Freeform optics for dynamic illumination

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ABSTRACT

Dynamic illumination can improve functionality for multiple application areas, including lighting, AR/VR, automotive, medicine, and security. Some applications require a uniform illumination pattern of continuously variable divergence or size for improved functionality. Such dynamic functionality has previously been achieved, for example, by longitudinally moving a source relative to a curved reflector, which can result poor uniformity, or through zoom configurations in which the longitudinal distances between lenses in the system are dynamically adjusted. Advances in high precision manufacturing methods such as diamond machining have facilitated the practical implementation of freeform optical components, enabling new design approaches and concepts for illumination systems. In this paper, we explore the use of arrays of transmissive pairs of freeform surfaces to enable efficient and uniform dynamic illumination in a compact package. This work builds on the Alvarez lens concept, in which a pair of transmissive XY-polynomial freeform surfaces generates variable optical power through lateral relative shifts. Design approaches and simulation results are presented.

Keywords: freeform, illumination, lighting, Alvarez lens, tunable

1. INTRODUCTION

Illumination design is an engineering process of transferring light from source(s) to desired target(s) [1]. Increasing requirements for illumination functionality in application areas such as advanced lighting, AR/VR, automotive, medicine, and security have led to significant progress in the field of illumination design. Some of these applications can benefit from uniform illumination patterns of continuously variable size for improved functionality. Specific illumination patterns are typically achieved using static arrangements of optical components (lenses and/or mirrors). Approaches requiring switching out of components also require additional assembly and alignment for each new operating mode which further increases costs.

Continuously variable illumination has been achieved previously, for example, by using configurations in which the source or other optical elements are moved longitudinally along the optical axis of the system [2-4]. In these systems, the chance of experiencing non-uniformity or other undesired defects in the illumination pattern is high. Adding lens arrays in zoom systems can significantly enhance the performance of the system [5-7], however, the required axial movement may be not desirable in applications requiring small package sizes. Another method to add variable functionality to illumination systems uses liquid lenses with adjustable membranes that can provide high tuning ranges [8, 9]. Potential disadvantages of such systems include leakage or evaporation, fabrication complexity, and sealing challenges [10].

The objective of the current design is to generate continuous tunable illumination for a flashlight, from spot mode with circular distribution to flood mode with a homogenized square pattern with side of 1000 mm at a distance of 4000 mm from the source, as illustrated in Figure 1.

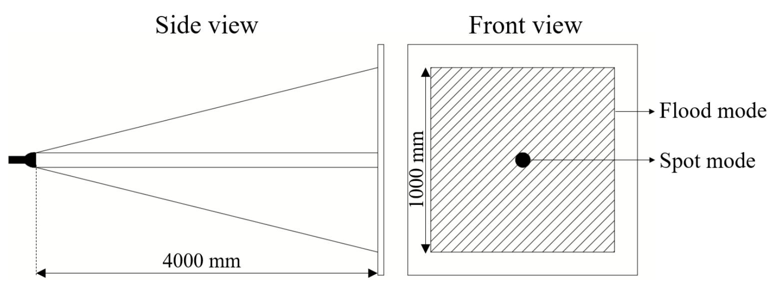

Figure 1. Schematic of target patterns for a variable illumination system.

In this paper, arrays of freeform optical components known as Alvarez lenses are used to achieve the desired designs goals. Section 2 presents background information on the Alvarez lens concept. Design approaches are presented in Section 3, including a description of the tunable illuminator its optical components. Results are discussed in Section 4 followed by the conclusion in Section 5.

2. ALVAREZ LENSES AND ARRAYS

Alvarez lenses provide variable spherical power through lateral relative translation between pairs of plano-freeform elements [11, 12]. In this section, we first introduce the Alvarez lens concept to enable variable spherical power, followed by a discussion of advantages of the use of arrays of Alvarez lenses to achieve the desired variable output illuminance pattern.

