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Fabrication and characterization of short-period double-layer cross-grating with holographic lithography

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ABSTRACT

A cross-grating with short period and double layer is designed, and a method combining holographic lithography and lithography-etch-lithography-etch is proposed to manufacture it. The scalar diffraction theory and the rigorous coupled wave analysis are employed to analyze the diffraction characteristics of the double-layer cross-grating (DLCG). It reveals that the efficiencies of the $(\pm 1, \pm 1)$ orders possess perfect complementarity under normal incidence. The equivalent high efficiency for TE and TM polarization can be realized which means the high signal-to-noise ratio and fringe contrast can be simultaneously achieved for heterodyne grating interferometers (HGIs). Furthermore, a gold-coated DLCG with grating pitch of 2 μm and pattern area of 60 mm × 60 mm etched on the quartz substrate is fabricated with the proposed method. The displacement resolution, measurement range and long-term stability can be reliably guaranteed for HGIs with this grating. The characteristics of the DLCG are also experimentally tested and compared with the theoretical analysis. Reasonable consistency is obtained and the capabilities of both the DLCG and the fabrication method are verified.

1. Introduction

Two-dimensional (2D) gratings have been widely used in a variety of fields, such as 2D beam splitter [1], color filtering [2], digital holography [3], X-ray imaging [4] and so on. The characteristics including diffraction efficiency, wavelength selectivity and polarization dependency are considered to be the main reason for 2D gratings to accomplish these functions [5,6]. Besides, the grating pitch and long-term stability sometimes are also quite important for 2D gratings, since they may be utilized as the benchmark in some optical metrology applications [7,8]. As a typical application for 2D gratings, heterodyne grating interferometers (HGIs) have been intensively investigated in recent years [9,10]. Inevitably, the overall performances of HGIs are also evidently affected by the utilized 2D grating. For example, the diffraction efficiency and polarization dependency properties of the 2D grating would direct influence the signal-to-noise ratio (SNR) and fringe contrast of measuring signals, which are critical to the phase measurement accuracy of HGIs [11]. Meanwhile, the grating pitch and effective pattern area are also quite important to the displacement resolution and measurement range of HGIs [12]. Additionally, the high reliability of the grating scale is indispensable for the good long-term stability of HGIs [13]. Therefore, 2D gratings with short period, large area, high stability and excellent diffraction characteristics are greatly expected to be developed for HGIs.

Since 2D gratings play an important role in optical metrology, special attentions have been paid on them recently. In our previous study [14], a single-layer cross-grating (SLCG) is designed and fabricated for HGIs. Combined with the proposed eightfold subdivision method, it can simultaneously realize the high SNR, high fringe contrast and high optical subdivision for HGIs. However, the designed SLCG is manufactured by the mask-based lithography in Ref. [14]. Since 2D masks with small feature size and large pattern area are hard to be produced, the short-period and large-area SLCGs would also be difficult to be fabricated with this method [15]. Holographic lithography (HL) perhaps is a promising approach for manufacturing large-area periodic 2D diffraction optical elements (DOEs) [16]. Kimura fabricated a short-period 2D grating utilizing the HL and double exposure technique for three-axis displacement measurement [17]. Li proposed a two-axis Lloyd's mirror interferometer for 2D metrological gratings fabrication [18]. Unfortunately, the surface profile induced by the double exposure technique was found to be different along the X- and Y-directions [18]. Meanwhile, since the effective pattern areas are mainly restricted by the mirror size and fringe contrast, large-area 2D gratings perhaps are also difficult to be manufactured with the ordinary two-axis Lloyd's mirror interferometer [19].

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Additionally, the two gratings [17,18] are all fabricated on the photoresist layer without etched on the quartz substrate. Since the rigidity and the thermal expansion coefficient of the photoresist material are relatively low and high [20], both the safety and the stability of the two gratings may be hard to be guaranteed during their applications. Hence, fabricating the SLCG with these two methods perhaps are difficult recently with the ordinary equipment, and the short-period and large-area etched 2D gratings with excellent diffraction characteristics are still needed to be investigated.

In this paper, a double-layer cross-grating (DLCG) with equivalent high efficiency for TE and TM polarization is designed, and a method combining HL and lithography-etch-lithography-etch (LELE) is proposed to manufacture it. The scalar diffraction theory (SDT) and the rigorous coupled wave analysis (RCWA) are firstly utilized to analyze the diffraction characteristics of the DLCG. The results are also compared with the SLCG to learn the differences between these two gratings. Then the fabrication process of the DLCG with the proposed method is presented, and a DLCG with grating pitch of 2 μm and pattern area of 60 mm × 60 mm is etched on the quartz substrate. The feasibility of this method used for short-period and large-area multilevel grating fabrication is also discussed. Finally, the diffraction characteristics of the manufactured DLCG are tested and compared with the theoretical analysis. The reasons for the discrepancy are also analyzed and the main works of this investigation are summarized.

