

# Compact Relay Lenses Using Microlenslet Arrays

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## ABSTRACT

In an investigation of approaches to compact relay lenses for special effect photography, the potential of microlenslet arrays in image formation is investigated. In this paper, various arrangements of microlenslet arrays and associated baffles are considered and their role on image quality presented. Findings through software simulations clearly demonstrate the trade-offs between image quality and compactness.

Key words: image formation, microlenslet arrays, photonics, image quality

## 1. INTRODUCTION

Driven by the requirement for compact optical scanning systems, the basic theory of microlenslet arrays in such systems was developed by R.H. Anderson.<sup>1</sup> In his work Anderson demonstrated that arrays of simple lenses can be used in close-up imaging systems for document copiers, oscilloscope cameras etc., as well as in scanning applications.

In this paper, we investigate the extent to which microlenslet-based relay systems could be used for imaging applications. We further investigate the extent to which the image quality would approach conventional relay optics. Fig. 1 summarizes a few possible configurations. The difference among these configurations is their overall length and each lenslet's field of view. For simplicity it is assumed that each array consists of lenses of same focal length  $f$  and same aperture  $D$ .

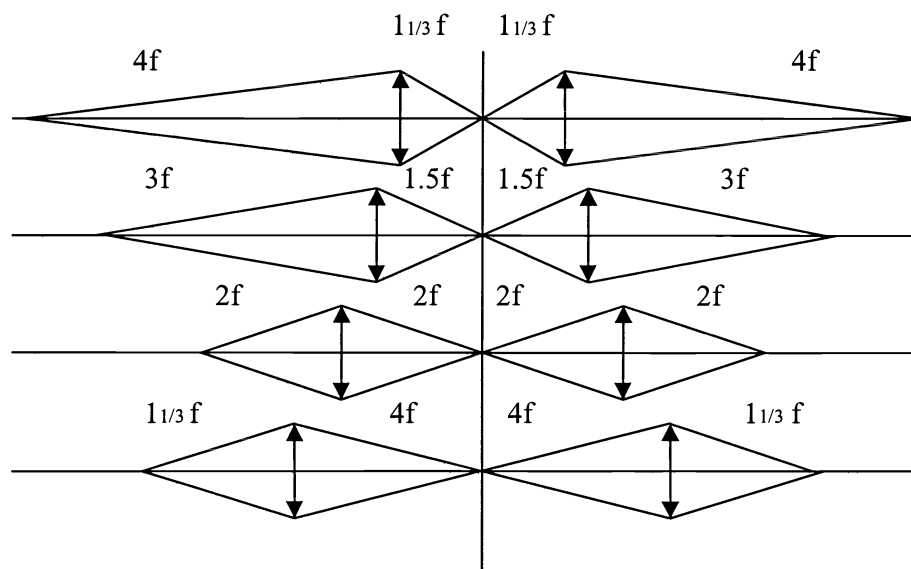


Fig. 1 Various relay lenses configurations

As shown in Fig. 1, the most compact arrangement is the “ $2f$ - $4f$ - $2f$ ” system in which the object plane is located at a distance  $2f$  in front of the first lens, its intermediary image is formed at a distance  $2f$  behind the first lens, and the final image plane is located at a distance  $2f$  behind the second lens. The magnification of the system is  $+1$  and the overall length of the system is  $8f$ . Due to symmetry, the full field of view, i.e. 100% vignetting at the edge, is equal to the aperture of each individual lenses.

Starting with the most compact arrangement of  $2f$ - $4f$ - $2f$ , two arrays of lenses are considered and raytraced.<sup>2</sup> A four lenslet element is shown in Fig. 2 as an example. The raytrace demonstrates the 1:1 image formation of the object as well as the formation of multiple ghost images. Thus, such configuration can not be used in itself for imaging purposes. Appropriate baffle arrays must be used in conjunction to the microlenslet arrays.

