Accurate position measurement of a high-density beam spot array in digital maskless lithography

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Received 9 May 2013; accepted 15 July 2013; posted 22 July 2013 (Doc. ID 189948); published 9 August 2013

Since patterns in digital maskless lithography are formed by accumulating the exposure energy of a high-density beam spot array, the accurate position measurement of the spot array is essential for the precise operation of the system. We propose a measurement technique for detecting the position of a high-density, subpixel size beam spot array with a charge-coupled device (CCD). In order to determine the position of each beam spot with a small number of CCD pixels, we assign $3 \times 3$ pixels of the CCD for each spot and scan the CCD to determine the signal of a center pixel. We numerically analyze the measurement uncertainty in the pixel position for various scanning conditions. We set up an experimental system for proof of concept and to detect the position of a $10 \times 10$ beam spot array with an uncertainty less than 100 nm. Additionally, the measurement uncertainty quantitatively matches the numerical analysis results. © 2013 Optical Society of America

OCIS codes: (230.0230) Optical devices; (110.2970) Image detection systems; (110.3960) Microlithography; (110.5220) Photolithography.

http://dx.doi.org/10.1364/AO.52.005862

1. Introduction

As the fabrication costs of photomasks increase and the production cycle is reduced, maskless lithography has received attention regarding its merit in saving photomask-related costs and time. [1–5] Various types of maskless lithography have been developed such as laser direct writing [6], zone plate array [7], maskless e-beam [8], and spatial light modulator-based lithography [9–11]. Digital micromirror device (DMD)-based digital maskless lithography (DML) has especially drawn attention due to the advantages of beam delivery efficiency, high throughput, and a simple operating mechanism [12–14].

In the DML system, the DMD is illuminated by a light source and illumination optics. The incident beam is reflected by DMD into the beam expander to illuminate a microlens array (MLA). The MLA focuses the beam on the spatial filter array (SFA) and converts the image of the micromirror array into a spot array. Finally, the spot array is projected to the sample surface for the exposure of lithographic patterns [13]. Because of the manufacturing tolerance of the SFA, MLA, and projection optics, the spot array suffers from position errors. Since the position error of the spot array deteriorates the pattern quality such as line edge roughness line width roughness, or overlay accuracy [13], the position error must be evaluated. Consequently, the position measurement method for the spot array in DML is required for precise patterning.

To measure the position of a spot array with a charge-coupled device (CCD), the pixel pitch must be sufficiently smaller than the spot size. According to previous research, when the ratio of the spot to pixel size is 4.4:1, the accuracy of the position measurement is 0.757 μm [15]. Considering the spot size of DML is 1–5 μm [12,13] and the pixel pitch of a 35 mm full frame size CCD ranges from 6 to 9 μm or more,
the spot is magnified or a small pixel CCD is needed. In the case of magnifying the spot image on the CCD, the entire spot array image needs to be stitched due to the decrease in the field of view (FOV). The distortion of the magnifying optics could also decrease the accuracy. In the case of a CCD with a small pixel pitch, a stitch problem also occurs due to the sensor size. The smallest pixel pitch among commercial digital cameras is 1.2 μm. As the CCD in this pitch is a 1/2.3-inch type, more than 30 times the stitches are needed than in the full frame size CCD. Therefore, both cases are not practical for measuring the position of the spot array in DML. Although there have been various studies measuring the position of a spot or a spot array, such as a position sensitive device, a Shack–Hartmann wavefront sensor, hyperacuity technique, and defocus spot measuring techniques, they fail to measure the subpixel size spot. [15–18] Consequently, a new method for the measurement of the subpixel size spot array is required for DML.

The goal of this article is to measure the position of a high-density spot array in DML. To achieve this aim, we estimated the position of the spot array from scan data that was acquired by scanning a CCD with a piezo-stage. We numerically analyzed the measurement uncertainty in the position of a spot for various scanning conditions. We set up an experimental system for proof of concept and to detect the position of a 10 × 10 beam spot array with uncertainty less than 100 nm.

2. Measurement Principle

In order to measure positions of a subpixel size spot array with a CCD, the spatial sampling frequency was increased by scanning the CCD step-by-step using a piezo-stage. As shown in Fig. 1(a), the scan data varied with respect to the scan distance because the overlap fraction of the spot intensity with the active area was changed. As the scan data can be approximated to a discrete convolution of the active area shape and spot intensity profile, the position of the spot in the scanning direction can be derived from the scan data. The relative position of a spot to a specific pixel was defined as the first moment of the scan data. In addition, the two-dimensional position of a spot was acquired by two orthogonal scans, which are depicted as X and Y scans in Fig. 1(b).

