Development of a long trace profiler in situ at National Synchrotron Radiation Research Center

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ABSTRACT

To achieve an ultrahigh resolution of a beamline for soft X-rays at the Taiwan Photon Source (TPS), the profile of a highly precise grating is required at various curvatures. The slope error could be decreased to 0.1 \(\mu\text{rad} \, \text{rms}\) at a thermal load with a specially designed bender having 25 actuators. In the meantime, a long-trace profiler (LTP) was developed \textit{in situ} to monitor the grating profile under a thermal load; it consists of a moving optical head, an air-bearing slide, an adjustable stand, and a glass viewport on the vacuum chamber. In the design of this system, a test chamber with an interior mirror was designed to simulate the chamber in the beamline. To prevent an error induced from a commercial viewport, a precision glass viewport (150CF, flatness 1/150 \(\lambda\) rms at 632.8 nm) was designed. The error induced from the slope error of the glass surface and the vacuum deformation was also simulated. The performance of the optical head of the LTP \textit{in situ} (ISLTP) has been tested in the metrology laboratory. The sources of error of this LTP including the linearity and the glass viewport were corrected after the measurement. For the beamline measurement, an optical head was mounted outside the vacuum chamber; the measuring beam passed through the glass viewport to measure the grating profile in vacuum. The measurement of the LTP after correction of the above errors yielded a precision about 0.2 \(\mu\text{rad} \, \text{rms}\). In a preliminary test, an ISLTP was used to measure the grating profile at soft X-ray beamline TPS 45A. The measured profile was for the bending mechanism to optimize the slope profile. From the measured energy spectrum, the slope error of the grating was estimated with software for optical simulation to be about 0.3 \(\mu\text{rad} \, \text{rms}\), consistent with our estimate of the ISLTP. In the future, it will be used to monitor the thermal bump under a large thermal load. In addition, an ISLTP was used to monitor the properties of optical elements—the twist and radius in the beamline during the installation phase.

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I. INTRODUCTION

In a synchrotron beamline, the high-power load of synchrotron light degrades the mirror profile with a thermal bump. Some papers about LTP \textit{in situ} (ISLTP) by Qian et al.\textsuperscript{1} have been published in 1996–1998.\textsuperscript{2,3} The thermal bump of a mirror in an undulator beamline at ELETTRA is about several \(\mu\text{rad}\). In the Taiwan Photon Source (TPS) beamline, operated at 400 mA, and with an undulator, the thermal load is great. In a soft X-ray beamline such as TPS 41A and 45A,\textsuperscript{4} a thermal bump on the grating under such conditions is estimated to be about 0.5–3 \(\mu\text{rad} \, \text{rms}\) under varied operating conditions. The grating is the key component for the energy resolution in such a beamline. A conventional bending mechanism is inadequate to compensate the local thermal bump from the large thermal load of the beam. In National Synchrotron Radiation Research Center (NSRRC), a bendable grating with 25 actuators has been developed to decrease the thermal deformation.\textsuperscript{5} Under normal operation, the bendable radius is from 45 m to 100 m; the length is about 170 mm. To achieve an ultrahigh-energy resolution of this beamline, the grating should be about 0.1 \(\mu\text{rad} \, \text{rms}\). The NSRRC staff developed a...
25-actuator bendable grating to decrease the thermal deformation and to achieve the design specification. In the metrology tools, long-trace profiler (LTP), the Nanometer Optical Component Measuring Machine (NOM) or stitching has been used in the surface profile measurement of mirrors. The application of an ISLTP was used to monitor the grating profile under a thermal load. These measured database will serve as a reference for an adjustment of the parameters of the actuators in the bender. This paper describes the design of an ISLTP system and the measurement at the beamline.

II. ISLTP SYSTEM

This system consists of a moving optical head, an air-bearing slide, an adjustable stand, and a glass viewport on the vacuum chamber, as shown in Fig. 1. The moving optical head is fixed to the air-bearing slide; the range of travel of the slide is about 200 mm. A three-point support serves to adjust the pitch and roll in the ISLTP system, to adjust the incident beam to the grating inside the chamber. The reference beam is used to correct the air-bearing errors during scanning. The detailed optical design is available in our preceding report. The ISLTP system was installed outside the vacuum chamber; the measurement beam passes through a glass viewport to measure the mirror or grating. Because a commercial glass viewport has typically a slope error as large as about 16 µrad (rms), a special flange (150CF) with a glass window was prepared that can fit the test chamber and the grating chamber in the beamline; this special flange is designed with suitable robustness to
ensure minimal deformation of the glass viewport under the vacuum conditions. We sealed the special flange to the chamber with a suitable torque and then glued the glass window on, making it a glass viewport for the ISLTP system. The rate of helium leakage is better than $1 \times 10^{-9}$ mbar l s$^{-1}$. In the chamber test, the special flange exhibited satisfactory repeatability for measurement of the ISLTP slope after sealing the flange many times. This special flange with a glass window is shown in Fig. 2. The glass window is made of fused silica, highly pure and high-quality flat glass (length 140 mm, width 40 mm, and thickness 20 ± 0.02 mm, and wedge thickness angle: ±150 µrad). The wedge angle of the glass window causes beam deviation, but this deviation is a fixed angle offset for the LTP measurement only. It does not affect the final slope error measurement accuracy. Anti-reflective coating was applied on the glass window centered at 635 nm for LTP measurement. As for the slope errors of the surfaces of both sides in a clear aperture as measured with an in-house LTP, the top surface has 0.30 µrad (rms) and the bottom surface has 0.28 µrad (rms); the window radius is >70 km, as shown in Fig. 3.

