РАСЧЕТ, ПРОЕКТИРОВАНИЕ И ПРОИЗВОДСТВО ОПТИЧЕСКИХ СИСТЕМ

СПОСОБ ФОРМИРОВАНИЯ ЗРАЧКА ДЛЯ ВНЕОСЕВОГО ОСВЕЩЕНИЯ В ОПТИЧЕСКОЙ ЛИТОГРАФИИ

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Внеосевое освещение фотошаблона – один из ключевых способов повышения разрешающей способности проекционной системы. Для его осуществления в большинстве конструкций литографов используются фазовые дифракционные оптические элементы. В работе предложен метод формирования выходного зрачка осветительной системы внеосевого освещения фотошаблона, основанный на использовании расширителя пучка, двух аксиконов, осевого дифракционного оптического элемента и фурье-объектива. Метод обеспечивает исключение осевого освещения фотошаблона при относительной простоте конструкции осветительной системы. Приведены результаты расчета структуры дифракционных оптических элементов, обеспечивающих различные условия внеосевого освещения фотошаблона.

A METHOD OF PUPIL SHAPING FOR OFF-AXIS ILLUMINATION IN OPTICAL LITHOGRAPHY

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Off-axis illumination is one of the key resolution enhancement technologies in projection lithography system. Phase type diffractive optical elements are adopted by most of the lithography machine manufactures to realize off-axis illumination. In this paper, a method of pupil shaping for off-axis illumination in optical lithography is introduced which contains a zoom beam expander, an, circularly symmetric diffractive optical elements and a Fourier lens. The method could produce required illumination pattern for off-axis illumination at pupil plane. Compared with the conventional method of off-axis illumination, the method in this paper could eliminate deterioration of the pupil thoroughly and reduces the difficulty of the optical design of zoom lens. Base on this method, several circularly symmetric diffractive optical elements are designed for experiments, and a remarkable improvement in eliminating deterioration of the pupil is observed compared with the conventional method.

Keywords: *optical lithography, off-axis illumination, axicon, diffractive optical element, Fourier lens.*

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Introduction

In projection lithography system, off-axis illumination (OAI) is extensively utilized for critical dimension shrinking, depth of focus enhancement and image contrast enhancement [1, 2]. Phase-only diffractive optical elements (DOEs) are adopted in pupil shaping unit of most of the deep-ultraviolet (DUV) lithography machines to realize OAI because of their design flexibility, high-quality freeform illumination mode generation and stable output against the fluctuation of the input laser beam [3–5]. The conventional method [6–8] of pupil shaping for off-axis illumination in optical lithography contains the DOEs, zoom lens and axicon. The DOEs are placed at the front focal plane of the zoom lens. DOEs could modulate the phase distribution of incident beam, the required diffractive patter can be obtained at back focal plane of the zoom lens. By changing the focal length of the zoom lens, the desired size of the diffractive pattern can be obtained. And the position of object plane and image plane of zoom lens could not be changed when the focal length of zoom lens is changed. The zoom lens also requires a large range of focal length. Following the zoom lens is the axicon. By moving one of the axicon elements, the coherence factor $\sigma_{\text{out/in}}$ of OAI is adjusted accordingly [9]. However, this method will cause deterioration of the pupil because of the astigmatic of axicon and the astigmatic increases with the distance between the convex axicon and concave axicon. In general, the specifications of the pupil such as opening angle, azimuth angle, especially pole balance, are the key factors since they affect the exposure performance [10–13]. So a clear contour of pupil is important to the lithography. In this paper, we describe a method of pupil shaping for OAI in optical lithography. Compared with the conventional method, this work uses circularly symmetric DOEs and could eliminate deterioration of the pupil thoroughly. The zoom lens is also easy to be designed, because it does not need a large range of focal length, and the position of object plane and image plane of zoom lens do not be fixed when the focal length of zoom lens is changed. At the same times, the diameter of axicon is also greatly reduced.

