The Progress in Design, Preparation and Measurement of MLL for HEPS

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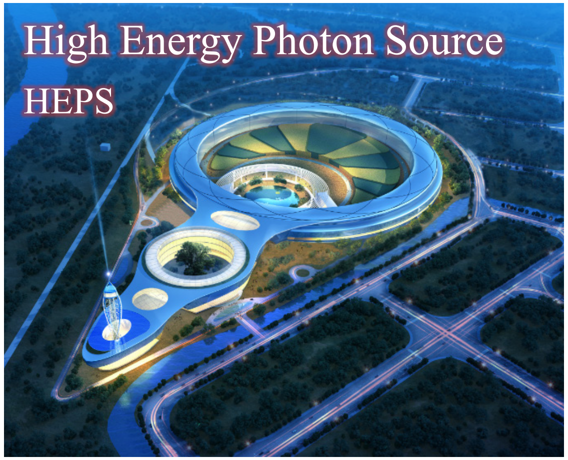
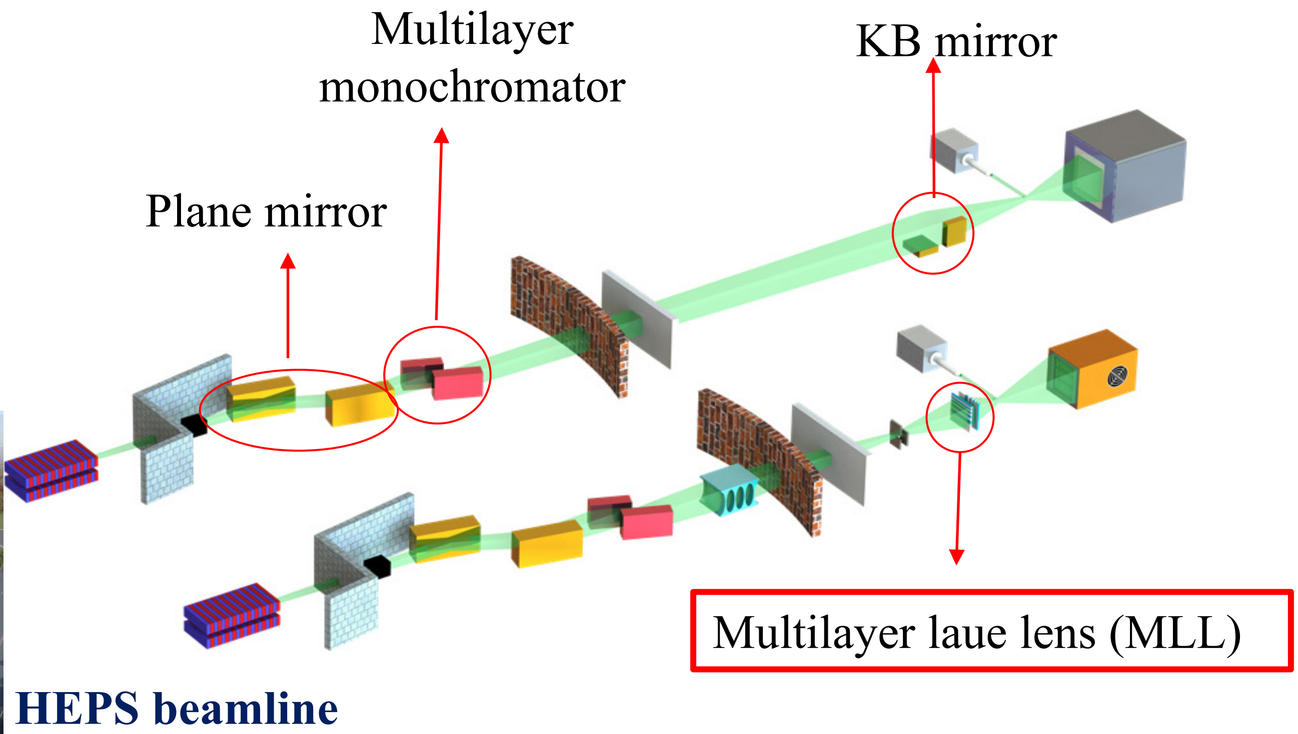
- Background
- Progress
  - Conventional design
  - MLL preparation
  - Measurement and calculation
- New design
- Conclusion

Background





The high brightness of the fourth generation Synchrotron light source can fully utilize the coating to achieve high-flux reflection, monochrome and focusing

