Iterative method for in situ measurement of lens aberrations in lithographic tools using CTC-based quadratic aberration model

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Abstract: This paper proposes an iterative method for in situ lens aberration measurement in lithographic tools based on a quadratic aberration model (QAM) that is a natural extension of the linear model formed by taking into account interactions among individual Zernike coefficients. By introducing a generalized operator named cross triple correlation (CTC), the quadratic model can be calculated very quickly and accurately with the help of fast Fourier transform (FFT). The Zernike coefficients up to the 37th order or even higher are determined by solving an inverse problem through an iterative procedure from several through-focus aerial images of a specially designed mask pattern. The simulation work has validated the theoretical derivation and confirms that such a method is simple to implement and yields a superior quality of wavefront estimate, particularly for the case when the aberrations are relatively large. It is fully expected that this method will provide a useful practical means for the in-line monitoring of the imaging quality of lithographic tools.

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References and links
1. Introduction

With ever decreasing feature sizes, lens aberration has become increasingly important for the imaging quality control of projection lithographic tools [1–3]. One method to mathematically model lens aberration utilizes Zernike polynomials, which are a complete orthogonal set of polynomials over the interior of the unit circle [4, 5]. The Zernike series representation is useful as it provides explicit expressions for the well-known aberrations such as spherical, coma, astigmatism, etc.; thus, the lens aberrations can be measured by characterizing its Zernike coefficients. In order to meet the requirement of optical path tolerances on the order of several nanometers over the extremely large numerical apertures (NAs) of current projection lenses, the higher-order coefficients of Zernike polynomials are becoming increasingly important for monitoring lens performance on a regular basis. In some circumstances, such as tool set-up during installation, the lens aberrations can be deteriorated beyond 0.1λ due to long-distance transportation and environmental change. Therefore, there is a need for the manufacturers of lithographic tools to develop in situ techniques and systems to accurately measure a wide range of aberrations up to the 37th or even higher-order Zernike coefficient.

Due to the advantage of lower cost and easier implementation in lithographic tools, aerial image based techniques have been widely used for the in situ metrology of lens aberrations. ASML Corporation has developed an aerial image based technique known as TAMIS (TIS at multiple illumination settings), which utilizes a TIS (transmission image sensor) built into the wafer stage for receiving the aerial image intensity of the test binary grating mark [6]. Although the main advantage of TAMIS is to present a simplified linear model in a simple form that can be fully characterized by a matrix of sensitivities, the matrix of sensitivities itself has to be carefully obtained in advance and can be only calculated by lithographic simulators or plenty of experimental data. Furthermore, the test marks used in TAMIS-based techniques are orientated to 0° and 90° or additional directions of 45° and 135°, which maintain high sensitivity only to spherical, coma and astigmatism, and are thus unable to measure high-order aberrations up to the 37th Zernike coefficient. In the meantime, Nikon Corporation has proposed a Z37 AIS (aerial image sensor) technique by introducing a set of 36 binary grating marks with different pitches and orientations [7, 8]. Although capable of measuring aberrations up to the 37th Zernike coefficient, the Z37 AIS technique only works best with coherent sources, and is therefore unsuitable for aberration measurement in lithographic tools under partially coherent illumination. Recently, we reported a technique for in situ metrology of lens aberrations up to the 37th Zernike coefficient with generalized...
formulations of odd and even aberration sensitivities suitable for arbitrarily shaped illumination sources [9, 10]. With a set of Zernike orders, these aberration sensitivities can be treated as a set of analytical kernels, which succeed in constructing a sensitivity function space. As each of the aberration sensitivities is presented in a compact analytical formulation and can be easily calculated in advance by a numerical method instead of only by a lithographic simulator, this technique leads to improved convenience for aberration metrology compared to the widely used TAMIS technique. Because it further considers the influence of the arbitrarily shaped illumination source on pupil sampling, this technique also overcomes the drawback of the Z37 AIS technique, as the latter only works best under the condition of highly coherent illumination. However, all of the above techniques, including ours, utilize a simplified linear response model relating the intensity difference of adjacent peaks in the one-dimensional binary gating images; thus, they are only suitable for small individual Zernike aberrations in the current lithographic tools.

