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Efficient Fresnel zoneplate pattern data preparation for high-resolution nanofabrication

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A R T I C L E I N F O

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A B S T R A C T

A Fresnel zoneplate is a diffractive optical element consisting of concentric rings (zones) for which the transmitted light produces a focal spot that is used in all wavelength regimes, including X-rays. The pattern of transmission openings determines the location of the spot and the sub-half wavelength size of the openings can adjust the intensity. Today, very general transmission zoneplate patterns are used for many special imaging and image compensation purposes. Manufacturing zoneplates require a zoneplate pattern file, which precisely describes the size, shape, and contour of the rings based on the desired optical properties of the lens. Generating such a pattern requires the delicate balance of achieving the required optical performance while maintaining manageable file sizes and computation times. Here we describe a new algorithm meeting these needs. By precisely controlling the number of shapes in each zone, the algorithm simultaneously optimizes the desired optical tolerances with the pattern file size.

1. Introduction

The Fresnel zoneplate is an imaging element widely used by the X-ray and extreme ultraviolet (EUV) communities. In the soft X-ray regime, Fresnel zoneplates enable the possibilities for biological imaging and material science study into sub-10 nm regime [1]. In the past, papers regarding high-resolution zoneplates have mostly focused on optimizing the fabrication process conditions, rarely mentioned the detail of their pattern data preparation algorithm [2–4]. In this paper, we focus on the zoneplate pattern generation algorithm which can generate the desired zoneplate pattern and properly render it to a pattern file based on designed optical properties [5]. Fig. 1 shows the general process flow of our algorithm. In the first section, we describe the generation of the target zoneplate pattern under various settings. Next, we discuss fracturing the zoneplate pattern to meet fabrication requirement and optimize its file size and computation time. Finally, we present a few fabrication examples using the new algorithm.

2. Fresnel zoneplate pattern generation algorithm

2.1. Zoneplate radii calculation algorithm

To calculate the zoneplate pattern, we need to define the zone radius at every point on the zoneplate to determine its contour. Fig. 2 shows the process flow to determine the zone radius based on zone number (n), object distance (p), image distance (q), wavelength (λ), and also the aberration/phase contrast condition using the Secant method. In numerical analysis, the secant method is finite difference approximation of Newton's method for finding the zero crossing of a function.

Since the function used in the zoneplate is the optical path difference (OPD) for the complete optical system, an initial guess is needed for the Secant method to determine the correct zone radius. For our algorithm, we start with the assumption in the simple idea circular zoneplate lens as shown in Fig. 2. With this initial guess, the non-ideal OPD for the combination of geometry, aberration, and phase contrast is used to define a difference metric. The secant sequential iteration method is then used to sequentially find new roots (zero estimates) for this metric that converges to the spatial location on the zoneplate where the metric is zero.

$$Metric = (OPD_{geometry} + OPD_{aberration} + OPD_{phase\_contrast}) - OPD_{zoneplate}. \quad (1)$$

This algorithm enables the possibility to (1) include arbitrary aberrations in the pattern calculation, and to (2) determine the balance between precision in locating the zone and computation time.

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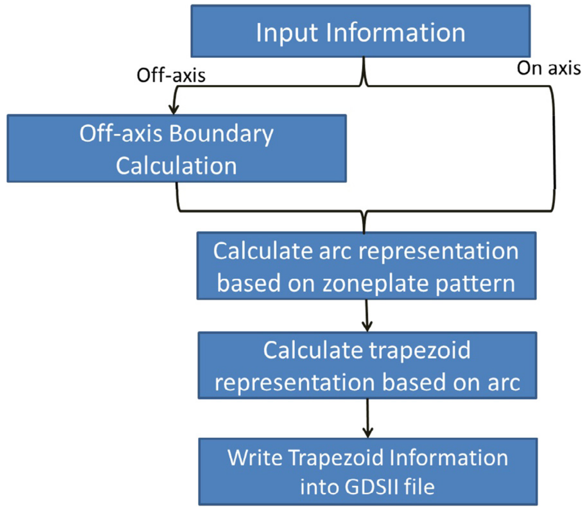

Fig. 1. The overall process flow of the zoneplate pattern generation algorithm.

2.2. On-axis/off-axis zoneplate

The process flow to determine a conventional on-axis zoneplate pattern is shown in Fig. 3. With design information like object distance, image distance, the numerical aperture (NA) and the wavelength, one can calculate the location, the width and the total number of the zones based on the equations shown in the previous section.

Off-axis zoneplates are useful for separating the zero order from the image forming orders and are used for the EUV mask reflection microscopy at Lawrence Berkeley National Laboratory [6]. In our algorithm, there is an extra step for the off-axis zoneplate compared to the on-axis zoneplate as shown in Fig. 3. The algorithm first calculates the opening angle for each zone based on the user-defined boundary condition and then generates the zoneplate pattern as done for the conventional on-axis zoneplate. Fig. 4 shows the GDSII pattern image of an off-axis zoneplate on top of its parent on-axis zoneplate.

