Single-nanometer focusing of hard X-rays using adaptive optical system

Current status of X-ray mirror development for coming coherent-X-ray

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Background and today’s contents

3rd generation SR facilities widely contribute to many S&T fields. 4th generation facility (XFEL) has already been here. Highly brilliant X-ray is not particular, now.

How should mirror optic contribute to coherent X-ray optical system?

Current research targets

1. Focusing down to sub-10nm (including brief introduction of sub-50nm focusing)
2. Full-field, achromatic and high-resolution imaging of incoherent X-rays
3. Focused and full coherent X-ray illumination for diffraction microscopy
Required accuracy for nano-focusing under D-limited condition

**Kirkpatrick-Baez mirrors**

Elliptical mirror \( \times 2 \)

Diffraction-limited focusing

Waves are in constructive interference state.

Phase error: \( \frac{2d \sin \theta}{\lambda} \)

\( \lambda \)

Error height: 2nm

Error height: 4nm

Error height: 6nm

Beam profile

Elliptical mirror

Designed profile (ellipse)

\( \mu m \)

40mm<\( L_s <50\)mm

100mm<\( L_s \)
Fabrication and figure testing technologies of Osaka University

◎ Plasma CVM (chemical vaporization machining)
  → Rough figuring (Rapid figuring with 10nm (P-V) level accuracy)

◎ EEM (elastic emission machining)
  → Final figuring and smoothing (Fine figuring with atomically smoothing)

◎ MSI (microstitching interferometry)
  → Figure tester with spatial resolution close to 0.01mm

◎ RADSI (relative-angle determinable stitching interferometry)
  → Figure tester for steeply curved ellipse of large NA mirror

JTEC URL http://www.j-tec.co.jp
Typical deterministic figuring properties using EEM
Sub-30nm focusing (2006)

Smallest size in hard-X-ray realized by total reflection achromatic mirror optics (focusing under diffraction limited condition)

Mimura et al., APL (2007)
“Hard-X-ray sub-10nm focusing and realization of high-resolution X-ray microscopy”
To realize Sub-10nm focusing K-B mirrors

From undulator

Slit (10μm)

Focal point

100 mm

>150m

150 mm

X-ray energy : 20keV

Focal length : 150mm

Acceptance width : 1.1mm

Incidence angle : 11.1mrad

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Focal point

100 mm

>150m

150 mm

X-ray energy : 20keV

Focal length : 150mm

Acceptance width : 1.1mm

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MSI with RADSII and EEM can prepare the surface figure with 1nm (P-V) accuracy.
Estimation of required accuracy

@20keV  Mirror length: 100mm, Focal length: 150mm

Figure error of 1nm is not allowable
Multi-layer technology is needed to realize large NA.

Not only figure error but also thickness deviation of the multilayer induce wavefront phase error.
At-wavelength phase-retrieval interferometry

![Diagram showing light source, mirror surface, and phase error compensation.](image)

- **Light source**: $I_1(z), \varphi_1(z)$
- **Mirror surface**: $I_2(x), \varphi_2(x)$
- **Phase error compensation**: (Phase error includes surface figure and ML thickness errors)

**Iteration**

- **Mirror**: $I_3(z), \varphi_3(z)$
- **Focal point**
- **Incident Slit**

**Blue**: known
**Red**: unknown

K. Yamauchi, SPIE’s Optics and Photonics 2005
New knife-edge method

Conventional knife-edge method

New method

Mimura et al.
Details of the new knife-edge method

Scanner is made of Pt with the thickness of 2.5μm.

Scanner is acting as a phase object

Phase is shifted with λ/2.

Spherically propagating X-ray

Beam waist

Modified wavefront

X-ray detector

Microroughness at the bridge

A-A’ profile
30nm-focusing mirror was employed for a demonstration of the proposed at-wavelength measurement.

- Not a multilayer optic.
- Surface is coated by Pt.
Performance of phase retrieval

Measured beam profile

Converged profile in the phase retrieval processing

Mimura et al.
Verification

To verify the reliability of the recovered phase error profile, we actually refigured the mirror by differential deposition method (G. Ice) using the recovered profile.
Comparison between the wave fields before and after phase compensation

Before DD

After DD

Focused beam profiles before and after DD

Handa et al. SIA(2008)
On-line compensation of wavefront

In-situ phase compensation

Sub-10nm

Piezo-electric phase compensator

Focusing mirror with phase error
Phase error = 2kd sin θ

Phase compensator
Focusing mirror

Focal point

X-ray

Glancing angle of compensator mirror is \( N \) times smaller.
(However, Consequently the length of the compensator becomes longer)

Required figure accuracy of the compensator mirror becomes \( N \) times lower.
Phase compensator

Objective shape
- Elementary beam theory
- Controlled shape using optical interferometer

Kimura et al.,
Sub-10nm focusing mirror

\[ \Lambda = \frac{\lambda}{2 \sqrt{n^2 - \cos^2 \theta}} \]

