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Design a Phase Plate to Extend the Depth of Field for an Inexpensive Microscope System to Have the Muti-focus Ability

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We propose an optical technique, also called wave front coding, that can extend the depth of field optically by phase plate without the need of post digital image processing (PDIP). This technique can replace the present expensive mechanical scanning for achieving 3D information recording or to avoid keeping adjusting the structure of the objective. This phase plate can be fabricated by the emerging technology of laser direct-write photoresist patterning and subsequent reactive ion etching on a germanium substrate.

The niche of our innovation is the exempt of PDIP. The dependence on PDIP causes the conventional researches in this field to develop a deteriorating phase plate to deteriorate the images in different depth to be the same worse. The deteriorated images can thus be fixed digitally by a same inverse optical transfer function method. In contrast, we replace the deteriorating plate with an improving plate. This plate can improve the defocus image in general. This freedom in limitation enables us to have a better imaging effect when designing the improvement plate. For example, in our design we do not need to worry about the null points existing in the inverse method since there is no inverse method for us at all.

Keywords: Wave Front Coding, Depth of Field, Optical Transfer Function, Microscope Systems.

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1. INTRODUCTION

Wavefront coding technology [1–3] is one of widely used methods to extend the depth of field in recent years. By applying a specially designed phase mask at the pupil plane, the whole system is insensitive to object distance. Therefore, wavefront coding technology can be employed to extend the depth of field of an microscope system. By arranging a specially designed phase mask between the objective and the tube lens, the previous time consuming work of frequently changing the structure of the objective [4] can be avoid, the optical and mechanical structure will remain the same except adding the phase mask. It is cost effective and more flexible in comparison with the previous method which alters the structure of the objective.

In contrast, the traditional light microscope systems are limited by small depth of field. Thick samples cannot be observed at one time. Usually mechanical scanning is used to achieve 3D volume information. In this way, it is impossible to use a traditional microscope system to observe the samples with dynamic changes.

Thanks to the newly developed film fabrication technology, the wavefront coding can use phase mask instead of amplitude mask. Therefore, it does not sacrifice resolution or illumination compared to other methods such as optical pupil apodization. Through laser direct-write photoresist patterning and subsequent reactive ion etching on a germanium substrate, it is possible to realize a diffractive lens with ten times depth of focus improvement over a conventional infrared lens of the same numerical aperture preparation.

The current image correction method uses a deteriorating phase plate, followed by the energy consuming Post Digital Image Processing (PDIP), in order to obtain a good image quality. Without more processing, this method would only reach a very poor visual quality caused by the necessary phase deteriorating plate. In other words, the conventional methods must go through a strong deteriorating phase plate before processing to fix the muti-focusing problem. This is to ensure that all images have approximately the same mis-focus, before beginning the Post Digital Image Processing. The same optical transfer functions make the post digital image processing manageable. Therefore, the deteriorated images can be fixed by a same inverse method digitally. This post-processing generally requires at least two dimensional forward Fourier transform and inverse Fourier transform and hence is computationally intensive.

2. DESIGN STRATEGY

The new proposed method would use an improving plate instead of the deteriorating plate, thus, obtaining an "OK" visual without any energy consumption. The design of this improving plate is possible by removing the design limitation due to the PDIP, which previously bounded the deteriorating phase plate's design. A possible reason for why, up until now, the proposal of an improving plate has not been strongly proclaimed, could be that the limitation, which bounded the previous plate's design, subconsciously limited them from designing a new plate.

2.1 PDIP Disadvantage

Therefore, the niche of our innovation is the removal of PDIP that was previously required. There are two advantages of removing PDIP, as mentioned in above,: to eliminate the energy consuming and the design limitation. The second is not as obvious as the first and needs more explanation below.

2.2 OTF Limitation 1

We start to note that the processing of PDIP is required to be the same for all images in different mis-focus levels; otherwise, the process involved would be too complex and time consuming. Therefore, researchers in this field developed a deteriorating phase plate so strong that it would deteriorate the images in different depth of fields to the same mis-focus level. In other words, the previous researchers intentionally achieved almost identical final imaging functions, also called optical transfer functions (OTF), for different cases of depth, thus enabling the PDIP to be more manageable.

