# FABRICATION OF OPTICAL MOSAIC TWO-DIMENSIONAL GRATINGS WITH A DUAL LLOYD'S MIRROR INTERFEROMETER

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**Abstract**:

Planar encoders can be used to measure two-dimensional (2D) displacements. In order to achieve large measuring ranges, planar encoders require large-size 2D gratings, which can be made by optical mosaic technique. We set up a dual Lloyd's mirror interferometer to make optical mosaic 2D gratings. The key point to obtain good mosaic gratings is to fine tune the attitude and position of the substrate relative to the exposure beams during consecutive exposures, which can be realized by utilizing the interference fringes formed by the diffraction of the exposure beams from the latent gratings (exposed but undeveloped gratings). As the diffraction efficiency of the latent gratings is extremely low (~ $10^{-5}$), we use a high-sensitivity CCD to monitor the interference fringes. The attitude error of the substrate needs to be adjusted only once in order to ensure the groove direction's parallelism for both dimensions of the grating. Experimentally we made 1 × 2 2D mosaics of 34 × (30+30) $mm^2$ area. A Fizeau interferometer is used to measure the mosaics. The Fizeau interferograms are well connected at the joint areas, demonstrating a good mosaic quality.

**Keywords**: Two-dimensional grating; Mosaic grating; Dual Lloyd's mirror interferometer; Latent grating

## 1. INTRODUCTION

Planar encoders can be used to measure two-dimensional (2D) displacements with laser interferometer-level resolution and precision, thus having broad application prospect in the field of semiconductor manufacturing and precision machining. In order to achieve large measuring ranges, planar encoders require large-size 2D gratings. Fabricating large gratings by a single holographic exposure requires large-aperture collimated exposure beams with low-distortion wavefront, which is costly and technically difficult.

To solve this problem, the optical mosaic technique, which makes multiple exposures in different areas of one substrate, has been proposed. One of the representatives is the holographic phase aperture synthesis technique [1] proposed by Turukhano et al. This technique uses two collimated beams in a small number of consecutive exposures with corresponding reference gratings for phase alignment. This method is simple, but is lack of attitude alignment for the substrates and suffers from drift errors between substrates and reference gratings. Another is the self-reference alignment mosaic method [2-3] developed by L. Shi et al. This method uses latent gratings (exposed but undeveloped gratings in photoresist) as the reference objects between and during consecutive exposures, getting rid of drift errors and making the whole system compact. Here we utilize this method to enlarge the size of 2D gratings.

We set up a dual Lloyd's mirror interferometer as the exposure system. Based on this system, the two dimensions of the 2D gratings can be exposed simultaneously rather than separately. The latent grating is used as the core object to monitor, adjust, and lock the attitude and position between the substrate and the exposure beams. The whole system, the mosaic method and the experimental results are presented in the following sections.

## 2. MOSAIC METHOD

Our mosaic system for 2D gratings is shown in Fig. 1. It consists of two subsystems. One is the exposure system for making exposures on the photoresist-coated substrate, and the other is the alignment system for aligning the relative attitude and position between the substrate and the exposure beams.

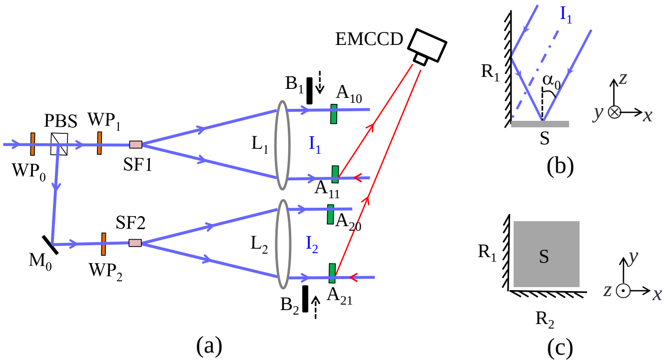


Fig. 1: (Color online) Mosaic system for 2D gratings. (a) Top view of the mosaic system's front part. (b) Side view of the Lloyd's mirror $R_1$ and the substrate S. (c) Top view of the two Lloyd's mirrors ($R_1$, $R_2$) and the substrate S.

