Improving the image quality of optical systems with radially symmetrical phase mask

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ABSTRACT

An optical system with a radially symmetrical phase mask allows to extend the depth of field. However, the contrast of the optical system is still lower than that of the diffraction pattern of the traditional optical system. In this paper, we introduce a new method for image enhancement of optical systems with radially symmetric phase masks. The optical system with a traditional radial symmetric phase mask would result in a dot point spread function. The optical system with an improved symmetric phase mask results in a dark center point spread function. The two images that will be obtained correspond to the optical system with two phase masks. On the basis of these two images, a mathematical relationship is proposed in order to obtain good quality images. The simulation results have demonstrated the proposed method to improve the image quality of the optical system with the radial symmetrical phase mask.

Keywords: Optical system; Depth of field; Radially symmetrical phase mask.

1. INTRODUCTION

Wavefront coding is a powerful technology that is used for extending the depth of field [1]. By placing a phase mask in the pupil plane, we can reduce the influence of the defocus error on the optical transfer function (OTF) or point spread function (PSF). Phase masks can be divided into two types: asymmetrical phase masks and radially symmetric phase masks. Various types of asymmetrical phase masks for increasing depth of field have been proposed, such as cubic phase masks [1], sinusoidal phase masks [2], logarithmic phase masks [3], tangent phase mask [4], exponential phase mask [5], polynomial phase mask [6]. Several radially symmetric phase masks have been introduced for depth-of-field extension, such as quartic phase masks (QPM) [7], logarithmic phase marks [8], diffraction hybrid phase mask [9] and aspherical phase mask [10].

Optical systems with asymmetric phase masks extend the depth of field better than optical systems with radially symmetric phase masks. However, the asymmetric phase mask requires image processing to restore sharp images, and the recovered images often appear as artifacts [11], while the symmetric phase mask gives an acceptable image without using any image processing, so the image generation time is faster. In addition, the resulting image of radially symmetrical phase masks does not appear to have impurities. However, the image quality of the radially symmetric phase mask is lower than that of the diffraction image of a traditional optical system.

Recently, wavefront encoding technology with a pair of phase mask has been widely used to improve the quality of optical systems for the extension of the depth of field. The method of using a conjugate phase mark pair is to remove the effect of impurities in the obtained image of the asymmetrical phase mask method [12]. However, this method leads to a reduced cutoff frequency of the optical system. Another method using a pair of radially symmetrical phase masks gives the modulation transfer function (MTF) more invariant over a wide range of depth of field [13]. However, the image quality of this method is still much lower than the diffraction image of the traditional optical system. In this paper, to improve the image quality of an optical system with a radially symmetric phase mask, the method of using two phase masks is proposed.

The paper is organized into the following sections: in section 2, the theory of image generation of the proposed method is presented, section 3 shows the simulation results and comparison, and finally, section 4 is the conclusion.

2. THE PROPOSED METHOD

The image obtained from an optical system is

$$g = o \otimes h \tag{1}$$

where o is the object, h is the point spread function (PSF).

The pupil function, p, of an optical system with a phase mask $f(x,y)$ and a defocus amount, ψ, can be expressed as follow:

The pupil function, p

$$p(x,y) = \begin{cases} \frac{1}{\sqrt{2}} \exp(i \times (f(x,y) + \psi(x^2+y^2))) & \text{if } x^2+y^2 \le 1 \\ 0 & \text{other} \end{cases} \tag{2}$$

where, $\psi = \frac{\pi L^2}{4\lambda}(\frac{1}{f'} - \frac{1}{d} - \frac{1}{d_0})$ and i is a complex number.

L is the pupil plane dimension, λ is the wavelength of light, f', d, d_0 are the focal length, object distance and the image distance, respectively.