2.3 OTF Limitation 2

OTF inverse ability) In order to understand the way how the PDIP operates, the OTF must first be explained. The OTF defines how an object transfers on to an image, which can be either focused or mis-focused. Therefore, the inverse of the mis-focused OTF can transform the mis-focused image back to the recovered original object. Additionally, the forward counterpart (the focused OTF) can be applied once more in order to transfer the recovered original object back to the desired focused image. In summary (put together), the desired transformation from a mis-focused image to the desired focused image, as defined in the reasoning above, is actually the ratio between the focused and mis-focused OTFs. To be more specific, in the ratio mentioned above, the inverse is the denominator and the forward counterpart is the numerator. This ratio (the desired transformation) is also exactly what the PDIP tries to achieve. Finally, the limitation to the PDIP ratio (OTFfocused/OTFmis-focused) is clear now: the denominator (OTFmis-focused) cannot be zero.

2.4 Limitation on Plate from OTF Limitation

The misfocus phenomenon can be understood by conceptually having an equivalent individual phase distortion plate according to the corresponding misfocus degree against the imaging lens in the imaging process. In this sense, there are different conceptual phase distortion plates for different misfocus levels.

OTF is the correlation of the pupil function. Pupil plates. In contrast to the strong deteriorating phase plate, we suggest replacing it with an improving plate to avoid the post digital image processing. This plate can improve the general defocus of the image. The improvement is not significant but good enough for many applications that do not require a high standard of visual quality, such as those used for entertainment purposes. Without the need for post digital image processing, not only would this consume no time and resources, but it would also reduce many limitations in optimization when designing the improvement plate. A limitation to the PDIP's ratio (OTFfocused/OTFmis-focused) is that the denominator (OTFmis-focused) cannot be zero. It is important to emphasize that a distortion phase plate is involved in computation (determine the computation result) of the OTFmis-focused since both solutions mentioned so far (deteriorating and improving approach) require phase plates to accomplish multi-focus imaging purpose. Consequentially, this will put a limitation on researchers when designing the distortion phase plate. Likewise, the improving plate determines the computation result of the OTFmis-focused_ improving. This OTF is the exact imaging function that transforms the object to the image. This freedom in limitation enables us to have a better imaging effect when designing the improvement plate. For example, in our design we do not need to make the inverse methods the same and hence do not to need to worry about the null points existing in the inverse method since there is no inverse method for us at all. As a summary, no computation and better imaging effect due to the omission of PDIP leads to new applications of multi-focus imaging such as the inexpensive microscope systems with extended depth of field applications mentioned in the previous section.

3. DESIGN METHOD

We will attempt to keep mathematics to a minimum in this part and to try rather to provide a basic understanding of the Optical Transfer Function (OTF) concept. In principle, if we know the OTF of an imaging system, we can predict exactly what the image of a given object will look like. One of the main advantages of using OTF is both to specify and evaluate the performance of an imaging system.

It can be shown that the OTF of an optical system can be determined from the autocorrelation of the pupil function as below:

$$OTF(u,v) = \frac{TT\_P(x,y)P^*(x-u,u-v)dxdy}{TT\_\,|P(x,y)|^2\ dxdy} \qquad (2.1)$$

where P(x,y) is the pupil function given by:

$$P(x,y) = \begin{cases} \exp\{ikW_{20}(x^2+y^2)\}, \sqrt{x^2+y^2}\,J\,1 \\ 0, otherwise \end{cases} \qquad (2.2)$$

Computing the OTF can be thought of as an evaluation about a fixed pupil with the other moving around. The offset of the two pupils can be understood as the special frequency of interest, as shown in Figure 1. The effective integration range for computing OTF at the given frequency (u,v) is the overlapping area.