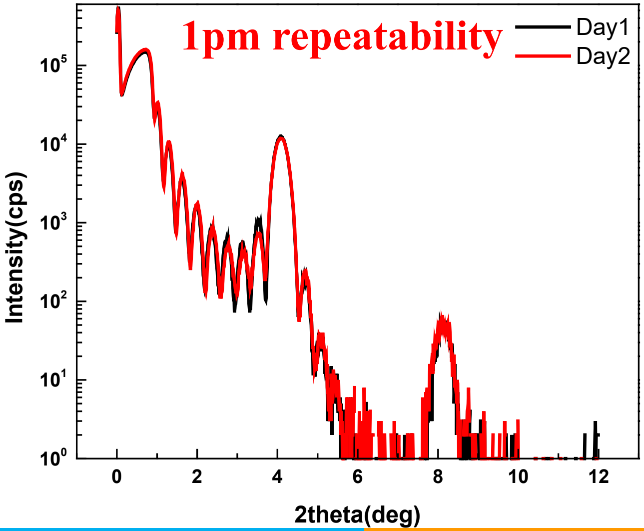
Background

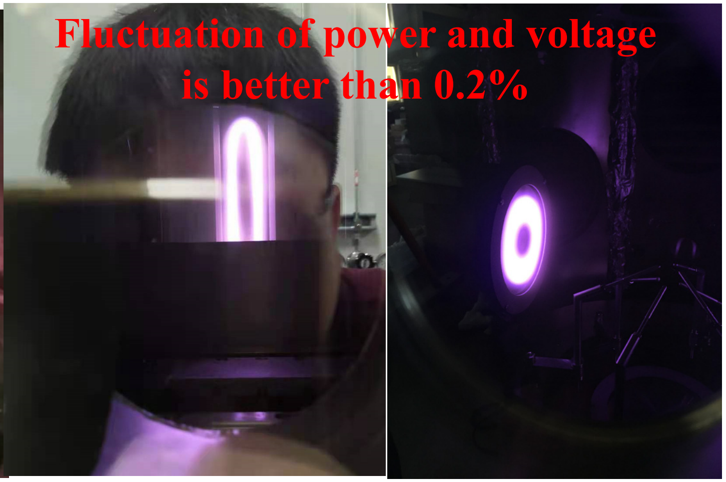
Multilayer Lens Coating Machine

Features: 9-target linear array, tens of thousands of layers, 100 microns thickness

Mirror Coating Machine

Features: up to1.2 m mirror, figuring and coating module integration



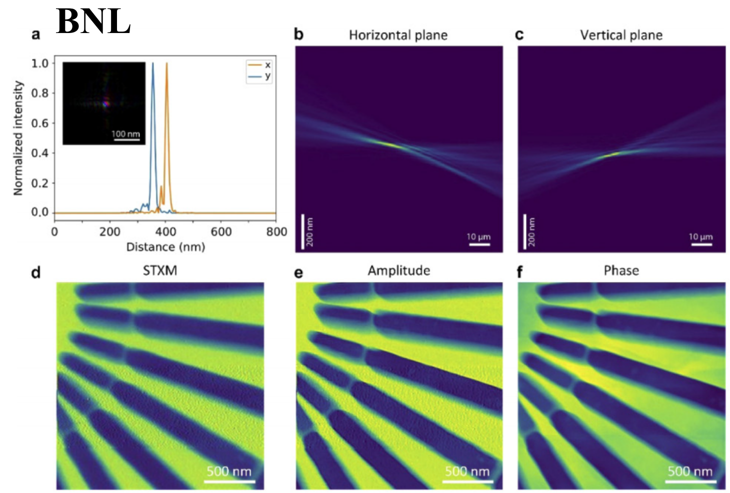


Background

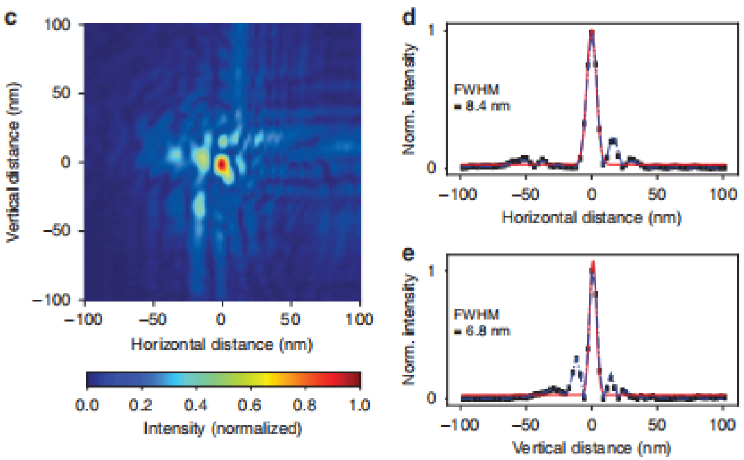
Hard X-ray nanoprobe

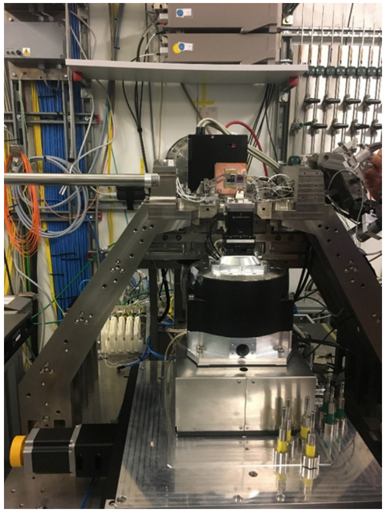
In order to improve the focusing resolution of MLL, a lot of research has been done by international researchers

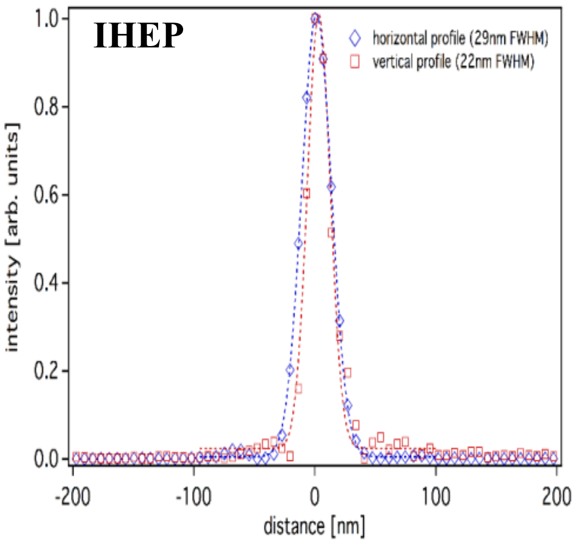
	DESY	BNL	IHEP
Energy(keV)	16.3	13.6	10
Aperture(μm)	29×22	53×43	17×17
Focus spot(nm)	8.4×6.8	14×13	23×29



