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Design of and metrological results from a bent parabolic mirror

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This article describes the successful design and fabrication of, and metrological results from, an elastically bent parabolic mirror. The mirror is equipped with a bending structure that allows the mirror to be bent meridionally to a parabolic shape. This bent parabolic mirror is the key component of the extremely high-quality monochromators designed for the SPring-8 figure-8 soft X-ray undulator and the 2.0 GeV high-brilliance synchrotron radiation source (VSX).

Keywords: bent parabolic mirrors; metrological results; photochemistry monochromators; high-brilliance synchrotron radiation source (VSX); SPring-8.

1. Introduction

In another article (Mashima *et al.*, 1998) we present the expected performance and features of the bent parabolic mirror monochromators that have been designed for the SPring-8 figure-8 soft X-ray undulator and the 2.0 GeV high-brilliance synchrotron radiation source (VSX) (Koseki *et al.*, 1995). The bent parabolic mirror monochromators require extremely high-quality parabolic mirrors where the r.m.s. slope error should be below 0.5 µrad. Among several alternatives (Ishiguro *et al.*, 1996), we chose to develop a bent-type parabolic mirror because after some calculations it turned out that it would be possible to optimize the bending parameters to provide high-quality parabolic mirrors.

The aim of this article is to answer the following questions:

(*a*) By bending a flat glass mirror, can an extremely high-quality parabolic mirror be designed?

(*b*) Comparing the computed systematic slope errors of a bent parabolic mirror with those measured, can the results of the calculations be confirmed?

(*c*) Regarding the intrinsic properties of a bent parabolic mirror, can better mirror performance be exploited?

The design and fabrication of, and metrological results from, an elastically bent parabolic mirror are discussed below.

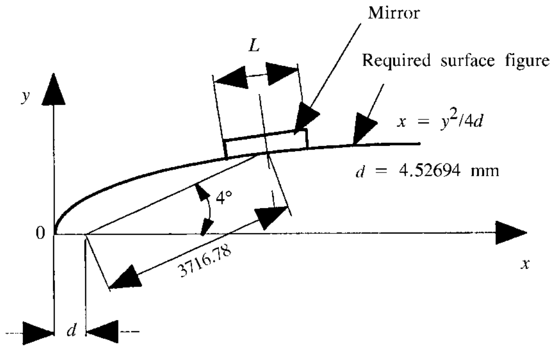

Figure 1
Required surface figure of the bending mirror that is an off-axis section of a cylindrical parabola.

2. Mirror design

Fig. 1 shows the ideal geometry of the required mirror surface (Mashima *et al.*, 1998). The surface must be an off-axis section of a cylindrical parabola given by:

$$X = Y^2/4d,$$

where d is the distance from the focal point to the origin of the parabola (4.52694 mm), L is the effective mirror length (500 mm) and 3716.75 mm is the distance from the focal point to the center of the surface where the surface normal is set to a 4° deviation from the Y axis.

Because the mirror length is much larger than the mirror width and the thickness, it can be regarded as a mechanical thin beam.

A three-dimensional sketch of the mirror bender (cut in half) is shown in Fig. 2(*a*). The bending mechanism is based on a torque-creating system that induces an asymmetric moment at both mirror ends. Fig. 2(*b*) shows the concept of this mechanism. The moment at both ends is provided by the respective forces P_1 and P_2 that are applied through the bending block on the back. The forces are controlled by the spacer thickness. The mirror is supported on the surface by two fulcra that have windows to allow a light beam onto or out from the mirror surface.

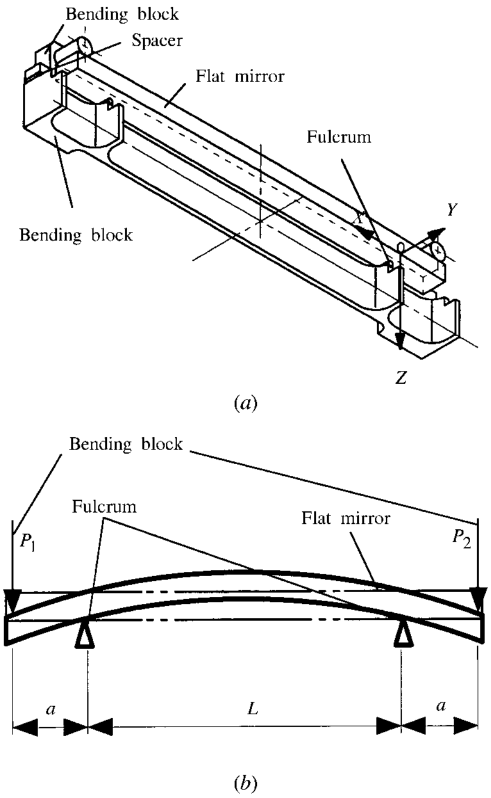

Figure 2
(*a*) Three-dimensional view of the mirror bender (cut in half). (*b*) Conceptual drawing of this bending mechanism. The asymmetric bending moment is created by vertical forces (P_1, P_2) acting through the bending blocks on the back.