It is well known that the imaging optics configuration in lithographic tools is typically a partially coherent system that is characterized by the intensity distribution of the effective source and the pupil function of the projection lens. Imaging properties of such partially coherent systems have to be described using a bilinear model [11, 12], which leads to time-consuming calculations and difficulties in comprehension, especially in the case when wavefront aberrations are involved. As the interactions among different types of aberrations also bring about the distinct deterioration of intensity distributions, particularly when large amounts of aberrations exist, higher order terms of the relationship between Zernike coefficients and aerial images need to be carefully considered [13]. A quadratic aberration model (QAM) is a natural extension of the linear response model by taking into account interactions among individual Zernike coefficients [14]. Recently, Zavyalova et al. reported an in situ aberration monitoring technique using phase wheel targets by solving an inverse imaging problem [15–17]. Although a compact mathematical quadratic model is developed to speed up the image calculation, the quadratic model itself has to be obtained in advance by using a simulation engine and a statistical analysis engine. Miyakawa et al. proposed an iterative procedure for in situ optical testing in extreme ultraviolet (EUV) lithography [18, 19]. The success of this technique also heavily relies on the accurate and rapid computation of many iterations, each of which involves the calculation of several aerial images. Although an approximate method by reduced optimized coherent sum (ROCS) decomposition is introduced to achieve this purpose, there is no explicit formulation to relate the individual Zernike coefficients to the aerial images. Most recently, we reported a cross triple correlation (CTC)-based algorithm for fast calculation of a quadratic aberration model in partially coherent imaging systems [20, 21]. This CTC-based quadratic model provides an explicit form that separates the Zernike terms from their corresponding basis image terms; thus, it is expected to have direct applications in the aerial image based aberration analysis and metrology.

In this paper, we propose an iterative method for in situ lens aberration measurement in lithographic tools by applying the CTC-based quadratic model. The Zernike coefficients up to the 37th order or even higher are determined by solving an inverse problem through an iterative procedure from several through-focus aerial images of a specially designed mask pattern. By taking into account interactions among individual Zernike aberrations, we decompose the conventional transmission cross-coefficient (TCC) in an aerial image calculation based on Hopkins’ theory into unaberrated TCC, linear TCC, and quadratic TCC terms, which are further expressed explicitly through many CTC terms. Each of these CTC terms can be calculated efficiently with the help of fast Fourier transform (FFT); then their corresponding basis image terms for the specially designed mask pattern need to be calculated only once and then can be stored in advance. Therefore, the total aerial image for the mask pattern can be quickly obtained by the weighted sum of these basis image terms multiplied by their corresponding Zernike terms. The overall performance of the proposed method was subsequently simulated in order to demonstrate its validity and accuracy for measuring
aberrations up to the 37th Zernike coefficient, particularly for the case when aberrations are relatively large.

2. Theory

2.1 The quadratic aberration model based on cross triple correlation

A schematic drawing of the optical lithographic imaging system is shown in Fig. 1, in which both the object and the light source are of finite extent. In order to simplify the expressions of the imaging system, we introduce the Cartesian object plane coordinates \( x_0 \), image plane coordinates \( x \), and pupil plane coordinates \( f \), which are all normalized according to canonical coordinates proposed by Hopkins [11]; thus, the cut off frequency from the pupil plane is normalized to the unit of one. The imaging process in optical lithography can be modeled as a pupil function with a partially coherent illumination source, namely the partially coherent system.

