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An artificial compound eye of photon Sieves

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ABSTRACT

The compound eye of insects has numerous extraordinary optical performances, such as minimum chromatic aberration, wide-angle field of view, and high sensitivity to the incidence light. Inspired by these unique performances, we present a novel artificial compound eye of photon sieves in this paper, where the photon sieves play the roles of insects' ommatidia. These photon sieves have the same focal length. The incidence light can be focused into the same focal plane and produce the superposition effect, the utilization ratio of energy can be largely improved. Through the numerical simulation, the results show that this novel structure has similar focusing performance with the conventional photon sieves, but has higher utilization ratio of energy and wider angle field of view than that of the conventional photon sieves. Our findings provide a new direction for optics and biology researchers, which will be beneficial for medical imaging, astronomy, etc.

1. Introduction

Diffractive optical elements (DOEs) have been widely used in optical systems because of their unique advantages of compact size, light weight, and high design flexibility [1–6]. With the development of nanofabrication technologies, higher resolution will be required in modern optical devices or systems, but the current DOEs can't meet this requirement. The other novel DOEs should be proposed to figure out this problem.

In 2001, the photon sieves (PS) was first proposed by Kipp as a novel DOEs, which consists of numerous pinholes on the corresponding transparent zones of the Fresnel zone plate [7]. Compared with the Fresnel zone plate, the PS can obtain a sharper focal spot by suppressing the secondary maxima and higher-order diffractive effect. Through the structural optimization, super-resolution imaging can be achieved. After that initial paper, a number of theoretical and experimental works related to PS have been published. Current researches mainly focus on several aspects of design theory [8–10], structural improvement [11–14], fabrication process [15], and applications [16–19]. Until now, the PS has been initially applied in the field of astronomy [16,17], soft X-ray microscopy [7,18], nano-lithography [19,20], etc.

However, according to the structure of PS, we can see that the pinholes are only distributed on transparent zones of corresponding Fresnel zone plate, which have positive contribution to the intensity of the focal spot. Meanwhile, the other zones and gaps between the pinholes have negative influence on the intensity of the focal spot, which reduce the energy of focal plane. So, most energy of incidence light is wasted. Many theoretical and experimental results have proved that the maximal energy utilization ratio of PS is only about 10%, and this value obtained under ideal conditions. In order to improve the utilization ratio of incidence light, Jiang et al. proposed phase photon sieves (PPS), many pinholes are distributed on both transparent zones and dark zones, but there is a phase difference between two adjacent zones. Compared with the conventional PS, the PPS has higher utilization ratio of incidence light, but the improvement effect is not obvious [13]. Xie et al. proposed a hybrid PS structure, which combines the Fresnel zone plate and conventional PS. The numerical simulation results showed that this hybrid structure can partially improve the utilization ratio of incidence light, not obviously. Moreover, the fabrication process of this hybrid structure becomes more complicate than conventional PS [21]. In summary, the current structures of PS are unable to balance the high resolution, expensive fabrication costs, and high utilization ratio of incidence light.

Fortunately, there are some insects with compound eyes (CEs) in nature, such as butterfly, dragonfly, lobster, etc. These CEs are extraordinary imaging systems with optical features such as minimum chromatic aberration, wide-angle field of view, high

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sensitivity to light and superb acuity to motion [22,23]. Some theoretical and experimental studies of the imaging principle and applications of natural CEs have been performed [24–26]. Inspired by these research results, artificial compound eyes (ACEs) were designed and fabricated, then used in modern optics devices and systems [27,28]. However, the current ACEs are mainly refractive, the image quality are poor [29]. It will be an attractive research topic if we combines the CEs of insects and PS.

In this paper, we proposed a novel artificial compound eye structure which consists of many PSs. Some details of the design process and numerical simulation were also performed. This novel structure has these advantages: high resolution, high utilization ratio of incidence light and wide-angle field of view. It will provide a good theoretical basis for its practical applications in the field of the medical imaging, astronomy, etc.