### *2.1 Exposure System*

The conventional method to fabricate a 2D grating by the holographic technique is to rotate the substrate by 90 degrees between two sequential exposures. To simplify the fabrication process, we design a dual Lloyd's mirror interferometer that produces a 2D grating through a single exposure.

As Fig. 1(a) shows, a linearly polarized laser beam passing through the half-wave plate $WP_0$ is divided and directed into two beams by the polarized beam splitter PBS and mirror $M_0$. The two beams get through half-wave plates $WP_1$ and $WP_2$, respectively. They are cleaned up by the spatial filters $SF_1$ and $SF_2$, collimated by the lenses $L_1$ and $L_2$, and finally form 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 $WP_1$ and $WP_2$ are used for adjusting the beams' polarization direction. Then, $I_1$ is reflected by a mirror (not shown in Fig. 1). The lower part of the reflected beam is directed into the photoresist-coated substrate S, while the upper part is reflected by the mirror $R_1$ before reaching S, as shown in Fig. 1(b). The two parts form an interference field in the surface of S. The interference fringes' period is $d = \lambda_0/(2\sin\alpha_0)$. Here, $\lambda_0$ is the wavelength of the exposure laser beam and $\alpha_0$ is the angle between the substrate's normal and the interference beams. Similarly, beam $I_2$ is reflected to the mirror $R_2$ and S, forming another interference field. The two mirrors $R_1$ and $R_2$, namely the so-called Lloyd's mirrors, are perpendicular to each other [Fig. 1(c)]. We set up a Cartesian coordinate system whose $x$, $y$, and $z$ axes are parallel to the normal of $R_1$, the normal of $R_2$, and the intersection line of $R_1$ and $R_2$, respectively. The substrate S is placed with its normal along the $z$ axis. The interference fringes formed by $I_1$ and $I_2$ have directions along the $y$ and $x$ axes, respectively. Thereby we can get a 2D latent grating with two orthogonal periodic directions through a single exposure.

### 2.2 Alignment System

The function of the alignment system is to adjust the mosaic errors to the minimum after the substrate is moved and then lock them during the exposures. It consists of the substrate S, the wedged attenuators $A_{10}$, $A_{11}$, $A_{20}$, $A_{21}$, and the high-sensitivity Electron-Multiplying CCD (EMCCD), as shown in Fig. 1(a).

After an exposure on the substrate, a latent 2D grating is produced, with two sets of grating lines along the $y$ and $x$ axes. Then $A_{10}$ and $A_{11}$ are inserted into $I_1$, while $A_{20}$ and $A_{21}$ are inserted into $I_2$. The portions of $I_1$ passing through $A_{10}$ and $A_{11}$ superpose each other on the surface of S, and they create 0th- and -1st-order diffraction beams from the latent grating's $y$-direction grating lines, respectively. The two diffracted beams are reflected by $A_{11}$ [red line in Fig. 1(a)] and form interference fringes, which are called latent fringes. As the diffraction efficiency of the latent grating is extremely low (~ $10^{-5}$), we use EMCCD to monitor the latent fringes. The wedge angle difference of $A_{10}$ and $A_{11}$ is designed to be about 20″ to produce interference fringes with proper fringe spacing. The transmittivities of $A_{10}$ and $A_{11}$ are around $10^{-6}$ and $10^{-2}$, respectively. The low transmittivities aim to protect the latent grating under the exposure beams and their ratio improves the latent fringes' contrast. Similarly, the portions of $I_2$ passing through $A_{20}$ and $A_{21}$ are diffracted by the latent grating's $x$-direction grating lines. Their latent fringes are reflected by $A_{21}$ [red line in Fig. 1(a)], and then recorded by EMCCD. The two sets of latent fringes are shown in Fig. 2.