Method

In this section, a method of pupil shaping for off-axis illumination in optical lithography is introduced. Fig. 1 is a simplified pupil shaping unit of optical lithography system. The light source emits a rounded parallel beam and enters the zoom beam expander. By changing the expansion ratio of the zoom beam expander, the desired size of the parallel beam can be obtained. Following the zoom beam expander is the axicon. By moving one of the axicon elements, the off-axis illumination can be obtained. After the axicon, the OAI passes through the circularly symmetric DOEs which could produce different off-axis illumination pattern at back focal plane (pupil plane) of the Fourier lens by irradiating the different annular zones of circularly symmetric DOEs. Circularly symmetric DOEs are adopted in pupil shaping unit in this method. We know that DOEs could modulate the phase distribution of incident beam, the required diffractive patter can be obtained. Several classical algorithms such as iterative Fourier transformation algorithm (IFTA) [14], simulated annealing algorithm [15] and genetic algorithm [16] have been used to design DOEs. The circularly symmetric DOE is divided into a lot of annular zones from 1 to n, and every annular zone is adjacent to each other as shown in Fig. 2. Every adjacent annular zone is specifically designed respectively. It has the different diffraction angle and could produce different off-axis illumination pattern correspondingly at pupil

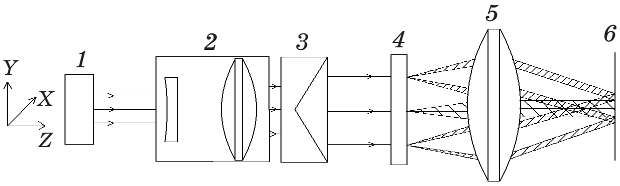

Fig. 1. Simplified pupil shaping unit for off-axis illumination in optical lithography. *1* – light source, *2* – zoom beam expander, *3* – axicon, *4* – circularly symmetric DOE, *5* – Fourier lens, *6* – pupil plane.

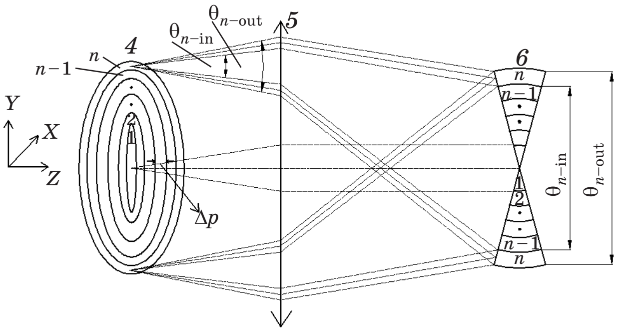

Fig. 2. Schematic diagram for principle of the circularly symmetric DOEs. *4* – circularly symmetric DOEs, *5* – Fourier lens, *6* – pupil plane.

plane. Fig. 2 demonstrates an example of circularly symmetric DOE which produces a dipole illumination pattern. When the incident beam irradiates the zone 1 of the circularly symmetric DOE, the zone 1 could modulate the phase distribution of incident beam and produces a dipole illumination pattern 1 at pupil plane. Similarly, zone n of the circularly symmetric DOE could modulate the phase distribution of incident beam and produces an off-axis dipole illumination pattern n at pupil plane. We design that the adjacent zones of the circularly symmetric DOE could modulate the phase distribution of incident beam and produce adjacent dipole illumination patterns at pupil plane. For example, when the incident beam irradiates the continuously zone 2 to (n − 1) only, the continuously dipole illumination pattern 2 to (n − 1) can be obtained at pupil plane. By this way, we can obtain the different off-axis illumination pattern by controlling incident beam to irradiate different annular zone of the circularly symmetric DOEs. The zoom beam expander and axicon are used to control the size of incident beam.

The size A of exit beam for zoom beam expander is expressed as

$$A = p \times \text{ratio}_{\text{expander}}, \tag{1}$$

where A is the exit beam size of zoom beam expander, p is the incident beam size of the zoom beam expander, p is also the exit beam size of the source, “$\text{ratio}_{\text{expander}}$” is the expansion ratio of the zoom beam expander.