The general form of an Alvarez lens consists of two plano-freeform elements with matching cubic surfaces that create a composite wavefront of continuous variable spherical power as opposite lateral shifts are applied (Figure 2). The freeform surface equation for each Alvarez surface following a first-order analytical approach is given by:

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

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 thickness of the element. By considering the composite surface, the resulting focal length can be shown to be:

$$f = \frac{1}{4Adx(n-1)} \tag{2}$$

where dx is the lateral shift experienced by each freeform element and n is the refractive index of the optical material. This general Alvarez surface form generates positive, negative, and zero optical power at negative, positive, and zero lateral shifts, respectively as illustrated in Figure 2. Note that light is constrained to pass through the overlapped area of the pair of Alvarez elements to have the proper functionality.

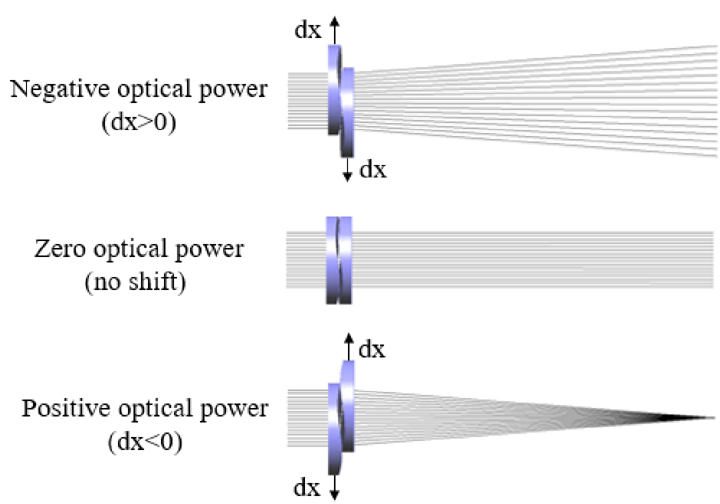

Figure 2. Schematic of Alvarez lens pair, light is entering the overlapped area.

Micro lens arrays are commonly used in beam homogenization [13]. In an illumination system, an array configuration can be combined with a collimator to enhance the uniformity of a target pattern. The target pattern in the far-field would be the superposition of illuminance patterns formed by each individual unit cell in the design [14]. Arrangement of the lenses in the array is an important factor in design that affects the shape of target pattern based on the edge ray principle [15].

The use of lens arrays in optical system can be extended to freeform optics, such as Alvarez arrays [16, 17]. Using Alvarez lens pairs in an array configuration enhances the uniformity of illuminance patterns and also enable power variation with small lateral shifts between the freeform elements. As discussed previously, light is required to pass only through the overlapped area of each Alvarez lens pair in the array. As a consequence, the light incident on an Alvarez array should be in the form of light channels, which is a notable design constraint.

3. DESIGN APPROACH

The assumptions and basic design elements of the proposed system can be considered in two main parts: (1) a static part that include a point source, parabolic reflector, and a pair of confocal lens arrays to generate collimated light channels with high efficiency; (2) a dynamic part consisting of a pair of Alvarez arrays to adjust the divergence angle and size of the illumination pattern. The basic structure of the design geometry is illustrated in Figure 3. A design wavelength of 550 nm was chosen, and the confocal lens arrays and the Alvarez arrays are both designed from polycarbonate (n = 1.5896 at 550 nm wavelength). An initial design for each part was constructed and parameterized [18,19]. The parameters were optimized through multiple stages in LightTools® to meet the design criteria. We now consider these two main parts of the system in more detail.

