Specifications and control of spatial frequency errors of components in two-beam laser static holographic exposure for pulse compression grating fabrication

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Abstract

Large-aperture pulse compression grating (PCG) is a critical component in generating an ultra-high-intensity, ultra-short-pulse laser, however, the size of PCG manufactured by transmission holographic exposure is limited to large-scale high-quality materials. The reflective method is a potential way for solving the size limitation, but there is still no successful precedent due to the lack of scientific specifications and advanced processing technology of exposure mirrors. In this paper, an analytical model is developed to clarify the specifications of components and advanced processing technology is adopted to control the spatial frequency errors. Hereafter, we have successfully fabricated a multilayer dielectric (MLD) grating of 200 mm × 150 mm by using off-axis reflective exposure system with Φ300 mm. This demonstration proves that PCGs can be manufactured by using reflection holographic exposure method and shows the potential for manufacturing of meters-level gratings used in 100 Pettawatt class high-power laser.

Keywords: PCG; specifications; spatial frequency errors; off-axis reflective exposure system; high-power laser

1. Introduction

Ultra-high-intensity, ultra-short-pulse laser have significantly advanced the development of inertial fusion[1], miniature compact free electron laser[2], and fundamental ultra-high-intensity interactions[3]. PCG plays a key role in the performance of the ultra-intensity ultra-short laser system, which in turn pushed PCGs toward their limits in terms of size, optical performance, and resistance to laser damage[4-6]. Over the last three decades, as the peak power of the high-power lasers has increased from several megawatts (MW) to 10 petawatts (PW)[7-10], the grating dimension is also enlarging. These laser systems today use meter-scale gratings to compress the final amplified chirped pulse.

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However, with the proposal and construction of the 100 PW class or even higher power laser systems\cite{11}, the size limitation of grating has been the bottleneck. Regarding manufacturing techniques for large aperture diffraction gratings\cite{12}, historically beginning with mechanical ruling, which was later accompanied by the mainstream two-beam interference lithography (often simply cited as holography), other representative techniques e.g. scanning beam interference lithography (SBIL)\cite{13, 14}, holographic phase aperture synthesis, grating stitching\cite{15, 16} etc. Ruling gratings suffer from expensive production and duplication costs and greater stray light levels than do holographic gratings\cite{17}, so they have been gradually replaced by the latter. At present, the world's largest two-beam laser interference lithography station is developed by Lawrence Livermore National Laboratory (LLNL), which utilizes 1.1 meter-diameter collimating lenses\cite{18}. Considering the homogeneity of large-
aperture transmission optical material, it is difficult to further improve the aperture of the lens. To break through the limitation, SBIL proposed by MIT and PGL research team, which uses small diameter beams (about 1 or 2 mm) to generate interference fringes and expose the interference image in the photoresist on the substrate[19]. The performance of the grating fabricated by this technology is ultimately dependent on the accuracy control of relative position between the substrate and the scanning beam. In particular, it becomes more challenging to maintain uniformity and consistency across a large area when scaling up to fabricate large-size gratings. The scanning process is time-consuming, and specialized equipment such as high-precision stages, complex optics, and precise control systems are required. The complexity and cost of these equipment will also become limiting factors. The other is stitching, which is mainly divided into exposure stitching by synthesis of multiple holographic phase sub-apertures represented by Leningrad Nuclear Physics Institute (LNPI)[20] and mechanical stitching (multiple small gratings are stitched into large gratings) proposed by the University of Rochester[21]. For this technique, the stitching errors caused by control accuracy needs to be significant strictly limited, otherwise the far-field focus may deteriorate. However, these researches transfer the difficulty of optical manufacturing to the accuracy of control systems. As a result, with the increase of grating dimension, today's control systems for the manufacture of state-of-the-art diffraction gratings have become extremely complex.

