Parallel laser writing system with scanning Dammann lithography

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Scanning Dammann lithography (SDL) is proposed and implemented, which uses a Dammann grating to generate multiple beams with sharp step boundary for writing large-sized gratings efficiently. One of the most attractive advantages is that this technique can accelerate the writing speed, e.g. 1×32 Dammann grating can be 32 times faster than the single laser scanning system. More importantly, the uniformity of the multi-beams-written lines is much better than the single laser beam scanning system in consideration of the environmental effects such as air turbulence, thermal instability, etc. Using the SDL system, a three-port high-efficiency beam splitter at visible wavelengths is fabricated quickly, and the theoretical and experimental diffraction efficiencies are both higher than 90%. Therefore, SDL should be a useful tool for fabrication of large-sized gratings.

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Diffraction grating is a kind of micro-optical component that is widely used in scientific experiments and industrial production. It has played an irreplaceable crucial role in the fields of spectrum analysis and optical measurement[1]. Holographic exposure technique, a traditional method to create diffraction grating, requires large aperture spherical or aspherical lenses with extremely high imaging quality, which is a serious challenge to the optical processing level[2,3]. As a complementary technique, laser scanning direct writing lithography is a unique technique with advantages of high flexibility, low cost, and short processing cycle[4−6]. These techniques generate patterns by writing lines on the substrate step by step.

Recently laser-scanning techniques have been introduced to produce masks and gratings. Scanning beam interference lithography (SBIL)[7], Massachusetts Institute of Technology (MIT) parallel scheme, is an excellent method for fast fabricating of large grating masks. In consideration of each scanning interference beams of the SBIL has a Gaussian intensity distribution and it is difficult to eliminate the stitching problem, Yu *et al.*[8] improved the interference lithography by grating imaging scanning while the image still had a jagged-edge boundary. Zone-plate-array lithography (ZPAL) represents another new approach to lithography, which has produced extensive experimental results over a very short time[9]. However, the system is extremely complex and costly, which is unacceptable to most scientific experiments. Multiple beams lithography with spatial light modulator (SLM) is a flexibility parallel scheme[10], while the SLM has a low spatial resolution and cost highly. Multiple-beam laser lithography technique based on microlens array (MLA) for large-area micro/nanostructure fabrication is proposed[11,12], it is a widely-used parallel scheme while it's hard to introduce the real-time dynamic auto-focus into the system for high-density grating fabrication.

In this letter, scanning Dammann lithography (SDL) technique based on a Dammann grating that greatly improves production efficiency is proposed to solve the above problems. We describe a laser-scanning system for direct writing lithography with a feature size better than 0.4 μm and a writing speed of dozens of times faster compared with traditional scanning single-point lithography (SSL) system. As to our knowledge, no one has presented the SDL technique for fabrication of large area gratings.

Experimental setup is shown schematically in Fig. 1. The parallel scanning in the horizontal direction is performed by a 1×32 Dammann grating and a nano-precision linear translation stage with a unidirectional repeatability of 0.01 μm. The 4f system, which has a linear filter and two lenses used for beam shaping, stands behind the Dammann grating. The vertical scanning is performed by another nano-precision linear translation stage.

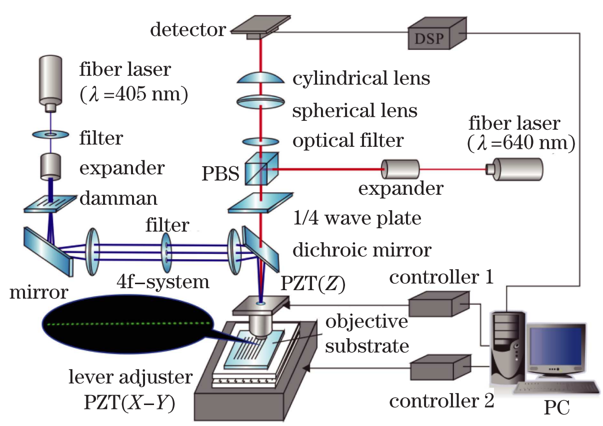

Fig. 1. Schematic illustration of the SDL system. DSP: digital signal processing.

