Grating imaging scanning lithography

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We present a grating imaging scanning lithography system for the fabrication of large-sized gratings. In this technology, ±1-order diffractive beams are generated by a phase grating and selected by a spatial filter. Meanwhile, a $4f$ system enables the ±1-order diffractive beams to form a grating image with a clear jagged-edge boundary on the substrate. A high-precision two-dimensional (2D) mobile stage is used for complementary cyclical scanning, thereby effectively eliminating image stitching errors. The absence of such errors results in a seamless and uniform large-sized grating. Characterized by a simple structure, high energy use, and good stability, this lithography system is highly relevant to the high-speed and cost-effective production of large-sized gratings.

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A diffraction grating is an optical component that disperses different wavelengths of an incident light into different diffraction angles. Diffraction gratings are widely used in laser-pulse compression, spectroscopy, dense wavelength division multiplexing devices, telecommunication multiplexing, and similar applications[1,2]. The demand for large-sized diffraction gratings in the spectrometer industry and laser fusion facilities continues to grow[3−7]. The fabrication method for such components is currently a significant research interest. Two main technical approaches are presently used to manufacture large-sized gratings. The mainstream approach is the holographic interference technique[6,8]. The other technique is scanning beam interference lithography, invented by the Massachusetts Institute of Technology[6,9,10].

The holographic interference technique is based on exposure with dual laser beam interference. With the advantages of good uniformity and high-quality wavefronts, the Lawrence Livermore National Laboratory[6] and Yvon[8] have exploited this technology to produce large-sized gratings. Despite its advantages, however, this technique requires well-collimated beams to generate aberration-free gratings and expensive high-quality optical devices, whose sizes should be larger than those of gratings (e.g., a meter-scale grating requires a meter-sized lens)[6]. A pair of meter-sized diffraction-limited lenses is extremely difficult and expensive to fabricate because of the stringent requirements of quality control processes.

Scanning beam interference lithography[5,9−11] is based on scanning beam interference technology, as well as traditional double-beam interference[9]. It uses two Gaussian beams produced by a beam splitter to induce double-beam interference on the substrate, and enables the fabrication of large-sized gratings through scanning techniques instead of through large-diameter lenses. Nevertheless, because the derived interference image is characterized by blurry boundaries and because its intensity is of Gaussian distribution[10], scanning exposure should be precisely assigned with neighboring last-time scanning. When misregistration occurs between adjacent scanning areas, noticeable defects form.

Anvik Corporation proposed a seamless scanning hexagonal imaging method for fabricating large-area, high-resolution elements for the microelectronics and optoelectronics industry[9]. This system uses the complementary overlap between adjacent hexagonal scans to form a consistent joined region that is free of stitching errors[9]. The Anvik scheme, however, is unsuitable for fabricating high-density gratings because such components have considerably large diffraction angles. Including all such diffraction orders presents extreme difficulties for an imaging lens.

In this letter, we propose grating imaging scanning lithography for fabricating large-sized gratings. In this technology, phase gratings with jagged edges are used to generate diffractive beams, and a spatial filter is used to select ±1-order diffractive beams, so that interference fringes are achieved by two collinear beams in a common path[11]. At the same time, a $4f$ system enables the phase gratings to form clear images in image planes, and complementary cyclical scanning with a high precision two-dimensional (2D) mobile stage enables the elimination of image stitching errors. These features result in seamless and uniform large-sized gratings. We report the details of the principle that governs the proposed technology, its operation procedure, and the analysis of the fabrication of large-sized gratings. Compared with traditional technical methods[6,9], the proposed technology features a simple structure, the absence of stray light, high energy use, and good stability. With this technology, producing gratings for custom-oriented applications is feasible.

The schematic of the developed grating imaging scanning lithography is presented in Fig. 1, which shows that a $4f$ system is used to form a grating area with clear boundaries[11].

