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Compact microlenslet-array-based magnifier

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An ultracompact optical imaging system allowing various magnifications or demagnifications and based on microlenslet arrays is presented for the first time to our knowledge. This research generalizes recent findings regarding microlenslet-array-based 1:1 relay systems [Appl. Opt. **42,** 6838 (2003)]. Through optical ray tracing, the feasibility of magnifying gray-scale images through a stack of two dissimilar microlenslet arrays is demonstrated for the first time to our knowledge. Results presented specifically demonstrate that a compact imaging system operating at a magnification of 2 is feasible with an overall length of ~9 mm. Optical aberrations of the most basic configuration are evaluated, and optimization is discussed. © 2004 Optical Society of America

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The imaging properties of microlenslet arrays and associated baffle for binary (i.e., black and white) imaging, such as the imaging needed in copiers and scanners, were first investigated by Anderson.[1] Later microlenslet arrays were found to be a useful tool in designing ultracompact imaging relay systems, as well as in realizing three-dimensional integral photography.[2–6] Current state-of-the-art micro-optics fabrication facilities make possible the manufacturing of microlenslet arrays of extremely short focal length with apertures of various shapes and size comparable with wavelength. Microlenslet arrays with refractive, diffractive, anamorphic, spherical and aspherical, and positive and negative optical surfaces are currently available.

The design of many optical imaging systems requires extremely compact and lightweight magnifying systems, for example, the magnification of miniature organic light-emitting diode displays in head-mounted projection displays (HMPDs), one of the applications driving our research, which does not have stringent resolution requirements in the magnification process.[7] An ultracompact solution would be extremely beneficial for such an application because it would allow for improved design, increased field of view, and overall higher performance. With conventional design techniques, even some of the most compact custom-designed conventional magnification 1:2 systems present an overall length of ~120 mm and weight of 700 g. To overcome such restrictions in size, an alternative approach had to be investigated. Optical magnification systems based on microlenslet arrays could provide a useful solution for such applications.

In this Letter we propose the use of microlenslet arrays to create compact, lightweight, and potentially cost-effective optical magnification systems for imaging at various magnifications. Previous work demonstrated the feasibility of imaging with microlenslet arrays in the special case of 1:1 relay systems. A key contribution of this Letter is the replacement of bulk macro-optic systems by multiaperture micro-optics. Another key contribution of this Letter is the generalization of imaging with microlenslet arrays for various magnifications or demagnifications. Specifically, we establish the detailed relationships necessary to describe the most general case of imaging with two stacks of microlenslet arrays and the appropriate baffles. Also, the simulation of such an imaging system is presented, which validates its feasibility.

There are numerous possible configurations that can be used to create an optical 1:M magnifying system with a stack of two dissimilar microlenslet arrays.[8] The general case for a stack of two microlenslet arrays is illustrated in Fig. 1. Provided that the microlenses in the first and the second arrays are of focal lengths f_1 and f_2, respectively, the overall length (OAL) of such a system, defined as the distance from the object to the final image plane, is given by

$$\mathrm{OAL} = \frac{(m_1 + 1)^2}{m_1} f_1 + \frac{(m_2 + 1)^2}{m_2} f_2 , \tag{1}$$

where the first and the second microlenslet arrays operate at magnifications of magnitudes m_1 and m_2, respectively. The magnitude of the overall magnification M of the system is defined as

$$M = m_1 m_2 . \tag{2}$$

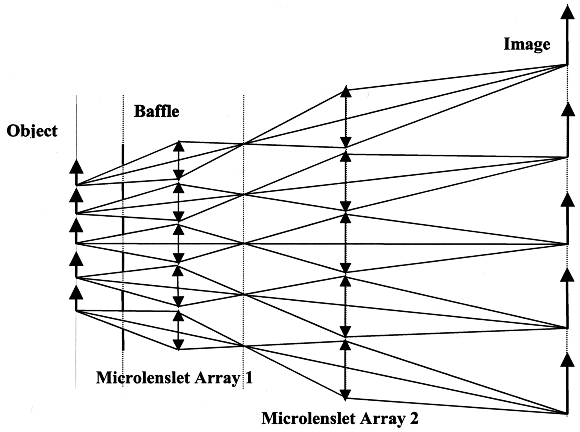

Fig. 1. Optical layout of 1:M imaging with a stack of two arrays of microlenses.

