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High-order wavefront aberration measurement method for hyper-NA lithographic projection lens based on a binary target and rotated regression matrix

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ABSTRACT

A high-order wavefront aberration (HWA) measurement method for a hyper-NA lithographic projection lens based on a binary target with eight directions and rotated regression matrix is proposed. A linear model between the aerial image intensity distribution of the hyper-NA lithographic projection lens and HWAs is built by principal component analysis and regression matrix rotation. Compared to the conventional method using a binary target with six directions, the proposed method improves the efficiency of pupil sampling, increases the modeling speed, extends the measuring range of the wavefront aberrations, and detects the HWAs of the hyper-NA lithographic projection lens accurately. The lithographic simulator PROLITH is used to validate the accuracies of the HWA measurement and analyze the impact of the illumination types of source on the accuracy of the HWA measurement, as well as the polarization rotation of illumination, the sample interval of the aerial images, and the manufacturing error of the test target. The results show that the proposed method retrieves 60 terms of Zernike coefficients (Z_5–Z_{64}) with measurement accuracy greater than $1.03\times10^{-3}\lambda$.

1. Introduction

Optical lithographic tools are highly essential pieces of equipment in the manufacturing of very large scale integrated circuits (VLSIs). A projection lens is one of the most important systems in an optical lithographic tool [1]. The aberrations of a projection lens lead to the deterioration of the lithographic imaging performance [2–4]. As the numerical aperture (NA) of a lithographic projection lens increases to 1.35, the high-order wavefront aberration (HWA) (Z_{38}–Z_{64}) cannot be neglected. Therefore, it is necessary and important to control the HWAs of a lithographic projection lens [5]. Furthermore, it is thus critical to detect the HWAs of a lithographic projection lens.

At present, an aberration measurement technique based on pupil measurement is the primary method for acquiring HWA measurements of a hyper-NA lithographic projection lens. In 2013, ASML developed an aberration measurement technique called Parallel Integrated Lens Interferometer At Scanner (PARIS) [5] that detects the HWAs of projection lens by integrating micro interferometers. The PARIS can detect 64 terms of Zernike coefficients (Z_1–Z_{64}) accurately. However, it is difficult to integrate micro-interferometers, and it requires extra financial resources.

An aberration measurement technique based on aerial images is another widely used technique that has the advantages of being relatively fast, accurate, and inexpensive, compared to other aberration measurement techniques. Some of the typical methods of aberration measurement techniques that use aerial images include TAMIS [6], Z37 AIS [7] and AMAI-PCA [8–14]. However, these methods are only suitable for lithographic projection lenses having an NA less than 0.93. In 2016, our research group improved the AMAI-PCA, and proposed a wavefront aberration measurement method for a hyper-NA lithographic projection lens by using aerial images based on principal component analysis (PCA) (hereafter referred to as conventional method) [15]. It builds the measurement model of a hyper-NA lithographic projection lens by using polarized light and a vector imaging model, as well as considering the polarization properties, and retrieves 33 terms of Zernike coefficients (Z_5–Z_{37}) accurately. Limited by the test target, the measurement model is insensitive to HWAs. Hence, this method is unsuitable to measure HWAs of a hyper-NA lithographic projection lens.

In this paper, we propose a HWA measurement method for a hyper-NA lithographic projection lens, based on a binary target with eight directions and rotated regression matrix. In this method, we establish

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a linear relationship between the aerial image intensity distribution of a hyper-NA lithographic projection lens and HWAs. The binary target with eight directions improves the efficiency of pupil sampling. Furthermore, the aerial image contains information about the HWAs. And the rotated regression matrix increases the modeling speed. The measurement model, which is sensitive to HWAs, is built using the principal component analysis (PCA) and multivariate linear regression analysis of the aerial images. Moreover, the HWAs of the hyper-NA lithographic projection lens are measured accurately. In addition, the impact of the illumination source, polarization rotation of the illumination, sample interval of the aerial images, and manufacturing error of the test target on the accuracy of the HWA measurement are analyzed.

