Simulation of the effect of incline incident angle in DMD Maskless Lithography

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Abstract. The aim of this study is to provide a simulation method for investigation of the intensity fluctuation caused by the inclined incident angle in DMD (digital micromirror device) maskless lithography. The simulation consists of eight main processes involving the simplification of the DMD aperture function and light propagation utilizing the non-parallel angular spectrum method. These processes provide a possibility of co-simulation in the spatial frequency domain, which combines the microlens array and DMD in the maskless lithography system. The simulation provided the spot shape and illumination distribution. These two parameters are crucial in determining the exposure dose in the existing maskless lithography system.

1. Introduction

Lithography is a central topic in integrated circuit manufacturing, and maskless lithography has drawn much attention in recent years. In maskless lithography, a digital micromirror device (DMD) plays the decisive role as a spatial light modulator. Maskless lithography involves the use of a DMD as a virtual mask in place of a physical mask. A DMD is composed of millions of micrometer-scale square mirrors. The micromirrors are tilted at ±12° along the diagonal line, which correspond to “on” and “off” states. However, the boundary of the micrometers results in diffraction. The stray diffracted light leads to disturbance once it accumulates to the exposure threshold of the photoresist.

In conventional photolithography using a photomask, various optical proximity correction (OPC) have been used to compensate for imaging errors such as edge placement and corner-rounding errors in order to achieve desired features in a pattern. Image errors such as the edge placement error and the corner-rounding effect also occur in maskless lithography[1]. It is necessary to consider the pattern quality in maskless lithography as in conventional photolithography resulting from the diffraction effect. J Hur et al. derived by approximating the intensity of the beam to the Gaussian distribution[2]. It would be better if Hur’s compensation is based on specific illumination distribution instead of Gaussian distribution. Furthermore, the incident light has tilt angle between DMD pixels in DMD maskless lithography system[3][4]. The illumination distribution may be different from normal incidence. Thus, the diffraction effect in non-parallel region should be studied.

In addition, illumination distribution is a crucial parameter in non-linear maskless lithography. Non-linear lithography is a potential sub-diffraction technology for resolution enhancement with physical method. J S Wei et al.[5] and J Koch et al.[6] broke the optical resolving limit in the aspect of physics by nonlinear effect. V Lyubin et al.[7] promote the non-linear lithography in the aspect of material by developing the nonlinear photoresists with transition dissolution curve for maskless photolithography. Research on the light source may drive the non-linear technology in the aspect of optics. For the reason that, slight intensity fluctuation within a light spot directly result in the change of spot size in non-line lithography system, which means edge placement error and the change of critical dimension.

Lastly, designer used to reduce edge placement error though increasing the redundancy. Redundancy means illumination accumulation both the target spot and the diffraction light. Redundancy tolerance should be under concerned.

The present paper extends the method to analyze the diffraction problem in the DMD lithography system. We primarily focus on light propagation in the non-parallel region. Although the angular
spectrum had been applied extensively in the field of ultrasound and hologram, it was not commonly used in the diffraction problem of DMD. This algorithm can be used to obtain the illumination distribution in any of the near field, Fresnel field, and Fraunhofer field. This simulation method provides a possibility to substitute the diffraction light with a plane wave as an incident beam with specific diffraction light in the MLA design. This model of calculation is under MATLAB’s software environment, which can process dynamic data exchange between Zemax flexibly. [8] Thus, this model may be suitable for co-simulation between a DMD and an MLA. In addition, the aperture function used in DMD was simplified for minimizing the computational cost. The aperture function was classified into four types according to whether the spatial frequencies fx and fy are zero or not. The aperture function, which contains zero spatial frequency, can be simplified.

2. Formula in simulation

In recent years, researchers have built some models to fit the diffraction effect of DMD lithography system. J P Rice et al. [9] considered a micromirror array that acts as a blazed grating. H Ryoo et al. [10] further hypothesized that a micromirror array acts as two perpendicular gratings. They utilized the two-dimensional grating equation to calculate the optimum incident angle. Furthermore, they suggested that the tilted incident angle(θ) contributed to the shift of the envelopes. When the incident angle and groove tilt were arranged to meet a blazed condition, the majority of the energy was concentrated at the blazed order. X. Zheng et al. [11] calculated the efficiency of different diffraction orders by means of Fourier transformation. X. Chen et al. [12] focused on the dispersion effect of high diffraction orders.

