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# Achieving multiple beam patterns using 3-D printed lens by changing the position of LEDs

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## ABSTRACT

As lighting has diversified across many applications, optical designers have been challenged to produce application-specific optical systems. For an instance where multiple beam distributions are required in an application, instead of making individual lenses catering to different beam shapes, it would be beneficial to create a single optic that can be used with different LED source positioning. Hence, this study proposes a method of positioning LEDs in a fixture to achieve multiple beam patterns using a fixed lens design. Through ray-tracing analysis, we showed that different beam distributions could be obtained by changing the LED position in a refractive lens array. The experimental study was conducted with a 3D-printed lens to validate the model. The results confirm the possibility of creating a single fixed lens to achieve multiple beam distributions via different LED positioning. The proposed novel method can replace the expensive and cumbersome process of developing separate lenses for each beam distribution. Further, our experimental results can guide fixture manufacturers on the use of 3D-printed optics for lighting applications.

**Keywords:** Beam shaping, Multiple beams, Lighting, 3D printing, Optics, Additive manufacturing

## 1. INTRODUCTION

In the past several decades, solid-state lighting (SSL) has steadily expanded to outperform many traditional lighting technologies due to its higher energy efficiency, longer lifetime, and reduced maintenance. Energy efficiency for a given lighting solution relies upon the optimum use of its sub-component. In a LED lighting system, secondary optical components are used to direct the photons to the target area. Hence, refined optical systems can maximize the total flux on the application surface and improve performance characteristics such as efficiency and uniformity.

Modern-day lighting designs are rapidly evolving and digressed from simple beam patterns. Lighting designers use different lighting distributions to express the environment based on its utilization, time of the day, etc. Such applications require various distributions of light to achieve different lighting effects. Light fixtures use secondary optics to shape the output beam distribution. To obtain multiple beam distributions from the same fixture, conventional fixtures need multiple secondary lenses with interchangeable capabilities. Developing fixtures with multiple lenses is a cumbersome and expensive process. Instead of making numerous lenses to cater to the different beam shapes, it would be beneficial to create a single optic that can be used with multiple LED arrays. This study focuses on developing a method to design optics that can create multiple beam distributions via the relative positioning of the LED (Figure 1).

Initially, we conducted a thorough literature review on existing lens designing methods, including lens arrays, freeform lenses, and Fresnel lenses. Microlens arrays use refractive lens arrays to achieve prescribed illumination distributions.<sup>1-5</sup> Study has investigated the effect of different parameters of microlenses such as depth, width, length, lens profile, and positioning on beam distribution.<sup>1</sup> Analyzed results of that study showed how changes in microlens structural parameters affect the shape and size of the delivered illumination distribution. However, microlens systems demand a beam collimating optical arrangement in front of the microlenses system. Instead of having a separate collimating system and lens arrays, several studies investigated the concept of optimizing an array of 3D printed refractive elements (like spherical or hemispherical) to achieve application-specific custom

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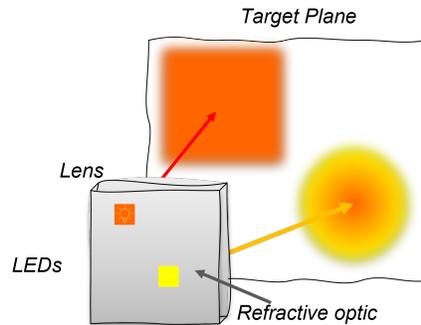


Figure 1: Obtaining different beam distributions based on LED positioning

lenses.<sup>6-8</sup> In addition to refractive array lenses, past literature introduced the concept of freeform optics design strategies as a convenient way to create surface geometries to achieve desired beam distribution.<sup>9,10</sup> However, previous lens design studies have exclusively focused on designing lens structures for a single desired beam distribution. Investigating the feasibility of developing a lens to attain multiple beam distributions with spherical refractive arrays remains to be addressed.

Lighting system manufactures investigated changing the beam distribution of LED systems using mechanisms such as framing projectors and changing the LED arrangement on substrates.<sup>11</sup> However, fixed or adjustable framing projectors used as light masking shutters will cut off a certain part of the beams, causing energy waste. Although studies have discussed LED chip level arrangements to obtain a given beam distribution,<sup>12-14</sup> to our knowledge, no prior studies have examined the possibility of changing the LED position in a given lens to achieve different beam distributions.

Manufacturing customized lenses to manipulate different distributions can lead to complex requirements. However, studies have confirmed that current 3D printing technologies and materials could be used to manufacture functional components for SSL fixtures.<sup>15,16</sup> Hence, manufacturing custom optical elements using expensive and cumbersome traditional methods can be replaced by using additive manufacturing, which creates a physical object by combining materials layer upon layer according to a CAD design.<sup>17</sup> The potential offered by additive manufacturing in optical design for illumination applications is due to the flexibility of transparent materials, creating new possibilities in optical designing and manufacturing.<sup>18,19</sup>

Based on our literature survey, no study to date yielded multiple beam distributions from the same lens. To elucidate this uncharted area, we set the goal of this study to analyze and develop an optic that can create multiple beam distributions with different positioning of LEDs in a light source. The study was conducted to investigate the relationship between lens parameters and LED positioning. Through geometrical optics calculations followed by ray-tracing simulations, we studied how the efficiency and uniformity change with the lens parameters. Using the results, the study proposed a method to obtain different beam distributions by changing the LED position in a refractive lens array. With developed relationships and optimization procedures, this research provides a solution to the challenging problem of accommodating multiple beam distributions from a single lens.

