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3D-printed refractive secondary optics for LED lighting

Indika U. Perera[a], Jean Paul Freyssinier[a], Nadarajah Narendran[a], and Akila S. Udage[b]

[a]Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY, 12180 USA
[b]formerly Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY, 12180 USA (Align Technology, Inc., 2820 Orchard Parkway, San Jose, CA, USA)

ABSTRACT

During the past several years, the interest for 3D printing of lighting optics has been growing rapidly. Most optical prototypes have been 3D printed using transparent photopolymer resin materials. However, the literature has limited information about the optical efficiency and the accuracy of beam shaping of such 3D-printed lenses. Therefore, to better understand the status of 3D printing lenses, a total internal reflection (TIR) lens was designed for use in replacement MR-16 (multifaceted-reflector) LED integral lamps. Several lenses were 3D printed in our laboratory and by two manufacturers. These 3D-printed samples were tested and the results were compared with a commercially available injection-molded TIR lens. The process and results of this benchmarking study are presented in this paper. The goal of this investigation was to study how 3D printer and material combination, build orientation, and post-processing affect the optical performance of LED lamps. The results showed differences in optical efficiency and beam shape for the printed samples. The highest optical efficiency achieved by these prototypes was 75%. The 3D-printed lenses with post-processing had similar performance to the injection-molded lens in terms of optical efficiency and beam width. The results showed that the layer height and print orientation affected the optical performance of the 3D-printed lenses. Our final conclusion is that 3D printing can achieve similar performance to commercially available polymer TIR lenses when suitable print parameters and post-processing are selected. Further studies are needed to identify the best build orientation and print layer height to minimize the light scattering that affects the lens performance.

Keywords: 3D printing, additive manufacturing, LED lighting, illumination, photopolymer, refractive optics, LED secondary optics, optical efficiency, beam shaping

1. INTRODUCTION

Light-emitting diode (LED) technology is the preferred lighting source in most general lighting applications today. This preference is due to LED lighting systems' potential energy efficiency and long lifetime, leading to operational cost savings. However, most lamps and lighting fixtures incorporating LED technology still have the traditional lamp and luminaire form factors due to limitations in manufacturing and tooling costs associated with unique custom-design geometries. 3D printing has the potential to address these limitations by relaxing some of the conventional manufacturing constraints.[1]-[3]

Optical components are one of several critical parts that make up a typical LED lamp or an LED luminaire. As such, the United States Department of Energy has identified the concept of customization of optical components as one of the opportunities where 3D printing can potentially increase U.S. presence in the LED supply chain by enabling the design and manufacturing of unique customized lighting systems.[4] Traditionally, optical components used on the LED packages and modules are referred to as secondary optics and can be of reflective type (i.e., reflectors), refractive type (i.e., lenses), or a combination of the two. These secondary optics control the beam and the direction of the light flux emitted by the LED source.

Corresponding author: Indika U. Perera
E-mail: pereru2@rpi.edu; Telephone: +1 (518) 276-7133; Website: https://www.lrc.rpi.edu/programs/solidstate/

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Past literature has reported stereolithography and multi-jet modeling 3D printing technologies as options for manufacturing refractive optical components.[2],[5]-[7] The authors conducted two benchmarking studies due to limited information on 3D-printed optical component performance in the published literature.

2. METHODOLOGY

Traditional halogen multifaceted-reflector (MR)-16 type lamps are a popular choice for interior lighting applications that require narrow beams for accent lighting. LED-type MR-16 integral lamps are replacing these traditional halogen sources. The secondary lenses used in these LED-type MR-16 lamps are typically injection molded. In this study, lenses were 3D printed and compared with a sample injection molded lens for the target application. The lens was designed for a multi-die LED array module (Figure 1) using the commercial Monte Carlo ray-tracing software package LightTools™. Using the ray files and specifications supplied by the LED module manufacturer, the authors created the optical model of the LED light source in the ray-tracing tool. The TIR surfaces of the lens were designed to provide an intensity distribution having 27±1° full width at half maximum (FWHM) and 50±3° full width at a tenth of maximum (FWTM) for lens materials with refractive index ranging from 1.45 to 1.55 (Figure 1: right). The outer and inner surface dimensions were fixed based on the heat sink and LED array module physical and mechanical requirements.