Axicon is positioned between the zoom beam expander and the circularly symmetric DOEs. The width of the illumination ring can be adjusted by moving one of the axicon element along the optical axis. Fig. 3 and Eqs. (2)–(5) show principle of the axicon

$$\beta = \arcsin(n \sin\alpha), \tag{2}$$

$$\gamma = \beta - \alpha, \tag{3}$$

$$B/2 = d \tan\gamma, \tag{4}$$

$$B/2 = d \tan[\arcsin(n \sin\alpha) - \alpha], \tag{5}$$

where A is the exit beam diameter of the zoom beam expander, and it is also the incident beam diameter of the axicon. B is the inner exit beam diameter of the axicon, $(A + B)$ is the outer exit beam diameter of the axicon. α is the cone angle of the axicon, d is the distance between the two axicon elements. According to the Eqs. (1)–(5), the required A and B can be obtained by change the value of “$\text{ratio}_{\text{expander}}$” and d respectively.

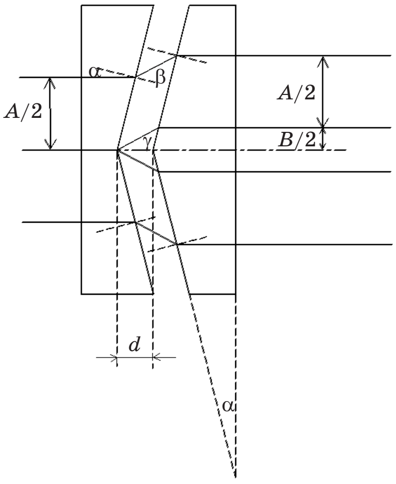

Fig. 3. Principle of axicon.

After axicon is the circularly symmetric DOEs which is divided into a lot of annular zones from 1 to n, and every annular zone has the same size and it is adjacent to each other. The width of every annular zone is Δp as shown in Fig. 2. The diffraction angle of every zone is off-axis distribution except the zone 1. The outer and inner diffraction angle of every zone is different and the subtraction result of outer and inner diffraction angle of every zone is designed to be same. After the circularly symmetric DOEs is the Fourier lens which transforms the angle distribution of circularly symmetric DOEs to the corresponding illumination pattern at pupil plane. The diffraction angle of every zone can be expressed as

$$\theta_{n-\text{out}} = D_{n-\text{out}}/f_f, \tag{6}$$

$$\theta_{n-\text{in}} = D_{n-\text{in}}/f_f, \tag{7}$$

$$\theta_{n-\text{out}} - \theta_{n-\text{in}} = D_{n-\text{out}}/f_f - D_{n-\text{in}}/f_f = \\ = (D_{n-\text{out}} - D_{n-\text{in}})/f_f, \tag{8}$$

where, $\theta_{n-\text{out}}$ is the outer diffraction angle of zone n, $\theta_{n-\text{in}}$ is the inner diffraction angle of zone n, $D_{n-\text{out}}$ is the corresponding illumination pattern outer size at pupil plane, and $D_{n-\text{in}}$ is the corresponding illumination pattern inner size at pupil plane. f_f is the focal length of Fourier lens. It is continuous and adjacent from illumination pattern 1 to n, and the annular width of illumination pattern 1 to n is also same. It is expressed as

$$D_{n-\text{in}} = D_{(n-1)-\text{out}},\ D_{(n-1)-\text{in}} = D_{(n-2)-\text{out}}, \\ D_{2-\text{in}} = D_{1-\text{out}}, \tag{9}$$

$$D_{n-\text{out}} - D_{n-\text{in}} = \\ = D_{(n-1)-\text{out}} - D_{(n-1)-\text{in}} = \ldots\ldots = D_{1-\text{out}}. \tag{10}$$

According to the Eqs. (6)–(10), we can design the diffraction angle of every zone of circularly symmetric DOEs to obtain the required illumination pattern.

