüneyt MEMİŞ

ABSTRACT

STATIC LOGO PROJECTION LAMP OPTICAL DESIGN FOR AUTOMOTIVE LIGHTING APPLICATIONS

MEMİŞ, Mustafa Cüneyt
M.Sc. in Optical Engineering
Supervisor: Prof. Dr. Ahmet BİNGÜL
Ocak 2024

47 pages

Projection lamps are a lighting technology that has been used in the automotive industry in recent years, providing the opportunity to get in and out of the vehicle safely by illuminating the surroundings of vehicles with a logo image, and aiming to minimize accident rates by reflecting turn and reverse signal lights on the ground. In this study, which was carried out by considering the Köhler lighting concept, which is one of the design approaches of modern illumination systems, light emitting diode (LED) was used as the illumination source. In the automotive lighting industry, polymer materials and injection molds are used to easily produce light-bending surfaces and enable mass production at low cost. In the design of the system, the optical properties of the polymer materials (Polycarbonate (PC) and Polymethyl methacrylate (PMMA) to be used in lenses and the limitations of injection molding technology were used as input in ANSYS Zemax OpticStudio, an optical design and analysis program. This logo lamp, located inside the exterior rearview mirror housing, has dimensional restrictions due to other components inside the mirror. For this reason, the number and size of lenses to be used in optical design are designed to be as small as possible while providing sufficient optical output performance. Thus, the optical design and performance analysis of a logo projection lamp that complies with the design requirements, has a compact structure with three lenses, optimized optical deviations and uniform light intensity distribution were carried out.

Key Words: Projection Lamp, Optical Design, Illumination, Zemax

ÖZET

OTOMOTİV AYDINLATMA UYGULAMALARI İÇİN STATİK LOGO PROJEKSİYON LAMBASININ OPTİK TASARIMI

MEMİŞ, Mustafa Cüneyt
Yüksek Lisans, Optik Mühendisliği
Danışman: Prof. Dr. Ahmet BİNGÜL
Ocak 2024
47 sayfa

Projeksiyon lambaları, otomotiv sektöründe son yıllarda kullanılmaya başlanan, araçların çevresini logo görüntüsüyle aydınlatarak güvenli bir şekilde araca binme ve inme imkanı sağlayan, dönüş ve geri sinyal ışıklarını yere yansıtarak kaza oranlarının en aza indirilmesini amaçlayan bir aydınlatma teknolojisidir. Modern aydınlatma sistemlerinin tasarım yaklaşımlarından biri olan Köhler aydınlatma konsepti dikkate alınarak gerçekleştirilen bu çalışmada aydınlatma kaynağı olarak ışık yayan diyot (LED) kullanılmıştır. Otomotiv aydınlatma sektöründe, ışığı büken yüzeylerin kolayca üretilmesi ve düşük maliyetle seri üretime olanak sağlanması için polimer malzemeler ve enjeksiyon kalıpları kullanılmaktadır. Sistemin tasarımında, lenslerde kullanılacak polimer malzemelerin (Polikarbonat (PC) ve Polimetil metakrilat (PMMA) optik özellikleri ve enjeksiyon kalıplama teknolojisinin sınırlamaları, optik tasarım ve analiz programı olan Optic Studio Zemax'te girdi olarak kullanılmıştır. Konumu dış dikiz aynası muhafazasının içi olarak belirlenen bu logo lambası, aynanın içindeki diğer bileşenlerden dolayı boyutsal kısıtlamalara sahiptir. Bu nedenle optik tasarımda kullanılacak lenslerin sayısı ve boyutu yeterli optik performans çıktısı sağlarken mümkün olduğu kadar küçük olacak şekilde tasarlanmaktadır. Böylece tasarım gerekliliklerine uygun, üç lensli kompakt yapıya sahip, optik sapmaları optimize edilmiş ve tekdüze ışık yoğunluğu dağılımına sahip bir logo projeksiyon lambasının optik tasarımı ve performans analizi gerçekleştirildi.

Anahtar Kelimeler: Projeksiyon Lambası, Optik Tasarım, Aydınlatma, Zemax

''Dedicated to my family''

ACKNOWLEDGEMENTS

I would like to express my gratitude, Prof. Dr. Ahmet BİNGÜL for his guidance and support throughout the study. During my undergraduate and master's years, he was not only my supervisor but also like my older brother. I am thankful for his encouragement and motivation.

I would like to thank FEKA Automotive management for their support during the time I worked there.

I would like to express my love and gratitude to my wife and daughter, who are my biggest source of motivation, for always being by my side and supporting me throughout both my academic and professional career.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

Q_v	Luminous energy
Φ_v	Luminous flux or Luminous power
I_v	Luminous intensity
E_v	Illuminance
L_v	Luminance
θ	Angle

LIST OF ABBREVIATIONS

LDE	Lens Data Editor
MFE	Merit Function Editor
COP	Cyclo Olefin Polymer
FDE	Field Data Editor
EMS	Electromagnetic Spectrum
GEO	Geometric Radius
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LPL	Logo Projection Lamp
MEMS	Micro Electro Mechanic Systems
MTF	Modulation Transfer Function
PC	Polycarbonate
PCB	Printed Circuit Board
PET	Polyethylene Terephthalate
PMMA	Polymethyl Methacrylate
USAF	United States Air Force
UV	Ultraviolet
3D	Three Dimensional

CHAPTER I

INTRODUCTION

From the inception of the automobile industry, safety precautions have been consistently enhanced and expanded, drawing from past experiences. The fundamental objective of these efforts is to guarantee road safety. Ensuring the safety of passengers inside the vehicle, pedestrians outside, animals, and the general public is a complex task. This is particularly crucial for autonomous vehicles, which are anticipated to become common in the future and must incorporate comprehensive safety measures. In this context, lighting and signaling devices to be installed on vehicles must be thoughtfully designed and possess specific characteristics. Consequently, the significance of industrial lighting products that reliably meet lighting requirements is on the rise. As a result, vehicles need to be more conspicuous and discernible.

Beyond ensuring road safety, the industry is also focusing on engaging customers with innovative lighting techniques. These include the use of logo lamps positioned in the front lighting clusters of the vehicles, inside the external rearview mirrors, or beneath the doors to project static or dynamic visuals onto the ground when entering or exiting the vehicle.

The primary consideration is to maintain the desired optical characteristics at every stage, from the design of the vehicle's lighting products to their delivery to the customer. Another key factor in lighting is that when the product is in use, the product image and the lit area should have a uniform light output throughout the lighting area, sharp contrast, high resolution, and no hot-spots or dark areas on the product. The requirement for a diverse range of functional lenses and light sources of different wavelengths to create products in various styles significantly escalates the design complexity and cost of the product. In this context, ensuring the compatibility of the lens materials and light sources used will decrease the number of components in the designed electronic printed circuit board (PCB) and the PCB driving current, thereby also reducing the cost. Simultaneously, using a light source with the least power will mitigate the thermal effect, power consumption, and intricate circuit designs on the product, enabling a more compact PCB and optical design. In the automotive lighting industry, polymethylmethacrylate (PMMA) and polycarbonate (PC) materials are the most favored transparent materials. These materials are among the polymer materials with the highest average light transmission in the visible region of the electromagnetic spectrum (EMS). Light-transmissive polymer materials are chosen over glass due to their numerous advantages such as impact absorption capability, low density, ease of manufacture, ability to facilitate more intricate surface designs, low labor cost, reusability, lightweight, and more flexible structure. PMMA polymer is particularly favored over PC polymers in the automotive lighting industry due to its resistance to ultraviolet (UV) rays. Furthermore, PC polymers are chosen for their flexibility and higher temperature resistance.

Automotive lighting products must undergo standard photometry measurements to identify and mitigate light defects that could arise due to environmental conditions and potential adverse effects on the vehicle. These tests are compulsory and necessary for the product to be approved for mass production. During these tests, the final lighting product's compliance with legal and customer specifications is verified by positioning it in the vehicle as per the standards. With the advancement of software technology, it is now feasible to analyze these tests by creating a numerical model prior to part production, using design and analysis programs based on fundamental scientific laws and formulas. Photometry tests conducted using a digital model can more easily detect issues such as insufficient light, contrast, aberration, light burn-in, and dark areas, eliminating additional costs in studies of new models and components under varying environmental conditions and positions. These photometry tests, carried out using an optical design and analysis program, expedite the design process and decrease troubleshooting costs when used concurrently with the design phase. Hence, conducting photometry tests by creating a numerical model is critically important in terms of cost-effectiveness and reliability. Particularly, the use of numerous optical lenses and the design and analysis of intricate lighting and signaling systems in more compact sizes necessitate expertise, experience, and proficiency.

Upon reviewing the literature, it is evident that there are investigations into the optical properties of logo projection lamps (LPL). However, it appears that studies involving numerical modeling of the optical properties of light-transmitting polymer materials based on their quantity, and those with high contrast and resolution, are relatively scarce. This thesis study aims to address this deficiency by conducting the optical design and performance analysis of a logo projection lamp. This LPL, with its three-lens compact structure, optimized optical deviations and uniform light intensity distribution, is being studied for the first time in our country. Another motivation is that the gains obtained from the static logo projection lamp will form the basis of dynamic projection logo lamps, which are expected to become more widespread in the future.

The initial segment of the study discusses the role of LPL in the automotive industry and its prospective significance. The subsequent part incorporates theoretical details like light, photometry, lenses, polymer materials, and aberrations that are essential in the design of LPL. The third section refers to the literature studies, the Ansys Zemax OpticStudio® program utilized in optical design and analysis, and the design steps. The final chapter presents and assesses the outcomes of all the studies conducted thus far.

CHAPTER II

THEORETICAL BACKGROUND

Light, a form of electromagnetic radiation, is a fundamental aspect of our visual perception and has been the subject of scientific inquiry since ancient times. Ibn al-Haytham, also known as father of modern optics, has made numerous significant contributions to the field of optics. His most influential work is the "Kitāb al-Manāẓir" (Book of Optics), written during 1011–1021, which significantly reformed the field of optics and laid the foundation for modern physical optics. He was the first to correctly explain the theory of vision, arguing that vision occurs in the brain and is subjective, affected by personal experience. He also stated the principle of least time for refraction, which would later become Fermat's principle. His major contributions to catoptrics and dioptrics include studying reflection, refraction, and the nature of images formed by light rays. These contributions have had a profound impact on the field of optics and continue to influence modern scientific thought. In the 17th century, Sir Isaac Newton conducted experiments with prisms and discovered that white light is composed of a spectrum of colors. He also proposed that light is made up of particles, which he called corpuscles. In the 19th century, James Clerk Maxwell developed a theory of electromagnetism that explained the behavior of light as an electromagnetic wave. This theory was later confirmed by experiments conducted by Heinrich Hertz.

2.1 Light, Optics and Photometry

2.1.1 Light

Light is an electromagnetic radiation that is visible to the human eye. It is typically defined as having wavelengths in the range of 400–700 nanometres [nm], corresponding to frequencies of 750–420 terahertz [1]. However, in physics, "light" may refer more broadly to electromagnetic radiation of any wavelength, whether visible or not Figure 2.1. Light waves are composed of a mixture of electricity and magnetism; hence they are referred to as electromagnetic waves. These waves travel at an incredible speed of about 300,000 kilometers (186,000 miles) per second. This means a beam of light could circumnavigate the world 7.5 times in just one second [1]. The primary properties of light include intensity, propagation direction, frequency or wavelength spectrum, and polarization. Its exact speed in a vacuum, is 299,792,458 m/s. This is one of the fundamental constants of nature. Light propagates by massless elementary particles called photons that represent the quanta of the electromagnetic field, and can be analyzed as both waves and particles.

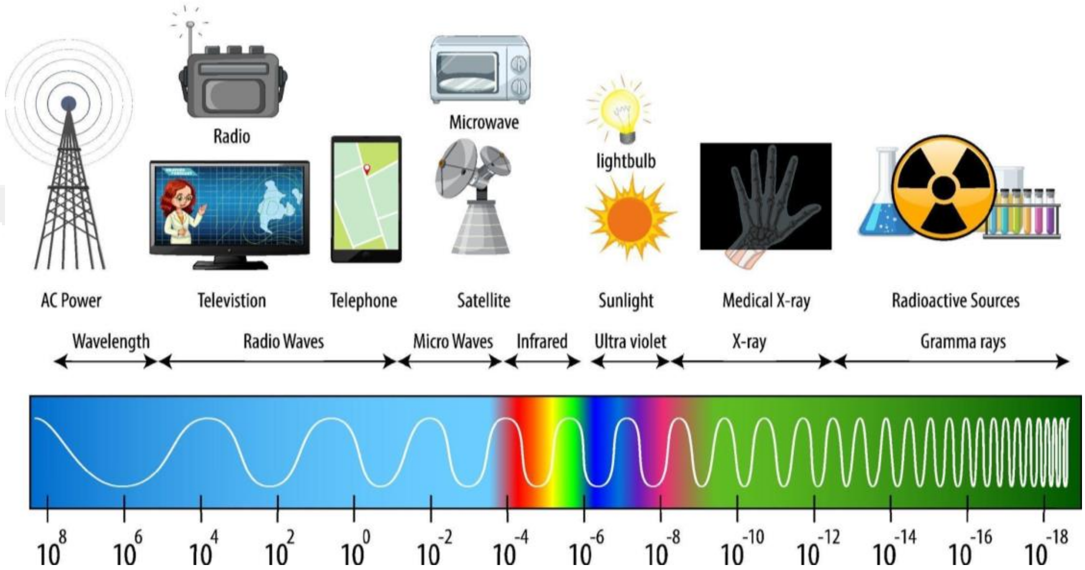


Figure 2.1 Electromagnetic spectrum.

2.1.2 Optics

Optics is a branch of physics that studies the properties and behavior of light, including its interactions with matter and the construction of instruments that use or detect it [2,3]. It can be divided into several branches:

i. *Geometrical Optics:* This branch of optics involves the use of light rays to determine how light interacts with planar and curved surfaces to produce images. It is concerned with the principles that govern the image-forming properties of devices that make use of light [2].

ii. *Physical Optics:* This branch deals with the wave properties of light. Topics such as interference, diffraction, coherence, and polarization fall under this category. It also covers the propagation of electromagnetic waves from multiple perspectives [3].

iii. *Quantum Optics:* This branch studies the quantum mechanical properties of light. It deals with the interaction of photons with matter and other photons, and the manipulation of light on the quantum level [2].

In the context of optics, light can travel in three ways from a source to another location: directly from the source through empty space; through various media; and after being reflected from a mirror. The index of refraction of a material is

$$n = c / v \tag{2.1}$$

where *v* is the speed of light in a material and *c* is the speed of light in a vacuum. The ray model of light describes the path of light as straight lines. The part of optics dealing with the ray aspect of light is called geometric optics [2].

The phenomena of reflection, refraction, transmission, absorption, diffusion and scattering are also crucial aspects of light's behavior (Figure 2.2.)

Reflection is the process by which light bounces off a surface and changes direction. The angle of incidence, or the angle at which the light strikes the surface, is equal to the angle of reflection, or the angle at which the light bounces off the surface. A smooth surface, such as a mirror, reflects light in a single direction, while a rough surface, such as paper, reflects light in many directions.

Refraction is the process by which light bends as it passes through a medium, such as air, water, or glass. The amount of bending depends on the angle at which the light enters the medium and the refractive index of the medium. The refractive index is a measure of how much the speed of light is reduced when it passes through the medium. When light passes from a medium with a low refractive index to a medium with a high refractive index, it bends towards the normal, or the line perpendicular to the surface of the medium. When light passes from a medium with a high refractive index to a medium with a low refractive index, it bends away from the normal.

Transmission is the process by which light passes through a medium without being absorbed or reflected. Transparent materials, such as glass, allow light to pass through them with little or no distortion. Translucent materials, such as frosted glass, allow some light to pass through them but scatter the light in many directions. Opaque materials, such as wood or metal, do not allow light to pass through them at all.