- X-ray energy: 20 keV
- Mirror length: 80 mm
- Focal distance: 75 mm
- Glancing angle: 7.0 mrad
- Multilayer material: [Pt/C]_{20}
- Substrate material: quartz glass

\( \Lambda \): d-space
\( \lambda \): X-ray wavelength
\( n \): Index
\( \theta \): Glancing angle
Optical configuration for active phase compensation

- Fizeau interferometer
- Knife edge scanner
- APD
- Deformable mirror
- Optical interferometer (ZYGO GPI)
- Adaptive mirror
- Focusing mirror (Mirror B)
- CCD camera (for alignment)
- Zooming tube + X-ray CCD
- 150mm
- 250mm
- Ion chamber
- Zooming tube + CCD
- APD placed at dark field
Sub-10nm focusing by using phase compensator

Profile at focal point

Compensated phase profile (shape of compensation mirror)

Maximum phase compensated here was $\lambda/2$. $\lambda$ was 0.06 nm.

Beam waist structure

This is the smallest light beam human-made.
Achromatic imaging device (AKB Mirrors)

KB mirrors

Total reflection axial-symmetric optics

Focusing

Imaging

It fills Abbe’s sine condition

easy to fabricate

KB mirrors

Ellipse

Hyperbola

Advanced Kirkpatrick–Baez mirrors


One-dimensional Wolter mirror

☆Advantage

- Wide field of view
- Easy fabrication

We tried to realize AKB mirrors having diffraction-limited performance.
1-dimentional Wolter mirror system

Magnification: 385x, Size of the point spread function: 43nm

Optical system of a one-dimensional Wolter optics

Elliptical mirror
Hyperbolic mirror

Mirror figures

Magnified image

Elliptical mirrors
Hyperbolic mirrors

Designed one-dimensional Wolter mirror

Object

PSF
@11.5keV
43 nm
Spatial resolution test

Point spread function measurement

Demagnified imaging system

X-ray: 11.5 keV
Slit (10 μm)

Focal point
Gold wire (ϕ 200 μm)
PIN

Demagnified image of the slit

X-ray: 11.5 keV
Slit (10 μm)

Focal point
Gold wire (ϕ 200 μm)
PIN

45 m

Intensity (arb.unit)
Position (μm)

10nm
11nm
13nm
Fit
Calculation

43nm
To evaluate a field of view (FOV), we measured beam size on plane A by changing the glancing angle ($\Delta \theta$).

This procedure is equivalent to shifting relevant points on the planes A and B.

Very wide angular width ($\Delta \theta$) of 122 $\mu$rad was obtained.

It is equivalent to the FOV of 12$\mu$m.
Summary of AKB development

1-dimensional Wolter mirror demonstrated theoretically expected performances both in the resolution and FOV!

Matsuyama et al., Optics Lett (2010)

AKB optics will be indispensable optics especially in coming XFEL experiment.
Focused x-ray illumination for diffraction microscopy

Spot size: \( \sim 1 \, \mu m \)
Photon density: \( \sim 1.0 \times 10^4 \) photons/nm\(^2\)/s

More than 100 times larger
Set-up and samples

◆ X-ray energy: 12keV
◆ Working distance: 450mm
◆ Camera length: 999mm
◆ CCD (Princeton Instruments PI-LCX:1300)

Pixel size: 20μm
1300 × 1340 pixels


Shape-Controlled Synthesis of Gold and Silver Nanoparticles
Yugang Sun and Younan Xia*

Monodisperse samples of silver nanocubes were synthesized in large quantities by reducing silver nitrate with ethylene glycol in the presence of poly(vinyl pyrrolidone) (PVP). These cubes were single crystals and were characterized by a slightly truncated shape bounded by [100], [110], and [111] facets. The presence of PVP and its molar ratio (in terms of repeating unit) relative to silver nitrate both played important roles in determining the geometric shape and size of the product. The silver cubes could serve as sacrificial templates to generate single-crystalline nanoboxes of gold: hollow polyhedra bounded by six [100] and eight [111] facets. Controlling the size, shape, and structure of metal nanoparticles is technologically important because of the strong correlation between these parameters and optical, electrical, and catalytic properties.

SEM image
Ag nanocube
~100 nm

Silver nanocube
Incident x ray
Diffacted x ray
Beam waist
\[ |q| = \frac{2\sin(\Theta/2)}{\lambda} \]

\( \lambda \): wavelength

\( \Theta \): Scattering angle

Sinc function: \( \frac{\sin(\alpha q)}{\alpha q} \)

Exposure time: 800 sec, 1.5x10^{11} Photons to the cube

Summary

- Achromatic total-reflection mirrors realized sub-30nm focusing of hard X-rays.
- In-site wavefront correction are promising techniques to construct highly accurate optical system of hard X-rays.

- KB mirrors could reach sub-10nm focusing.
- AKB mirrors enable achromatic imaging of incoherent x-rays with sub-50nm-resolution.
- KB mirrors could condense x-rays with preserving coherency and could heighten the spatial resolution of diffraction microscopy up to sub-5nm.