The measurement area of the glass window is the cross line area with the coating surface near the edge; in the beamline measurement, the window is used in the central part without coating to allow the measuring beam to pass through. The error induced from the slope error of the surface and the radius of the glass window were calculated with a simplified ISLTP model transfer to an optical model shown in Fig. 4 and Eq. (1).

![FIG. 4. Optical system of a LTP in situ and a glass viewport.](image)

Equation (1) is a ray-transfer matrix that serves to describe the effect of elements on a light ray. The input $\begin{bmatrix} r_{in} \\ \theta_{in} \end{bmatrix}$ is described with a vector as position $r$ and angle $\theta$ from the measurement of a ray with the LTP in situ. Position $r$ is measured in a range from −50 mm to +50 mm. The angle $\theta$ of the ray measured with the LTP in situ is zero. $d_1$ is the distance (100 mm) between the ISLTP and the window; $d_2$ is the thickness (20 mm) of the window; and $d_3$ is the distance (100 mm) between the window and the mirror. $n_1$ is the refractive index of air with value 1; $n_2$ is the refractive index of fused silica with value 1.4585. $R_1$ is the radius of the window’s left surface; $R_2$ is the radius of

![FIG. 5. CAD model and FEM simulation boundary conditions. (a) Air pressure (101 kPa) at the test chamber cover and glass window. (b) Fixed boundary at the joint area at the bottom bolt of the test chamber cover.](image)
the window’s right surface; and \( R_3 \) is the radius of the reflecting mirror. Equation (1) describes a measuring beam passing through the glass window to the reflecting mirror and the reflected beam returning into the LTP in situ through the window as shown with green and red lines in Fig. 4. The result \( \begin{bmatrix} r_{\text{out}} \\ \theta_{\text{out}} \end{bmatrix} \) is a vector that describes the output beam after passing through the optical system of the glass viewport.

As the test chamber operates under vacuum, the effect of the force from the air pressure on the cover glass window must be considered. We are required to estimate \( R_1 \) and \( R_2 \) under vacuum. The computer-aided design (CAD) model of the chamber cover and window glass and the boundary conditions for air pressure are shown in Fig. 5. Air pressure 101 kPa is applied to the glass window and the cover of the test chamber when the chamber was under vacuum, as shown in Fig. 5(a); the cover of the test chamber was fixed at the joint area of the bottom bolt, as shown in Fig. 5(b). The CAD model and boundary conditions can be used to calculate the deformation of the glass window using FEM software; the FEM simulation results are shown in Fig. 6. The deformation radius of the glass window along the LTP scan direction is smaller than in other directions. The area of maximum deformation is at the center of the window glass. The deformation peak to valley (PV) of the top side of the window glass is 0.577 \( \mu \)m; the deformation PV of the bottom side of the glass window is 0.644 \( \mu \)m. The bottom side of the glass window has a deformation and surface radius hence larger than the top side. The approximate radius of the glass window is shown in Table I. Equation (1) and the results of the parameter calculation can yield the ray distortion with the LTP measured in situ at the optical axis; each data point at the glass window can also be calculated. There are two sources of error contributing to the error of curvature measurement: One is the surface slope error of the window and the other is the bending effect by the vacuum force. Both errors are the spatial low frequency of the window under vacuum. The value of the induced error is the difference between the cases with and without a glass window; the results of the calculation appear in Table I. Under the assumption of good uniformity of glass, we see that the influence of the slope error due to the surface of the glass window exceeds that of its radius.

