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Optimizing 3D printable refractive spherical arrays for application-specific custom lenses

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ABSTRACT

In the past two decades, solid-state lighting has steadily expanded to outperform many traditional lighting technologies due to its higher energy efficiency, longer lifetime, and reduced maintenance. The effectiveness of a solid-state lighting design for a given application relies upon the optimum use of its sub-components. An LED lighting system uses an optical subsystem with secondary optics to optimize the total luminous flux on the application surface, thus increasing its application efficiency. Therefore, it is essential to use well-defined secondary optics to achieve desired illumination patterns, luminous efficiency, and lighting uniformity. Hence, this study focused on developing a 3D printable refractive lens structure that collects luminous flux from the LED light source and redirects it into the spherical lens array. Subsequently, the spherical refractive array structures are designed in the lens to redirect the accumulated luminous flux onto the target plane to increase the application efficacy and uniformity. The designed lens is later fabricated using 3D printing to perform the experimental study. The results confirm the possibility of using a refractive array lens with a backend structure to achieve higher application efficacy.

Keywords: Beam shaping, lighting, Application efficacy, Uniformity, 3D printing, Optics, Additive manufacturing

1. INTRODUCTION

Lighting applications today are dominated by light-emitting diodes (LEDs) due to their potential for energy and maintenance cost savings. However, most of the bare LEDs without any optical optimization have a Lambertian distribution, which distributes a non-uniform circular spot in the target surface, where light intensity is bright in the center and decays in the radial direction.[1,2] Studies have shown that uniform illuminance in lighting applications such as parking lot illumination could increase the application efficacy and thus lower the energy use. Furthermore, uniform illumination in lighting applications increases user acceptance due to better visibility and higher perception of safety.[3] In an LED lighting system, it is the optical system that maximizes the total luminous flux and defines the illuminance distribution on the application surface. Hence, a well-defined optical system can improve the application efficiency and the uniformity of illumination applications.

The design and fabrication of refractive optical systems for illumination applications is widely discussed in previous literature.[4–6]Nevertheless, limitations in conventional lens fabrication methods constrain the complex lens design structures that can further improve the flux efficiency. A previous study conducted by Narendran and Perera at Rensselaer Polytechnic Institute's Lighting Research Center explored 3D printed optics for beam shaping.[7] This study discussed the feasibility of using an array of refractive hemispherical bump and dimple structures. Extending this study, Narendran and Udage designed custom 3D printed refractive optics for an outdoor light fixture with improved application efficiency and better uniformity.[8]

As presented by the previous studies, custom lenses can be designed to direct most of the light from the LED to the application area to achieve high application efficacy and desired uniformity levels. However, making custom lenses with traditional manufacturing methods is an expensive and time-consuming process. Recently, researchers investigated using optical 3D printing to design and make novel and custom refractive optics for

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illumination applications.[9,10] As an alternative to traditional fabrication methods, 3D printing can provide high fabrication quality and great resolution while saving time, resources, and money.[11]

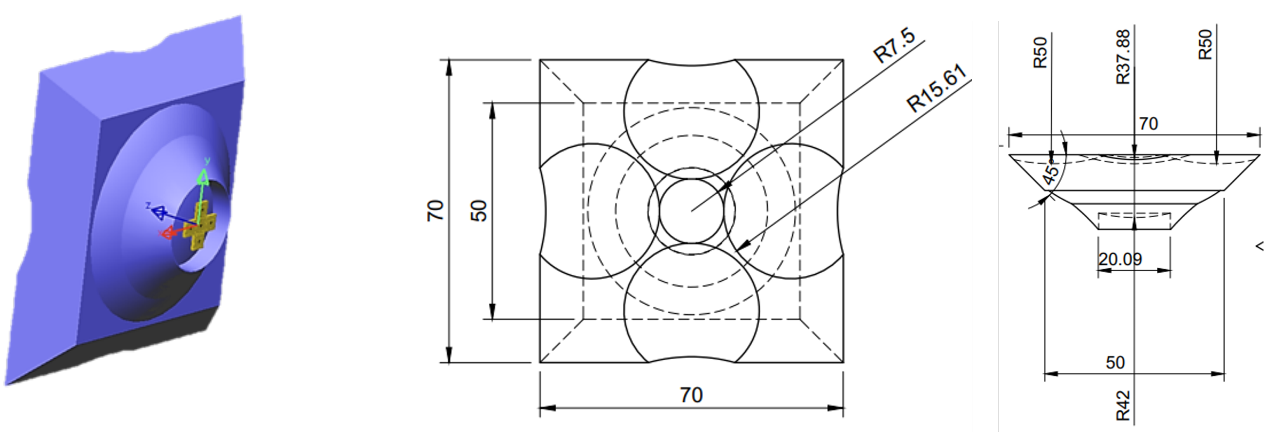
During this study, we propose a 3-D printable refractive array lens structure with a backend configured to receive and redirect light from a light source. Furthermore, the lens is composed of spherical refractive array structures that redirect the accumulated luminous flux onto the target plane to achieve the prescribed illuminance distribution with higher application efficacy. Finally, the proposed custom lens structure is printed using optical 3D printing to assess the performance of the printed optics.