2. Theoretical analysis

2.1. The design theory of PS

According to the basic model of PS, the pinholes only located on transparent zones, corresponding to the Fresnel zone plate. For a given incidence wavelength λ and focal length f, the radius of the nth transparent zone r_n can be expressed by [17]:

$$r_n^2 = 2nf\lambda + n^2\lambda^2 \quad (1)$$

The corresponding width w_n can be expressed by:

$$w_n = \frac{\lambda f}{2r_n} \quad (2)$$

The diameter of pinholes on each transparent zone d_n can be expressed by:

$$d_n = k \times w_n \quad (3)$$

where, k is a constant value and $k > 1$, which is decided through the optimization process.

The zone numbers of the PS can be expressed by:

$$N \approx \frac{D^2}{4\lambda f} \quad (4)$$

where, N is the zone numbers of the PS, D is the diameter of the PS, λ is the wavelength of incidence light, f is the design value of the focal length of the PS.

To get the high resolution and image contrast, the numbers of pinholes on each transparent zone are optimized by suitable window function, and Gaussian window function was chosen in this paper.

2.2. The structure of ACEs

Fig. 1 shows the schematic diagram of the ACEs, which consists of incidence light (1), PS (2), metal thin film (3), substrate (4), and focal plane (5). As shown in Fig. 1, the function of PS is similar with the insects' ommatidia. The number of ommatidia in the ACEs is M. The PS is a film structure, which can be easily compacted on the surface of semi-sphere. To reduce the complexity of fabrication process, all the PSs are set as the same structural parameters. Meanwhile, these PSs with the same focal length can focus the incidence light into the same focal plane and produce the superposition effect, the utilization ratio of incidence light will be largely increased.

The parameters of ACEs are decided through the optimal design process, not arbitrary values. More details about the design process can be seen in Section 2.3.

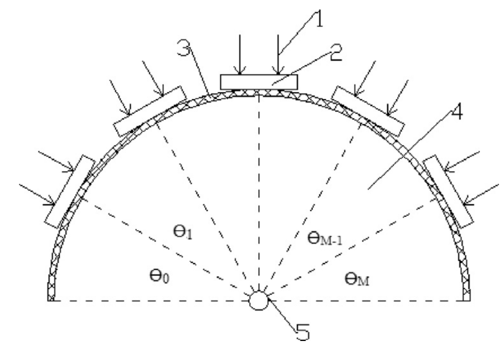

Fig. 1. The schematic diagram of the artificial compound eye.

2.3. The design process

1. According to the actual requirement, determine the radius of the ACEs, which is approximately equal to the focal length of PS (f);
2. According to the rule that two adjacent PSs cannot be overlapped each other, determine the number of PSs (M) and the diameter of each PS (D). It is worth mentioning that the gap areas between PSs is opacity, the incidence light can't pass by these gaps. To obtain high utilization ratio of incidence light, the gap areas should be as small as possible, but cannot be overlapped. Generally, for the semi-sphere substrate, M and D should meet this relationship: $M \times D < \pi \times R$, where R is the radius of the ACEs;
3. Substitute the parameters of PS (λ, D, f) into the equation group (1)–(4), optimize the structure of PS;
4. Choose the materials of the metal thin film and the substrate. And the thickness of the metal thin film was optimized by the simulations and experimental testing, it's about several tens microns;
5. The design process is over.

3. Numerical simulation and discussions

3.1. Initial parameters

In this paper, the initial parameters are as follows: The radius of the ACEs is 200 mm, and all the ommatidia are uniformly distributed on the surface of semi-sphere; the angles between two adjacent ommatidia are set as the same values, $\theta_1 = \theta_2 = \ldots = \theta_{M-1}$; The PS is a film structure, $D = 25$ mm, $\lambda = 635$ nm, $f = 250$ mm.

Then, substitute these parameters into Eq. (4), figure out the zone numbers $N = 984$, the pinholes on each zone are optimized by Gaussian window function.

The Cr metal and quartz glass were used as the materials of the metal thin film and substrate for their good performance, respectively. The thickness of metal thin film is about 60 μm.

3.2. Results and discussions

To give more details about the properties of the ACEs, some numerical simulation have been performed between the PS and ACEs, more details can be shown in this section.

1. Focusing performance comparison between PS and ACEs
   Fig. 2 shows the focusing performance comparison between PS and ACEs with 30 ommatidia, where the X-axis is the distance from the focal plane, and the Y-axis is the normalized intensity. From Fig. 2, we can see that the focusing property of ACEs is