From above-mentioned, we know that different off-axis illuminations patterns can be obtained at pupil plane by irradiating the different annular zones of circularly symmetric DOEs according to the Eqs. (6)–(10). The zoom beam expander and axicon are used to produce required annular illumination to irradiate different zone of the circularly symmetric DOEs according to the Eqs. (1)–(5).

Experiment and results

The previous section discusses the general description of the design method of pupil shaping unit for off-axis illumination. In this section, for the demonstration of the proposed method, several experiments are carried out where a reflective type spatial light modulator (SLM) is adopted to represent DOEs. The utilized SLM (HOLOEYE Leto, with 1920×1080 pixels of 6.4 μm in size) works under visible light illumination. Therefore the DOEs are designed under such condition. In our design for experiment, the circularly symmetric DOEs are just designed two zones to simplify the description. We design three kinds of circularly symmetric DOEs (traditional, dipole and quasar) by using the IFTA. The software called LightTrans VirtualLabR is utilized to execute the task. It is a design result of traditional pattern circularly symmetric DOE which is divided into two zones and each zone is designed individually as shown in Fig. 4b. The phase distributions of two zones are designed respectively (Figs. 4a, c). When the incident beam irradiates the zone 1 only as shown in Fig. 4b, we can obtain the illumination pattern at pupil plane (Fig. 4d). When the incident beam irradiates the zone 2 only (Fig. 4b), we can obtain the illumination pattern at pupil plane (Fig. 4e). The illumination patterns produced by the zone 1 and zone 2 respectively is designed adjacently each other. So when the incident beam irradiates the zone 1 and zone 2 (Fig. 4b), we can obtain the illumination pattern at pupil plane (Fig. 4f). The design results of dipole and quasar circularly symmetric DOEs are also designed in the same situation.

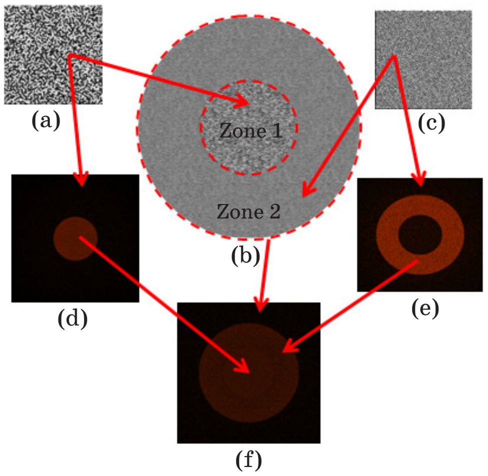

Fig. 4. Design result of traditional illumination pattern for the experiment. Explanations are in the text.

The experimental setup is shown in Fig. 5. The beam emits from an interferometer source which is a parallel light. The wavelength of the light emitted from the interferometer source is 632.8 nm. The parallel light from the interferometer source

