Development of a novel deformable X-ray mirror based on a single-crystal piezoelectric element

Junya Yoshimizu[1], Takato Inoue[1,2,#], Maaya Kano[1], Sota Nakabayashi[1], Yoshiki Kohmura[3], Makina Yabashi[3], and Satoshi Matsuyama[4,1,2]

1 Department of Materials Physics, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan
2 Department of Precision Science and Technology, Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita, Osaka 565-0871, Japan
3 RIKEN SPring-8 Center, 1-1-1 Kouto, Sayo-cho, Sayo-gunm, Hyogo 679-5148, Japan
4 Research Center for Crystalline Materials Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan
Corresponding Author / Email:inoue@mp.pse.nagoya-u.ac.jp, TEL: +81-052-789-3789

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X-ray microscopy is a unique tool that enables non-destructive observation of the internal structure of samples at the nanometer scale. However, X-ray microscopy has not yet gained the popularity of other microscopy methods. One of the reasons is that controlling X-rays, particularly the beam size, remains very challenging even with state-of-the-art technology. To control the X-ray beam size, we developed a novel deformable mirror(DM) based on a thin single-crystal piezoelectric element, which offers a large deformation, excellent linearity, and stability. Results from the actual shape measurement using Fizeau interferometer demonstrates that the novel DM achieved a deformation of approximately 1 µm in peak to valley, in good agreement with the finite element method.

1. Introduction

X-ray microscopy is a unique technique for several reasons. (i) X-rays have a high penetrating power, facilitating nondestructive observation of the internal structure of the samples. (ii) X-ray wavelengths are thousands of times shorter than those of visible light, enabling a much higher spatial resolution than that of optical microscopes. (iii) X-rays have high photon energy, allowing interactions with the inner-shell electrons of atoms. However, X-ray microscopy has not become as popular as other microscopic techniques owing to significant challenges in X-ray optics. Optical and electron microscopes offer easily modifiable observation conditions by switching the objective lenses in a turret or by adjusting the parameters of the magnetic lenses. However, X-ray optics face the following barriers: (i) high permeability interferes with the lens function; (ii) the requirement of extremely high manufacturing precision owing to the short wavelength of X-rays; (iii) practical operation with multiple interchangeable X-ray lenses is not realistic because the need for high-precision and specialized optics results in high costs.

To solve these problems, deformable mirrors (DMs) that can change the shapes of their reflecting surfaces have been developed. DMs are commonly used in wavefront-compensation optical systems for ground-based visible telescopes. High-precision piezoelectric bimorph mirrors are widely used in the X-ray region, in which the DMs comprise a super-polished mirror substrate and piezoelectric elements such as lead zirconate titanate (PZT) attached to the substrate[1,2]. When a voltage is applied, the piezoelectric elements expand or contract, generating bending moments in the substrate, which results in mirror surface deformation. The deformation curvature is proportional to the applied voltage. Consequently, by controlling the voltage distribution, it is theoretically possible to optimize the surface shape to the order of the atomic size. Previously, successful control of X-ray beam size was achieved using DMs, as shown in Fig. 1 [3,4].

However, the deformation stabilities of conventional mirrors are problematic. While PZT offers a large amount of deformation owing to its high piezoelectric constant, the convergence of deformations takes time, and significant hysteresis is observed[5]. Further, the bonding of the PZTs and the substrate amplifies the instability. To overcome these issues, we propose a new DM based on lithium niobate (LN).

In this study, we developed and demonstrated a new DM based on LN. The deformation was tested using an optical interferometer. Consequently, the results were consistent with those calculated using the finite element method (FEM). Moreover, good linearity of the deformation was observed.

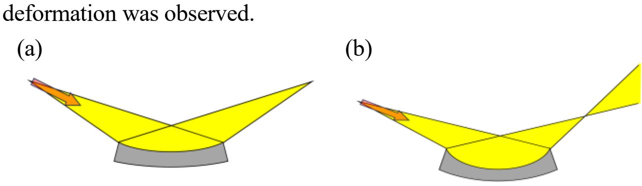

Fig. 1 Schematic of a variable-beam-size optical system based on a DM. (a) Small numerical aperture (b) Large numerical aperture.

2. Deformable Mirror

We employed a single-crystal LN as a driving force for the DM because it consists of a single domain that can achieve relatively smaller creep and hysteresis effects, resulting in stable and precise X-ray beam control[6]. In addition, the surface of the LN can be atomically smoothed, enabling the development of monolithic DMs in which an LN plate can function as a mirror surface and driving force for deformation, unlike conventional piezoelectric DMs that bond a mirror substrate and piezoelectric plates. However, the achievable deformation is only of the order of nanometers owing to the relatively small piezoelectric constant. Although a bimorph structure can increase the amount of deformation, it is not possible to develop piezoelectric bimorph mirrors with bond-free structures using conventional approaches. Consequently, simple DMs using LN face the fatal problem of the range of beam-size variations being significantly limited.

To address this problem, we focused on LN polarization inversion, which is a unique feature of LN. It has been reported that the polarization direction of LN can be partially reversed along the substrate thickness direction by heating it at high temperatures around the Curie point[7] (Fig. 2(a)). Consequently, despite being a monolithic mirror, significant deformations can be achieved owing to the practical bimorph structure derived from domain inversion (Fig. 2(b)).

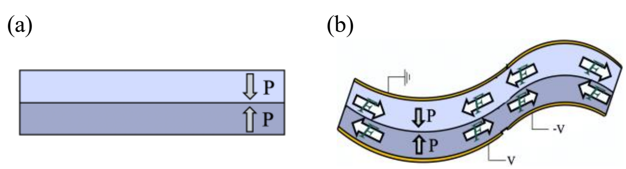

Fig. 2 Schematic of bimorph LNDM in which the LN substrate has two layers with up and down polarization. (a) Before applying voltages. (b) After applying voltages, resulting in deformation.