In order to measure the positions of a spot array, an observation pixel must be assigned to a spot. As depicted in Fig. 1(b), the number of CCD pixels must be greater than that of the spots to avoid crosstalk. The observation pixel for a spot was assigned to the brightest pixel within an area of interest. Moreover, when assigning the observation pixels, the CCD must be placed in the center of the scan for the scan data to include the entire information of the spot.

Multiple scans are needed to measure the subpixel size spot array. As the aperture ratio of the active area to the pixel area is generally 0.1 to 0.2, the SNR could be very low when only one scan is fulfilled [see Scan 3 in Fig. 2(a) and 3(b)]. However, the SNR can be enhanced by adding each scan data by a matrix operation, which is indicated as $1 + 2 + 3$ in the graph of Fig. 2.

The major parameters of the CCD scan method were step, scan length, period, and scan width. The step was the unit length of translation of the piezo-stage. (b) A scheme of orthogonal scans for measuring the two-dimensional coordinate of the spot array. Observation pixels are assigned for acquiring the scan data of each spot.
observation pixel, the spot would be located within the range of a half of the CCD pixel pitch from the center of the active area. We assumed that the spot was an airy disc of which the first dark ring diameter was 5 μm, the pixel pitch was 9.0 μm, and the width and height of the active area were 2.6 μm and 6.8 μm, respectively. Therefore, the minimum scan length could be defined as (spot diameter) + (CCD pixel pitch) + (active area height) = (5.0 μm) + (9.0 μm) + (6.8 μm) = 20.8 μm.

The period was the lateral distance between adjacent scans, and the scan width was the lateral distance between the first and last of the multiple scans (Fig. 2). The number of scans, N, was defined as (9/period) + 1. When determining the scan width, we assumed that the trace of the active area, which was made by multiple scans, must cover the center of the spot. Therefore, the minimum scan width was defined as (spot diameter) + (CCD pixel pitch) - 2 × (active area width) = (5.0 μm) + (9.0 μm) - 2 × (2.6 μm) = 8.8 μm. For convenience, the scan length and width were set to 27 μm and 9 μm for both the x and y scans, respectively.

The position of the spot array was defined by the coordinate of the observation pixel and the first moment of the scan data. By assuming the pitch error of the CCD is negligible, the positions of the spot array are defined as Eq. (1):

\[ X = P_x + M_x, \quad Y = P_y + M_y \]  

(1)

where \( X \) and \( Y \) were \( x \) and \( y \) coordinates of the spot \( S_{ij} \), respectively (μm), \( S_{ij} \) was a spot of which the array index was \((i,j)\), \( P_x \) and \( P_y \) were \( x \) and \( y \) positions of the observation pixel, respectively (μm), and \( M_x \) and \( M_y \) were the first moment of the scan data in the \( x \) and \( y \) directions, respectively (μm). The position of the observation pixel could be derived \( P_x = p \times P_i, \quad P_y = p \times P_j \), where \( p \) was the pixel pitch of the CCD, and \((P_i,P_j)\) indicated the array coordinate of the observation pixel. \( M_x \) and \( M_y \) were defined in Eq. (2):

\[
M_x = \frac{\sum_i I_x(i_j) \times (i_j \times \Delta s)}{\sum_i I_x(i_j)}, \\
M_y = \frac{\sum_j I_y(j_s) \times (j_s \times \Delta s)}{\sum_j I_y(j_s)}.
\]  

(2)

where \( I_x \) and \( I_y \) are the observation pixel signal at each step when scanning the \( x \) and \( y \) direction, respectively, \( i_j \) and \( j_s \) were the index of the step, and \( \Delta s \) was the step size. \( I_x \) and \( I_y \) were the emerged scan data that was described in Figure 2.

### 3. Simulation

We performed simulations to determine the accuracy of the CCD scanning method under ideal conditions and to optimize the scanning parameters. The spot was assumed to be an ideal airy disc and two cases of the first dark ring diameter, 3 and 5 μm, were considered. We considered the airy disc up to the second ring. In the simulation, the first moment estimation error that originated from the discrete sampling of the spot intensity was the only source of error.

To calculate the position of the spot by simulation, the pixel signal at each step and period must be derived. We assumed the pixel signal to be the integration of the energy of the airy disc on the active area [Eq. (3)]:

\[
I(n,m) = \int_{m_s}^{m_s+w_x} \int_{n_s}^{n_s+w_y} J_1(2.44 \pi w_0 \sqrt{(x_0-x)^2+(y_0-y)^2})^2 \times \left[ 2.44 \pi w_0 \sqrt{(x_0-x)^2+(y_0-y)^2} \right] \, dx \, dy.
\]  

(3)

where \( J_1 \) is the first-order Bessel function of the first kind, \( w_0 \) is the first dark ring diameter of the airy disc, \((m_s,n_s)\) is the left upper position of an active area at a specific step and period, \((x_0,y_0)\) is the maximum intensity position of the spot, and \( w_x \) and \( w_y \) are the width and height of the active area, respectively. \( m_s \) and \( n_s \) can be derived as \( m_s = \Delta s \times (m-1) + m_{x0}, \quad n_s = p \times (n-1) + m_{y0} \), where \( \Delta s \) is the step size, \( p \) is the period size, \( m \) and \( n \) are integer (\( m = 1,2,\ldots,M \), \( n = 1,2,\ldots,N \)), and \((m_{x0},m_{y0})\) is the initial \( x \) and \( y \) positions of the active area. Equation (3) was applied repeatedly for different offset positions of the active area to build up the scan signal that would presumably resemble the measurement examples shown in Fig. 2.

