In-situ measurement of lens aberrations in lithographic tools using CTC-based quadratic aberration model

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ABSTRACT

With ever decreasing of feature sizes, the measurement of lens aberration has become increasingly important for the imaging quality control of projection lithographic tools. In this paper, we propose a method for in-situ aberration measurement based on a quadratic aberration model, which represents the bilinear relationship between the aerial image intensity and the Zernike coefficients. The concept of cross triple correlation (CTC) is introduced, so that the quadratic model can be calculated in a fast speed with the help of fast Fourier transform (FFT). We then develop a method for the Zernike coefficients characterization using the genetic optimization algorithm from the through focus aerial images of a nine contacts mask pattern. Simulation results demonstrate that this method is simple to implement and will have potential applications for in-situ metrology of lens aberration in lithographic tools.

Keywords: optical lithography, wavefront aberration, aberration measurement, quadratic aberration model, cross triple correlation (CTC), transmission cross coefficient (TCC)

1. INTRODUCTION

As the limit of optical lithography is pushed and feature densities continue to increase, lens aberration has become one of the most important factors to evaluate the imaging quality of lithographic tools [1-3]. One method to mathematically model lens aberrations 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 aberration can be measured by characterizing its Zernike coefficients. Therefore, a model that represents the relationship between the measured response and the Zernike coefficients is often built to extract the coefficients, and it is highly desired to establish an accurate and fast model for aberration measurement.

The aerial image based technique has been widely used for in-situ aberration measurement due to its low cost and easy implementation [6]. The imaging property of optical lithography tools is typically a partially coherent system, which is a bilinear system [7, 8]. An approximate linear model of Zernike coefficients to the aerial image displacement has been reported and widely utilized for aberration comprehension and measurement [9]. The linear relationship can be established between the intensity differences of adjacent peaks in the one dimensional binary gating images, by supposing that the individual Zernike aberration in the current lithographic projection lens is very small. However, due to the bilinear nature of imaging properties, the linear model is not suitable for aberration measurement with relatively large coefficients.

The quadratic model is a natural extension of the linear model, and can be more accurate since higher order effects of Zernike coefficients to aerial image are considered [10]. In recent years, the quadratic aberration model has been tested and verified under both one-dimensional and two-dimensional masks, and applied in aberration monitoring. Zavyalova *et al.* proposed an in-situ aberration monitoring method based on quadratic model using phase wheel targets, which gain the advantage of higher accuracy [11,12]. However, the model is generated though lithography simulation tools, and is quite

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time consuming. Miyakawa *et al.* proposed another in-situ aberration metrology method with iterative procedure, and utilized the reduced optical coherent system (ROCS) decomposition to reduce the computation time of aerial image in each iteration for partially coherent systems [13,14]. Most recently, we proposed a cross triple correlation (CTC) based fast quadratic model calculation algorithm, which provides an explicit form of aerial image to each Zernike term [15, 16].

In this paper, we propose a method of aberration measurement based on the quadratic aberration model, which can be calculated efficiently by introducing the concept of CTC. The conventional transmission cross coefficient (TCC) in aerial image calculation based on Hopkins' theory is decomposed into unaberrated, linear, and quadratic CTC terms with an explicit expression. Each of these CTC terms can then be calculated efficiently with the help of fast Fourier transform (FFT), thus the unaberrated, linear, and quadratic aerial image terms can be calculated efficiently. Since the CTC terms and aerial image terms can be saved in advance, the aerial image of different Zernike coefficients can be obtained by the sum of these aerial images terms proportional to the coefficients with a fast speed. Therefore, this algorithm is suitable for aerial image calculation for both of different mask patterns and variable Zernike coefficients. It will be convenient to design more generalized mask patterns which are sensitive to more Zernike aberrations, and to develop efficient algorithm for in-situ aberration characterization and monitoring.

