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Design, fabrication, and test of extreme ultraviolet microscope with 30-nm spatial resolution

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Outline

1. **Motivation**

   Two-stage imaging system for high magnification

2. **Interferometry for the two-stage imaging system**
3. **Low-order aberration correction with deformable multilayer mirror**
4. **Summary and future plans**

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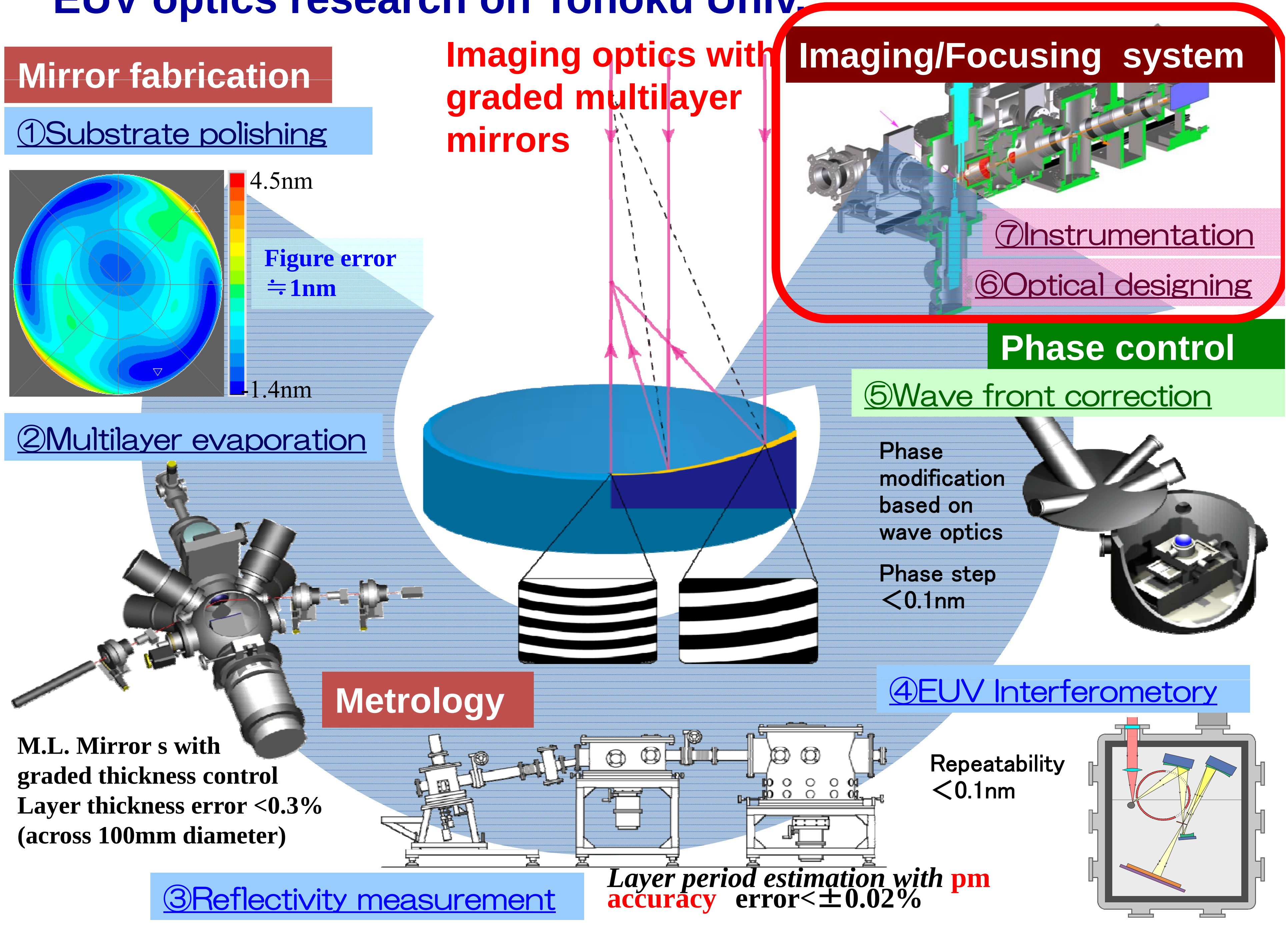
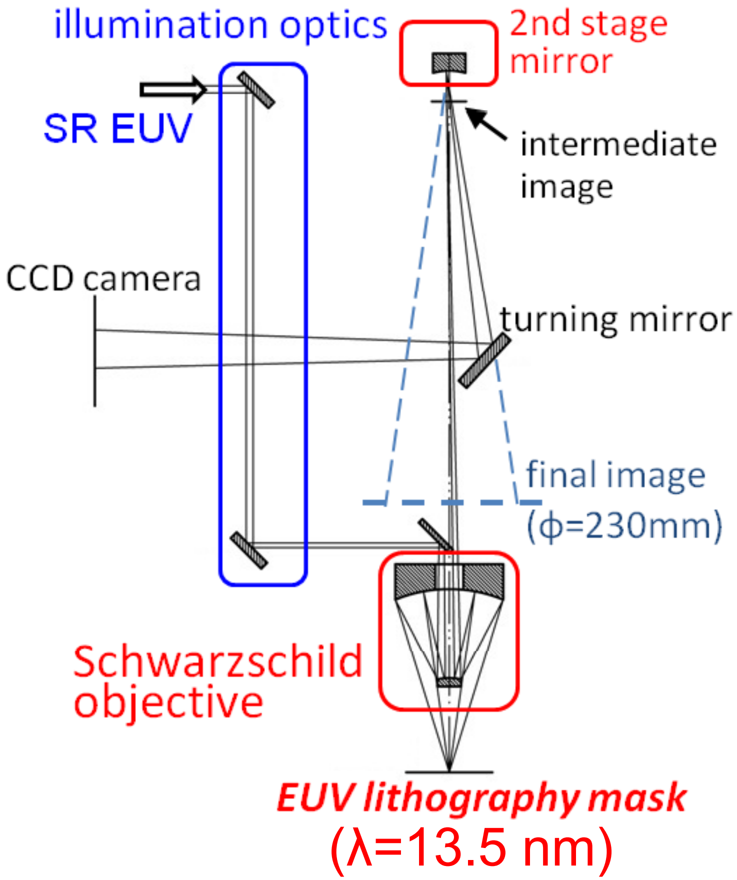
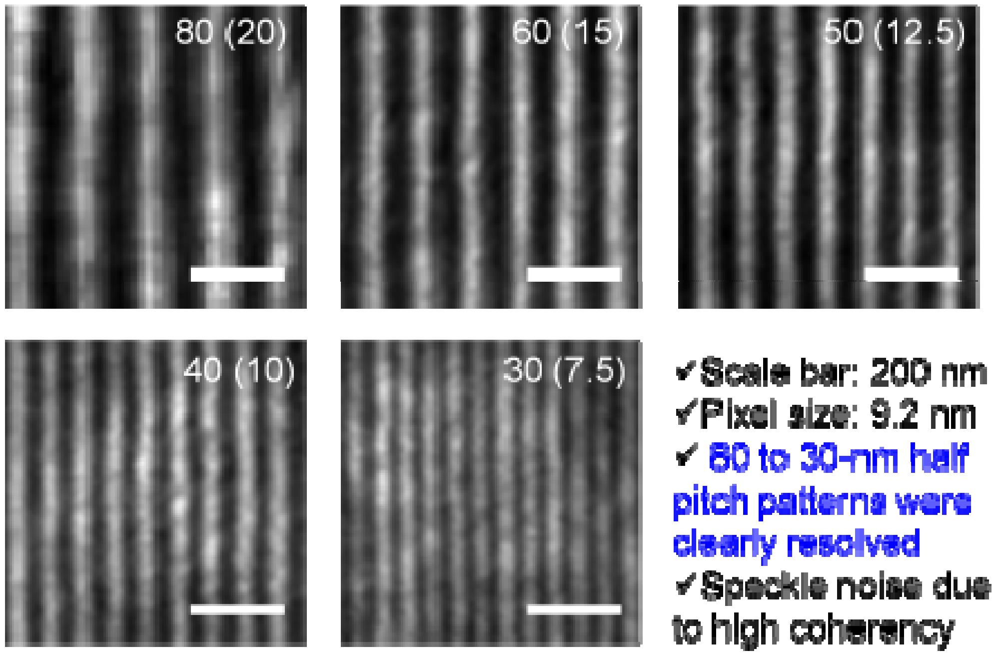
EUV optics research on Tohoku Univ.