Absorption is the process by which light is absorbed by a material and converted into other forms of energy, such as heat. Different materials absorb different wavelengths of light. For example, a red apple appears red because it absorbs all colors of light except for red, which it reflects.

Diffusion is the process by which light is scattered in many directions as it passes through a medium. This can occur when light passes through a medium with particles that are larger than the wavelength of the light. The particles scatter the light in many directions, causing it to appear hazy or cloudy.

Scattering is the process by which light is redirected in many directions as it passes through a medium. This can occur when light passes through a medium with particles that are smaller than the wavelength of the light. The particles scatter the light in many directions, causing it to appear blue or red depending on the size of the particles.

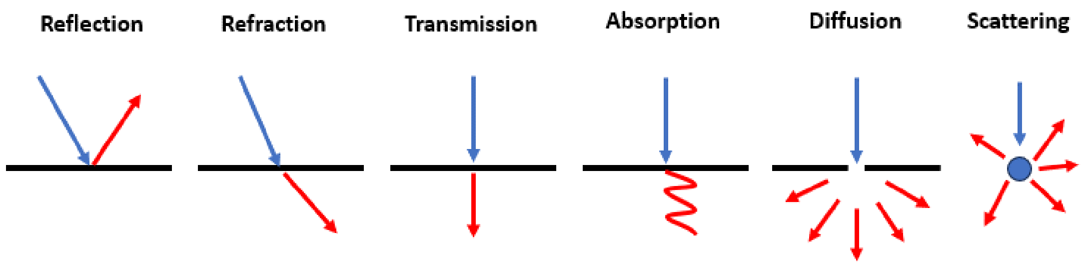


Figure 2.2 Light's behavior in optical region.

2.1.3 Radiometry and Photometry

Radiometry and photometry are both branches of optics that deal with the measurement of light, but they differ in the types of light they focus on [4-7].

Radiometry is the science of measuring light in any portion of the electromagnetic spectrum. In practice, the term is usually limited to the measurement of infrared, visible, and ultraviolet light using optical instruments [4]. Radiometry measures the spatial properties of light and performs lighting calculations in a physically correct manner. It assumes a geometric optics model of light, where photons travel in straight lines, represented by rays [5].

On the other hand, photometry is the science of measuring visible light in units that are weighted according to the sensitivity of the human eye. It is a quantitative science based on a statistical model of the human visual response to light under carefully controlled conditions. In photometry, we do not measure watts of radiant energy. Rather, we attempt to measure the subjective impression produced by stimulating the human eye-brain visual system with radiant energy [4].

Photometry has several key concepts [8]:

Luminous Flux: The total amount of visible light emitted by a source per unit of time, measured in lumens.
Luminous Intensity: The amount of visible light emitted by a source in a particular direction, measured in candela.
Illuminance: The total amount of visible light illuminating a surface, measured in lux
Luminance: The amount of visible light leaving a point on a surface in a particular direction, measured in candela per square meter.
The luminosity function (or luminous efficiency function) describes the average spectral sensitivity of human visual perception of brightness. This function is determined by International Commission on Illumination (CIE) is the international authority on light, illumination, color, and color spaces.

Table 2.1 Some SI photometric units.

Quantity	Symbol	SI unit	Abbreviation
Luminous energy	Q_v	lumen.second	lm.s
Luminous flux or Luminous power	Φ_v	lumen	lm
Luminous intensity	I_v	candela	cd = lm/sr
Illuminance	E_v	lumen per meter-square	lux = lm/m^2
Luminance	L_v	lumen per steradian per meter-square	$lm/sr.m^2 = cd/m^2$

Photometric measurements are essential in various fields such as lighting design, photography, and astronomy. In lighting design, photometry is used to plan and install lighting systems for adequate illumination. In photography, photometric measurements help set the correct exposure. In astronomy, photometry provides critical information about celestial bodies, including their size, temperature, and chemical composition [8,9].

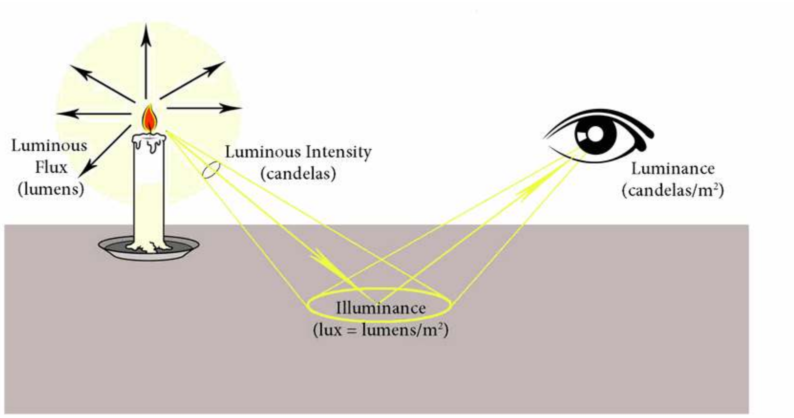


Figure 2.3 Representation of photometric units [10].

2.2 Optical Lenses: Principles and Classification

Optical lenses, fundamental components in the field of optics, are essential for manipulating and controlling light. Understanding the principles governing optical lenses is crucial for appreciating their diverse applications in various scientific, medical, and technological disciplines. This chapter provides an in-depth exploration of the principles behind optical lenses, including the fundamental concept of refraction, and categorizes lenses based on their shapes, curvatures, and applications.

2.2.1 Refraction and Lens Formation

Refraction is a phenomenon that occurs when light passes from one medium to another with a different refractive index. The refractive index is a measure of how much the speed of light is reduced in a particular medium. As light travels through a medium with a different refractive index, its path is bent. This bending of light is essential for the operation of lenses.

The amount by which light is bent depends on the refractive indices of the two media and the angle at which the light enters the second medium. This relationship is described by Snell's Law, which states:

$$n_1 \, sin(\theta_1) = n_2 \, sin(\theta_2) \tag{2.2}$$

where:

n_1 and n_2 are the refractive indices of the two media,

θ_1 is the angle of incidence, θ_2 is the angle of refraction.

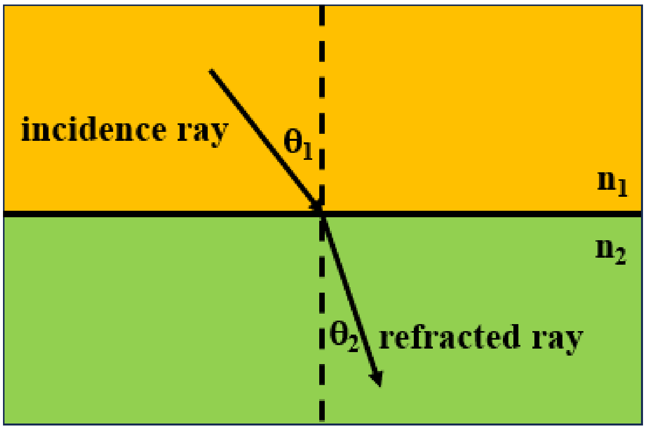


Figure 2.4 Snell's law for refraction.

The basic building block of a lens is a curved piece of transparent material, commonly glass or plastic. Lenses can be categorized based on their curvature, with two primary types: convex and concave (Figure 2.5).

i. Convex Lenses (Converging Lenses): These lenses are thicker at the center than at the edges. When parallel rays of light pass through a convex lens, they converge to a focal point on the opposite side of the lens. This convergence is a result of the curvature of the lens and the refractive index differential between the lens material and the surrounding medium.

ii. Concave Lenses (Diverging Lenses): In contrast, concave lenses are thinner at the center and cause parallel rays of light to diverge. The apparent divergence of these rays occurs as if they are originating from a virtual focal point behind the lens. This virtual focal point is a consequence of the refractive properties of the concave lens.

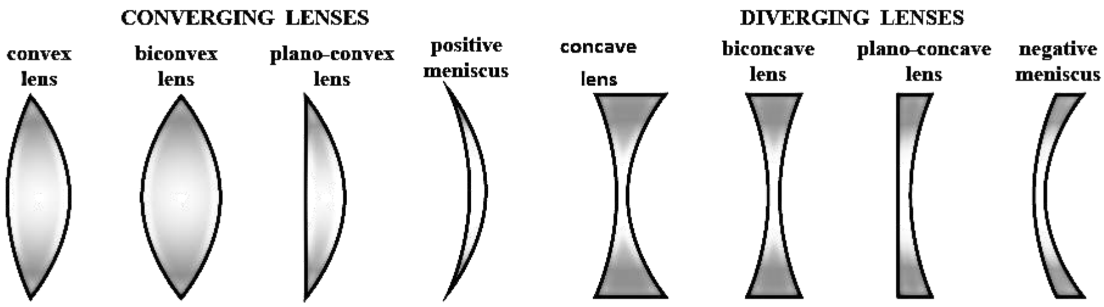


Figure 2.5 Types of convex and concave lens.

The design and optimization of lenses involve precise calculations to achieve desired optical properties. The lens maker's equation provides a mathematical relationship between the radii of curvature (R_1 and R_2), the refractive index of the lens material (*n*), and the thickness of the lens (*d*) (Figure 2.6). The equation is given by:

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right) \quad (2.3)$$

where:

f is the focal length of the lens.

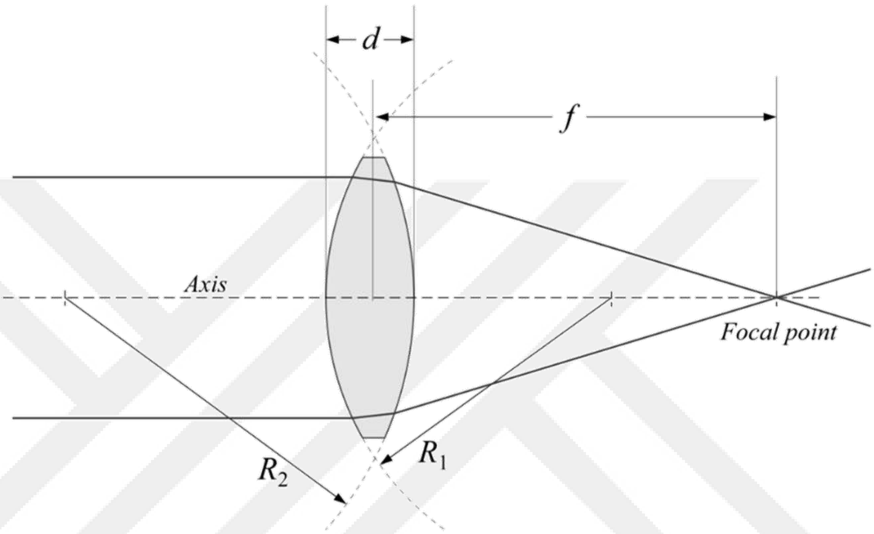


Figure 2.6 Lensmaker's formula for thin lens

The lensmaker's equation is crucial in lens design, allowing engineers and scientists to determine the necessary parameters for achieving specific optical characteristics, such as focal length and image formation.

2.3 Optical Aberrations

Lens aberrations refer to imperfections or deviations from the ideal behavior of optical lenses, which can impact the quality of images produced. These aberrations arise due to the inherent challenges in designing and manufacturing lenses that precisely focus light without introducing distortions. Understanding these aberrations is crucial for lens designers and engineers to improve optical systems and enhance image quality.

Once the various categories and kinds of chromatic and monochromatic optical aberrations have been established, the challenging aspect involves their identification within a system. This can be achieved through either computerized analysis or practical observation, followed by corrective measures to mitigate the aberrations.

Optical designers commonly initiate the process by inputting the system into optical design software like Ansys Zemax OpticStudio ® to assess its performance and aberrations. It is crucial to emphasize that aberrations become evident through the observation of the system's output after the optical components have been manufactured. Upon the completion of system design and manufacturing, the examination of aberrations entails the imaging of a singular point source, such as a laser, through the system to ascertain the manifestation of the singular point on the image plane. Despite the potential presence of multiple aberrations concurrently, a prevailing criterion posits that the closer the image approximates a spot, the fewer aberrations are likely to be extant. This criterion persists regardless of the spot's s

ize, taking into account the possible magnification by the system. These instances comprise simulations of distorted images utilizing standardized test targets (Figure 2.7) and propose potential corrective measures to mitigate the impact of aberrations [10].

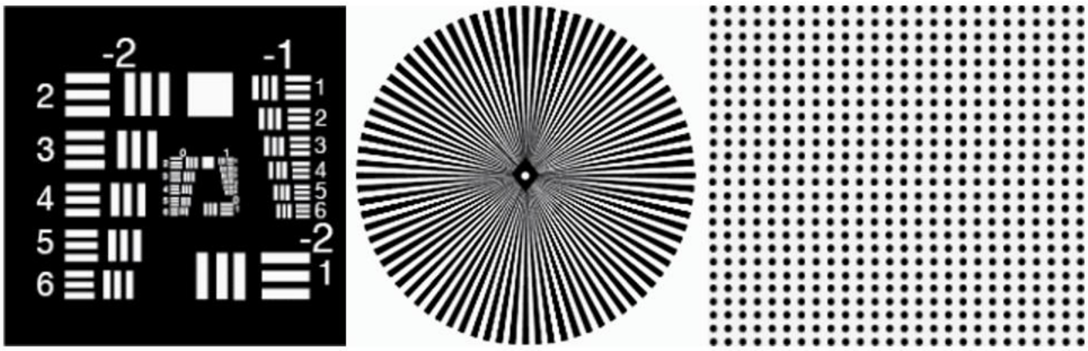


Figure 2.7 Negative Contrast 1951 USAF Resolution Target (Left), Star Target (middle), and Fixed Frequency Grid Distortion Target (right).

2.3.1 Spherical aberration

Spherical aberration occurs when light rays passing through different parts of a lens converge or diverge at different points instead of focusing at a single focal point (Figure 2.8) [10]. This aberration is primarily caused by the spherical shape of lens surfaces, which results in varying path lengths for off-axis and on-axis light rays. Spherical aberration leads to blurring and a lack of sharpness in the image. It is especially noticeable in large-aperture lenses and when imaging off-axis objects. Advanced lens designs, such as using aspheric lens elements, can help minimize spherical aberration. Aspheric lenses have non-spherical surfaces that correct for the differences in the path lengths of light rays.

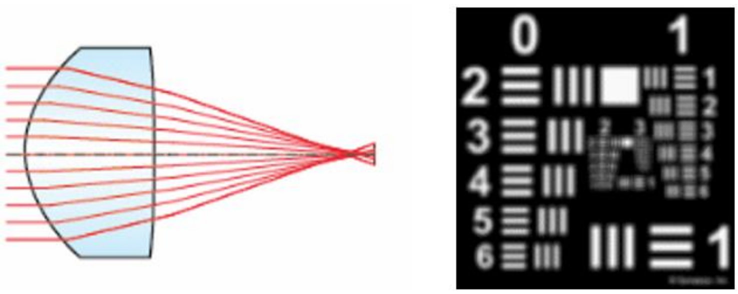


Figure 2.8 Representation of Spherical Aberration.

2.3.2 Coma

Coma is an aberration that causes off-axis points of light to appear comet-shaped or distorted (Figure 2.9) [10]. Coma occurs when light rays entering the lens at an angle do not converge at a single point, but instead form a shape resembling a comet's tail. Coma results in distorted images, especially for off-axis objects. It is particularly noticeable in astrophotography and other applications where precise point-source imaging is crucial. While coma cannot be entirely eliminated, its effects can be reduced through careful lens design and the use of specialized optical elements.

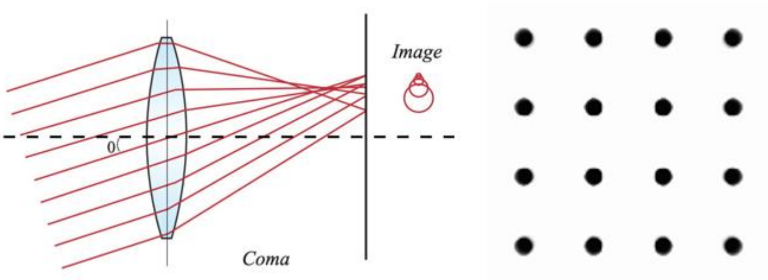


Figure 2.9 Representation of Coma.