2. METHODOLOGY

In this experiment, we introduced a method to design a 3D printable refractive spherical array lens to illuminate outdoor lighting applications. The *type V square* beam shape was selected from the beam shapes defined by the Illumination Engineering Society of North America (IESNA) for outdoor lighting applications. Target distance and illuminance map dimensions were selected corresponding to the *type V-very short* beam requirements. For the given application, this study used five Cree XLamp XP-E LEDs with near Lambertian distribution and 107°viewing angle. Five LEDs were arranged with one LED in the middle and four LEDs placed a 5mm distance from each side of the LED in the center.

Initially, we used Monte Carlo ray tracing simulation in LightTools optical design software to understand the optimum lens parameters to achieve the desired beam shape. Initial ray tracing analysis was performed to maximize the light transferred from the LED array to the target area. After selecting an appropriate LED–lens distance, the simulation continued to assess the effect of different spherical structure parameters on output beam distribution. The given lens used two refractive surfaces with spherical arrays. The initial ray incident array consisted of an array of convex spherical structures to converge the emitted ray from the LED source. The ray exiting surface contained concave spherical structures arranged to shape the radially distributed beam to the square shape beam distribution. During the initial optimization process, the flux efficiency at the target value was measured while changing the radius of curvature. The same experiment was conducted for multiple depths of spherical structures to understand optimum radius and depth parameters for higher efficiency.

After identifying the appropriate radius of curvatures and depths of the spherical structure for both surfaces, we introduced an additional middle concave spherical structure for the ray exiting surface of the lens. Using the additional concave structure in the middle, we continued our ray tracing simulation to improve the uniformity on the target plane. We recorded the flux efficiency and the target plane uniformity using different spherical depths for the added middle concave structure. From our initial ray tracing simulations, we identified that, due to the LED distribution pattern and the gap between the LED and the lens, nearly 7% of the LED's emitted flux was