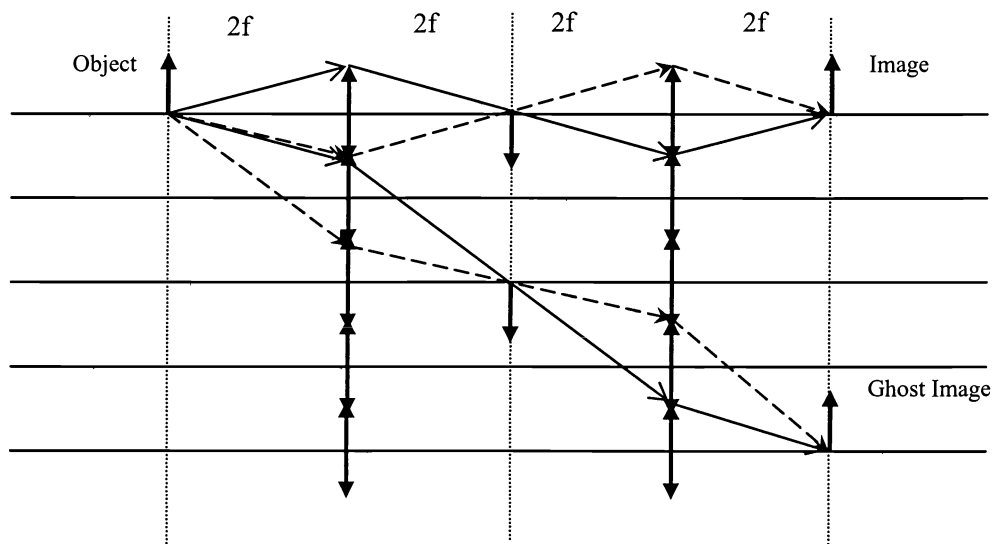


Fig. 2 Ray Sketching illustrating the presence of ghost images

In order to determine the location and size of the appropriate baffles further analysis of the properties of the  $2f$ - $4f$ - $2f$  optical system shown in Fig. 1 is conducted.<sup>2,3</sup> Let's consider a pair of lenslets as shown in Fig. 1 and denote the first and second lens  $L_1$  and  $L_2$ , respectively. From the theory of pupils and stops, it is seen in Fig. 1 that both  $L_1$  and  $L_2$  limit equally the amount of light entering the system from a point on axis, thus any one of them can be chosen as the aperture stop, the other one being automatically the window.

Let's assume that  $L_1$  is the aperture stop (AS) of the system. The exit pupil of the optical system is by definition the image of the AS in image space. Starting with the Descartes imaging equations, the location and size of the exit pupil can be calculated to be at  $4/3 f$  after the second lens, and its size is three times smaller than the diameter of  $L_1$ . Similarly, the location of the entrance window can be computed as the image of  $L_2$  through  $L_1$ .

In order to prevent the formation of ghost images when using microlenslet arrays, baffles may be positioned at the locations of the entrance window and the exit pupil, and their size must be set according to the imaging properties of system. The location of the baffles for the  $2f$ - $4f$ - $2f$  is

shown in Fig. 4. With appropriate baffles, we predict a unique image formation of each object point.

