An approach to remove defocused aberration on array confocal microscope

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KEYWORDS : Ambiguity function, lateral resolution, confocal microscope, Modulation transfer function, Incoherent image

Abstract：In order to obtain a high resolution image required for ultra-precision measurement of microstructural object, a new approach is proposed for 3D microstructures. It uses the modulation transfer function with defocus aberration based on the ambiguity function and stable phase principle to achieve an optical phase filter, and utilizes generalized a spheric phase optical element to encode defocus images, and uses deconvolution technology to recover the images. In comparison with conventional optical system, the phase filter used in the optical system can make focal spot smaller when measure object defocusing, eliminates the effect of the defocus aberration, and improves the defocused property. Numerical results indicate the designed phase filter can improve lateral resolution of optical system, and the axial resolution of the optical system is not affect by the filter and defocus aberration. For different defocus plate, the phase filter can make character of modulation transfer function of lateral direction uniform approximation.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

NA = numerical aperture
ACM = array confocal microscope
AF= ambiguity function

1. Introduction

Optical scanning confocal microscopy is a well established technique in which the capability of optical sectioning allows the three-dimensional reconstruction of the topography of technical surfaces to be built up from a series of hundreds of depth discriminated height slices [1-4]. High lateral resolution can be obtained by the use of high Numerical Aperture (NA) objectives, but the resulting view field size is small. This disadvantage can be overcome by the use of a high NA microlens array, instead of a single objective, to extend the field size and add the possibility of parallel scanning. In order to obtain high quality, microlens arrays a small focal depth and small spherical aberration must be used. Considerable effort has been undertaken in recent years in the fabrication of lens arrays for a variety of applications. However, it is a difficult work to make microlens array a small focal depth and small spherical aberration.

Recent studies identify the ambiguity function (AF) as an important tool for describing techniques to recover phase information from intensity measurements [5-8]. This includes primarily deterministic phase retrieval method, which are based on the transport of intensity equation, as well as phase-space tomography. Here the AF is explored more systematically as a universal framework to describe and compare phase retrieval methods. It is shown that this can be used to obtain a rather intuitive understanding of issue related to phase retrieval. In particular, the phase problem is described in term of the AF. Iterative and deterministic phase retrieval methods are identified as techniques to recover sufficient information about the AF for computing the complex amplitude of the signal. In addition, a scheme for generalized deterministic phase retrieval is presented which is equally applicable to 1D and 2D signals.

In this paper, we use AF to design phase filter, and employ image processing technology to remove defocus aberration on the array confocal microscope. The main advantage of the proposed method is that it makes use of the phase filter to suppress the defocus factor. This property gives us the ability to recover image using the same degenerate function. It will improve the lateral resolution of the optical system, and keep the axial resolution invariant.

2. Theory

For our discussion we represent the aperture of the pupil by the function circ(u), which is equal to unity when $|u|\leq 0.5$. Otherwise it is equal to zero. To design the mask the polar coordinates at the exit pupil plane (ρ, θ) and cylindrical coordinates are employed at the image space.

According to principle of physical optics, the generalized pupil function of a spherical lens is written as:

$$Q(\rho) = P(\rho)\exp[ikW_{20}\rho^2] \quad (1)$$

Where $k = 2\pi/\lambda$ is the magnitude of the wave vector, λ stand for the wavelength of incident light, and W_{20} stands for the Hopkin defocus coefficient. It represents the optical path difference at the edge of the pupil.