We simulated the measurement procedure for various positions of a spot. The spot position was varied by changing the value of \((x_0,y_0)\). Considering the
position of the spot was shifted by a single step size along the scan direction, the scan data would be shifted by exactly one data point. Thus, the first moment estimation error of the spot at the initial position and one step-shifted position may be exactly one step. Specifically, the position measurement error must be the same when the spot was shifted by an integer multiple of steps. The position of the spot was calculated by varying its position within one step size. The grid size was determined to be 10 nm as there was no change in the position measurement error below 10 nm.

As shown in Fig. 3, we introduced a concept of the error vector, a displacement from a reference position to a measured position, to describe the accuracy. The error vector indicated the error of a single measurement. However, the absolute value of the error vector was not identical to the real measurement error because the position relationship between the reference and the real coordinate was not known. As a result, we defined the accuracy as the standard deviation of the error vectors to cancel out the deviation of the reference position to the real position of a spot.

We calculated the effects of the step and period on the accuracy by numerical simulation. The values of the parameters were considered within a practical range. In the case of the step variation, the step was varied from 0.45 to 2.25 μm and the period was fixed at 1 μm. As shown in Fig. 4(a), the accuracy decreased with respect to the step, and it is expected that the accuracy would be less than 100 nm in a range smaller than half of the spot size. The minimum accuracy of the 3- and 5 μm spot was 22 and 19 nm, respectively. In the case of the period variation, the period was varied from 1 to 4.5 μm for three step cases of 0.45, 1.50, and 2.25 μm. The decrease of the accuracy according to the period was within 20% of the minimum value, as shown in Figs. 4(b) and 4(c). From the simulation results, it was expected that the accuracy could decline for longer steps and period cases, and the step primarily determined the accuracy, whereas the period was not a critical parameter for the accuracy.

4. Experiment

We set up a single spot measurement system to verify the simulation results as shown in Fig. 5(a). The light source was a continuous wave laser with
A wavelength of 532 nm. The beam was delivered to the collimator by a single mode fiber. The collimated beam was focused by an aspheric lens (C220TME-A, Thorlabs) to produce a 5 μm airy disc on the CCD. The numerical aperture (NA) of the focusing lens was 0.25 and the NA was controlled by a diaphragm to adjust the spot size. A full frame size CCD (36 mm × 24 mm, 4008 × 2672 array, 9 μm pixel pitch, 6.8 μm × 2.6 μm active area size) was chosen. Additionally, we used a MLA-detached CCD since the irregularities of the shape and pitch of the MLA could be a source of measurement error. The bit depth of the CCD was 12 and the maximum frame rate was 6.4 frames per second. The piezo-stage was attached to the CCD for scanning and its precision was 1 μm, which was sufficient performance for the experiment. Since the overall travel length was 15 μm, whereas the scan length was 27 μm, two adjacent pixels in the scanning direction participated to meet the scan length. Therefore, the effective scan length was 27 μm using 3 observation pixels, though the actual scan length was 9 μm. The pixels that were in the center line of the 3 × 3 pixel area were used as observation pixels for x and y scanning.

The CCD was aligned to make the smallest spot size. The spot size was determined by taking its size from the FWHM of the scan signal. In the simulation, we found that the FWHM of the x-direction scan data for the 3, 5, and 7 μm spots was 2.6, 2.8, and 3.4 μm, respectively. In the experiment, we obtained the FWHM of the x-direction scan data of 2.9 μm and we estimate the spot size of 5.3 μm.

Before starting the experiment, the system was preheated for an hour to thermally stabilize the piezo-stage, CCD and light source. After warming up, the power fluctuation of the light source was less than 0.94%. The image of the spot was captured by the CCD camera at each step and then the captured images were rearranged, pixel by pixel, to produce scan data of each spot. The position of the spot was calculated from the scan data by using Eqs. (1) and (2). As the position measurement error is a function of spot position, the spot was offset to different positions and measured at each position. The spot was shifted to 3 × 3 (= 9) positions and the distance between adjacent positions was 1 μm, equally.