![Fig. 1. Optical lithography imaging system.](image)

According to Hopkins’ imaging theory, the behavior of partially coherent imaging is depicted as:

\[
I(x) = \int \int O(f_1)O^*(f_2)TCC(f_1, f_2) \exp\left[ -2\pi i (f_1 - f_2) \cdot x \right] df_1 df_2, \quad (1)
\]

where \( O(f) \) is the diffraction spectrum of a mask pattern, and \( TCC(f_1, f_2) \) is introduced as the concept of the transmission cross-coefficient:

\[
TCC(f_1, f_2) = \int J(f)H(f + f_1)H^*(f + f_2) df. \quad (2)
\]

Here \( J(f) \) describes the effective source intensity distribution in the pupil plane under Kohler illumination. The objective pupil function \( H(f) \) represents the information of lens aberration and defocus, which can be represented as:

\[
H(f) = P(f) \exp\left[ -ik \sum n Z_n R_n(f) \right], \quad (3)
\]

where \( k = 2\pi/\lambda \) is the wave number, \( \lambda \) is the wavelength of the monochromatic light source, \( n \) indicates Zernike index, \( Z_n \) is the \( n \)th Zernike coefficient, and \( R_n(f) \) indicates the \( n \)th Zernike polynomial for the normalized Cartesian coordinate over the pupil plane. \( P(f) \) is the defocused pupil function without lens aberration, and is represented by:

\[
P(f) = \text{circ} (|f|) \exp\left[ -ikW_{\text{defocus}}(f) \right], \quad (4)
\]

Here, an even-type aberration \( W_{\text{defocus}}(f) \) is induced by a defocus \( h \) (in nm) of the image plane:

\[
W_{\text{defocus}}(f) = h \cdot W_{\text{defocus}}(f) = h \left[ \sqrt{1 - NA^2 |f|^2} - 1 \right]. \quad (5)
\]
where \( NA \) is the image-side numerical aperture of the projection lens.

According to our previously proposed quadratic aberration model (QAM) [20], the total aerial image intensity distribution can be expressed in the following formulation:

\[
I(x) = I_0(x) + I_1(x) + I_2(x) = I_0(x) + \sum_n Z_n I_{\text{lin}}^{(n)}(x) + \sum_n \sum m Z_n Z_m I_{\text{quad}}^{(n,m)}(x),
\]

where \( I_0(x) \) is called the aberration-free intensity; \( I_1(x) \) and \( I_2(x) \) display the aberration-induced intensity distributions of linear and quadratic terms respectively. The \( I_1(x) \) and \( I_2(x) \) can be further decomposed into \( I_{\text{lin}}^{(n)}(x) \) and \( I_{\text{quad}}^{(n,m)}(x) \) multiplied by the corresponding Zernike coefficients, where \( I_{\text{lin}}^{(n)}(x) \) and \( I_{\text{quad}}^{(n,m)}(x) \) respectively represent the linearly and quadratically aberrated image terms based on individual Zernike aberrations. The \( I_0(x) \), \( I_{\text{lin}}^{(n)}(x) \), and \( I_{\text{quad}}^{(n,m)}(x) \) are called the basis image terms, and can be directly calculated from \( T_0(f_1,f_2) \), \( T_{\text{lin}}^{(n)}(f_1,f_2) \), and \( T_{\text{quad}}^{(n,m)}(f_1,f_2) \) by the formulations of

\[
\begin{align*}
I_0(x) &= \int \int O(f_1)O^*(f_2)T_0(f_1,f_2) \exp[-2\pi i(f_1 - f_2) \cdot x] df_1 df_2, \\
I_{\text{lin}}^{(n)}(x) &= \int \int O(f_1)O^*(f_2)T_{\text{lin}}^{(n)}(f_1,f_2) \exp[-2\pi i(f_1 - f_2) \cdot x] df_1 df_2, \\
I_{\text{quad}}^{(n,m)}(x) &= \int \int O(f_1)O^*(f_2)T_{\text{quad}}^{(n,m)}(f_1,f_2) \exp[-2\pi i(f_1 - f_2) \cdot x] df_1 df_2.
\end{align*}
\]