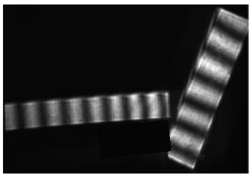
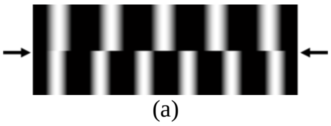


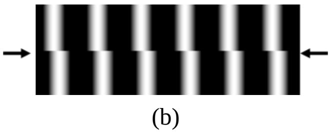
Fig.2: Two sets of latent fringes from a 2D latent grating. The left and the right are from the $y$-direction and $x$-direction grating lines, respectively.

After one exposure, the substrate will be moved to the position of next exposure. The substrate has six degrees of freedom during this movement.

For the $y$-direction grating lines, only three degrees of freedom will lead to mosaic errors: the rotation angle $\Delta\theta_z$ (rotation about the $z$ axis), the tilt angle $\Delta\theta_y$ (rotation about the $y$ axis) and the moving distance $\Delta x$ (movement along the $x$ axis). If the substrate has a rotation angle $\Delta\theta_z$, groove directions of the two exposure areas will be nonparallel to each other, which in turn makes the diffraction wavefront have a rotation angle of $\Delta\gamma = m\lambda_0\Delta\theta_z/d$ along the $y$ axis [2], where $m$ is the diffraction order number. As a result, the latent fringes will have a fringe spacing variation relative to the initial ones, as shown in Fig. 3(a). If the substrate has a tilt angle $\Delta\theta_y$, the grating period will have an error of $\Delta d = d/\cos(\Delta\theta_y)$, which is second order in $\Delta\theta_y$ and is negligible when $\Delta\theta_y \ll 1$. If the moving distance $\Delta x$ is not an integer multiple of the grating period $d$, the wavefront between the two exposure areas of the mosaic grating will have a step error, which results in phase mismatch between the real-time latent fringes and the initial ones, as Fig. 3(b) shows.



(a)



(b)

Fig. 3: Variations of the latent fringes for the $y$-direction grating lines after the substrate is moved. (a) Fringe spacing variation caused by $\Delta\theta_z$ error. (b) Phase mismatch caused by $\Delta x$ error. For both (a) and (b), the lower and the upper half images are the initial and real-time fringes, respectively.

To compensate the above errors $\Delta\theta_z$ and $\Delta x$, we arrange a motorized $\theta_z$ aligner (with 0.2 μrad resolution) and a XY piezo nanopositioning stage (with 1 nm resolution) under the substrate. The substrate is rotated or moved precisely until the real-time and initial latent fringes match well.

Likewise, for the $x$-direction grating lines, $\Delta\theta_z$ and $\Delta y$ (movement along the $y$ axis) will result in mosaic errors.

Fortunately, the attitude error $\Delta\theta_z$ has the same impact on the $y$-direction and $x$-direction grating lines. So the fringe spacing variations caused by $\Delta\theta_z$ are simultaneous and equal for both sets of latent fringes. We can utilize either set of latent fringes to monitor $\Delta\theta_z$, and ensure the groove direction's parallelism throughout the whole mosaic area for both *y*-direction and *x*-direction grating lines simultaneously.

### *2.3 Mosaic Procedure*

According to the above mosaic method, we summarize the mosaic procedure in Tab. 1. In each step, the projections of relevant optical elements in the directions of beams $I_1$ and $I_2$ onto the substrate S are depicted in Fig. 4.