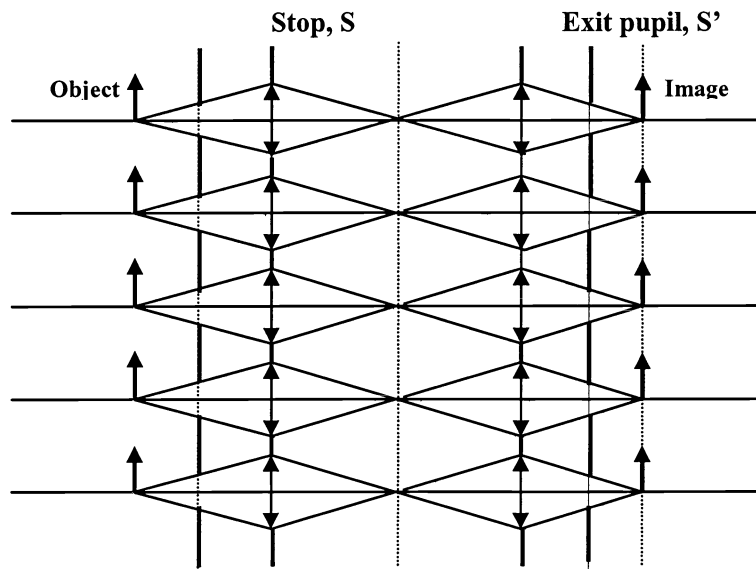


Fig. 4 Microlenslet arrays with appropriate baffles to limit ghost images

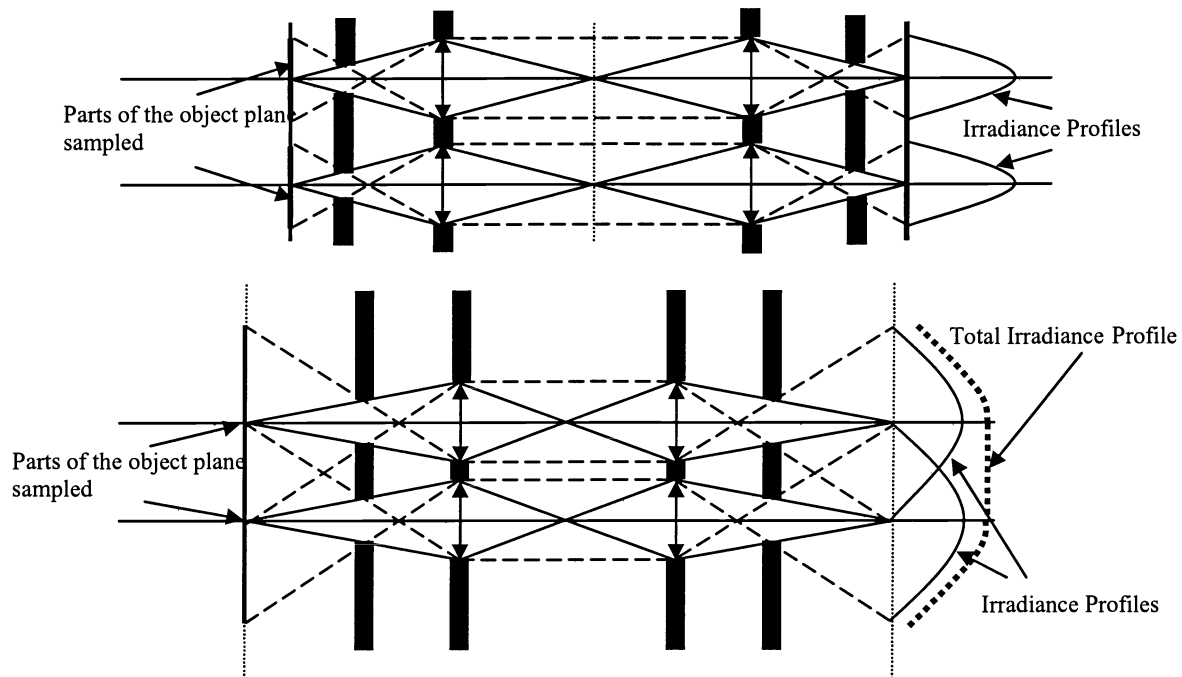


Fig. 5 Illustration of the irradiance profiles of an extended object images through (a) a 2f-4f-2f microlenslet array relay lens (b) a 3f-3f-3f microlenslet array relay lens.

Another characteristic of image formation with microlenslet arrays is the apparent lenslet pixelization of an image. Such characteristic is illustrated in fig. 5 (a) and (b) for the 2f-4f-2f and the 3f-3f-3f configurations, respectively. The simple paraxial layout shown in Fig 5 shows

that lenslet pixelization of the image begins to disappear for the 3f-3f-3f configuration, while it is maximum in the 2f-4f-2f configuration. The suppression of the lenslet-pixelization is dependent upon the vignetting induced by the baffles for small extended objects seen by each lenslet, and the amount of overlap of images formed by contiguous lenslets. For example in the 2f-4f-2f configuration, the field of view of each individual pair of lenses measured in the object plane is exactly equal to the aperture of the lens and therefore a pixelization in the object plane occurs. The  $4f-2\frac{2}{3}f-4f$  configuration, however, provides almost no pixelization. The trade-off is naturally resolution.

#### 4. EXPERIMENTAL MODELING

In order to further analyze the performance of different arrangements of microlenslet arrays and study the image quality of image formation, a computer model using ASAP was created. For the initial studies a simple ellipse was used as an object and the image of this ellipse was examined. The first optical system created was the most compact 2f-4f-2f configuration and consisted of two 5 by 5 microlenslet arrays and associated baffles shown in Fig. 6.