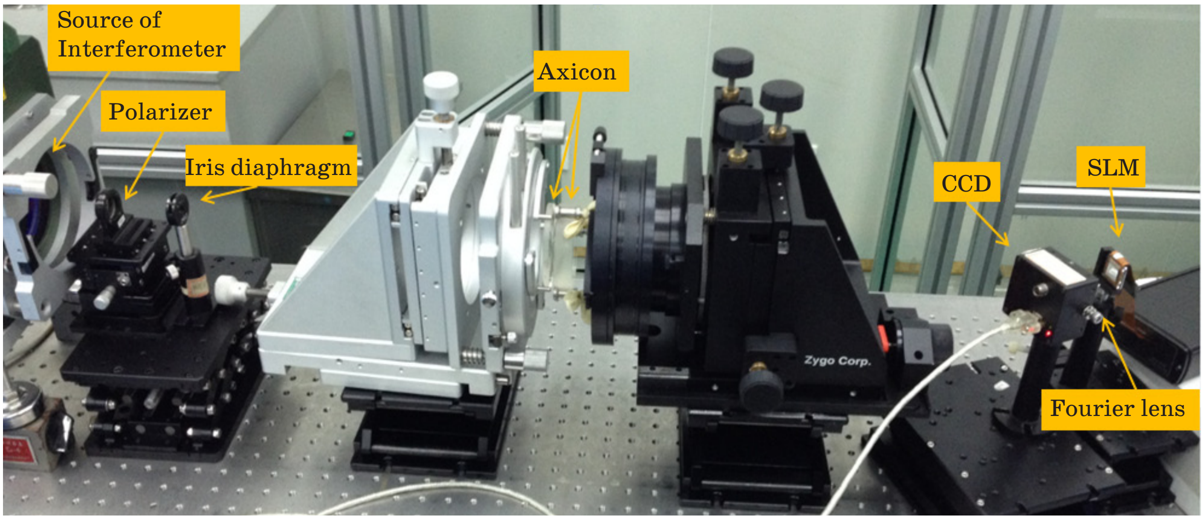

Fig. 5. Experimental setup where the SLM is used to represent DOEs.

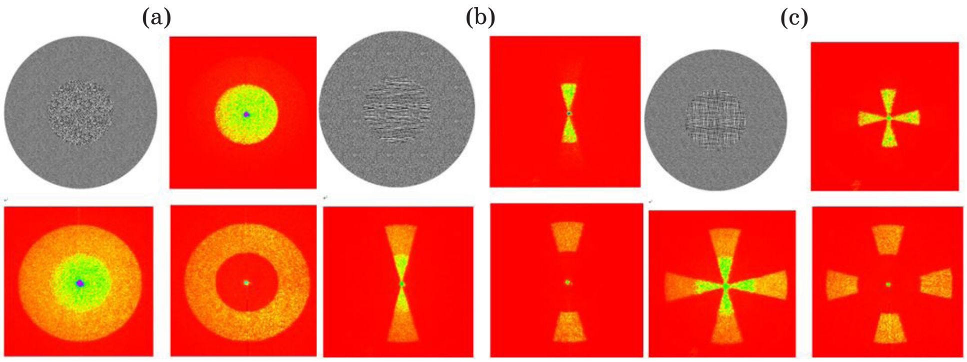

Fig. 6. Experimental results of (a) traditional, (b) dipole, (c) quasar circularly symmetric DOEs.

passes through a polarizer which is utilized to adjust the polarization state of the incident beam impinging onto the SLM, on which the designed circularly symmetric DOEs are displayed. An iris diaphragm is after the polarizer and plays a role of the zoom beam expander in the pupil shaping unit mentioned above. We can obtain the required beam size by changing the aperture of the iris diaphragm. Following the iris diaphragm is the axicon. By moving one of the axicon elements, the inner ring width of illumination is adjusted accordingly. The beam is then reflected by the SLM and Fourier transformed by using a focal length equal 50 mm Fourier lens. At the back focal plane of the Fourier transform lens, a CCD camera is placed to record the diffraction patterns produced by the circularly symmetric DOEs. And the number of pixels and the size of pixels of the CCD camera are 1280×1024 and 5.2 μm.

The design results of circularly symmetric DOEs are imported respectively to the SLM. Then we control the incident beam irradiate different zones of SLM to obtain different illumination patterns by adjusting the aperture of iris diaphragm and the distance of two elements of axicon. Fig. 6a is an experiment result of traditional circularly symmetric DOEs. Fig. 6b is an experiment result of dipole circularly symmetric DOEs. Fig. 6c is an experiment result of quasar circularly symmetric DOEs.

In the experiments, the patterns captured by the CCD camera are shown in Fig. 6. The intensity distributions are consistent with the designed results except for the zero orders. The zero order is unexpected to our optical system for the very strong energy density. However, the zero order indeed exists for fabrication errors of DOE and calibration errors and fill factor of SLM. A simple method to eliminate zero order is to add a stop at the pupil plane. It is easy to find that the results of experiments are consistent with the design results of circularly symmetric DOEs.