EUV microscope for lithography mask inspection





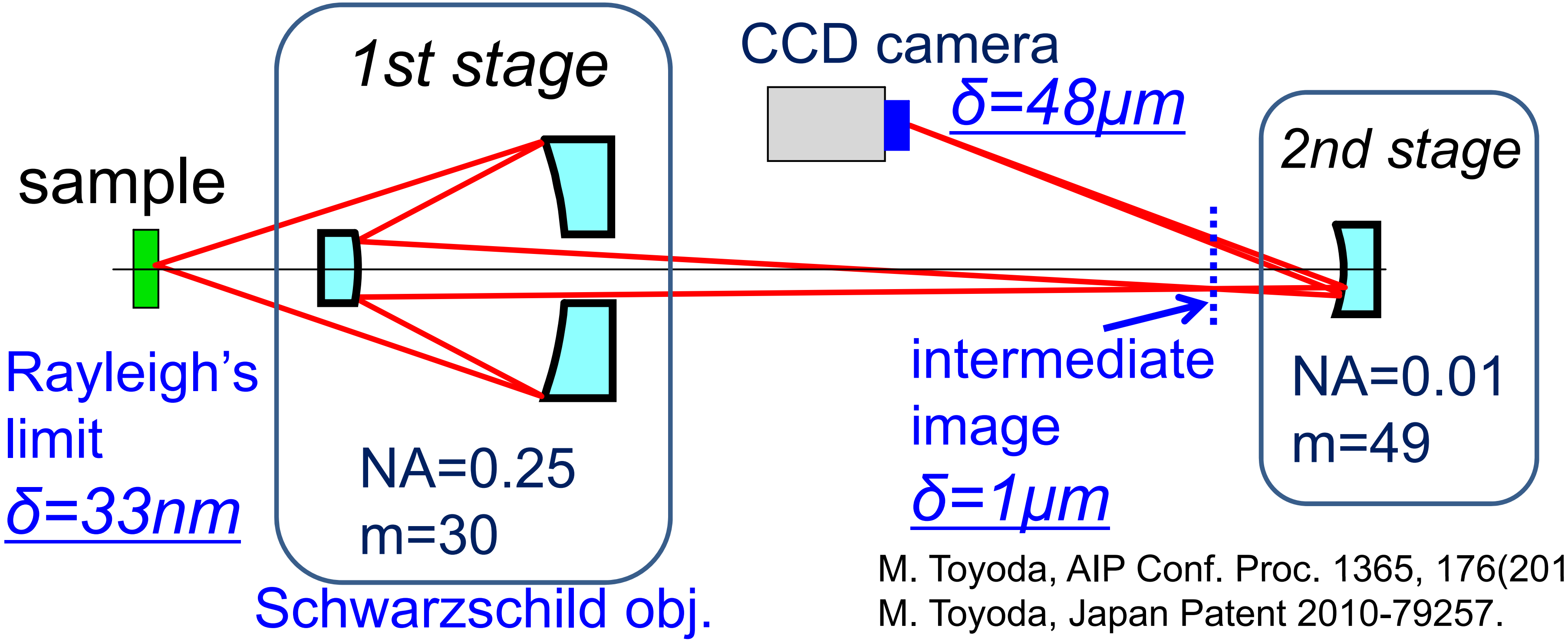
✓Scale bar: 200 nm
✓Pixel size: 9.2 nm
✓ 80 to 30-nm half pitch patterns were clearly resolved
✓Speckle noise due to high coherency

M. Toyoda et.al., App. Phys. Express 7 (2014),102502.

✓Seven multilayer mirrors (Mo/Si)
✓Large numerical aperture(NA=0.25)

Diffraction-limited resolution of 30 nm was successfully demonstrated (world record)

Two-stage imaging system for high magnification



M. Toyoda, AIP Conf. Proc. 1365, 176(2011).
M. Toyoda, Japan Patent 2010-79257.

✓Higher magnification (m=1460)

⇒ Resolution of 30nm with EUV-CCD camera

✓Good *correction of off-axis aberrations*

Practical requirements for optics: Aberrations

Marechal criterion

For diffraction-limited resolution: $\Delta = 0.61\lambda / NA$

Wave aberration

$$W = \underline{W_{design}} + \underline{W_{figure}} + \underline{W_{decenter}} < \frac{\lambda}{14} = 1\,\mathrm{nm\ rms.}$$

(@λ=13.5nm)