Table 1: Summary of the mosaic procedure

| Step | Function | Implementation |
|---|---|---|
| I | Expose the process edge [Fig. 4(a)] | Insert the beam blocks $B_1$ and $B_2$ [as shown in Fig. 1(a)] to shield most part of the interference field. |
| | | Open the shutter to expose the process edge with the rest part of the interference field, getting a latent grating with L-shaped area [Fig. 4(f)]. |
| II | Record the reference latent fringes [Fig. 4(b)] | Insert $A_{10}$, $A_{11}$, $A_{20}$ and $A_{21}$, whose projections onto S superpose on the area of the process edge. |
| | | Open the shutter and record the two sets of reference latent fringes, as Fig. 2 shows. Close the shutter. |
| III | Expose Area I [Fig. 4(c)] | Withdraw $B_1$ and $B_2$. |
| | | Open the shutter, lock the attitude and position errors, and expose Area I. Close the shutter. |
| IV | Adjust the attitude and position errors [Fig. 4(d)] | Insert $B_1$ and $B_2$. Move S to the position of next exposure. |
| | | Open the shutter. Adjust the attitude and position errors with the aid of reference latent fringes. |
| V | Expose Area II [Fig. 4(e)] | Withdraw $B_1$ and $B_2$. |
| | | Open the shutter, lock the attitude and position errors, and expose Area II. Close the shutter. |

The process edge is a 2D latent grating with an L-shaped area, whose distribution on the substrate is shown in Fig. 4(f). The vertical and horizontal parts of the process edge produce latent fringes for *y*-direction and *x*-direction grating lines, respectively. The process edge just works for the subsequent steps and does not belong to the official mosaic area. In all steps, there are two sets of latent fringes, from *y*-direction and *x*-direction grating lines, to monitor the attitude ($\Delta\theta_z$) and position ($\Delta x$ and $\Delta y$) errors. Generally, the set from *y*-direction grating lines is used to monitor $\Delta x$, while the set from *x*-direction grating lines is used to monitor $\Delta y$. However, for $\Delta\theta_z$, it is necessary to choose the proper set of latent fringes in different mosaic directions: If the substrate is moved along the *x* axis, we should use the set from *y*-direction grating lines to monitor $\Delta\theta_z$; if the substrate is moved along the *y* axis, the set from *x*-direction grating lines will be used.

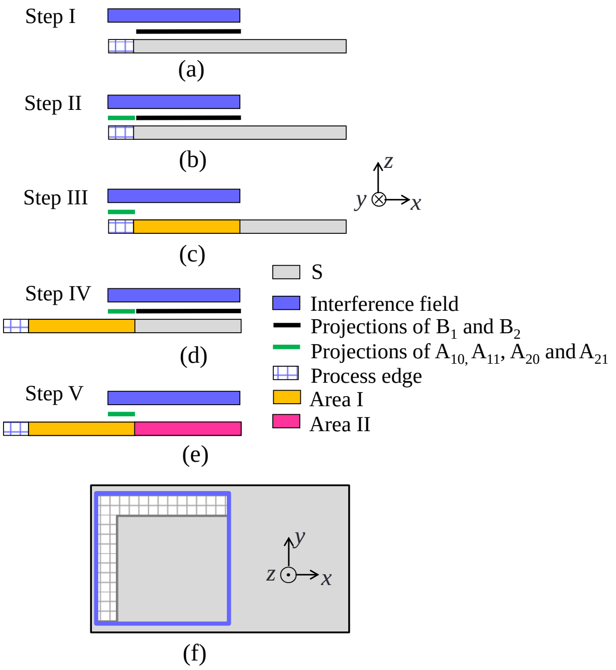


Fig. 4: (Color online) Mosaic steps and projections of relevant optical elements in the directions of beam $I_1$ and $I_2$ onto the substrate S. (a) ~ (e) Mosaic steps from I ~ V. (f) Distribution of the L-shaped process edge on the substrate. The vertical and horizontal parts of the process edge produce latent fringes for *y*-direction and *x*-direction grating lines, respectively.