2. METHOD

2.1 CTC based quadratic aberration model

The imaging process in optical lithography can be modeled as a pupil function with a partially coherent illumination source, namely the partially coherent system. According to Hopkins' theory, the intensity $I(\mathbf{x})$ in the image plane can be expressed as

$$I(\mathbf{x}) = \iint O(\mathbf{f}_1) O^*(\mathbf{f}_2) \,\mathrm{TCC}(\mathbf{f}_1, \mathbf{f}_2) \exp\left[-2\pi i(\mathbf{f}_1 - \mathbf{f}_2)\cdot\mathbf{x}\right] d\mathbf{f}_1 d\mathbf{f}_2, \tag{1}$$

where $O(\mathbf{f})$ is the diffraction spectrum of a mask pattern, $\mathbf{x}$ represent the spatial coordinate (x, y), $\mathrm{TCC}(\mathbf{f}_1, \mathbf{f}_2)$ is introduced as the concept of the transmission cross coefficient:

$$\mathrm{TCC}(\mathbf{f}_1, \mathbf{f}_2) = \int J(\mathbf{f}) H(\mathbf{f} + \mathbf{f}_1) H^*(\mathbf{f} + \mathbf{f}_2) d\mathbf{f}. \tag{2}$$

Here $J(\mathbf{f})$ describes the effective source intensity distribution under Kohler illumination. $H(\mathbf{f})$ is the objective pupil function, which often represented the information of lens aberration and defocus, and can be represented as

$$H(\mathbf{f}) = P(\mathbf{f}) \exp\left[-ik \sum_n Z_n R_n(\mathbf{f})\right], \tag{3}$$

where $P(\mathbf{f})$ is a unit circle after the all of the spatial coordinates are normalized, Z_n is the Zernike coefficient of nth order, and $R_n(\mathbf{f})$ is the Zernike polynomial. According to our previously proposed quadratic aberration model [15], the aerial image intensity distribution is decomposed into unaberrated term, linear term, and quadratic term, which can be represented as

$$I(\mathbf{x}) \approx I_0(\mathbf{x}) + I_1(\mathbf{x}) + I_2(\mathbf{x}) = I_0(\mathbf{x}) + \sum_n Z_n I_{\mathrm{lin}}^{(n)}(\mathbf{x}) + \sum_n \sum_m Z_n Z_m I_{\mathrm{quad}}^{(n,m)}(\mathbf{x}), \tag{4}$$

where each term is represented as

$$I_0(\mathbf{x}) = \iint O(\mathbf{f}_1) O^*(\mathbf{f}_2) T_0(\mathbf{f}_1, \mathbf{f}_2) \exp\left[-2\pi i(\mathbf{f}_1 - \mathbf{f}_2)\cdot\mathbf{x}\right] d\mathbf{f}_1 d\mathbf{f}_2, \tag{5}$$

$$I_{\mathrm{lin}}^{(n)}(\mathbf{x}) = \iint O(\mathbf{f}_1) O^*(\mathbf{f}_2) T_{\mathrm{lin}}^{(n)}(\mathbf{f}_1, \mathbf{f}_2) \exp\left[-2\pi i(\mathbf{f}_1 - \mathbf{f}_2)\cdot\mathbf{x}\right] d\mathbf{f}_1 d\mathbf{f}_2, \tag{6}$$

$$I_{\mathrm{quad}}^{(n,m)}(\mathbf{x}) = \iint O(\mathbf{f}_1) O^*(\mathbf{f}_2) T_{\mathrm{quad}}^{(n,m)} \exp\left[-2\pi i(\mathbf{f}_1 - \mathbf{f}_2)\cdot\mathbf{x}\right] d\mathbf{f}_1 d\mathbf{f}_2. \tag{7}$$

Here T_0, T_{lin}, T_{quad} is the unaberrated, linear and quadratic TCC term, which can be expressed as the sum of several CTC term:

$$T_0(\mathbf{f}_1, \mathbf{f}_2) = C_{0,0;0,0}(\mathbf{f}_1, \mathbf{f}_2), \tag{8}$$

$$T_{\text{lin}}^{(n)}(\mathbf{f}_1,\mathbf{f}_2) = -ik\left[C_{n,0;0,0}(\mathbf{f}_1,\mathbf{f}_2) - C_{0,0;n,0}(\mathbf{f}_1,\mathbf{f}_2)\right], \tag{9}$$

$$T_{\text{quad}}^{(n,m)}(\mathbf{f}_1,\mathbf{f}_2) = -\frac{1}{2}k^2\left[C_{n,m;0,0}(\mathbf{f}_1,\mathbf{f}_2) - C_{n,0;m,0}(\mathbf{f}_1,\mathbf{f}_2) - C_{m,0;n,0}(\mathbf{f}_1,\mathbf{f}_2) + C_{0,0;n,m}(\mathbf{f}_1,\mathbf{f}_2)\right], \tag{10}$$

where $C_{k,l;m,n}(\mathbf{f}_1,\mathbf{f}_2)$ is a special CTC:

$$C_{k,l;m,n}(\mathbf{f}_1,\mathbf{f}_2) = \int J(\mathbf{f})\left\{P(\mathbf{f}+\mathbf{f}_1)\left[R_k(\mathbf{f}+\mathbf{f}_1)\cdot R_l(\mathbf{f}+\mathbf{f}_1)\right]\right\}\left\{P^*(\mathbf{f}+\mathbf{f}_2)\left[R_m(\mathbf{f}+\mathbf{f}_2)\cdot R_n(\mathbf{f}+\mathbf{f}_2)\right]\right\}d\mathbf{f}. \tag{11}$$