2.3.3 Distortion

Distortion is a deformation of the image, causing straight lines to appear curved or bent. Distortion can be classified into two types—*barrel* distortion, where lines near the edges of the image curve outward, and *pincushion* distortion, where lines curve inward (Figure 2.10) [10]. These distortions often arise due to the complex interaction of different lens elements. Distortion is visually apparent in images where straight lines should appear straight. It is a common consideration in applications such as architectural photography. Correcting distortion often involves careful optical design and the use of corrective lens elements to counteract the inherent distortions introduced by the lens.

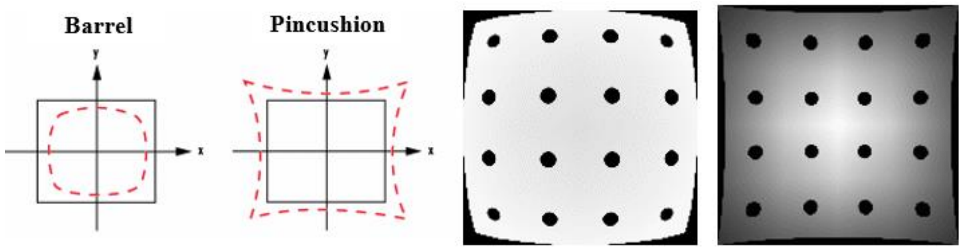


Figure 2.10 Representation of Distortion.

2.3.4 Astigmatism

Astigmatism is an optical aberration that results in different focal points for light rays in different meridians (planes perpendicular to the optical axis). In other words, instead of focusing at a single point, light rays focus at multiple points, causing blurred or distorted images (Figure 2.11) [10]. Astigmatism can occur due to asymmetric lens surfaces or non-uniform refractive indices across different sections of a lens. This results in different amounts of bending for light rays in different orientations. Astigmatism manifests as elongated or stretched images, particularly noticeable for off-axis objects. In photography or imaging systems, points of light may appear as streaks or lines instead of well-defined points. Correcting astigmatism often involves using specially shaped lens elements or incorporating multiple lenses in a system to balance the refractive power in different meridians. Aspheric lens surfaces can also be employed to mitigate astigmatism.

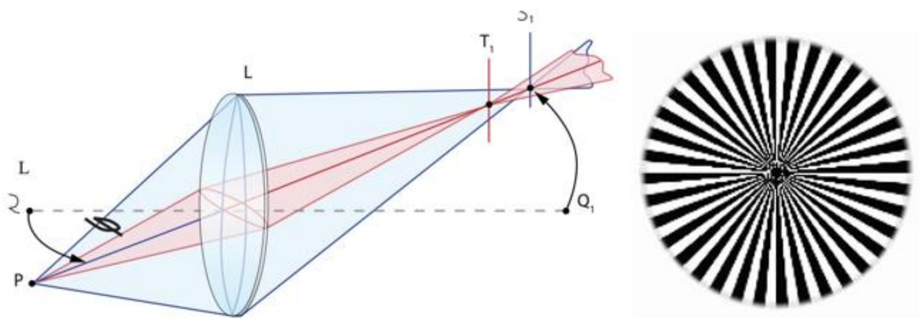


Figure 2.11 Representation of Astigmatism.

2.3.5 Petzval Curvature

Petzval curvature, also known as field curvature, is an aberration that causes a curved image plane rather than a flat one. This means that objects located at different distances from the lens may not all be in sharp focus simultaneously (Figure 2.12) [10]. Petzval curvature results from the complex interplay of lens surfaces and their curvatures. In lenses with spherical surfaces, the curved image plane is inherent due to the varying focal lengths across the field of view. When Petzval curvature is present, objects away from the center of the image may appear out of focus even if the central portion is in focus. This can be especially problematic for imaging systems that require a flat field of focus. The correction of Petzval curvature often involves the use of multiple lens elements with specific curvatures and arrangements. Employing aspheric lens elements and optimizing lens designs for a flat field are common strategies to mitigate Petzval curvature.

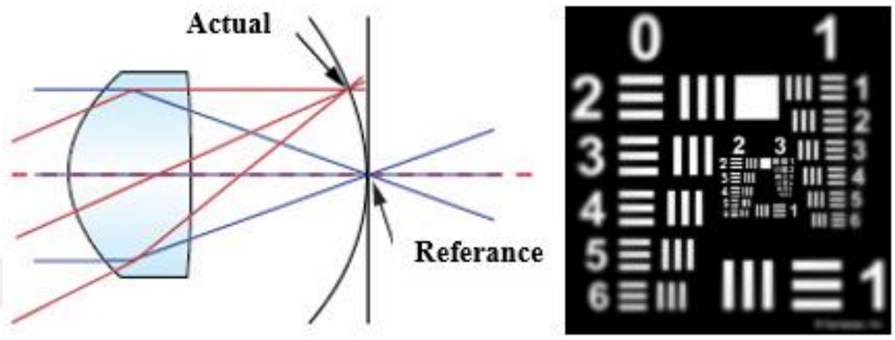


Figure 2.12 Representation of Petzval Curvature.

2.3.6 Chromatic Aberration

Chromatic aberration, also known as color fringing, occurs when different colors of light are focused at different distances (Figure 2.13) [10]. This aberration is a result of the dispersion of light, where different colors have different refractive indices. As a result, when passing through a lens, each color component is refracted by a slightly different amount. Chromatic aberration manifests as color fringes around high-contrast edges in images. It can be observed as colored halos, with the most common colors being purple and green. Achromatic lenses, which combine multiple lens elements made of different materials to counteract dispersion, are commonly used to minimize chromatic aberration. More advanced corrective measures, such as apochromatic lenses, further reduce color fringing.

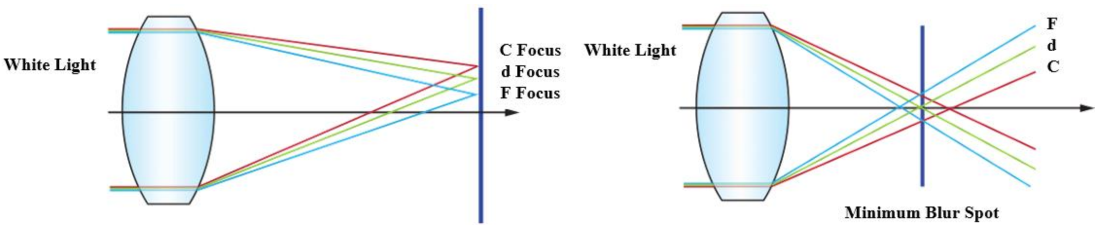


Figure 2.13 Representation of Chromatic Aberration (C: 656.3nm (red), d: 587.6nm (yellow), and F: 486.1 nm (blue)).

2.4 Contrast and Resolution

2.4.1 Contrast

Contrast refers to the difference in intensity or brightness between different parts of an image. In optical systems, high contrast is desirable as it allows for clear differentiation between objects or details within an image (Figure 2.14) [10].

High contrast enhances the visibility of fine details and edges within an image, providing a clear representation of the subject. Contrast contributes to the visual appeal of an image and aids in the interpretation of details, textures, and structures.

The design and quality of the optical lens significantly impact the contrast in an image. Well-corrected lenses with minimal aberrations contribute to high contrast. Adequate and controlled lighting is essential for achieving optimal contrast. The angle, intensity, and direction of light can influence contrast levels. The sensitivity and dynamic range of the image sensor or detector in the optical system play a role in capturing and reproducing subtle variations in intensity.

Contrast can be quantitatively measured using metrics such as the modulation transfer function (MTF), which describes the ability of an optical system to transfer contrast at different spatial frequencies.

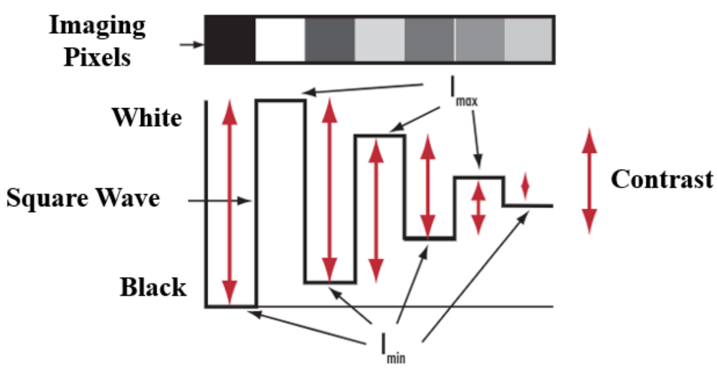


Figure 2.14 Change in contrast as one move from black to white.

2.4.2 Resolution

Resolution refers to the ability of an optical system to distinguish between fine details or closely spaced objects in an image. It is a measure of the system's ability to capture and reproduce details with clarity.

Higher resolution allows for the visualization of finer details, enabling the observation of small structures or features within the imaged subject. In scientific and industrial applications, resolution is critical for accurate measurement of object dimensions and characteristics.

The quality of the lens, including its design, materials, and coatings, has a direct impact on the resolution of an optical system. The size of the aperture or lens opening influences the system's resolving power. Smaller apertures can enhance resolution by reducing optical aberrations. In digital imaging systems, the size and density of pixels on the image sensor influence the spatial resolution.

Resolution is often quantified using metrics such as line pairs per millimeter (lp/mm), which indicates the number of alternating dark and light lines that can be distinguished within a millimeter.

2.4.3 Contrast vs. Resolution Trade-off

Achieving an optimal balance between contrast and resolution is often a challenge in optical system design. In some cases, measures taken to enhance resolution may result in a decrease in contrast, and vice versa. Engineers and researchers must carefully consider the specific requirements of their applications and strike a balance that aligns with the desired imaging outcomes.

2.5 Aspherical Surfaces

Aspherical surfaces play a crucial role in optical design, particularly in the development of lenses and optical systems. Unlike traditional spherical lenses, which have a constant curvature across their surfaces, aspherical lenses feature surfaces with varying curvatures, allowing for improved correction of optical aberrations.

Creating aspheric surfaces involves defining mathematical formulas that describe the shape of the surface. Unlike the simple equations used for spherical surfaces, aspheric surfaces often require higher-order polynomials to represent their complex shapes accurately. The general form of an aspheric surface equation is typically expressed as a power series expansion. Here are some common representations [11]:

- Conic Sections
- Zernike Polynomials
- Polynomial Expressions

Aspheric surfaces can often be described by *conic sections,* which include shapes such as spheres, paraboloids, ellipsoids, hyperboloids, and more (Figure 2.15). The general equation for a conic section is given by:

$$z = \frac{c}{1+\sqrt{1-(1+k)c^2r^2}} \tag{2.4}$$

where:

- z is the sag of the surface,
- C is the curvature,
- k is the conic constant,
- r is the radial distance from the optical axis.

The conic constant (k) determines the specific type of conic section. *Zernike polynomials* are a set of orthogonal functions often used to describe wavefront aberrations, including aspheric surfaces. The Zernike polynomial expansion is given by:

$$W(r,\theta) = \sum_{n=0}^{N} \sum_{m=0}^{n} A_{nm} R_{nm}(r) \cos(m\theta) \tag{2.5}$$

where:

- $W(r,\theta)$ is the wavefront aberration,
- A_{nm} are the coefficients,
- $R_{nm}(r)$ are the radial polynomials.

Each term in the expansion contributes to a specific aberration mode, and by adjusting the coefficients, one can tailor the shape of the aspheric surface.

Aspheric surfaces can be defined using *polynomial expressions* that represent deviations from a reference sphere. The general form of a polynomial expression for an even aspheric surface is given by:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \alpha_2 r^2 + \alpha_4 r^4 + \alpha_6 r^6 + \alpha_8 r^8 + \alpha_{10} r^{10} + \alpha_{12} r^{12} \tag{2.6}$$

where:

- $z(r)$ is the sag of the surface as a function of radial distance r,
- $c=1/R$ is the surface curvature (R is the radius),
- k is the conic constant,
- α_n is the even polynomial coefficient.

The choice of coefficients and parameters allows for the creation of various aspheric shapes. The conic constant, denoted as k, serves as a parameter characterizing the configuration of a conic surface. In the case of $k = 0$, the surface takes on the form of a sphere. In a broader context, the conic shapes are outlined in Table 2.2.

Table 2.2 Conic constant conditions and surface forms.

Conic constant	Surface description
$k > 0$	Oblate ellipsoid
$k = 0$	Sphere
$-1 < k < 0$	Prolate ellipsoid
$k = -1$	Paraboloid
$k < -1$	Hyperboloid

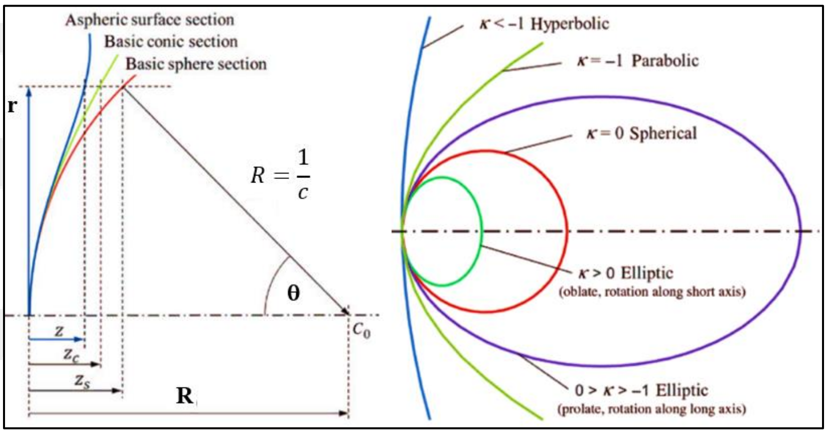


Figure 2.15 Surface sagitta form as a function of radial distance r (left) and Conic surface forms (right).

Creating aspheric surfaces involves a combination of mathematical insight, design goals, and sometimes iterative optimization processes. The choice of formula depends on the specific requirements of the optical system and the desired correction of aberrations. Aspheric surface creation is a critical aspect of lens design, contributing to improved optical performance in applications ranging from cameras and telescopes to microscopes and corrective lenses [11].

2.6 Polymer Materials

Polymer materials play a significant role in illumination engineering and automotive lighting, providing designers with versatile options for creating efficient and aesthetically pleasing lighting systems. From headlamps to interior lighting, polymer materials contribute to the performance, durability, and design flexibility of automotive lighting systems (Figure 2.16).

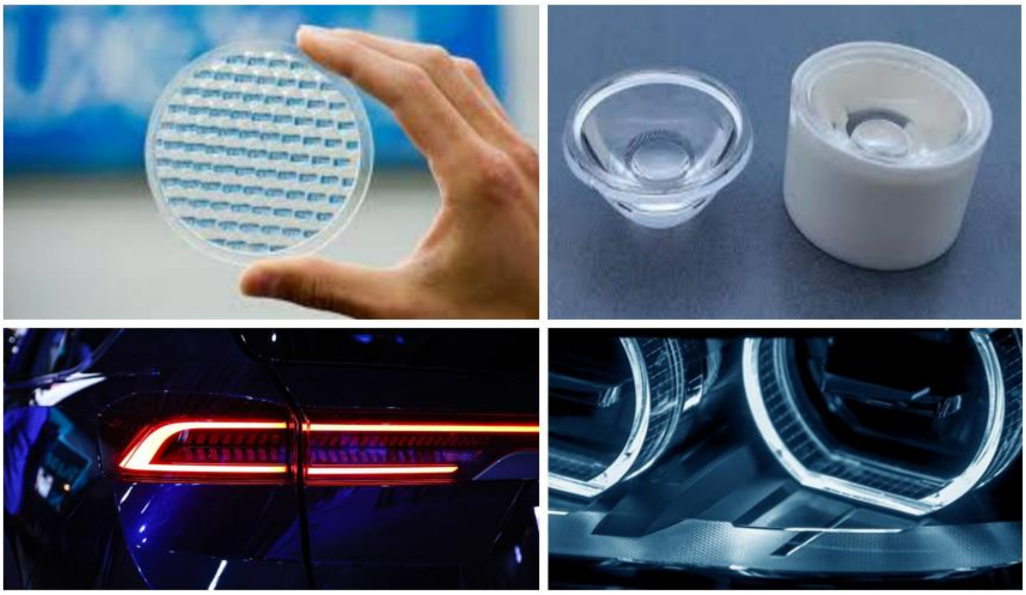


Figure 2.16 Some examples for polymer lenses.