⇒Wave front sensing and control with 0.1 nm accuracy

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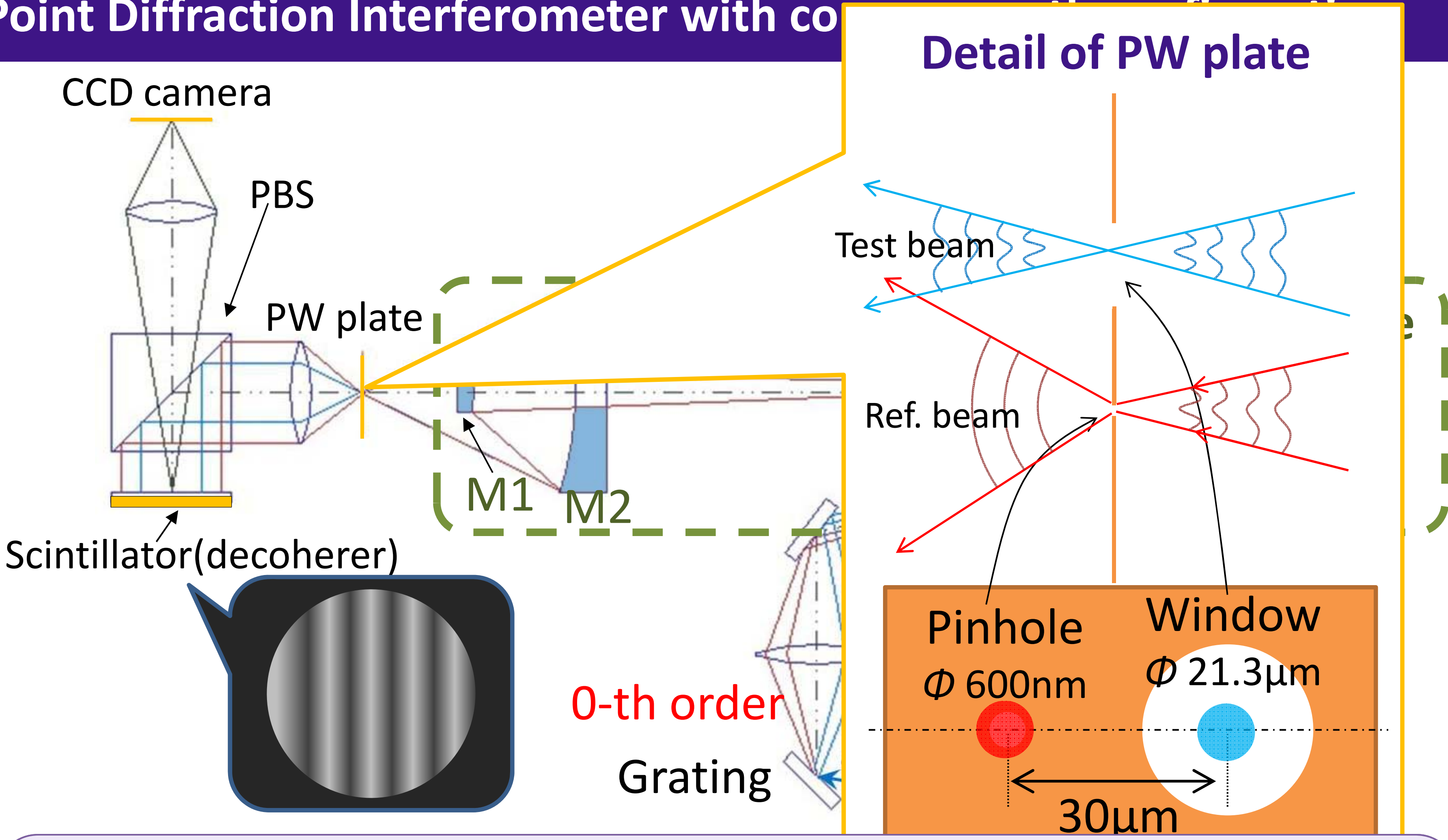
Point Diffraction Interferometer with co

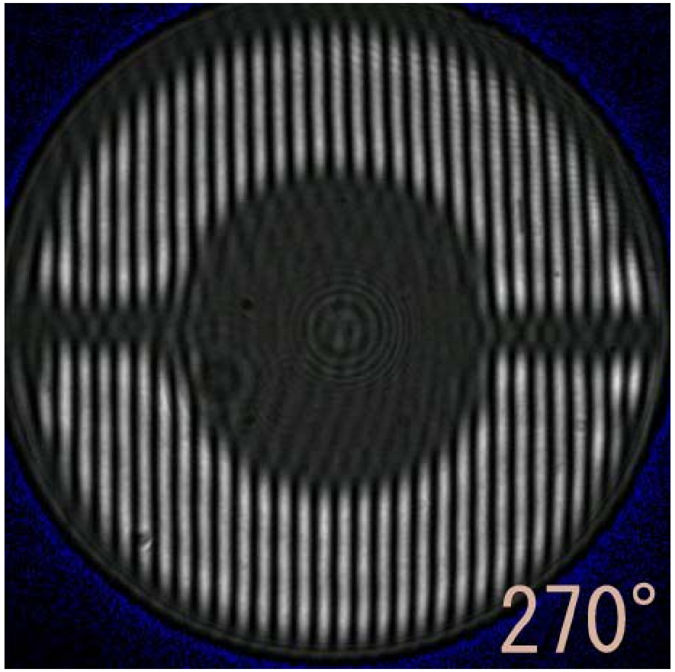


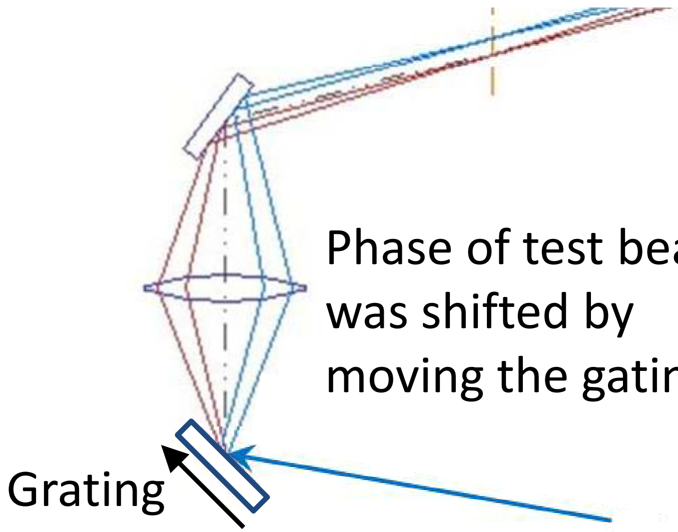
✓Common-path configuration with good repeatability