The above studies were based on the grating equation or Fraunhofer diffraction model. However, most of them only focused on the diffraction efficiency. These methods share a common constraint in calculating the diffraction efficiency in the non-parallel condition or in the near field. In addition to diffraction efficiency, the illumination distribution is important. These two parameters provide a possibility of co-simulation between a microlens array (MLA) and a DMD. Conventional microlens array optimization presupposes that the light source is a plane wave. However, after modulation by the DMD, the light source is no longer a plane wave, because of the diffraction effect of DMD pixels. J Li et al. [13] compared the numerical computational accuracy of the Kirchhoff formula, Rayleigh-Sommerfeld formula, and angular spectrum transmission formula. They suggested that the angular spectrum transmission formula was the easiest for achieving sufficient sampling. K. Matsushima et al. [14] proposed a Jacobian matrix enable coordinate transformation in angular spectrum transmission.

2.1. Angular spectrum

For comprehension convenience, the basic concept of angular spectrum is introduced briefly in 2.1. the angular spectrum theory is a more rigorous method to study light propagation in comparison with the Fraunhofer diffraction model and Fresnel diffraction model. In particular, the diffraction distance is relatively small such that the image plane is not in the Fresnel field.

The basic concept of the angular spectrum method is to describe a complex wave field as an equivalence of an infinite number of plane waves in all directions [15]. The method aims at determining the field $E_x(x,y,z)$ as a function of $E_x(x,y,0)$ without approximation. The z co-ordinate is considered as the propagation direction.

$$G_x(f_x,f_y) = G_0(f_x,f_y)\exp\left[j\frac{2\pi}{\lambda} z\sqrt{1 - (f_x^2 - (f_y^2)}\right]$$ (1)

Equation (1) defines the angular spectrum transfer function. In the propagating wave model, corresponding to spatial frequencies with $(f_x^2 + f_y^2) < 1/\lambda^2$, the frequency spectrum acquires a phase delay due to the propagation in the z direction. Therefore, this component is called the propagating component.

2.2. Co-ordinate transform
According to the Huygens-Fresnel principle, every point on the wavefront becomes a source of a spherical wave. These secondary waves reconstruct the form of the wave at subsequent times. As shown in Fig. 1, only frequency spectra within the dashed line can reach the imaging plane.

\[
\begin{pmatrix}
\alpha_1 & \alpha_2 & \alpha_3 \\
\alpha_4 & \alpha_5 & \alpha_6 \\
\alpha_7 & \alpha_8 & \alpha_9
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos\alpha & -\sin\alpha \\
0 & \sin\alpha & \cos\alpha
\end{pmatrix}
\]  

\[\begin{pmatrix}
f_x0 \\
f_y0
\end{pmatrix} =
\begin{pmatrix}
\alpha_1 & \alpha_2 & \alpha_3 \\
\alpha_4 & \alpha_5 & \alpha_6 \\
\alpha_7 & \alpha_8 & \alpha_9
\end{pmatrix}
\begin{pmatrix}
\hat{f}_x \\
\hat{f}_y
\end{pmatrix}
\]  

Because the z direction is the propagation direction, the x-y plane is observed as the cross-section. We only pay attention to the x and y direction. 

\[
\begin{align*}
f_{x0} &= \alpha (\hat{f}_x, \hat{f}_y) = a_x \hat{f}_x + a_y \hat{f}_y + a_z \hat{f}_z \\
f_{y0} &= \beta (\hat{f}_x, \hat{f}_y) = a_x \hat{f}_x + a_y \hat{f}_y + a_z \hat{f}_z
\end{align*}
\]  