The properties and application areas of polymer materials frequently used in automotive lighting are given below:

- ❖ Polycarbonate (PC):
  - Properties: High impact resistance, optical clarity, and ease of molding.
  - Applications: Headlamp lenses and covers, taillight lenses.
- ❖ Polymethyl Methacrylate (PMMA):
  - Properties: Optical transparency, lightweight, and UV resistance.
  - Applications: Headlamp lenses, interior lighting covers.
- ❖ Polypropylene (PP):
  - Properties: Low cost, lightweight.
  - Applications: Housing and structural components in lighting assemblies.
- ❖ Cyclo Olefin Polymer (COP):
  - Properties: High transmission, low birefringence, chemical resistance.
  - Applications: Headlamp lenses, light guides
- ❖ Polyethylene Terephthalate (PET):
  - Properties: Good optical clarity, chemical resistance.
  - Applications: Optical fibers, light guides.

Polymer materials in automotive lighting represent a dynamic and evolving field of research. Academic studies continue to advance the understanding of polymer properties, optimize their performance in automotive applications, and explore innovative solutions for future automotive lighting systems. The interdisciplinary nature of this research encompasses materials science, optics, engineering, and sustainability considerations, contributing to the ongoing evolution of automotive lighting technologies.

2.7 Illumination Optics

Illumination optics is a specialized field within optics that focuses on the methodical examination and development of optical systems designed to deliver precise and optimized lighting in imaging devices. This aspect is crucial in optical engineering, as it tackles the complexities associated with attaining consistent and effective lighting to improve the quality and clarity of images.

The primary goal of illumination optics is to carefully manage how light is distributed, guaranteeing that the object or specimen being observed receives uniform and fitting illumination. This process includes minimizing unwanted optical effects like glare and shadows, thereby playing a pivotal role in enhancing the overall performance of imaging systems.

There are two basic concepts to the design of illumination systems. Most modern illumination systems are designed by using one of these approaches []:

Abbe illumination, also known as critical illumination, involves directly projecting the light source onto the target object, as depicted in the paraxial model illustrated in Figure 2.17. This method is applied when the light source meets the system's uniformity requirements. Utilizing an illumination condenser lens, the source is imaged onto the object, which can then be captured on film, such as in a movie projector or a 35-mm slide, or displayed on a transmissive or reflective LCD panel, as seen in a desktop projector.

For effective implementation, the light source must either inherently possess uniformity, as previously mentioned, or the condenser must introduce sufficient aberrations to blur the source image adequately, eliminating its structure at the transparency plane. The subsequent projection lens not only images the object (transparency) onto the screen but also projects the image of the source onto the screen. This approach is effective with frosted bulbs or large sources, but it is less suitable for high-brightness sources requiring high throughput, especially those with significant structure, such as filament lamps and arc lamps.

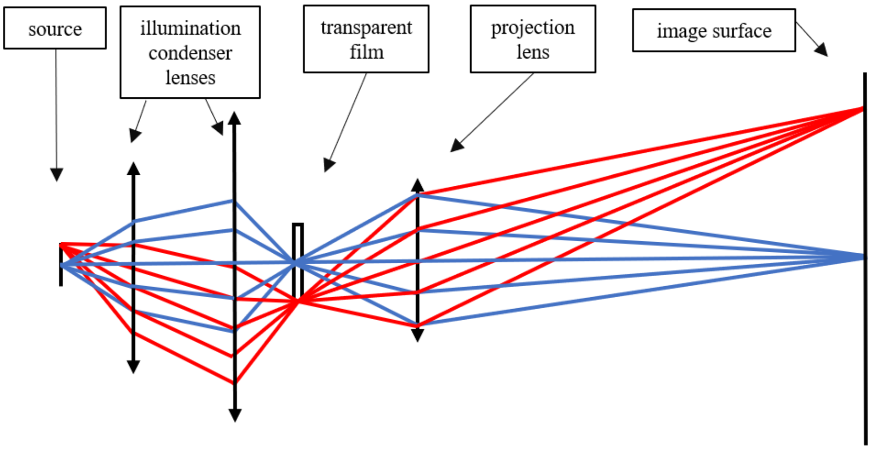


Figure 2.17 The paraxial layout of Abbe illumination used in a projection system.

In instances involving a small yet intensely non-uniform source, like an arc, a filament lamp or LED, achieving uniform brightness at the image can be realized through *Köhler illumination*, illustrated in Figure 2.18. In this approach, an illumination relay lens or condenser lens projects the source into the pupil of the projection lens, deviating from the conventional method of directing it onto the object undergoing projection.

This illumination relay system incorporates its aperture stop at the position of the film or object that is intended for projection onto the screen or into the eye. As each point of the source uniformly illuminates the entire surface of the film, a uniform illumination of the film is inherently attained. However, it is essential to note that brightness non-uniformity with Köhler illumination may arise from substantial and intense irregularities within the source itself.

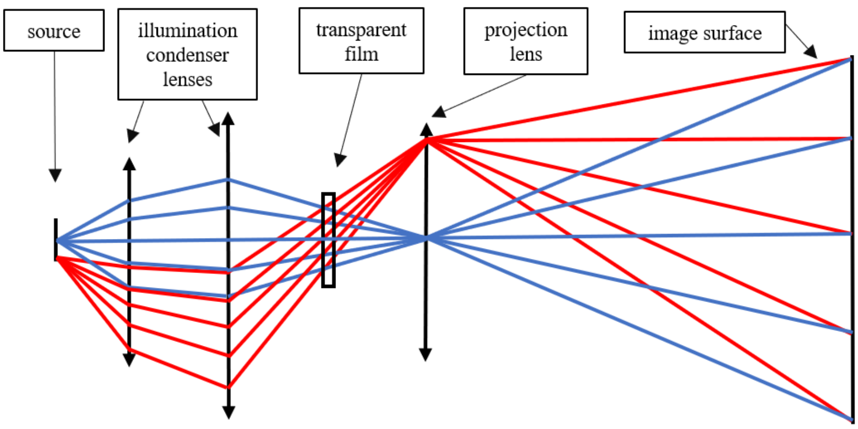


Figure 2.18 The paraxial layout of Köhler illumination used in a projection system.

CHAPTER III

OPTICAL SYSTEM DESIGN FOR LOGO PROJECTION

3.1 Literature

In the existing literature, there are studies directly or indirectly related to various designs and fields, but when it comes to the automotive lighting sector, the available studies appear to be limited and insufficient. Particularly, the number of studies exploring the use of different optical lenses in automotive lighting is notably minimal. While there are studies dedicated to creating and validating numerical models for static optical designs, especially within optical design and analysis programs, the same cannot be said for dynamic optical systems – the count of such studies is scarce and can be counted on one hand. Previous research in this context has primarily delved into automotive interior and exterior lighting.

The study conducted by Uhlenberg et al. aimed to outline design considerations for the development of both simple Logo Projection Lens (LPL) placed within car doors, outside rearview mirrors, fog lamp positions, and more intricate locations. The focus was particularly on investigating ambient illumination in car parking garages during dusk and nighttime darkness (Figure 3.1) [13]. A central illuminance value of 300 lx is aimed for as a guideline in this paper for the reference designs being discussed. This target is expected to ensure sufficient visibility in indoor parking areas or on dry asphalt roads during twilight. Additionally, the study presented two distinct dynamic LPL examples created by the research teams. In the first dynamic LPL design, multiple LED light sources were arranged side by side, with a single lens in front, attempting to generate animation on the asphalt surface (Figure 3.2) [13]. The second LPL example involved a moving mirror (MEMS: micro-electro-mechanic systems) within an optical system with a single LED, aiming to create animation on the asphalt by oscillating the mirror at a specific frequency (Figure 3.3) [13]. Notably, the first design allows for simultaneous patterns on the asphalt due to multiple LEDs, while the second design forms one pattern at a time, with pattern positions changing according to the mirror's oscillatory movement.

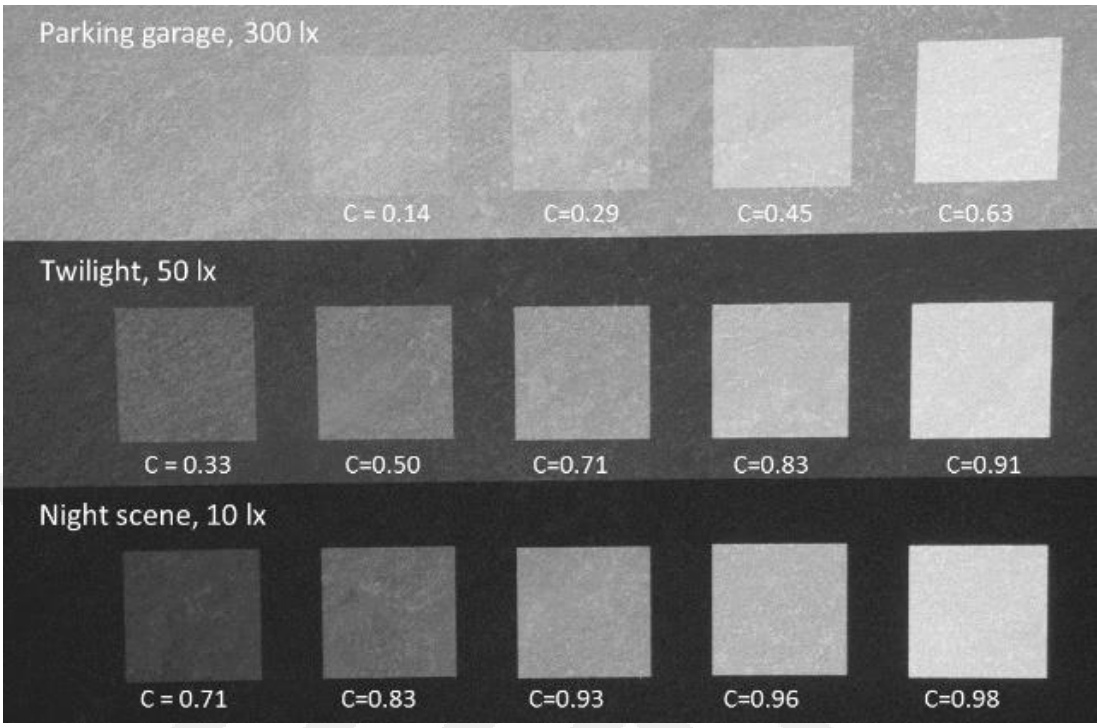


Figure 3.1 A test pattern is projected onto an asphalt surface, demonstrating luminance contrast for different levels of object and background brightness.

A critical drawback of the study lies in its theoretical nature, lacking practical implementation. Furthermore, the discussion on optical design parameters for dynamic LPLs remains superficial, with no mention of essential details such as optical lens types, LED specifications, driving current, product size, etc. Another research, highlighted the role of lighting products in automobiles, emphasizing their contribution to road safety and the visibility of vehicles during nighttime. He detailed his work, which allows drivers to personalize the lighting design of their cars through the use of new technologies and customizable matrix rear lights. Moreover, Studeny explored how microlens arrays and holographic optical elements could facilitate new designs and functions. For instance, the implementation of a projection logo lamp aims to enhance parking safety by providing illumination that indicates vehicle boundaries during traditional parking (Figure 3.3) [14].

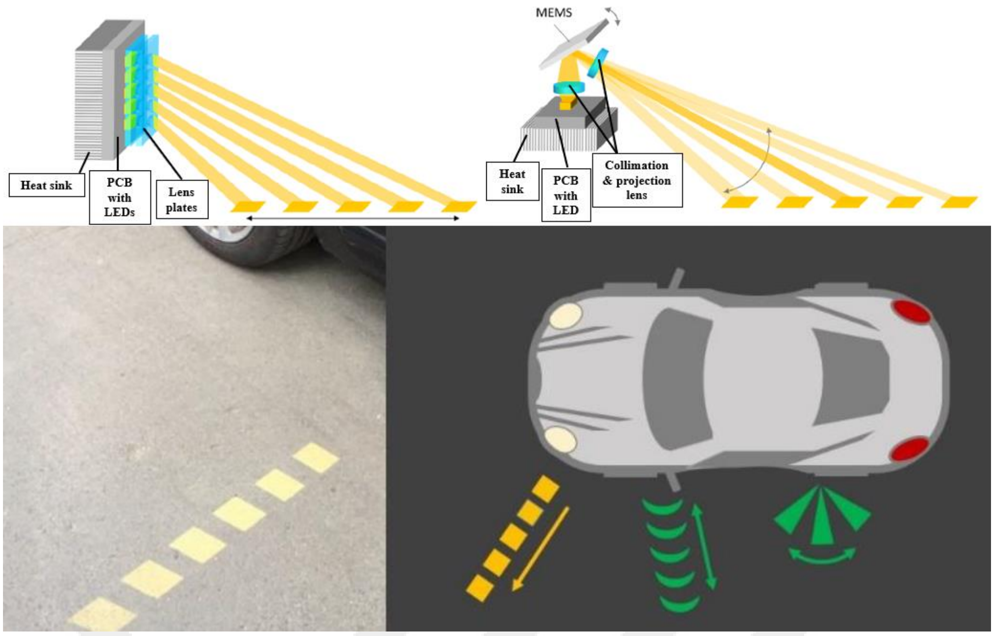


Figure 3.2 Repeating light sequences which are performed by different LPL concepts.

The study also discussed scenarios involving a static warning lamp with LPL placed at the corners of the vehicle during turns. While the study envisions the future usability of such lighting products across vehicle types, a notable limitation is its exclusive focus on static lighting products, lacking comprehensive design information for dynamic applications.

Figure 3.3 The effect of LPL on awareness when used in rear light applications.

Azouigui et al. conducted a study investigating the security impact of using LPL as a signaling feature in real-life scenarios. A specific scenario was devised to assess the security effects, and upon evaluating the data gathered, the study concluded that LPL significantly enhanced security and was deemed necessary. In this scenario, an LPL was positioned on the vehicle's bumper, and upon shifting into reverse gear, it produced three arrow patterns illuminating the asphalt behind the vehicle. The goal was to gauge the reactions of pedestrians and other drivers as the vehicle moved backward in a designated parking lot. The study highlighted that the LPL signaling system proved to be more effective and detectable from longer distances compared to the current signal lamps. Despite being the first application of LPL, the light pattern was well understood. However, the study noted that positive results were not achieved for cyclists, attributing this to the speed and movement patterns of cyclists. A significant contribution of this work lies in its experimental demonstration of the practical use of LPL in real-life situations [15].

In Rosenauer et al.'s study, they elucidate the architecture of LPL utilization within the 360° environment of vehicles. The study encompasses the development of products tailored for static, semi-dynamic, and fully dynamic projection applications, all aimed at creating vibrant patterns on the asphalt surface. The detailed explanation includes optical and electronic diagrams for various projection logo lamps, highlighting the diversity in lighting patterns achievable in different areas and for various purposes, along with their respective advantages. The study employs RGB (red-green-blue) LEDs, specifically chosen for generating colorful patterns, necessitating distinct optical, mechanical, and electronic designs for each product. While some designs use a single LED, others demonstrate that both multiple LEDs and intricate optical systems are essential. The study concludes by indicating that the current market trends in LPLs reflect an increasing demand for privatization, communication, and security. Additionally, a closer examination of three main projection concepts tailored for different use cases is provided. Ultimately, LPL is presented as a comprehensive platform in collaborative lighting, offering customized features, enhanced safety, and support for automated driving (Figure 3.4) [16].

Figure 3.4 LPL usage examples for different functions.

