Tunable LED-based Illuminator Using Freeform Arrays

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Abstract: We present a tunable LED-based illuminator using custom arrays of Alvarez lenses with commercially available secondary optics. Design methods and characterization of the system performance are discussed. ©2021 The Author(s)

1. Introduction

Tunable illumination with high uniformity can enhance the functionality and performance of lighting applications. Providing variably sized illumination patterns has been previously achieved, for example, using configurations in which longitudinal movement along the optical axis of the system applies to source or other optical elements [1, 2]. In these systems, the chance of experiencing an undesired non-uniformity in the illuminance pattern is significant. Adding a lens array can significantly improve performance [3, 4]; however, the axial movement may be undesirable in some compact applications. Alvarez lenses [5] provide variable spherical power through lateral relative translation between pairs of plano-freeform elements and have the potential to enable more compact illumination systems. We have previously reported a dynamic illuminator based on a parabolic reflector, a pair of fixed confocal lens arrays, and an array of Alvarez lenses [6]. While the presented system shows the desired performance, the system requires multiple custom components and assumes the use of a point source.

In this paper, we present a refined tunable illumination system that uses a commercial-off-the-shelf (COTS) TIR lens with an integrated lens array, a commercially available white light LED source, and a custom Alvarez lens array (Fig. 1). The system is modelled as a LED-based lamp with continuously variable divergence (from a spot mode to a flood mode) and high uniformity. The use of COTS component can shorten manufacturing time and decrease system costs. However, the selected compound TIR lens was not fully specified by the manufacturer and it was necessary to first reverse engineer and measure the part geometry for use in simulation and design. We discuss the modeling of the compound lens and its matched LED and characterize system performance using LightTools®. We also discuss the analysis and adjustment of the Alvarez lens surface form to improve the quality of the projected illumination patterns.

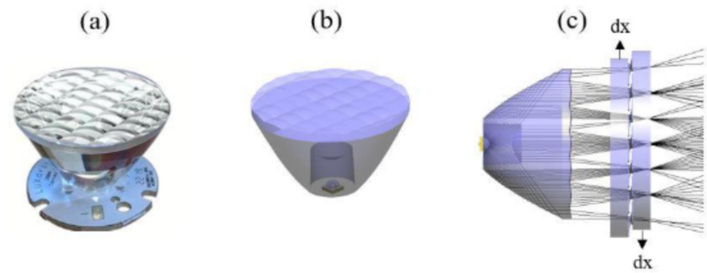

Fig. 1. (a) The COTS lens mounted on the LED board, and simulated models of (b) COTS lens and LED, and (c) tunable LED-based illumination system.

2. Methods

In the current design, light emitted from a commercial white LED is collimated and then distributed into convergent light channels using the COTS TIR component. The convergent ray bundles are adjusted by passing through the laterally shifted Alvarez arrays. The Alvarez surface parameters are the main design variables since the LED and COTS lens parameters are fixed. The dynamic power of the Alvarez arrays is adjusted by adding optical power parameters to the general form of Alvarez surface equation as follows:

$$z(x,y) = A\left(\frac{x^3}{3} + xy^2\right) + Bx^2 + Cy^2 + Dx \quad (1)$$

where A controls the depth modulation of the surface, B and C correspond to the added cylindrical optical power terms, and D is a prism term impacting the element thickness.

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System design and optimization requires knowledge of the COTS component parameters. The TIR part of the compound lens was modeled based on the available information. The lenses in the integrated lens array had an unknown radius of curvature (ROC) which was a critical design parameter. To this end, surface measurements of the ROC were performed at the Center of Precision Metrology (CPM) at UNC Charlotte using scanning white-light interferometry. With this information LightTools® was used to simultaneously optimize two configurations associated with the spot and flood modes of the system, with maximum lateral shifts of the Alvarez arrays in opposite directions. The double-configuration system was optimized for a collimated beam at spot mode and a uniform rectangular mesh target for the flood mode.

3. Results and Discussion

Fig. 2(a) shows the illuminance patterns for three selected modes within the tunable range of our illumination system. As seen in the true color chart, a significant distortion defect is present in the illumination flood mode. To find the cause of this effect, a form analysis was performed by passing a uniform ray bundle through one surface to identify the individual effect of each Alvarez surface parameter. Comparison of the results suggested that the distortion defect arises from the xy^2 term in Eq. (1) in the first Alvarez array and is not fully compensated by the second Alvarez array due to the air gap. Based on this analysis, an additional term proportional to x^2y^2 was added to the Alvarez surface equation in Eq. (2) and manually adjusted to minimize the distortion defect; the improved results are shown in Fig. 2(b). The area of the illuminance pattern slightly decreased after refinement and the average deviation of the pattern illuminance values over this region did not change significantly. Fabrication and testing to verify and characterize the performance of this proposed system are underway.

$$z(x,y) = A\left(\frac{x^3}{3} + xy^2\right) + Bx^2 + Cy^2 + Dx - Ex^2y^2 \tag{2}$$

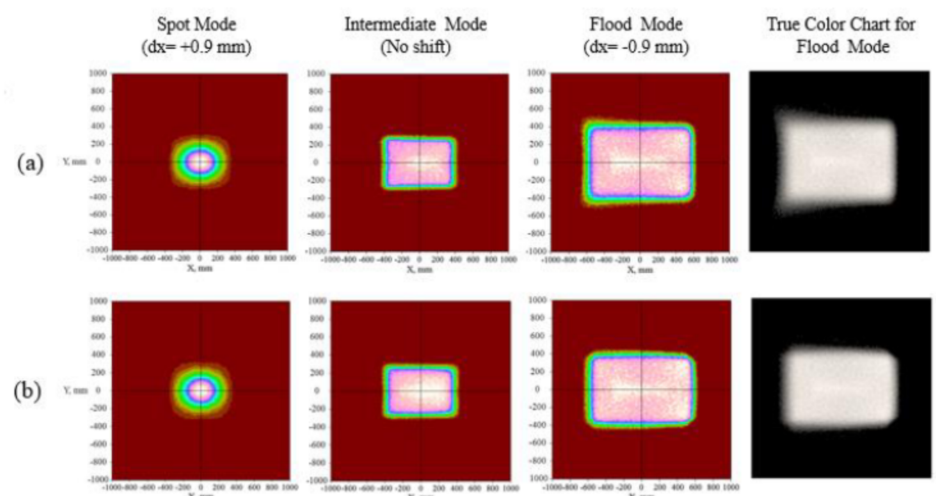

Fig. 2. Resulting illuminance patterns of the tunable LED-based illuminator at 2m from the LED source for 3 selected modes with (a) the general Alvarez form given by Eq. (1), and (b) the refined Alvarez form given by Eq. (2).

4. Acknowledgments

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5. References

[1] R. D. White and D. P. Weiss, "Lighting device with dynamic bulb position," U.S. Patent 4,339,788 (3 July 1982).
[2] W. Jiang, "Zoom lens system for LED-based spotlight," U.S. Patent 8,641,230 (4 February 2014).
[3] D. J. Stavely, "Variable focus illuminator," U.S. Patent Application 13/294,026 (17 May 2012).
[4] J. B. Lee, I. Brian, Y. Chiang and H. K. Ho, "Zoom spotlight using LED array," U.S. Patent 8,979,316 (17 March 2015).
[5] L. W. Alvarez and W. E. Humphrey, "Variable-power lens and system," U.S. Patent 3,507,565 (21 April 1970).
[6] S. Shadalou and T. J. Suleski, "Freeform optics for dynamic illumination," Proc. SPIE 11495, 114950B (2020).