Therefore, the reflection exposure method has the potential to overcome some of the challenges faced in fabricating large-size gratings. By utilizing this method, issues related to optical materials, stitching, and scanning methods can be eliminated. However, the focus then shifts to the fabrication of the mirror, which becomes the key difficulty in this approach. Achieving high-quality and uniform mirrors at a large scale is a challenging task. In order to evaluate the performance of the mirror, the specifications must be established to meet the needs of uniformity of the light field. For example, in the NIF, because imperfections in the optical components can lead to problems at certain spatial frequencies such as scatter and beam divergence as well as intensity modulations that undergo nonlinear gain, the low/mid/high spatial frequency (LSF/MSF/HSF) specification of the optics played a critical role in feedback the polishing process to improve the quality of the optical components[22]. Similarly, to achieve the high brightness of the third and fourth generation synchrotron / free electron laser (FEL) light source, it is necessary to characterize optical surface figure, slope errors and roughness on X-ray optics over spatial frequencies as short as 0.1 mm and with slope errors reaching less than 100 nm rms or surface figure errors close to 1 nm[23]. For reflective two-beam laser static interference lithography, there is still no precedent of successfully fabricating grating by reflection exposure method due to the lack of scientific technology. Different from the traditional focusing optical system (e.g., inertial confinement fusion, shortwave focusing), the interference lithography system is a beam expander system and the spatial frequency error of the exposure light field for varying degrees and further determines the grating quality, but the lack of scientific specification makes the manufacturing processing blind and hard to meet the requirement. For the advanced processing technology, the synchronous suppression of the LSF/MSF/HSF error is the key problem for complex curved surface. Although various polishing techniques such as small-tool polishing[24], magnetorheological finishing (MRF)[25] and ion beam finishing (IBF)[26] have been invented, it still seems difficult to achieve efficient convergence of full-spatial-frequency errors. Therefore, the mechanism between exposure quality and surface error should be first studied to clarify the manufacturing difficulties and key specification; on this basis, advanced fabrication technology needs to be further developed to achieve the success of grating fabrication by reflective exposure method.

In this paper, the multi-layer dielectric diffraction grating has successfully fabricated by reflection exposure method. A reflective static interference exposure system was designed; the influence of surface error on the uniformity of the light field was strictly proved and the mirrors' specification was established; besides, the novel combination process technology for exposure mirror was proposed to realize ultra-precision forming. The development gives a brand-new approach to fabricate diffraction grating, which paves the way for the manufacture of larger gratings to support the construction of large scientific devices.

2. Reflective two-beam laser static holographic exposure for PCG fabrication

2.1. Design of reflective two beam static interference exposure system

According to the principle of two beams interference in classical physical optics[27], two monochromatic plane waves with the same polarization direction and constant path difference meet, and the light intensity distribution of the composite light field after superposition is as follows:

\[ I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos \Phi, \]

where \( I_1 \) and \( I_2 \) are the light intensity of two beams respectively, and their phase difference \( \Phi \) can be expressed as:

\[ \Phi(r) = k \cdot r + \Phi_0. \]

Among them, \( k = k_1 - k_2 \) is the wave vector difference of two light waves, \( r \) is the vector path of the coherent point, and \( \Phi_0 \) is the initial phase difference. In general, under the
condition of two beam exposure, the wave vector of coherent beam and the grating plane form isosceles triangle, then $|k_1|=|k_2|=2\pi/\lambda$. The wavelength of exposed beam is $\lambda$, and the angle between $k_1$ and $k_2$ is $2\theta$, then $|k|=(4\pi/\lambda)\sin\theta$. At this time, the spatial period of interference fringes or the spacing of grating fringes are expressed as follows:

$$d = 2(2\pi / k) = \lambda / (2 \sin \theta).$$ (3)

