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Akila S. Udage, Nadarajah Narendran, "3D printed internal cavity lens for illumination applications," Proc. SPIE 12216, Novel Optical Systems, Methods, and Applications XXV, 122160L (3 October 2022); doi: 10.1117/12.2641775

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Event: SPIE Optical Engineering + Applications, 2022, San Diego, California, United States

# 3D printed internal cavity lens for illumination applications

Akila S. Udage[a] and Nadarajah Narendran [a]

[a]Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY USA

## ABSTRACT

With LED lighting technology having matured in the past few years, lighting fixture manufacturers are now looking to add value to LED systems by introducing novel concepts through different sub-components. In conventional refractive optical systems, the lens outer surface geometries are used to shape the output beam distribution. As a result of geometries used on external surfaces, dust and dirt could accumulate on the surface of the secondary optics, decreasing the fixture's efficiency over time. Furthermore, exterior surfaces with complex geometries are difficult to clean and maintain. Hence, this study is focused on developing a 3D printable lens with planar exterior surfaces and internal cavity structures for beam shaping. The authors investigated the feasibility of using internal cavity structures with refractive spherical arrays to achieve prescribed illuminance distribution. The lens design strategy contains an iterative optimization procedure on internal cavity parameters to improve optical efficiency. Also, the study suggests that 3D printing can be used to manufacture internal cavity structures that are challenging to create using conventional methods.

**Keywords:** Cavity lens, Air lens, 3D printing, Beam shaping Optics, Additive manufacturing

## 1. INTRODUCTION

Since its introduction, solid-state lighting (SSL) has steadily proven itself to outperform traditional lighting technologies due to its cost competitiveness, lifetime, versatility, and energy efficiency.[1] The overall performance of an SSL system for a given application relies on the optimal use of each sub-component. In a LED lighting system, performance characteristics such as light output and application efficiency are firmly subject to the system's thermal and optical design. Secondary optical systems use refractive and reflective components to shape the output beam distribution. With the current advancement in optical design strategies and manufacturing capabilities, optical systems can be designed to introduce value additions beyond energy savings.

In refractive optical systems, surface boundaries between two media with different refractive indices are used for beam shaping. Generally, refractive optics use the external lens surface geometry to shape the output beam distribution. Over time, these exterior surfaces with refractive textures could cause dirt and dust to accumulate on the secondary optics, decreasing the luminance of the fixture. Lighting designers account for this loss using the Light Loss Factor (LLF), which is a multiplication factor that predicts future performance (maintained illuminance) of a lighting system based on its initial properties.[2] When lighting designers design LED lighting systems, they use higher outputs to compensate for anticipated losses due to dust and dirt accumulation on optical surfaces.

Instead of using external surfaces with complex refractive geometries that are difficult to clean and maintain, this study focused on developing a lens structure with two internal refractive surface geometries with flat external surfaces. This novel concept of using internal cavity lenses for beam shaping could minimize dust and dirt accumulation while accommodating easy maintenance. During this study, we investigated designing two internal cavity structures with refractive spherical arrays to achieve the prescribed illuminance distribution while using an iterative optimization procedure to improve optical efficiency. The latter part of the study discusses how the limitations of manufacturing internal cavity structures using conventional methods can be lessened with 3D printing.

Our initial literature search discovered studies that have investigated the concept of beam shaping using aspherical and freeform lens pairs with spaces between lenses.[3–5] However, these studies investigated a method

Corresponding author: Nadarajah Narendran
E-mail: narenn2@rpi.edu;, Telephone: +1 (518) 687-7100, Website: https://www.lrc.rpi.edu/programs/solidstate/

Novel Optical Systems, Methods, and Applications XXV, edited by Cornelius F. Hahlweg, Joseph R. Mulley, Proc. of SPIE Vol. 12216, 122160L · © 2022 SPIE
0277-786X · doi: 10.1117/12.2641775

of designing two individual lens structures for collimated coherent input beam distributions. With two separately designed lens structures, accurate spacing between the two lenses is a crucial factor for desired beam distribution. Further, when developing secondary optics for illumination applications using LEDs, it is essential to design a lens that can shape non-coherent radially distributed input beam distributions. In the area of developing lenses with internal structures for illumination, study presented lenses with inner freeform surfaces designed for LED downlight applications.[6] However, this lenses was designed with freeform surfaces to gather and project light through total internal reflection. Further, the lenses were designed with non-planar complex external surfaces exposed to the outside. According to a recent patent published by Narendran & Perera in 2022, beam forming can be achieved using 3D printed optical internal structures between surfaces.[7]