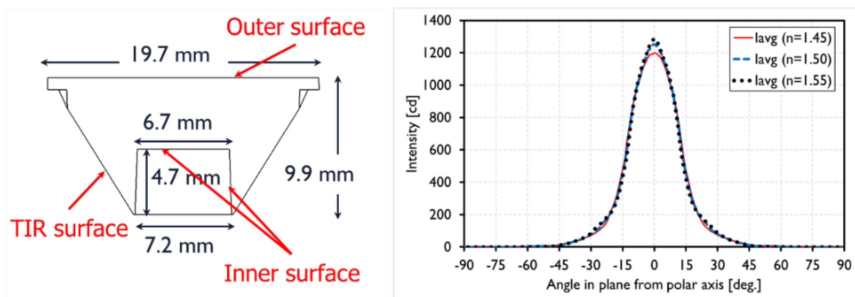

Figure 1. Schematic diagram of the lens design (left) and intensity distribution for refractive index ranging from 1.45 to 1.55 (right)

The two benchmarking studies discussed here include:

- Study I: 3D-printed lenses provided by Alliance for Solid-State Illumination Systems and Technologies (ASSIST) 3D Printing for Lighting Consortium members based on the CAD model provided by the LRC (Figure 1: left)
- Study II: 3D-printed in-house and post-processed lenses of the same geometry

This paper presents the results of these benchmarking studies on optical performance to identify the effect of:

- 3D printer and material combination (Study I),
- Build orientation (Study I and II), and
- Post-processing (Study II),

of 3D-printed total internal reflection (TIR) lenses for a multifaceted-reflector (MR)-16 type LED integral lamp.

2.1 Study I: 3D-printing technologies and material

ASSIST 3D Printing for Lighting Consortium members provided three 3D-printed lenses (**Error! Reference source not found.**). These three samples included:

1. Lens A: single sample of a lens 3D–printed using multi-jet modeling (MJM) with photo-curable resin and post-processed using a clear coating

2. Lens B-H: A single sample of the lens 3D-printed using digital light processing (DLP) with photo-curable resin with the optical axis normal to the print bed with the lens outer surface away from the print bed
3. Lens B-V: A single sample of the lens 3D-printed using DLP with photo-curable resin (same material as Lens B-H) with the optical axis parallel to the print bed

A similar outer and inner surface injection molded lens was also characterized, although the TIR surface geometry and intensity distribution differed from the designed lens used for the study. The optical efficiency, total flux, and flux exiting the outer surface were measured using integration sphere measurements, and beam quality was characterized using the intensity distribution measurements using goniophotometer measurements.

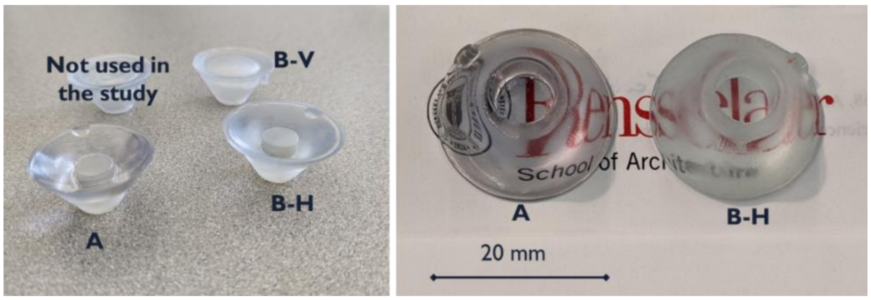

Figure 2. 3D-printed lens samples received from ASSIST 3D Printing for Lighting Consortium members

2.2 Study II: 3D printing orientation and post-processing

In this study, TIR lenses were 3D-printed using a Stratasys Objet 30 Pro 3D printer with VeroClear RGD810 photopolymer lens material and Support SUP705 support material. The lenses were 3D-printed at a layer height of ~15 µm and were 3D-printed in three different build orientations (Figure 3).