2. Diffraction characteristics analysis

2.1. Scalar diffraction theory

The structure of the designed double-layer cross-grating is shown in Fig. 1. The grating pitches and duty cycles along two perpendicular directions are denoted as d_x, d_y, f_x and f_y. The groove depth of the first and the second layer are denoted as h_1 and h_2, and the incident angle and azimuthal angle of the incident laser are denoted as θ and ϕ, respectively. The transmission function $T(x,y)$ of the DLCG can be expressed as $t(x,y)\exp\left[j\phi(x,y)\right]$, where $t(x,y)$ and $\phi(x,y)$ represent the amplitude and the phase modulation parts of the grating, respectively. Since phase gratings are a better choice to achieve higher efficiency compared with amplitude gratings, the $t(x,y)$ will be set to 1 in the following analysis. According to the Cartesian coordinates system *OXYZ* constructed on the DLCG in Fig. 1, the transmission function for the reflection type DLCG can be written as:

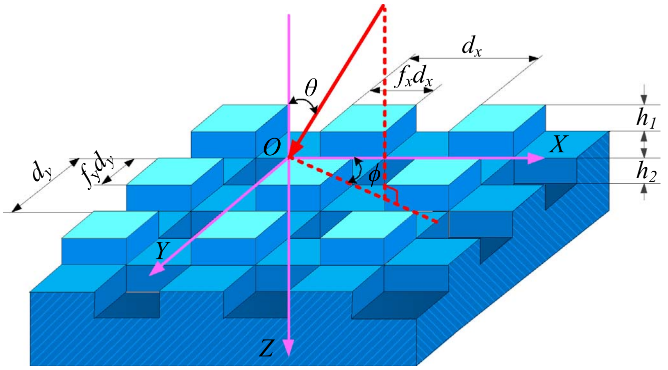

Fig. 1. Structure of the designed double-layer cross-grating.

$$T(x,y)=\begin{cases}1 & 0\le x<f_xd_x, \quad 0\le y<f_yd_y\\ \exp\left[i\alpha_1(x,y)\right] & f_xd_x\le x\le d_x, \quad 0\le y<f_yd_y\\ \exp\left[i\alpha_1(x,y)\right] & 0\le x<f_xd_x, \quad f_yd_y\le y\le d_y\\ \exp\left[i\alpha_2(x,y)\right] & f_xd_x\le x\le d_x, \quad f_yd_y\le y\le d_y\end{cases} \tag{1}$$

with

$$\alpha_1(x,y)=4\pi nh_1/\lambda \tag{2}$$

$$\alpha_2(x,y)=4\pi n\left(h_1+h_2\right)/\lambda \tag{3}$$

where n is the refraction index of air around the grating and λ is the incident wavelength. To facilitate the grating fabrication, the groove depth of the first and the second layer are assumed to be equal. Moreover, the normalized depth h_n which is defined as the ratio of groove depth and incident wavelength is utilized for convenience [21]. Then the phase modulation part of the grating can be expressed as:

$$\alpha_2(x,y)=2\alpha_1(x,y)=8\pi nh_n \tag{4}$$

Based on the deduced transmission function, the relative amplitude of the specific diffraction order of the DLCG can be calculated with the SDT [22]:

$$\eta(m,n)=\frac{1}{d_xd_y}\int_0^{d_x}\int_0^{d_y}T(x,y)\exp\left[-i\left(\frac{2\pi mx}{d_x}+\frac{2\pi ny}{d_y}\right)\right]\mathrm{d}x\mathrm{d}y \tag{5}$$

where m and n denote the diffraction order along the x and y directions [23], respectively. Then the diffraction efficiency of the (m,n) order can be obtained as $\eta^2(m,n)$. Since only the duty cycle and groove depth of the grating can be optimized with SDT, the diffraction efficiencies of the (0, 0), (0, 1), (1, 1) and (0, 2) orders as a function of duty cycle and normalized depth are illustrated in Fig. 2. The color bar at the right of each figure indicates the achievable diffraction efficiency with the unit of percentage. The result reveals that the diffraction efficiencies of all the four orders are symmetrical with the duty cycle of 0.5. Besides, they are all periodically varied with the normalized depth of 0.5. The efficiencies of the (0, 0) and (1, 1) orders almost present an opposite response to the structure parameters. Meanwhile, the efficiencies of the (0, 1) and (0, 2) orders exhibit complex relationship with the structure parameters. With the duty cycle of 0.5 and normalized depth of 0.25, the (1, 1) order get the highest efficiency of 16.32% and all the other three orders vanish. This can be chosen as the optimal structure parameters for DLCGs. Additionally, since the practical fabrication parameters of DLCGs cannot be exactly consistent with the design values, the influence of the imperfect fabricating parameters can also be learned from Fig. 2. When the structure parameters deviate from the optimal values, the efficiencies of all the diffraction orders would also be affected. Thus the practical performances of nearly all the fabricated DOEs are observed to be degraded compared with the theoretical results [24–26].

2.2. Rigorous coupled wave analysis

Since the SDT might be not totally reliable when the grating pitch shrinks to the order of incident wavelength [27], the RCWA compiled by ourselves with the MATLAB language is then utilized to investigate the diffraction efficiency, wavelength selectivity and polarization dependency of the DLCG. Gold is selected as the coating material for its high reflectivity in the visible region. The incident angle and azimuthal angle are set to be zero, and the grating pitches and duty cycles of both directions are assumed to