DESY



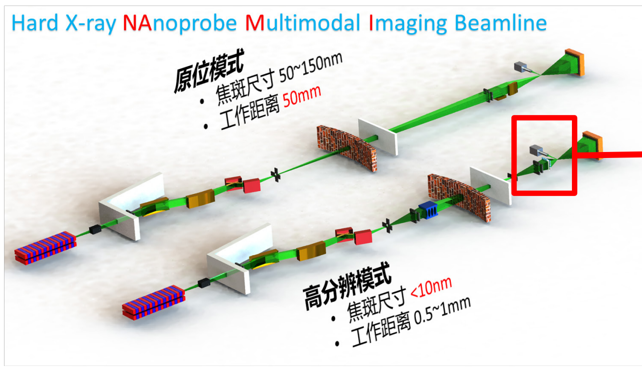


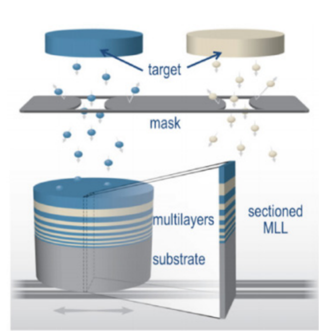


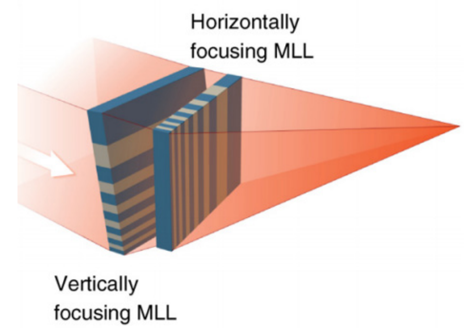
Saša Bajt,Light: Science & Applications (2018) 7, 17162;
XU W,Opt Express, 2020, 28(12)

Background

To achieve high spatial resolution, the MLL is the key element to realize small beam size less than 10nm.



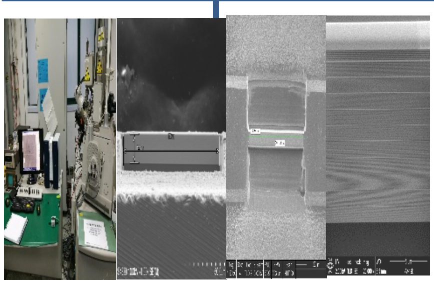




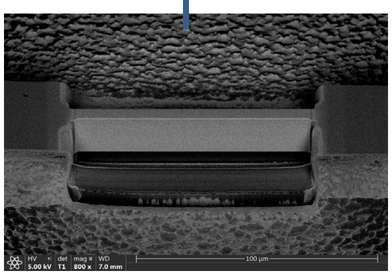
Outermost layer thickness: 7nm→3nm， layers: 1736→13030， Aperture: 17μm→64 μm

HEPS-TF (2017–2018) | HEPS (2021–2022~2023)

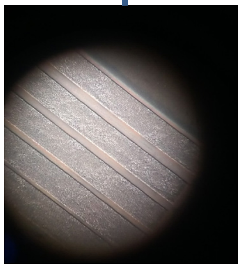
2017 — 2018 — 2019~2020 — 2021 — 2022~2023



FIB technology

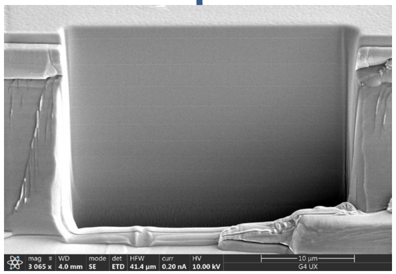


1736 layers， 17μm aperture



laser etching

coating machine



13030 l ayers 64μm aperture

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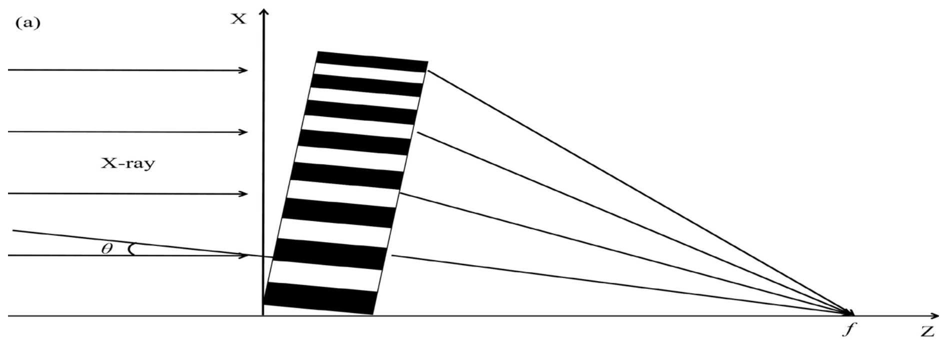
Progress

MLL Conventional Design

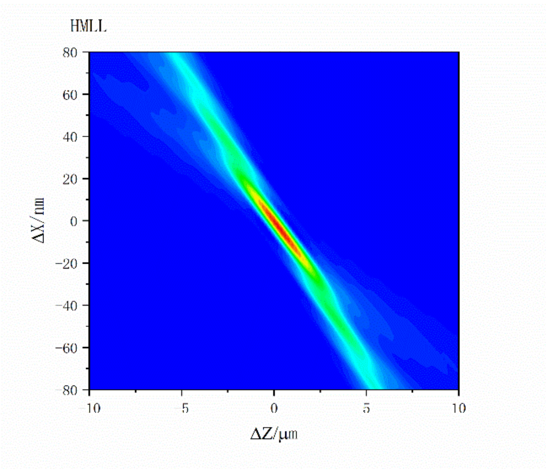
Table 1: MLL design parameter

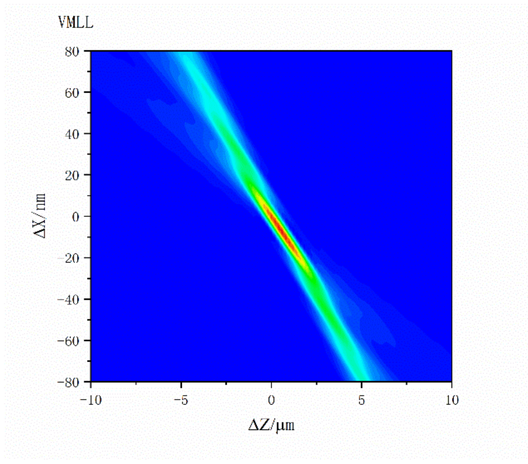
MLL@10KeV	Horizontal	Vertical
Aperture [μm]	43	63
Thickness [nm]	3.3-15	3-14
Layers	8030	13030
Optimum depth [μm]	3.5	3.3
Efficiency	8.4%	7.2%
Focal length [mm]	3	4
FWHM [nm]	8	8
Tilt angle [mrad]	7.4	8.3