The blue laser beam is focused onto the photo-resist by a microscope objective. Scanning of the focus is achieved by the piezoelectric ceramics actuator (PZT) system, on which the microscope objective is mounted. Parallel laser beams split by the Dammann grating are focused at the entrance pupil of the microscope objective. Any perturbation inside or outside the system would distort the linearity of the scan. Therefore, the four-quadrant detector as well as the PZT must be placed to track and keep focal points of the laser beams always onto surface of the substrate.

The SDL system, using a modular design, includes four parts: the auto-focus module, the writing lithography module, the sample scanning module, and the controlling module. Entrance pupil of the microscope objective is illuminated by the parallel beams. Resolution (Res: full-width-half-maximum of the focus point) and depth of focus (DOF) are given by Res=$k_1\lambda/NA$ and DOF $= k_2\lambda/\mathrm{NA}^2$, respectively. Here NA is the numerical aperture of the objective and λ is the wavelength of the laser. The values of coefficients k_1 and k_2 depend on the condition of the illumination to the objective. For plane wave illumination the coefficients $k_1 = 1.22$ and $k_2 = 0.61$ according to Rayleigh criterion. Depending on the high contrast of the resist and the developing conditions, the effective value of k_1 can reach 0.6−1.6 for the lithographic process. In the SDL system a microscope objective with NA of 0.90 is used. Theoretically, using a semiconductor laser with wavelength of 405 nm, we can achieve Res=0.549 μm and DOF=0.305 μm.

A highly stabilized fiber laser with power and waveform controlling unit are introduced to modulate the laser beam. Rise and fall time as short as 2 ns is obtained by focusing the laser beam into the digital modulation controller. Since the laser beam is distorted by the digital modulation controller, an optical filter is placed in the light path to restore the beam shape.

For accurate focus controlling during exposure, an auto-focus module, with a fiber laser (λ= 640 nm) as the light source, is introduced to the SDL system (Fig. 1). The photoresist is insensitive at the wavelength of 640 nm. From Fig. 1, the detective beam from the fiber laser, linearly polarized, is reflected down to the substrate surface by a polarization beam splitter (PBS) and reflected back by the photoresist layer coated on the substrate surface. The reflected beam from the substrate is received by the four-quadrant detector. The received light intensity of the detector depends on the focus position for controlling the z-position of the microscope objective. High accuracy mechanical motions in the z-direction are achieved by the PZT.

Dammann gratings, as one kind of beam splitter devices, are widely used in the fields of optical communication, image processing, and optical interconnections in recent years[13]. Dammann grating is a phase grating which has a periodical phase structure of multiple optimized linewidths. When a Dammann grating is mounted into the system, which is shown in Fig. 2, the output beam is equally divided into several dozens parts[14]. Besides, the powers of different diffraction points are with the same intensity. Experimentally, the measuring energy deviations of different diffraction points are within the range of 2.5% and the diffraction angles are linear (Fig. 1, the elliptic region: photo of 1×32 Dammann array spots). These characters make it very suitable for beam splitting while integrated into a laser scanner system.

We also measure that the uniformity of the mask can be sufficient while the energy deviation of sub-beams is less than 5%. In order to reduce the quality requirements of the Dammann grating and to focus the sub-beams into entrance pupil of the microscope objective, a transformation optical (4f) system, depicted in Fig. 2, is introduced to the system. The focal length of the two lenses in the 4f system reaches 150 mm, which makes the distance between different sub-beams large enough to easily modify the uneven ones.

Once the structure of the target grating is determined, and then the character of Dammann grating and the distance between substrate and focus plane of the microscope objective can be figured out. The distance can be changed by moving the objective connected to the nano-positioning system (PZT). A 1×32 Dammann grating (Fig. 1, the elliptic region) was selected in this experiment. The laser expanded by the beam expander passes through the Dammann grating and then is split into 32 sub-beams, which is depicted in Fig. 2. According to grating equation, the divergence angle of the Dammann grating sub-beams can be obtained: $\sin\theta = \lambda/d$ =0.74 mrad, where d is the period of Dammann grating (547.3 μm) and λ is the wavelength of expose source (405 nm). The distances between the adjacent sub-beams on the substrate are as follows: $d_\mathrm{s} = f\sin\theta = 1.48$ μm, where f = 2 mm is the focal length of the objective. Figure 3 shows clearly that gratings with tunable periods can be fabricated by rotating the Dammann grating which is mounted on a high-precision rotation platform. Rotating the Dammann grating along the optical axis by $\varphi = 44.257°$, the writing period on the substrate will reach: $d_0 = d_\mathrm{s}\cos(44.257°)$=1.06 μm and the scanning field width is 33.92 μm, which will be used in the following experiment.