Optical designers work with different lens design techniques to achieve optimum lens designs for given applications. From traditional lenses using single spherical surfaces to shape the beams, refractive lens systems adopt the method of using lens arrays to shape the beam while achieving higher uniformity. While the majority of the lens array designs apply the structured microlens array method to achieve prescribed illumination distributions,[8,9] there are studies investigating the concept of optimizing an array of 3D printed refractive elements for beam shaping.[10,11]

With the growing complexity found in optical lens designs, using conventional manufacturing methods has become inefficient and arduous. As a solution, additive manufacturing, also known as 3D printing, has recently captured the attention of optical system manufacturers. Recent studies have recognized the potential benefits in 3D printing for SSL applications and investigated the possibility of printing different sub-components, including secondary optics of light fixtures, using 3D printing technology.[12,13] In optics, additive manufacturing offers a high degree of potential because of its ability to create new designs such as internal cavity lens structures.

According to our literature survey, no study to date has investigated the concept of using an internal cavity lens structure with planar exterior surfaces for illumination applications. Hence, this study is focused on developing 3D printable internal cavity structures with refractive spherical arrays. We propose a method for optimizing internal refractive array surfaces to improve efficiency and uniformity. Based on the results, this study presents an internal cavity lens optimized for a given illumination application. Furthermore, the study investigated the feasibility of using 3D printing to create internal cavity structures.

## 2. METHODOLOGY

This study used refractive array spherical components to design an internal cavity lens. Various depths ($h$) are used to section spherical structures with radius $R$ in order to achieve optimal flux efficiency and beam distributions. Symbol $d$ represents cord lengths created by the sectioning of the spherical structure. The relationship between parameters of two surface structures is defined by variable $k$. As given in figure 1, the first internal surface is designed with convex spherical arrays to converge the input beam, and the second internal lens is designed with concave spherical arrays. The initial phase of the study was dedicated to understanding the relationship between lens parameters and the output beam distribution. During the study, we first conducted sequential changes to the two internal refractive lens arrays to understand the effect of relative changes in array positioning on output beam distribution.

Using Monte Carlo ray tracing simulation in LightTools illumination design software, we observed the illuminance distributions as two internal spherical arrays were repositioned relative to one another. Figure 2

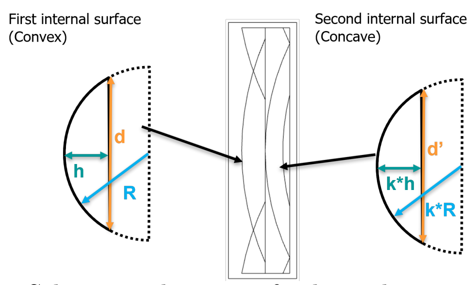


Figure 1: Schematic diagram of spherical internal cavity lens

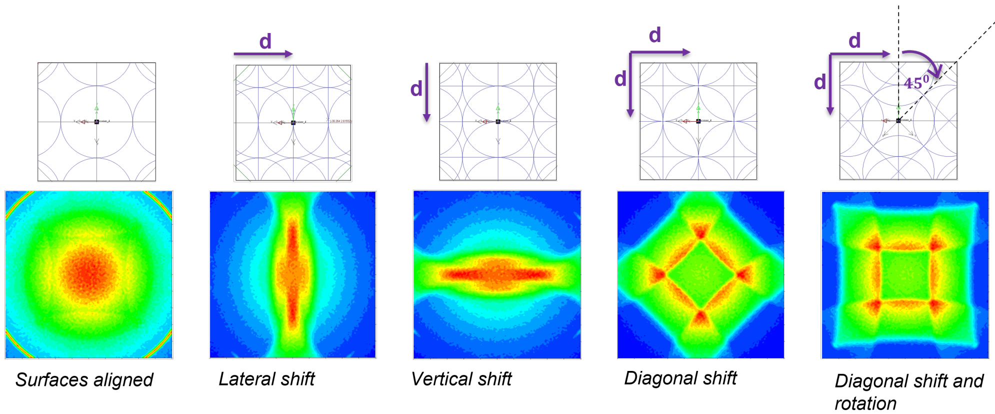
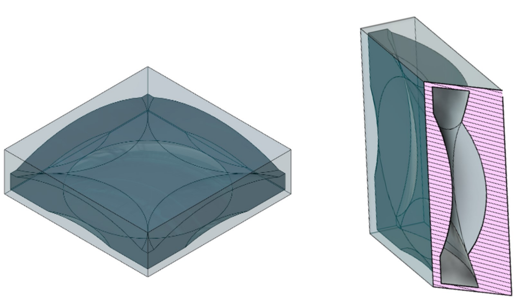


