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Method to fabricate orthogonal crossed gratings based on a dual Lloyd's mirror interferometer

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 propose a dual Lloyd's mirror interferometer with two mutually perpendicular mirrors to fabricate orthogonal crossed gratings through a single exposure. Theoretical analysis shows that in this interferometer the angle between two main periodic directions of the crossed grating is solely determined by the normal directions of the two Lloyd's mirrors and the substrate. To verify this theoretical prediction, four groups of crossed gratings were fabricated. The measurement results agree well with the theoretical relationship.

1. Introduction

A planar encoder can be used to measure two-dimensional (2D) displacements with nanometer resolution [1,2]. Because of the compact structure, the planar encoder is immune to the environmental disturbance and less vulnerable to Abbe errors, thus having a broad range of application prospect in the field of semiconductor manufacturing [3] and precision machining [4]. The key component in a planar encoder is a crossed grating, i.e., a grating that is periodic in two directions. Crossed gratings have also been used for evaluating the 2D contouring errors of machine tools [5], or calibrating the lateral scales of many kinds of microscopes [6,7] such as the scanning electron microscope (SEM) and the atomic force microscope (AFM). The angle between the two periodic directions is an important technical parameter for a crossed grating. For example, if this angle deviates from 90°, cross-talk error will be caused during the measurement in a planar encoder [8]. Therefore, it is necessary to study the factors influencing the angle between the two periodic directions during the fabrication process.

Interference lithography is a traditional method for fabricating crossed gratings. Recently, both two-beam interference technique [9,10] and multiple-beam interference technique [11–14] have been investigated theoretically and experimentally. In the two-beam interference technique, a crossed grating can be made by rotating the substrate between two sequential exposures [15,16]; while the multiple-beam interference technique brings convenience because a crossed grating can be produced through a single exposure [14]. The Lloyd's mirror interferometer system has distinct advantages such as simple configuration, fast alignment and high flexibility in adjusting grating period, and thus is a typical setup for the multiple-beam interference technique. Several different configurations of multi-beam Lloyd's mirror interferometers were proposed recently for fabricating two-dimensional periodic structures with a single exposure. Li et al. [17] presented a two-axis Lloyd's mirror interferometer to fabricate crossed gratings, in which the angles between the substrate and two Lloyd's mirrors are both larger than 90°. Boor et al. [18] created hexagonal hole/dot arrays by a modified Lloyd's mirror interferometer where the two Lloyd's mirrors are at an angle of 120° and both perpendicular to the substrate. Vala et al. [19] proposed a corner reflector-like interferometer formed by two Lloyd's mirrors and a substrate to fabricate periodic plasmonic arrays with rectangular symmetry. However, the above researches did not focus on the relationship between the system configuration and the angle of two periodic directions for the crossed grating.

In this paper, we present a dual Lloyd's mirror interferometer system with two mutually perpendicular mirrors to fabricate orthogonal crossed gratings. This system allows fabricating a crossed grating with a single exposure. The factors influencing the angle between the two periodic directions of the crossed grating are analyzed in detail and a theoretical formula is given that shows the angle of two periodic directions is solely determined by the normal directions of the two Lloyd's mirrors and the substrate.

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

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Experimental results agree well with the theoretical prediction. Our formula is applicable to not only our system but also the systems of Refs. [17–19].

2. Exposure system

The dual Lloyd's mirror interferometer is depicted in Fig. 1(a). A linearly polarized laser beam is divided into two beams by the polarization beam splitter PBS_1 and one of them is directed by the mirror M_0. The two beams are cleaned up by the spatial filters SF_1 and SF_2, collimated by the lenses L_1 and L_2, limited to have rectangular sectional profiles by the optical diaphragms D_1 and D_2, reflected by the mirrors M_1 and M_2, and finally form the collimated exposure beams I_1 and I_2. The half-wave plate WP_0 is used for adjusting the intensity ratio between I_1 and I_2, while the half-wave plates WP_1 and WP_2 are used for adjusting the beams' polarization directions. The Lloyd's mirrors R_1, R_2, and the substrate S are perpendicular to each other. The path $WP_i \to SF_i \to L_i \to D_i \to M_i \to (R_i/S)$ forms a Lloyd's mirror interferometer, where $i=1,2$. The white dash–dot line and dotted line represent the optical axes of the two paths, and they go through the intersection lines of the planar surfaces of R_i and S. Half of beam I_1 meets S directly, while the other half is reflected by R_1 before reaching S, as shown in Fig. 1(b). The two parts interfere with each other and produce a set of line fringes [red lines in Fig. 1(b)] on the surface of S. Similarly, beam I_2 is projected onto R_2 and S, forming another set of line fringes on S (approximately perpendicular to the first set, not shown in the figure).