## 2. METHODOLOGY

During the initial stage of the study, we observed changes in the beam distribution due to different source positions. Through a series of optical ray-tracing simulations using LightTools followed by experimental results with 3D printed lenses, we were able to identify how the output beam will change based on the position of the light source. Based on lens array parameters, we derived a mathematical calculation procedure that can provide illuminance distributions at the target plane. Among other parameters, the focus of this study is on adjusting the radius of curvature and depth by changing the sphere equation. Optical ray-tracing software LightTools was used to perform Monte Carlo ray simulations to assess the effect of parameter changes on efficacy and output illuminance distribution. After analyzing the input and output parameters, this method was used to predict the efficiency of the lens system for different lens parameters.



Figure 2: 3D printed lens based on optimization

Polyjet print
Material - VeroClear
Layer Thickness - 0.015mm
1002 Layers
Print Time 5h 49min

Table 2: 3D printing parameters for two lenses

Later, observations from the initial phase of the study (to obtain different beam distributions via relative placements of LEDs in a spherical refractive array and parametric optimization results) were used to find a solution for the challenging problem of accommodating multiple beam distributions from a single lens.

By using the given optimization process, we designed a lens with appropriate radius and depth values to provide different beam distributions from the same lens. Different illuminance patterns were obtained by designing the lens with different spacing of the dimple array. Using LightTools, we designed the lens and extracted the CAD model to 3D print the lens using Polyjet 3D printing methods (Table 2). After the print, the lenses went through post-processing with polishing and clear coating to improve the surface finish and optical properties. The final lens image is given in figure 2. The projection of the illuminance map for each condition was collected using a CCD radiant imaging camera.

### 3. RESULTS

Simulation results with corresponding experiment results suggest that we can obtain different beam distributions by changing the source placement. As we analyzed the results further, we concluded that when LEDs are placed among dimples, the area among four dimples is correlated with the illuminance pattern. Furthermore, we rearranged the spacing among dimple structures to observe their output beam distribution. As presented in figure 3, simulations and corresponding experimental results have shown that it is possible to change the output beam distribution by altering the lens array gaps.

During the study, we selected the square beam shape to optimize for the efficiency using the radius and depth of the spherical structures. While changing the spherical parameters, we recorded the flux gathered on the target plane. Efficiency of the lens is calculated as a ratio of flux gathered on the target plane to the flux incident on

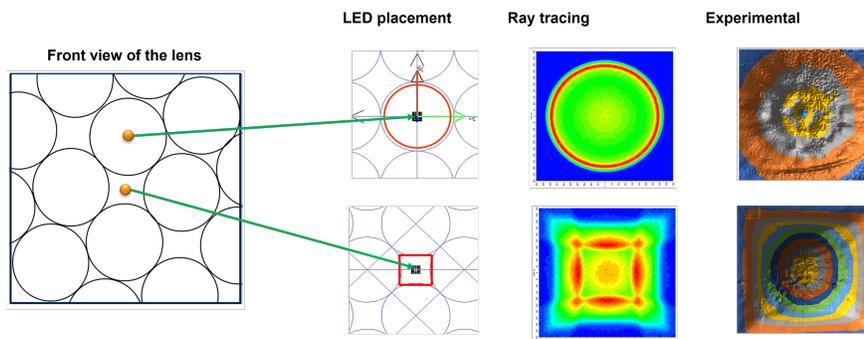
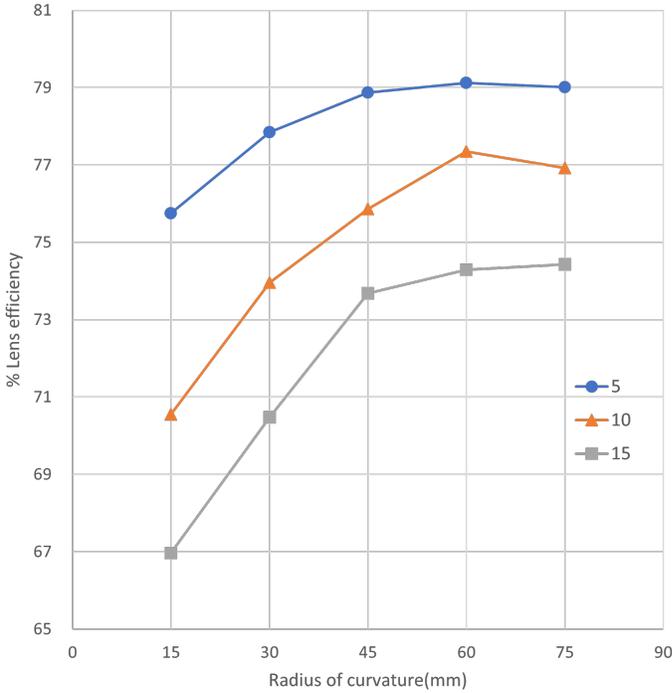
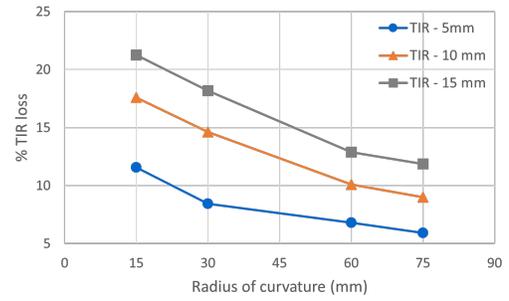