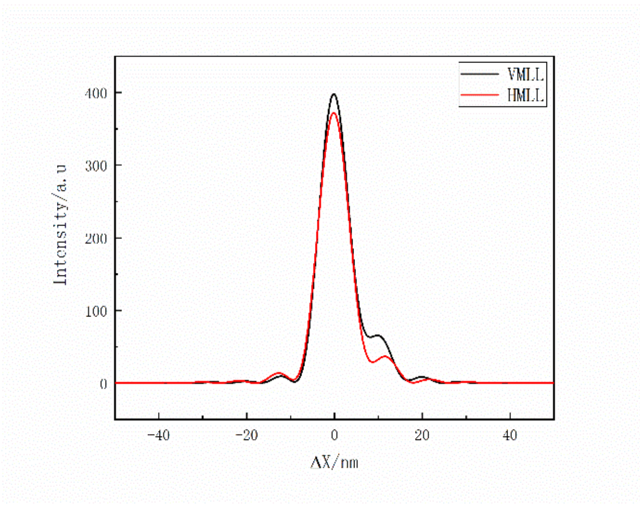
The MLL consists of alternating regions made of two different materials. The thickness distribution is similar to that of a Fresnel zone plate (FZP). resulting in a 8nm focusing effect.



$$x_{\mathrm{n}}^{2} = n\lambda f + n^{2}\lambda^{2} / 4$$







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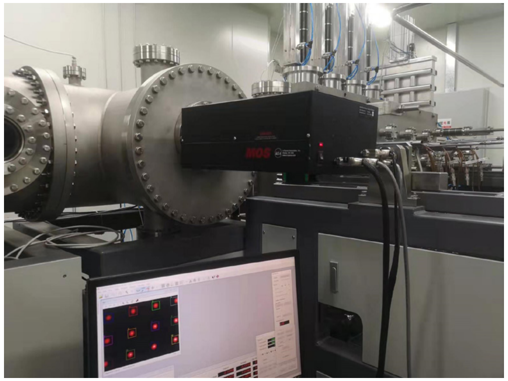
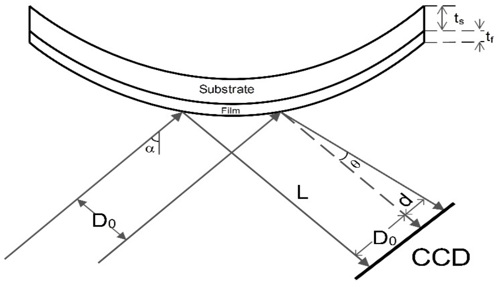
2.Progress

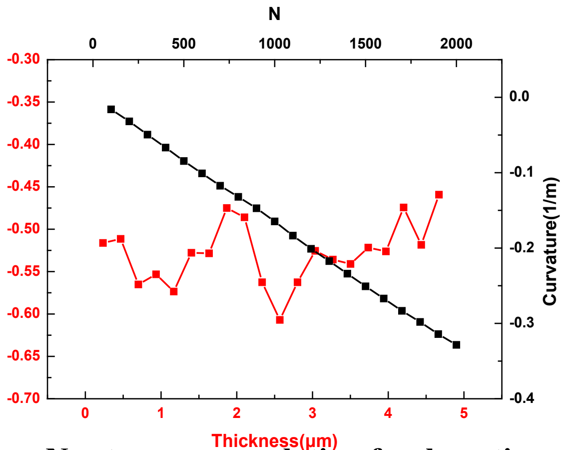
MLL Preparation——stress measurement and optimize

The stress optimization of MLL is the key to the preparation. If the stress is too high during the deposition process, the multilayer will deform and even fall off