✓Ideal spherical wave made by point diffraction

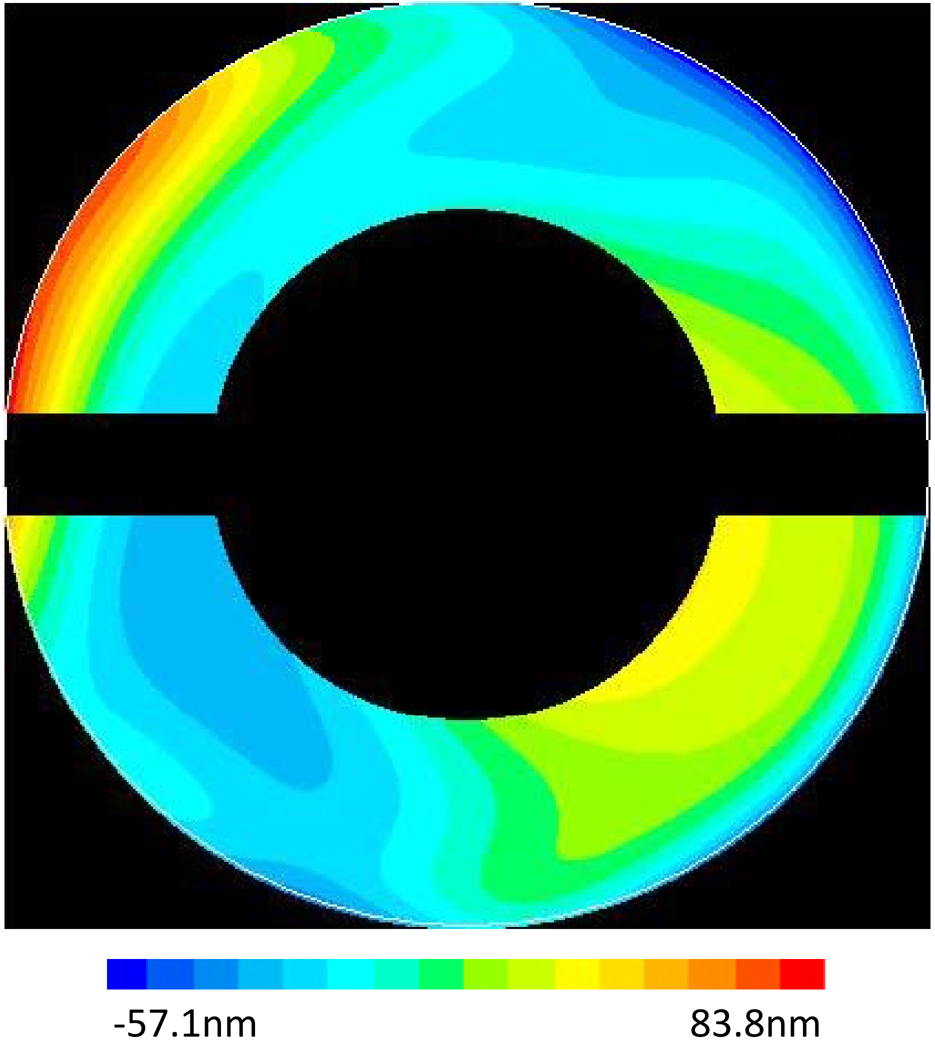
⇒ Interferometry with sub-nm accuracy

Experimental Result (1): wave front map





Phase of test beam was shifted by moving the gating

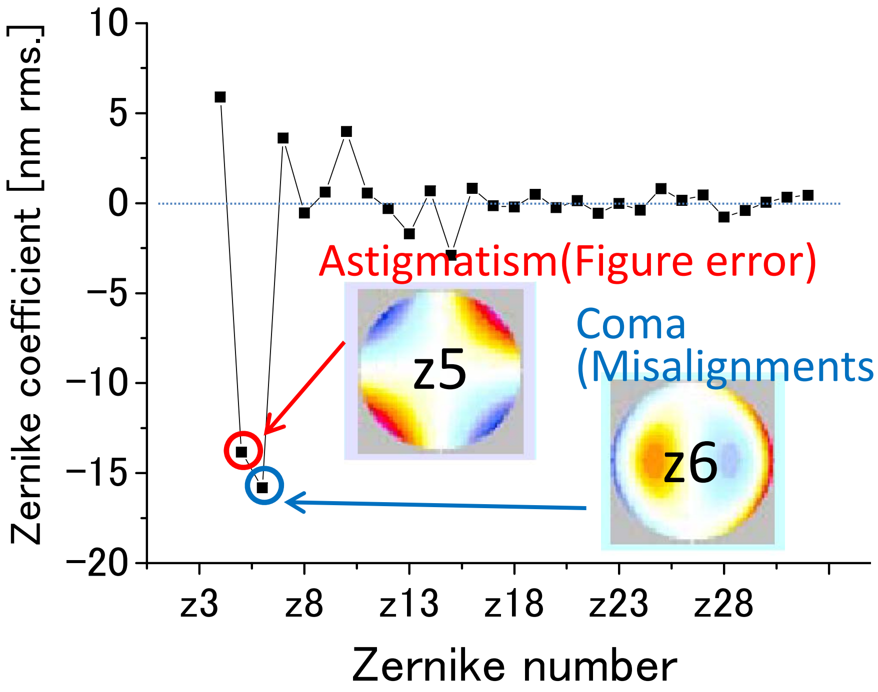


W_{RMS}=22.9nm

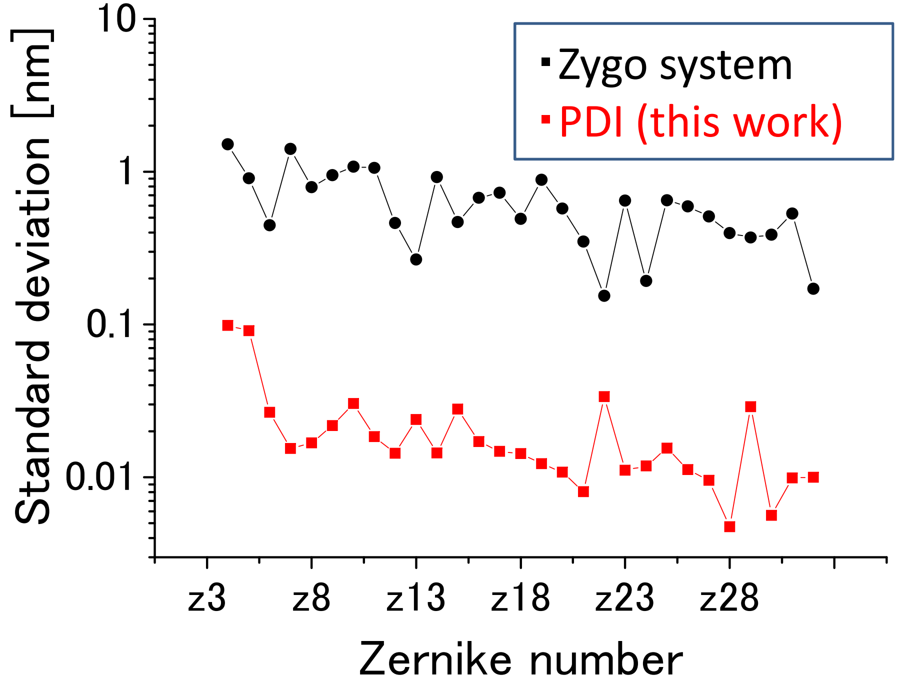
*Effect of tilts and defocus were removed

Experimental Result (2): Zernike polynomials

▪Average (over 50 measurements)



▪Repeatability



Repeatability for coefficients (Z3 to Z32) were bellow 0.1 nm.

✓Capability of measuring wave aberration with sub-nm accuracy was successfully confirmed.