Suppose there is no interference between I_1 and I_2 in Fig. 1. The photoresist-coated substrate S is exposed by the two sets of line fringes, and then a crossed grating is generated as shown in Fig. 2(a), where the gray dots form the lattice of the crossed grating; the red lines and green lines represent two sets of grating grooves produced by beams I_1 and I_2 respectively; $\hat{\mathbf{b}}_1$ and $\hat{\mathbf{b}}_2$ are unit vectors along the two periodic directions whose included angle is α. Fig. 2(b) is the corresponding reciprocal lattice, where $\hat{\boldsymbol{\kappa}}_1$ and $\hat{\boldsymbol{\kappa}}_2$ are unit vectors along the grating vectors $\mathbf{K}_1$ and $\mathbf{K}_2$ respectively, and their included angle ω is supplementary to the angle α,

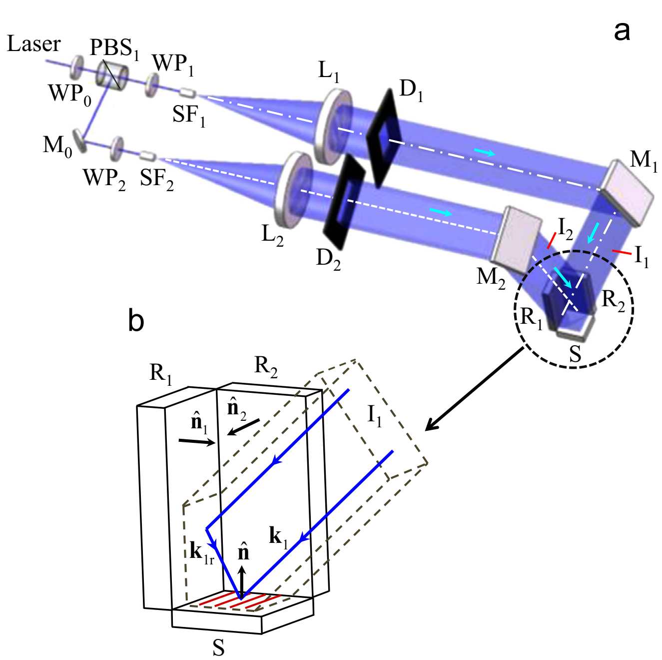

Fig. 1. Optical setup for fabricating crossed gratings. (a) The dual Lloyd's mirror interferometer. (b) Layout of the Lloyd's mirrors and the substrate.

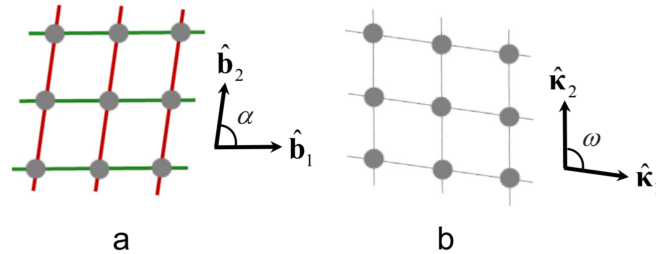

Fig. 2. The real space lattice (a) and reciprocal space lattice (b) of a crossed grating.

namely $\omega = 180° - \alpha$.