This term can be calculated by introducing the fast Fourier transform (FFT) algorithm, and thus the quadratic aberration model can be established in a fast speed. It is also noted that each TCC term can be saved for a given optical system, and the aberration model will be easy to build when changing the mask pattern.

In addition, some of the aerial image terms are very small due to the small value of TCC term. It is natural that the number of quadratic terms will be very large especially in the case of aberration measurement for high Zernike coefficients. For example, when the lens aberration is measured up to 25th order, which is highly desirable to represent the aberration with high accuracy, the number of quadratic terms will be 325 terms. It will leads to large storage requirement and computational difficulty in aerial image calculation. Fortunately, as the TCC is the integration of the source function and two pupil functions, it would be very small when the integration of the two pupil function is zero. Thus, it is possible to use much less aerial image terms in the quadratic model, which will reduce the storage requirement and computational difficulty.

2.2 Aberration measurement method

The quadratic aberration model provides an accurate approach to represent the relationship between the aerial image intensity distribution and the Zernike coefficients. 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. 1, where a quadratic aberration model is firstly established with the help of CTC based fast algorithm. Then the sensitivity analysis model is built to determine the effect of each Zernike coefficient to the aerial image. The average aerial image intensity is defined as the criteria to evaluate the aerial image term:

$$R = \frac{\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\left|I(x,y)\right|}{N_x N_y}, \tag{12}$$

where N_x, N_y are the number of grid points in x and y directions of the aerial image. If the average intensity is extremely small, it can be considered that it does not have any effect on the total aerial image, and thus can be omitted from the quadratic model.

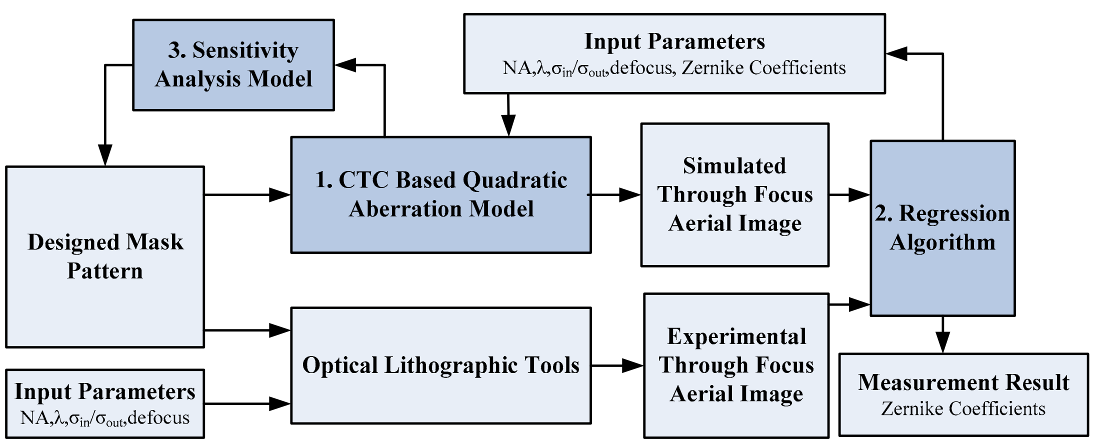

Fig.1. The flowchart of the aberration measurement using the CTC-based quadratic aberration model. The Zernike coefficients are extracted by the regression algorithm from the experimental through focus aerial images.