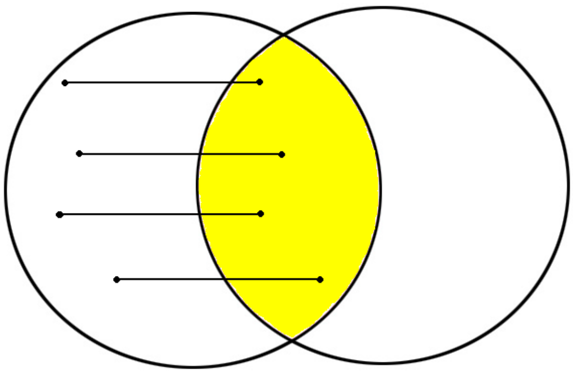


Fig. 1 – The schematics for computing the OTF at the frequency (u,v): the frequency (u,v) determine the offset of the pupil circle, the yellow overlapping area is the integration area, and the segments denotes the product of optical transmittance in the equation (1).

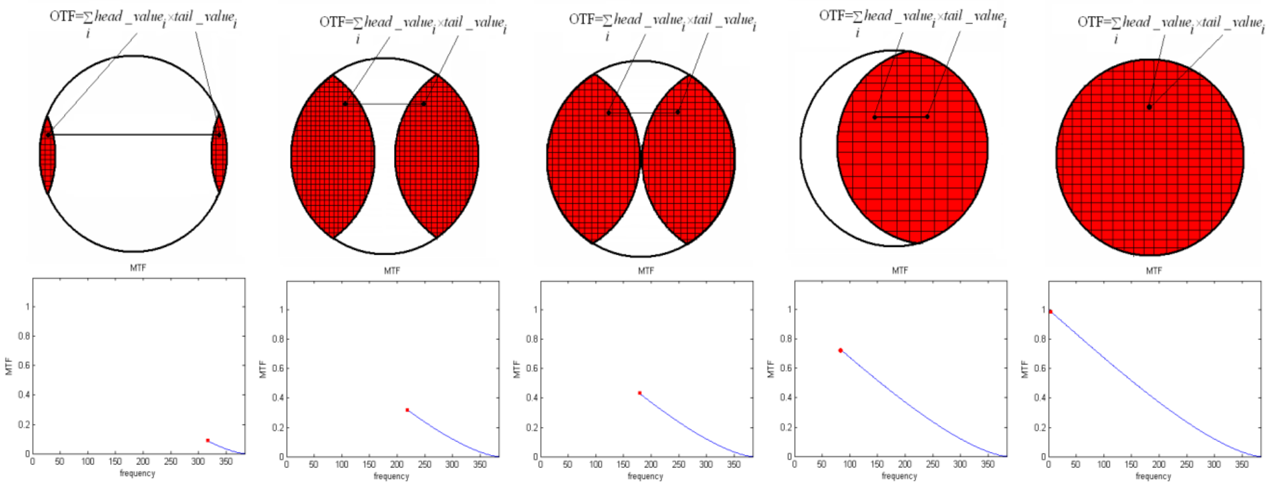


Fig. 2 – An example of computation progression in frequency

$$OTF_{screen}(u,v) = K_0 \sum_{i=1\sim100} e^{iF_h(x_i,y_i)+kW_{20}(x_i^2+y_i^2)} e^{iF_t(x_i-u,y_i-v)+kW_{20}((x_i-u)^2+(y_i-v)^2)} =$$
$$= K_0 \sum_{Egg\, i=1\sim90} e^{iF_h(x_i,y_i)+kW_{20}(x_i^2+y_i^2)} e^{iF_t(x_i-u,y_i-v)+kW_{20}((x_i-u)^2+(y_i-v)^2)} +$$
$$+ K_0 \sum_{Ring\, i=91\sim100} e^{iF_h(x_i,y_i)+kW_{20}(x_i^2+y_i^2)} e^{iF_t(x_i-u,y_i-v)+kW_{20}((x_i-u)^2+(y_i-v)^2)} = K_0(E+B) \quad (2.3)$$

The basic principle of the Optical Transfer Function (OTF) computation can be explained by an example of its progression in frequency. It is important to note that the distance between the two pupils depends on the frequency (opposite), indeed a higher frequency will involve a smaller period, and the two pupils will be overlapping more to each other. As shown in the computation progress example in the Figure 2, when the

frequency is decreasing, the displacement is accordingly decreasing, causing the overlapping area increasing, finally causing the Modulation Transfer Function (MTF) for a common imaging system increasing too. This explains the descending shape of the MTF.