According to the above formula, the period of grating can be controlled by changing the angle between two interference plane waves. The two interfering waves are usually created by division of wavefront or amplitude in an interferometer setup. The experimental layout mainly draws inspiration from the transmission-based exposure layout used by LLNL[28]. However, in this study, it has been modified by replacing the two exposure lenses with off-axis parabolic mirrors for reflection, as shown in Figure 1. The single longitudinal mode Kr+ laser (wavelength $\lambda = 413.1$nm) is divided by polarizing beam splitter (PBS). By rotating the $\lambda/2$ plate, the linear polarization angle of the laser incident on PBS is changed, and the energy distribution ratio of the two beams is changed. Another $\lambda/2$ plate is placed in one optical path behind PBS to adjust the polarization direction of the two beams to the same angle, then a spatial filter is placed in each arm to filter the beam. The spatial filter is composed of micro objective lens and pinhole, which is placed at the focal point of off-axis paraboloid (OAP) mirror to form the off-axis reflection beam expanding system, so that two plane waves are projected onto the grating substrate surface coated with photoresist to form interference fringes, and the grating mask is made. The optical parameters of the OAP mirror are shown in Table 1. Before exposure, the fringe spacing can be precisely controlled by adjusting the half angle between the mirrors.

![Figure 1. Setup of two-beam interference lithography for MLD gratings. Abbreviations are as follows: L – Kr+ laser, M – mirror, PM – piezo mirror, $\lambda/2$ – Polarization rotator (e.g. half-wave plate), PBS – polarization beam splitter, SF – spatial filter, SH – shutter, OAP – Off axis parabolic mirror, S – substrate with mount, RG - Reference grating, G - Ground glass.](image)

Table 1 The OAP mirror optical design prescription

<table>
<thead>
<tr>
<th>Optical parameter</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror diameter</td>
<td>300mm</td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Glass Ceramics</td>
<td></td>
</tr>
<tr>
<td>Vertex radius of curvature</td>
<td>3000mm</td>
<td></td>
</tr>
<tr>
<td>off-axis distance</td>
<td>240mm</td>
<td>Distance from the parent vertex</td>
</tr>
<tr>
<td>Conic constant</td>
<td>-1</td>
<td>parabola</td>
</tr>
<tr>
<td>Aspheric departure</td>
<td>24μm</td>
<td>Astigmatic peak-to-valley departure</td>
</tr>
<tr>
<td>Measure method</td>
<td>Null test with standard plane mirror</td>
<td></td>
</tr>
</tbody>
</table>

In addition, in order to overcome the influence of environment and ensure the stability of interference fringes, a phase locking system composed of a piezo mirror and fringes monitoring system is introduced to control the absolute phase difference between two arms. The fringe monitoring system consists of a reference grating and a CCD. The grating period of the reference grating is half of that of the grating to be fabricated, which is installed at the coplanar position with the grating substrate. In this way, the first-order diffraction beams of two beams incident on the reference grating will coincide to form an interference, and the fringes are recorded by CCD. At this time, the phase of the interference fringes of the reference grating is only related to the phase of the exposure fringes, so as to realize the fringes locking.

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2.2. Manufacturing method of MLD grating

A multilayer dielectric structure consisting of HfO\textsubscript{2} with high refractive index and SiO\textsubscript{2} with low refractive index was deposited on the surface of fused silica substrate with a size of 200 mm × 150 mm. A single-layer SiO\textsubscript{2} layer with high laser damage threshold was selected as the grating etching layer. The photoresist (~ 500 nm) was coated on the surface of the substrate by the rotary coating process, and the photoresist was more closely combined with the substrate by baking. The grating pattern was exposed into the photoresist layer using reflective two-beam laser static interference lithography station, shown in Figure 2, utilizing 300 millimeter-diameter OAP mirrors and 413 nm Kr-ion laser light.

After development, the grating lines of photoresist were examined at several positions by AFM to realize the uniformity monitoring of exposure/development process. Baking hardens the mask to suit the ion beam etching, and introduces photoresist ashing process to remove the residual glue. The mask structure was transferred by ion beam etching machine MRIBE-300M of Veeco company. After etching, the remaining photoresist mask was removed by chemical method to complete the fabrication of the grating, as shown in Figure 3.