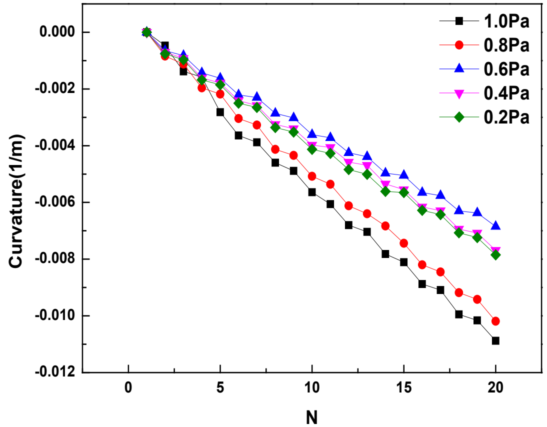


$$\kappa_{post} - \kappa_{pre} = \frac{6\sigma h_f (1-\nu_s)}{E_s h_s^2}$$

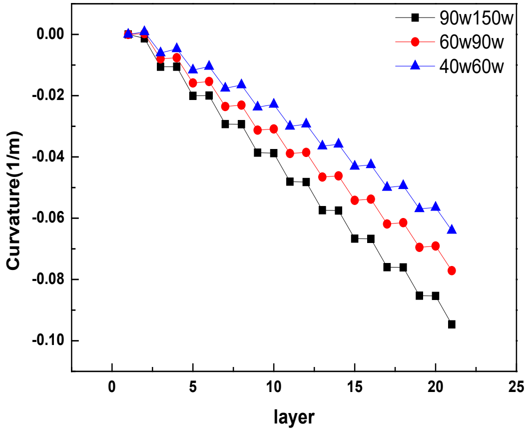


On-line thin film stress measurement

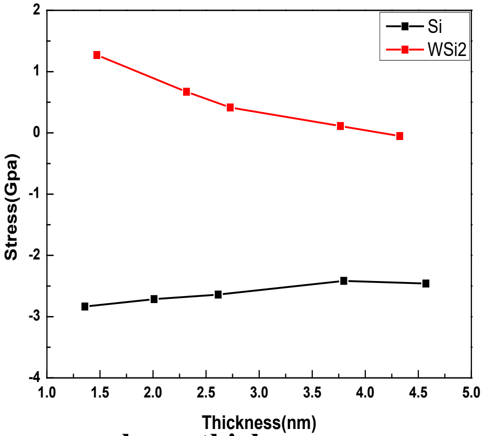
No stress accumulation for long time



Ar pressure



sputtering power



layer thickness

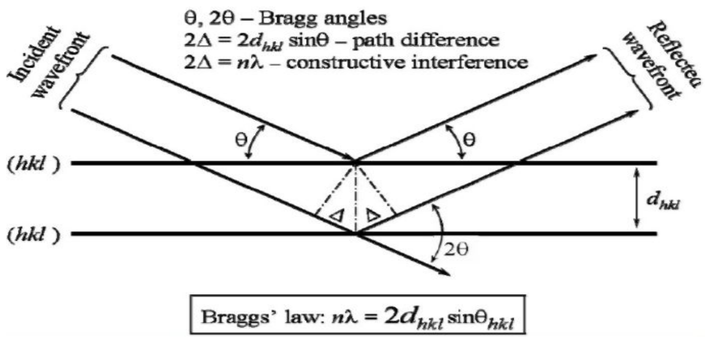
Optimize the minimum stress coating process

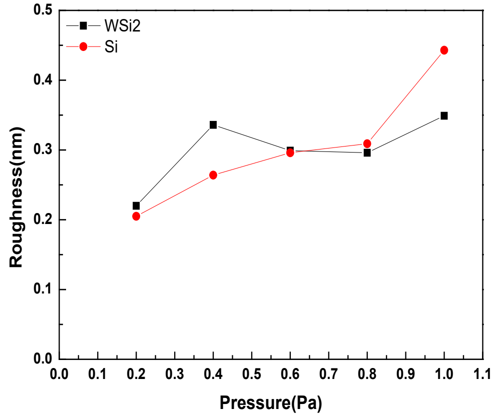
2.Progress

MLL Preparation——Multilayer interface roughness optimization

We measured the GIXRR at different working pressure, thickness and power to minimize the stress and reduce the interface roughness of the multilayers as much as possible.

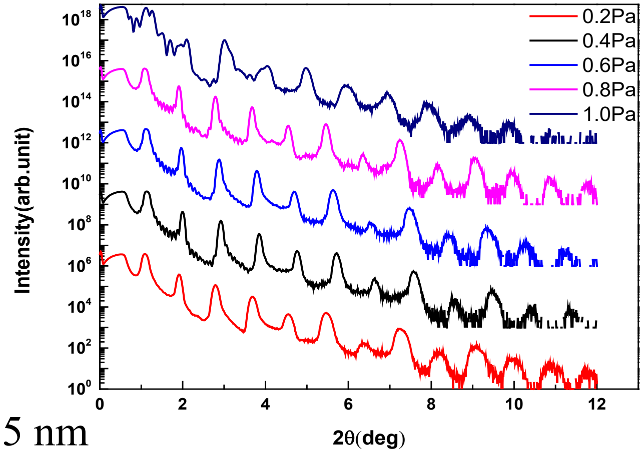
grazing incidence X-ray reflectivity (GIXRR)



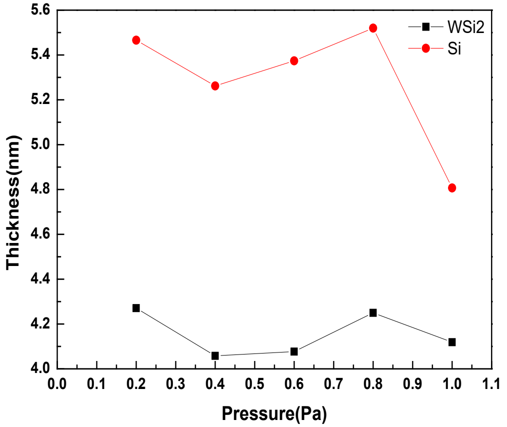


Interface roughness of different working pressure

Process priority:
Stress > roughness.
The stress is minimum
the roughness is less than 0.5 nm