The Optical Transfer Function (OTF) can be expressed as the autocorrelation for the generalized pupil function Q(ρ):

$$H(u) = \int_{-\infty}^{+\infty} Q(\xi)Q^*(\xi - \lambda l'u/2)d\xi \quad (2)$$

By substituting Eq.(1) into Eq.(2) we obtain an expression for the OTF as an autocorrelation operation:

$$H(u) = \int_{-\infty}^{+\infty} P(\xi + \lambda l'u/2)P^*(\xi - \lambda l'u/2)\exp(ik2W_{20}\xi u)d\xi \quad (3)$$

According to the definitions of the 1-D Ambiguity Function (AF) [9,10],

$$A(u,y) = \int_{-\infty}^{\infty} P(\xi + u/2)P^*(\xi - u/2)\exp[i2\pi y\xi]d\xi \quad (4)$$

And we are able to identify the following relationship

$$H(u;W_{20}) = A(u, y = \frac{2W_{20}}{\lambda}u) \quad (5)$$

From Eq.(5) it is apparent that the OTFs, for variable focus error, can be obtained by the ambiguity function if we select the values of a line with a slope of $2W_{20}/\lambda$. In Fig.1, the Modulation Transfer Functions (MTFs) are shown for different W_{20}. It is obviously seen that the main lobe of the curve decreases, while the side lobe increase, as the W_{20} increases. In the other words, the focal spot size is increasing as the increasing in defocus aberration W_{20}. Hence, it is necessary that the phase filter should be designed.

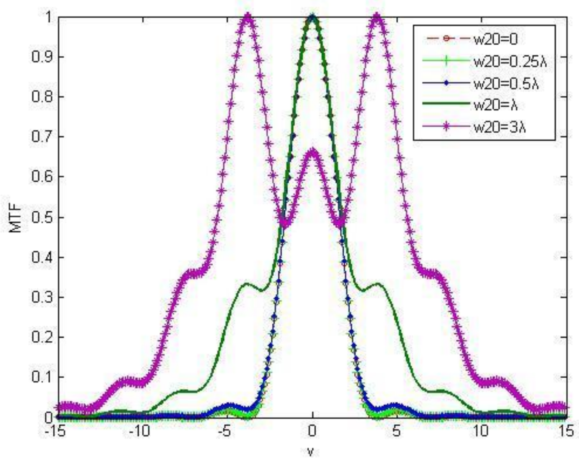


Fig. 1 Lateral normalized Modulation Transfer Function for different W_{20}

The optical aberration can deform wavefront when the observation plane is defocused. In order to increase lateral resolution, the phase mask can be designed to change the pupil function. The normalized pupil function can be expressed as follows:

$$q(u) = \exp(iku^r)P(u) \quad |\xi| \le 1 \quad (6)$$

The AF of $q(u)$ is

$$A(u,y) = \int_{-\infty}^{\infty} q(\xi + u/2)q^*(\xi - u/2)\exp[i2\pi y\xi]d\xi = \int_{1-|u|/2}^{1+|u|/2} \exp(ik\xi^r + i2\pi y\xi)d\xi \quad (7)$$

Using Stationary Phase Method, Stationary phase point ξi can be gained by:

$$\frac{d}{d\xi}[k\xi^r + 2\pi y\xi]_{\xi=\xi_i} = 0 \quad (8)$$

Thus, Eq.(7) can be written as:

$$A(u,y) \approx \int_{\xi_i-\varepsilon}^{\xi_i+\varepsilon} \exp(ik\xi^r + i2\pi y\xi)d\xi = \int_{\xi_i-\varepsilon}^{\xi_i+\varepsilon} \exp[ik\theta(\xi)]d\xi \quad (9)$$

The solution of Eq.(9) can be expressed as,

$$A(u,y) = \sqrt{\frac{-\pi}{2\theta''(\xi_i)}}\exp[-\frac{i\pi}{4} - ik(\xi^r + \lambda y\xi)]\frac{1}{\sqrt{k}} \quad (10)$$

From Eq.(10), the modulus of the ambiguity function $A(u,y)$ is only related with $\theta''(\xi_i)$. Hence, if r=3, then $|A(u,y)|$ is independent of W_{20}. In the other words, when the optical system add the cubic phase function to change the pupil function, the MTF will be not affected by the defocus modulate W_{20}.