The computation of OTF has to follow some rules regarding which points to take or not. Indeed, when it comes to the calculation of the OTF, we need values from current iteration or last iteration. Our computation needs to make sure that we give the priority to the current iteration.

It is shown in Figure3 where is the different area that we are working on. As it has already be said, (x, y) can be regarded as the head points defining the head area (red), and (x-u, y-v) can be regarded as the tail points defining the tail area (green). Then, the designed

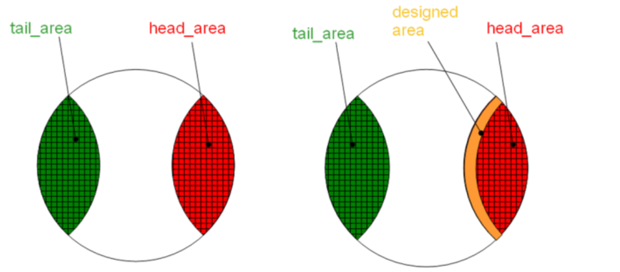


Fig. 3 – Schemes for illustrating the design area in the incremental strip for the working frequency.

area (orange) which is part of the head area corresponds to the area we need to get the value to make the final screen. In this case, we assume that the designed area is the same as the incremental area.

The optical transfer function of our screen, as a function of refocusing to satisfy the basic from Equation 1.2, in an optical imaging system can be represented in the following form in Equation 2.2 :

It is noted that E and B in Equation 2.3 are the constants determined from the previously already designed green area and the now designing strip respectively. In other words, E is the variable to be determined by the phase value arranged for the strip at that designing moment. In this computation we also introduced the concept of the weight, aimed at various out of focus we give different weights, during the movement of the computation the value can be the treatment from various out of focus.

So we hope that for cases where the out of focus is more severe, we can get a good result effect. Indeed loss of focus for the more serious cases gives more weight, hoping to get one of the best in the final screen. The design approach of our final screen is shown in

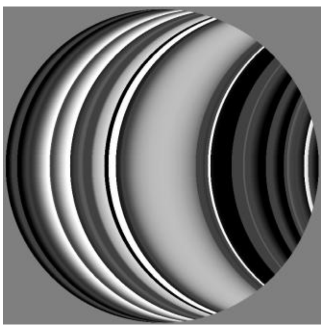


Fig. 4 – The accomplished phase plate by our design method.

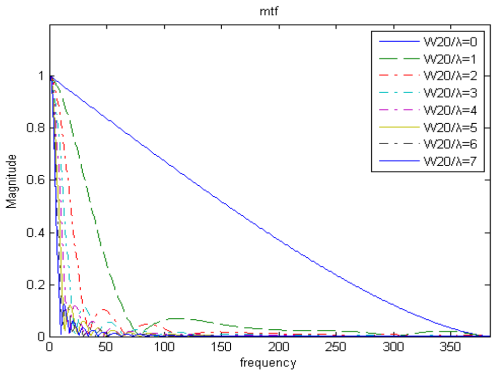
Figure 4, due to a computation of a strip of value, the appearance presented in Figure 4 corresponds to a stripe distribution.

4. SIMULATION RESULTS

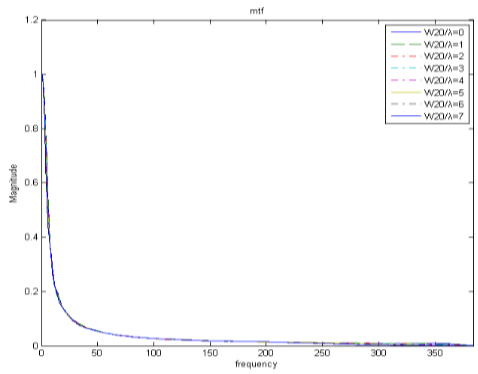
We experimentally demonstrated the performance comparison with two other imaging systems for our proposed scheme in this section. We first compare the imaging function OTF and then compare the visual effects in images.

