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Tunable illumination for LED-based systems using refractive freeform arrays

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Abstract: Tunable illumination with high uniformity can improve functionality for multiple application areas. In lighting applications, dynamic illumination has been achieved by applying axial movement to the source(s) or other optical elements, resulting in poor uniformity, or using a liquid lens that adds design complexity. Advances in high-precision manufacturing methods have facilitated the practical implementation of freeform optical components, enabling new design approaches for illumination systems. This paper explores the use of arrays of varifocal transmissive freeform Alvarez lenses for an LED-based illumination system. The design is initialized using paraxial geometrical optics concepts and then refined for a 1mm-by−1 mm white LED source through a multi-step optimization. Design procedures are discussed, and simulation results are presented for an example illumination system that varies from a small circular spot mode to a large square uniform flood mode through millimeter-scale lateral translation between the Alvarez lens arrays.

1. Introduction

Illumination systems with the ability to provide spatial light distribution with continuously variable size can be beneficial for multiple applications such as advanced lighting, entertainment, medicine, automotive, and security. High uniformity is desirable to avoid illumination defects that can impact system performance or visual perception [1]. Design of illumination systems with high efficiency is also desirable for energy conservation. Modern illumination systems commonly use light-emitting diode (LED) sources, which significantly enhance lighting efficiency. In addition to low power consumption, LED sources offer high reliability, controllability, and long lifetimes [2].

Variably sized illumination patterns have been previously achieved, for example, by applying longitudinal movements along the optical axis of the system to the source(s) or other optical elements [3–6]. However, the chance of experiencing non-uniformity in the illuminance pattern is high. Uniformity in illumination systems can be improved, for example by using a plurality of sources [7–10] or by using integrating lens arrays [11–13]. The arrangement of lenses or source arrays is an important factor in the design of such systems that impacts the shape of output illuminance patterns [14] as well as system size. Utilizing multiple LEDs or using lens arrays in a zoom arrangement enhances uniformity but may not result in sufficiently compact systems for some applications.

Improvements in high-precision manufacturing techniques such as diamond machining have facilitated the implementation of freeform optics in optical systems. Freeform optics offer additional design freedoms in the absence of constraints imposed by rotationally symmetric optics [15]. The use of freeform optics in illumination systems to provide prescribed illuminance patterns has also gained significant interest among designers [16]. Freeform design has also enabled highly uniform illuminance patterns from LED sources with non-uniform Lambertian distribution [17–20]. To improve the functionality in illumination systems, researchers have proposed

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LED-based illumination systems with multiple operating modes using freeform optics [21,22]. However, these approaches cannot provide continuously tunable illumination. Researchers have previously reported refractive two-element systems based on freeform optics converting Gaussian laser distribution to flat-top outputs with adjustable diameter [23,24]. However, this approach is based on monochromatic, collimated, Gaussian beams, but LEDs have non-collimated Lambertian light distributions. Reviewing the literature shows that continuously variable illumination in LED-based systems using freeform optics has not received sufficient attention.

We previously reported a dynamic illuminator based on a parabolic reflector, a pair of fixed confocal lens arrays, and an array of freeform Alvarez lenses, as can be seen in Fig. 1(a) [25]. In that system, the light incident on the Alvarez lenses is collimated and the Alvarez lenses provide variable spherical power through lateral relative translation between pairs of plano-freeform elements [26]. The use of arrays in the design enhances uniformity while also reducing the maximum lateral shift needed between the freeform elements. This system demonstrates dynamic illumination from spot mode to a homogenized flood mode, but the system assumes a point source and uses a limited scanning range of the Alvarez arrays.