In order to evaluate the performance of the SDL system, feature size, lithography efficiency ratio, and the alignment of successively written exposure areas are compared between this SDL system and the traditional lithography system.

To obtain the minimum feature size of the SDL setup, grating microstructures have been produced on fused silica substrates. For this purpose photoresist (Model S1805, Shipley, USA, thickness 570 nm) was exposed by the laser scanner and developed with DPD-200 developing solution. At the wavelength of 405 nm, a single-point exposure power of 3 μW is needed corresponding to the writing velocity of 10 mm/s. In the SDL system, with 32

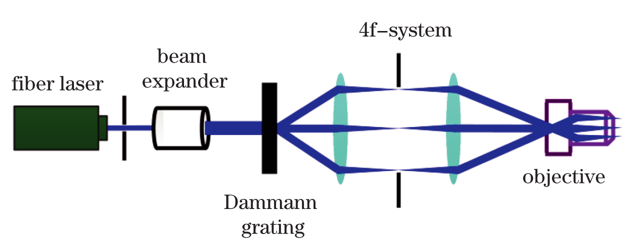

Fig. 2. Illustration of Dammann grating in the writing lithography module.

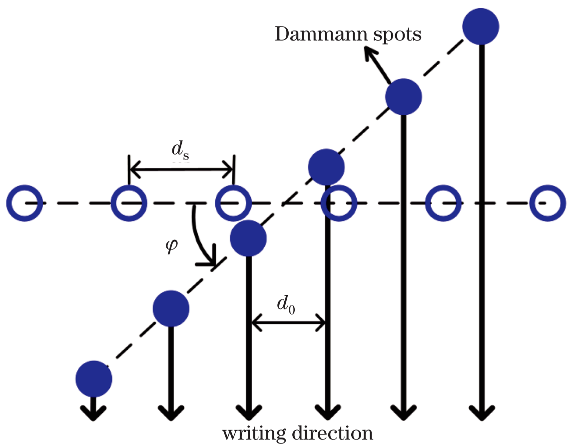

Fig. 3. Schematic of rotating Dammann splitting for writing tunable-period grating.

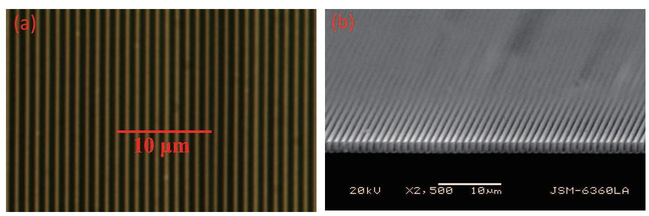

Fig. 4. (a) Microscope photo of chromium grating mask with period of 1.06 μm and linewidth of 0.4 μm, (b) SEM photograph of the three-port beam splitter grating with period of 1.06 μm and duty cycle of 0.62.

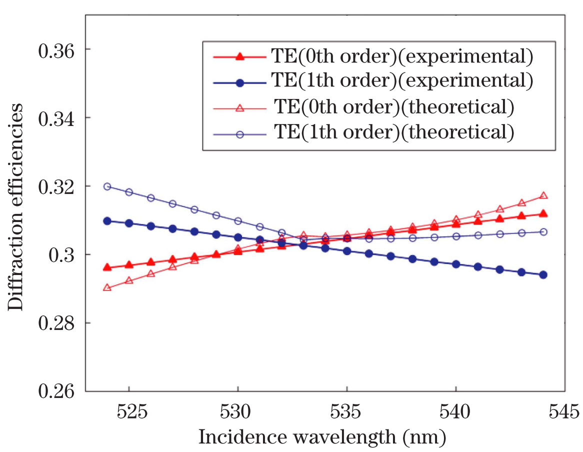

Fig. 5. Theoretical and experimental diffraction efficiencies of the three-port beam splitter grating at different incidence wavelengths for TE polarization.

sub-beams, the threshold exposure power available after the microscope objective is no less than 96 μW. Obviously, the available energy of common lasers is sufficient for high-speed writing.