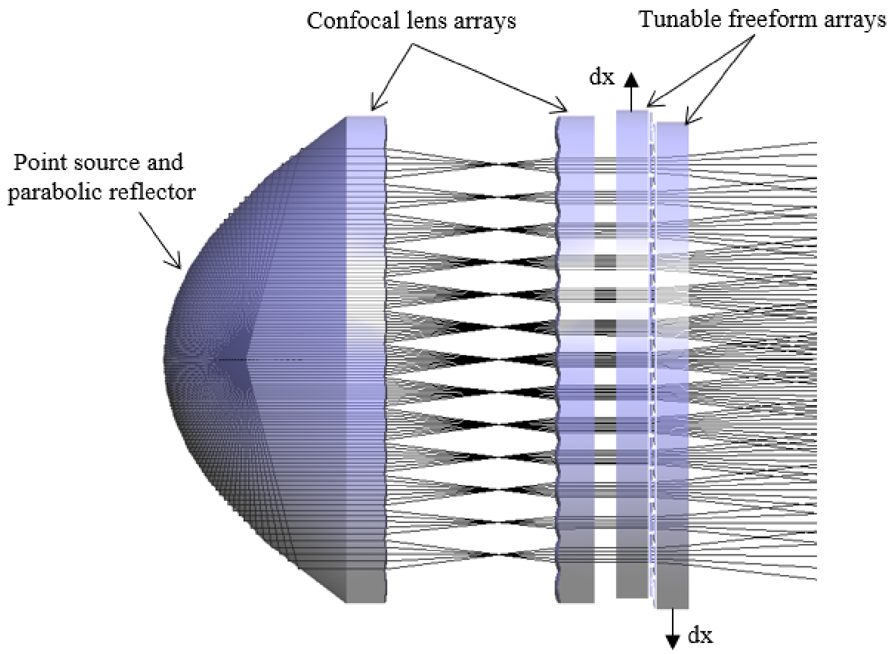

Figure 3. Schematic of dynamic illumination design.

3.1 Designing the static part of the illuminator

The static part of the illumination system is responsible for generating collimated light channels to enter the Alvarez arrays. A parabolic reflector was selected to collimate light from a uniform point source. The collimated light can be distributed in channels by adding an aperture array in front of the reflector. However, blocking light in this manner significantly reduces the transfer efficiency. Instead, we used confocal lens arrays to create the required light channels with high throughput. Since the target pattern in flood mode has a square shape, the lenslets in both lens arrays were set with 4 mm square apertures in a square lattice arrangement with 4 mm spacing.

Design optimizations were run over the confocal system to first enable the collimated parallel light channels, and second to provide a uniform square shape distribution over each channel with full width half max (FWHM) of 2 mm along each side. The specifications of the static part components after optimization are listed in Table 1.

Table 1. Specifications of static optical components in the illuminator

Component	Specification
Source	1-Watt point source at 550nm, half viewing angle = 115°
Parabolic reflector	10 mm focal length; 60 mm total diameter
Confocal lens arrays	Square arrangement with 4 mm spacing, 5 mm part thickness and 60 mm part diameter; 20.87 mm between arrays
Unit cell of 1st lens array	Aspheric convex lens with 13.57 mm focal length. Conic constant = -3
Unit cell of 2nd lens array	Aspheric convex lens with 6.78 mm focal length. Conic constant = -3

3.2 Designing the dynamic part of the illuminator

The dynamic part of the design illuminator includes adjustable Alvarez arrays which were constructed on the same 4 mm square lattice as the confocal lens arrays. The size of each Alvarez lens in the unit cell was chosen based on the incident ray bundle (2 mm square) and manufacturability considerations, as shown in Figure 4.

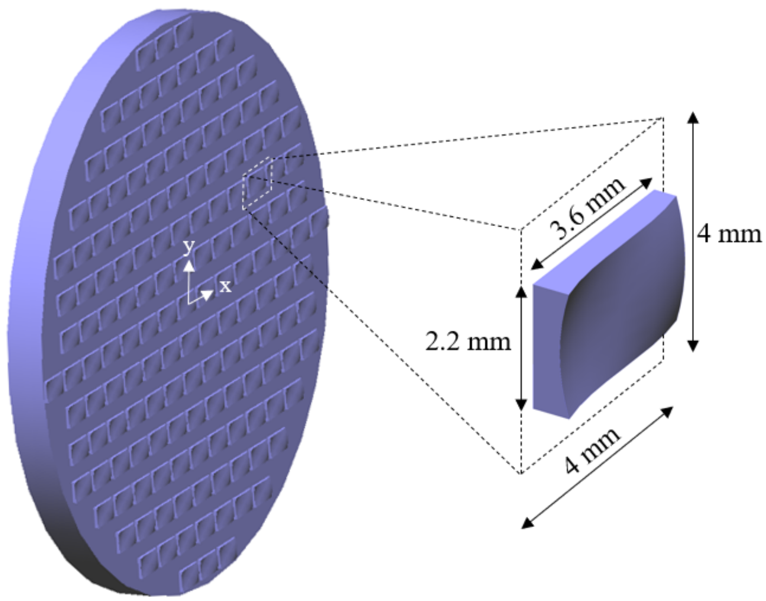

Figure 4. 3D model of the 1st Alvarez array in LightTools®, with a zoomed unit cell.