The point spread function, h, can be determined by the pupil function as follows:

$$h = |FFT(p(x,y))|^2 \tag{3}$$

In the paper, we introduce a new approach to wavefront encoding technology for radially symmetrical phase mask. In the subtraction method, the optical system consists of two branches. One branch leads to the point spread function, h_{dot}, and one branch leads to the dark point spread function, h_{dark}. These two spread functions will lead to two images, respectively, I_{dot}, I_{dark}. To get good quality images, the paper introduces a mathematical relationship between these two images. The proposed mathematical relationship is shown in formula (4):

$$g = (o \otimes h_{dot}) \times \log_2(\frac{o \otimes h_{dot} + \alpha}{o \otimes h_{dark} + \beta}) = I_{dot} \times \log_2(\frac{I_{dot} + \alpha}{I_{dark} + \beta}) \tag{4}$$

where α and β are parameters. In the article, the parameters α and β are chosen by 1.2 and 1. The principle of image generation of the proposed method is shown in figure 1. Figure 1(a) shows the dot PSF, h_{dot}. Figure 1(b) shows the dark PSF, h_{dark}. Assuming the object is a delta pulse, using expression (2), the PSF of the proposed method is obtained in figure 1(c). The PSF of the proposed method has a smaller size than the PSF in figure 1(a). It means that the image quality due to the PSF in figure 1(c) will be better.

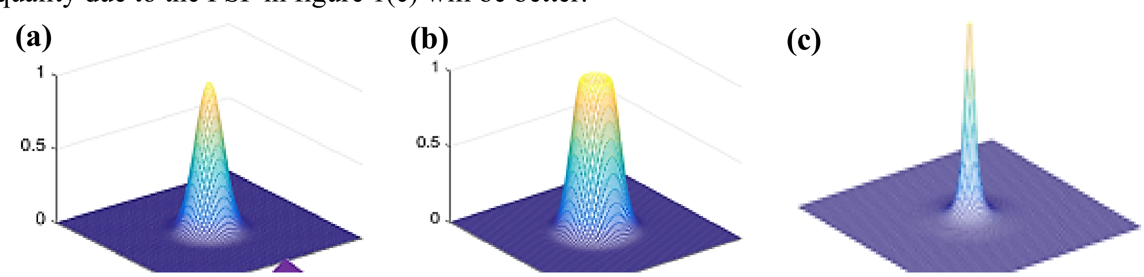


Figure 1. *Principle of image quality enhancement of the proposed method.*

Radially symmetrical phase mask often results in a dot PSF. To demonstrate the effectiveness of the proposed method, in this paper, the quartic phase mask (QPM) is used. This is a common radially symmetrical phase mask. The QPM is shown by formula (5)[7]:

$$f_{QPM}(x,y)=\begin{cases}a(x^2+y^2)^2-b(x^2+y^2) & \text{if } (x^2+y^2)\le 1\\ 0 & \text{other}\end{cases} \quad (5)$$

where, a and b are profile control parameters of the QPM.

The important thing of the proposed method is to create an additional dark point spread function that has an invariant depth of field over a range of depth of field of the QPM. Through survey and research, a phase mask by adding QPM with twisted phase mask 0-2π, ϕ, can obtain a central dark PSF that achieves the above required properties (as shown in Fig. 1). This phase mask is called a twisted QPM, denoted QPMX. This QPMX phase mask has the following profile:

$$f_{QPMX}(x,y)=\begin{cases}a(x^2+y^2)^2-b(x^2+y^2)+\phi(x,y) & \text{if } (x^2+y^2)\le 1\\ 0 & \text{other}\end{cases} \quad (6)$$

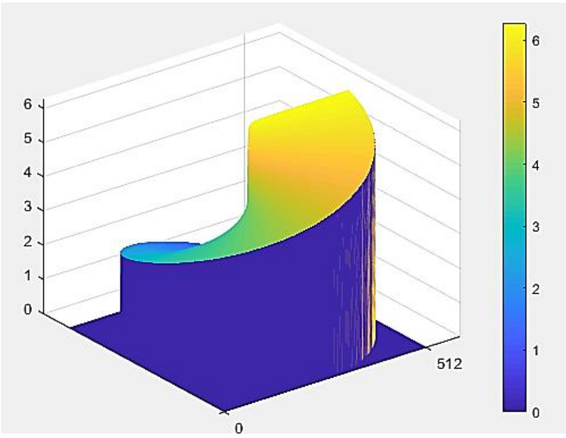


Figure 2. *Contour of twisted phase mask 0-2π, ϕ.*

Optimizing the phase mask parameters is very important due to the random phase mask parameters can lead to the poor image quality of the optical system. The QPM is a popular phase mask and has been optimized for the best image quality. Here, the parameter of QPM is taken according to the reference [7], a = 1.5π^2, b = 12.99. With these phase mask parameters, the contours of the QPM and the QPMX are shown in figure 3.

