Optics Communications 381 (2016) 365–370

Contents lists available at ScienceDirect

Optics Communications

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

A new method to optimize the azimuth angle of elements in a projection lens

Chunlai Liu*, Hongbo Shang, Yang Zhao, Ping Wang, Quansong Li, Shudong Men

Engineering Research Center of Extreme Precision Optics, State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Science, Changchun 130033, China

ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form
9 July 2016
Accepted 9 July 2016

Keywords:
Photolithography lens
Azimuth angle optimization
Surface figure error
Wavefront aberration

ABSTRACT

In the manufacturing process of high-precision photolithography lens, clocking of lens element is a commonly used and efficient method to compensate the surface figure error. This method obtains the optimal azimuth angles of a lens element. With complex description of the surface figure error, developing a mathematical model to optimize the azimuth angle of the element is difficult. This work expresses the surface figure error and wavefront aberration of a lens system with Zernike polynomials. Results indicate that the surface figure error is linearly correlated with the induced wavefront aberration at any point field of view. Thus, a mathematical model adopting this linear relationship is proposed to optimize the azimuth angles of a lens element. Employing the proposed mathematical model, the optimization keeps good efficiency and precision. The clocking optimization instance confirms that the mathematical model is effective for clocking optimization.

1. Introduction

To achieve near-perfect image quality, photolithography projection lens almost utilize the limit level of manufacturing but still cannot meet the rigorous demands. Thus, multi-compensation strategies must be employed to further enhance the quality of photolithography lens [1–3]. Rotation of the element is one of these methods, and this strategy has been used to compensate the surface figure error with two dimensions (2D). The most crucial task of the compensation process is to determine the optimal azimuth angle of the lens element.

Because of the complexity of the 2D error, it is difficult to obtain convergence for the optimization. Thus, lens designers usually rotate the lens element manually to determine the optimal azimuth angle. However, this technique results in low efficiency and precision. To achieve automatic optimization of the azimuth angle, an approximate mathematical model was proposed to calculate the induced aberration of photolithography lens caused by surface figure error. This model equates the surface figure errors to the transmitted wavefront errors and the superimposed transmitted wavefront errors on a single field of view (FOV) point was considered as the induced aberration of lens. However, meeting the compensation demand of photolithography lens is difficult because of the lower accuracy of the model [4]. To improve the precision, a model adopting commercial optical design software to calculate the induced aberration was proposed, and Particle Swarm Optimization (PSO) algorithm was utilized to determine the optimal azimuth angle. The precision of the model was equal to the precision of commercial software. However, it needs a longer computation time for commercial software to evaluate the quality of a lens with errors and it means a longer searching time because of the innate character of PSO algorithm [5]. Thus, the present work proposes a new mathematical model that employs the sensitivity of the 2D error to calculate the induced aberration of photolithography lens. This model improves the search efficiency and maintains good accuracy.

A 2D error mentioned in the paper only denotes low frequency of the surface figure error. The surface figure error is usually expressed with a Zernike polynomial, which is orthogonal in a round area. Sensitivity refers to the aberration induced by an element surface figure error that can be expressed with one unit term of a Zernike polynomial. Usually, the element surface figure error of the photolithography lens is close to 1 nm RMS (Root Mean Square). In this level, the element surface error exhibits a linear relationship with the induced aberration. On the basis of the linear relationship, the current work proposes a model that calculates the induced aberration caused by the 2D error. The use of this model in clocking optimization results in improved accuracy and efficiency.

* Corresponding author.
E-mail address: lcl8627@163.com (C. Liu).

http://dx.doi.org/10.1016/j.optcom.2016.07.024
0030-4018/

2. Sensitivity

Surface figure error is generally expressed with Zernike polynomials because these polynomials are composed of terms similar to the types of aberrations often observed in optical tests. Zernike polynomials are presented in a simple form, and competent for representing 2D data in a round zone. These polynomials exhibit simple rotational symmetry properties and satisfy the requirement that the form of the polynomial does not change when the coordinate system is rotated by an angle. Thus, a Zernike polynomial particularly in a polar coordinate is the most suitable for the algorithm of rotation. The polar coordinate expression of Zernike polynomials is described as follows:

$$w_z(\rho,\theta) = \sum_{p=0}^{\infty}\sum_{q=0}^{p} c_{pq}Z_p^q(\rho,\theta) \tag{1}$$

where c_{pq} is the coefficient of the Zernike polynomials and (ρ, θ) is the coordinate of the points. Therefore, for one point, w_z represents the summary of contributions of the many terms of Zernike polynomials, and each contribution demonstrates a linear relationship with the coefficient of the term. Fringe Zernike Polynomials is a subset of Eq. (1), but has a different order [6–8]. This paper uses the order of Fringe Zernike Polynomials.

Photolithography lens exhibit a large field of view and generally select several points on the object field or on the image field to evaluate the quality of the lens. The illuminated portion of an optical surface for one field of view point is called footprint [9]. The footprint area of the different field of view point on the same optical surface varies. The Fig. 1 shows the footprint of several field points along a radial line.