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Two key aspects of imaging with a stack of two microlenslet arrays are lensletization and ghost images.[2] The key to overcoming ghost-image formation in a system consisting of arrays of microlenslets is placing an array of baffles of the correct size at the appropriate location in the system.[2] The minimum of the function given by Eq. (1), after substituting for m_2 with Eq. (2), yields the most compact configuration of the two microlenslet arrays and is given by

$$\frac{\partial \mathrm{OAL}}{\partial m_1} = 0\,, \tag{3}$$

which yields

$$m_1 f_2 (m_2 - 1)(m_2 + 1) = m_2 f_1 (m_1 - 1)(m_2 + 1)\,. \tag{4}$$

One of the solutions to Eq. (4) yields $m_1 = m_2 = M = 1$, which simplifies the system to a microlenslet-array-based 1:1 relay $2f$ system.[2] Furthermore, if M is given, Eq. (4) may be solved for m_1 to minimize OAL. In this case it can be shown that

$$m_1 = \left(\frac{Mf_1 + M^2 f_2}{Mf_1 + f_2}\right)^{1/2}. \tag{5}$$

Furthermore, in all cases (i.e., $\forall\, M$), to best eliminate ghost images in the final image plane, the intermediary subimages after the first microlenslet array must not overlap to allow placement of a baffle at the entrance pupil of the system. Such a condition naturally requires $m_1 < 1$. Without loss of generality let $f_2 = \gamma f_1$. Then Eq. (5), which sets the minimum OAL, combined with the requirement that $m_1 < 1$, leads to a system with an overall demagnification (i.e., $M < 1$). Thus for $M > 1$ a configuration can be established, but it will not correspond to the minimum OAL. It should be noted, however, that the most compact arrangement might not correspond to optimal first-order image quality, as previously found in 1:1 relay systems.[2] Specifically, first-order image quality is also highly dependent on image lensletization. Overcoming this effect is less straightforward than suppressing ghost images. It requires overlapping of the individual subfields of view of each individual pair of lenses at the expense of an increase in OAL and a natural decrease in resolution.[2]

To validate the feasibility of the conceived 1:2 imaging system, an $F/5$, 500-μm focal-length microlenslet array was selected in the front location without loss of generality, and an $F/8.3$, 1000-μm array was selected in the back location. Furthermore, the microlenses in each array were square plano–convex lenses with a thickness of 150 μm. The microlenslet arrays operate at $m_1 = 0.5$ and $m_2 = 4$, respectively. In such a configuration it can be shown from basic principles that the second lenslet in each pair is the aperture stop of the system; therefore the baffle has to be placed in the location of the entrance pupil, which is a conjugate of the aperture stop. Furthermore, the baffle must be established for the correct magnification of the pupils. In the case investigated, a set of microbaffles with a computed diameter of 40 μm was placed at the appropriate location in the system.

A software model for imaging assessment was developed with custom-developed software based on the Advanced Systems Analysis Program (ASAP). The optical layout of the system, made of 11 × 11 microlenses in each array, is shown in Fig. 2. An analysis of the minimum number of rays satisfying 99% accuracy of the ray-traced image was performed, and it was found that the minimum number of rays needed was 2.5×10^9. With the current state of hardware and software such accuracy would require more than 3 weeks of computational time. Based on the accuracy of the ray-trace analysis shown in Fig. 3, an accuracy of 97% was selected for image quality feasibility because it satisfies both the criterion of ~48 h computational time on a 2.8-GHz PC and the criterion of more than 95% accuracy commonly accepted as a threshold for assessing feasibility.[9]

Results of the simulation shown in Fig. 4 demonstrate that a 1:2 relay lens based on a stack of two dissimilar microlenslet arrays can be achieved with no ghost images, yet a small residual lensletization

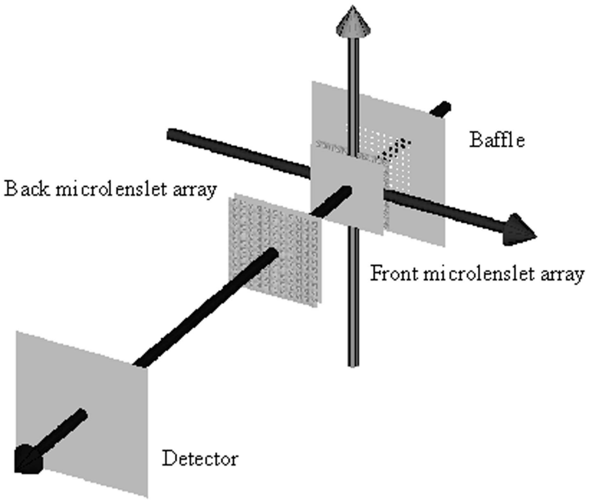

Fig. 2. ASAP layout of 1:2 microlenslet-array-based magnification system with two 11 × 11 arrays of microlenses and the appropriate baffle. From right to left, the baffle, the two dissimilar microlenslet arrays made of square plano–convex lenses, and the detector upon which an image will be formed given an object in front of the baffle are shown.