The Zernike coefficients of lens aberration can be extracted by regression algorithm through simulated aerial image and measured response. The through focus aerial images of the designed mask pattern were utilized for aberration characterization. As shown in Eq. (13), the difference *F* between the simulated through focus aerial image and experimental through focus aerial image is defined as a cost function, so that the Zernike coefficients is changed to derive an aerial image distribution that is the same with the measured image response:

$$F = \frac{\sum_{d=1}^{N}\sum_{i=1}^{N_x}\sum_{j=1}^{N_y}\left|I_d(x,y) - I'_d(x,y)\right|}{N_x N_y}, \tag{13}$$

where I_d is the aerial image intensity calculated from the quadratic model, $I'_d(x,y)$ the measured through focus aerial image in *d* focus plane, *N* indicates the number of focus plane for aberration measurement. As I_d can be calculated efficiently from Eq. (3) with the Zernike coefficients, the purpose of aberration measurement is to derive a set of Zernike coefficients with the minimal *F*.

3. SIMULATIONS

In order to verify and analyze the quadratic aberration model for aberration measurement, we performed simulations on MATLAB platform in an HPZ800 Workstation of 3.46 GHz Opteron with Windows 7 (64-bit) operating system. The optical system of the lithography tool was set as a partially coherent imaging system with a quasar source illumination whose outer radius is $\sigma_{out} = 0.8$ and whose inner radius is $\sigma_{in} = 0.4$.The wavelength in the simulation was set to be λ=193 nm, and the numerical aperture was set as 0.75. We built the quadratic aberration model for nine contacts mask pattern, as shown in Fig. 2. The width of central contact is 600 nm, and the width of all of its surrounding contact is 360 nm, and the simulation range of the mask pattern is [-1287 nm, 1287 nm].

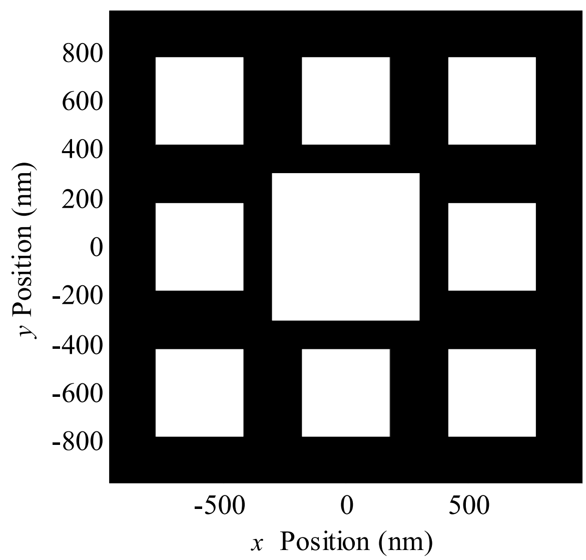

Fig. 2. The test mask pattern in aberration measurement

Figures 3 and 4 show the simulated linear terms and quadratic terms of odd aberrations (Z7, Z8), even aberrations (Z6, Z9), and defocus term (D) respectively. It is noted that the linear terms of Z6, Z9, and defocus are zero, and the quadratic terms including $I_{\text{quad}}^{(6,7)}(\mathbf{x})$, $I_{\text{quad}}^{(6,8)}(\mathbf{x})$, $I_{\text{quad}}^{(7,9)}(\mathbf{x})$, $I_{\text{quad}}^{(7,D)}(\mathbf{x})$, $I_{\text{quad}}^{(8,9)}(\mathbf{x})$, $I_{\text{quad}}^{(8,D)}(\mathbf{x})$ 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.

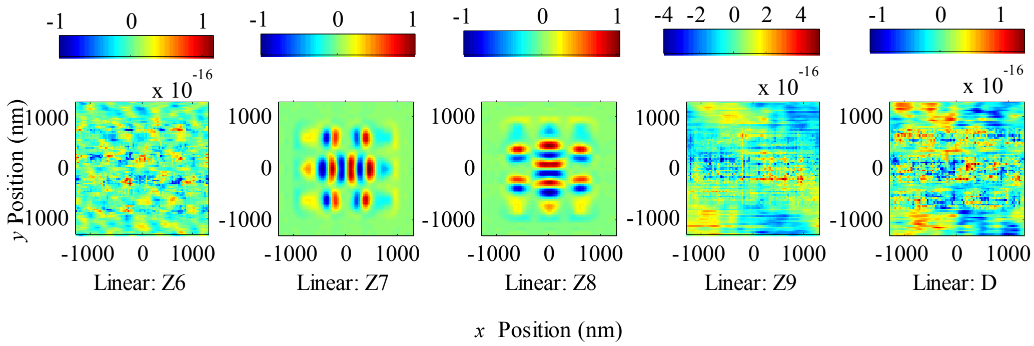

Fig. 3. The linear aerial image terms for Z6, Z7, Z8, Z9, and defocus.