3. Specifications and control of spatial frequency errors of components in two-beam laser static holographic exposure

3.1. Establishment of the exposure mirrors’ specification for reflection exposure system

The non-uniformity of light field intensity modulated by the figure error of the exposure mirror is the main bottleneck restricting the quality of grating fabricated by reflection exposure method; insufficient surface error can affect grating groove shape and continuity, which deteriorate the diffraction wavefront and efficiency. In order to guide the surface finishing technology of the exposure mirror, the influence of the figure error on the light field non-uniformity must be clarified, and the exposure mirrors’ specification for reflection exposure system should be established.

Generally, it is considered that the manufacturing difficulty of reflective mirrors is higher than that of transmission optics. Because for the reflective mirrors, the wavefront error is twice the figure error, while for the transmission optics, it is about 0.5 times. Therefore, the light intensity modulation caused by the figure error, the reflection is about 4 times of the transmission, which can be expressed as:

\[
U_{\text{reflection}} = A \cdot e^{\frac{2\pi}{\lambda}zW_0}
\]

transmission: \[
U_{\text{transmission}} = A \cdot e^{\frac{2\pi}{\lambda}(x-1)W_0}
\]

where \(U_0\) is the input wave function, \(\lambda\) is the wavelength, \(A\) is the amplitude of the light field, the \(W_0\) is the figure error distribution, and \(n\) is the refractive index of the transmission optics, with the average value of 1.5.

According to the angular spectrum diffraction theory\cite{29}, the light field distribution after propagating \(z\) unit distance \((U_z)\) can be expressed as:

\[
U_z = \Phi^{-1}\left[\Phi\left(U_0\right) \cdot \exp\left(i \cdot \frac{2\pi}{\lambda}z \cdot \sqrt{1 - \left(\lambda f_x\right)^2 - \left(\lambda f_y\right)^2}\right)\right], \tag{5}
\]

where \(\Phi\) is the symbol of the Fourier transform, \(f_x\) and \(f_y\) represent the horizontal and vertical frequency components in the frequency domain.

In order to directly find out the influence mechanism of figure error on the uniformity of light field, we convert the complex number in the formula to real number. Furthermore, in the laser holographic exposure system, the figure error of the mirror is generally much smaller than the laser wavelength, therefore, the input wave function of the reflection exposure mirror can be further simplified by the Taylor formul:

\[
U_0 \approx A \cdot (1 + i \cdot \frac{4\pi}{\lambda}W_0), \tag{6}
\]
The Fourier transform of input wave function is represented as the form of the impulse function, then the light field can be expressed as:

\[ U_i = A \cdot F^{-1} \left\{ \left( \mathcal{F}(f_s, f_f) + \int \frac{4 \pi}{\lambda} \mathcal{F} \mathcal{F} \mathcal{F} \right) \right\} e^{i \left( \Phi + 2 \pi f \right)} \]

where \( \delta(f_s, f_f) \) is the impulse function, \( F \mathcal{F} \mathcal{F} \) represents the Fourier transform of the figure error \( \mathcal{F} \mathcal{F} \), and \( \alpha, \beta \) are the intermediate variable to rewrite the formula by impulse function convolution.

Furthermore, the figure error distribution \( \mathcal{F} \mathcal{F} \) is always a real function, therefore, Eq. (7) can be further simplified as:

\[ \mathcal{F} \mathcal{F} = A \cdot e^{\frac{2 \pi i}{\lambda}} \left\{ \left( 1 + \frac{4 \pi}{\lambda} r(a, b) e^{i (a \theta)} \right) \mathcal{F} \mathcal{F} \right\} \]

where \( r(f_s, f_f) \) and \( \theta(f_s, f_f) \) are the module and the argument of Fourier transform of \( \mathcal{F} \mathcal{F} \).