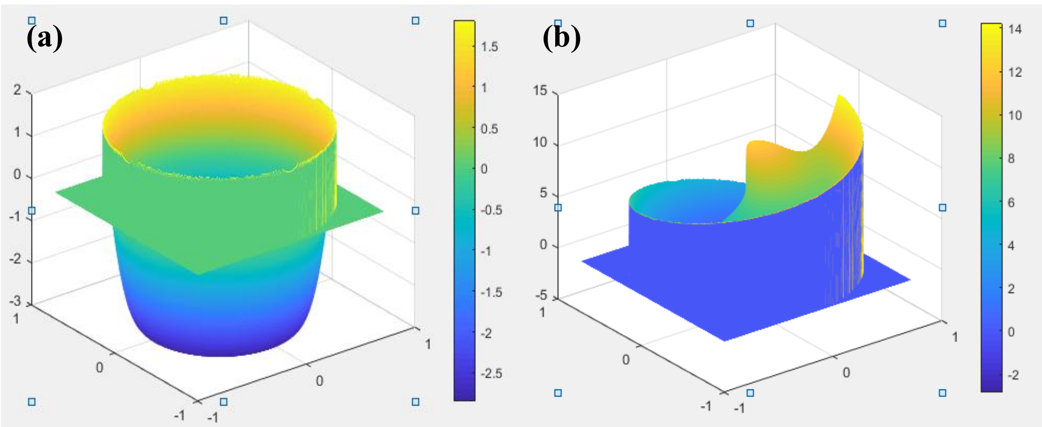


Figure 3. *Phase mask contours: (a) QPM and (b) QPMX.*

The PSFs of the two QPM and QPMX are shown in figure 4. The PSF of the QPM has a point shape, while the PSF of the QPMX has a central dark form. The shapes of these two PSFs are consistent with the theoretical requirements of the proposed method.