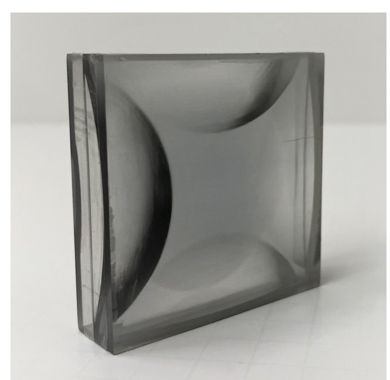

Figure 2: Relative movement of internal refractive arrays

demonstrates how the lateral, vertical, diagonal, and rotational movements of the second internal lens surface with respect to the first internal surface resulted in the output beam distribution. Based on the application requirement, the second surface is diagonally shifted through a lateral and vertical shift of cord length $d$ and 45°rotation to obtain a square beam shape. The selected internal lens array arrangement is then used to optimize using the lens parameters. During the initial optimization process, the lens efficiency at the target value and the uniformity ratio of maximum to minimum illuminance is calculated while changing the radius of curvature. During the results analysis, the lens efficiency is calculated as the ratio between captured flux at the target plane and the LED's flux output. The same procedure was conducted for multiple depths of spherical structures to understand optimum radius and depth parameters for higher efficiency and better uniformity. Once the optimum radius value and depth are obtained from the initial optimization process, the optimization process is further extended using the variable $k$ (relationship variable between the two internal surfaces). After a series of ray tracing simulations for different $k$ values, the optimum relationship parameter for spherical structures is defined.

By using the given sequence, we designed a lens with optimum radius and depth values to provide different beam distributions from the same lens. The designed lens structure has been fabricated using the multijetting 3D printing method. Due to current limitations of the available 3D printing method, the designed lens had to go through an extra step to prepare for 3D printing. Initially, a 3D CAD model of the designed lens structure was split along the plane between the first and the second internal lens structures. Then the two sections of the lens were printed using a Stratasys Objet30 PolyJet 3D printer. The print used a layer thickness of $15\mu m$ with VeroClear transparent material. After the print, the lenses went through post-processing with polishing and clear coating to improve the surface finish and optical properties. The printed lens and the complete CAD model are given in figures 3a and 3b.