The distribution of the light intensity is the modulus of the light field, and considering that the figure error of the exposure mirror is much smaller than half of the wavelength, it can be further expressed as:

\[ \| \mathcal{F} \mathcal{F} \| = \mathcal{F} \mathcal{F} \cdot \mathcal{F} \mathcal{F} \]

\[ = A \cdot \int \frac{1}{\lambda} r(a, b) e^{i (a \theta)} \mathcal{F} \mathcal{F} \mathcal{F} \mathcal{F} \mathcal{F} \]

\[ = A \cdot \int \frac{4 \pi}{\lambda} r(a, b) e^{i (a \theta)} \mathcal{F} \mathcal{F} \mathcal{F} \mathcal{F} \mathcal{F} \]

It is interesting to find that the diffraction law of light field in the exposure system can be simplified as a filter of sine function, as shown in Figure 4.

The proposed model successfully reveals the quantitative evolution law of light field non-uniformity affected by figure error of mirrors in exposure system. Different from the traditional understanding that the periodic figure error is prohibited due to the Talbot effect, the full-spatial-frequency errors are all needed to be strictly constraint. Essentially, the Talbot effect is a special case of the proposed model, where the detail derivations are shown below.

Figure 4. (a) Schematic diagram of the light field diffraction law in the exposure system. (b) Local figure error example with MSF and HSF error. (c) Actual light field photo caused by the example surface. (d) Theoretical prediction result calculated by proposed model. (e) Sine filter characteristic of light field diffraction law.
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For periodic figure error $W_0 = A_{awc} \sin \left( \frac{2\pi}{\Lambda} \cdot x \right)$

\[
\frac{U_p}{A} = 1 - \frac{4\pi A_{awc}}{\lambda} \cdot F^{-1} \left( F \left( \sin \left( \frac{2\pi}{\Lambda} \cdot x \right) \cdot \sin \left( \Phi(f_x, f_y, z) \right) \right) \right)
\]

\[
= 1 - \frac{4\pi A_{awc}}{\lambda} \cdot F^{-1} \left( \delta(f_x \pm \frac{1}{\Lambda}, f_y) \cdot \sin \left( \Phi(f_x, f_y, z) \right) \right)
\]

\[
= 1 - \sin \left( -\pi \cdot z \cdot \frac{1}{\Lambda^2} \right) \cdot \frac{4\pi A_{awc}}{\lambda} \cdot \sin \left( \frac{2\pi}{\Lambda} \cdot x \right),
\]

where $\Lambda$ is the period of the figure error and $A$ is the amplitude of the light field.

The spectrum of the periodic figure error is impulse function, the light field distribution of the periodic figure error is still a periodic, and the amplitude changes periodically with the propagation distance $z$. The Talbot distance period $z_{Talbot}$ is $2\Lambda^2/\lambda$, which is consistent with the Talbot theory.

Obviously, based on the above quantitative evolution law, we can establish a general standard to judge whether the mirrors’ specifications of the exposure system meet the requirements. Since the optical specifications of the mirrors are largely based on results of propagation modeling described above, modeling of the light field and the optical specifications are closely tied and should be consistent with one another. In both modeling and specifications, we differentiate between spatial frequency regions, since each involves different light field performance issue. In order to cover these frequency bands, it is also necessary to consider the frequency band range of different measuring instruments.

To deal with these issues, we break the spatial frequency regime into three regions, namely the low/mid/high spatial frequency (LSF/MSF/HSF) specification of the optics. Considering the unique shape of the sine filter, the light field is insensitive to the LSF error since sine filter tends to 0 in LSF region, and the Talbot effect appear stably in the MSF band because it is less affected by the perturbation of the propagation distance. Therefore, we use the first period of sine function as the boundary to divide the MSF and HSF error, and the boundary between the LSF and MSF error is defined which follows -10 dB formula\textsuperscript{30}, which also facilitates the field of view connection of the measuring instruments. The spatial frequency error higher than the $1/\lambda$ is the evanescent wave which should be excluded from the frequency range. Hereafter, the frequency error division scheme applicable to the grating exposure system can be shown as below