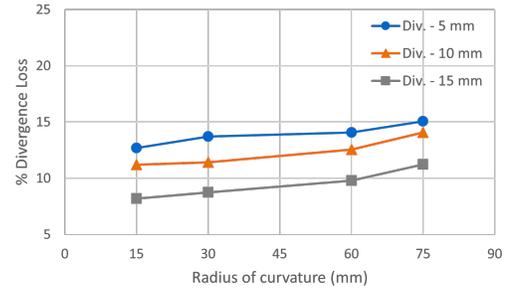
Figure 3: Change in illuminance distribution with different refractive structure arrangements



(a) Change in efficiency with spherical structure parameters



(b) TIR losses in the system



(c) Divergence losses in the system

Figure 4: Efficiency and losses of the optical system with different spherical structure parameters

the lens. Calculated efficiency values are presented in figure 4a. . Ray-tracing analysis results allow for selecting maximum efficiencies as a function of radius and depth. To further understand the losses in the optical system, we gathered the losses due to Total Internal Reflections (TIR) (figure 4b) ) and flux divergence after refraction through the lens (figure 4c).

We used a 3D printed lens to compare the experimental results with the simulated results to the validate our proposed design method. The experimental set up was developed with 3 OSRAM LEDs as light sources, and the movement of the LED was mimicked by turning on the respective LED to obtain the desired beam pattern. Extracted image data from the CCD camera and LightTools were normalized to compare results among simulation and lenses. The comparison given in figure 5 demonstrates that the novel method we introduced to achieve multiple beam distributions from a single lens can be effectively used in lighting applications. Further, experiment results from 3D printed lenses support the argument for developing 3D printed lenses for beam shaping applications.

#### 4. DISCUSSION

To our knowledge, this is the first study investigating the refractive lens array to obtain multiple illuminance distributions using different positioning of the source. Despite the number of studies available on optimization of lens arrays, the literature has not addressed the issue of 3D printable millimeter range lens arrays for multiple beam distributions. Hence, we presented a novel concept for obtaining different output beams with different LED positioning in array gaps. Our results confirm the possibility of creating a single fixed lens to achieve multiple beam distributions via different LED positioning.

This paper intends to introduce the concept of using a single lens for multiple beam distributions. However, the given study only discussed achieving two commonly used illuminance distributions using the spherical structure. In future studies, we expect to develop lenses that can produce multiple complex beam distributions with higher efficiency and uniformity.

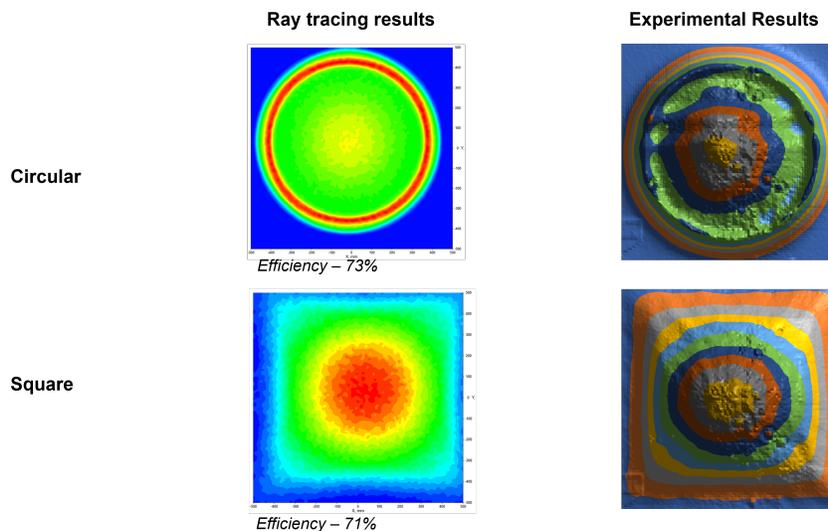


Figure 5: Simulation and experimental results comparison for multi-lens design

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