2.3. Tilted zoneplate

For tilted zoneplates, the zoneplate orientation is no longer normal to the optical axis, but each zone on the zoneplate still has to image the object to the same image plane position. Eq. (2) shows the OPD calculation for a standard zoneplate:

$$OPD = (\sqrt{p^2 + r^2} - p) + (\sqrt{q^2 + r^2} - q). \tag{2}$$

Here p, q, r represent the object distance, the image distance and the zone radius before tilt. For tilted zoneplates, these parameters have to be adjusted accordingly. Fig. 5(a) shows the schematic diagram of a tilted zoneplate and the adjustment required to Eq. (2). The tilted zoneplate which has the imaging capability based on p and q will be stretched on each side of the zoneplate as shown in Fig. 5(b). In order to incorporate the tilted zoneplate situation into the pattern generation code, our algorithm adjusts the OPD definition as shown in Fig. 5(a) in the same process flow as for conventional on-axis zoneplate.

2.4. Phase contrast/aberration zoneplate

In general, the zone position is determined by the OPD including the geometric terms, aberration and phase contrast as shown in Eq. (3):

$$OPD = Geometric + Aberration + Phase\_Contrast. \tag{3}$$

Zernike phase contrast is readily achieved in zoneplates by shifting the zones in the Zernike phase shift region to achieve a 90° relative phase shift. As shown in Eq. (1), the OPD for a standard zoneplate is in the range of half wavelength which can be transferred to 180° phase shifts. For phase contrast zoneplate with 90° phase shifts, our algorithm has to include quarter wavelength into the OPD calculation to account for the phase difference. As shown in Fig. 6(a), the shifts of the zone from its original position create the relative phase shifts between these 2 areas.

A similar approach can be applied to aberrations. Each point on the zoneplate has its own relative phase shift based on the input aberration condition. Thus the algorithm adjusts the OPD calculation accordingly to satisfy the condition at each location. For the pattern generation algorithm, the input aberration map consists of a Zernike polynomial representation [7]. Thus it can be used to prescribe not only the single aberration term onto the Fresnel zoneplate, but also more realistic aberration situations. Fig. 6(b) shows the result of defocus aberration with a weight of half wavelength.

2.5. Apodization/free-standing zoneplate

Apodization is used to filter or modify the transmission function of optical elements [8,9]. In order to achieve this in the algorithm, we add blocks to the ring-shaped zoneplate to prevent the light from passing through the zoneplate, instead of varying the zone width (duty cycle) which might be limited by the fabrication capability. Based on the designed transmission condition in each zone, we can calculate the percentage of the zone area that needs to be blocked, and then randomly (but with uniform density) distribute the blocks to each zone as shown in Fig. 7(a). Stronger apodization means lower transmission which leads to more blocks in each zone. For a constant apodization to be applied to a specific area of the zoneplate, blocks are randomly (but with uniform density) distributed in each zone. Fig. 7(a) shows the comparison between a standard zoneplate and a zoneplate with constant apodization.

To improve zoneplate efficiency, zoneplates can be fabricated as free-standing structures instead of onto a membrane. In order to support the arc-shaped zoneplate structure, bridges are required as shown in Fig. 7(b) to hold the structure together. In the algorithm, the addition of these bridges is similar to the apodization process. Moreover, the algorithm supports the random distribution of the bridges preventing the unexpected frequency filtering by the Fresnel zoneplate.

3. Fresnel zoneplate pattern rendering algorithm

3.1. Arc-shaped representation of the zoneplate pattern

Having a desired Fresnel zoneplate pattern, the design must be transferred into a file that can be read by lithography tools to fabricate the zoneplate. In order to achieve this, we need to find a proper representation of the zoneplate design using arcs or polygons. Therefore, an algorithm to render the zoneplate pattern is needed to balance the trade-off between file size (computation time) and precision of the polygons/arcs representation.

Fig. 8 shows the process flow of fracturing the zoneplate pattern with arcs and the definition of the arc parameters for the zoneplate pattern representation. We start with an initial opening angle for the pattern. Then we use 3 sets of coordinates from this zone pattern to define the arc. Along the contour of the zone pattern and the arc, we compare the coordinate difference between them and check it within the user-defined tolerance. If it is within the range, the algorithm extends the opening angle to seek the opportunity using this arc to represent a larger zoneplate pattern. If not, then a smaller opening angle is used to check the condition again. This helps us minimize the number of arcs to represent the zoneplate pattern. With this algorithm, conventional zoneplates with a perfect circular shape can be represented by 1 arc (opening angle = 360°) as expected. Other zoneplates with exotic design will have its optimum number of arcs.