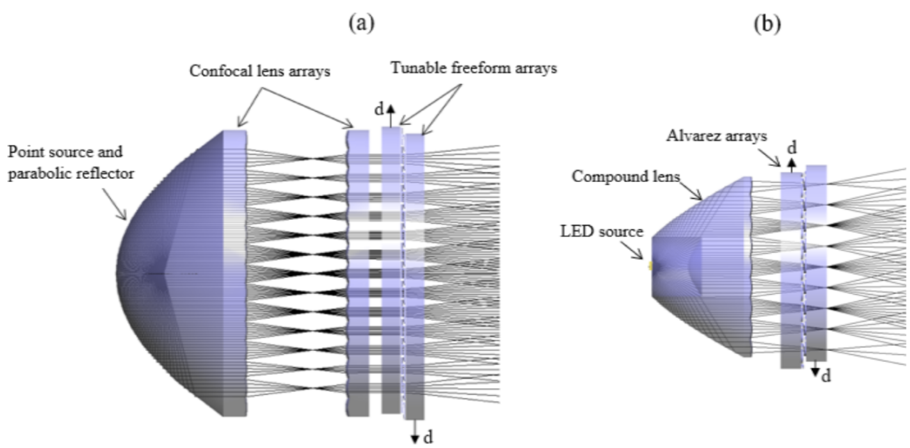

Fig. 1. (a) Schematic of dynamic illumination design from [25]; (b) Tunable LED-based illumination system based on convergent ray bundles.

In this paper, we present a compact tunable illuminator shown in Fig. 1(b) using a real LED source, a compound optic consisting of a total internal reflection (TIR) lens with an integrated lens array, and arrays of Alvarez lenses. The use of the compound optic reduces the number of components and creates convergent ray bundles that extend the practical working range of the Alvarez arrays and results in a more compact system. The initial design is constructed by assuming a point source and applying paraxial geometrical optics concepts. A simultaneous optimization approach is then demonstrated to expand and enhance the performance of the design based on a real LED [27].

Section 2 presents the general design approach and background information. This approach is demonstrated in detail through a design example in Section 3. Simulation results are discussed in Section 4, followed by conclusions in Section 5.

2. General design approach

This work combines two main concepts: (1) homogenizing the illuminance pattern using an integrated lens array, and (2) generating variable divergence illumination utilizing arrays of freeform Alvarez lenses.

A lens array can be combined with a collimator to generate a homogenized illuminance pattern from a non-collimated source. Using a TIR lens is a common approach to collimate a LED light distribution. Besides uniformity, different arrangements of lenses in the array (e.g., rectangular, hexagonal, and so on) enable generation of various shapes of illuminance patterns. This behavior can be explained by considering the target pattern as a convolution of the source intensity and lenslet response. The lenslet response depends on the aperture shape and curvature of each lenslet [14].

Alvarez lens arrays [e.g., 28,29] can be used in an illumination system to enable tunability while also reducing the system size compared to a single pair of Alvarez lenses. The general form of the Alvarez lens pairs consists of two plano-freeform elements with matching cubic surfaces resulting in a continuously variable spherical power as opposite lateral shifts are applied. The freeform surface equation following a first-order analytical approach is given by:

$$z(x, y) = A(\frac{x^3}{3} + xy^2) + Cx, \tag{1}$$

where z corresponds to the surface thickness, coefficient A controls the depth modulation of the surface, and coefficient C is a prism term impacting the element's thickness. The equivalent optical power P for the composite surface is then:

$$P = -4Ad(n_m - n_s), \tag{2}$$

where d is the lateral shift of each freeform element along the x direction and n_m and n_s are the refractive indices of the optical material and surrounding medium. This general form generates positive, negative, or zero optical power at negative, positive, and zero lateral shifts of the elements, respectively [26].

The use of Alvarez lens pairs with collimated light results in the minimum divergence angle (spot mode) to occur with no shift between the Alvarez lenslets (Fig. 2(a)). A similar spread (flood mode) is achieved with both positive and negative lens shifts. To ensure that only the overlap area of the Alvarez lenses is illuminated, additional array optics are used. This was done using two lens surfaces in the previous system [25]. An alternative approach is to use a converging beam to illuminate the Alvarez lenses so that the collimated beam (spot mode) occurs with the lenses shifted in the positive direction (Fig. 2(b)). This means the negative shift can produce an even wider beam spread (flood mode) compared to the conventional layout.

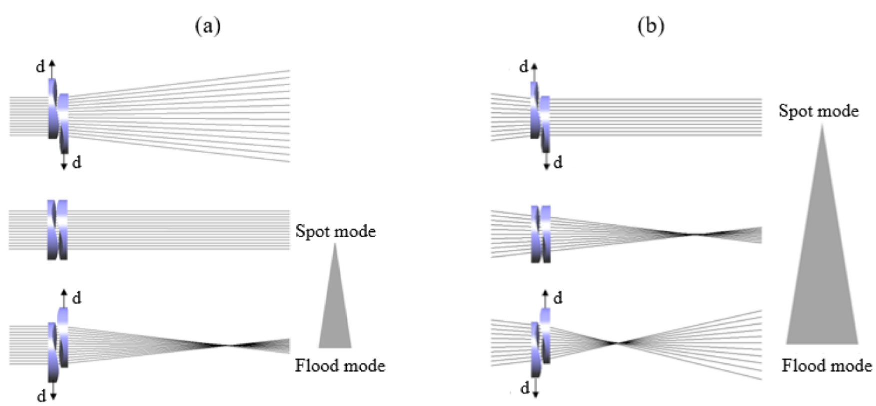

Fig. 2. Alvarez lens pair with (a) parallel incident ray bundle and (b) convergent ray bundle.