4.1 OTF Comparison

We evaluate numerically the OTF for our proposed phase masks.



a



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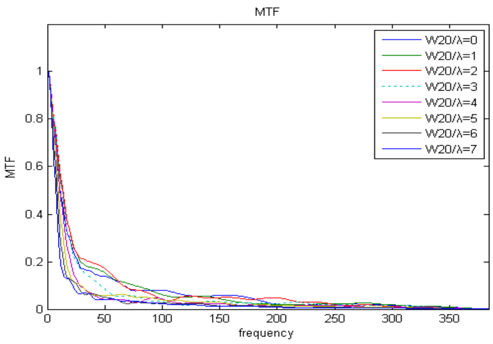


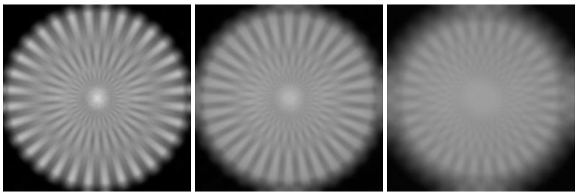
c

Fig. 5 – OTF comparison on their magnitude MTF: (a) without phase plate (b) with cubic phase plate (c) with the proposed phase plate.

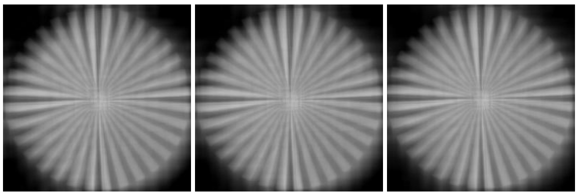
The first set is obtained by use of a standard incoherent imaging system without phase plate, and the second and the third set are obtained with the same system but with the conventional cubic phase plate and the proposed plate respectively at its exit pupil.

4.2 Example of Simulated Imaging

To demonstrate the imaging effect, we compare three sets of computer-simulated images of a spoke target for the three different imaging systems with different defocus parameter values specified as above. It is apparent from these figures that the proposed phase profiles do extend the depth of field.



a



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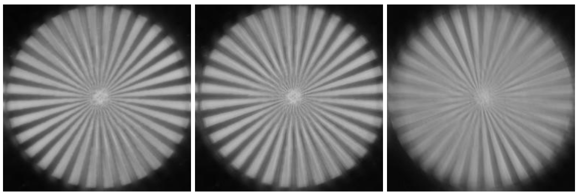

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Fig. 6 – Visual comparison for mis-focus w20/wavelength = 2,3.5 from left to right respectively (a) without phase plate (b) with cubic phase plate (c) with the proposed phase plate.

5. CONCLUSION

The current image correction method uses a deteriorating phase plate, followed by the energy consuming Post Digital Image Processing (PDIP), in order to obtain a good image quality. Without more processing, this method would only reach a very poor visual quality caused by the necessary phase deteriorating plate. In other words, the conventional methods must go through a strong deteriorating phase plate before processing to fix the muti-focusing problem. This is to ensure that all images have approximately the same mis-focus, before beginning the Post Digital Image Processing. The same optical transfer functions make the post digital image processing manageable. Therefore, the deteriorated images can be fixed by a same inverse method digitally. This post-processing generally requires at least two dimensional forward Fourier transform and inverse Fourier transform and hence is computationally intensive.

The new proposed method would use an improving plate instead of the deteriorating plate, thus, obtaining an "OK" visual without any energy consumption. The design of this improving plate is possible by removing the design limitation due to the PDIP, which previously bounded the deteriorating phase plate's design. Our phase plate is composed of many concentric rings. We design the phase of the ring with an associated optical frequency. We further associate each frequency with a corresponding depth of field. We therefore achieve our design methodology: each strip with a purpose for fixing one kind of mis-focus.

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