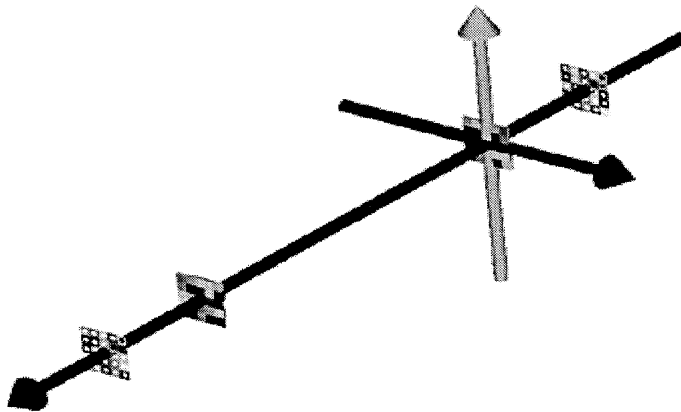
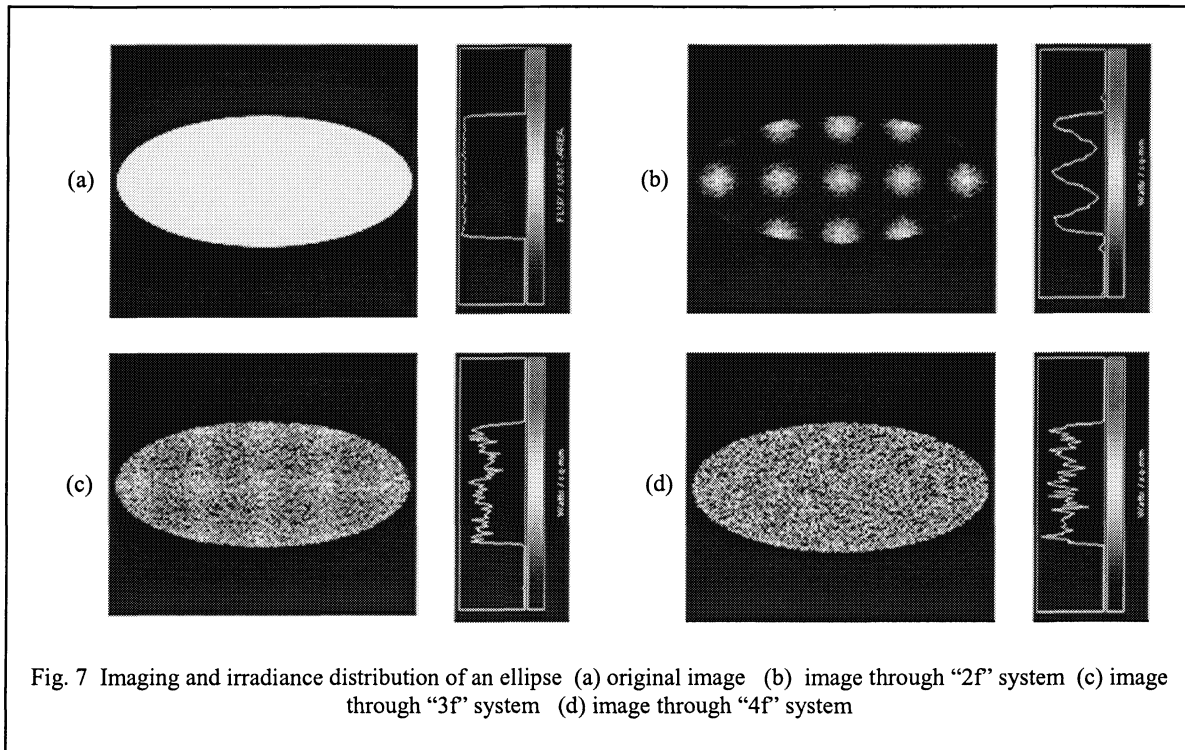


Fig. 6 Optical layout of a 5x5 microlenslet array relay system using ASAP.

The source was chosen to be a uniform ellipse shown in fig. 7a. Such stimuli was chosen to examine the effects of lenslet pixelization by choosing a large scale object as well as resolution by looking at the sharpness of the light distribution transition at the edges of the ellipse. Each individual lens in the microlenslet arrays is an f/5, 50mm lens.

The result of the simulation is shown in Fig. 7b. The sampling in the object due to the lapse of overlap of each lens' field of view is clearly seen, as well as the irradiance distribution and vignetting previously described. While the "2f" system is most compact, the lenslet pixelization will not lend this system to be suitable for imaging purpose.



The imaging properties of the “3f-3f-3f and the 4f (i.e. the upper configuration in Fig.1) configurations were investigated, and the result of the simulations are shown in Fig. 7b and 7c, respectively. Results show that the 3f-3f-3f still presents some level of lenslet pixelization, while the pixelization disappears for the 4f system.

Furthermore a test with more complex objects, such as actual bitmap images, was made using the “3f” system.<sup>4</sup> The object and the obtained image are shown in Fig. 11(a) and (b), respectively. The noise in the image is due to limitations in the number of rays used for this simulation. The simulation however demonstrates the capability of the system to do image forming.

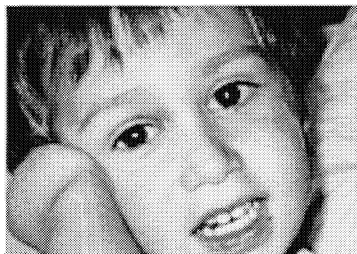


Fig. 11 (a) Original picture, courtesy of Roman Scher-Rolland

(b) Image of the picture on the left through a “4f” system

## 5. CONCLUSION

In this paper we investigated the image forming capability of microlenslet arrays. This investigation demonstrates the existing trade-off between lenslet pixelization, resolution, and compactness. This research leads to the idea of possible use of microlenslet arrays in the domain of special effects, where the image quality of the final image is already distorted by the applied effects, and the prime task is to achieve compactness.

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