\[
\begin{align*}
-10\text{dB rule:} & \quad \sin(\Phi) \approx -\sin\left(\pi\lambda \cdot z \cdot \left(f^2_x + f^2_y\right)^{1/2}\right) = 0.1 \\
\text{let } f_1 &= \sqrt{f^2_x + f^2_y} \\
\Rightarrow f_1 &\approx \sqrt{1/(30\lambda z)} \\
\text{first period:} & \quad \pi\lambda \cdot z \cdot \left(f^2_x + f^2_y\right)^{1/2} = 2\pi \\
\text{let } f_3 &= \sqrt{f^2_x + f^2_y} \\
\Rightarrow f_3 &\approx \sqrt{2/(\lambda z)} \\
\end{align*}
\]

Figure 5. The frequency error division scheme for the grating exposure system

In proposed frequency error division specification, the LSF error mainly affects the straightness of grating line, where the light field uniformity is insensitive to the LSF error. According to previous research\textsuperscript{31}, to ensure the diffracted wavefront for the grating of $\lambda/2$ PV or even better, the LSF error of the exposure mirror should be as low as $\lambda/10$ PV.

The MSF and HSF errors, we named MHSF errors, are the main factor to deteriorate the light field uniformity. The errors with frequency greater than $f_1$ can all be mapped into the exposure light field distribution. Therefore, the MHSF errors in each sub-aperture of the exposure mirror should be controlled.
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To ensure the non-uniformity of light field meets the requirement of the exposure system, we limit the non-uniformity of light field below the non-uniformity of light source as the basis. Considering the light field non-uniformity of the commonly exposure light source is around ±5%, combining with the Plancherel's theorem and 3-sigma rule\textsuperscript{[30]}, the exposure mirrors’ specification can be established to ensure that the light field does not deteriorate. The exposure mirrors’ specification listed in Eq.(11) constrains both mid and high-spatial-frequency error for the whole surface, besides, to ensure the MHSF error distribution consistency, random sampling measurements in multiple positions should be done to avoid the local unsatisfied region.
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\[
\frac{4\pi}{\lambda} \cdot 3 \cdot \text{RMS} \left( \text{Err}_{\text{MHSF}} \cdot \sin(\Phi(f)) \right) < 5%
\]

with \( f_r = \sqrt{f_z^2 + f_z^2} \in \left( \frac{1}{30\lambda z}, \frac{1}{\lambda} \right) \) (11)

\[
\Rightarrow \frac{12\pi}{\lambda} \cdot \int_{1/30\lambda z}^{1/\lambda} \sin^2(\Phi) d\Phi < 5%
\]

\[
\Rightarrow \text{RMS}_{\text{MHSF}} < \lambda / 533 \left( \frac{1}{\sqrt{30\lambda z}} < f < \frac{1}{\lambda} \right),
\]

The laser wavelength used in our exposure system is 413.1 nm, therefore, the RMS MHSF in each region should be controlled to be lower than 0.77 nm. In addition, since the existence of the Talbot effect can reprint the periodic light field non-uniformity distribution similar to the grating structure, we have added the power spectra density (PSD) curve constraint to avoid the periodic structure in the figure error.

The results of MSF and HSF error mentioned in Eq.(11) are mixed together, which is not convenient for the judgment of practical measurement results. We decompose each spatial frequency error specification of the exposure mirror as is shown in Table 2, respectively.