(a) Lens with backend TIR optic

(b) Front view and the side view of the optimized lens design

Figure 1: Optimized lens design

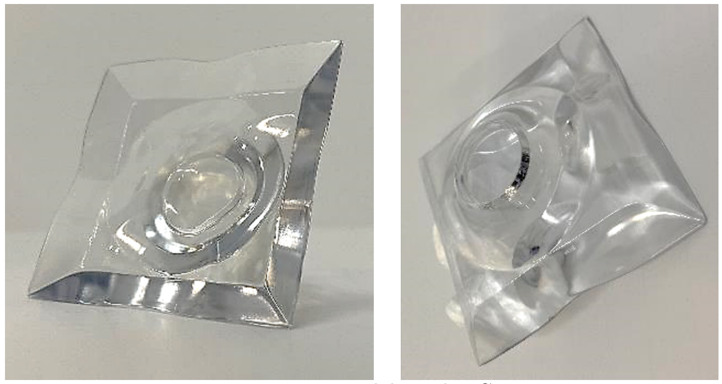


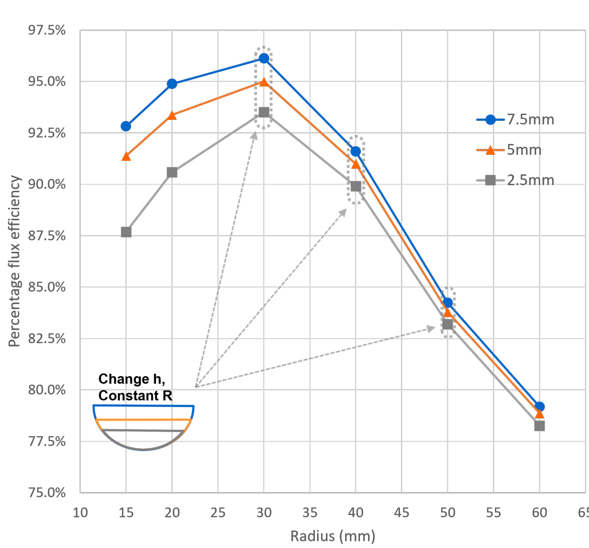
Figure 2: 3D printed lens by Stratasys

not reaching the incident surface of the lens structure. Hence, we introduced an additional TIR lens component to reflect those rays to the lens and direct them to the target plane. Further, an added backend configuration was designed in a way that it could rest on an LED substrate to facilitate easy alignment of the lens with the LEDs.

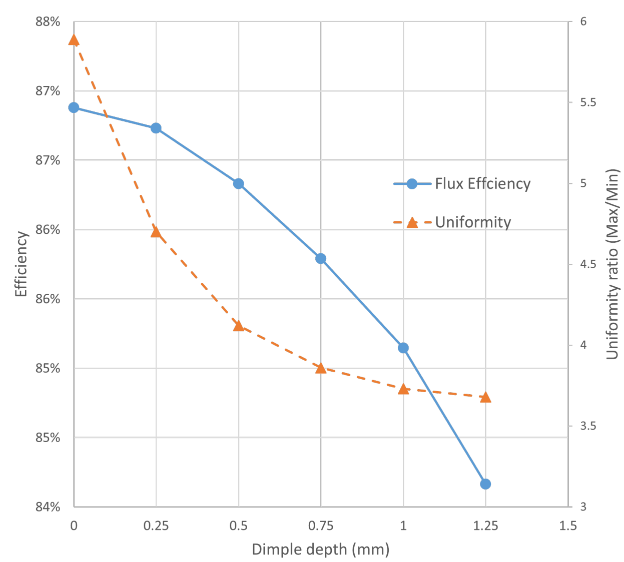
After realizing the optimum spherical array parameters for both lens surfaces for higher application efficacy while maintaining an acceptable uniformity ratio, we proposed the custom lens structure given in figure 1. The designed lens was later fabricated using 3D printing and went through post-processing and clear coating to improve the optical properties.(figure 2) Once the lens was fabricated, we collected the intensity distribution of the lens setup using a rotating mirror goniometer. Later, the gathered results were compared with the ray tracing simulation results to assess the performance of the 3D printed model.

3. RESULTS

Figure 3a shows a summary of results obtained during the ray tracing simulation. Results were gathered while changing the radius of the spherical structure for three different spherical heights. As we can see in figure 3a,



(a) Change in percentage flux efficacy with spherical parameters



(b) Change in efficiency and uniformity with dimple depth

Figure 3: Percentage flux efficacy variations with spherical parameter optimization

the captured flux efficiency at the target plane is optimum around 30mm radius of curvature. Further, it can be observed that when the spherical height is higher, the flux efficiency increases. After considering the flux efficiency and geometrical placements of spherical structures, we further optimized the ray exiting lens surface for higher uniformity.