Ataşalan's research delved into the design, analysis, and production of a prototype for both static and dynamic projection lamps, focusing on the details of the optical lens systems. The design process for these optical lens systems was executed using the Zemax program. Prior to producing the prototype for the static projection lamp, intricate optical lens systems comprising 3, 4, and 5 lenses were individually designed and simulated. This approach facilitated a comparison of brightness and aberration levels among optical systems with varying numbers of lenses. The reference part chosen for prototype production was the five-lens optical system with the lowest aberration [17].

3.2 Ansys Zemax OpticStudio

ANSYS Optic Studio, formerly known as Zemax, has a rich history dating back to its original development in 1990 by Ken Moore. Originally named Max after the programmer's dog, it was the first optical design program specifically tailored for Microsoft Windows. Due to a trademark conflict, the name was later changed to Zemax. In 2021, ANSYS, Inc. completed the acquisition of Zemax and its name became ANSYS OpticStudio. It is widely used across industries, including aerospace, automotive, healthcare, and consumer electronics, for the design and analysis of optical systems in applications such as cameras, telescopes, microscopes, and imaging devices. It plays a crucial role in advancing optical technology by enabling engineers to create innovative and high-performance optical systems [18].

Zemax is primarily used for designing and optimizing optical systems, ranging from simple lenses to complex imaging systems. It supports the creation of detailed optical designs, allowing users to define lenses, mirrors, light sources, detectors, and other optical components. The software employs advanced ray tracing algorithms to simulate the path of light through the optical system, predicting how it will behave and interact with different components. Zemax facilitates the analysis of optical systems, including imaging quality, aberrations, and efficiency. Optimization tools help engineers improve the performance of optical systems by adjusting parameters to meet specific design goals. Zemax allows users to perform tolerance analysis, assessing the impact of manufacturing variations on the performance of the optical system. Engineers can create virtual prototypes of optical designs, enabling rapid iteration and evaluation before physical prototypes are built.

There are two type design and analysis approach in Zemax: sequential and non-sequential mode. Sequential mode follows a step-by-step sequence, allowing users to define and analyze optical systems linearly. This mode is particularly useful for systems where light travels through the optical elements in a sequential order, such as traditional imaging systems. Figure 3.5 shows the sequential mode interface in ANSYS Zemax OpticStudio [19].

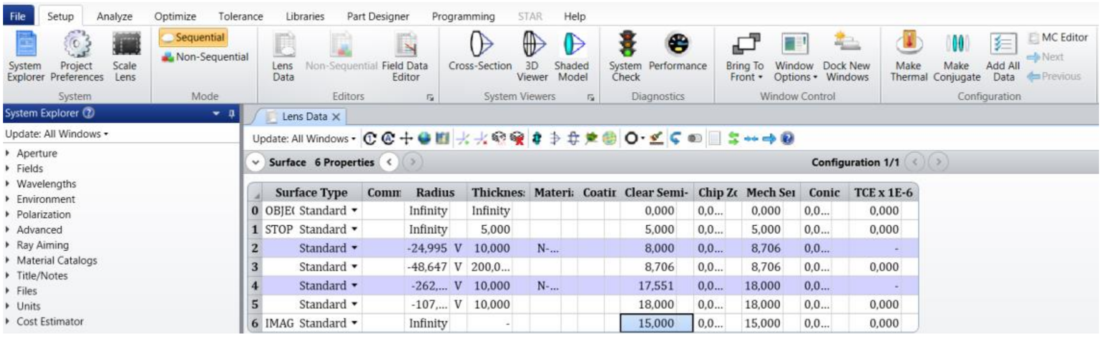


Figure 3.5 User interface in sequential mode.

Users define optical components one after the other, starting from the object surface and progressing through each optical element until reaching the image plane. Sequential ray tracing is performed to simulate the path of light through the optical system, enabling the analysis of imaging quality, aberrations, and other performance metrics. Various analyses, such as spot diagram analysis, MTF calculations, and optimization for specific design goals, can be performed at different stages of the optical design. Tolerance analysis tools are available for assessing the impact of manufacturing variations on system performance.

Non-sequential mode is an alternative design and analysis approach in ANSYS OpticStudio that does not strictly follow the sequential path of light through optical elements. This mode is particularly suited for systems where light propagation is not limited to a sequential order, such as in illumination systems, stray light analysis, or systems involving multiple light sources. Figure 3.6 shows the non-sequential mode interface in ANSYS Zemax Optic Studio [19].

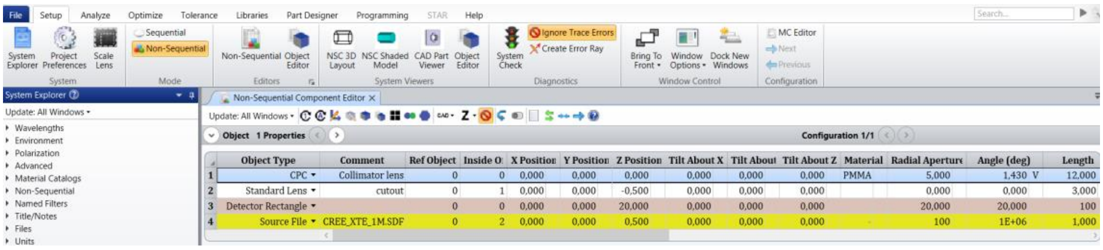


Figure 3.6 User interface in non-sequential mode.

Non-sequential mode allows for the modeling of complex light paths that may involve reflections, scattering, and interactions with multiple surfaces simultaneously.

Particularly useful for designing and analyzing systems like illumination systems, solar concentrators, lightpipes, and optical systems involving complex light interactions. Non-sequential mode supports ray splitting and combining, enabling the modeling of systems with multiple light sources or detectors. It is well-suited for stray light analysis, where the paths of unintended or scattered light are critical for evaluating system performance. Allows for a more flexible and versatile modeling approach, accommodating scenarios where light paths may deviate from a strict sequential order.

The choice between sequential and non-sequential modes depends on the nature of the optical system being designed. Sequential mode is suitable for traditional imaging systems, while non-sequential mode offers greater flexibility for systems with complex light paths and interactions.

3.3 Design Steps

An optical system design process consists of many sequential steps, each of which is important. The optical design steps of the logo projection lamp discussed in this study are as follows:

i. *Define Requirements:* Clearly outline the requirements for the logo projection, including the desired size, brightness, and distance of the projected logo. Consider the environmental conditions where the projection will occur.

ii. *Select Light Source:* Choose an appropriate light source for the logo projection. Common sources include LEDs or lasers, each with its advantages and considerations. Consider factors such as color temperature and intensity.

iii. *Optical System Layout:* Design the layout of the optical system, including the positioning of the light source, lenses, and other optical components. Consider the size and shape of the projected image.

iv. *Lens Selection:* Choose suitable lenses based on the optical requirements. Consider the focal length, lens type (e.g., converging or diverging), and the desired projection distance. Multiple lenses may be used to achieve the desired image quality.

v. *Aberration Correction:* Address optical aberrations, such as spherical aberration and chromatic aberration, to ensure a clear and focused image. This may involve selecting appropriate lens coatings and materials.

vi. *Image Magnification and Size Control:* Adjust the optical system parameters to control the magnification and size of the projected logo. Ensure that the logo fits within the desired area and maintains clarity.

vii. *Uniform Illumination:* Implement techniques for achieving uniform illumination across the projected logo. This may involve using diffusers, reflective surfaces, or optimizing the light distribution from the source.

viii. *Image Distortion Correction:* Correct any distortions in the projected image to ensure that the logo maintains its intended shape and proportions.

ix. *Optimization:* Employ optimization tools within optical design software to fine-tune the system parameters. This may involve iterative adjustments to achieve the best compromise between various design constraints.

Taking these steps into consideration, the design requirements for this study is given in Table 3.1. According to design requirements, LPL must be compact and be able to create a high-contrast image on the target surface to be illuminated. For this, it is necessary to choose an LED with as small a light emitting area as possible and high-power light output. In order to fulfill these requirements, the LUW CEUN.CE model of the Compact CM family of OSRAM is one of the best choices as white LED. *7L bin* is selected to achieve high illumination on the target surface. If this LED is operated at room temperature with a nominal operating current of 350 mA, an average of 150 lumens of light output is obtained.

Table 3.1 Design requirements.

Requirements	**Value**
Max. diameter of a lens (in mm)	10
Lens quantity (pcs.)	≤ 5
Total axial length (in mm)	≤ 20
Distance between LPL and target surface (in mm)	≥ 1000
Logo diameter on target surface (in mm)	≥ 600
Peak Illuminance on target surface (lux)	≥ 300
Uniformity	≥ 80%
Projected logo color	White
Lens Materials	Polymers

Brightness Groups

Group	Luminous Flux [1] I_F = 350 mA min. Φ_V	Luminous Flux [1] I_F = 350 mA max. Φ_V
7K	90 lm	100 lm
8K	100 lm	112 lm
5L	112 lm	125 lm
6L	125 lm	140 lm
7L	140 lm	159 lm

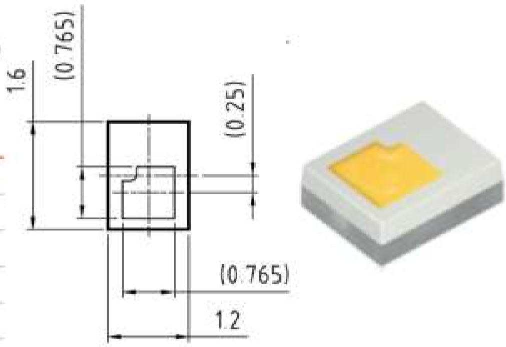


Figure 3.7 Specifications of OSRAM LUW CEUN.CE LED.

A simple version of the main functional elements of the LPL concept is shown in Figure 3.8.

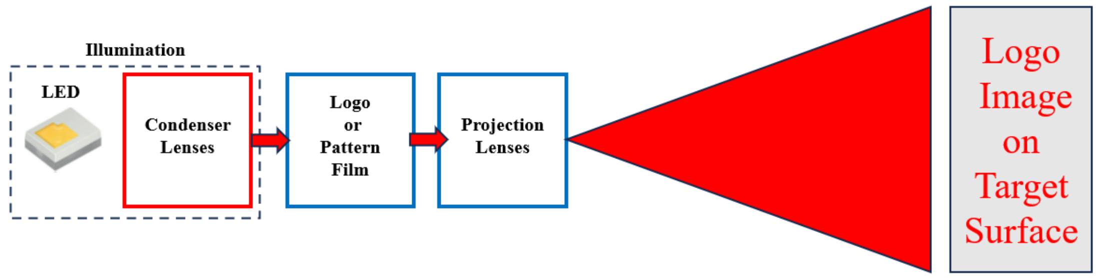


Figure 3.8 Schematic representation of LPL concept.

This LPL consists of a total of four optical components, three of which are lenses and one logo film. Since the LPL concept is compact and LED is used as the lighting source, it must be designed according to the Köhler illumination approach as described in Chapter 2. First of all, in order to obtain a homogeneous image on the target surface, the light coming from each point of the source must illuminate the film surface homogeneously with the help of the condenser lens, which is the first lens of the system. In order to meet this condition in seq-mode in Zemax, the film surface is defined as stop aperture. In the design phase, first the light source definition must be made correctly. In Seq-mode, field definition is made by considering only the area where the source emits light as the source input. As shown in Figure 3.7, the edge length of the light emitting area of the LED selected for LPL is 0,765 mm. Half of this value, 0.38 mm, is entered into the field data editor (FDE) as negative and positive, as shown by the red boxes in Figure 3.9, and an edge length of the emitting area is defined.

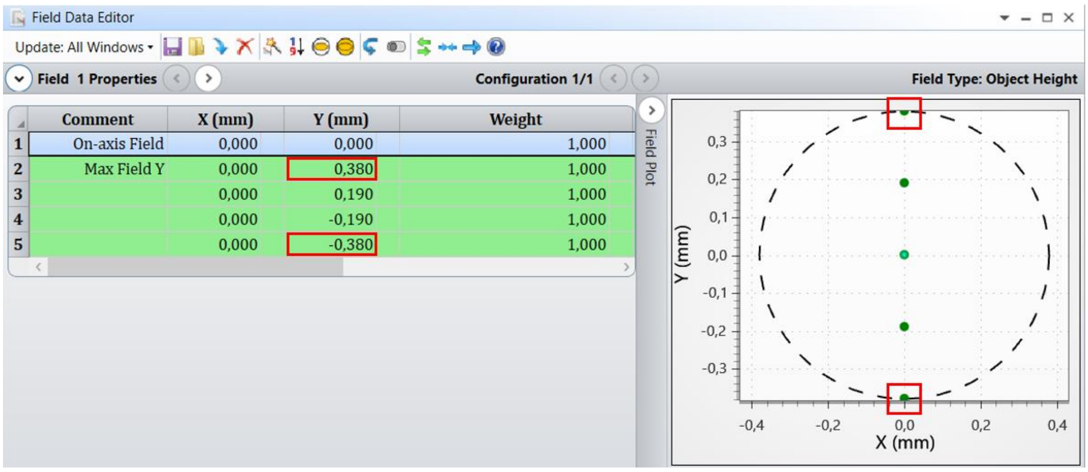


Figure 3.9 Light source definition for condenser lens in Field Data Editor.

Since LED is a Lambertian emitter, it emits light uniformly in all directions. This means that the luminance (brightness) of the emitted light is the same, regardless of the viewing angle. Therefore, different field points at equal distances from each other are defined at different points in the field data editor.

After source identification in the FDE, constraints are determined according to design requirements. Lens parameters with rough values are entered in the lens data editor (LDE). Since the rays coming from the source at a very short distance are tried to be distributed homogeneously on the film surface by using a single lens, both surfaces of the condenser lens must be aspheric. Therefore, during optimization, in addition to radius, thickness and conic parameters, aspheric surface coefficients are also defined as variables, up to sixth order term. Figure 3.10 shows the merit function editor (MFE) and operand parameters after optimization and the operands used in the MFE are given in Table 3.2.


Merit Function Editor

Wizards and Operands — Merit Function: 0,0582843328835063

	Type		Wave	Target	Weight	Value	% Contrib
1	EFFL		2	2,000	0,000	4,999	0,000
2	CTGT	1		2,000	0,000	2,000	0,000
3	TOTR			0,000	0,000	17,008	0,000
4	OPLT	3		17,000	1,000	17,008	0,078
5	OPLT	1		30,000	1,000	30,000	0,000
6	COGT	2		-60,000	1,000	-60,000	0,000
7	COLT	2		20,000	1,000	20,000	0,000

Figure 3.10 Merit function editor and operand parameters after condenser lens optimization.

Table 3.2 Merit function operands.

Operand Type	Description
EFFL	Effective focal length in lens units. The wavelength used is defined by Wave. This is paraxial, and may not be accurate for non-paraxial systems.
CTGT	Center thickness greater than. This boundary operand constrains the center thickness of the surface defined by Surf to be greater than the specified target value.
TOTR	Total track (length) of lens in lens units.
OPLT	Operand less than. This is used to make the value of the operand defined by Op# less than the target value.
COGT	Boundary operand that constrains the conic of the surface defined by Surf to be greater than the specified target value.
COLT	Boundary operand that constrains the conic of the surface defined by Surf to be less than the specified target value.

The layout of the condenser lens obtained according to these parameters is given in Figure 3.11.