The surface figure error on the footprint area of the optical element induces error to the transmitted wavefront of a specific field of view point. Their relationship can be expressed as follows:

$$w_s = (n-1)SE \tag{2}$$

where w_s is the transmission wavefront error, SE is the surface figure error, and n is the refractive index of the element material. In this paper, Zernike polynomials are used to describe SE, m is the number of surfaces of the objective lens and the refraction angle error caused by the surface figure error is disregarded. For a single field of view point, wavefront aberration W can be expressed as follows:

$$W = \sum_{s=1}^{m}\left((n_s-1)\sum_{p=0}^{\infty}\sum_{q=0}^{p}\left(c_{spq}Z_p^q(\rho,\theta)\right)\right) = \sum_{s=1}^{m}\sum_{p=0}^{\infty}\sum_{q=0}^{p}\left((n_s-1)c_{spq}Z_p^q(\rho,\theta)\right) \tag{3}$$

where (ρ, θ) is the coordinate of the points on the footprint area of the optical surface and c_{spq} is the coefficient of the Zernike polynomials of the sth surface figure error. Two conclusions can be drawn from Eq. (3). First, wavefront aberration can be considered as the superposition of the wavefront error induced by each Zernike term of every surface figure error and these can be described as superposition characteristic. Second, the size of the wavefront error induced by each Zernike term of every surface figure error demonstrates a linear relationship with the Zernike coefficients and these can be described as linearship characteristic.

The above conclusions can be verified by an example. The optical structure of a patent photolithography lens is described in Fig. 2. The main specifications are shown in the Table 1.

The lens has a rectangular field. The image field size is 26 mm × 10.5 mm. There are 20 elements and 40 optical surfaces in the lens. Using the commercial optical design software CodeV, surface figure error containing only the Z5 term (the fifth Fringe Zernike term) is assigned to the seventh surface, and the coefficient of Z5 increased regularly from 1 nm to 10 nm. The induced wavefront aberration of the 3 × 7 field of view points on the image plane is analyzed and extracted from CodeV. The wavefront aberration can also be described with Zernike polynomials, and Fig. 3 presents the value and distribution of Z5 and Z7 coefficients of the wavefront aberration of the 3 × 7 field of view points on the image plane as the surface figure error of the seventh surface increases and the grey scale means the value of Z5 and Z7 coefficients.

As shown in Fig. 3, the Z5 and Z7 coefficients of the wavefront aberration retain the same distribution form along the image field as the Z5 coefficient of the surface figure error increases, and the sizes of these coefficients increase gradually.

The Pearson correlation coefficient that could be calculated by Eq. (4) is used to evaluate the strength of linear association between two variables. In this paper, we calculate the Pearson correlation coefficient for each field of view points between Z5 coefficient of surface figure error and Z5 and Z7 coefficient of induced wavefront aberration.

$$r = \frac{n\sum_{i=1}^{n}x_iy_i - \sum_{i=1}^{n}x_i\sum_{i=1}^{n}y_i}{\sqrt{n\sum_{i=1}^{n}x_i^2-\left(\sum_{i=1}^{n}x_i\right)^2}\bullet\sqrt{n\sum_{i=1}^{n}y_i^2-\left(\sum_{i=1}^{n}y_i\right)^2}} \tag{4}$$

Table 2 and 3 shows the Pearson correlation coefficients for Z5 and Z7 coefficients. As the Z7 coefficients are nearly zero at the line field of view points when X=0, the Pearson correlation coefficients cannot be calculate by Eq. (4), but it also can be treated as linear relationship. The Pearson correlation coefficients of the other field of view points are 1or −1, and it means that the surface figure error has a perfect linear relationship with the induced wavefront aberration.

To clearly exhibit the linear relationship, Legendre polynomials are applied to express each Zernike term of the wavefront aberration of the full field. The 2D Legendre polynomial is orthogonal in a rectangular area, and this polynomial is expressed

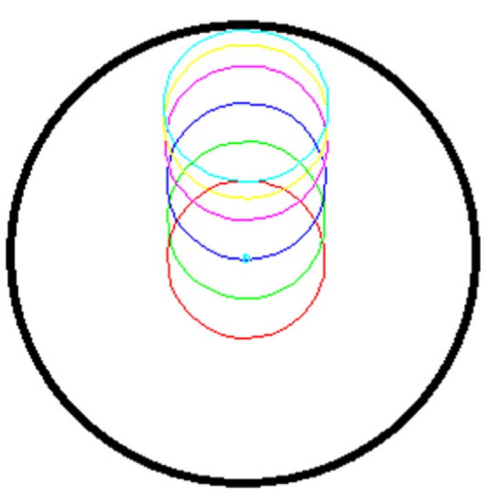

Fig. 1. Footprint of several field of view points on a surface.