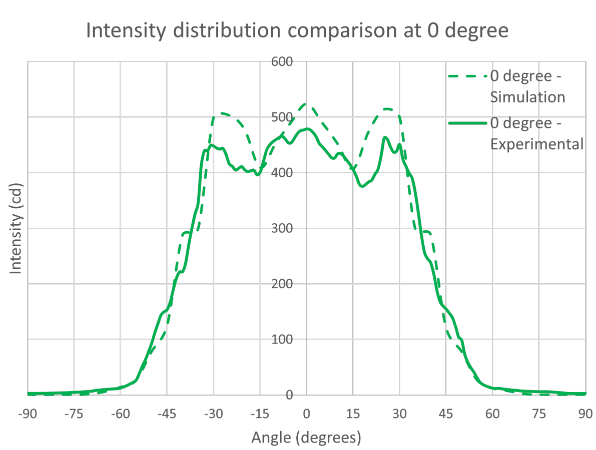
Figure 3b presents the change in flux efficiency and uniformity ratio for different middle concave structure (dimple) depths. The uniformity ratio is calculated as the ratio between minimum to maximum flux on the target plane. Based on the results given in figure 3b, we can observe that the flux efficiency decreases with an increase in dimple depth. This reduction of captured flux is caused by the divergence of the rays due to the introduced concave structure. However, divergence caused by the added concave structure enabled the gathered flux in the middle of the illuminance map to be distributed evenly over the target area. From figure3b, we can observe that uniformity ratio and efficiency both decreased with the added concave structure depth. Hence, to achieve the desired uniformity with compensated efficiency value, we picked the dimple depth of 0.75mm for the final lens design.

Figure 4 shows the intensity distribution comparisons of the ray tracing results and experimental results gathered from the 3D printed lens. Figure 4a and 4b respectively present intensity distribution comparisons of 0°and 45°angles. As given in the results, we can observe that the experimental values closely follow the ray tracing results. However, due to optical losses such as chattering and the Fresnel losses in the printed lenses, experimental intensity values are lower than the predicted ray tracing results. Overall, the presented results provide evidence for the possibility of designing and 3D printing application-specific custom lenses using refractive spherical arrays.

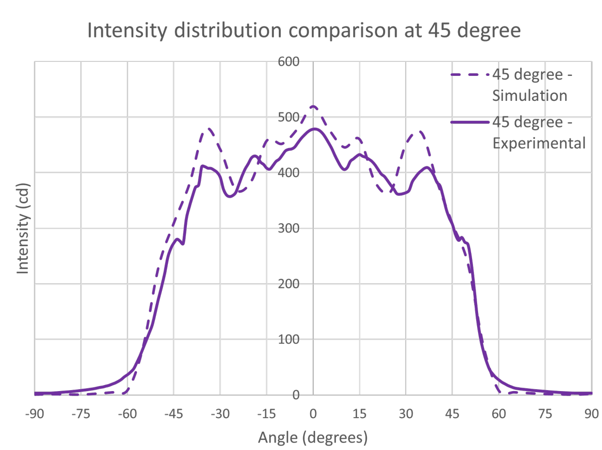
4. DISCUSSION

This study proposes a novel 3D printable refractive array lens structure with a backend configured to receive and redirect light from a light source. Furthermore, the lens is composed of spherical refractive array structures that redirect the accumulated luminous flux onto the target plane to achieve the prescribed illuminance distribution with higher application efficacy. Arrangement of the spherical structures on the first surface converges the LED ray distribution, while the spherical structure arrangement on the second surface is used to shape the beam for the desired illuminance distribution on the target surface. An additional spherical structure arrangement is proposed to improve the uniformity of the illuminance map. The fabrication of the proposed lens using 3D printing and assessing its performance demonstrated the potential in optical design manufacturing for illumination applications offered by additive manufacturing.

Gathered results confirm the possibility of using different structure parameters and array positioning to achieve the prescribed illuminance beam distribution with desired uniformity. Further, the results demonstrate



(a) Intensity distribution comparison at 0°angle



(b) Intensity distribution comparison at 45°angle

Figure 4: Intensity distribution comparison of experimental and simulated results

that the introduced backend configuration can significantly improve the flux efficiency at the target plane. In addition, to improve efficiency, the proposed backend configuration is used to precisely align the LEDs with the lens structure. The approach utilized suffers from the limitation of using an iterative design procedure. With the proof of concept given by these results, further investigation is needed on developing a design strategy using spherical refractive arrays with a direct designs approach.

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