Here \( T_0(f_1,f_2) \), \( T_{\text{lin}}^{(n)}(f_1,f_2) \), and \( T_{\text{quad}}^{(n,m)}(f_1,f_2) \) are respectively called the aberration-free TCC, linearly aberrated TCC and quadratically aberrated TCC based on individual Zernike aberrations. Each term of \( T_0(f_1,f_2) \), \( T_{\text{lin}}^{(n)}(f_1,f_2) \), and \( T_{\text{quad}}^{(n,m)}(f_1,f_2) \) can be represented as a weighted sum of several cross triple correlation (CTC) terms:

\[
T_0(f_1,f_2) = C_{0,0,0,0}(f_1,f_2),
\]

\[
T_{\text{lin}}^{(n)}(f_1,f_2) = -ik \left[ C_{n,0,0,0}(f_1,f_2) - C_{0,0,n,0}(f_1,f_2) \right],
\]

\[
T_{\text{quad}}^{(n,m)}(f_1,f_2) = -\frac{1}{2} k^2 \left[ C_{n,m,0,0}(f_1,f_2) - C_{n,0,m,0}(f_1,f_2) - C_{0,n,m,0}(f_1,f_2) + C_{0,0,n,m}(f_1,f_2) \right],
\]

where \( C_{l,m,n,j}(f_1,f_2) \) is a special CTC of the following notation with the definition \( R_0(f) = 1 \):

\[
C_{l,m,n,j}(f_1,f_2) = \int \int \int J(f_1)[P(f_1 + f_2)[R_{0}(f_1 + f_2) \cdot R_{j}(f + f_2)]][P^*(f_1 + f_2)[R_{0}(f_1 + f_2) \cdot R_{j}(f + f_2)]] df_1 df_2.
\]

The general form of CTC is defined as [22]:

\[
\text{CTC}(f_1,f_2) = \int a(f)b(f + f_2)c(f + f_2) df,
\]

where \( a(f), b(f), \) and \( c(f) \) are three different functions.

It is noted that the final function CTC\((f_1,f_2)\) is four-dimensional and can be efficiently obtained by introducing the fast Fourier transform (FFT), which directly leads to a fast algorithm for the CTC calculation, therefore avoiding the time-consuming integration in Eqs. (13) and (14) [20]. It is also noted that each basis image terms of \( I_0(x) \), \( I_{\text{lin}}^{(n)}(x) \), and \( I_{\text{quad}}^{(n,m)}(x) \) need to be calculated only once and then can be stored in advance for a given mask pattern. The total aerial image for the mask pattern can be quickly obtained by the weighted sum of these basis image terms multiplied by their corresponding Zernike terms. This property is particularly useful in the iterative procedure for retrieval of Zernike coefficients, as many iterations have to be performed and each iteration involves the calculation of several aerial images.

It is expected that the number of basis image terms, especially the number of quadratic terms shown in Eq. (9) is very large when all of the high order Zernike coefficients are taken
into account. For example, when the lens aberrations need to be measured up to the 37th order, the number of quadratic terms is $C_{37}^2 = 666$, which will lead to a large storage requirement and time-consuming aerial image calculations. Fortunately, some of the basis image terms shown in Eq. (9) are quite small due to the small value of their corresponding CTC terms shown in Eq. (12). Thus, it is possible to use many fewer basis image terms in the quadratic model, which will further reduce the storage requirement and computational intensity.

2.2 The iterative method for aberration measurement

Since the quadratic terms are taken into account in Eq. (6), it is not possible to establish a simplified model with a matrix of sensitivities to linearly relate the aerial image to the individual Zernike coefficients, which is the case for TAMIS, Z37 AIS and our previously proposed methods [6–10]. Here the aerial image is nonlinearly related to the individual Zernike coefficients as their interactions are considered. Therefore, the extraction of the Zernike coefficients becomes an inverse optimization problem as shown in Fig. 2, and an iterative procedure has to be performed to solve this problem.

