Design of Freeform Phase Plate Pairs for Variable Extended Depth of Field in Imaging Systems

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Abstract: Increasing depth of field is highly beneficial, particularly for high NA imaging systems. We discuss approaches to enable variable, extended depth of field through relative movements between pairs of freeform surfaces.

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1. Introduction

Increasing depth of field (DoF) in imaging systems is of special interest, particularly for applications such as microscopy that require high numerical aperture (NA) and have correspondingly short DoF. Researchers have previously demonstrated the concept of extended depth of field (EDoF) using cubic or logarithmic phase plates [1-2]. Figure 1 shows a comparison between through-focus spot diagrams of two optical systems. Implementing a fixed cubic phase plate in front of the lens makes the spots larger but less sensitive to defocus, as expected. These phase components alter the point spread function (PSF) of the optical system so that it is invariant with respect to defocus. Logarithmic phase plates have been shown to provide better EDoF performance than cubic phase plates [2].

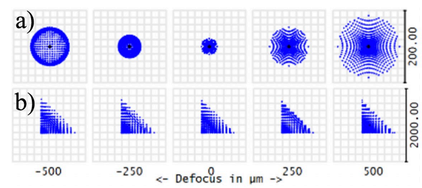

Fig. 1. Through-focus spot diagrams for: a) F/4 lens, b) F/4 lens with cubic phase plate.

Such phase plates are generally designed for a specific optical system, so a different phase plate must be made for each system. Thus, methods that can enable variable EDoF for different systems are very beneficial. Previous work has been done to enable EDoF with variable performance, for example, using deformable mirrors [3] and liquid lenses [4]. Researchers have also previously demonstrated variable EDoF through, for instance, a controlled relative rotation [5] or lateral shift [6] between pairs of phase plates.

In this paper, we explore the design of pairs of freeform surfaces that can enable variable EDoF for different optical systems through a relative shift of freeform surfaces, conceptually similar to the approach used by Alvarez [7] to create a variable focal length lens through lateral relative motion between two cubic surfaces (Fig. 2). In particular, we discuss the design and EDoF performance of variable logarithmic phase plates (VLPP) based on laterally translated pairs of freeform surfaces.

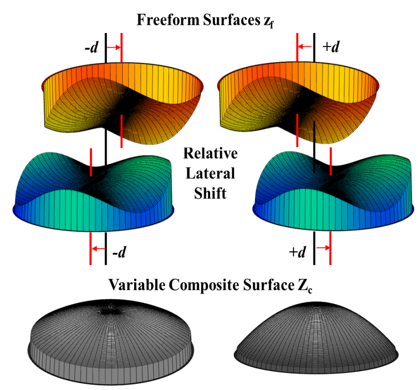

Fig. 2. General demonstration of two freeform surfaces with a controlled relative shift creating a variable composite wavefront.

2. Methods and Discussion

Hellmuth *et al* [6] previously demonstrated pairs of quartic surfaces for generation of a variable cubic wavefront for EDoF. We build on this work and previous work on fixed logarithmic phase plates by Sherif *et al* [2] by exploring approaches to realize variable *logarithmic* phase plates, which should result in improved performance. The surface description for the fixed logarithmic phase plate is given by [2]:

$$f(x,y) = sgn(x)\alpha x_{max}^2 x^2(log|x| + \beta) - \frac{u' x_{max} x}{z_i} + sgn(y)\alpha y_{max}^2 y^2(log|y| + \beta) - \frac{v' y_{max} y}{z_i} \quad , \qquad (1)$$

where α and β are surface parameters, x_{max} and y_{max} are the half-widths of the aperture, $u'$and v' are arbitrary points in the image plane and z_i is the image distance. The surface parameters are optimized for a specific imaging system.

To design the freeform phase plate pair for variable performance, we start with an x-y polynomial fit to the surface of a fixed logarithmic phase plate (Fig. 3). The equation for the polynomial is given by:

$$P(x,y) = \sum_{m=0}^{10} \sum_{n=0}^{10} P_{mn} x^n y^m \, , \qquad (2)$$

where P_{mn} are polynomial coefficients. This process is repeated for multiple fixed logarithmic surfaces with different surface parameters across the desired performance range. The resulting set of surfaces is represented by the variable composite surface Z_c in Figure 2. Next, the equation for the freeform surfaces, Z_f, which produce a variable composite wavefront through the small relative shift of the surfaces, is derived using a derivative relation introduced by Palusinski *et al.* [8] and expanded on by Smilie *et al* [9].