Based on the presented design ideas, light emitted from a Lambertian LED is considered to pass through a collimator and be redistributed into convergent ray bundles by an integrated lens array. Each of these convergent channels then enters a unit cell in the Alvarez arrays, and their angular path is adjusted by applying lateral relative shifts to the Alvarez freeform lenses.

A model of the illuminator including the source, collimator, and Alvarez arrays can be constructed in optical software. The initial design parameters can be calculated by applying paraxial geometrical optics concepts to edge rays passing through a single unit at the boundary conditions. Figure 3 shows a single converging ray bundle from a lenslet of power P_1 that is adjusted to the final viewing angle by passing through the shifted Alvarez lens pair with power -P_2 for spot mode and power P_2 for flood mode. The incident angle of the edge ray for the collimated ray bundle (u_1) is zero and the refracted angles for the spot and flood modes can be calculated based on the target geometry.

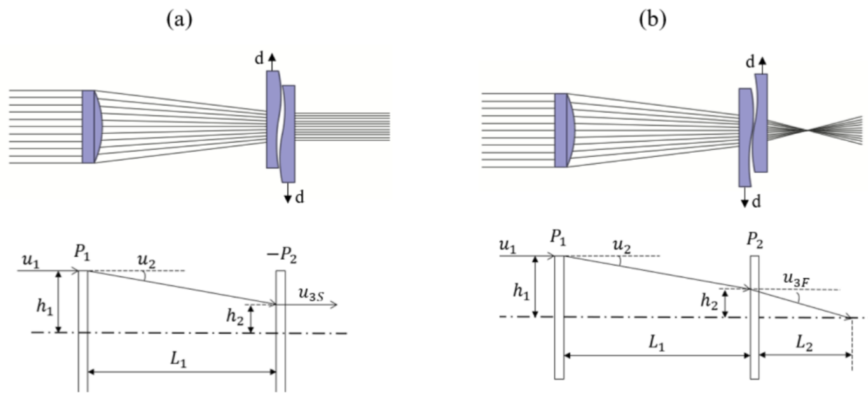

Fig. 3. Edge ray trace at boundary conditions: (a) spot mode, and (b) flood mode.

The edge ray geometries are the same in both spot and flood modes before entering the Alvarez lens. The refracted angle of the edge ray u_2 from the plano-convex lenslet and its height (h_2) before entering the Alvarez lens are given respectively from the transfer function as:

$$u_2 = u_1 - P_1 h_1, \tag{3}$$

$$h_2 = h_1 - u_2 L_1, \tag{4}$$

where P_1 is the optical power of the lenslet and L_1 is the distance between the lenslet and the Alvarez lens. After passing the Alvarez lens pair, the refracted angles of the edge rays for spot mode (u_{3S}) and flood mode (u_{3F}) are respectively:

$$u_{3S} = -u_2 + P_2 h_2, \tag{5}$$

$$u_{3F} = -u_2 - P_2 h_2. \tag{6}$$

Using Eqs. (3) to (6), we calculate the optical power of the lenslet (P_1), the maximum optical power of the Alvarez lens pairs (P_2), and the distance between them (L_1), respectively as:

$$P_1 = \frac{(2u_2 + u_{3S} + u_{3F})}{2h_1}, \tag{7}$$

$$P_2 = \frac{u_{3F} - u_{3S}}{2h_2}, \tag{8}$$

$$L_1 = \frac{2(h_1 - h_2)}{u_{3S} + u_{3F}}. \tag{9}$$

The radius of curvature (R) of the lenslets can be found by applying the lens-maker's equation to Eq. (7):

$$R = \frac{2h_1(n_m - n_s)}{2u_1 + u_{3S} + u_{3F}}. \tag{10}$$

The A coefficient of the Alvarez surface can then be obtained using Eqs. (2) and (8):

$$A = \frac{u_{3F} - u_{3S}}{8h_2 d_{\max}(n_m - n_s)}. \tag{11}$$

The required values u_{3S}, u_{3F}, h_1, and h_2 needed to calculate the main design parameters are set by the requirement of the illumination system. The main design parameters obtained from the above paraxial calculations provide a starting design for the optical system. The design process can be accelerated by using multi-step optimizations beginning with an infinitesimal monochromatic Lambertian source and a small number of rays continuing with gradually increasing the number of beams and replacing the point source with a real LED model [27]. The full design process is illustrated in more detail through an example in the next section.