The nonlinearity of the rotation transformation was offset by the Jacobian matrix \(df_x df_y\), which was replaced by \(J(\hat{f}_x, \hat{f}_y) df_x df_y\) to give\[16\]

\[
J(\hat{f}_x, \hat{f}_y) =
\begin{pmatrix}
\frac{\partial \alpha}{\partial \hat{f}_x} & \frac{\partial \alpha}{\partial \hat{f}_y} \\
\frac{\partial \beta}{\partial \hat{f}_x} & \frac{\partial \beta}{\partial \hat{f}_y}
\end{pmatrix}
\]  

\[= (\alpha_\alpha - \alpha_\alpha \alpha_\alpha) \frac{\hat{f}_x}{f_x} + (\alpha_\alpha - \alpha_\alpha \alpha_\alpha) \frac{\hat{f}_y}{f_y} + (\alpha_\alpha - \alpha_\alpha \alpha_\alpha) \frac{\hat{f}_z}{f_z}
\]  

In the mirror co-ordinate system, an incident beam is given by

\[
E_i(x, y, 0) = E_0(x, y, 0) \exp \left( -j \frac{2\pi}{\lambda} \sin \theta \right)
\]  

According to the shifting property in the Fourier transform,

\[
\mathcal{F}(E_i(x, y, 0)) = G \left( f_{x0}, f_{y0} + \frac{\sin \theta}{\lambda} \right)
\]  

2.3. Simulation procedure

The illumination distribution can be calculated as a function of distance z. The basic idea and steps are as follows:

Step 1. An inclined wave is propagated to an intermediate plane that is parallel to the imaging plane.

Step 2. Waves on the intermediate plane are decomposed into plane waves by Fourier transformation.

Step 3. Co-ordinate translation and rotation in the spatial domain by means of shifting theorem.
Step 4. Co-ordinate rotation in the Fourier domain.
Step 5. Nonlinearity compensation with a Jacobian Matrix.
Step 6. Spectrum filtering for efficacious propagation.
Step 7. Propagation calculation with angular spectrum method.
Step 8. Spectrum restoration and inverse Fourier transformation.

2.4. Simplification of aperture function of DMD pixel
The center of the micromirror should coincide with the origin of the co-ordinate system. Further, it is tilted by ±12° along the diagonal line. However, the computational cost for such a model is high because all four quadrants are occupied, as shown in Fig. 2. To simplify the analytical solution, we initially move the DMD to the first quadrant, and then return it in the frequency domain based on the shifting property. The spatial spectrum of a single micromirror is given by

\[ T(f_x, f_y) = \int_0^\infty \exp(-j2\pi x_0 f_x) \exp(-j2\pi y_0 f_y) dx_0 dy_0 \quad (8) \]

\[ \text{Fig. 2 Rectangular light beam in the spatial domain} \]

To deal with a possible case in which a denominator in equation (8) becomes zero, a brief discussion is made on different classification criteria.

1) When \( f_x \neq 0, f_y \neq 0 \)
   \[ T(f_x, f_y) = -\frac{\exp(-j2\pi a f_x) - 1}{4\pi^2 f_x f_y} \quad (9) \]

2) When \( f_x = 0, f_y \neq 0 \)
   \[ T(f_x, f_y) = -\frac{j a (1 - \exp[-j2\pi a f_y])}{2\pi f_y} \quad (10) \]

3) When \( f_x \neq 0, f_y = 0 \)
   \[ T(f_x, f_y) = -\frac{j a (1 - \exp[-j2\pi a f_x])}{2\pi f_x} \quad (11) \]

4) When \( f_x = 0, f_y = 0 \)
   \[ T(f_x, f_y) = a^2 \quad (12) \]

3. Examples using this algorithm for analysis
As analysed in Section 1, the diffraction effect is affected by the incident wavelength \( \lambda \), image distance \( z \), incident angle \( \theta \), and pixel size determined by \( x_0 \) and \( y_0 \). The rotation angle about the x-axis also affects the diffraction effect. In the DMD system, this rotation angle is a constant (\( \alpha = 45^\circ \)).

In the following examples, we defined the control group as the incident angle \( \theta_i = 12^\circ \), incident wavelength \( \lambda = 405nm \), and the DMD pixel size (\( x_0 \) and \( y_0 \)) is 7.25 μm.