## 3. EXPERIMENTAL RESULTS

Following the above mosaic procedure, we made 1 × 2 2D mosaic grating with period $d$ = 574 nm on the quartz substrate that was coated with a 100 nm thick chromium film and a 170 nm thick photoresist layer. The wavelength of the laser beam from a HeCd laser was $\lambda_0$ = 441.6 nm. The focal lengths of the lenses $L_1$ and $L_2$ were 816 mm. The area of the whole interference field was 50 ×45 mm$^2$ and the official mosaic area was 34 × (30+30) mm$^2$.

We used a Fizeau interferometer to measure the -1st-order diffraction wavefront of the 2D mosaic grating. Figure 5(a) and (b) show the results for the *y*-direction and *x*-direction grating lines respectively. The Fizeau interferograms are in phase and have the same fringe spacing on both sides of the joint, which demonstrates the feasibility of our mosaic method.

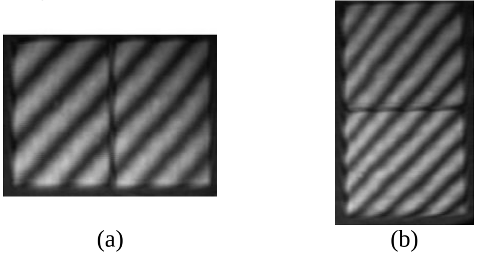

(a) (b)

Fig. 5: Fizeau interferograms formed by the -1st-order diffraction wavefront of the 1 × 2 2D mosaic grating. (a) Interferograms for the *y*-direction grating lines. (b) Interferograms for the *x*-direction grating lines.

## 4. DISCUSSION

### 4.1 Other sources of mosaic errors

During the mosaic procedure, especially when the substrate is moving, other optical elements may drift away from the initial conditions and result in mosaic errors. Fortunately, most of them can be monitored by the latent fringes and then compensated by rotating the substrate, moving the substrate, or moving the spatial filter. For example, the drift of $SF_1$ or the rotation of $R_1$ about the $y$ axis would lead to the tilt of the latent fringes. In both cases, this tilt can be compensated by moving $SF_1$ along the proper axis. If $R_1$ has a rotation about the $z$ axis, the fringe spacing of the latent fringes would change, which can be compensated by rotating the substrate about the $z$ axis.

In our mosaic experiments, the latent fringes had no obvious tilt, so we did not move the spatial filter. The other variation of the latent fringes, including fringe spacing variation and phase mismatch, had been compensated by rotating or moving the substrate.

### 4.2 Drift error existing in step I and II

In our mosaic method, the latent grating instead of the reference grating acts as the monitored object, therefore the drift errors between the monitored object and the substrate are avoided. However, there is another inevitable drift error existing in Step I and II in Tab. 1. After the process edge is exposed (step I), certain relative drift may occur between the substrate and the exposure beams, because we don't lock them to each other. So the recorded reference latent fringes (step II) do not always represent the initial conditions of the substrate relative to the exposure beams. If we use this set of latent fringes for the subsequent exposures, there would be an accumulative mosaic error. The solution is to transfer the reference fringes from the process edge to area I, similar to the method in Ref. 3.

## 5. CONCLUSION

We have designed a dual Lloyd's mirror interferometer to make 2D gratings through a single exposure. Based on this system, we can apply the mosaic technique into making large-size 2D gratings. The key point is to fine tune the attitude and position errors of the substrates by utilizing the latent fringes as the core monitored objects. Because this adjustment method doesn't use any other auxiliary reference objects, it eliminates the drift errors and guarantees high mosaic quality. As the two dimensions of the grating are exposed simultaneously, we can utilize either set of latent fringes to monitor $\Delta\theta_z$ and ensure the groove parallelism for both dimensions of the 2D mosaics. Experimentally we made $1 \times 2$ 2D mosaics of $34 \times (30+30)$ $\mathrm{mm}^2$ area. The Fizeau interferograms of both dimensions are well linked around the joint. This preliminary work has verified the performance of our mosaic system and method.

In the future, mosaic errors should be analyzed in detail and $2 \times 2$ mosaics would be made.

## ACKNOWLEDGEMENTS

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