<table>
<thead>
<tr>
<th>Table 2 Exposure mirrors’ specification for reflection exposure system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
</tr>
<tr>
<td>LSF error</td>
</tr>
<tr>
<td>MSF error</td>
</tr>
<tr>
<td>HSF error</td>
</tr>
<tr>
<td>Other</td>
</tr>
</tbody>
</table>

* \( \lambda \) is the working wavelength of exposure system; \( z \) is the propagation distance

It can be seen that the difficulty of the fabrication also depends on the propagation distance of the exposure system, according to the Figure 5. Therefore, the difficulty of the fabrication will increase with the increase of the propagation distance, because more LSF error is introduced by the change of the filter. Therefore, the optical path length of the exposure system is designed to be more compact, where the propagation distance in our experiment is shortened to be 3.3 m. Hereafter, the MHSF region is varied from 0.156 to 2.42 \( \times 10^3 \) mm\(^{-1} \), which reduces the difficulty of the fabrication process. Hereafter, we combined with the experimental results to verify that the main factor affecting the non-uniformity of light field intensity is the MHSF error.

3.2. Processing technology and results for the exposure mirrors

Based on the exposure mirrors’ specification shown above, it is not easy to fabricate a satisfactory mirror by the traditional deterministic optical processing technologies; the complex curved mirror cannot be fabricated by full-aperture processing method, but the MHSF error is easy to be introduced during sub-aperture grinding and polishing process (e.g. magnetorheological finishing, MRF; computer-controlled optical surfacing, CCOS and Ion-Beam finishing, IBF), such as the tool trace and surface micro plough on the processed optical surface. At present, magnetorheological polishing technology is an effective means to realize high-efficiency and high-precision machining of components. However, for traditional orthogonal MRF processing method, the periodic MSF error is hard to be eliminated. After the mirror (93% effective
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aperture) is polished by MRF, though the RMS of low frequency profile converges to 5.07nm rapidly, however, there is obvious periodic MSF error distribution, as shown in Figure 6(a)(b). It can be found that the figure error reaches a high precision, but the RMS of the MSF error has already exceeded the proposed specification.

The light field distribution is in the shape of MSF error, which is consistent with the theoretical prediction, as shown in Figure 6 (b). Besides, power spectral density (PSD) function specification is used to judge whether there is periodic structure\textsuperscript{[32]}. The calculated results are shown in Figure 6(d). It can be seen that the PSD curve has an obvious peak at the period of 1mm, which is consistent with the processing step of MRF, indicating that the traditional processing raster path of MRF is the main reason for the MSF error and cannot be used in the exposure system.

Besides, the HSF error is also a crucial source to affect the light field uniformity, especially the marks in micron scale. First, the MRF tool can introduce the microscale "regular striations" along the rotation direction of the MR wheel; second, the mismatch between the tool and asphere and the slurry agglomeration can introduce randomized marks on the polishing surface. We observe the influence of HSF error on mask quality by the optical microscope (magnified 200 times), as shown in Figure 6(c).

The microscale "regular striations" can be reflected in the grating mask, which means the existence of the non-uniformity light field distribution. The microscale "regular striations" is formed during the shear removal process of the MRF polishing powder, where the scattered plastic deformation occurs.
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Although the "regular striations" only exists in few regions (Figure 6(c)), the RMS in the small area can be enlarged up to 3 nm, as shown in Figure 6(c). The photo of the microscale grating mask also have significant similar striations. The results indicate that all the "regular striations" at the micron-level should be prohibited, which makes the polishing process significantly more difficult.

Figure 6. Surface shape error distribution of off-axis paraboloid mirror under traditional polishing process. (a) The figure error of off-axis mirror measured by using 4” Zygo interferometer; (b) The MSF error filtered according to the model specification and the photo of the light field distribution; (c) The HSF error measured by Zygo white light profiler with 20x lens and the photo of the microscale grating mask. (d) 1D-PSD curves.

To fabricate a satisfactory mirror without above error, we introduced a series self-developed novel processing technology. To suppress the MHSF error introduced by MRF tool, we utilized the “magic” angle step state of the MRF[33], which involves specific path angles and steps with a bandwidth of only tens of microns (‘magic’ angle step). This state allows for the stable realization of a surface error convergence without significant path ripple. The schematic diagram is shown in Figure 7(a); besides, the composition ratio of MR fluid and the flow rate/viscosity of the MR wheel have been optimized to reduce the "regular striations" depth. To overcome the defects produced by the small tool, we introduced the smooth pseudo-random path[34] to smooth the MSF error and adopted the semi-flexible pitch tool[35] to achieve a better surface quality, as shown in Figure 7(b).