3. Design example

We next apply the approach presented in Section 2 to the conceptual design of a desk lamp. the goal of this design is to generate continuous variable illumination from spot mode to uniform square shape ($w = 1000$mm) flood mode over a desk at a fixed distance of $h = 2000$ mm from the LED source, as illustrated in Fig. 4.

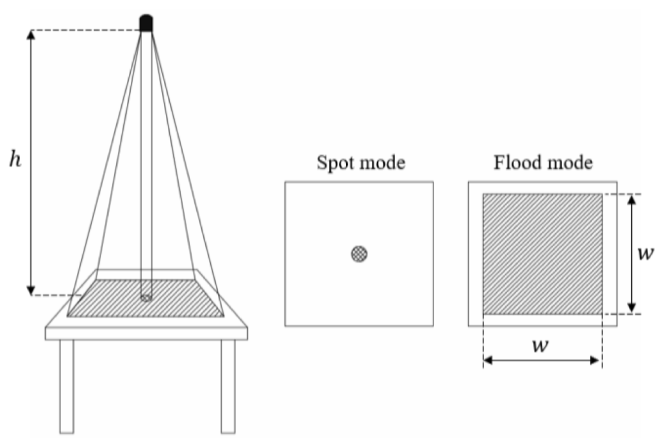

Fig. 4. Schematic of a variable illumination desk lamp used as a design example.

As discussed in Section 2, the dynamic illumination system includes a Lambertian LED source, a TIR lens to collimate the light, a lens array to distribute the light into the convergent ray bundles, and Alvarez arrays to dynamically control the size of the illumination pattern.

The first step in the design is initializing the main design parameters. For the current design, the size of each unit is 4 mm-by-4 mm, and the Alvarez lens clear aperture is 1.5mm-by-1.5mm. Therefore, h_1 and h_2 are 2mm and 0.75mm, respectively. The maximum shift d of the Alvarez arrays is set as ±0.7mm. The design material is polycarbonate, and the space material is air (refractive indices of 1.5968 and 1, respectively). Based on the target geometry, the desired half-viewing angle from the illuminator at flood mode (u_{3F}) is equal to $w/2h$ and for the spot mode u_{3S}=0. Considering these assumptions and using Eqs. (9) to (11), for the lenslets R=9.44 mm, the optical distance between the lenslet array and Alvarez arrays (L_1) is 10mm, and the A

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coefficient for the Alvarez surface is 0.1 mm^{-2}. These values are used as initial parameters for the design.

For the source, we selected a Lambertian white light LED from the default library of LightTools with the following specifications: flux=148 Lumens, viewing angle=120°, chip LED size 1mm-by-1mm. We then designed a compound lens, including the TIR lens and lens array. The "LED lens design" feature in LightTools was used to develop the TIR lens. The lens array was modeled by creating a cylindrical base and adding a spherical bump 3D texture with unit size of 4mm-by-4mm. This lens array was immersed in the TIR lens to serve as one compound element, as illustrated in Fig. 5.

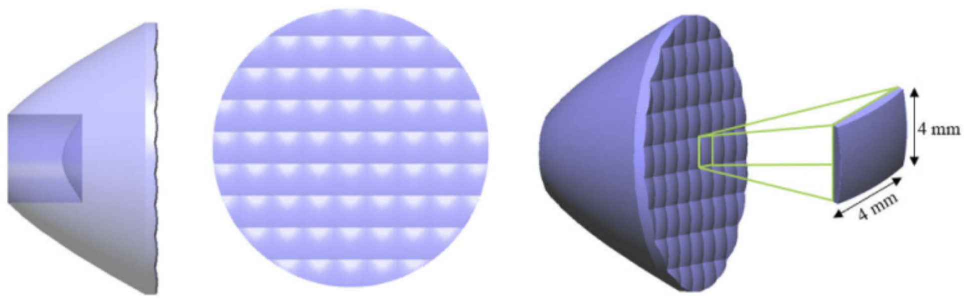

Fig. 5. 3D model of TIR lens with an integrated lens array in LightTools.

