Wavefront aberration compensation of projection lens using clocking lens elements

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For extremely high-performance lithographic lenses, the edge level accuracy of the manufacturing process and multicompensation strategies must be applied. Element clocking can be effectively used to compensate for the low-order figure errors of the elements. Considering that commercial optical software is usually incapable of obtaining good convergence for clocking optimization, this paper proposes a mathematical model of a lithographic lens containing the errors of a surface figure, after which a clocking optimization algorithm is programmed. A clocking optimization instance proving that the clocking optimization algorithm is capable of finding the optimized angle of elements and that clocking is an effective compensation strategy. The calculated accuracy of the proposed mathematic model was found to be acceptable for clocking optimization. © 2013 Optical Society of America

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1. Introduction

To narrow down the pattern width of semiconductor devices, the k1 factors in lithography were gradually reduced. In this process, significantly higher performance of exposure tools was constantly required, thus causing the modern manufacturing of an optical and mechanical projection lithography lens to use the limit level. However, some manufacturing errors cannot be avoided. Because of the difficulty in meeting the requirements of imaging performance, solutions for compensation must be used to improve imaging quality [1–3]. The deviation of the radius of curvature and thickness of the element as well as the positional deviation of the component assembled are generally adjusted using eccentric and axial compensators [1]. The surface figure of elements is an important source of error that degrades the imaging quality of the projection lens, and only a very small part of the error can be compensated for by decentering and spacing. Furthermore, the clocking of the elements serves an important function.

Several types of optical design software are competent for most design and optimization tasks but show unsatisfactory performance in the rotation angle optimization of elements considering the surface figure, thus hindering the achievement of optimization convergence. This paper considers how the surface figure affects the wavefront error of the projection lens and thus proposes a mathematical model that can be used in the optimization algorithm to determine the appropriate angle of projection of the lens elements. Moreover, a rotation optimization for a specific objective lens system was implemented and gets a better optimization result. A comparison of the optimization model with the optical design software showed relative errors of the model in the optical design software, but these errors do not influence the convergence of the iterations, and the optimization algorithm can still find the correct angles.

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2. Representation of Surface Figure

Clocking aims at compensating for the element surface figure and the measurement errors influence the accuracy of the angles identified by the optimization. With the development of absolute measurement, as well as the study of interference detection errors, figure measurement accuracy has reached subnanometer levels [4,5].

To construct a mathematical model, a simple and unified data representation should be used. The surface figure or the wavefront aberration of the projection lens can be expressed in the form of Zernike polynomials, which have universal applications [3,6]. Clocking compensation focuses on the low-frequency part of the surface figure, thus necessitating the use of Zernike polynomials to fit the figure fully to meet the requirements of clocking optimization. Surface figure errors can be considered as transmitted wavefront errors in the objective lens system. The relationship of the transmitted wavefront error with the surface figure is given by

$$W = \mathrm{SE}/(n-1), \tag{1}$$

where W is the transmitted wavefront error, SE is the surface figure, and n is the refractive index of the optical material. In the mathematical model, the rotation of the projection lens element indicates the synchronized rotation of the figures of the two element surfaces. The change in the Zernike coefficient in the polar form can be easily computed when rotated by an arbitrary angle. The formula used to obtain the coefficient vector $C(\theta)$ after rotating the coefficient C to angle θ is given by

$$C(\theta) = B(\theta) * C, \tag{2}$$

where $B(\theta)$ is the rotation matrix:

$$B(\theta) = \begin{bmatrix} 1 & 0 & 0 & & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) & \cdots & 0 & 0 \\ 0 & \sin(\theta) & \cos(\theta) & & & \\ & & & \ddots & & \\ 0 & 0 & \cdots & \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & & 0 & 0 & 1 \end{bmatrix}. \tag{3}$$

3. Mathematical Model

The mathematical model is the key to the clocking compensation optimization algorithm, which determines the accuracy and efficiency of optimization algorithms. The mathematical model should be capable of simulating the impact of the element surface figure on the projection lens wavefront aberration and reflect the change in the projection lens wavefront aberration after rotation of the elements.

Figure 1 shows the optical structure of a projection lens with 20 optical elements and a numerical aperture of 0.75. The visual field of the object side is 26 mm × 10.5 mm. In Fig. 1, the dark regions of the optical elements are irradiated by the light of a single field of view (FOV) point. The irradiated area of the surface figure errors will be superimposed, thus causing the wavefront aberration deterioration of the FOV point. When lens design errors and element dimensions and assembly errors are not considered, the wavefront aberration of the single FOV point can be equal to the combination of the transmitted wavefront error caused by the irradiated area of its surface figure.

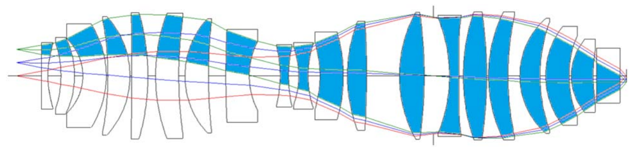

Fig. 1. Optical structure of a projection lens.