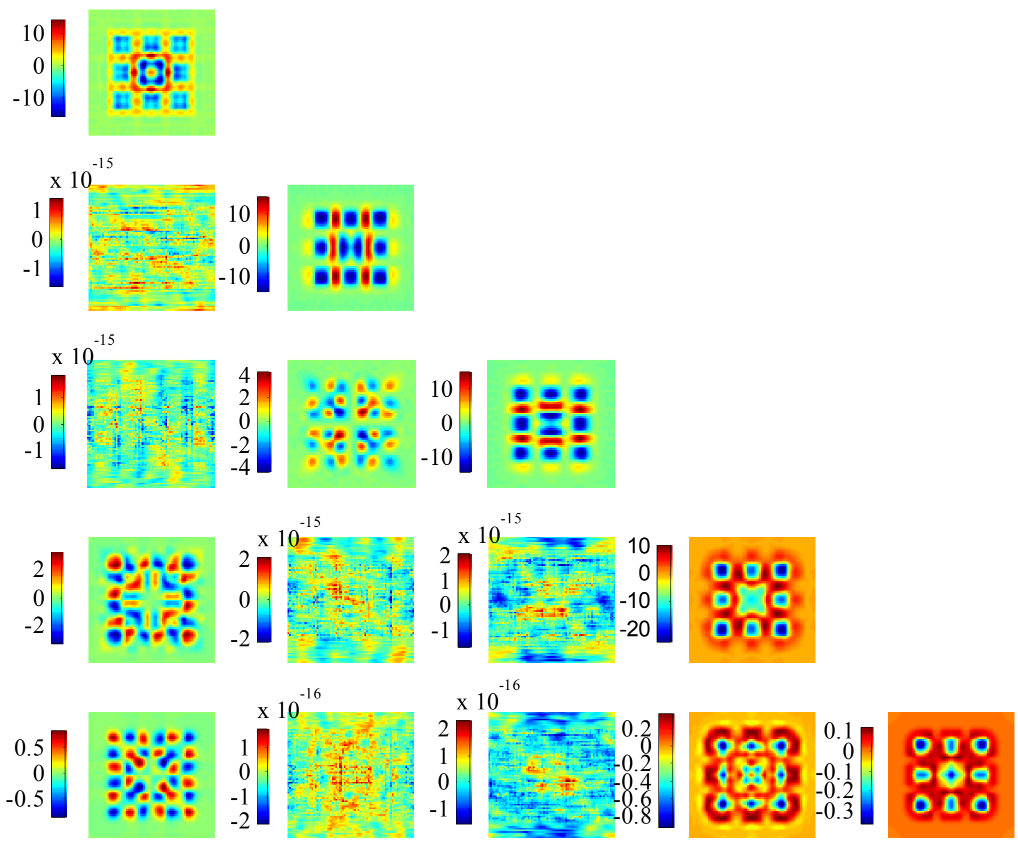

Fig. 4. The quadratic aerial image terms for Z6, Z7, Z8, Z9, and defocus, and their interaction terms. The *x*-axis and *y*-axis is *x* Position, and *y* Position for the aerial image term, and their range is [-1287nm, 1287nm]. The first column is the 6th order Zernike interact with all others, namely $I_{\text{quad}}^{(6,6)}(\mathbf{x})$ to $I_{\text{quad}}^{(6,D)}(\mathbf{x})$, the then the 7th~9th Zernike to defocus in the following column.

From Fig. 4 it is also noted that the quadratic terms occupy most of the terms in the aberration model. For aberration metrology with much higher order Zernike coefficients, for example 25 terms, the quadratic term will be 325 terms. It is highly desirable to reduce the aerial image terms by omitting some of the terms that have no impact on the total aerial image. We performed simulation to establish the aberration model for up to 25 Zernike orders, so that the effect of individual Zernike term to the aerial image can be evaluated. The average aerial image intensity distribution was considered as the criteria to evaluate the effect to the total aerial image, as shown in Fig. 5. It is noted that some of the quadratic terms is very small, that they can be eliminated for aberration induced aerial image model. Thus, it is possible to use much less aerial image term in the quadratic aberration model for total aerial image calculation. Based on the analysis of the simulation, only 169 quadratic aberration terms are required for aerial image calculation after eliminating those extremely small terms.