The Alvarez arrays were realized in LightTools by first creating a unit cell consisting of a single Alvarez lens. The freeform surface is specified by a polynomial equation, as discussed in Section 2. The circular Alvarez lens was intersected by a mechanical element with the desired geometry to construct an oval-shaped Alvarez lens with major axis of 3.8 mm and minor axis of 2.5 mm which takes the 1D lateral shift into consideration. The oval shape of the Alvarez lens minimizes the overall depth modulation and limits the precise manufacturing area to the required clear aperture. The Alvarez arrays were constructed in LightTools by adding a 3D texture of a single Alvarez lens as a library element to a cylindrical flat base, as shown in Fig. 6.

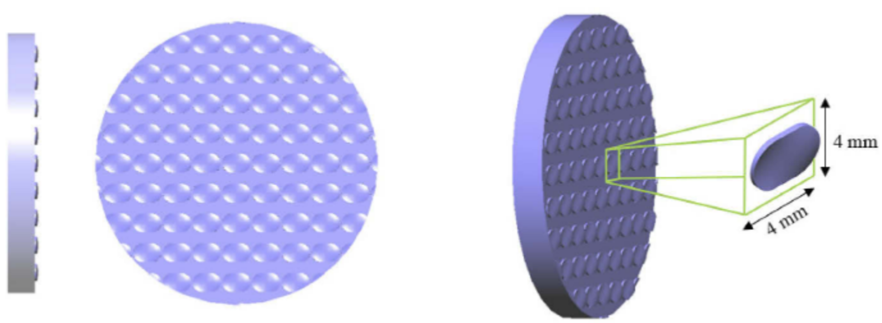

Fig. 6. 3D model of first Alvarez array in LightTools.

We next created two parallel configurations associated with the spot and flood modes using the initial calculated design parameters and corresponding to the maximum lateral shifts of the Alvarez arrays (+0.7 mm for the spot mode and −0.7 mm for the flood mode, respectively) for simulation in LightTools. We added filters to the plane receivers and pickups to the optimization variables to connect these configurations. The collimated merit function was set for the spot mode configuration, and a uniform square-shaped mesh merit function was set for the flood mode configuration to perform the simultaneous Monte Carlo optimization. The first optimization step was based on an ideal monochromatic (550nm) infinitesimal Lambertian source. Further optimizations were performed while gradually increasing the number of rays and replacing the source with a real LED. The resulting final geometry is shown in Fig. 7.

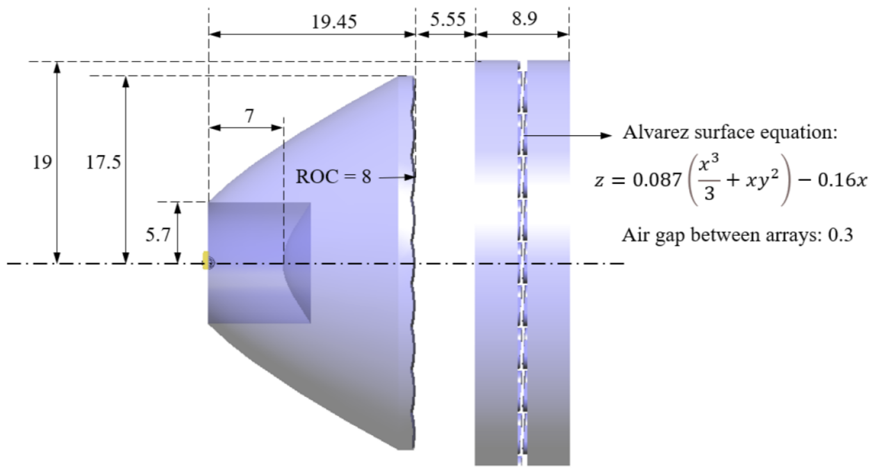

Fig. 7. The final geometry of the tunable illumination system after optimization (all units in mm).

4. Simulation results

Simulation results for a design example show a continuously variable illuminance pattern from a circular spot mode to a homogenized square flood mode from a 1mm-by-1 mm white LED source. The full width at half maximum (FWHM) in the *x*-direction throughout the entire shift range of the Alvarez arrays is shown in Fig. 8.