Obtaining the transmitted wavefront error of elements corresponding to a FOV point is an important step in establishing the mathematical model. The full aperture transmission wavefront error of the element caused by the surface figure can be obtained through a simple conversion [Eq. (1)] that includes the transmitted wavefront error of a FOV point. In the optical system, the area that the light of a single FOV point irradiated on the surface of an element is called the footprint [7]. Figure 2 shows the footprint of six FOV points on two surfaces. The first surface that is far from the stop has a smaller footprint size, whereas the latter that is close to the stop has a larger footprint that almost occupies the full aperture.

Figure 2 shows that most of the footprints of the element surfaces are not concentric, and the position and size of the footprints differ for the same FOV point on different surfaces. If, regardless of the irradiation uniformity of the footprint, to determine the combination of transmitted wavefront errors of the footprints on different surfaces for a FOV point, the most direct method is to select the same number of discrete points on the footprint and superimpose the transmitted wavefront values of corresponding points on different surfaces. The rms of the superimposed values of the discrete points can then be

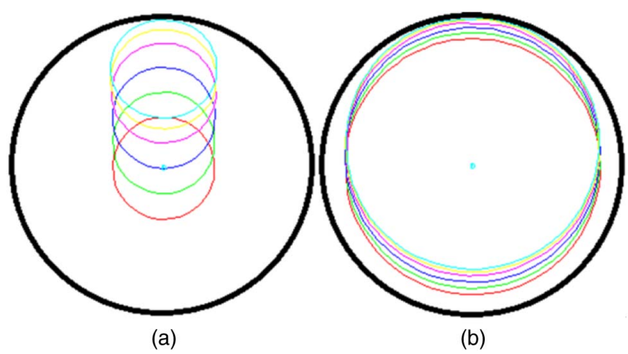

Fig. 2. Footprint of two surfaces: (a) away from the stop and (b) near the stop.

calculated and it is the approximate wavefront aberration of a FOV point that just considers the surface figure error. This process is very similar to the principle of ray tracing. The weighted average of wavefront aberration values of multiple field points is the objective value of the optimization algorithm.

The discretization of Zernike polynomials requires a huge amount of computation and would be incapable of executing the iterations of the optimization algorithm. Consider the characteristics of the footprint of the projection lens. When the element is rotated, the location and size of the footprint of each FOV point does not change relative to the projection lens. Therefore, the first step is the calculation of the Zernike fundamental matrix of the footprint of each FOV point, and these matrices do not change with the rotation of the element. Then the multiplication of the Zernike fundamental matrix of the footprint and the Zernike coefficient vector will yield the footprint discrete transmittance wavefront error data W_D as follows:

$$W_D = B_z * C(\theta), \tag{4}$$

where B_z is a Zernike fundamental matrix of the footprint, and $C(\theta)$ is the Zernike coefficient when rotated to an angle of θ. Figure 3 shows the process of the optimization algorithm. The calculation of the Zernike fundamental matrices requires a great deal of time, but these matrices are calculated before the optimization iterations. The iterative process only requires the multiplication of the matrix and vector, as shown in Eq. (4), thus improving the optimization efficiency significantly.

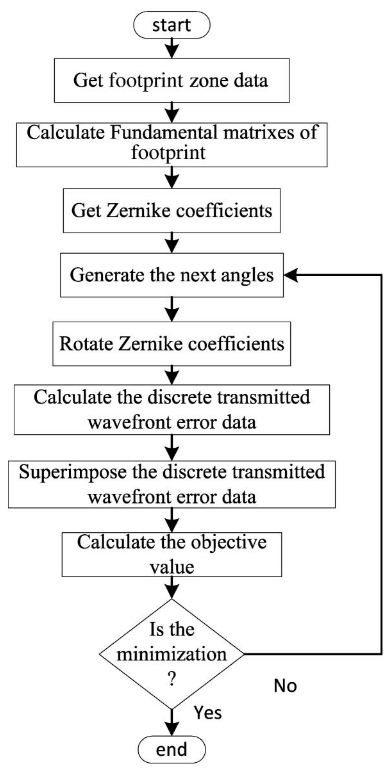

Fig. 3. Process of the optimization algorithm.

4. Optimization Instance and Error Analysis

Based on the process of the optimization algorithm that showed in Fig. 3, a program was developed to optimize the element angles of the projection lens showed in Fig. 1. Figure 4 shows the rms values of transmitted wavefront errors constructed based on the surface figure errors of elements in the projection lens.

Figure 5 shows the wavefront aberration of the exit pupil of the projection lens before optimization, at the center of the FOV (Field 0), half of the FOV (Field 0.5), and the edge of the FOV (Field 1).