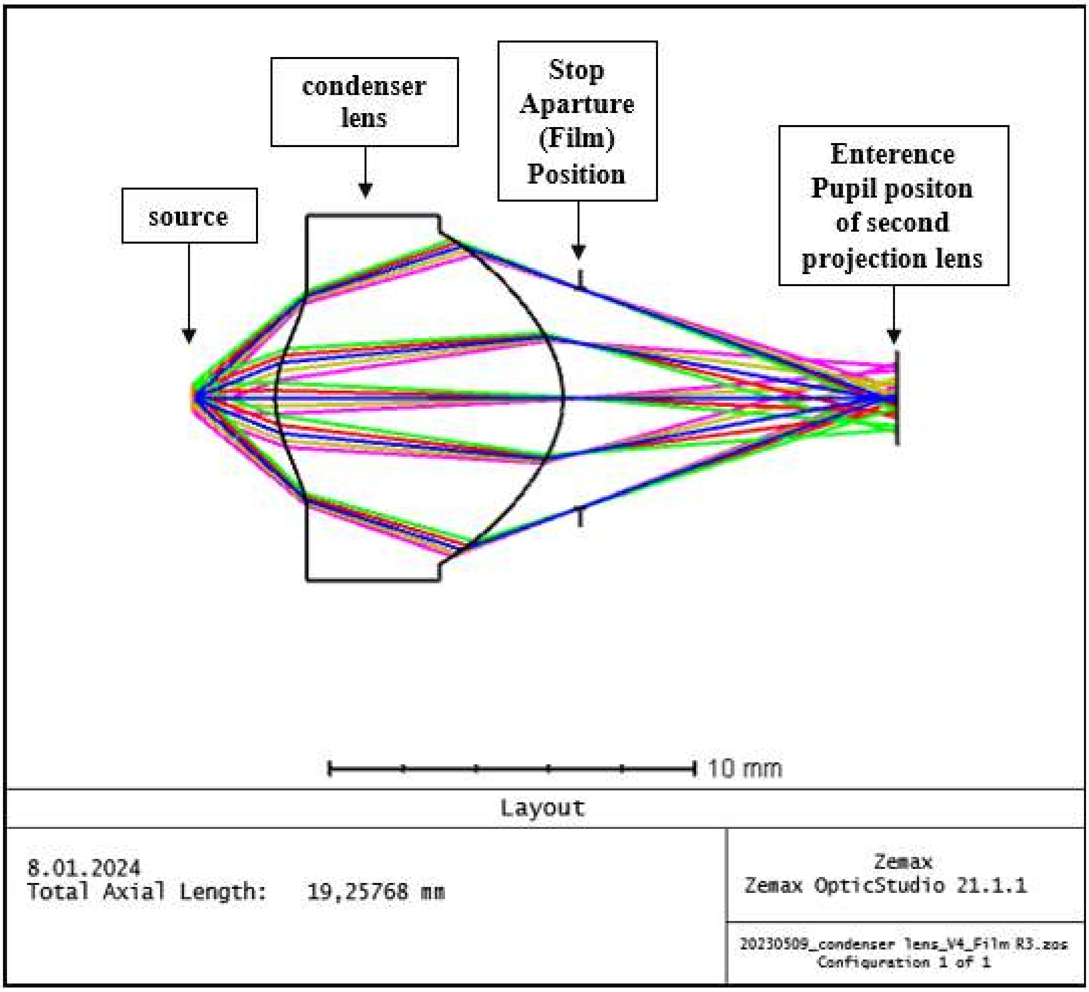


Figure 3.11 Layout of the condenser lens after optimization in Zemax.

Table 3.3 lists the lens parameters obtained after optimization through many iterations.

Table 3.3 Condenser lens parameters.

Surface Type	Radius	Thick.	Conic	Material	Semi-Dia.	2.order	4.order	6.order
Object	Infinity	2,25			0,38			
Even Asphere	-0,085	7,878	-1	PC	3,085	6,116	0,044	2,68E-3
Even Asphere	-0,115	0,472	-1		4,562	4,166	0,015	-1,171E-5

After the condenser lens design, the design of the last two lenses of the system, defined as projection lenses, begins. When designing these lenses, the draft should be created from the perspective of DSLR camera lens design. The camera lens collects the light reflected from the object at a certain distance with a certain field of view (FOV) angle and tries to focus it on the sensor. Projection lenses, on the other hand, try to magnify and reflect the light coming out of the film surface homogeneously to the target surface at a certain distance with a certain FOV angle. The only conceptual difference between the two systems is that the light travels in opposite directions. Therefore, according to this approach, the target surface (image plane) on which the light is reflected should be considered as the object plane, and the film surface on which the light comes should be considered as the image plane. Then, the obtained lenses must be combined by reversing their orientation such that location overlaps the film surface position (stop aperture) in the condenser lens design with the image plane determined in the projection lens design.

After the design path is determined, field is defined in FDE, as it is done at the beginning of condenser lens design. Unlike the field defined in the condenser lens design, it is necessary to determine the angle value, not the position. This angle is the angle value that the light coming out of the LPL that makes with the optical axis. Therefore, as shown in Figure 3.12, the distance between the LPL given in the design requirements and the target surface is geometrically related to the diameter of the logo image on the target surface.

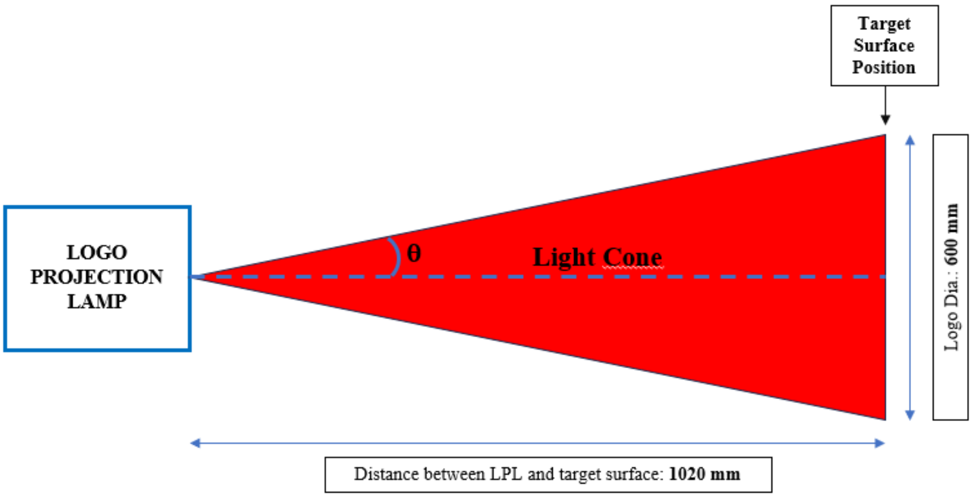


Figure 3.12 The path that lights emerging from LPL, according to design requirements.

Angle θ specified in Figure 3.12 is the field angle that will be used as input in Zemax FDE. Its value is given below by a simple geometric calculation:

$$\theta = tan^{-1}\left(\frac{radius\ of\ logo}{Distance\ between\ LPL\ to\ target\ surface}\right) = \frac{600/2}{1020} = 16.4\ deg \qquad (3.1)$$

Ideally, the field angle should be 16.4 degrees. But, considering the deviations that may arise from optical aberrations, the field angle is selected as 20 degrees with the margin, as shown in Figure 3.13.

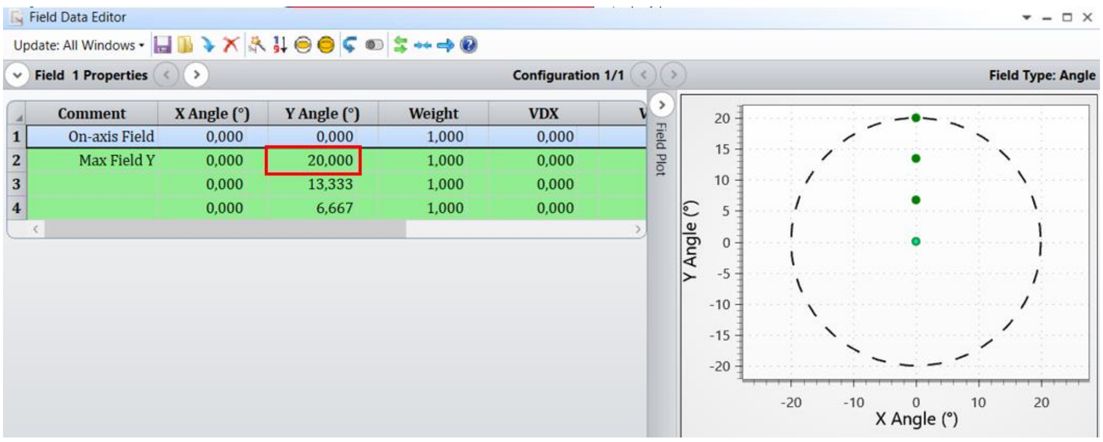


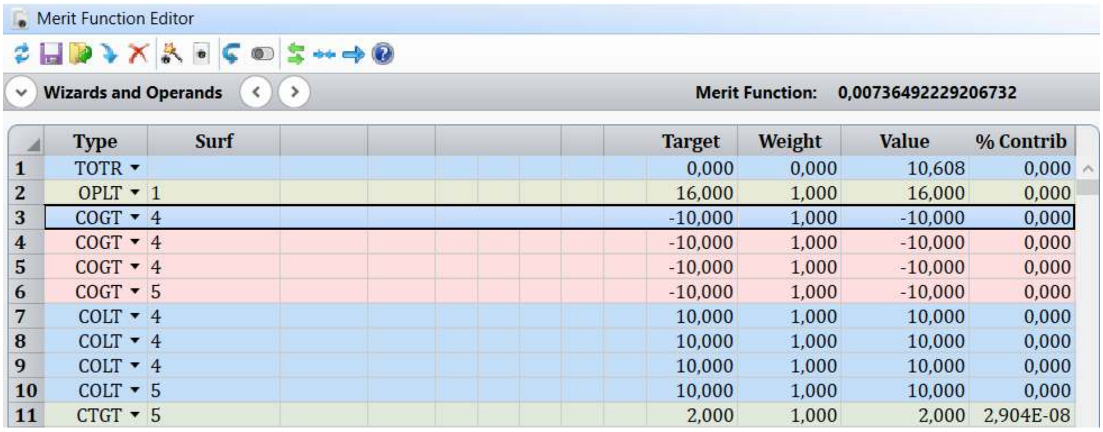
Figure 3.13 Field definition for projection lenses in Field Data Editor.

After the FDE is determined, the lens is designed with rough values, as in the condenser lens design, taking into account the geometric constraints in the design requirements. Then, radius, thickness, conic and aspheric constants are defined as variables and finally optimization is performed. The lens parameters obtained as a result of optimization are given in Table 3.4.

Table 3.4. Parameters of the first and second projection lenses.

Surface Type	Radius	Thick.	Conic	Material	Semi-Dia.	2.order	4.order	6.order
Object	Infinity	Infinity			Infinity			
Even Asphere	0,189	1,45	-1,005	PMMA	1,815	-2,538	0,083	-7,28E-3
Even Asphere	-0,271	0,5	-1,013		1,815	1,829	-0,098	4,186E-3
Stop	Infinity	1,658			1,000			
Even Asphere	-0,536	5,000	-0,949	PC	1,524	0,933	0,026	3,166E-3
Even Asphere	-0,294	2,000	-1,004		2,844	1,761	-0,024	3,385E-5

As shown in Figure 3.14, the operands used in optimization are the same as the operand types given in Table 3.2.


Merit Function Editor

Wizards and Operands — Merit Function: 0,00736492229206732

	Type	Surf	Target	Weight	Value	% Contrib
1	TOTR		0,000	0,000	10,608	0,000
2	OPLT	1	16,000	1,000	16,000	0,000
3	COGT	4	-10,000	1,000	-10,000	0,000
4	COGT	4	-10,000	1,000	-10,000	0,000
5	COGT	4	-10,000	1,000	-10,000	0,000
6	COGT	5	-10,000	1,000	-10,000	0,000
7	COLT	4	10,000	1,000	10,000	0,000
8	COLT	4	10,000	1,000	10,000	0,000
9	COLT	4	10,000	1,000	10,000	0,000
10	COLT	5	10,000	1,000	10,000	0,000
11	CTGT	5	2,000	1,000	2,000	2,904E-08

Figure 3.14 Merit function editor and operand parameters after projection lens optimization.

Given projection lens parameters in Table 3.4 obtained after optimization through many iterations. The layout of the projection lens obtained according to these parameters is given in Figure 3.15.

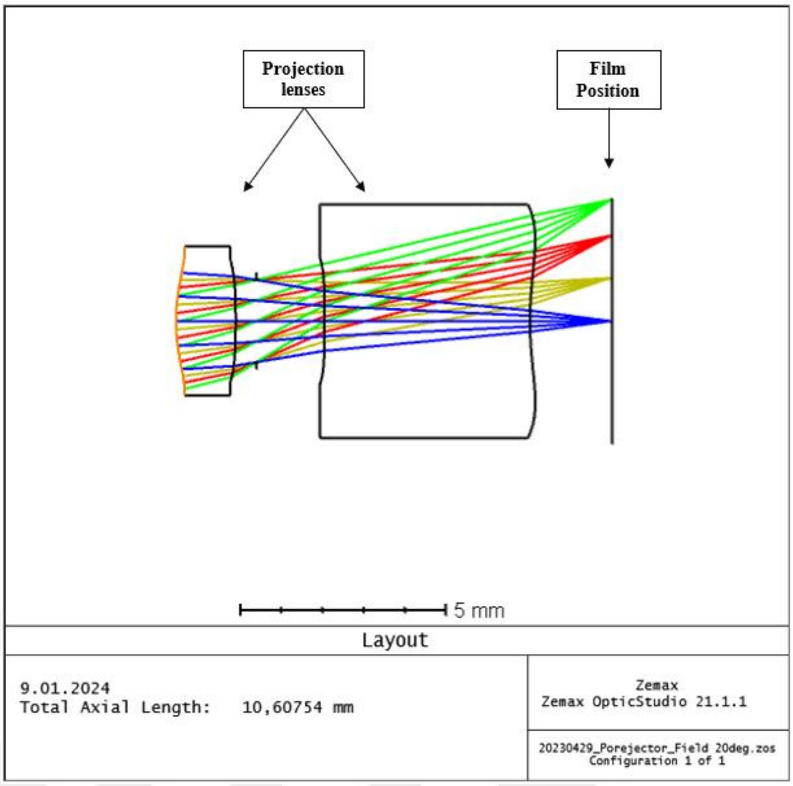


Figure 3.15 Layout of the projection lenses after optimization in Zemax.

One of the performance metrics of projection lenses is the spot diagram which is shown in Figure 3.16.

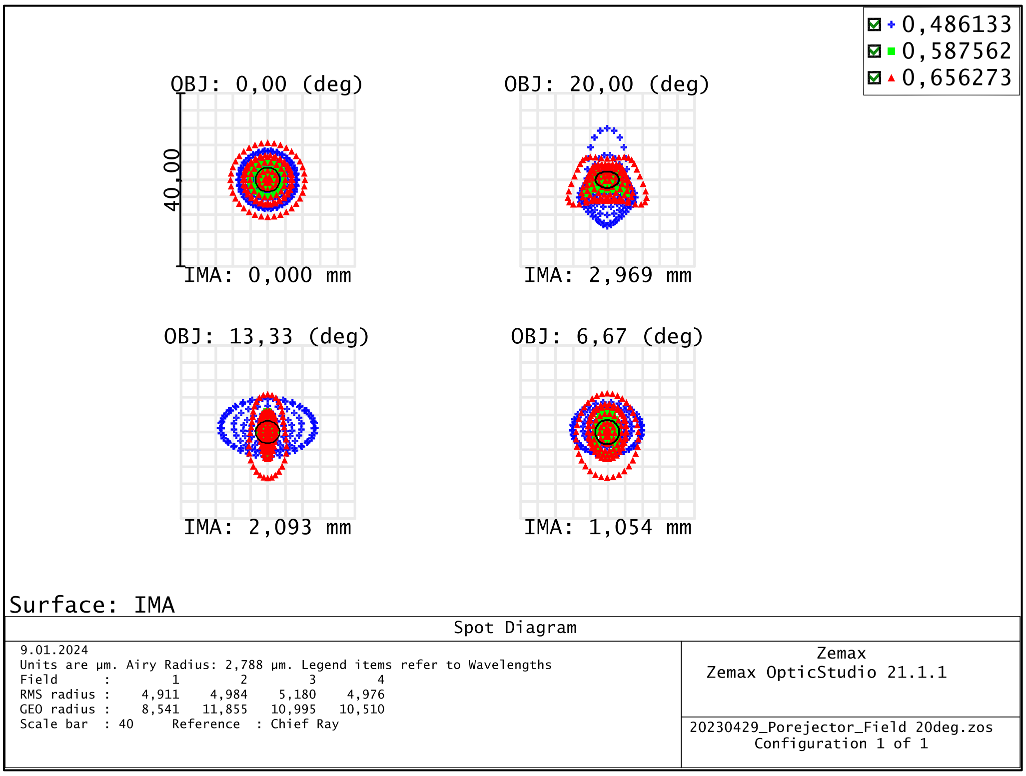


Figure 3.16 Spot diagram of projection lenses.