2. Principle

2.1. Test target

According to the Hopkins theory of vector partially coherent imaging [16], the intensity distribution of the aerial image can be expressed as

$$\begin{aligned} I(\hat{x}_i,\hat{y}_i,\Delta z) = \int\cdots\int & J(\hat{f},\hat{g})H(\hat{f}+\hat{f}',\hat{g}+\hat{g}')H^*(\hat{f}+\hat{f}'',\hat{g}+\hat{g}'') \\ & \times[O(\hat{f}',\hat{g}')\mathbf{M}_0(\hat{f}+\hat{f}',\hat{g}+\hat{g}')\mathbf{J_{Jones}}(\hat{f}+\hat{f}',\hat{g}+\hat{g}')\mathbf{E}_0] \\ & \times[O(\hat{f}'',\hat{g}'')\mathbf{M}_0(\hat{f}+\hat{f}'',\hat{g}+\hat{g}'')\mathbf{J_{Jones}}(\hat{f}+\hat{f}'',\hat{g}+\hat{g}'')\mathbf{E}_0]^* \\ & \times\exp\left\{-i2\pi[(\hat{f}'-\hat{f}'')\hat{x}_i+(\hat{g}'-\hat{g}'')\hat{y}_i]\right\}d\hat{f}d\hat{g}d\hat{f}'d\hat{g}'d\hat{f}''d\hat{g}'', \end{aligned} \tag{1}$$

where $J(\hat{f},\hat{g})$ is the effective source function, $H(\hat{f},\hat{g})$ is the pupil function, $O(\hat{f},\hat{g})$ is the diffraction spectrum of a mask, E_0 is the electric field vector at the entrance pupil presenting the polarization type of the illumination source, and $M_0(\hat{f},\hat{g})$ is a 3×2 transfer matrix that transfers the electric field entering the pupil to the electric field on the image plane, the imaging plane coordinates of $\hat{x},\hat{y}$ and the pupil coordinates of $\hat{f},\hat{g}$ are normalized, $\mathbf{J_{Jones}}(\hat{f},\hat{g})$ is a 2×2 Jones matrix that describes the polarization aberrations of the lithographic projection lens at the pupil coordinates $(\hat{f},\hat{g})$. It can be expressed as

$$\mathbf{J}_{Jones}(\hat{f},\hat{g}) = \begin{bmatrix} J_{xx} & J_{xy} \\ J_{yx} & J_{yy} \end{bmatrix} = \begin{bmatrix} a_0+a_1 & a_2-ia_3 \\ a_2+ia_3 & a_0-a_1 \end{bmatrix}, \tag{2}$$

where $a_k(k = 0,1,2,3)$ are the complex-valued coefficients of the Pauli matrices, the amplitude and phase of a_0, along with the real and imaginary parts of $a_1 \sim a_3$ are utilized to define the polarization aberrations.

The pupil function $H(\hat{f},\hat{g})$ can be expressed as

$$H(\hat{f},\hat{g}) = \begin{cases} \exp[-jkW(\hat{f},\hat{g})] & \text{if } \hat{f}^2+\hat{g}^2<1 \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

where $W(\hat{f},\hat{g})$ represents the aberrations of the projection lens, which can be expressed in terms of Fringe Zernike polynomials [17]. In polar coordinates, $W(\hat{f},\hat{g})$ can be transformed to $W(\rho,\theta)$, which can be expressed as

$$\begin{aligned} W(\rho,\theta) &= \sum_{n=1}^{\infty} Z_n R_n(\rho,\theta) \\ &= Z_1 + Z_2\cdot\rho\cos\theta + Z_3\cdot\rho\sin\theta + Z_4\cdot\left(2\rho^2-1\right) \\ &\quad + Z_5\cdot\rho^2\cos2\theta + Z_6\cdot\rho^2\sin2\theta + Z_7\cdot\left(3\rho^3-2\rho\right)\cos\theta \\ &\quad + \cdots, \end{aligned} \tag{4}$$

where ρ is the radius of the pupil, and θ is the azimuth angle, Z_n is Zernike coefficients, $R_n(\rho,\theta)$ is Zernike polynomial.