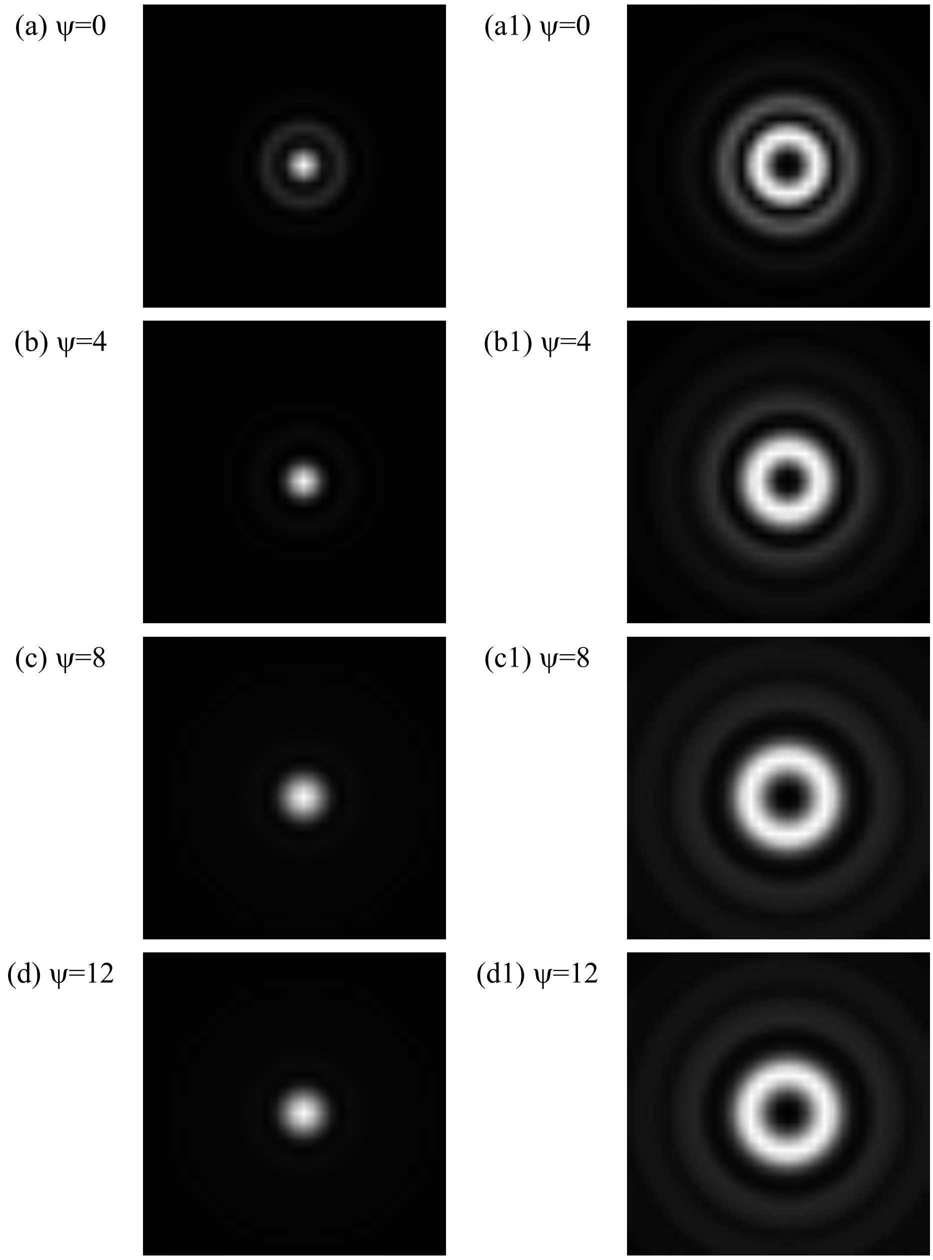


Figure 4. *PSFs of QPM and QPMX at different depths of field.*

3. SIMULATION RESULTS

Based on the phase mask parameters defined above, in this section, the simulation process of the imaging generation of the optical system and the efficiency of the method will be studied. To perform the simulation, the spoke image is used, as shown in figure 5. An amount of white Gaussian noise of 10 dB will be added to the image for simulation. The simulated image will be obtained at four depth of field positions with values at $\psi = 0$, $\psi = 4$, $\psi = 8$ and $\psi = 12$.

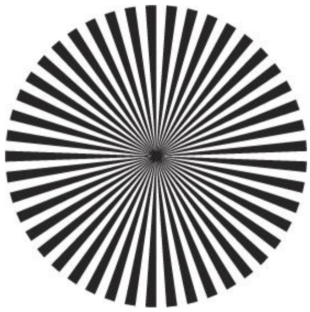
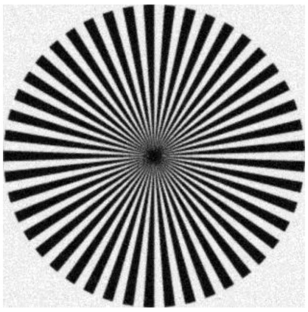
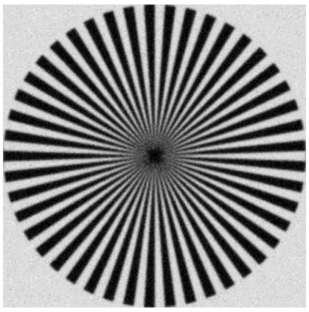


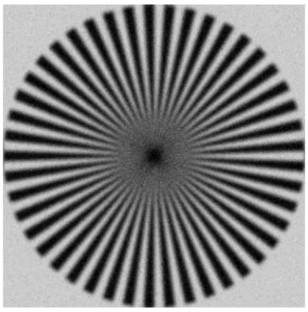
Figure 5. *Original image for simulation input.*