Spot diagrams are a valuable tool in optical design and analysis, providing a visual and quantitative means to assess and improve the performance of optical systems. The spots on the image plane represent the locations where individual rays converge after passing through the optical system. The shape and size of these spots provide insights into the imaging quality. In an ideal optical system, all rays from a point source should converge to a single point on the image plane, resulting in a single, small spot. Deviations from this ideal spot indicate optical imperfections. The size and spread of the spots in the diagram provide quantitative measures of image quality. A smaller and more focused spot indicates better image quality.

The black ring in Figure 3.16 represents the airy radius (i.e. diffraction limit). When we examined it visually, a spot distribution close to the airy radius was obtained at every field value from 0 to 20 degrees. Quantitative values of the spot diagram are given in the lower left corner of Figure 3.16. According to these values, the airy radius is 2,788 μm, while the largest geometric radius (GEO) is 11,855 μm. In other words, it can be seen in the comparison of quantitative values that a spot distribution very close to the diffraction limit value is obtained.

The "RMS vs Field" optical performance metric is a way to evaluate the root mean square (RMS) wavefront error across the field of view of an optical system. This metric to assess the uniformity of optical performance across the entire field. RMS versus Field graph of projection lenses is shown below in Figure 3.17.

The solid black line in the graph shows the diffraction limit. The blue, green and red colored curves represent three different wavelengths and the black curved line represents the average of these wavelengths. The closer the curves are to the solid black line, the better the performance of the optical system. When looking at the black curved line representing the average, it is close to the diffraction limit curve and almost flat up to a field angle of approximately 19 degrees. When defining the field angle for the projection lens in FDA, it was calculated as approximately 16,5 degrees (see figure 3.12). However, it was planned to make the design in a safer area by adding a margin of 3,5 degrees to this value. When this calculation is taken into consideration, it can be seen that the optical performance of the design is quite good according to the RMS versus field graph.

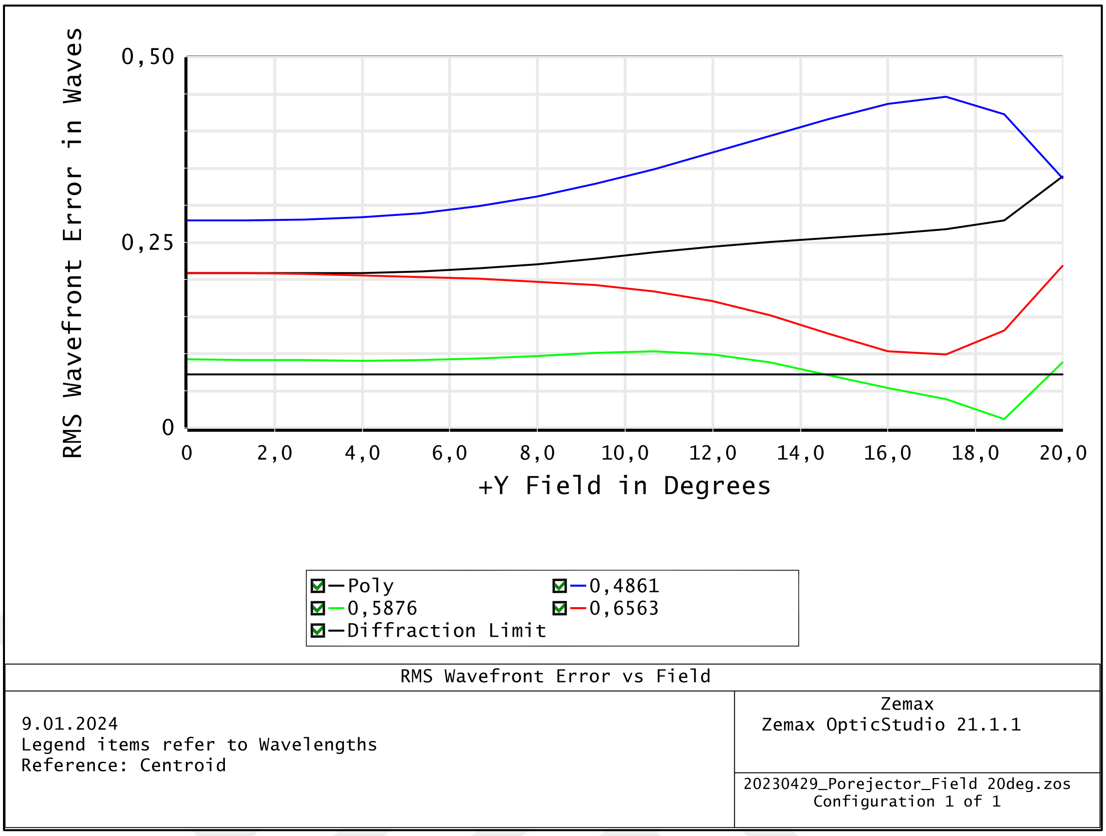


Figure 3.17 RMS vs. Field graph for projection lenses.

As mentioned before, the orientations and positions of the projection lenses from the LDE must be reversed, before combining the projection lenses obtained with the condenser lens. The layout obtained as a result of the process is as shown in Figure 3.18.

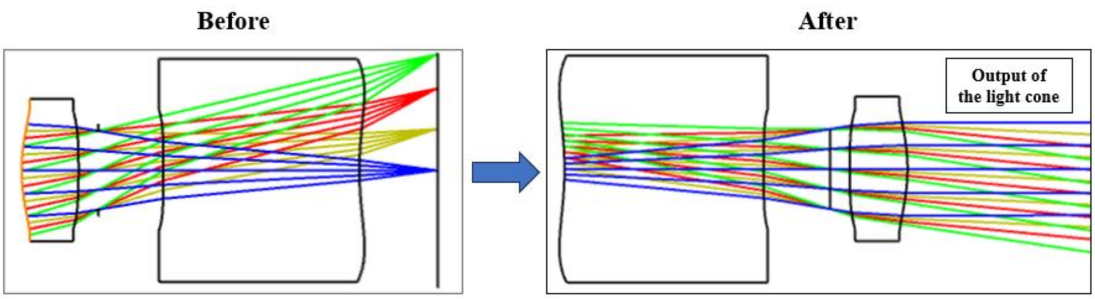


Figure 3.18 Reversing of projection lenses.

The object position (i.e., film surface position) of the inverted projection lenses is combined in the LDE to coincide with the stop aperture of the condenser lens. After the parameters are combined, the LDE and layout of all systems look like in Figure 3.19 and Figure 3.20, respectively.

Lens Data

Update: All Windows

Surface 1 Properties

	Surface Type		Comment	Radius	Thickness	Conic	Material	Clear Semi-Dia	Mech Semi-Dia	
0	OBJECT	Standard		Infinity	2,250	0,000		0,380	0,380	
1		Even Asphere		-0,085 V	7,878 V	-1,000 V	POLYCARB	3,085	5,000 U	Condenser Lens
2		Even Asphere		-0,115 V	0,472 V	-1,000 V		4,562	5,000 U	
3	STOP	Standard	film	Infinity	2,086	0,000		3,000 U	3,000	
4	(aper)	Even Asphere		0,294 V	5,000 V	-1,004 V	POLYCARB	2,844 U	2,844	Projection Lens-1
5	(aper)	Even Asphere		0,536 V	1,658 V	-0,949 V		1,524 U	2,844	
6	(aper)	Standard		Infinity	0,500 V	0,000		1,000 U	1,000	
7	(aper)	Even Asphere		0,271 V	1,450	-1,013 V	PMMA	1,492 U	1,815	Projection Lens-2
8	(aper)	Even Asphere		-0,189 V	1000,000	-1,005 V		1,815 U	1,815	
9		Standard		Infinity	0,000	0,000		384,180	384,180	
10	IMAGE	Standard		Infinity	-	0,000		1,300 U	1,300	

Figure 3.19 Lens data after combining condenser lens and projection lenses.

In Figure 3.20, there is a close-up view of the LPL on the left, and on the right is the LPL with the light cone extending to the target surface. While it is stated in the bottom left that the total axial length of the system is 1021 mm, it is shown in the figure on the right that the length of the maximum logo diameter formed on the target surface is 735 mm. These values show that the design requirements given in Table 3.1 are met.

After the LPL design is finalized in Seq-mode, the existing design parameters are moved to non-seq mode in order to create a real logo image on the target surface and perform to non-seq mode in order to create a real logo image on the target surface and perform uniformity and illuminance analysis. This process can be done quickly with the help of the "convert to NSC group" tool included in Zemax.

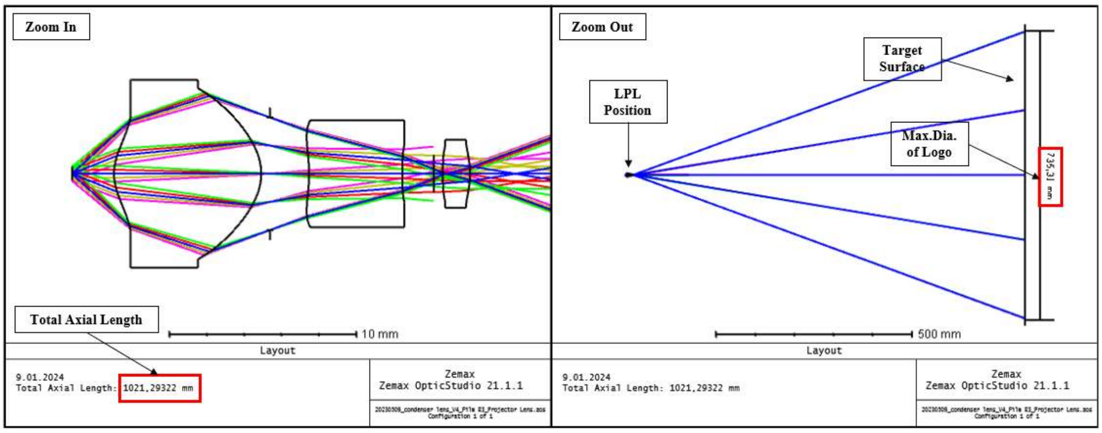


Figure 3.20 Layout of all systems: zoom in (left) and zoom out (right).

The 3D view of the LPL obtained after the conversion is completed is given in Figure 3.21.

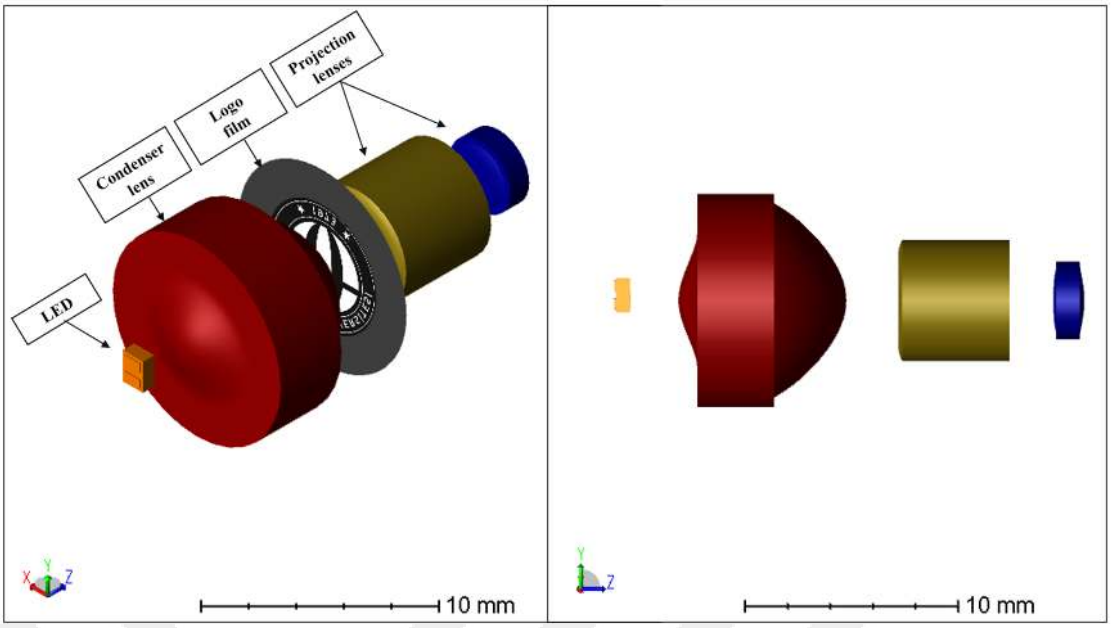


Figure 3.21 3D view of LPL (left: Isometric 3D view of LPL, right: y-z view).

After the ray tracing is performed, the false color image of two different logo on the detector is given in Figure 3.22 and Figure 3.23.

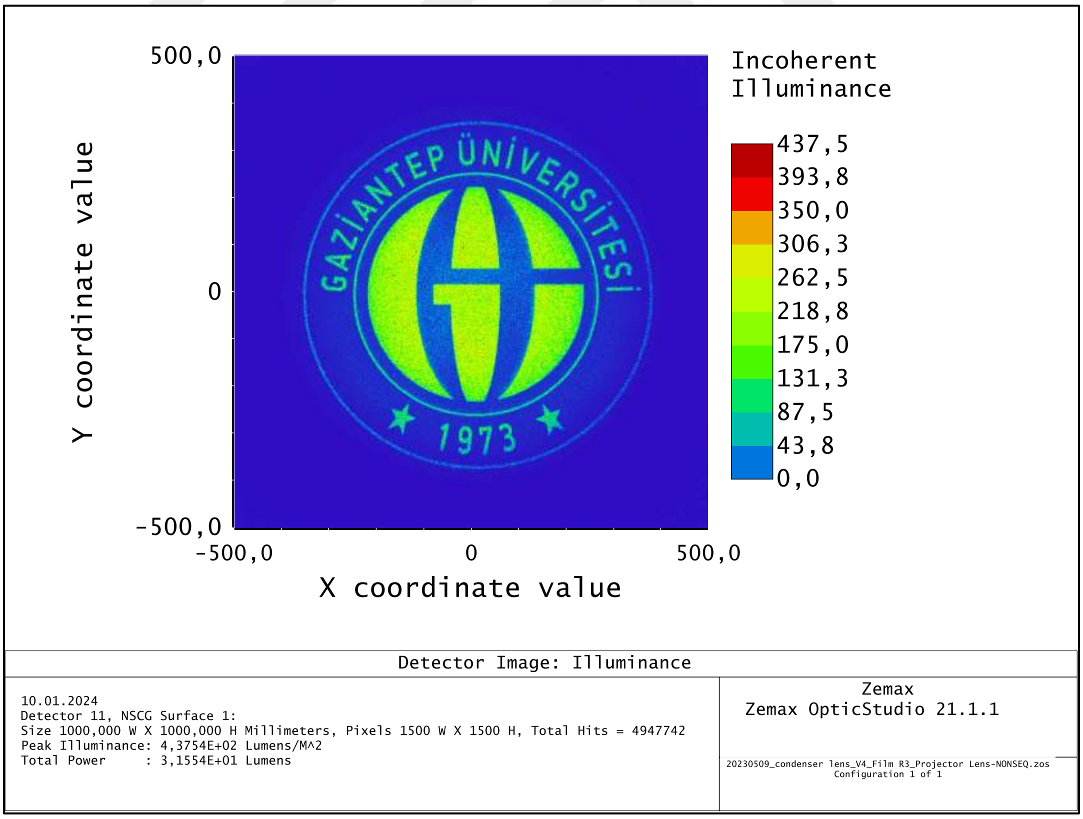


Figure 3.22 False color image on the detector.