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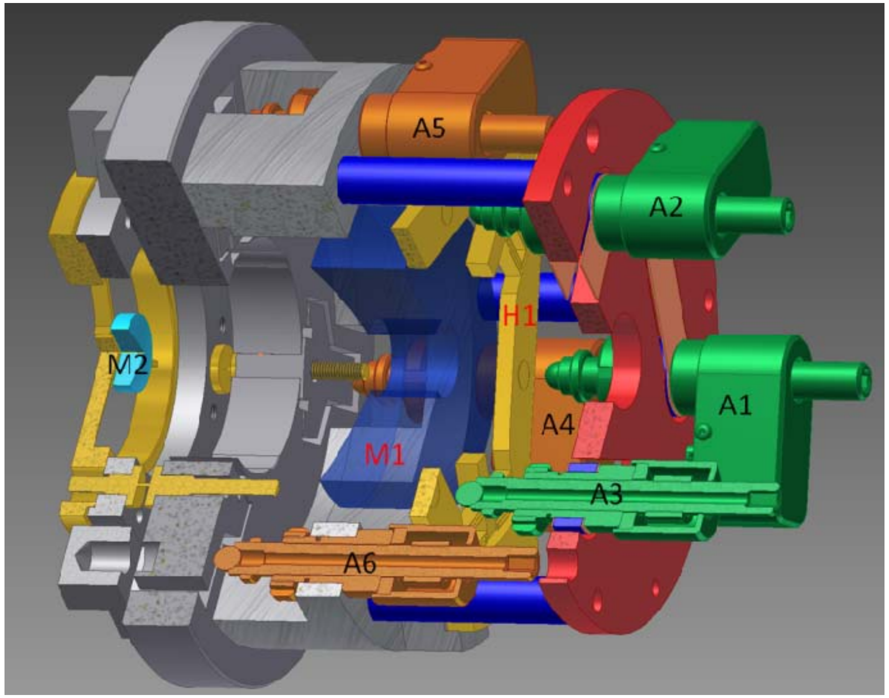
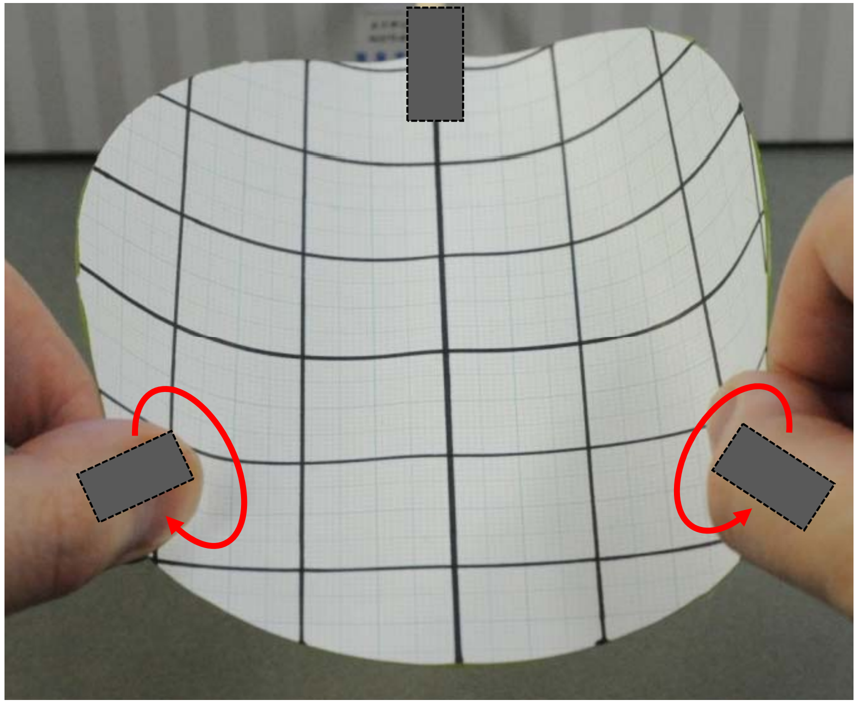
Mechanical design for deformable mirror

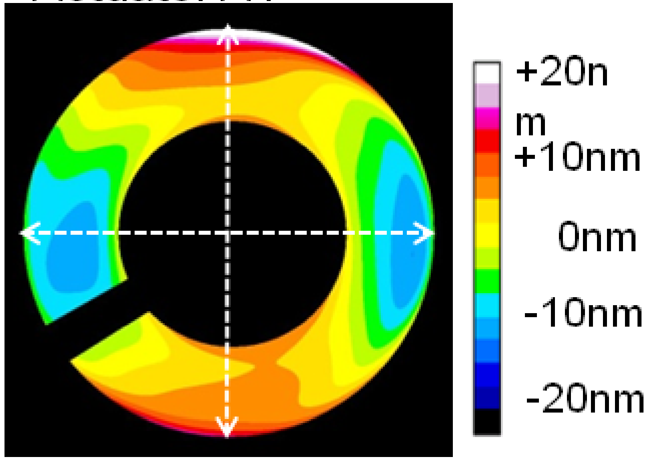




- ✓ Concave mirror (M1) is glued to three holding arms.
- ✓ Flexure springs absorb thermal expansion.
- ✓ **Picomotors (A1-A3)** can apply force (max: 20 N) on holding plate (H1) <u>to correct astigmatism</u>. (Stigmator)
- ✓ Three-axis stage with **Picomotors (A4-A6)** for fine alignment of convex mirror (M2) <u>to correct coma</u>.

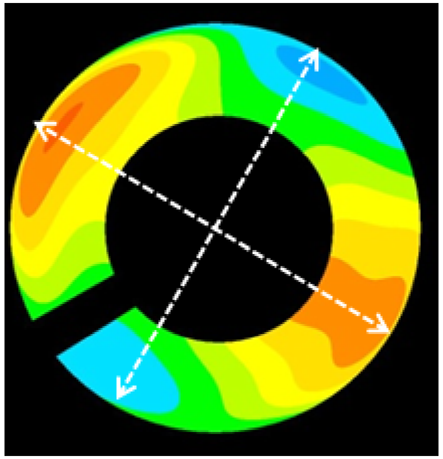
Wave aberration resulting from stigmator