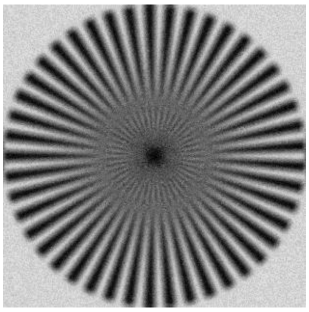
(a) ψ = 0



(b) ψ = 4



(c) ψ = 8

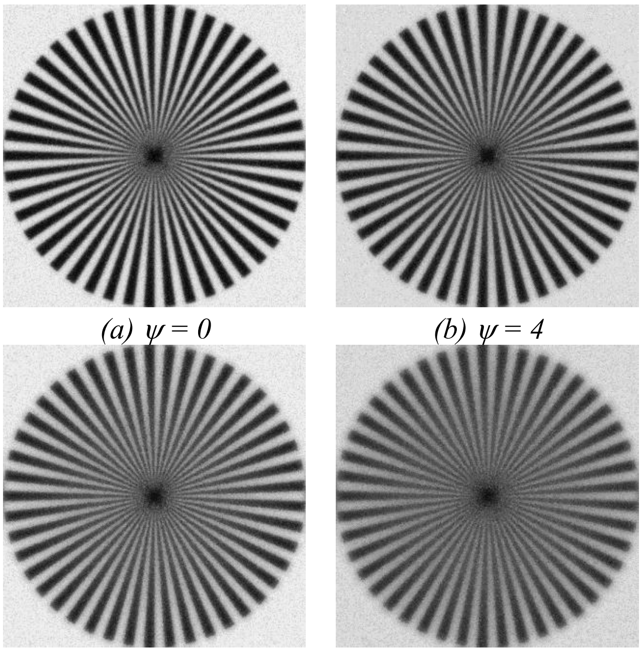


(d) ψ = 12

Figure 6. *Images of the conventional optical system at different depths of field.*

The simulated images of the conventional optical system are shown in figure 6. Here, the conventional optical system is defined as there is no phase mask added to the optical system. Figure 6(a) ,6(b), 6(c) and 6(d) show the ideal optical system images corresponding to ψ=0, ψ = 4, ψ = 8 and ψ = 12. It can be seen that the image in figure 6(a) has the best quality. When the value of focal deviation ψ is larger, the quality of the optical system image decreases rapidly. As shown in figure 6(d), the edges of the spokes are blurred and the high frequency areas are no longer able to distinguish between the black and white lines. In addition, some high frequency areas have been lost. As a result, objects located at different depths of the field would result in different image qualities.

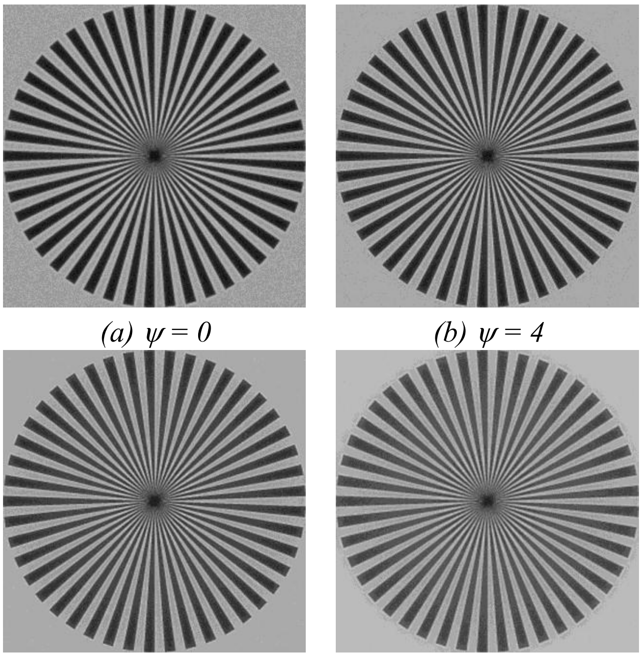
The simulation image using the traditional QPM is shown in figure 7. Figure 7(a), 7(b), 7(c), and 7(d) show the ideal optical system images corresponding to ψ =0, ψ = 4, ψ = 8 and ψ = 12. It is clear that the black and white lines of the simulated image at all depths of the field could be distinguished. Image resolution at all depths of the field remains the same. In other words, the image quality of the optical system with the QPM is preserved over a large depth of field. However, the image quality of these images is still lower than that of the conventional optical system at the position ψ =0. Especially in the high frequency areas, the contrast is significantly reduced.