Field curvature of the high power objective has effect to the SDL system. Here a plan apochromatic objective Nikon CFI LU Plan Epi 100×, was applied to eliminate the effect of the curvature. Drifting of the foci inside the photoresist along the z-axis will also cause changes on grating line width. However, the introduced servo autofocus system keeps the foci within the photoresist coated on the substrate precisely. The accuracy of the stages is a key factor for the quality of the produced masks. A deviation from the target position by less than one-tenth of the minimum feature size could be acceptable. The resolution of the nano-precision stages are less than 10 nm, which show an acceptable position deviation in both directions of scanning lines and periods. Figure 4(a) presents microscope image of chromium grating mask. It is clear that a feature size of 0.4 μm is obtained by the SDL system, which is in agreement with the theoretical size calculated above (coefficient k_1 in the formula: Res=$k_1\lambda$/NA can be 0.6−1.6 according to the technological level). Furthermore, it is worth mentioning that the stripes uniformity is excellent and no stitching problem exists for the 1×32 parallel writing lithography. The quality of the exposed structures proves the stability of the synchronization between mechanic movements and electrical controls.

In order to verify the performance of the SDL system further, a functional device of binary phase fused-silica grating as a three-port beam splitter at the wavelength of 532.8 nm is designed and fabricated. The structure parameters are optimized by using the rigorous coupled-wave analysis (RCWA) and simulated annealing (SA) algorithm. The optimized parameters are as follows: period 1.06 μm, duty cycle 0.62, groove depth 1.3 μm. Compared with the previous thesis[15], the above structure is easy to be fabricated quickly using the SDL technique since low depth-to-width ratio grating is easy to be etched. The low aspect ratio benefits from the freely-changed duty cycle of the SDL technique, while the grating splitter in Ref. [15] are produced by holography lithography in which the duty cycle can not be controlled freely. Figure 4(b) presents the SEM photo of the high efficiency three-port splitter grating and Fig. 5 shows the theoretical and experimental diffraction efficiencies of the splitter grating with varying incidence wavelengths for TE polarization. And $\eta_0^{\mathrm{THE}} = 30.89\%$, $\eta_1^{\mathrm{THE}} = \eta_{-1}^{\mathrm{THE}} = 30.71\%$, $\eta_0^{\mathrm{EXP}} = 30.42\%$, $\eta_1^{\mathrm{EXP}} = \eta_{-1}^{\mathrm{EXP}} = 30.32\%$ are acquired at normal incidence. The operating wavelength is 532.8 nm and the diffraction efficiencies of the 0th and the ±1st all exceed 30% theoretically and experimentally. We can see from Fig. 5 that experimental efficiencies agree approximately with the theoretical values, which verifies firmly the writing performance of the SDL technique.

The parallel scanning technique based on Dammann grating is suitable for making large-area grating pattern. For example, a large area grating of 500×500 (mm) with period of 2 μm can be finished within 8 h. However it will cost at least 250 h for the traditional laser direct writing technique, which is too long to accept for fabrication. Compared with the traditional single-point laser scanning technique, production cycle of the SDL system is greatly reduced.

In conclusion, a laser scanning system based on a Dammann grating for fast direct writing lithography is developed. The described system can be applied to fabricate various grating masks, especially for large-area high-density patterns. The SDL technique has no stitching problems between adjacent scanning region and the uniformity of all sub-beams is very high. Besides, a three-port grating splitter as a functional device is designed and fabricated by the SDL setup and the performance is proved to be excellent. Next step we prepare to fabricate larger grating with a 1×128 or larger splitting number Dammann grating and a higher writing velocity of at least 300 mm/s. Under this condition a grating mask of 1×1 (m) with period of 1 μm will be finished within 8 h. Therefore, the SDL system should have extensive applications for fabrication of large-area gratings.

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