From Eq. (4), we can see that the circumstances of the pupil sampling will influence the intensity distribution of the aerial image. Hence, the performance of wavefront aberration measurements depends on the efficiency of the pupil sampling. Our research group proposed two kinds of binary targets with six directions as the test target, which produces AMAI-PCA with the capability of measuring 33 terms of Zernike coefficients (Z_5–Z_{37}) for the lithographic projection lens [13, 15]. One of kinds of test targets is composed of openings with widths of 250 nm, spaced by 3000 nm (at wafer level), and oriented in the 0°/30°/60°/90°/120°/150° directions, as shown in Fig. 1(a). The diffraction patterns of this test target present the same equal angle-interval. Fig. 2 shows the pupil sampling effect to Z_{38} and Z_{53} by this test target. Z_{38} and Z_{53} are plotted on the pupil plane, as shown in Fig. 2(a) and (b), respectively. The red dotted lines depict the sample positions on the pupil plane generated by the target. It can be seen from Fig. 2 that the pupil sampling agrees with the zero phase of Z_{38} and Z_{53}, which means this kind of pupil sampling is invalid to Z_{38} and Z_{53}. Therefore, Z_{38} and Z_{53} cannot be measured by this test target.

Fig. 1(b) shows the other binary target, whose openings are oriented in the 0°/30°/45°/90°/120°/135° directions. Since the high-order Zernike polynomials contain high angular frequencies, the pupil sampling is not enough by the binary target. For example, the first quadrant information of the pupil is expressed only by the sampling the results of the 30° and 45° directions. Therefore, the pupil sampling is of low efficiency, which increases the crosstalk among the Zernike coefficients. Besides, the condition number can be used to judge the pupil sampling effect by the test target as well [18], which will be further explained in Section 2.2. The pupil of the Zernike coefficients Z_5–Z_{64} can be sampled with low efficiency by this test target, owing to the large condition number of the regression matrix, which results in poor measurement accuracy of HWAs.

A novel test target is proposed in this paper for HWA measurements of a hyper-NA lithographic projection lens. It is a binary target with eight directions, which is composed of openings with widths of 250 nm, spaced 3000 nm (at wafer level) apart, and oriented in the 0°/30°/45°/60°/90°/120°/135°/150° directions, as shown in Fig. 3.

Since Z_{50} and Z_{51} are the coefficients of $\rho^7\cos(7\theta)$ and $\rho^7\sin(7\theta)$, 14 orientations can sample them clearly. However, more orientations means more difficulty in manufacturing, especially some special angles. Considering the manufacturing feasibility, a binary target with eight directions is suitable to measure the HWAs.

Fig. 4 shows the pupil sampling effect on Z_{38} and Z_{53} by the proposed binary target with eight directions. The red dotted lines depict the sample positions on the pupil plane generated by the target. Z_{38} and Z_{53} have been sampled successfully at 45° and 135° directions. The efficiencies of the pupil sampling by the binary target with eight directions on other Zernike coefficients Z_5–Z_{64} are similar. Hence, the proposed target can improve the efficiency of pupil sampling to Zernike coefficients Z_5–Z_{64}, which is conducive to detecting HWAs of the hyper-NA lithographic projection lens accurately.

2.2. Aberration measurement

In the development of hyper-NA lithographic tools, HWAs of a projection lens cannot be neglected because of the stringent requirements of the overlay and imaging resolution. Therefore, a linear relationship needs to be established between the high-order Zernike coefficients and the aerial-image intensity distribution of the hyper-NA lithographic projection lens, in order to accurately measure the HWAs.

The pupil function $H(\hat{f},\hat{g})$ can be expanded by Taylor expansion. When wavefront aberration is small enough, the first two items of Taylor expansion can similarly represent the pupil function, which is expressed as

$$H(\hat{f},\hat{g}) = \exp[-jkW(\hat{f},\hat{g})] \approx 1 - jk\sum_n Z_n\cdot R_n(\hat{f},\hat{g}). \tag{5}$$

Therefore, Eq. (1) can be transformed to Eq. (6), expressed as