Optics Communications 411 (2018) 80–87

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Extended depth-of field imaging by both radially symmetrical conjugating phase masks with spatial frequency post-processing

L.V. Nhu [a,c], Cuifang Kuang [a,b], Xu Liu [a,b,*]

[a] State Key Laboratory of Modern Optical Instrumentation, College of Optical Science & Engineering, Zhejiang University, Hangzhou 310027, China
[b] Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, 030006, China
[c] Department of Optical Engineering, Le Quy Don Technical University, Hanoi, Viet Nam

ARTICLE INFO

Keywords:
Computational imaging
Imaging systems
Fourier transform
Extending depth of field

ABSTRACT

In this paper, we propose a method to improve the contrast of image by using both radially symmetrical conjugating phase masks. The method is based on the generation of synthetic optical transfer function (OTF) from OTFs of both radially symmetrical conjugating phase masks. Both quartic phase mask (QPM) and its conjugating phase mask (cQPM) are used as an example. Two images are captured by QPM and cQPM. In Fourier domain, a combination of both QPM and cQPM produces the improvement of the contrast of images in all spatial frequency positions. The simulation results demonstrated that the contrast improvement of image of proposed method is obtained.

1. Introduction

In traditional imaging system, due to the limit of the lens aperture, the defocus has a disadvantageous impact on the sharpness of the image. However, there are many practical applications that require a wide range of defocus for the acquisition of three-dimensional objective information such as biomedical imaging [1], vision-based applications [2], reduction of aberrations [3] and so on. A simple way to extend the depth of field is the use of aperture apodization. However, this method can result in the reduction of contrast and signal-to-noise ratio (SNR) because optical flux is decreased by the use of apodized aperture. Recently, the phase pupil filters placed in the pupil plane have also presented a solution when the optical flux is maintained.

When a phase mask (PM) is placed in the pupil plane of an optical system, a long focusing line is obtained and the imaging characteristic is invariant to defocus. The phase masks can be divided into two types including the radially symmetrical PMs and the asymmetrical PMs [4]. Some asymmetrical PMs to extend the depth of field have been introduced, such as the cubic phase mask [5], the logarithmic phase mask [6], the root square phase mask [7], the exponential phase mask [8], the sinusoidal phase mask [9], the tangent phase mask [10] and the polynomial phase mask [11]. When the asymmetrical PMs are used, there is blurring in encoded images. However, this blur is nearly uniform. The digital processing should be used to obtain final high-quality image suitable for human viewing or as pre-processing for image-based tasks. However, the image artifacts and SNR are both intrinsic problems of the asymmetrical PMs [12–14]. Some radially symmetrical phase masks to enhance the depth of field have been suggested, such as QPM [15,16], logarithmic axicon [17], diffraction hybrid lens [18], and logarithmic asphere [19]. The radially symmetrical PMs has symmetrical and sharpness point spread function (PSF). When the radially symmetrical PMs are used, sharp image can be directly obtained so that there is no need for digital processing. Additionally, images obtained from the method of using radially symmetrical PMs are free of artifacts.

The asymmetrical PMs generate the PSF symmetrical through the in-focus plane in axial direction. While, the radially PMs generate the PSF asymmetrical through the in-focus plane in axial direction [20,21]. In other words, the defocused modulation transfer functions (MTFs) at positive and negative focusing positions are different when the defocus value is the same. The difference generates interesting property of the radially symmetrical PMs. Since the radially symmetrical phase function is an even function, it is possible for a conjugated PM pair to produce symmetrical imaging property through the in-focus plane in axial direction [20]. For QPM and cQPM, defocused MTFs are symmetrical via the in-focus plane in axial direction. On one hand, the defocused MTFs of cQPM at positive focusing positions are higher in low frequency region and high frequency region than that of QPM. On the other,

* Corresponding author at: State Key Laboratory of Modern Optical Instrumentation, College of Optical Science & Engineering, Zhejiang University, Hangzhou 310027, China.
E-mail address: liuxu@zju.edu.cn (X. Liu).

https://doi.org/10.1016/j.optcom.2017.10.082
Received 9 September 2017; Received in revised form 25 October 2017; Accepted 29 October 2017
0030-4018/