3.1. Influence of propagation distance \( z \)
For the purpose of observing the diffraction effect that changes along with the propagation distance, we obtained the simulation results for \( z = 0.01 \) mm, \( z = 1 \) mm, and \( z = 130 \) mm; these parameters were chosen from the definition of near field, Fresnel field, and Fraunhofer field, respectively.
Fig. 3 Illuminance distribution and its contour lines obtained at different distances

Fig. 3 demonstrates that the diffraction effect becomes more obvious as the imaging distance increases. The illumination area is not flat, and there are peaks in the middle. Four tails arise around the pixel. As the propagation distance increases, the light uniformity decreases.

3.2. Influence of pixel size

Commercial DMDs have four types of standard sizes. To investigate the influence of pixel size, we obtained the simulation results under experimental conditions of $a_1 = 7.25 \mu m$, $a_2 = 10.8 \mu m$, $a_3 = 13.68 \mu m$, and $a_4 = 16 \mu m$. The parameter $a$ is the pixel size corresponding to $x_0$ and $y_0$.

Fig. 4 Illuminance distribution and its contour lines obtained with different pixel sizes

Fig. 4 demonstrates that the number of peaks increases as the pixel size increases. Meanwhile, peaks appear denser and less undulatory. When $a_1 = 7.25 \mu m$, there are two peaks. When $a_2 = 10.8 \mu m$, there are four peaks. When $a_3 = 13.68 \mu m$, there are six peaks. When $a_4 = 16 \mu m$, there are eight peaks.

3.3. Influence of incident angle $\theta$

The incident angle is affected by the optical structure owing to the space limitation. To investigate the influence of incident angle $\theta$, we obtained the simulation results under the experimental conditions of $\theta_1 = 12^\circ$, $\theta_2 = 18^\circ$, $\theta_3 = 24^\circ$, $\theta_4 = 30^\circ$. 
Neighboring peaks move closer to each other as the incident angle \( \theta \) increases. The peaks are merged when the incident angle \( \theta \) is greater than 24°. Fig. 5 (d) demonstrates the light intensity when \( \theta = 30° \). Three distinct color steps represent intensity steps. The spot appears as a clip in the center.

3.4. Influence of wavelength \( \lambda \)
There are three types of typical wavelengths in conventional lithography. To investigate the influence of the wavelength, we obtained the simulation result under experimental conditions of \( \lambda_i = 0.365 \) μm, \( \lambda_h = 0.405 \) μm, \( \lambda_g = 0.436 \) μm.

Fig. 6 demonstrates that the incident wavelength has less influence on the spot shape in comparison with other independent variables. It mainly contributes to the slope of peaks. However, the influence is small and seems nonlinear.

Figures 3 to 6 show the common characteristics of illumination distribution:
(1) Illumination is not a flat-topped mode. (2) Sawteeth encircle the depression center. (3) There are four main peaks at the corner. (4) Tails are distributed along the horizontal and normal directions.

4. Calculation of diffraction disturbance
Diffraction may lead to a disturbance between the pixels. Stray light must be controlled within threshold level, particularly in a pulse width modulation resolution enhancement system.[17] This system obtains a smaller spot by controlling the incident intensity, which is based on the nonlinear absorption effect.
Furthermore, this system is sensitive to the light intensity. Superfluous illumination causes pixel deformation and blots.

A new criterion is defined to describe the disturbance in a DMD lithography system:

$$P_d = \frac{1}{4} \left(1 - \frac{I_e}{I_t}\right)$$  \hspace{1cm} (13)

where $I_t$ is the total illumination reaching the imaging plane and $I_e$ is the effective illumination at the center. The effective illumination is different from diffraction efficiency. The criterion of the diffraction efficiency is that the ratio of the power diffracting into a designated direction to the power incident at the diffractive element. In contrast, the disturbance percentage quantifies how much optical power is diffracted into a designated direction compared to the optical power reaching the imaging plane. The power lost in propagation is negligible with respect to the disturbance.