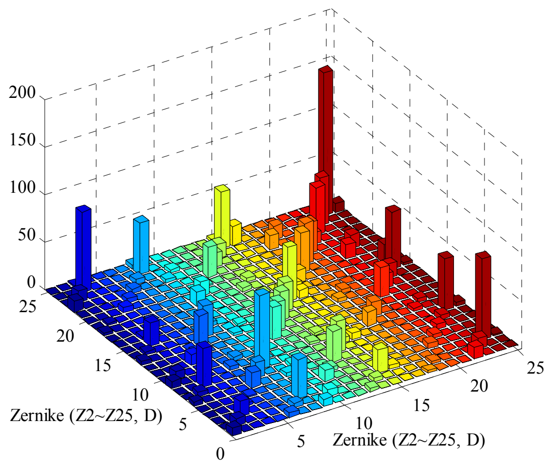

Fig. 5. The average intensity of quadratic aerial image terms for Zernike coefficients up to 25th order

We then performed simulations of aberration measurement with the above quadratic model. The aerial image intensity distribution based on regular Hopkins's theory was considered as the measured response, and the cost function was defined as the distance between the measured response and the aerial image calculated with the quadratic aberration model. The genetic algorithm was introduced for Zernike coefficients extraction. An example of aberration measurement is shown in Fig. 6, where the input and measured Zernike coefficients and pupil is depicted. The input aberration was a random number in the range of [-80mλ, 80mλ], which is relatively large for aberration measurement. Simulation result demonstrates that the proposed algorithm is suitable for aberration measurement, and the measurement accuracy is able to achieve 1mλ. It is also shown that the proposed aberration measurement methods is simple to implement, and will have potential application for in-situ aberration measurement with relatively large lens aberration.

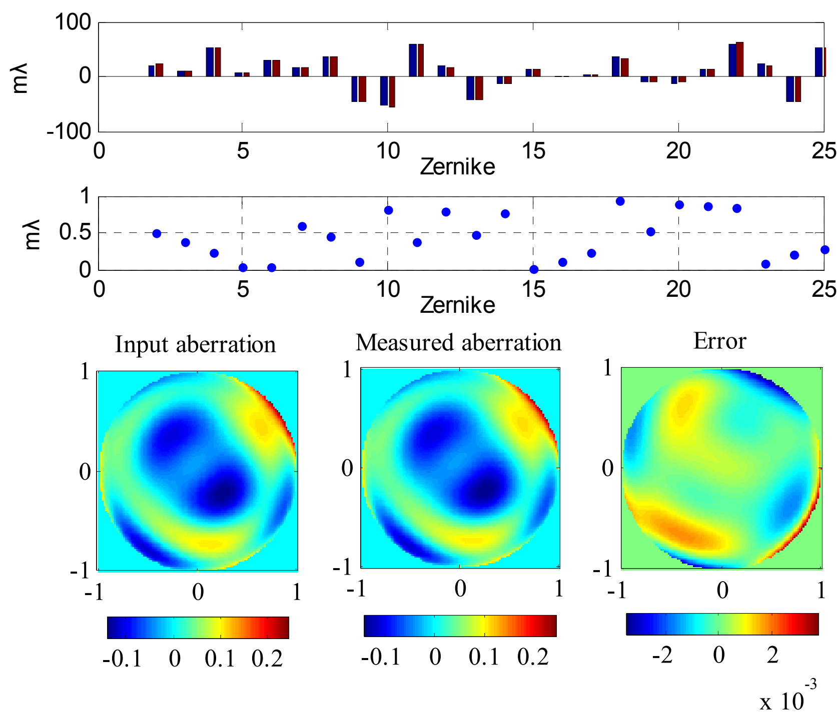

Fig. 6. Simulation result of aberration measurement for Zernike coefficients up to 25th order.

4. CONCLUSIONS

In this paper, we propose an aberration measurement method with a CTC based quadratic aberration model. The quadratic aberration model, a natural extension of the linear model between the aerial image intensity and the Zernike coefficients, has been established and realized for Zernike coefficient up to 25th order. This model is also simplified by eliminating some of the aerial image terms, and the total terms for are greatly reduced. Then we apply this model into aberration measurement. A cost function is defined between the simulated through focus aerial image intensity and measured response, and the genetic algorithm is introduced to extract the Zernike coefficients. Simulation result performed with a nine contacts mask pattern has demonstrated that the quadratic aberration model is simple to realize, and efficient in aerial image calculation. It is suitable for aberration measurement with relatively large lens aberration, and the measurement accuracy of lens aberration could achieve 1 mλ.

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