1. Lens A: optical axis perpendicular to the print bed with the lens outer surface on the print bed (Qty: 3; A-1, A-2, and A-3)
2. Lens B: optical axis perpendicular to the print bed with the lens outer surface away from the print bed (Qty: 1)
3. Lens C: optical axis parallel to the print bed (Qty: 1)

The lenses were then post–processed after initial washing and removal of the support material. The cleaned lenses were then illuminated under LED illuminance ~150,000 lx with an approximate correlated color temperature of 5,000K for 24 hrs to remove discoloration of the lens material after the initial build. These lenses were then characterized using the goniophotometer. Finally, automotive headlamp spray coatings were applied to some of the lenses and cured before retesting to characterize post-processing effects.

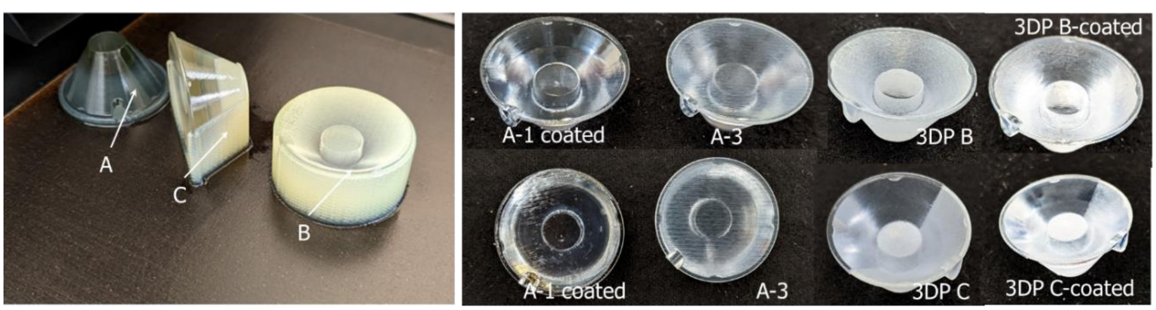

Figure 3. Lens samples 3D-printed at the LRC: Three different build orientations (left) and post-processed A-1, as-printed A-3 (middle), and as-printed and post-processed B and C lenses (right)

In Study II, only the beam quality was characterized using the calculated intensity distribution using goniophotometer measurements.

3. RESULTS

3.1 Study I: 3D-printing technologies and material

Figure 4 illustrates the total flux, i.e., the combined total flux exiting both the outer surface (A) and the TIR surface (B), and the flux exiting the outer surface (A) only. The LED array module at 75 mA drive current produces 321 lm. The total flux efficiency of a 3D-printed lens was defined as the percent ratio between the total flux of the lens and the flux of the LED array module. The total flux efficiencies of the 3D-printed lenses A, B-H, and B-V were 75%, 71%, and 74%, respectively. The total flux characterization from the lenses A, B-H, and B-V indicated the lens materials used for 3D printing of the lenses had similar optical properties, including refractive indices, optical absorption, and bulk scattering properties.

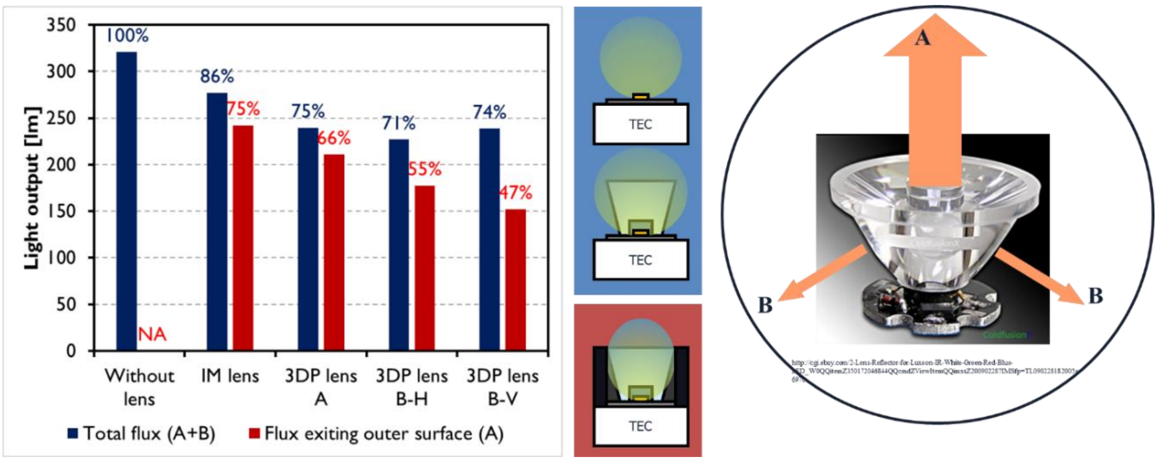

Figure 4. Integrating sphere light output characterization results: total flux and flux exiting the outer surface.

