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Optical mosaic method for orthogonally crossed gratings by utilizing information about both main periodic directions simultaneously

Hengyan Zhou, Lijiang Zeng*

State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instrument, Tsinghua University, Beijing 100084, China

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ABSTRACT

We present a method to make optical mosaic orthogonally crossed gratings by utilizing information about both main periodic directions simultaneously. The whole mosaic system for orthogonally crossed gratings is set up based on the dual Lloyd's mirror interferometer that fabricates orthogonally crossed gratings through a single exposure. The interference fringes formed by the diffractions of the exposure beams from the exposed grating areas are used as the reference to fine tune the position and attitude of the exposure beams relative to the substrates during consecutive exposures. A procedure to make mosaic for two main periodic directions simultaneously is proposed based on the presupposition that the angle between two sets of main lattice lines is constant during the mosaic. Experimentally we made a 2×1 mosaic crossed grating with a period of 574 nm in (30+30) mm ×35 mm area. The peak-valley errors of the (−1, 0)th- and (0, −1)st-order diffraction wavefronts over the whole mosaic grating area are 0.104λ and 0.163λ, respectively.

1. Introduction

Precise planar displacement measurement techniques are in demand in various fields such as semiconductor manufacturing [1], microscopic techniques [2], precision machinery [3], and so on. The most commonly used methods to measure planar displacement are laser interferometers and linear encoders. Laser interferometers offer a wide measurement range up to several meters with nanometric resolution, but the accuracy is subject to air turbulence [4]. In comparison with laser interferometers, linear encoders are more stable to environmental disturbance and less expensive [5,6]. A combination of two linear encoders can accomplish the measurement of planar displacement [7], but the combination is bulky and the linear encoder can only obtain position information on its assembled axis. To solve the above problems, planar encoders have been developed. A planar encoder, comprised of a crossed grating and a single optical head, is able to measure two-dimensional displacements simultaneously with a single measuring point and compact structure.

Planar encoders have been used in some modern lithography steppers [8,9] and precision machine tools [10]. The measuring ranges depend on the size of the crossed gratings. In recent years, the maximum diameter of the wafer used in the semiconductor industry is increasing and a transition from 300 mm to 450 mm is the current trend [11,12]; on the other hand, the sizes of optical components in some precision equipment such as astronomical telescopes and aerospace facilities are becoming much larger [13]. All the above applications require the planar encoders to have large measuring ranges. For this aim, Shimizu et al. [14] proposed the concept of aligning multiple crossed gratings in a matrix on a plane to extend the measuring ranges along the x and y axes. But this design needed a complicated optical head and complex signal processing, and the relative shift between multiple crossed gratings during measurement would result in measurement errors. Therefore, it is necessary to fabricate a large-size crossed grating on a single substrate. However, fabricating large gratings by holographic exposure requires large-aperture collimated exposure beams with low-distortion wavefront, which is costly and technically difficult.

To overcome these difficulties, researchers at MIT developed the scanning beam interference lithography (SBIL) that uses two small Gaussian beams (~1 mm diameter) to generate large-area gratings by scanning a resist-coated substrate [15,16]. The phase of exposure fringes is locked by an acousto-optic heterodyne, and the substrate displacement is controlled by a high-precision stage interferometer. As an alternative to SBIL, the optical mosaic technique, which makes multiple exposures in different areas of one substrate, has also been proposed to extend grating size. For example, Turukhano et al. presented the holographic phase aperture synthesis technique [17] by utilizing two collimated beams in a small number of consecutive

* Corresponding author.
E-mail address: zenglj@tsinghua.edu.cn (L. Zeng).

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exposures with corresponding reference gratings for phase alignment to fabricate long gratings; but this technique is lack of attitude alignment for the substrate and suffers from drift errors between the substrate and reference gratings. Another representative of the optical mosaic technique is the self-reference alignment mosaic method [18] developed by Shi et al. This method uses the latent grating (exposed but undeveloped grating in photoresist) as the reference to fine tune the position and attitude of the substrate relative to the exposure beams during consecutive exposures, getting rid of drift errors and making the whole system compact. The disadvantage of this method is the impossibility to obtain high mosaic accuracy and large exposure area simultaneously when making mosaics along the grating lines. In addition to the above methods, Gamet et al. proposed a method to print long gratings adopting a transmission grating illuminated by an intensity modulated laser beam [19]; Chen et al. presented a step-and-align interference lithography technique to fabricate large-area seamless gratings by stitching the unit exposure area step by step [20]. However, all the above methods to make large gratings aimed at one-dimensional gratings and little attention was paid to the crossed gratings. Besides, in order to get metallic crossed gratings, a common fabrication process is to make photoresist crossed gratings by holographic exposure, etch the photoresist crossed gratings, and coat the etched gratings with metallic films or replicate the etched gratings. Therefore, we mainly concern the fabrication of photoresist crossed gratings with large size.

In this paper, we focus on the optical mosaic method for orthogonally crossed gratings. We utilize the self-reference alignment mosaic method [18] to enlarge the size of orthogonally crossed gratings, with emphasis on how to obtain both high mosaic accuracy and large exposure area when making mosaics along the main lattice lines (lines connecting each periodic unit along the two main periodic directions). The optical mosaic system is an extension from the dual Lloyd's mirror interferometer system presented in our previous work [21]. The mosaic system, the mosaic procedure and the experimental results are presented in the following sections.