3. Simulink and analysis

In order to validate the validity of phase mask designed by the Eq.(10), the focusing of the lens with the parameters incident wavelength λ=0.632 um and radius of lens R=2.5 mm. The corresponding Number Aperture (NA) of the designed lens is 0.65 and the phase distribution function can be described by Eq.(6) (r=3). As comparison, the focusing characteristics of conventional lens and lens governed by phase filter with the same other parameters are also calculated. The calculated Modulation Transfer Functions (MTFs) for conventional lens and lens with phase filter are shown in Fig.2 and 3 at the same W_{20}. The solid and dashed-dot curves correspond to conventional lens and lens with phase filter designed by Eq.(6), respectively. It is shown that side lobe of the MFT curve of the conventional lens is less than that of the lens with phase filter for W_{20}=0. But the side lobe of the MTF of the conventional lens is bigger than that of the lens with phase filter when the W_{20} is grater than or equal to 0.25λ. The projection of 2-D lateral intensity distribute is shown in Fig.4 for conventional lens and lens with the phase filter at W_{20}=3λ. The bright regions correspond to high light intensities, while the dark regions correspond to low light intensities. It is easily seen that the focal spot size decreasing when the phase filter is used in the optical system.

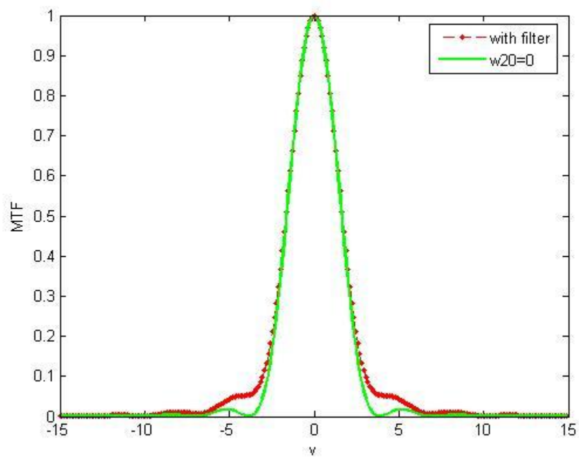


Fig. 2 Comparison of lateral normalized MTF: solid curve is no filter, dash-dot curve is with phase filter for W_{20}=0.

Examination of the data revealed several important facts which are made evident in Fig.2, Fig.3 and Fig.4. First, for W_{20} less than 0.25λ, the intensity response of the lens is little affected by the phase filter designed, and when W_{20} is greater than 0.25λ, the phase filter can play an important role in increasing the lateral resolution. Second, for variant W_{20}, the axial intensity distribution which is shown in Fig.5, is shifted along u (or z) axis direction. It is shown that the axial resolution is not affected by W_{20} and phase filter. Meantime, the filter designed by Eq.(6) can decrease the size of focal spot and suppress the side lobe of the focal spot.

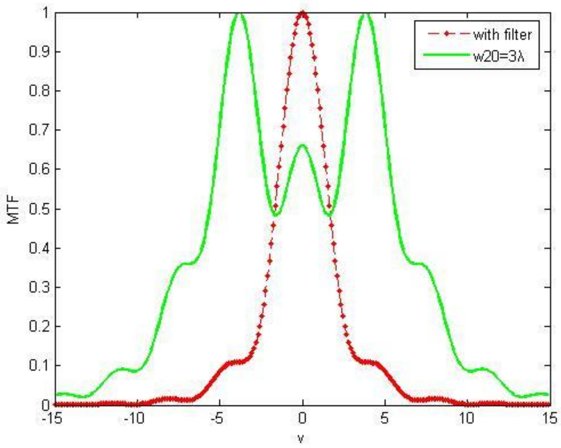
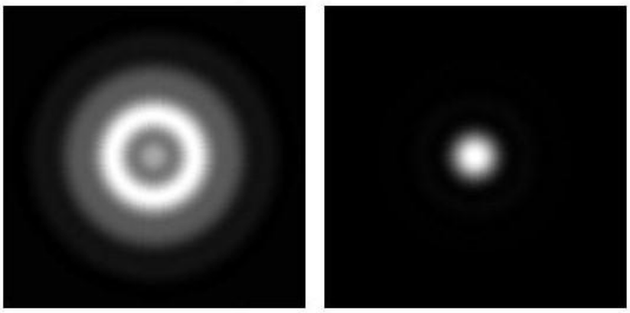


Fig. 3 Comparison of lateral normalized MTF: solid curve is no filter, dash-dot curve is with phase filter for W_{20}=3λ.