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Systematic slope-error and maximum-bending-stress calculations were carried out based on the equation of mechanical thin-beam theory (Pilkey, 1994). The systematic slope-error calculation consists of two independent steps. In the first step, a slope error due only to an asymmetric moment at both mirror ends is considered. In the second step, the gravity effect on the slope error is independently taken into account (*i.e.* the weight of the mirror is considered as continuously distributed over the mirror surface). Then both calculations are linearly superimposed to give the total systematic slope error.

In order to confirm that the flexures are strong enough to survive, the maximum bending stresses due not only to bending, but also to gravity were calculated. The maximum tolerable stresses are estimated as 2.1 and 3.4 kg mm^{-2} for SiO_2 and Si mirrors, respectively.

Fig. 3 shows the computed systematic slope errors and the maximum bending stresses as a function of the mirror thickness for the SiO_2 and Si mirrors. The slope curve of the SiO_2 mirror shows that for a mirror thickness of over about 35 mm, the slope error is reduced below 0.5 μrad and is a minimum (0.04 μrad) at 40 mm thickness. On the other hand, the slope curve of the Si mirror is a minimum (0.02 μrad) at 40 mm thickness. From the maximum-bending-stress curves at 35 mm (SiO_2) and 40 mm (Si), both the maximum bending stresses (0.7 kg mm^{-2}, SiO_2; 1.4 kg mm^{-2}, Si) are found to be within tolerable values.

In order to confirm this slope-error calculation, the computed systematic slope errors of a glass mirror of thickness 25 mm will be compared with those found by optical metrology in the next section. Using the same equation, the computed systematic slope error along the length of the parabolic mirror due to bending (including the gravity effect) is shown in Fig. 4.

3. Results of metrological measurements

3.1. *Microroughness measurements*

A Chapman MP2000 (Chapman Instruments Inc., Rochester, USA) was used for microroughness measurements. The r.m.s.

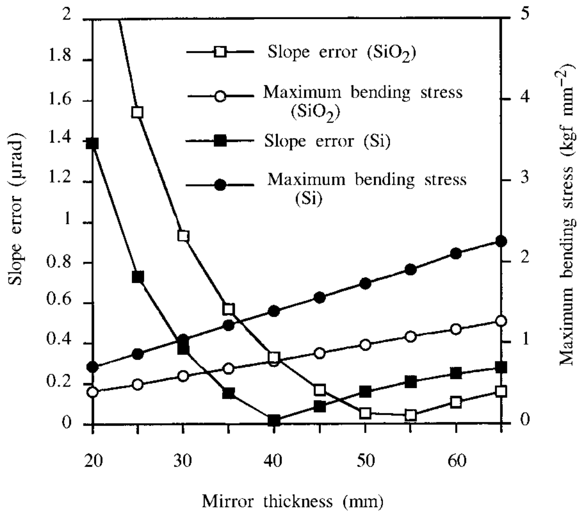

Figure 3
Computed systematic slope errors and maximum bending stresses as a function of mirror thickness for the SiO_2 and Si mirrors. The slope-error measurements were carried out for a 25 mm-thick SiO_2 mirror. The slope curve of the Si mirror is a minimum at a thickness of 40 mm.

roughnesses were 0.2 and 0.3 nm for the SiO_2 and Si mirrors, respectively.