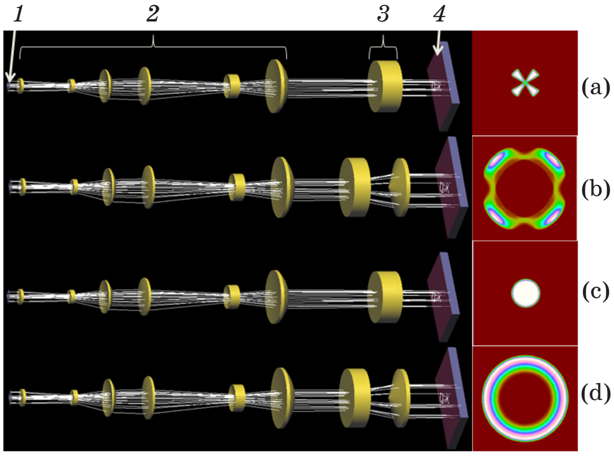

Fig. 7. Simulation results of pupil shaping for conventional method. (a) Two elements of axicon are put together, (b) the zoom lens is fixed and one element of axicon moves, (c, d) – are the same situation to the (a, b), and it just changes the DOE from quasar to traditional. *1* – circularly symmetric DOEs, *2* – zoom beam expander, *3* – axicon, *4* – pupil plane.

Fig. 7 demonstrates the simulation results of pupil shaping for conventional method mentioned in introduction. It has a DOE with fixed diffraction angle which is at the front focal plane of zoom lens. The focal length of zoom lens is designed to be 500–2500 mm. After the zoom lens is the axicon and the pupil plane is at back focal plane of the zoom lens. Fig. 7 exemplifies an example of conventional method which produces different illumination patterns. When two elements of axicon are put together, we can optimize cam curve of zoom lens to obtain a good quasar illumination pattern at pupil plane (Fig. 7a). It keeps the zoom lens is fixed and one element of axicon moves to obtain OAI, the OIA at pupil plane gets worse obviously (Fig. 7b). Compared with the fig. 6c, we find that the four poles of illumination pattern are widened in tangential direction and the opening angle of every pole becomes larger than the designed results. This problem is due to the astigmatic of axicon and the astigmatic of axicon will be changed when the distance between the two elements of axicon is changed. It means that different OAIs need different astigmatism compensation. It is difficult to find a suitable cam curve of zoom lens. We try to solve this problem by re-optimizing cam curve of zoom lens to compensate the astigmatic of axicon, but the astigmatic of axicon can not be completely eliminated. Fig. 7c, d are the same situation to the Fig. 7a, b, and it just changes the DOE from quasar to traditional. Fig. 7c is a good traditional illumination pattern. When it moves one element of axicon to obtain the OAI, there is no pupil deterioration phenomenon at pupil plane as shown in Fig. 7d. The reason is that the astigmatic of axicon is just in tangential direction and the annular illumination pattern can not appear the phenomenon caused by astigmatism of axicon.

Compared with the conventional method, the method in this paper uses circularly symmetric (DOEs) and only need the annular illumination to irradiating the circularly symmetric DOEs. So this method could eliminate deterioration of the pupil successfully, and it has been shown in experimental results. Meanwhile, the diameter of axicon is similar the size of illumination pattern in conventional method as shown in Fig. 7, but the diameter of axicon is similar to the size of circularly symmetric DOEs in this paper. The diameter of axicon is greatly reduced.

Conclusion

This work proposed a methodology to design a pupil shaping unit that can offer required OAI without astigmatic. The detailed procedures are presented and explained in this paper. The experiment results show that different OAI could be obtained by irradiating difference zones of the circularly symmetric DOEs and the contour of illumination pattern at pupil plane is clear because the method in this paper has very small aberration. This method is based on zoom beam expander, axicon, circularly symmetric DOEs and Fourier lens, compared with the conventional method, eliminating deterioration of the pupil thoroughly and having the advantage of reducing the difficulty of optical design for the zoom lens. Because the diameter of axicon is similar to the diameter of DOEs, so the difficult of optical machining is also reduced. This method of pupil shaping produces OAI of lithographic system more easily and it improves the quality of the OIA which affects the exposure performance of lithographic. This simple method is believed to be helpful for lithographic OAI technology.

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