GIXRR of different working pressure

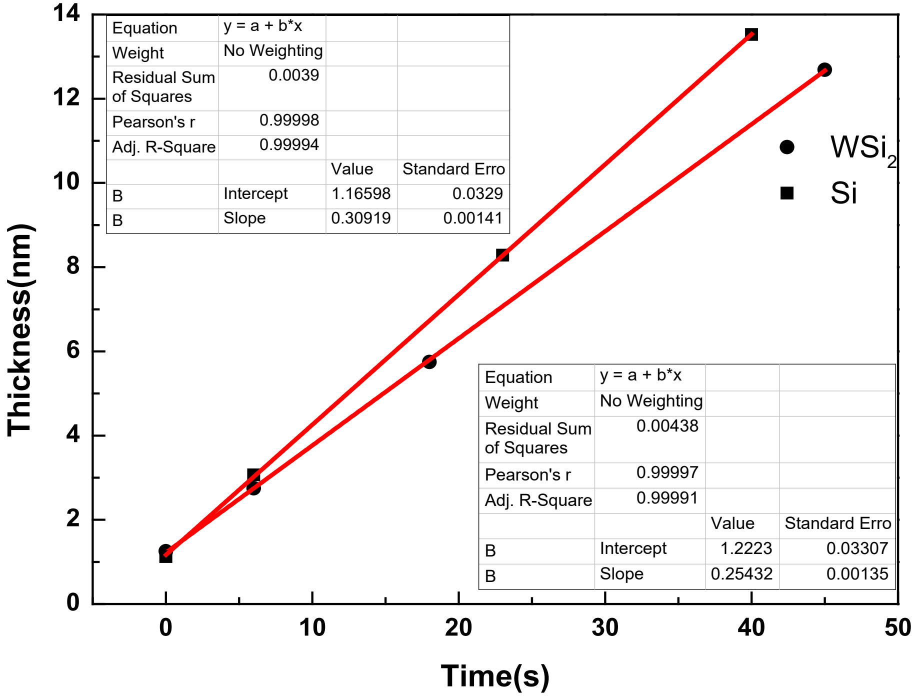


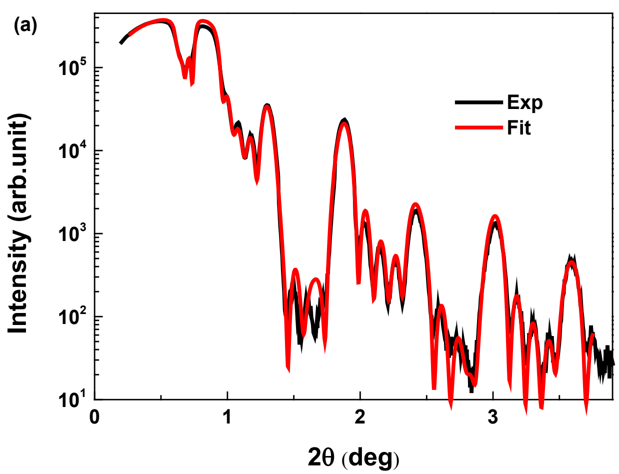
Thickness of different working pressure

2.Progress

MLL Multilayer Preparation

The layer thicknesses range of the designed MLLs is varied from **3~15nm**. Several fixed individual thicknesses within the range are selected to process periodic multilayers to calculate the **relationship between thickness and deposition time**





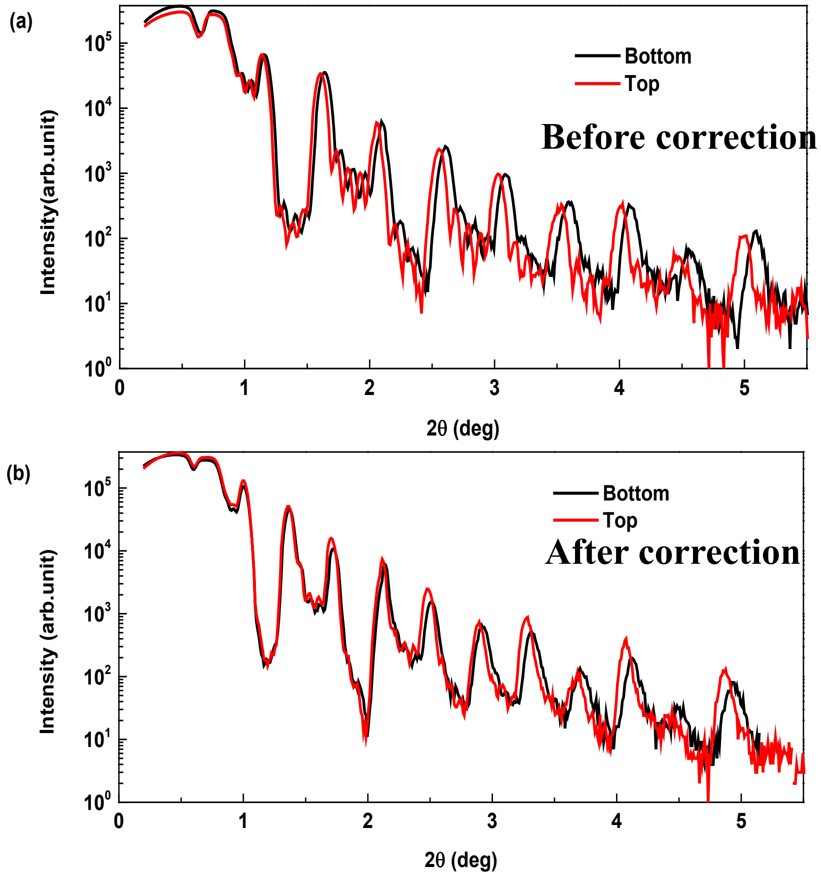
GIXRR

WSi_2 : d=0.25t+1.22 ; Si : d=0.31t+1.17
where d represents the thickness of individual material, t represents the deposition time

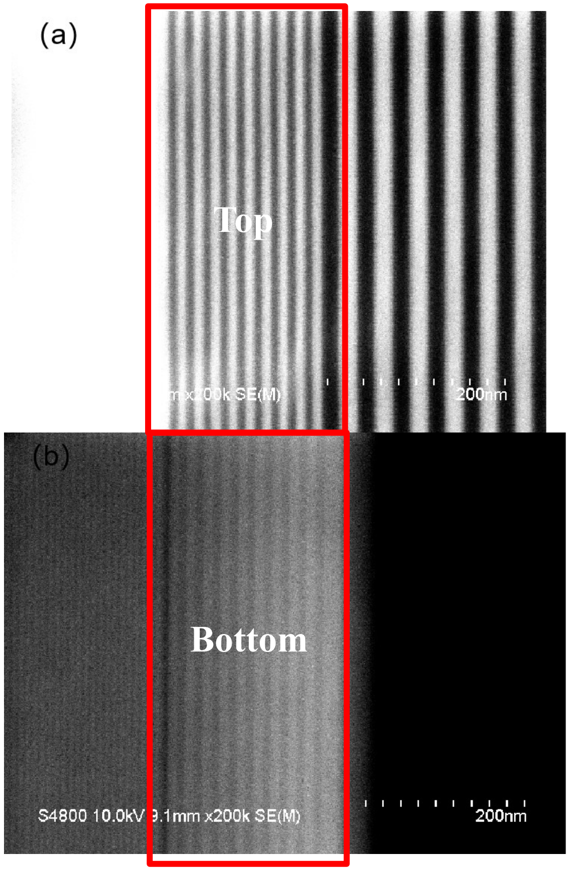
2.Progress

MLL Preparation——Decrease rate drift.