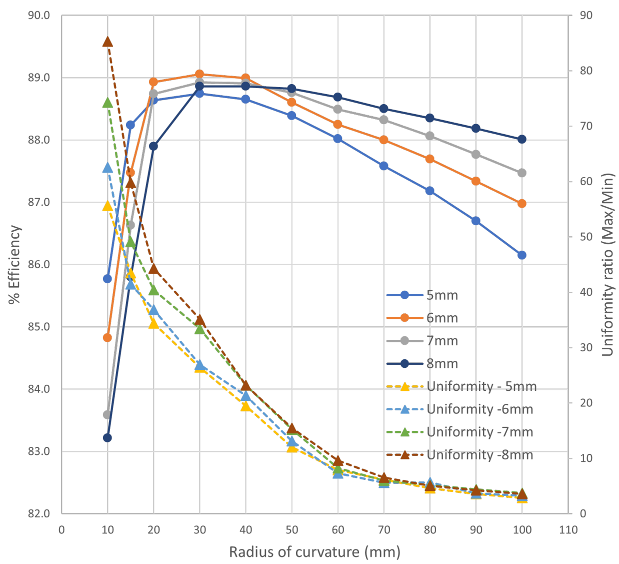


(a) 3D model of the lens

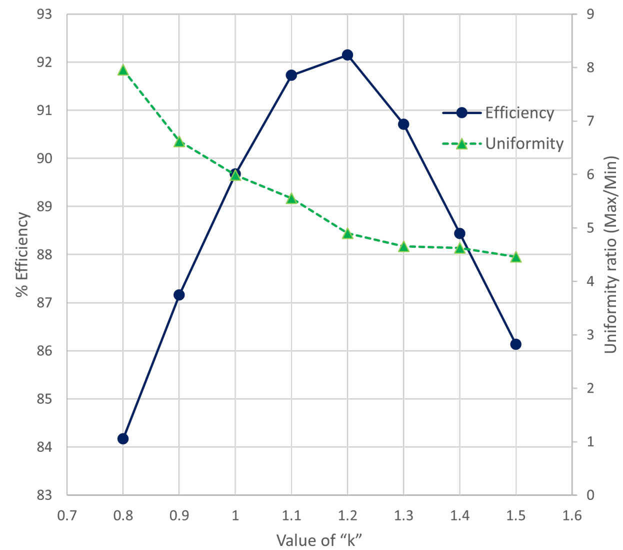


(b) 3D printed internal cavity lens

Figure 3: 3D printed internal cavity lens




(a) Change in efficiency and uniformity with radius




(b) Change in efficiency and uniformity with "k"

Figure 4: Parametric optimization for higher efficiency and uniformity

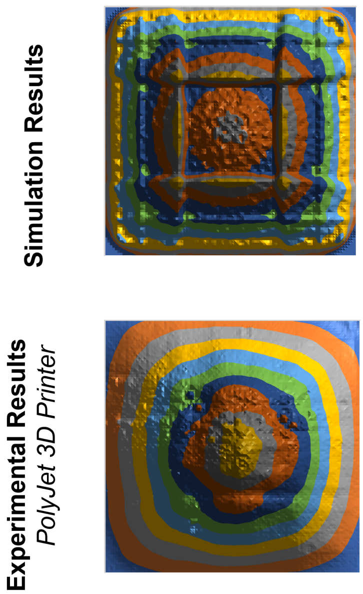
## 3. RESULTS

During our initial analysis, we conducted a sequential change of radius of curvatures in spherical parameters for different spherical structure heights. The flux efficiency at the target plane and uniformity ratio for each condition were collected in this study. Figure 4a presents the efficiency and uniformity fluctuation for the different radius of curvatures at different spherical heights. When the radius of curvature is increasing, the results demonstrate peak efficiency around 20mm to 40mm for all four different spherical depths and a decrease in efficiency with radius.

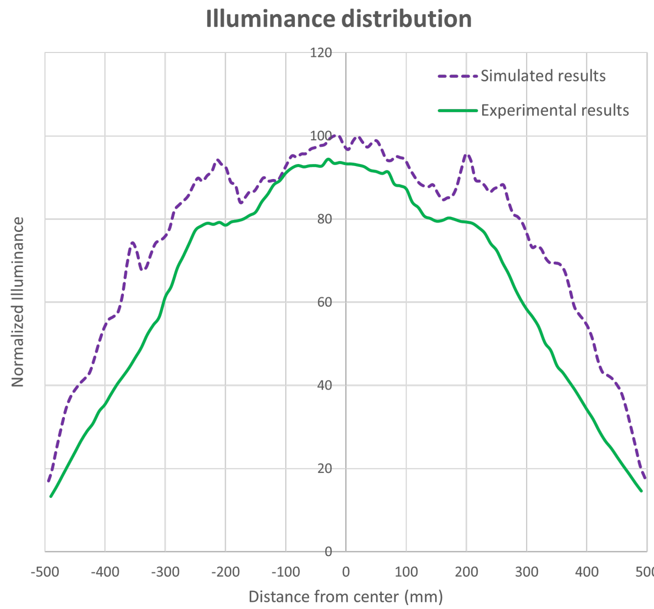
Additionally, we observed that the rate of efficiency decrease is lower for higher spherical depth structures than for lower spherical depth structures. As the radius of curvature increases, the uniformity ratio decreases, and the rate of decrease decreases as well. When selecting an optimized spherical lens array, this study considered achieving higher efficiency and uniformity. Even though a higher flux efficiency can be obtained at the radius range of 20mm to 40mm, maximum to minimum uniformity ratios are higher than desired levels. Hence, considering both aspects and physical dimensions, we selected the spherical array structure with a 70mm radius of curvature and a 7mm spherical height for further optimization.