In the single spot measurement, the goal was to optimize the parameters by comparing the results of the simulation and experiment. As shown in Fig. 4(b), the accuracy starts to decrease at a period of 3 μm, which was greater than the half-width of the active area. The increasing tendency was most relevant in the 2.25 μm step case. As the simulation was performed under ideal conditions, the accuracy could decline more in the experiment than the simulation accuracy. Thus, the parameter ranges were adjusted by the results of the simulation. In the case of the step variation, the fixed value of the period was altered from 1 to 2.25 μm to save time as there was no relevant variation of the accuracy up to a period of 2.25 μm as shown in Fig. 4(b). In the case of the period variation, the fixed value of the step was determined to be 1.8 μm.

To measure the position of the spot array, we modified the setup as shown in Fig. 5(b). We utilized a pinhole array with a pinhole diameter of 3 μm and a pitch of 100 μm. The collimated beam was incident to the pinhole array and the transmitted light from each pinhole was imaged by a microscope objective lens pair. The magnification was 1 and the distortion aberration was minimized as the object side and the image side of the lens pair was symmetric about the aperture stop. The NA was 0.25 and the expected spot size (pinhole diameter + first dark ring diameter of the optics) was 3.0 μm + 2.1 μm = 5.1 μm. The FOV was 2 mm and a 10 × 10 spot array was measured to minimize the effect of the aberration.

The pinhole array was fabricated at an aluminum coating on the quartz substrate by lithography. We evaluated the shape and pitch of the pinhole array. The shape was measured by atomic force microscopy and was nearly circular. The difference of the shorter and longer axis was less than 5%, 150 nm. The pitch error was measured by a microscope, which was 140 nm (1σ).

5. Results and Analysis
The experimental result of the single spot case is plotted in Fig. 6. In the step variation case [Fig. 6(a)], the accuracy decreased slightly when compared to
the simulation result. The maximum deviation of the simulation and experiment was 24 nm at the step size of 0.45 μm. As shown in Fig. 6(b), the measurement error slightly decreased until a period of 3 μm compared to the simulation result. The accuracy for the period variation ranged from 44 to 63 nm. The error bar in Fig. 6 represents the standard deviation of 5 measurements for each parameter.

The position measurement result of the spot array is shown in Fig. 7. The step size and period size were determined by considering the accuracy and time consumption as 0.9 and 1.8 μm, respectively. In this experiment, the measured position contained a systematic error such as the rotation of the array and the magnification error of the microscope objective lens pair. The rotation of the spot array was derived from the measured spot positions by numerical fitting. The magnification error was calculated by comparing the average distance between the adjacent spots in a row or column direction to its original pitch. Each point in Fig. 7 indicates a spot in the array and the color shows the absolute value of the error vector. The standard deviation of the error vectors for the spot array measurement was 180 nm and the accuracy for the single spot measurement with the same parameters was 38 nm. Considering the pitch error of the pinhole array and shape, the result is expected to coincide well with the simulation result.

In the simulation, the electrical noise of the CCD and the fluctuation of the laser source power were ignored. The variation of the signal from the CCD pixel at a fixed position was measured. The standard deviation of the signal was 0.69% when 900 shots were captured. This variation was due to the effect of both the CCD noise and power fluctuation. We simulated the repeatability for a fixed position using the value, 0.69%. The result had a 14 nm standard deviation.

Additionally, we tested the repeatability by measuring a fixed spot. The measured position did not vary randomly, but rather in a certain direction. The directional nature was caused by the hysteresis of the piezo-stage. To measure the hysteresis effect, the signal fluctuation effect must be avoided. Therefore, 10 shots were averaged at each step and the standard deviation of repeatability was 16 nm. In conclusion, the root mean square uncertainty was\[[(\text{signal fluctuation})^2 + (\text{stage hysteresis})^2]^{1/2} = [(14 \text{ nm})^2 + (16 \text{ nm})^2]^{1/2} = 21 \text{ nm}\]. Therefore, the minimum achievable accuracy of the method was expected to be the sum of theoretical accuracy and the uncertainty, 19 + 21 nm = 40 nm, which coincided well with the result of the single spot case, 38 nm.

6. Conclusion

The position measurement of the spot array is an important method to estimate the pattern quality of the DML. We suggested the CCD scanning technique to measure the position of a high-density, subpixel-size spot array. We verified the accuracy in the ideal case by simulation and the experimental results coincided well with the simulation. The uncertainty of the measurement was analyzed, and it well explained the difference of the best accuracy between simulations and experiments. Our research has demonstrated the feasibility to measure the position of the spot array in the DML without using a magnification lens and minimizing the stitching error. The CCD scanning method may provide fundamental data to estimate the pattern quality of the DML.
This work was supported by the Ministry of Knowledge Economy of Korea (Project No. 2011-8-2255).

References