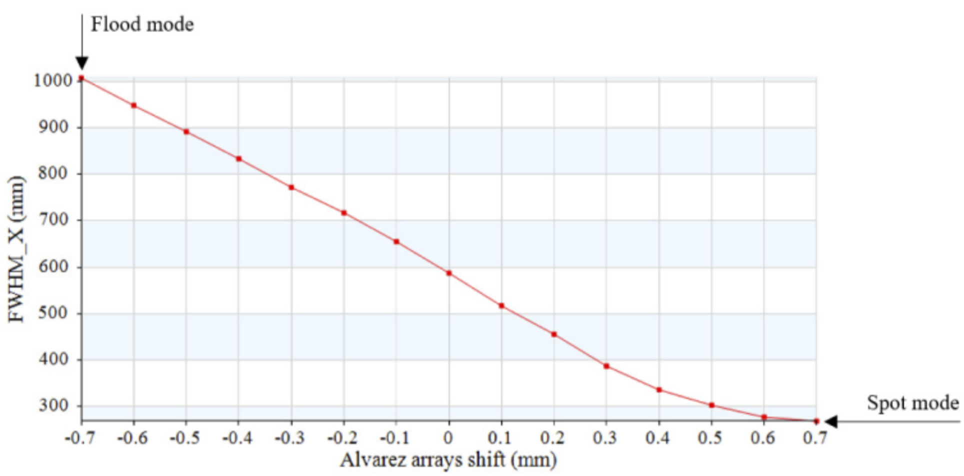

Fig. 8. FWHM(x) as a function of Alvarez shift (*d*).

Simulated true color and illuminance patterns for three selected modes within the continuous variable illumination range after tracing 1,000,000 rays through the system are shown in Fig. 9. The true color image shows good color homogeneity from the white LED source. The sizes of the illuminance patterns for these three modes are listed in Table 1.

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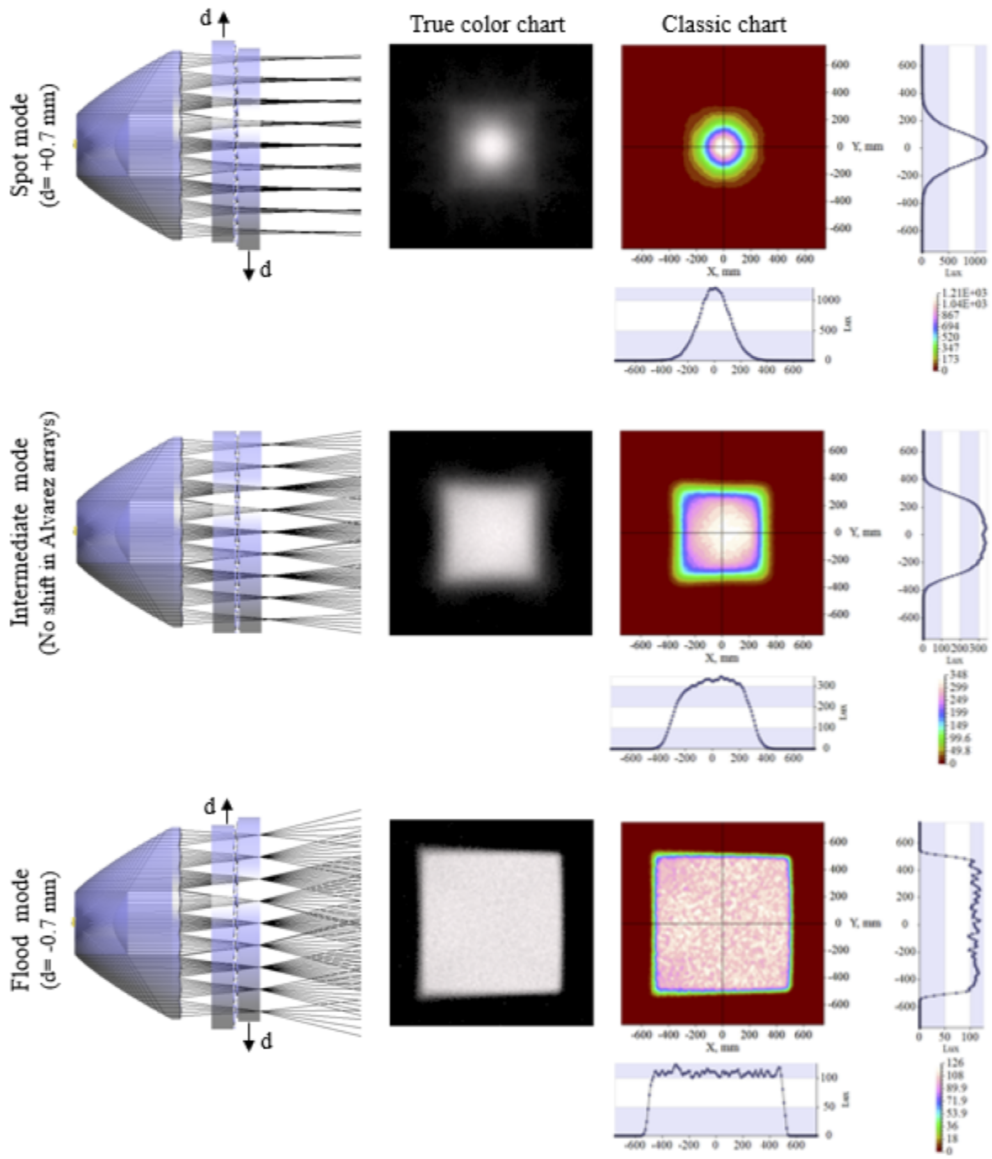