It is important to note that this study used the same radii and depth values for both internal array lenses when measuring output while changing the radius and spherical depth. As defined earlier, the relationship between two surface parameters is defined by the variable k. Hence, during the next step of the optimization, this study changed the k value to assess the output characteristics of the selected lens. Figure 4b presents the change in flux efficiency and uniformity for different spherical parameter ratios between first and second internal refractive arrays. As observed in the results, when $k = 1.2$, this lens will be able to achieve the highest flux efficiency values with desirable uniformity levels. Hence, we selected the internal cavity lens structure containing the first lens with spherical arrays radius of 70mm and 7mm depth and the second internal lens with 84mm radius and 8.4mm depth.

Followed up by the simulations, the study was extended to validate the lens design using experimental results with the 3D printed lens structure given in figure 3b. The printed lens was used in a setup consisting of an LED with a near Lambertian distribution. The CCD radiant imaging camera was used to gather illuminance data on the target plane. A comparison of predicted results from Monte Carlo simulations and experimental results is shown in figure 5. Based on the initial results, we found that the experiment and ray tracing results did not closely match and required further investigation. In our initial ray tracing simulation study, we used the




(a) Target plan illuminance maps




(b) Normalized illuminance distribution

Figure 5: Comparison of simulation and experimental illuminance distribution at target plane

refractive index of the printed material as 1.5 and assumed the Fresnel losses of the system to be zero. As given in figure 6 we identified that by including Fresnel losses and changing the material refractive index to 1.4, it is possible to attain ray-tracing simulation results that agree with our experimental outcome. By comparing the results presented in figure 6, it is possible to state that the proposed lens design procedure for the internal cavity lens structure was able to validate the experimental results.

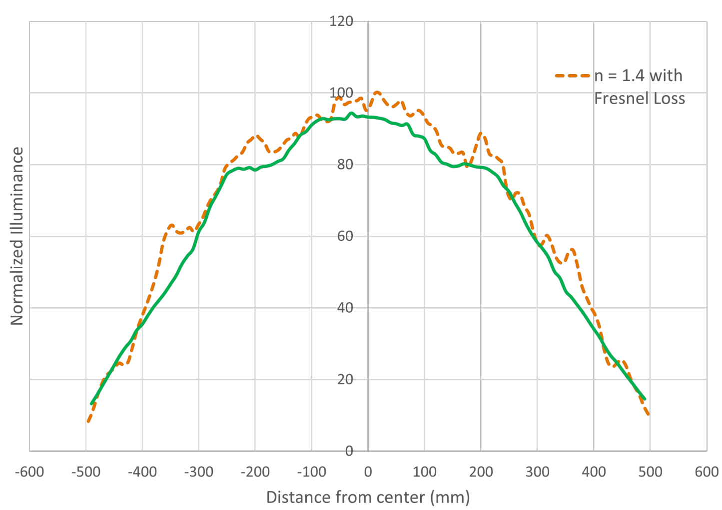



Figure 6: Comparison of experimental and simulation illuminance distribution after simulating with Fresnel losses and refractive index of 1.4

## 4. DISCUSSION

There have been isolated studies devoted to different aspects of developing lenses with cavity lens structures. However, to our knowledge, this is the first report investigating the development of internal air cavity lens structures with planar surfaces for illumination applications. Through this study, we proposed the novel concept of internal cavity lens structure and the capabilities of 3D printing optics with complex lens designs. Our findings provide a potential mechanism for developing internal cavity lenses with two internal surfaces to achieve desirable beam distribution. Further, this study proposed a method of optimization to achieve higher efficiency and uniformity.

One limitation of the proposed method is that it depends on an iterative optimization procedure based on spherical structure rather than a direct design method for a given distribution. Future research should consider the potential internal cavity lens designing strategies for desired beam distributions. In conclusion, this study was able to introduce the novel optical design concept of internal cavity lenses for illumination applications. Future studies are required to improve design strategies for more complex beam patterns.

## ACKNOWLEDGMENTS

We gratefully appreciate Jennifer Taylor from the Lighting Research Center (LRC) for her help in preparing this manuscript. Further, we are thankful to Jean Paul Freyssinier and Indika U. Perera of the LRC for their support. We also thank the Office of Graduate Education at Rensselaer Polytechnic Institute for their financial assistance to attend the SPIE conference.

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