A comparison of Figs. 5 and 6 shows that, after clocking optimization, the exit pupil wavefront aberration of the center of the FOV is reduced from 10.19 to 2.94 nm, half of the FOV is reduced from 9.67 to 2.51 nm, and the edge of the FOV is reduced from 9.37 to 2.21 nm. Moreover, after the clocking compensation, most of the nonrotation symmetrical items of the exit pupil wavefront aberrations were compensated for, and the rotation symmetry items became major components. However, most rotation symmetry items may be compensated for by the Z compensators, suggesting that clocking serves an important function

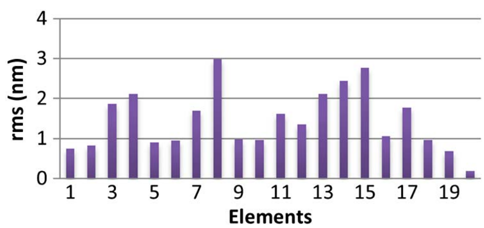

Fig. 4. rms values of transmitted wavefront errors of elements.

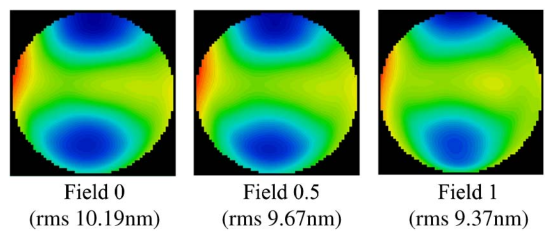

Fig. 5. Exit pupil wavefront aberration of the projection lens before optimization.

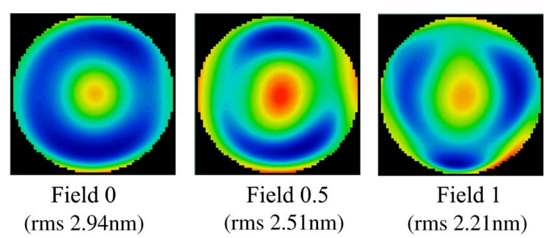

Fig. 6. Exit pupil wavefront aberration of the projection lens after optimization.

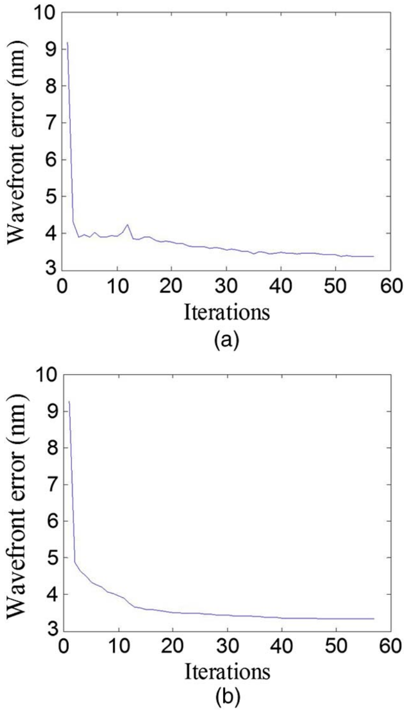

Fig. 7. Contrast of objective values for the iterations: (a) computed by the mathematical model and (b) computed by optical software.

in compensating for the surface figure errors of elements in the projection lens.

Given that the optimization mathematical model of the projection lens is simplified and that the complex distribution of the real rays on the footprint was not considered, some calculation errors cannot be avoided. The objective values computed by the mathematical model for all iterations in an optimization process are then compared with the objective values computed by optical software at the same rotation angle of the elements.

Figure 7(a) shows the convergence curve of the objective values computed by the mathematical model, whereas Fig. 7(b) shows the convergence curve of the objective values computed by the optical software. The presence of the model error caused the objective value computed by the optical software to have some fluctuations despite the fact that the objective value of the optimization model is a smooth convergence. However, the maximum fluctuation range of the objective value is under the subnanometer level and the whole process showed that the convergence was maintained.

The existence of the mathematical model error, the testing error of the surface figure, and the alignment angle error of elements in the manufacturing process cause the deviation of the actual wavefront aberration from the theoretical predictions. However, the clocking compensation method proposed can identify the optimum rotation angle when the elements are assembled, thus reducing the risk of deterioration of the projection lens image quality induced by the complex surface figure error of elements.

5. Conclusions

This paper equates the surface figure errors of an element to the transmitted wavefront errors expressed by Zernike polynomial, considering that a transmitted wavefront error can simply be superimposed on a single FOV point. A mathematical model that can be used for clocking optimization was constructed. An optimization algorithm was then programmed for clocking. This algorithm was used to facilitate an optimization instance for a projection lens with a good result, where 71.6% of the wavefront aberration was compensated for. To assess the impact of the model error, the objective values computed using the mathematical model and those computed by the optical software during the convergence process were compared. The results showed that the calculation error is acceptable for clocking optimization.

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