As explained in Section 2, the Alvarez lenses have no optical power at zero lateral shift; therefore, the collimated light from the static part remains collimated for Alvarez arrays with zero shift, resulting in the spot mode. The design configuration with Alvarez arrays shifted by a maximum desired amount generates the flood mode. The maximum shift was chosen to be $dx = +0.7$ mm based on the available geometry over each Alvarez unit cell. Each Alvarez lens in the arrays is a plano-freeform element. An initial estimate for the Alvarez surface coefficient A is obtained using Eq. (2) with $dx = +0.7$ mm and by applying geometrical optics concepts for a single ray bundle.

After adding the dynamic part to the illuminator to the system in LightTools®, the system was optimized for a uniform square illumination target at the maximum shift. After optimization, the Alvarez surface is given by:

$$z(x,y) = 0.075\left(\frac{x^3}{3} + xy^2\right) - 0.1x \tag{3}$$

The Alvarez arrays have an overall diameter of 60 mm, and 4.5 mm thickness. The airgap between the arrays is 300 µm and the depth modulation over each Alvarez unit is 270 µm.

4. RESULTS AND DISCUSSION

The final design of the dynamic illuminator after multi-stage optimization in LightTools® meets the design criteria. This design enables continuously variable illumination from spot mode at zero shift of the Alvarez arrays, to a flood mode with homogenized square shape distribution at $dx = +0.7$ mm. Figure 5 shows the illuminance patterns for three selected modes within the continuous variable illumination range after tracing 1,000,000 rays through the system. The sizes of the illuminance patterns for these three selected modes are found in Table 2. The results meet the stated design criteria.