3.2. *Figure and slope-error measurements*

Because of the aberration-free property of this parabolic mirror system, the 'local slope', which can contribute to 'reflecting rays', can be considered as an averaged slope over the coherently illuminated area on a mirror surface. This means that, during the 'slope'-error measurement, the short period cutoff can be limited by the 'coherent illumination width' on a surface. The coherent illumination width, W_c, is estimated as

$$W_c = r\lambda/(\pi s \sin\alpha),$$

where r is the distance from the mirror to the image plane, λ the illuminating wavelength, s the image size and α the glancing angle of the incident/reflected beam. To estimate the short-period cutoff for our monochromator optics, we chose as a typical mirror

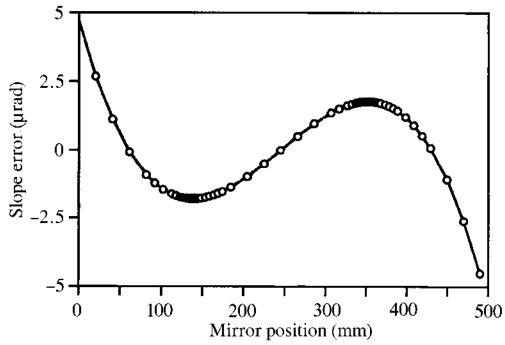

Figure 4
Computed systematic slope error along the length of the parabolic mirror (SiO_2, 25 mm thick) due to bending.

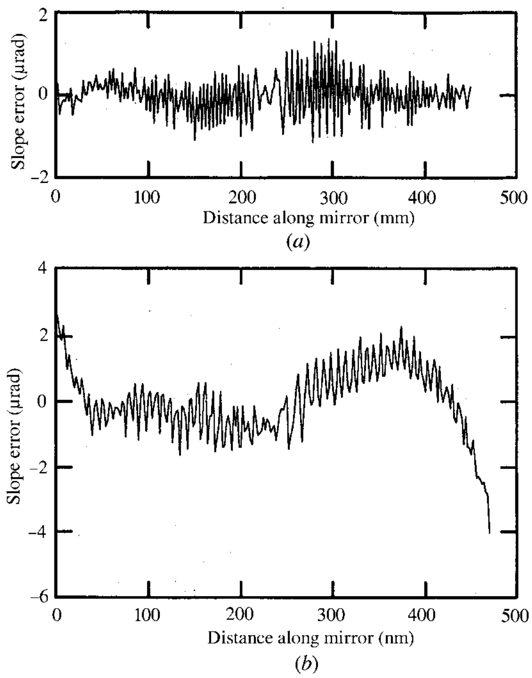

Figure 5
(*a*) Measured slope error along the length of the flat SiO_2 mirror (25 mm thick). The initial r.m.s. slope error is 0.51 (12) μrad. (*b*) Measured slope error along the length of the same SiO_2 mirror due to bending into a parabola. The final r.m.s. slope error is 1.07 (20) μrad.

one with r = 3717 mm, λ = 0.1 nm, s = 2 μm and $\alpha = 1^\circ$, which gives a coherent illumination width of 3.4 mm.

A long trace profiler (Continental Optical Corp., New York, USA) was used for measuring the actual slope errors. This system is based on the pencil beam interferometer concept and Fourier imaging theory.

The measurements were performed for an SiO_2 mirror of thickness 25 mm and the reproducibility of the system was estimated as follows (Takacs, 1997):

(*a*) Each scan was performed with a step size of 2 mm per point over a total distance of 490 mm.

(*b*) A series of ten scans were performed and each individual slope scan was adjusted to remove the mean.

(*c*) The set of ten adjusted slope profiles was then averaged to produce a single 'averaged slope profile'. These 'averaged slope profiles' are presented in Figs. 5(*a*) and 5(*b*).

(*d*) Then this average slope error was subtracted from each individual adjusted profile. From this result, with ten 'residual slopes', the reproducibility of the measurement was computed.

Fig. 5(*a*) shows the measured slope error along the length of the flat SiO_2 mirror (25 mm thick). The initial r.m.s. slope error is 0.51 (12) μrad. Fig. 5(*b*) shows the measured slope error along the length of the same SiO_2 mirror including the effect of bending into the parabola. The final r.m.s. slope error is 1.07 (20) μrad.

4. Conclusions

A deformation analysis based on mechanical thin-beam theory has been performed. This study shows that by bending a flat glass mirror of 40 mm thickness, the systematic r.m.s. slope errors that occur due to bending can be reduced to below 0.5 μrad (which is comparable to the measured slope error of the flat glass mirror). In order to confirm this slope-error calculation, the computed slope errors of a glass mirror of thickness 25 mm have been compared with those found through optical metrology. The measured r.m.s. slope error [1.0 (2) μrad] and the slope curve along the length of the bent parabolic mirror are in good agreement with the systematic slope-error calculation of 1.5 μrad.

Furthermore, this analysis also shows that it may be possible to achieve an r.m.s. slope error below 0.5 μrad by bending a flat Si mirror (40 mm thick). In this case, the residual slope error would be mainly due to the slope error of the flat glass mirror and the additional slope error due to bending might be negligibly small.

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