The analysis of the $4f$ system from the perspective of Fourier optics indicates that input image $E(x,\, y)$ and output image $E'(x,\, y)$ have the following relationship:

$$E'(x,y)=\iint_{-\infty}^{\infty}E(x,y)\delta(x+x',y+y')\mathrm{d}x\mathrm{d}y. \qquad (1)$$

Equation (1) shows that after two Fourier transforms, only the symbol of independent variables is reversed, indicating that the output and input images are identical but reversed. Another feature of the $4f$ system is that a spatial filter can be added in the spectrum plane to enable only ±1-order diffractive beams to pass through.

We use a transmission phase grating with grating period d, whose diffraction angle θ is determined by

$$d\sin\theta=m\lambda \quad m=0,\pm1,\pm2,\ldots. \qquad (2)$$

As shown in Fig. 1, the angle ω between ±1-order diffractive beams is 2θ. As derived from Eq. (2), $\sin\theta=\lambda/d$.

Through the $4f$ system, ±1-order diffractive beams form periodic interference fringes on an image plane[11]. The angle between coherent beams ω' is equal to that between ±1-order diffractive beams ω under two identical lenses. Grating period Λ is related to the angle between coherent beams ω' in the following manner:

$$\Lambda=\lambda/\left(2\sin\frac{\omega}{2}\right)=d/2. \qquad (3)$$

Thus, the final grating period Λ is half of transmission grating period d.

In our experiment, a large-sized diffraction grating is fabricated by the proposed grating imaging scanning lithography. We use a He-Cd laser with a wavelength of 442 nm. The laser beam is incident into an expanding system and a collimating lens (focal length, 400 mm; diameter, 100 mm). The collimated beam is split through a phase grating with a jagged edge (groove density, 100 lines/mm; groove depth, 442 nm). Then, the beam enters the $4f$ system lenses L1 and L2 (focal length, 700 mm; diameter, 120 mm). A spatial filter is used to enable only ±1-order diffractive beams to pass through. Finally, a grating image is formed on the photoresist layer on a substrate that is fixed onto a high-precision 2D mobile stage (M-511.HD, Physik Instrumente, 100 mm travel range, 50-nm positioning accuracy). As shown in Fig. 2, a large-sized grating is obtained through the cyclical scanning of the mobile stage.

With this lithographic technology, we obtain a grating with a period of 5 μm and dimensions of 100 × 100 (mm). The scanning electron microscope (SEM) of the splicing area between double scanning is shown in Fig. 3, in which stitching errors can hardly be observed.

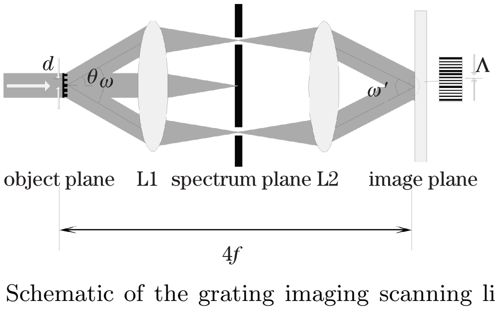

Fig. 1. Schematic of the grating imaging scanning lithography.

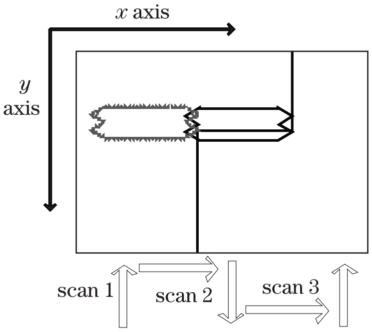

Fig. 2. Cyclical scanning process. The dotted portion indicates previously proposed scanning and the solid portion shows complementary scanning.

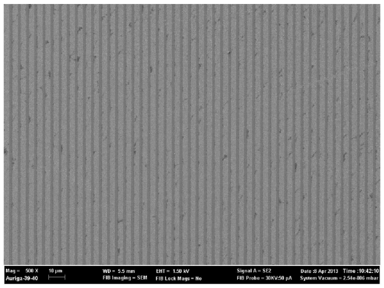

Fig. 3. SEM image of the splicing area between double scanning.

