Imaging with an extended depth of field by means of the peacock eye optical element

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Abstract—The paper presents imaging properties of the peacock eye optical element. Its abilities for imaging with an extended depth of field is illustrated experimentally in monochromatic, as well as polychromatic light. According to the obtained results the element makes it possible to maintain the acceptable resolution, contrast and brightness of output images for a wide range of defocusing.

The limited range of focus is a significant disadvantage of incoherent imaging systems. The depth of field is especially important when three-dimensional scenes or three-dimensional objects are imaged. The most promising optical elements for imaging with an extended depth of field in real-time seem to be optical elements focusing an incident plane wave into a focal line segment. These elements can be regarded as modified lenses with controlled aberrations. A fixed point of the focal segment is connected to a proper input plane in an imaging process. The optical elements of this kind have been studied lately in many papers. Their authors attempted to solve the problem of an extended focal depth by different methods leading to different optical structures as for example axicons [1], elements defined by a numerical iterative approach [2–3], optical diffusers [4] and axilens [5] based on the design proposed by Davidson *et al.* [6]. All the above mentioned optical elements exhibit radial symmetry. According to the results presented for imaging set-ups with such elements, it is very difficult to maintain high quality of output images when defocus becomes large. Some disadvantages of these elements can be overcome when their symmetry of revolution is intentionally disturbed in a controlled way. A good example is the light sword optical element (LSOE) where the additional angular modulation enables acceptable imaging with large depth of field [7–9].

The aim of this paper is to illustrate the usefulness of the peacock eye optical element (PEOE) [10] for imaging with an extended depth of field. Similarly to the LSOE, the PEOE is also a phase structure that exhibits the lack of revolution symmetry. The name "peacock eye" results from a characteristic pattern of the element's phase coded in the binary-amplitude way. Lately it has been proved that the PEOE corresponding to large focal lengths can be used successfully for imaging with an extended depth focus [11]. In the present paper we have intentionally chosen the parameters of imaging arrangement similar to those described in the works dealing with a presbyopia correction [1, 2, 9], since it enables to analyze the PEOE characterized by small values of focal lengths. Moreover, such an arrangement makes it possible to evaluate the usefulness of an investigated element for ophthalmologic purposes and machine vision.

The imaging set-up includes the PEOE in the form of a thin optical element. The imaging plane is placed in a fixed distance 20 mm behind the element. The distances between the input objects and the element vary and belong to the range [25 cm, ∞). According to geometrical optics, the thin optical element focusing incident plane wave into a proper light segment makes it possible to realize imaging with an extended depth of field in the above set-up. The points of the focal segment should be situated from distance $(d - L/2) = 18.5$mm up to distance $(d + L/2) = 20$mm behind the element in order to cover the assumed range of object distances. Hence $L = 1.5$mm denotes the length of the focal segment. The PEOE fulfilling the above conditions was designed. We have assumed a square aperture of the element with the width $A = 4$ mm and the wavelength $\lambda = 633$nm of monochromatic illumination. The phase of the PEOE is given by $2\pi\Phi(x,y)/\lambda$, where:

$$\Phi(x,y) = -\frac{y^2}{2(Lx/A+d)} - \frac{Ax}{L} + \frac{dA^2}{L^2}\ln\left|Lx/A+d\right|. \quad (1)$$

The geometry of focusing according to geometrical optics, illustrated in Fig. 1 was presented in detail in Ref. [10, 11]. In approximation, an infinitesimal vertical strip of the element focuses an incident plane wave in a proper point of the focal segment.

In our experiments we have used the PEOE described above and, for comparison, a refractive spherical lens with a focal length of 20cm. The PEOE was fabricated as a binary-phase diffractive structure by electron-beam lithography at the Institute of Electronic Materials in Warsaw. The produced binary-phase diffractive element has limited diffraction efficiency, theoretically equal to 40.5%. The output images are formed only by the (+1) order of the structure. Nevertheless, in our imaging system the other orders have negligible influence on output intensity distributions. As input objects we applied Snellen optotypes with an angular dimension of 7.14 minutes of arc located in the following object distances: 2.1m; 1.4m; 1.05m; 0.84m; 0.7m; 0.42m.