![Fig. 2. Forward modeling and inverse problem for aberration measurement.](image)

The CTC-based quadratic model provides a fast and accurate approach to represent the relationship between the Zernike coefficients and the aerial image intensity distribution. It could be utilized for aberration measurement by extracting the coefficients from the measured aerial image intensity. The flow of aberration measurement using the quadratic model is shown in Fig. 3, where the quadratic model is first established with the help of the CTC-based fast algorithm, which is the theoretical basis for efficiently simulating the through-focus series of aerial images.

![Fig. 3. The flowchart of the aberration measurement using the CTC-based quadratic aberration model. The Zernike coefficients are extracted by the regression algorithm from the experimental through-focus aerial images.](image)
Theoretically, any nonlinear regression methods such as local optimization algorithms can be used to solve the inverse problem for aberration measurement. The iteration process with the local optimization algorithm can be finished in several iterations, but it easily leads to only a local rather than a global solution. Therefore, we adopt the genetic algorithm to guarantee a global solution [23, 24], in which the Zernike coefficients are adjusted until the simulated aerial image intensity distribution fits the measured data. The optimization problem is formulated as follows:

$$\hat{\mathbf{Z}} = \arg \min_{\mathbf{Z}} \sum_{i=1}^{N_h} \sum_{j=1}^{N_x} \sum_{k=1}^{N_y} |I^m_{i,j}(x, y) - I^c_{i,j}(x, y)|$$

where $\hat{\mathbf{Z}}$ represents the optimized vector of Zernike coefficients; $\mathbf{Z} = [Z_2, Z_3, ..., Z_N]$ represents the vector containing Zernike coefficients up to the $N$th order; $I^m_{i,j}(x, y)$ and $I^c_{i,j}(x, y)$ respectively represent the measured and theoretical simulated aerial image at a coordinate of $(x_i, y_j)$ and at a defocus of $h_k$; $N_h$ indicates the number of defocus planes for aberration measurement; $N_x$ and $N_y$ indicate the number of image pixels in the $x$ and $y$ directions respectively. $T(\cdot)$ represents the forward modeling function transforming the Zernike coefficient vector $\mathbf{Z}$ into the theoretical simulated image, which can be calculated efficiently from Eq. (6).

3. Simulation

3.1 Simulation parameters

The lithographic simulator PROLITH was used to simulate the overall measurement performance by the proposed method. The simulations were performed on an HP Z800 Workstation of 3.46 GHz Opteron with MATLAB platform in a Windows 7 (64-bit) operating system. The optical system of the lithography tool was set as a partially coherent imaging system for a quadrupole source illumination with $\sigma_{\text{out}} = 0.8$, $\sigma_{\text{in}} = 0.4$, and degree = $45^\circ$. The wavelength used in the simulation is 193 nm, and the NA is 0.75. Figure 4 shows the aberrated wavefront values with Zernike coefficients from $Z_2$ up to $Z_{37}$ that we used as inputs for simulation. The Zernike coefficients are random in the range of $[-45m\lambda, 45m\lambda]$, leading to the aberrations in the range of $[-150m\lambda, 150m\lambda]$, which are relatively very large.