Compared with previously proposed fabrication technologies, our method presents a number of advantages. Firstly, the spatial filter can eliminate other diffraction beams except ±1-order diffractive beams, which form interference gratings on substrates. Given that these two beams are collinear and move along a common path, coherence and fringe uniformity are easily achieved. Meanwhile, phase gratings can weaken zero-order beams and enhance ±1-order diffractive beams; thus, energy efficiency is high and exposure time is reduced.

Secondly, with the $4f$ system, phase gratings can produce real images with clear boundaries, both sides of which have the same jagged edges (Fig. 2). Complementary cyclical scanning through jagged parts ensures uniform energy and matching fringes[12]. In this manner, eliminating stitching errors is feasible, resulting in seamless and uniform large-sized gratings.

Thirdly, the proposed method can be used to fabricate gratings of different densities and sizes. In the proof-of-principle experiment, the numerical aperture (NA) of the lens is 0.1. When grating density increases, for example, creating a pulse compression grating with a density of 1780 lines/mm for a laser confinement fusion system[5] necessitates a large diffractive angle between ±1-order diffractive beams; thus, the lens with a high NA is required to ensure that ±1-order diffractive beams can freely enter the $4f$ system. When the He-Cd laser with a 442-nm wavelength is used, in accordance with the principle of the proposed technology, the input phase grating density should be 890 lines/mm with a period d of 1.12 μm. The angle ω between ±1-order diffractive beams is given by

$$\omega=2\theta=2\mathrm{arc}\sin\lambda/d=46.5^\circ. \qquad (4)$$

The NA of the lens is

$$\mathrm{NA} \geqslant \tan\theta = 0.43. \qquad (5)$$

Therefore, fabricating a pulse compression grating with a density of 1 780 lines/mm is feasible with the use of a lens with an NA of less than 0.5.

Reducing the wavelength of incident beams to decrease lens NA is also feasible. We take the KrF laser with a 249-nm wavelength as an example. At a lens NA of 0.5 and angle ω between ±1-order diffractive beams of 46.5°, the period of the phase grating is 630 nm and the density of a large-sized grating is 3 100 lines/mm, according to Eq. (4). Conversely, when a pulse compression grating with a density of 1 780 lines/mm is fabricated, the angle ω between ±1-order diffractive beams is 25.7°. That is, the NA of the lens should be 0.23, a feasible value.

In the experiment, grating size depends on the travel range of the mobile stage. We use a high-precision 2D mobile stage with a 50-nm positioning accuracy and 100-mm travel range for precise movement control. At this travel range, the largest grating size is 100 × 100 (mm). Thus, selecting a larger mobile stage is necessary for fabricating large gratings.

Fourthly, the proposed approach enables the convenient fabrication of double-density gratings of the same size. According to Eq. (3), the density of output gratings is twice that of input gratings. Fabricating a grating with a density of 3 600 lines/mm necessitates the recursive use of an optical system, from 900 to 1 800 lines/mm, and then from 1 800 to 3 600 lines/mm. If a higher density grating is necessary, another feasible approach is to use a shorter wavelength laser and corresponding lenses.

Although this letter reports the first proof-of-principle demonstration of an effective approach to fabricating large-sized gratings, our approach currently does not extend to suitable highly numerical lenses and expensive long-distance travel high-precision mobile stage for producing large high-density gratings. This research is motivated by our recognition that if we can overcome all technical challenges in the implementation of this approach, then this technique can be used to fabricate the aforementioned components.

In conclusion, we propose a technology for grating imaging scanning lithography for fabricating large-sized gratings. Our technology has two improvements over Anvik's hexagonal imaging plan[12]. Firstly, the former uses a spatial filter to select ±1-order diffractive beams on a spectrum plane, resulting in two collinear beams in a common path and achieving interference fringes. Secondly, a $4f$ system enables phase gratings with jagged edges to form clear images on image planes. Complementary cyclical scanning demonstrates the feasibility of eliminating stitching errors. Finally, we obtain a seamless and uniform large-sized grating with a period of 5 μm and dimensions of 100 × 100 (mm). The advantages of this technology for the generation of large-sized gratings are the simple structure, absence of stray light, high energy use, and stability. This technique therefore enables the efficient fabrication of large-sized gratings.

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