3. Theoretical analysis

Theoretical calculation for the value of angle α is performed as follows. We define $\hat{\mathbf{n}}_1$, $\hat{\mathbf{n}}_2$, and $\hat{\mathbf{n}}$ as the unit normal vectors of R_1, R_2, and S, respectively, as shown in Fig. 1(b). The beam I_i is considered as a perfect plane wave and the surface of R_i is considered as an ideal plane. The wave vectors of beam I_i and its reflected beam after R_i are respectively denoted by $\mathbf{k}_i$ and $\mathbf{k}_{ir}$ ($i=1,2$). The relationship between them is

$$\mathbf{k}_{ir} = \mathbf{k}_i - 2(\mathbf{k}_i \cdot \hat{\mathbf{n}}_i)\hat{\mathbf{n}}_i. \tag{1}$$

Denote $\Delta\mathbf{k}_i$ as the difference between $\mathbf{k}_i$ and $\mathbf{k}_{ir}$. The equiphase plane of the interference field in space produced by I_i and its reflected beam is

$$\Delta\mathbf{k}_i \cdot \mathbf{r} = 2(\mathbf{k}_i \cdot \hat{\mathbf{n}}_i)\hat{\mathbf{n}}_i \cdot \mathbf{r} = \varphi = \text{const}, \tag{2}$$

where $\mathbf{r}$ is the position vector of an arbitrary point and φ is the phase at that point. $\Delta\mathbf{k}_i$ is perpendicular to the equiphase plane, and its projection on the substrate surface is the grating vector, namely

$$\mathbf{K}_i = \hat{\mathbf{n}} \times \Delta\mathbf{k}_i \times \hat{\mathbf{n}} = 2(\mathbf{k}_i \cdot \hat{\mathbf{n}}_i)[\hat{\mathbf{n}}_i - (\hat{\mathbf{n}}_i \cdot \hat{\mathbf{n}})\hat{\mathbf{n}}]. \tag{3}$$

Therefore, the angle α is determined by

$$\cos\alpha = -\cos\omega = \frac{-\mathbf{K}_1 \cdot \mathbf{K}_2}{|\mathbf{K}_1||\mathbf{K}_2|} = \frac{(\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}})(\hat{\mathbf{n}}_2 \cdot \hat{\mathbf{n}}) - \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2}{\sqrt{1 - (\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}})^2}\sqrt{1 - (\hat{\mathbf{n}}_2 \cdot \hat{\mathbf{n}})^2}}. \tag{4}$$

The above equation implies that the angle α is independent of the incident wave vector $\mathbf{k}_i$ and solely determined by the normal directions of the two Lloyd's mirrors and the substrate.

In planar encoders, to decrease cross-talk errors during the measurement, orthogonal crossed gratings (i.e., $\alpha = 90°$) are needed, for which the value of $(\alpha - 90°)$ is defined as the orthogonality error and denoted by θ. Eq. (4) demonstrates that when $\hat{\mathbf{n}}_i \cdot \hat{\mathbf{n}} = 0$ ($i=1$, or 2) and $\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2 = 0$, orthogonal crossed gratings can be obtained. For simplicity three variables u, v, and w are defined as $u = \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}} = \cos\beta_1$, $v = \hat{\mathbf{n}}_2 \cdot \hat{\mathbf{n}} = \cos\beta_2$, and $w = \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2 = \cos\beta_0$, where β_0, β_1, and β_2 are the intersection angles between $\hat{\mathbf{n}}_1$, $\hat{\mathbf{n}}_2$, and $\hat{\mathbf{n}}$. For $u \ll 1$ and $v \ll 1$, Eq. (4) can be approximated as

$$\cos\alpha = -\sin\theta \approx (uv - w)\left(1 + \frac{1}{2}u^2\right)\left(1 + \frac{1}{2}v^2\right). \tag{5}$$

The above equation demonstrates that w has a first-order effect on $\sin\theta$, while the effects of uv, u^2, and v^2 are in second-order. If the accuracy of the orthogonality error θ is required to be 0.2″, those second-order terms can be negligible when $|u| < 10^{-3}$ and $|v| < 10^{-3}$, namely $|90° - \beta_i| < 206''$ ($i=1, 2$). We refer to this condition as the attitude condition of the substrate S. When S meets the attitude condition, Eq. (5) can be approximated as $\sin\theta \approx w = \cos\beta_0$, namely