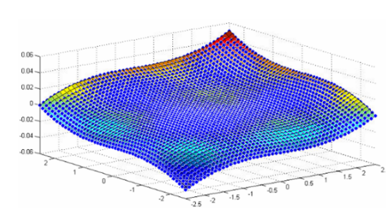

Fig. 3. XY polynomial fit to a fixed logarithmic phase plate surface.

3. Example

As an example, Figure 4 shows through-focus spot diagrams for a VLPP placed in front of a F/4 lens with an object at infinity (λ=587.56 nm) for different amounts of lateral relative shift. The comparison between through-focus spot diagrams show that with the VLPP implemented, the spots are less sensitive to defocus and maintain their size and shape. More importantly, different amounts of shift result in differing EDoF performance, which suggests that one set of freeform phase plates can be used to create optimized EDoF conditions for multiple optical systems.

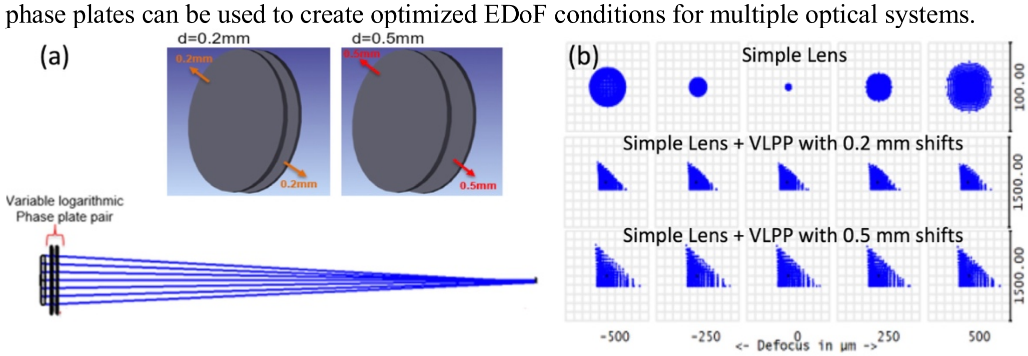

Fig. 4. (a) VLPP optical system; (b) Sample through-focus spot diagrams for different VLPP configurations.

4. Acknowledgments

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5. References

[1] E. R. Dowski and W. T. Cathey, "Extended depth of field through wave-front coding," Appl. Opt. 34, 1859-1866 (1995)

[2] S. S. Sherif, W. T. Cathey, and E. R. Dowski, "Phase plate to extend the depth of field of incoherent hybrid imaging systems," Appl. Opt. 43, 2709-2721 (2004).

[3] W. Shain, N. Vickers, B. Goldberg, T. Bifano, and J. Mertz, "Extended depth-of-field microscopy with a high-speed deformable mirror," Opt. Lett. 42, 995-998 (2017).

[4] S. Liu and H. Hua, "Extended depth-of-field microscopic imaging with a variable focus microscope objective," Opt. Express 19, 353-362 (2011).

[5] M. Demenikov, G. Muyo, and A. R. Harvey, "Experimental demonstration of continuously variable optical encoding in a hybrid imaging system," Opt. Lett. 35, 2100-2102 (2010).

[6] T. Hellmuth, A. Bich, R. Börret, A. Holschbach, A. Kelm, "Variable phaseplates for focus invariant optical systems," Proc. SPIE 5962, Optical Design and Engineering II, 596215 (2005).

[7] L.W. Alvarez, "Two-element variable-power spherical lens," U.S Patent 3,305,294 (1967).

[8] I. A. Palusinski, J. M. Sasián, and J. E. Greivenkamp, "Lateral-shift variable aberration generators," Appl. Opt. 38, 86-90 (1999).

[9] P. J. Smilie and T. J. Suleski, "Variable-diameter refractive beam shaping with freeform optical surfaces," Opt. Lett. 36, 4170-4172 (2011).