The percent ratio of the light output (B) exiting through the TIR surface to total flux (A+B), defined as TIR % loss. The TIR % loss was similar in magnitude between the injection molded lens and the 3D-printed lens A (~12%). This shows that the lens A TIR surface with post-processing from the lens manufacturer had a similar performance to the TIR surface of the injection molded lens. Respectively, the 3D-printed lenses B-H and B-V had TIR loss % values at 23% and 36%. This change in flux exiting the TIR surface suggests the 3D printing parameters such as layer height (DLP layer height range ~25-100μm, and MJM layer height range ~16-32 μm) and build orientation had a significant effect on the optical performance of the 3D-printed lenses.

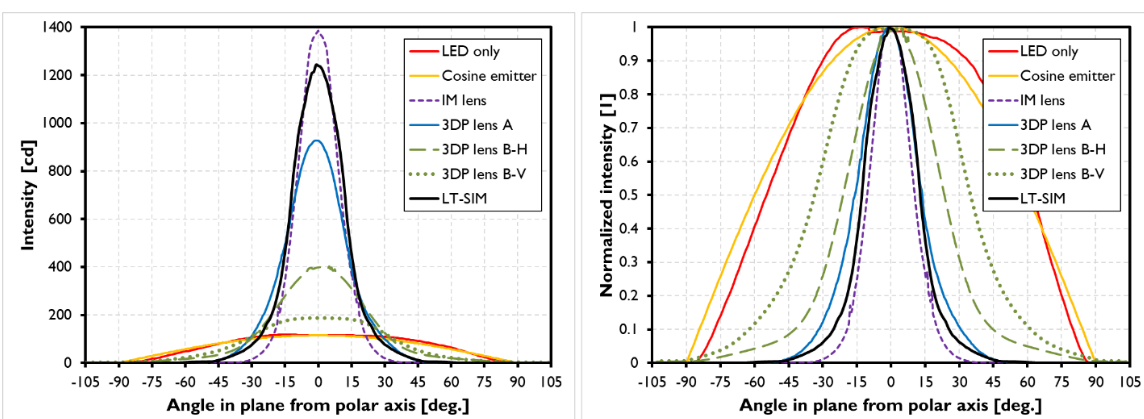

Figure 5. Study I goniophotometer characterization results: calculated intensity distribution (left) and normalized intensity (right)

Figure 5 shows the calculated intensity distribution from goniophotometer testing. The decrease in beam quality due to 3D-printing layer height and orientation is further illustrated here with the reduction of the absolute intensity and the broadening of both the FWHM and FWTM of the intensity distribution of lenses B-H and B-V compared to lens A. The simulated lens (using PMMA as the lens material) and injection molded lens intensity distributions are also shown in Figure 5 for reference. Lens A had a 30° FWHM slightly wider than the simulated results (FWHM 26°).

3.2 Study II: 3D printing orientation and post-processing

Figure 6 shows the calculated intensity distribution results from the goniophotometer characterization. Lenses A (1-3), B, and C show the effect of beam quality due to orientation on the print platform. Center beam candlepower (CBCP) was the highest and had the narrowest spread of the FWHM and FWTM when the optical axis of the lens was perpendicular to the print bed with the lens outer surface on the print bed (lens A) compared to other print orientations (lenses B and C).

The post-processing of the 3D-printed lenses increased CBCP in all three build orientations, as seen in Figure 6. The improvement of the FWHM can also be seen in the normalized intensity plot with the narrowing of the intensity distribution from lens B → lens C → lens A with the post-processing (Figure 6: right).