Figure 7. (a) MRF and “magic” angle step technology. (b) Small tool processing and smooth pseudo random path.

Combining the proposed polishing technologies above, a novel polishing process based on MRF and small tool smoothing technology is formed. The figure error of the exposure mirror after polishing is shown in Figure 8(a). The MSF error filtered according to the model specification is shown in Figure 8(b), where the RMS of the MSF error is suppressed down to 0.586 nm and the periodic error is fully eliminated. Besides, the microscale sharp "regular striations" are greatly suppressed by the developed smoothing process, and the RMS of the HSF is suppressed down to 0.462 nm. Both the MSF and HSF errors have high isotropic distributions, the PSD curves are smooth and has no peaks, as shown in Figure 8(d). The MHSF error can be expressed as the square average of the MSF and HSF error, then the MHSF error is 0.746 nm, which meets the proposed specification shown in Table 2.
Figure 8. Surface shape error distribution of off-axis paraboloid mirror after the combined polishing process. (a) Use 4" Zygo interferometer to measure the figure error of off-axis mirror; (b) The MSF error filtered according to the model specification and the photo of the light field distribution; (c) The HSF error measured by Zygo white light profiler with 20x lens and the photo of the microscale grating mask. (d) 1D-PSD curves

Furthermore, the light field distribution and the mask quality are also checked up to ensure the effectiveness of the new mirror fabricated by the novel combination process, as shown in Figure 8(b)(c). It is obvious to find that the non-uniformity has been greatly suppressed, which is highly consistent with the proposed prediction model. Hereafter, the diffraction grating can be made by the new mirrors fabricated by the proposed new processing method.

3.3. Performance of grating fabricated by reflection exposure method

The grating was examined by full-aperture interferometry using a Zygo 24"-aperture, phase-shifting interferometer operating at 1053 nm. Figure 9 shows the diffracted wavefront at ±1 order and zero order. The overall PV of 0.315 waves is considered to be good, for a MLD grating of this size and shape, that has both surface figure and holographic errors.

A laser photometry map of the grating’s diffraction efficiency, the average diffraction efficiency of -1 order was 98.1%, which reaches the same level of diffraction grating fabricated by transmission method, as shown in Figure 9(d).

The successful grating fabrication by reflection method proves the accessibility issue of surface manufacturing for reflection requirements, which has paved the way for future large-aperture reflection exposure systems, and related work is also being developed.

Figure 9. Diffraction wavefront and efficiency distribution of MLD grating. (a) -1 order diffracted wavefront, (b) Zero order diffracted wavefront, (c) +1 order diffracted wavefront, (d) Diffraction efficiency map of the MLD grating at 1740 l/mm shows excellent uniformity of diffraction efficiency over the entire aperture for 1053 nm (Ave = 98.1%, σ=0.3%, Max =98.6%); (e) a 200× 150 mm, 1740 l/mm MLD grating designed for use at 1053 nm, fabricated by...
4. Conclusions

In conclusion, we have proposed and demonstrated a model to describe the phase modulations due to figure errors of the optics in the system which are transformed into exposure optical field intensity modulation. Based on the model, the specification of the optics meeting the performance of off-axis reflective exposure system was developed. It was found that different from the focusing optical system, the relationship between the light field and figure errors follows a sine function spatial filtering process and varies with the propagation distance. Advanced manufacturing process to achieve controllable optical figuring and finishing of the off-axis reflective exposure mirrors were developed under the guidance of the specification. Finally, the grating fabricated by reflective two-beam laser static interference lithography can reach the same quality as that fabricated by transmission method. We believe that the reflective exposure method opens new avenues for solving the size limitation of PCG and can benefit high power laser technology that rely on large gratings.

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References


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