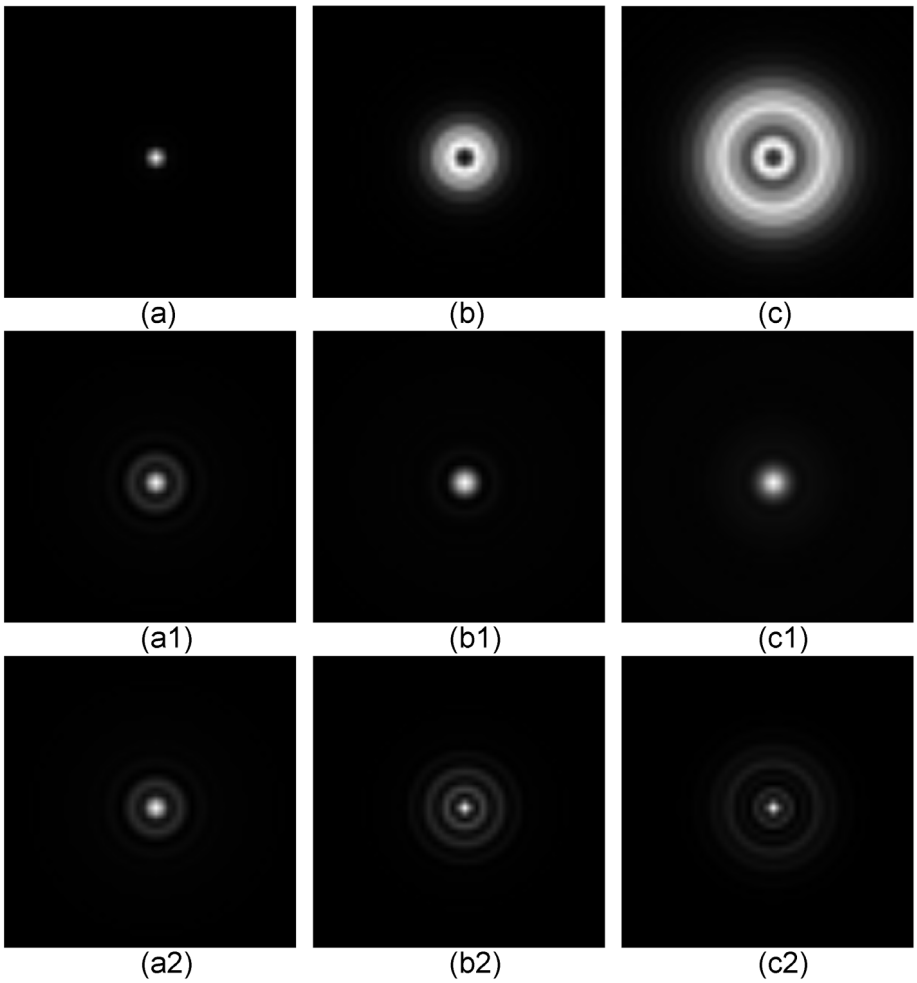

Fig. 1. The defocused PSFs of top: traditional imaging system, middle: QPM and bottom: cQPM. The left column $\psi = 0$, the middle column $\psi = 6$ and the right column $\psi = 12$.

the defocused MTFs of QPM at positive focusing positions in middle frequency region are higher than that of cQPM (where the defocus value is same). Therefore, based on the use of the defocused MTFs of both QPM and cQPM, a post processing for combining between the low and high frequency regions of the defocused MTF of cQPM and the middle frequency region of the defocused MTFs of QPM at positive focusing position can give high-quality image. The process can be summarized as follows. Firstly, we calculate the defocused MTFs of conjugated PM pair. Then, we compare the defocused MTFs of conjugated PM pair and find the parts that provide better results. Secondly, we select these better regions from each one of these two PMs in Fourier spectrum, and multiplex them. Thirdly, an inverse Fourier transform is calculated, giving the improved image.

The paper is organized as follows. Section 2 presents optimization and analysis of phase masks. Simulation results and analysis of both radially symmetrical conjugating phase masks are shown in Section 3. Finally, conclusions are presented in Section 4.

2. Optimization and analysis of phase mask

The PSF, h, of an optical imaging system is expressed by the square modulus of fast Fourier transform, *FFT*, of the complex amplitude pupil function, $P(x, y)$ and can be presented as,

$$h(x_0, y_0) = |FFT\,[P(x, y)]|^2 \tag{1}$$

where both x and y are the normalized coordinates in the pupil plane, both x_0 and y_0 are the normalized coordinates in the image plane.

The complex amplitude pupil function of an imaging system with the PM, $f(x, y)$ and defocus parameter, ψ, can be presented as

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

where

$$\psi = \frac{\pi L^2}{4\lambda}\left(\frac{1}{f} - \frac{1}{d} - \frac{1}{d_0}\right) \tag{3}$$

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

The OTF, H, is equal to fast Fourier transform of the PSF and can be represented by,

$$H(f_x, f_y) = FFT\left[h(x_0, y_0)\right] \tag{4}$$

where f_x and f_y are the normalized spatial frequencies.

Several radially symmetrical PMs, such as QPM, logarithmic axicon, diffraction hybrid lens, and logarithmic asphere have been proposed to extend the depth of field. In this paper, we use the QPM to prove our concept. The phase function of the QPM can be presented as,

$$f(x, y) = a(x^2 + y^2)^2 + b(x^2 + y^2) \tag{5}$$

Based on the phase function of the QPM in Eq. (5), its conjugate phase function (cQPM) can be expressed by,

$$f(x, y) = -a(x^2 + y^2)^2 - b(x^2 + y^2) \tag{6}$$