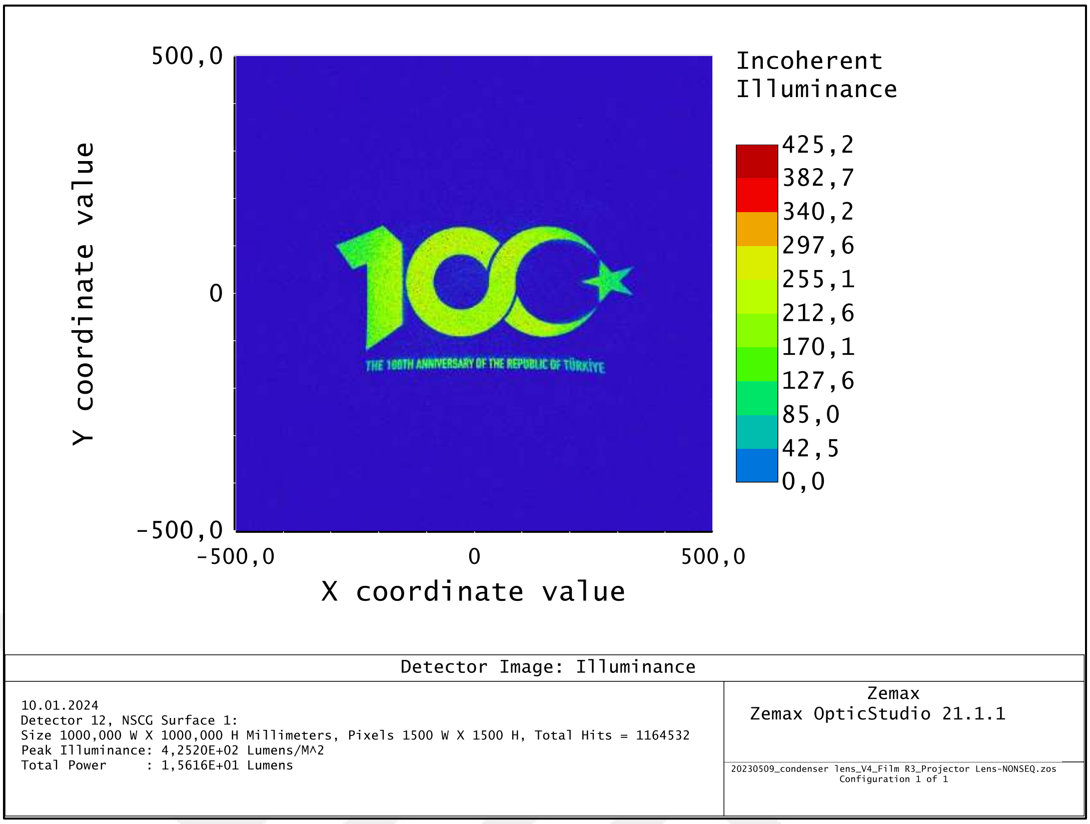


Figure 3.23 False color image on the detector.

The peak illuminance value of each logo is max 435 lm/m^2 (lux) (seen in the lower left corner of the Figure 3.22 and Figure 3.23). The Pincushion distortion aberration shown in Figure 2.10 is seen in the logo image given in Figure 3.23.

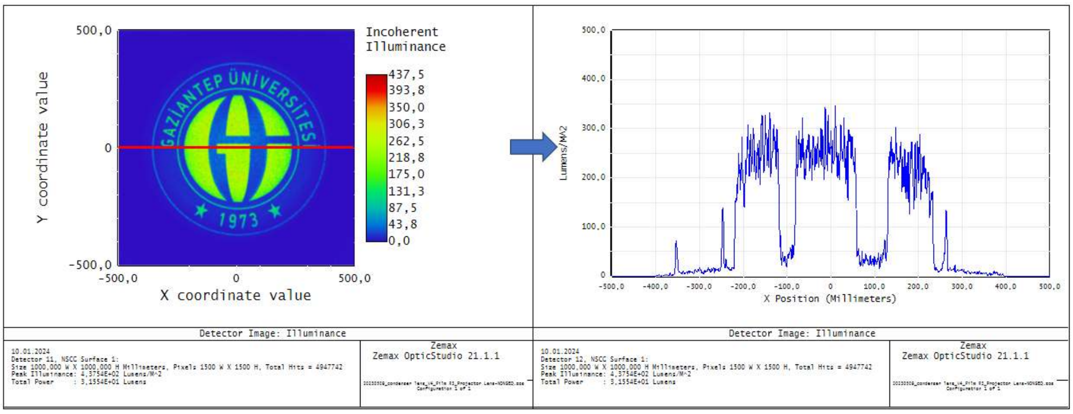


Figure 3.24 Illumination distribution for the horizontal section of the detector image at a distance 1 m away from the LPL.

When a horizontal section is taken from the y = 0 point on the detector (solid red line), the illuminance distribution of the section is shown in Figure 3.24.

3.4. Uniformity Analysis

Uniformity of illuminance distribution on the target surface is one of the most important factors determining LPL performance. In order to determine this performance indicator, illumination is made on the target surface without using a logo film. Then, a section with the diameter of the illuminated area is taken as shown in Figure 3.25 and uniformity calculations are made with illuminance distribution data.

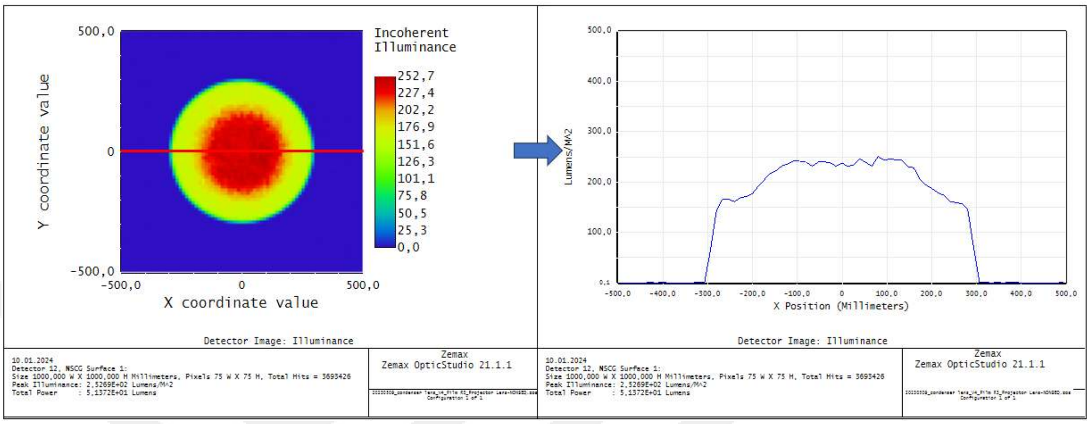


Figure 3.25 Illumination distribution for the horizontal section of the detector image.

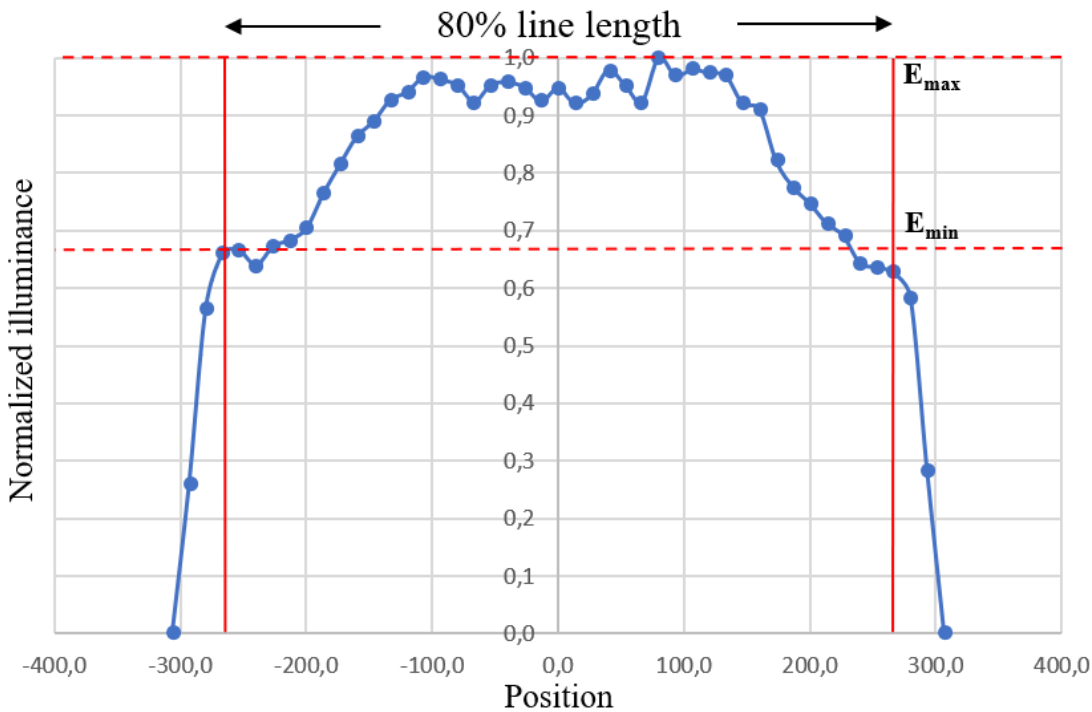


Figure 3.26 Illuminance distribution position vs. Normalized illuminance.

In this study, the uniformity is defined as [21]:

$$U = \left(1 - \frac{E_{max} - E_{min}}{E_{max} + E_{min}}\right) \times 100 \qquad (3.2)$$

For data in Figure 3.26, the uniformity is found to be 80,2%.

On the other hand, one can define uniformity as [22]:

$$U = \frac{E_{min}}{E_{avg}} \tag{3.3}$$

which gives 74.1%.

Usually, uniformity value greater than 60% is recommended in working areas. Because, above this level, the change in light levels cannot be sensed by people and that makes them comfortable [22].

CHAPTER IV

SUMMARY AND CONCLUSION

In this study, a triplet lens design consisting of polymer materials for a Logo Projection Lamp (LPL) to be used in automotive lighting is proposed. As a light source, the white LED named OSRAM LUW CEUN.CE is used since its size small and provides high optical power. The design is implemented and analyzed in Zemax OpticStudio 2023 R1 software using both sequential and non-sequential modes. While the design steps and related performance analysis are discussed in detail, tolerance and thermal analysis of the optical system are not performed.

Initial design requirements and results obtained by our final design are shown in Table 4.1. The proposed design with three lenses within very small volume fulfill the desired specifications.

Table 4.1 Design requirements vs results.

Requirements	**Desired Values**	**Results from proposed design**
Diameter of a lens (in mm)	≤ 10	10
Lens quantity (pcs.)	≤ 5	3
Total axial length (in mm)	≤ 25	21.3
Distance between LPL and target surface (in mm)	≥ 1000	1000
Logo diameter on target surface (in mm)	≥ 600	735
Peak Illuminance on target surface (lux) [13]	≥ 300	435
Uniformity	≥ 80%	80.2%
Projected logo color	White	White
Lens Materials	Polymers	PC and PMMA

One of the goals of the proposed design is to be cost effective. Polymer lenses can be manufactured by well-known injection molding technique. The cost total optical system will increase linearly with the number of lenses. Since our design contains three aspheric lenses, it will be cheaper than that of a design including more lenses. However, the more lenses the system includes, the better the optical performance.

REFERENCES

[1] Haglund, R. F. (2012). *The properties of light*. Springer Handbook of Lasers and Optics, 3-33.

[2] Born, M., & Wolf, E. (2000). *Book Review: Principles of optics.-7th expanded ed.* Cambridge U Press, 1999. The Observatory, vol. 120, no. 1155, p. 149 (2000), 120, 149.

[3] Giusfredi, G. (2019). *Physical Optics: Concepts, Optical Elements, and Techniques.* Springer Nature.

[4] Ashdown, I., & Eng, P. (2002). *Photometry and radiometry.* President by Heart Consultants Limited.

[5] Anonymous, (2019). *Lecture 11: Measuring Light: Radiometry and Photometry*. University of California, Berkeley.

[6] Palmer, J. M., & Carroll, L. (1999). *Radiometry and photometry FAQ*. URL: http://www.optics.arizona.edu/Palmer/rpfag/rpfag.htm

[7] Ohno, Y. (2001). *Radiometry and photometry review for vision optics*. Handbook of Optics, 3, 2.

[8] DeCusatis, C. (Ed.). (1997). *Handbook of applied photometry*. New York: American Institute of Physics.

[9] Bukshtab, M. (2019). *Photometry, radiometry, and measurements of optical losses*. Springer Singapore.

[10] Anonymous, (n.d.). *Contrast.* Edmund Optics Inc. https://www.edmundoptics.com/knowledge-center/application-notes/imaging/contrast/

[11] Kingslake, R., & Johnson, R. B. (2009). *Lens design fundamentals.* Academic press.

[12] Fischer, R. E., Tadic-Galeb, B., & Yoder Jr, P. R. (2008). *Optical system design*. Mcgraw-hill (pp. 321-324).

[13] Uhlenberg, G., Müller, J., Chiu, H. P., & Wang, A. (2017). Design Considerations on Logo and Pattern Projection. In International Symposium on Automotive Lighting (pp. 773-781).

[14] Studeny, C. (2019). New trends and functionalities in signal lighting. In International Symposium on Automotive Lighting (pp. 147-156).

[15] Azouigui, S., Barbedette, B., Saudrais, S., Sortais, Y., Bordel, S., Neumann, C., & Jahn, P. (2019). Impact of advanced lighting function based on road projection for departing indication in parking lots. In 13th International Symposium on Automotive Lightning-ISAL.

[16] Rosenauer, M., Muster, J., & Forster, G. (2020). Lighting solutions to increase acceptance of autonomous vehicles. ATZelectronics worldwide, 15(4), 54-57. https://doi.org/10.1007/s38314-020-0177-3

[17] Ataşalan, M., F. (2021). *Otonom Araçlar İçin Statik Ve Dinamik Logo Projeksiyon Lambalarinin Geliştirilmesi.* Uludağ Üniversitesi.

[18] Anonymous, (n.d.). *Ansys Zemax OpticStudio.* https://www.ansys.com/products/optics/ansys-zemax-opticstudio

[19] Anonymous, (2023). *Zemax OpticStudio 23.1 User Manual*. ANSYS, Inc.

[21] Anonymous, (n.d.). *Powell Lens.* *https://www.coherent.com/news/glossary/powell-lens*

[22] Anonymous. (n.d.). *Uniformity.* *https://lightingequipmentsales.com/uniformity.html#:~:text=Uniformity*

CURRICULUM VITAE

Mustafa Cüneyt MEMİŞ

WORK EXPERIENCE

- 22.05.2023 – Current | Ankara, Türkiye
  SYSTEM DESIGN ENGINEER - TUSAŞ
- 15.06.2021 – 19.05.2023 | Bursa, Türkiye
  OPTICAL DESIGN AND ANALYSIS ENGINEER - FEKA AUTOMOTIVE
- 20.04.2019 – 04.06.2021 | Bursa, Türkiye
  OPTICAL DESIGN ENGINEER - ERMAKSAN
- 08.04.2014 – 19.04.2019 | Bursa, Türkiye
  SEMICONDUCTOR TECHNOLOGIES RESEARCHER - ERMAKSAN

EDUCATION

- 09/2020 – 01/2024
  OPTICAL ENGINEERING (MSc)
  Gaziantep University
- 09/2014 – 09/2018
  MATERIAL SCIENCE AND ENGINEERING (MSc)
  Bursa Technical University
- 09/2006 – 01/2013
  PYHSICS ENGINEERING (BSc)
  Gaziantep University

DIGITAL SKILLS

- Optical Design and Analysis Programs
  ANSYS Zemax OpticStudio | Synopsys LucidShape | ANSYS Speos
- Mechanical Design Programs
  Catia V5 | Solidworks