2. Mosaic principle

2.1. Orthogonally crossed grating equation

A crossed grating is periodic in two directions. Fig. 1 shows the real space lattice of an orthogonally crossed grating. We set up a rectangular Cartesian coordinate system whose x and y axes are parallel to the two periodic directions respectively and the z axis is perpendicular to the grating plane. The two main periods are denoted by d_1 and d_2; $\boldsymbol{\kappa}_1$ and $\boldsymbol{\kappa}_2$ are unit vectors along the two grating vectors. The two sets of main lattice lines are indicated by the red and blue lines; the main lattice lines along the y and x axes are named y-direction lattice lines and x-direction lattice lines respectively.

For ease of discussion in the sections below, we make a brief introduction about the orthogonally crossed grating equation. Define $\mathbf{n}$ as the unit normal vector of the grating plane, $\mathbf{k}_{inc}$ as the wave vector of

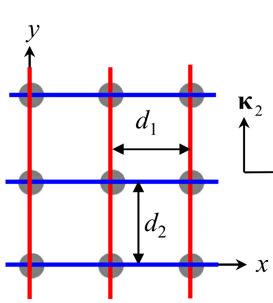

Fig. 1. Real space lattice of an orthogonally crossed grating.(For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

the incident beam, and $\mathbf{k}_{mn}$ as the wave vector of the (m, n)th diffracted order. The reciprocal lattice of an orthogonally crossed grating is given by

$$\mathbf{G}_{mn} = mK_1\boldsymbol{\kappa}_1 + nK_2\boldsymbol{\kappa}_2, \tag{1}$$

where $K_1=2\pi/d_1$ and $K_2=2\pi/d_2$. The orthogonally crossed grating equation is given by

$$\mathbf{n}\times(\mathbf{k}_{mn}-\mathbf{k}_{inc})\times\mathbf{n} = \mathbf{G}_{mn}, \quad \mathbf{k}_{mn}^2 = k^2, \tag{2}$$

where k is the wave number of the medium in which the diffraction order $\mathbf{k}_{mn}$ is considered. Solving for $\mathbf{k}_{mn}$ from Eq. (2) we have

$$\mathbf{k}_{mn} = \mathbf{k}_{mn}^{//} + \mathbf{n}\gamma_{mn}, \tag{3}$$

where

$$\mathbf{k}_{mn}^{//} = \mathbf{G}_{mn} + \mathbf{n}\times\mathbf{k}_{inc}\times\mathbf{n}, \tag{4}$$

$$\gamma_{mn} = \pm\sqrt{k^2-(\mathbf{k}_{mn}^{//})^2}, \tag{5}$$

in which reflected orders take positive sign and transmitted orders take negative sign. When the crossed grating rotates about an arbitrary axis $\mathbf{c}$ for an infinitesimal rotation $d\theta$ while $\mathbf{k}_{inc}$ is fixed, the directional change of (m, n)th diffracted wave vector is given by

$$d^g\mathbf{k}_{mn} = \mathbf{c}\times(\mathbf{k}_{mn}-\mathbf{k}_{inc})d\theta + \frac{\mathbf{n}\mathbf{k}_{mn}}{\mathbf{n}\cdot\mathbf{k}_{mn}}\cdot(\mathbf{c}\times\mathbf{k}_{inc})d\theta. \tag{6}$$

2.2. Mosaic conditions

The optical mosaic method is to make multiple exposures in different areas of one substrate. After one exposure, the substrate is moved to the position of next exposure. The substrate has six degrees of freedom during this movement, and five of them may lead to mosaic errors.

If the moving distance Δx along the x axis is not an integer multiple of the grating period d_1, phase error for the y-direction lattice lines between the two exposure areas (i.e., Areas I and II) will be caused, as Fig. 2(a) shows. Similarly, if the moving distance Δy along the y axis is not an integer multiple of the grating period d_2, there will be a phase error for the x-direction lattice lines between Areas I and II.

If the substrate has a tilt angle $\Delta\theta_y$ about the y axis, the period of y-direction lattice lines between two exposure areas will have an error of $\Delta d_1=d_1-d_1'=d_1-d_1/\cos(\Delta\theta_y)$, which is second order in $\Delta\theta_y$ and can be ignored when $\Delta\theta_y \ll 1$, as Fig. 2(b) shows. Likewise, if the substrate has a tilt angle $\Delta\theta_x$ about the x axis, the period of x-direction lattice lines between two exposure areas will have an error of $\Delta d_2=d_2-d_2'=d_2-d_2/\cos(\Delta\theta_x)$, which can be ignored when $\Delta\theta_x \ll 1$.

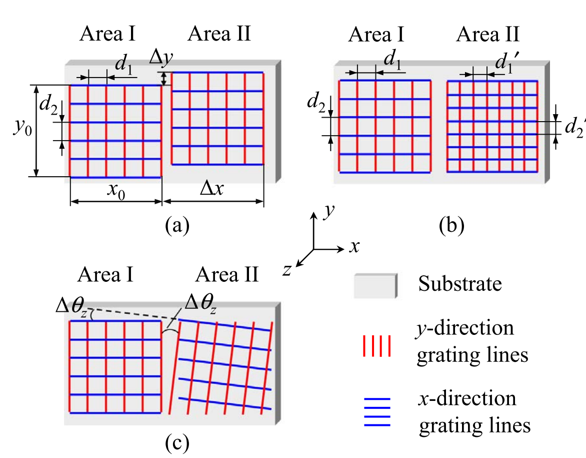

Fig. 2. Mosaic errors. (a) Phase error. (b) Lattice lines' period error. (c) Lattice lines' direction error.