3. Results

3.1 Simulation

The deformation of the proposed DM was investigated using the FEM. The calculation model consisted of a 0.25 mm thick LN substrate with two electrodes. The LN substrate consisted of two domain layers with opposite polarizations in the direction of the substrate thickness, with the midpoint of the thickness as the boundary. Fig. 3 shows the deformation shapes of the mirror surface when voltages ranging from 50 to 150 V were applied to the electrodes. The simulation results showed that this mirror can achieve a deformation of approximately 1 µm in peak to valley, although the deformation by a DM without the domain inversion layer provides only a few nm.

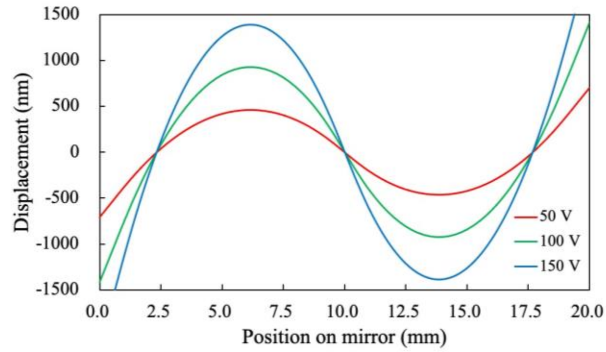

Fig. 3 Calculated deformation of the LN DM

3.2 Experiment

Fig. 4 shows the prototype of the LN DM. The prototype is 0.25 mm thick, 15 mm wide, and 20 mm long. The mirror was heated in an electric furnace at its Curie point. Subsequently, Crelectrodes and a Cr reflective layer were produced via DC magnetron sputtering. The deformation of the DM was measured using a Fizeau interferometer (VeriFire XP/D, Zygo) while various DC voltages were applied to the electrodes. Consequently, the average value of the measured deformation is close to the calculated value, which is sufficient for the DM to control the beam size (Fig. 5). This suggests that the annealing treatment produced the expected polarization inversion layer. This deformation is uniform enough to be used as a DM. In addition, a linear correlation was observed between the applied voltage and curvature of the deformation, demonstrating that each polarization layer of the LN substrate consisted of a single domain.

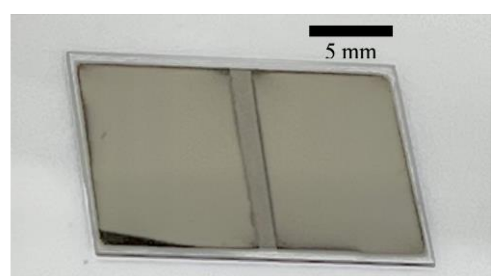

Fig. 4 Photograph of the DM used in the experiment

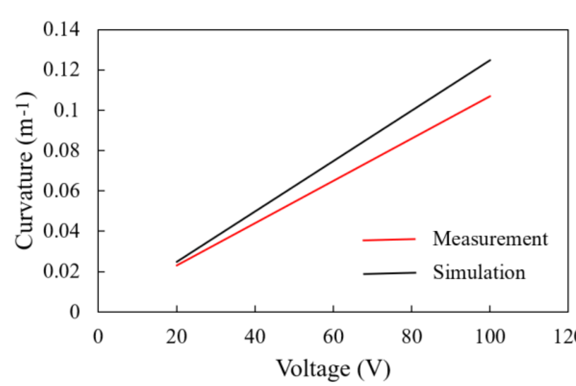

Fig. 5 Dependence of the curvature on the applied voltage in measurements and calculations

4. Conclusions

In this study, we developed a novel bimorph DM based on thermally formed domain-inverted LN to achieve high stability and significant deformability. The experimental results confirmed that the developed DM could deform almost as predicted by FEM. We plan to install the DM in a variable-beam-size optical system.

REFERENCES

1. Signorato, R., Hignette, O. and Goulon, J., “Multi-segmented piezoelectric mirrors as active/adaptive optics components,” J. Sync. Radiat. Vol. 5, pp. 797-800, 1998.
2. Nakamori, H., Matsuyama, S., Imai, S., Kimura, K., Sano, Y., Kohmura, Y., Tamasaku, K., Yabashi, M., Ishikawa, T.and Yamauchi, K., ”Experimental and simulation study of undesirable short-period deformation in piezoelectric deformable x-ray mirrors,” Rev. Sci. Instrum Vol. **83**, 053701, 2012.
3. Wang, H., Sutter, J., and Sawhney, K., “Advanced in situ metrology for x-ray beam shaping with super precision,” Optics Exp. Vol. 23, Issue 2, pp. 1605-1614, 2015.
4. Matsuyama, S., Nakamori, H., Goto, T., Kimura, T., Krishna P. Khakurel, Kohmura, Y., Sano, Y., Yabashi, M., Ishikawa, T., Nishino, Y. and Yamauchi, K., “Nearly diffraction-limited X-ray focusing with variable-numerical- aperture focusing optical system based on four deformable mirrors,” Sci. Reports Vol. 6, 24801, 2016.
5. Junga, H., and Gweon, D., “Creep characteristics of piezoelectric actuators,” Review of scientific instruments Vol. 71, No. 4, 2000.
6. Nakamura, K. and Shimizu, H., “Hysteresis-free piezoelectric actuators using LiNbO3 plates with a ferroelectric inversion layer,” Ferroelectrics Vol. 93, 1989.
7. Nakamura, K., Ando, H. and Shimizu, H., “Ferroelectric domain inversion caused in LiNbO3 plates by heat treatment,” Appl. Phys. Lett. Vol. 50, 1413, 1987.