(a) Without filter at W_{20}=3λ (b) With phase filter at W_{20}=3λ

Fig. 4 Comparison of 2D image of focal spot

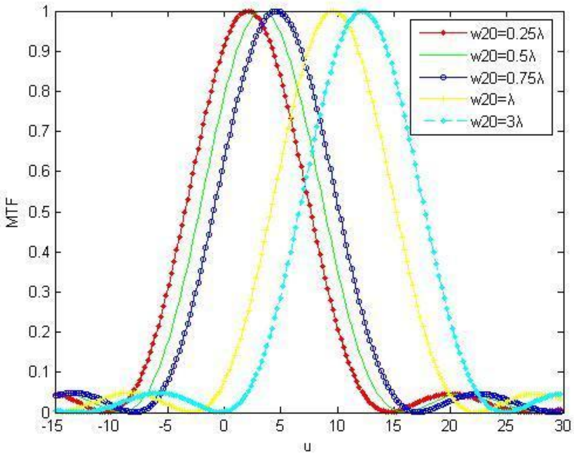


Fig. 5 Axial intensity distributions with different W_{20}

Furthermore, the axial resolution of the optical system with the filter is approximate for different W_{20}. The corresponding normalized light intensity of the designed optical system with filter is also shown in Fig.6. Phase variation in the pupil plane of the optical systems produces a MTF that is almost invariant for the different defocus aberration. Hence, it is possible to recover the original object by application of a simple inverse filter to the distorted image. In this manner, the same inverse filter is able to restore images for different values of defocus.

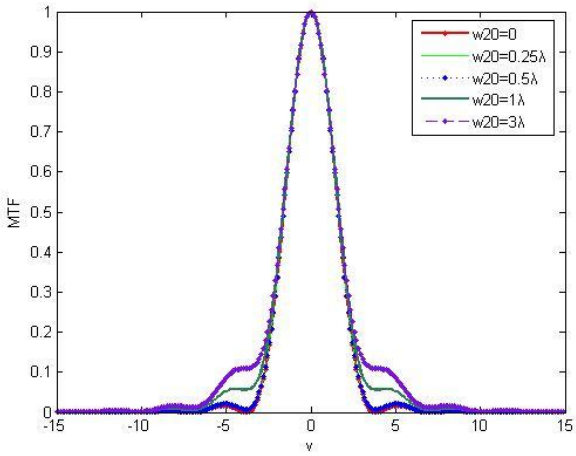


Fig.6 lateral MTFs with phase filter for variant W_{20}

4. Conclusions

In order to satisfy requirement for the lateral super-resolution measurement, an approach to remove defocus aberration is presented and a phase filter is designed to decrease the size of focal spot. Using the phase filter, the side lobe of lateral intensity distribution curve is greatly reduced, and the character of axial intensity distribution is invariant in optical system with defocus aberration. Furthermore, for different defocus plate, the phase filter can make character of modulation transfer function of lateral direction uniform approximation, and elimination the effect of defocus aberration. It means that one can easily implement image restoration by applying appropriate image recovery technology to an optical system with defocus aberration. Numerical results indicate that the designed phase filter can improve the imaging quality and achieve high lateral resolution. The validity of the ambiguity function (AF) is confirmed in this paper. Our research offers a simple method of improving the lateral resolution of confocal microscope.

ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundation of China (Grant No. 51075096) and the National Natural Science Foundation of Heilongjiang Province. (Grant No. LC201038).

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