![Fig. 4. Input values of aberrated wavefront for simulation.](image)

As Zavyalova et al. have confirmed that the phase wheel target is highly sensitive to different types of aberrations [15–17], we utilized a similar input mask pattern but without phase shift shown in Fig. 5 as an example for the first demonstration of our aberration measurement method. The width of central contact is 600 nm while the width of all its surrounding contacts is 360 nm, and the simulation range of the mask pattern is [-1287 nm, 1287 nm].
3.2 Aerial image calculations by the CTC-based quadratic aberration model

Figures 6 and 7 show the simulated linear terms and quadratic terms of odd aberrations ($Z_7$, $Z_8$) and even aberrations ($Z_6$, $Z_9$) respectively, for the test mask pattern shown in Fig. 5. It is noted that the linear terms of $Z_6$ and $Z_9$ are zero, and the quadratic terms, including $I_{\text{quad}}^{(6,7)}(x)$, $I_{\text{quad}}^{(6,8)}(x)$, $I_{\text{quad}}^{(7,9)}(x)$, and $I_{\text{quad}}^{(8,9)}(x)$, are extremely small. Thus, these terms will have no impact on the total aerial image intensity distribution, and can be eliminated from the aberration model.

It is also noted from Fig. 7 that the number of quadratic terms is very large when all of the high order Zernike coefficients are taken into account, which is expected from Eq. (9). For example, when the lens aberration needs to be measured up to the 37th order, the number of quadratic terms is 666. It is thus highly desirable to reduce the quadratic terms by omitting some of the terms that have no impact on the total aerial image. We performed simulations to establish the aberration model for 37th Zernike orders, so that the effect of individual Zernike term on the aerial image can be evaluated. The average aerial image intensity distribution was considered as the criterion to evaluate the impact on the total aerial image. As shown in Fig. 7, it is noted that the intercross terms between pairs of an odd Zernike coefficient and an even Zernike coefficient are small enough to be eliminated; hence, only the intercross terms between the same kinds of Zernike coefficients make sense. Therefore, it is possible to use many fewer quadratic terms in the quadratic model for total aerial image calculation. Based on the analysis of the simulations, the 666 quadratic terms can be reduced to 324 after eliminating those extremely small terms.
Figure 7. The quadratic image terms of the mask pattern shown in Fig. 5 for intercross between pairs of Z₆, Z₇, Z₈, and Z₉.

Figure 8 depicts the aerial image calculation results for the test mask pattern shown in Fig. 5 with aberrations as Input Aberration 1 in Fig. 4. For the given mask pattern, the whole forward model took only 64.5 seconds to be built with an intensity error on the order 10⁻³ compared to that simulated by PROLITH. From this simulation and lots of other simulation results [20, 21], it is found that the proposed CTC-based quadratic model is suitable for fast and accurate aerial image calculations.

3.3 Aberration measurement by the proposed iterative method

We then performed simulations of aberration measurement by solving the inverse optimization problem shown in Eq. (15), where the genetic algorithm was introduced for Zernike coefficients extraction. The experimental through-focus images were simulated by PROLITH at 3 defocus planes with defocus h = -30 nm, 0 nm, and 30 nm.
Figure 9 shows the simulation result by the proposed method for the Input Aberration 1. The upper chart represents a comparison of the input Zernike coefficients with the measured values, and the lower chart represents the absolute errors of Zernike coefficients. The measured values of the Zernike coefficients are noted to coincide quite closely with the input values. From the simulation results, the absolute errors of all Zernike coefficients are less than 0.45\(\lambda\), and the root-mean-square of the absolute errors of Zernike coefficients up to \(Z_{37}\) is 0.14\(\lambda\).

![Zernike Coefficient Index vs. Magnitude](image1)

Fig. 9. Simulation result of aberration measurement for Zernike coefficients up to 37th order for the Input Aberration 1.

To test the accuracy of the proposed technique, all the aberrated wavefronts shown in Fig. 4 were inputed into the lithographic simulator for the simulated measurements of Zernike coefficients up to \(Z_{37}\). Figure 10 shows the simulation result of the measurement errors of individual Zernike coefficients from \(Z_2\) up to \(Z_{37}\).

![Zernike Coefficient Index vs. Error](image2)

Fig. 10. Simulation result of the measurement errors of Zernike coefficients for all the input aberrated wavefronts.