(a) ψ = 0 *(b) ψ = 4*

(c) ψ = 8 *(d) ψ = 12*

***Figure** 7. Images with QPM at different depths of field.*



(a) ψ = 0 *(b) ψ = 4*

(c) ψ = 8 *(d) ψ =12*

***Figure 8.** Images of the proposed method at different depths of the field.*

The images of the proposed method are illustrated in figure 8. Figure 8(a), 8(b), 8(c), and 8(d) show the ideal optical system image corresponding to $\psi = 0$, $\psi = 4$, $\psi = 8$ and $\psi = 12$. The results in figure 8 show that the images over the entire depth of field are sharp, clear, and in high contrast. The image quality obtained by the proposed method is close to the image quality of the conventional optical system at $\psi = 0$. In comparison, these obtained images are better than the images obtained by the optical system with the QPM. In addition, the noise in the image is significantly smoothed out. It means that the proposed method is capable of improving the image quality of the optical system with the radially symmetrical phase mask.

(a)

(b)

Figure 9. *Obtained images of (a) QPM and (b) proposed method at $\psi = 12$.*

Next, we use the LENA image as the original image for the simulation. An amount of white Gaussian noise of 15 dB will be added for simulation. The resulting image of the QPM is figure 9(a), while the image of the proposed method is figure 9(b). The results show that the image obtained by the proposed method is clearer and has better quality.

4. CONCLUSIONS

The paper has successfully proposed a solution to enhance the imaging quality of optical systems with radially symmetrical phase masks. The traditional radial symmetrical phase mask results in a dot PSF. The improved phase mask results in a dark PSF. The mathematical relationship has been proposed to enhance image quality. The images of the proposed method have been provided through the simulation to illustrate the effectiveness of the method. By comparison with images obtained by the optical system using a conventional phase mask, the images of the proposed method have better quality.

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TÓM TẮT

Cải thiện chất lượng hình ảnh cho hệ thống quang với mặt nạ pha đối xứng xuyên tâm

Hệ thống quang học với mặt nạ pha đối xứng xuyên tâm cho phép mở rộng độ sâu trường ảnh. Tuy nhiên, độ tương phản hình ảnh của hệ thống quang học vẫn thấp hơn hình ảnh nhiễu xạ của hệ thống quang học truyền thống. Trong bài báo này, chúng tôi giới thiệu một phương pháp mới để tăng cường chất lượng ảnh của hệ thống quang học với mặt nạ pha đối xứng xuyên tâm. Hệ thống quang học với mặt nạ pha đối xứng xuyên tâm truyền thống sẽ tạo ra hàm nhòe điểm dạng chấm. Hệ thống quang học với mặt nạ pha đối xứng cải tiến cho hàm nhòe điểm dạng tối ở tâm. Hai hình ảnh thu được tương ứng với hệ thống quang học có hai mặt nạ pha. Trên cơ sở của hai hình ảnh này, một mối quan hệ toán học được đề xuất nhằm cho hình ảnh có chất lượng tốt hơn. Kết quả mô phỏng đã chứng minh hiệu quả của phương pháp đề xuất để cải thiện chất lượng hình ảnh của hệ thống quang học với mặt nạ pha đối xứng xuyên tâm.

Từ khoá: Hệ thống quang học; Độ sâu trường; Mặt nạ pha đối xứng xuyên tâm.