It should be noticed that, there is a $\frac{1}{4}$ in the beginning of the formula (18). That’s because diffraction occurs in four direction. $P_d$ only indicates the disturbance from a certain direction. We defined $P_d$ from the perspective of the photoresist, instead of the DMD pixel. Because in scanning maskless lithography system, the pattern contribute by multi-exposure, which means the actual exposure does is the sum of the actived DMD pixels and the disturbances from adjacent pixels passing over a certain point of photoresist. For example, in Fig 7, “A” is a certain point in photoresist, while 1~4 is 4 pixels passing over “A” in sequence. Pixel 1 and 3 is actived, which means they will be in “on state” when they pass over A. Pixel 2 and 4 is not active when they pass over A. The total exposure dose of “A” in photoresist is the sum illumination contribute by pixel 1 and 3, and the disturbance caused by actived pixels adjacent pixel 1~4. Fig 8 shows the disturbance caused by actived adjacent pixels as an example. Fig 8 reveals that the disturbance is not always come from all 4 direction. The disturbance in Fig 8 is 3 $P_d$ in such situation. In consideration of practical situation mentioned above, we defined the new criteria $P_d$, which indicates the disturbance percentage of a certain pixel in one direction. The total disturbance $T_d$ in an area of photoresist is

$$T_d = \sum^n_m n \times P_d$$  \hspace{1cm} (14)

Where $n$ is the number of adjacent actived pixels in a particular moment, $m$ is the number of pixel passing over the area “A” through the scanning process.

It should be noticed that, illumination accumulates at the same moment should be superposed in the form of complex amplitude. But the illumination accumulates at different time should be superposed in the form of light intensity. That is because the data is in the form of plural, which implies it contains the phase information. The superposition of complex amplitude refers to coherent addition in the same moment while the superposition of light intensity refers to incoherent addition in different time.

![Diagram](image)

Fig.7 take 4 pixels passing over a certain point “A” on the photoresist as an example of considering the total exposure does from the perspective of photoresist.
The simulation parameters are set as $\lambda = 0.405 \, \mu m$, $z = 1 \, mm$, $x_0 = y_0 = 7.25$, incident angle $\theta = 12^\circ$ and rotation angle $\alpha = 45^\circ$. The simulation result of $P_d$ is 7%.

5. Discussion

This simulation method can be used to determine the exposure doses, scanning path, and incident light source characteristics in maskless lithography. This method is based on a half analytical method. The simulation has three application ranges. The first application range relates to non-linear sub-diffraction lithography, which requires precise control of the spot shape and illumination distribution. These are key parameters to determine the resolution and error tolerance. Thus, this study may contribute to further study in non-linear sub-diffraction lithography, from spot-scanning to plane-scanning. The second application range deals with the scanning path. The aerial image of DMD stretches along the horizontal and normal direction. This extension may lead to a disturbance between the neighboring pixels. This disturbance accumulates further in the scanning procedure. In the maskless lithography system, the pixel field source gives multiple exposures to the imaging point, instead of a single, static exposure during scanning. Thus, the scanning procedure results in disturbance accumulation. On the other hand, the exposure repetition number relates to the scanning path. In the above condition, the degree of disturbance is 7%. We assume that the exposure threshold is 50% and that only one diffracting pixel exists near the non-exposed area. The number of acceptable repeated exposures is less than 7. Otherwise, stray light accumulates to the exposure threshold of the photoresist, resulting in the error spot. The third application involves co-simulation. The conventional optimization of a microlens array assumes that the incident beam is a plane wave. In fact, the aerial image of DMD has light intensity in the form of sawteeth on the edge. These sawteeth may result from interference within a pixel. Reducing the degree of coherence may make a more uniform intensity pattern, but reduce the resolution at the same time. [18] Hence, the MLA should co-simulate with DMD pixel so as to balance the resolution and the uniformity of the aerial image as they are projected onto the photoresist.

6. Conclusion

In this study, the non-parallel spectrum method was applied for the diffraction analysis of DMD. This algorithm can be utilized in the non-parallel region, whereas the previous simulation methods cannot. The simulation procedure involves eight main steps was presented. The process of computing was simplified for the DMD. A critical point was calculated for determining the simulation range. This model can be utilized in practical application with various incident angles, propagation distances, and pixel sizes. As an example of using this model, we obtained the diffraction efficiency of the control group. We also obtained the qualitative relationship between illumination distribution and the wavelength $\lambda$, image distance $z$, incident angle $\theta$, and pixel size $x_0$ and $y_0$ as another example using this algorithm. We summarized the common characteristics of illumination distribution and the shape of the light spot according to the simulation results for perceptual knowledge. These simulation results provide a reference for the scanning path and exposure doses in maskless lithography.

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