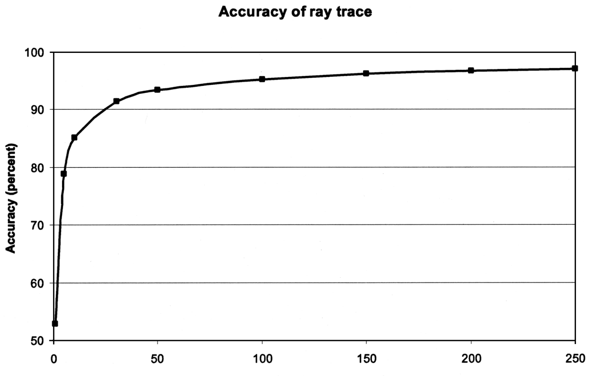

Fig. 3. Accuracy of the ray trace in percents as a function of the number of rays emitted from the object.

Fig. 4. Imaging of a gray-scale object through a 1:2 microlenslet-array-based magnifying system: (a) object and (b) magnified image.

of the image may be observed. Such lensletization would be overcome in a final optimized configuration by further overlapping the subfields of view. With commercially available microlenslet arrays, such a system would have an overall length of 8.7 mm and a weight of ~1 g. An analysis of the image quality of the system shows that the diffraction-limited point-spread function is 41.67 μm. Such a spot size is large compared with the 10-μm pixel size found in most commonly available CCD cameras. A smaller pixel size of 10 μm may be achieved by increasing the apertures of the microlenslets in both arrays to 410 μm in the front and 500 μm in the back. However, increasing the apertures of microlenslets while keeping their focal length invariant naturally occurs at the expense of decreasing the working *F* number. Such a decrease leads to a more complex performance-optimization task, yet it does not compromise the feasibility of the design. In this case the OAL is still compact and ~9.5 mm. Such resolution requires simulations with more pixels to cover an equivalent field of view and thus fewer rays per pixel, leading to a ray-trace accuracy of ~85% based on the criterion of ~48-h computational time on a 2.8-GHz PC. The results obtained for that system were consistent with the results obtained with 97% accuracy, confirming the feasibility of the system. This simple analysis, however, points to the reason we originally chose microlenslets of smaller diameter: We can run simulations at higher accuracy with the intrinsic understanding that diffraction is limiting and can be reduced with larger microlenslets. If the system is made of simple plano–convex lenses, as considered for the feasibility investigation, both monochromatic and chromatic aberrations will limit the image quality. However, because the sine condition is quasi-satisfied (i.e., $<0.02\%$ discrepancy), if the lenslets located in the subpupils are aspherized, coma will be negligible. Furthermore, per modulation transfer function analysis astigmatism limits the image quality and can be corrected by aspherization of the lenslets in the first array, which is the entrance window. Distortion for any pair of lenslets is nonnegligible and requires further investigation in how it practically affects image quality. Finally, given that simple plano–convex lenslets were used, the system will suffer both axial and transverse chromatic aberrations. An analysis shows that axial chromatism is significant and will need to be corrected with a lenslet doublet in the pupil. Lateral color, however, is less than 5 μm at the edge of the field of view and will thus most likely not require any further minimization. However, if an application required no lateral color, another lenslet doublet located in the entrance window could be used.

In conclusion, we have studied the imaging properties of magnification systems based on a stack of two microlenslet arrays and have demonstrated that ultracompact imaging optical relay systems can be designed with an overall length of only a few millimeters. Any design of such a magnifier has to be application driven. However, in all cases of imaging gray-scale or color images, lensletization will likely need to be minimized below the level at which it is perceived. Beyond that point, applications may impose different compactness and resolution requirements, which will lead to more or less complexity in the design of each array. In HMPDs, for example, compactness and low weight are critical; however, some loss in resolution will likely be tolerable and even desired to remove the pixelization of the microdisplay being magnified through the main HMPD optics.

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