As shown in Fig. 10, all the measurement errors of Zernike coefficients tend to be randomly distributed and converge within ± 0.6 \(\lambda\) (or ± 0.116 nm), with the input aberration in the relatively large range of [-150\(\lambda\), 150\(\lambda\)]. Furthermore, the agreement between the input and measured aberrated wavefronts is illustrated in Fig. 11. It is noted that the absolute measurement errors are less than 2.5 \(\lambda\) (or 0.483 nm).
3.4 Comparison to the linear model method

We also performed a simulation to compare the measurement accuracy of the proposed iterative method using the quadratic model to the conventional method using the linear model. Recently, we reported a technique for in situ measurement of lens aberrations up to the 37th Zernike coefficient suitable for arbitrarily shaped illumination sources, and this technique has been demonstrated to outperform the widely used TAMIS and Z37 AIS techniques [9, 10]. With generalized formulations of odd and even aberration sensitivities, this technique is actually a simplified linear model method. Figure 12 shows the absolute measurement error of Zernike coefficients up to Z_{37} for different ranges of input aberrations, using both the proposed quadratic model and the simplified linear model.

From Fig. 12, it is clear that both methods achieve a very good accuracy of wavefronts on the order of mλs when the input aberrations are small (less than 50 mλ). However, the measurement error when using the simplified linear model increases significantly as the aberration range increases, while that using the proposed quadratic model remains almost unchanged within the aberration range up to 160 mλ. This simulation demonstrates that the simplified linear model only works best only under the condition of small aberrations, while...
the proposed method significantly improves the measurement accuracy, particularly when the aberration is relatively large. This advantage of the proposed method is due to its further consideration of the quadratic terms.

4. Conclusion and future work

In this paper, we propose a method for *in situ* measurement of lens aberration in lithographic tools using a CTC-based quadratic model. By introducing the concept of CTC, the quadratic model can be calculated very quickly and accurately with the help of FFT. The Zernike coefficients up to the 37th order or even higher can be determined by solving an inverse problem through an iterative procedure with a genetic algorithm from several through-focus aerial images of a specially designed mask pattern.

Although capable of measuring aberrations up to the $Z_{37}$ term, the widely used linear response model only works best under the condition of small aberrations. As the aberrations increase in size, the linear response model no longer maintains a high accuracy of wavefront estimates, because it ignores the interactions among individual Zernike aberrations. Using both theoretical analysis and simulation, the proposed method has overcome the significant drawback of the linear response model by further considering the quadratic terms.

Simulation results performed on a specially designed mask pattern has demonstrated that the proposed method is suitable for *in situ* measurement of Zernike coefficients up to the 37th order for a wide range of aberrations. It is particularly suitable for relatively large aberrations, with the measurement accuracy of Zernike coefficients on the order of 0.1 μλ (λ = 193 nm) and an accuracy of wavefronts on the order of μλs. The method also has the advantage of being simple to implement, and can be made to work in existing tools with no additional experimental setup.

It is worth pointing out that the sensitivity of the test mask pattern is critical for the aberration measurement, as the aberrations have unique characteristics in a manner that they influence specific portions of the lens pupil. For the purpose of aberration measurement, the mask pattern should be carefully designed so that it is most sensitive to particular aberration types and orders. With the fast algorithm of the CTC-based quadratic model, we will be able to perform the sensitivity analysis to optimize the mask pattern in our future work.

In the proposed method, the values of the effective source intensity distribution, defocus, and NA are all treated as known parameters that are inputed into the quadratic model for calculation of the theoretical aerial image. The measured aerial image should also be obtained so that the iterative process can be performed. For practical applications, however, all the input values of these parameters might be different from the real values in the lithographic tool, which means that all of these parameters might be error sources or uncertainty sources. To quantitatively evaluate the influence of these errors on the accuracy and precision of aberration measurement, we need to perform error analysis or uncertainty analysis, which is actually another important and challenging issue encountered in all kinds of inverse problems. We will deal with this issue together with experimental verification in our future work.

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