We prepare periodic multilayers with the same parameters on the bottom and top of the MLL, with a d-spacing of approximately 20nm. The thicknesses are measured by GIXRR and SEM before and after correction.



Rate drift decreased from 2% to 0.6%

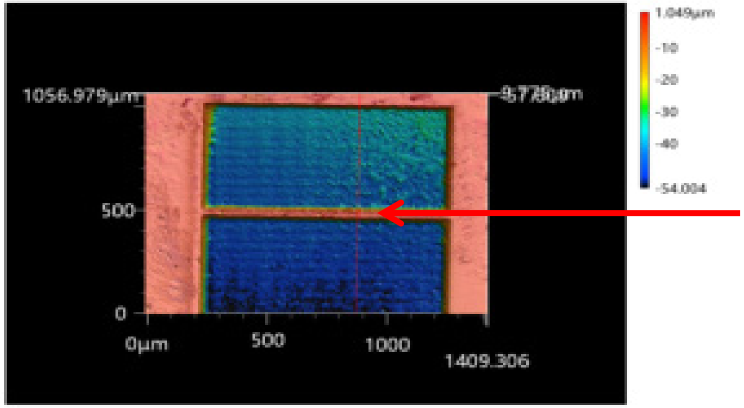


YUE S P, et al. Nucl Sci Tech, 2022, 33(9)

2.Progress

MLL Lenses Fabrication

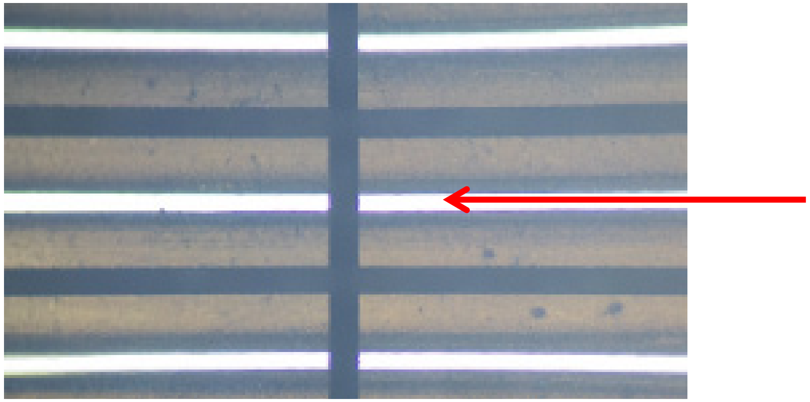
In order to precisely control the depth of the lenses and to achieve high-quality fine polishing of the entrance and exit surfaces, we use laser etching, dicing, and FIB polishing.