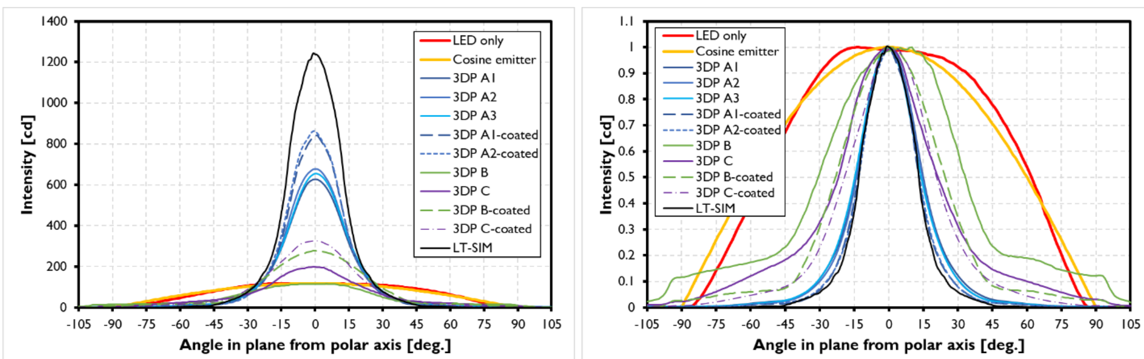

Figure 6. Study II goniophotometer characterization results: calculated intensity distribution (left) and normalized intensity (right)

Figure 7 also shows the improvement of both the FWHM and the FWTM of lens A as the print orientation and not using support material on the TIR surface (lens A) compared to lenses B and C.

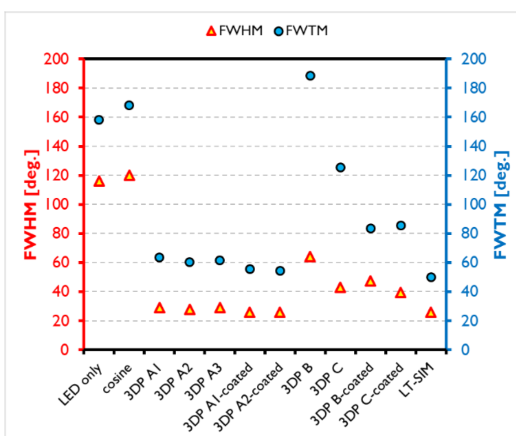

Figure 7. Study II results of FWHM and FWTM angle calculation

The post-process improved the FWHM of the lenses A-1 and A-2 to the required FWHM of 26° (from the ray-tracing simulations). Although the post-processing also improves the FWTM (55-56°), the gain is lower than the ray-tracing simulation results (50°). The broadening of the intensity distribution can be attributed to the scattering at the TIR surfaces present even after the post-processing steps. The TIR surface could be improved by post-processing, including mechanical polishing, chemical smoothening, thicker coatings, etc.

4. SUMMARY

Results from benchmarking studies look into the combination of 3D printer and material, print orientation, and post-processing of optical components using a 3D-printed TIR lens for LED lighting as an example. The results of the 3D-printed lenses showed a 75% maximum total flux efficiency, while 88% of that flux was exiting through the outer surface of the lens (i.e., the TIR % loss was 12%). Ray-tracing simulations for the same lens showed 90% total flux efficiency. Although the total flux efficiency was lower than the simulation results, the fraction of flux exiting the TIR surface to total flux was similar in magnitude between the injection molded lens and the 3D-printed lens A (~12%), indicating the TIR surface with post-processing from the lens manufacturer had a similar performance to the TIR surface of the injection molded lens.

The tested lenses satisfied the 26° FWHM criterion for the narrow spot with 3D-printed lenses (Study II: post-processed lens A). The scattering at the TIR surface due to the layered printing process could be resolved by post-processing, such as polishing and spray-coating or dip-coating, which could lead to reduced scattering and increased CBCP. The optical efficiency and beam quality are lower in the 3D-printed lenses due to the light scattering at the TIR surfaces.

Studies I and II both indicated the layer height and orientation on the build platform of the CAD model was a significant contributing factor to the optical performance of the 3D-printed lens. Although post-processing, such as spray coating, could improve the performance, it was critical to identify the best build orientation and the print layer height to minimize the light scattering at critical surfaces such as the TIR surface.

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