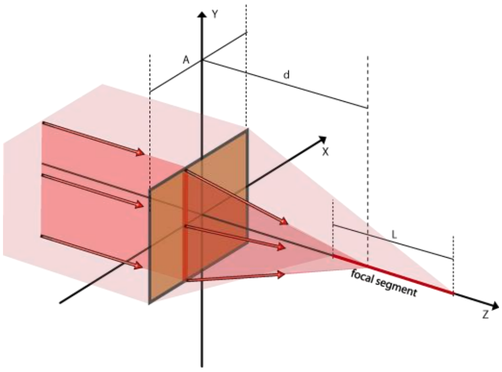


Fig. 1. Geometry of focusing by the PEOE.

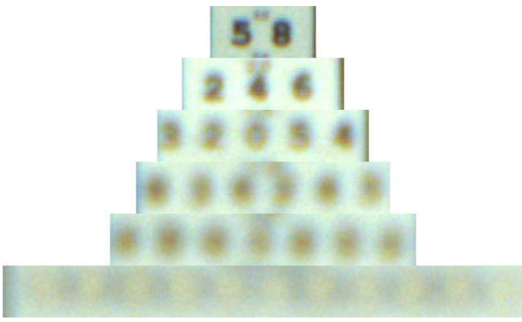
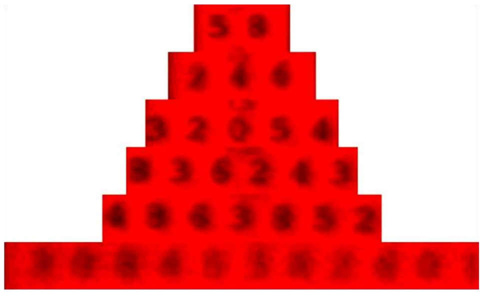
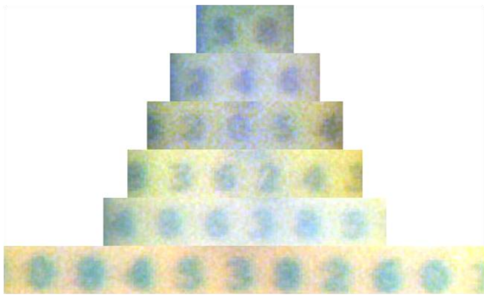


Fig. 2. Images formed in white light by a refractive spherical lens adjusted at infinity.

The satisfying recognition of such Snellen optotypes corresponds to slightly limited 7/10 vision acuity. Additionally, we put onto the both imaging elements circular apertures with a diameter of 3mm. The used refractive spherical lens was adjusted to objects located at infinity. According to our design of the PEOE, the circular aperture limited corresponding object distances to the range [0.3m, 2.1m]. The experimental results are shown in Figs. 2 and 3, where object distances increase from bottom to top. Figure 2 and Fig. 3(b) illustrate the cases where white light illuminated the optotypes. Figure 3(a) shows output images when white light was additionally filtered by a monochromatic filter placed just before the PEOE. The maximum transmittance of the filter corresponded to λ = 625nm with the FWHM equal to Δλ = 8nm.



(a)



(b)

Fig. 3. Images formed by the PEOE in monochromatic (a) and white light (b). In the latter case the chromatic aberration of a diffractive element is clearly visible.

According to Fig. 3, the images of Snellen optotypes are recognizable for different object distances while the spherical lens forms acceptable images of far objects only (Fig. 2). A little better readability of Fig 3b compared with Fig. 3a can be caused by lower light intensity due to filter application and therefore lower signal–to-noise ratio. The lack of revolution symmetry of the PEOE changes the flow of energy during focusing, which can improve imaging quality. Therefore the peacock eye optical element seems to be suitable for imaging with an extended focal depth and constitutes an interesting alternative for optical structures used so far in machine vision and ophthalmology. This conclusion coincides well with the obtained results presented in Ref. [11].

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