Fig. 9. True color and illuminance patterns of spot, intermediate, and flood modes at 2000mm from the source.

Table 1. Width at 50% of the center value (FWHM).

Mode name	Alvarez array shift (dx)	FWHM along x	FWHM along y	Average FWHM
Spot	+0.7 mm	—	—	270 mm
Intermediate	0	587mm	580 mm	—
Flood	−0.7 mm	1007 mm	1007 mm	—

The simulation results show the expected square distribution shape in flood mode because the lenslets are imaged onto the target and the source size only has a small effect. Other flood distribution shapes could be achieved by changing the shape of the lenslets in the lens array (e.g., hexagonal or rectangular).

When moving from flood mode towards spot mode, the size of the extended source becomes increasingly important since the TIR collimator must conserve etendue [30] and does not provide perfect collimation. Notice that the edges of the square pattern in intermediate mode are smeared more than in flood mode. In spot mode, there is additional smearing due to the extended source, with the result of a somewhat rotationally symmetric Gaussian distribution.

The Average Deviation (AD), defined as (standard deviation/average illuminance), was used to provide a quantitative evaluation of the uniformity of the illuminance patterns. Zero AD corresponds to a perfectly uniform pattern. A circular aperture was used for the spot mode and a square aperture for the flood mode for the uniformity calculations. The values of AD over the apertures with the target patterns' exact size are listed in Table 2. The significant value of AD for the flood mode is due primarily to the edge of the pattern.

Table 2. Mesh data of illuminance patterns over the target areas.

Illumination mode	Aperture geometry	Average illuminance	Average deviation
Spot mode	Circle with a diameter of 270 mm	838 Lux	28%
Flood mode	Square with a side of 1000 mm	104 Lux	12%

5. Conclusions

A general design approach has been presented that enables dynamic variation of illumination patterns with high uniformity in an LED-based system using arrays of freeform Alvarez lenses. Convergent light channels from an LED source were created using a TIR lens combined with a lens array to utilize the entire working range of the Alvarez arrays in varying from spot mode to flood mode in the example illumination system. The change in beam width between spot and flood mode is maximized by illuminating the Alvarez array with converging wave fronts. This system enables dynamic illumination with high uniformity along the working range through millimeter-scale lateral shifts to the Alvarez arrays, which is beneficial for applications where the system size and dynamic range of physical movement are limited. The exit surface for this system is also planar and easy to clean.

The starting point for the design was defined by applying paraxial geometrical optics concepts to the system's boundary conditions based on the design application, followed by a simultaneous Monte Carlo optimization over the spot and flood mode to achieve the desired targets. The optimization process begins with an infinitesimal monochromatic Lambertian source and a small number of rays, followed with gradually increasing the number of rays and replacing the source with a real LED model. Simulation results show that the system meets the desired design goals with good uniformity. Additional work to fabricate and experimentally characterize the performance of the system is underway.

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Data availability. Design details for construction and analysis of the systems in LightTools are included in the manuscript. No additional data were used in the presented research.

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