・Actuator A1

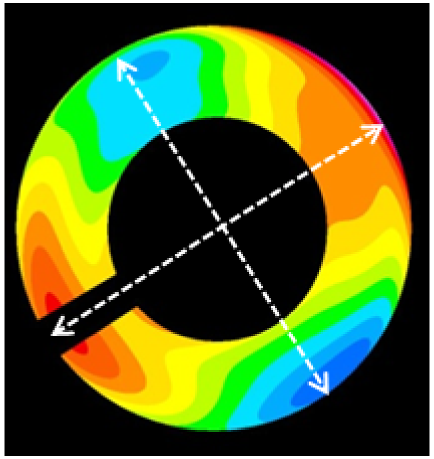


Load force: 10 N

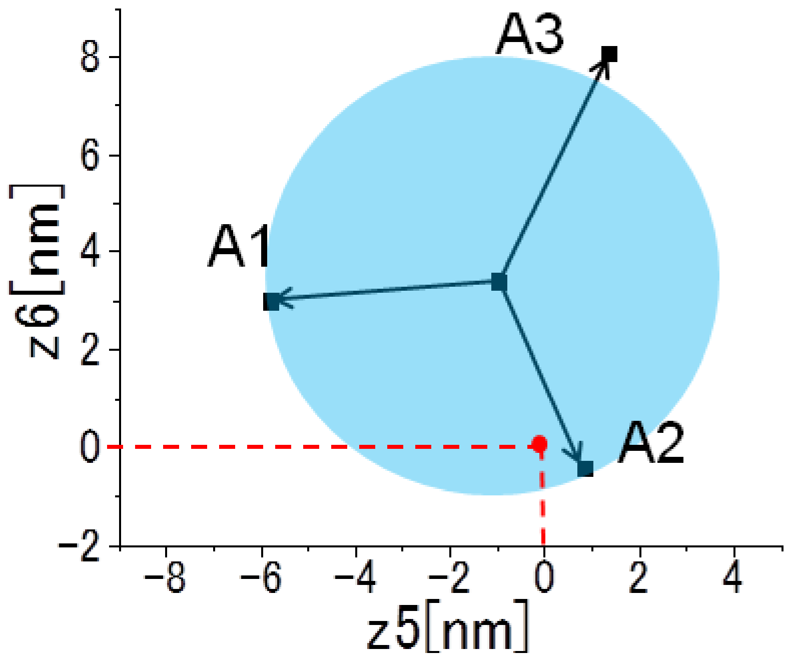
・Actuator A2



・Actuator A3



・Annular Zernike coefficients



✓ Astigmatism was clearly observed in all data.

✓ Control range as stigmator: ±4 nm rms.

Wavefront control with fine optical alignment

Marechal Criterion

Wrms < λ/14

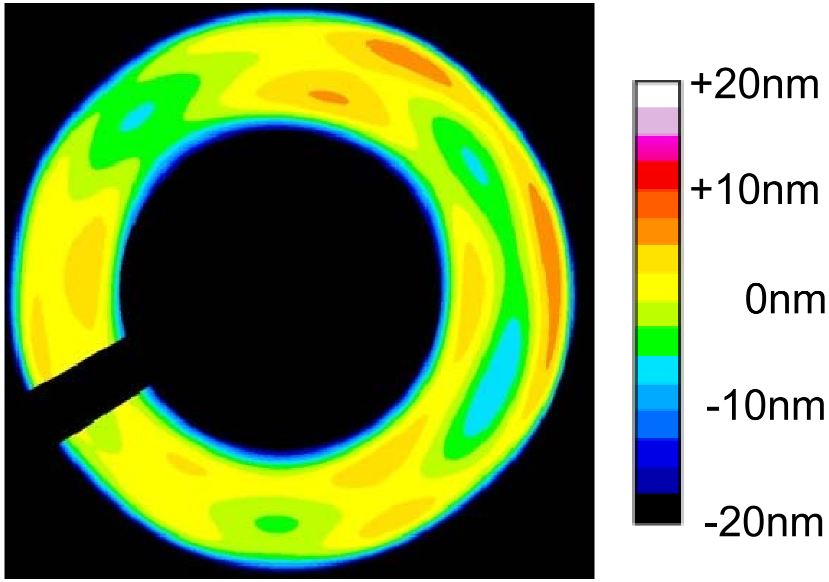
=1 nm (@λ=13.5 nm)

Alignment

Astigmatism: stigmator (mirror bending)

Coma: mirror tilt

Spherical: mirror separation



	Astigmatism		Coma		Spherial	Total (z5 to z9) RMS.
low-order terms	 z5	 z6	 z7	 z8	 z9	
W_{RMS}	0.04nm	0.17nm	0.21nm	-0.08nm	0.07nm	0.29nm

4. Summary

✓A high magnification EUV microscope based on all-reflective objective is proposed.

✓Point diffraction interferometer enables wave front sensing with sub-nm accuracy

✓ Wavefront control is successfully demonstrated

⇒ EUV objective with diffraction-limited resolution

Future plans

✓At-wavelength observation of mask defects

✓Lab-scale EUV microscope with a plasma light source