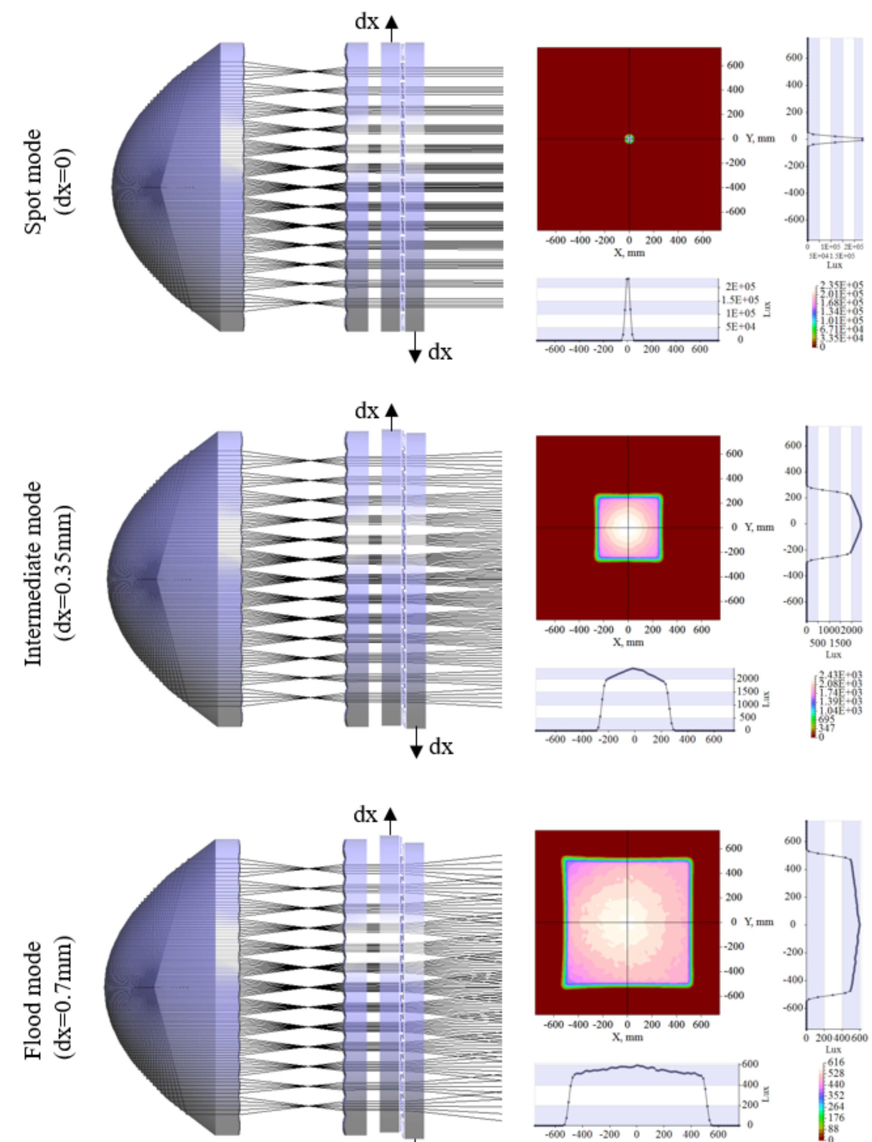

Figure 5. Illuminance patterns of tunable freeform illuminator at 4000 mm from the source.

Table 2. Illumination output dimensions

Mode name	Alvarez array shift	FWHM along x and y
Spot	0	47 mm
Intermediate	+0.35 mm	500 mm
Flood	+0.7 mm	1004 mm

Figure 6 shows how the size of the target distribution changes along the x-axis on the target plane with lateral shifts of the Alvarez arrays. The output distribution has minimum FWHM at zero shift (spot mode) and increases linearly with higher shifts up to the maximum FWHM of 1000 mm (flood mode) at maximum shift of +0.7mm.

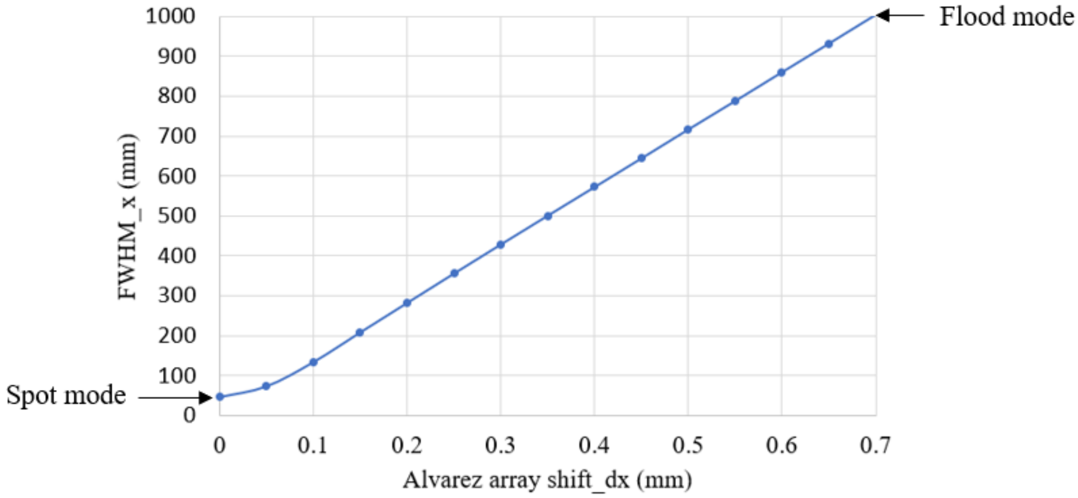

Figure 6. FWHM of target distribution as a function of lateral shift dx between the Alvarez arrays.

5. CONCLUSIONS

A compact, dynamic illuminator was designed to enable continuously variable illumination from a spot mode with circular distribution to a flood mode with uniform square output in a target plane. In this design, arrays of tunable freeform optics (Alvarez lenses) were used to enable dynamic tunabililty. The required light channel inputs for the Alvarez arrays were generated with confocal aspherical lens arrays for high efficiency. Using Alvarez lenses in an array configuration also enhances the uniformity of the illuminance patterns due to the superposition concept. The square arrangement of the arrays results in the desired square output pattern in flood mode due to edge ray theory. The designs were simulated and optimized using LightTools®. Additional work is underway to refine the initial designs, incorporate LED sources, and to experimentally fabricate and characterize the proposed designs.

6. ACKNOWLEDGMENTS

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