### III. ISLTP PERFORMANCE

The performance of an ISLTP with a glass viewport in the beamline area is shown in Table II. In this area, the

<table>
<thead>
<tr>
<th>Item</th>
<th>LTP in situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scan repeatability</td>
<td>0.15 ( \mu )rad (rms)</td>
</tr>
<tr>
<td>Viewport induced error</td>
<td>0.3 ( \mu )rad (rms)</td>
</tr>
<tr>
<td>Type of scanning</td>
<td>Moving optics board</td>
</tr>
<tr>
<td>Measurement speed</td>
<td>1 mm s (^{-1})</td>
</tr>
<tr>
<td>Sample rate</td>
<td>20 s (^{-1})</td>
</tr>
<tr>
<td>Spatial sampling</td>
<td>1 mm ( \times ) 1 mm</td>
</tr>
</tbody>
</table>
temperature variation is about 0.5 °C during a day. In this environment, the repeatability is 0.15 μrad (rms) for a plane mirror and 0.17 μrad (rms) for a mirror (radius 10 m) at measuring speed 1 mm s⁻¹, as shown in Fig. 7. An autocollimator (Elcomat 3000) served as a reference for the system calibration. The slope difference of the measurement is within ±1 μrad. Data appear in Fig. 8. One of our measurement corrections was for the effect of the glass viewport. First, we measured the effect of the glass viewport with a precision flat mirror, as shown in Fig. 9, in which there are local slope variations (black line) along the measurement direction of value about 0.3 μrad (rms) from a real test, which is a little greater than expected (red line) from the simulation, 0.1 μrad (rms) as in Sec. II and in Fig. 9. The simulation is under the assumption of good uniformity of glass. Another contribution of the slope error might result from the various lines along which we measured on the glass viewport, as shown in Fig. 10. Because the operating radius of our bendable grating is from 50 to 100 m, we measured the difference between slope errors for mirrors of radii 48 and 94 m, with and without a measurement of the glass viewport, as shown in Fig. 11, the results of Figs. 10 and 11 are correction parameter for the real measurement.

IV. BEAMLINE MEASUREMENTS

The layout of the beamline TPS 45A and the location of an ISLTP are shown in Fig. 12 for a beamline for soft x-ray spectra. The source is an elliptically polarized undulator with a magnet of period 46 mm. The active grating that we measured is the third optical element, with thermal load 5 W. Before the
FIG. 10. Slope difference with and without a glass viewport for various lines along the glass viewport. The mirror under test is in vacuum.

FIG. 11. Slope difference with and without a glass viewport on measuring mirrors of radii 48 and 94 m. The mirrors under test are in vacuum.

FIG. 13. Variation with the temperature of the long-term stability of an ISLTP.

Before the bender was activated, the slope error was 1.3 µrad (rms), as shown in Fig. 14. The measured data of the ISLTP were obtained after correction for the effect of the curvature and the position of the scan line of the glass viewport.

In our preliminary test, we drove the 25-actuator bender with the ISLTP data and the energy spectrum to correct the slope error of the grating. The slope error was decreased to 0.3 µrad (rms), as shown in Fig. 14. To confirm the grating slope error, we measured the energy resolution with valence-band photoemission experiments; the Fermi-edge spectrum is shown in Fig. 15. The Fermi edge was fitted with a Fermi-Dirac function at 80 K convoluted with a Gaussian function for the energy resolution. The experimental result shows an energy resolution of 30 meV at a photon energy of 84 eV, corresponding to an energy resolving power of 28 000. Parameters of this beamline are as follows: the entrance and exit slits have widths of 3 and 3 µm, respectively; the density of the test of the beamline in situ, we measured the long-term point stability; the result is shown in Fig. 13. There is a satisfactory correlation between the point stability and the temperature, which implies that the temperature should be controlled ±0.1 °C with a suitable shield to decrease the thermal drift. Before the bender was activated, the slope error was 1.3 µrad (rms), as shown in Fig. 14. The measured data of the ISLTP were obtained after correction for the effect of the curvature and the position of the scan line of the glass viewport.
V. SUMMARY

We have designed an ISLTP system to measure the slope error on a bendable grating at NSRRC beamline TPS 45A. The system includes a moving optical head, an air bearing, an adjustable support, and a special glass viewport. The repeatability of measurement ten times at the beamline through the glass viewport is about 0.15 $\mu rad$ (rms). Much effort was devoted to the correction of the viewport slope error, even at 0.3 $\mu rad$ (rms). The influence of temperature on the stability of ISLTP was also studied; it is feasible to diminish the temperature variation to within 0.2 $^\circ$C. In a preliminary test at the beamline, we obtained an energy resolution about 28 000. Based on the resolution data, estimates of the slope error of the bendable grating from optical simulation were about 0.3 $\mu rad$ (rms), consistent with our estimate of the ISLTP. Based on the above correction and ambient control, it is a powerful tool to enable the bender to refine the grating profile under a thermal load.

REFERENCES


grating ruling is 1200 l/mm. From the optical simulation, the slope error of the grating is estimated to be better than 0.5 $\mu rad$ (rms), which is consistent with our data measured with the ISLTP. In the future, it will be used to monitor the thermal bump under a large thermal load and corrected with the bender.