MLL

laser etching

Dicing machine

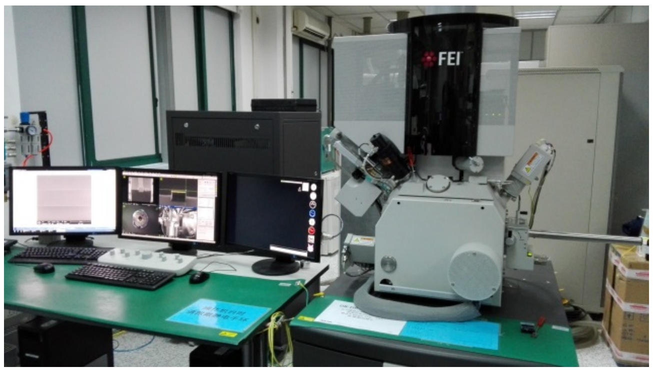


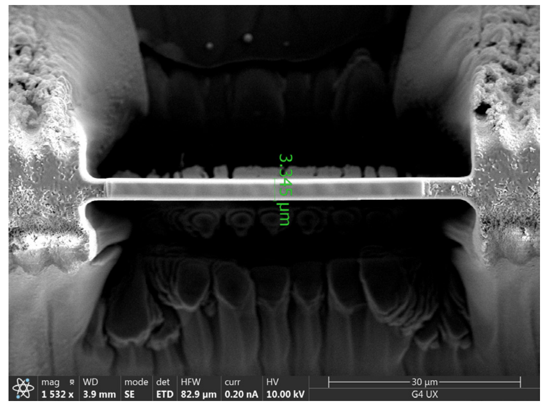
MLL

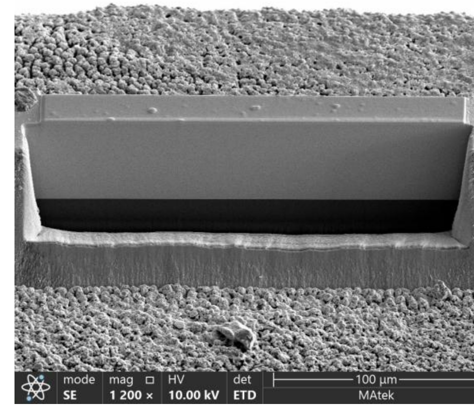
2.Progress

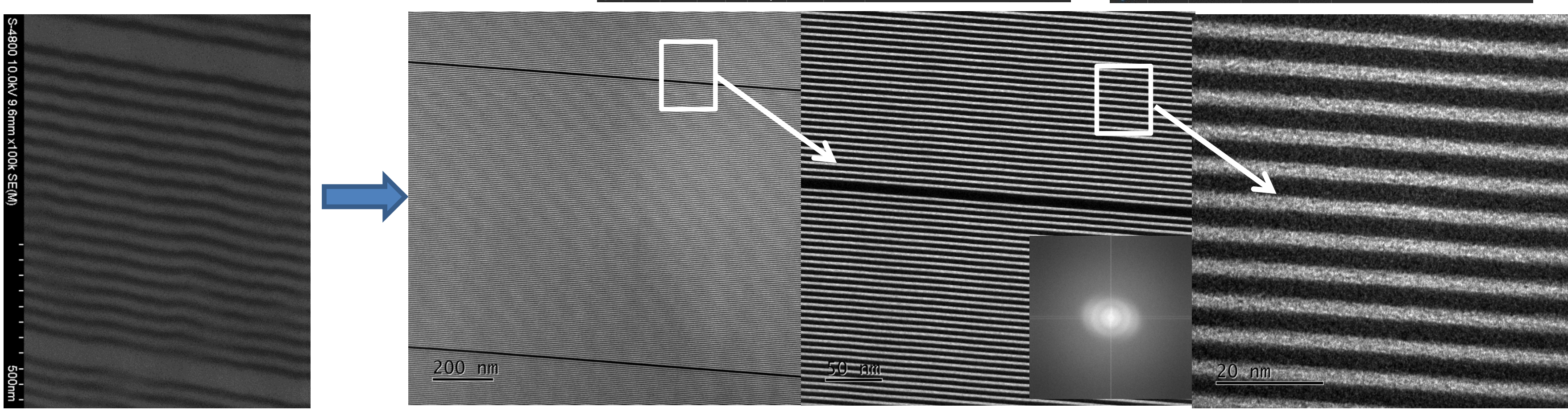
MLL Lenses Fabrication

FIB polishing——to final thinning and polishing the cross-section to satisfy the diffraction dynamics with supporting functions such as coating and imaging









600layers 10μm aperture with distortion→13000layers 64μm aperture without distortion

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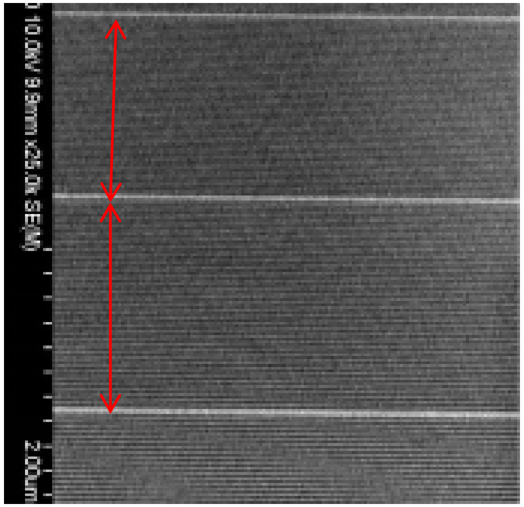
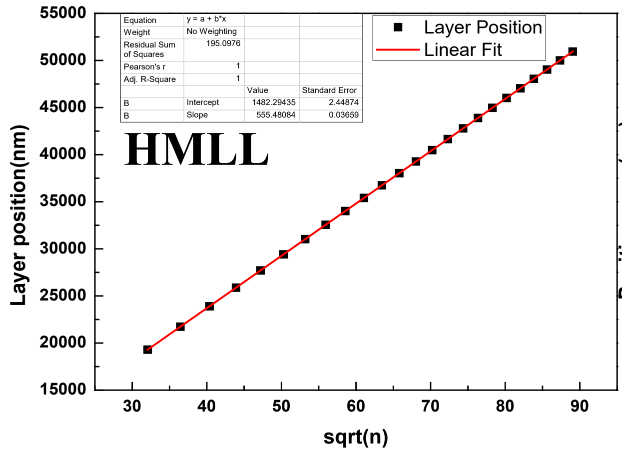
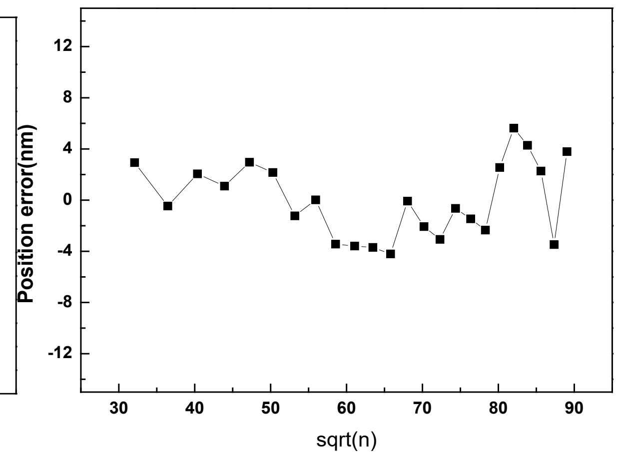
2.Progress

Calculated Focusing Performance of MLL
SEM image processing is combined with diffraction dynamics

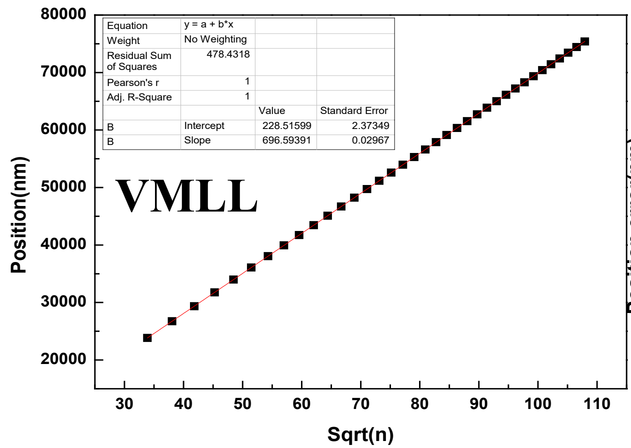


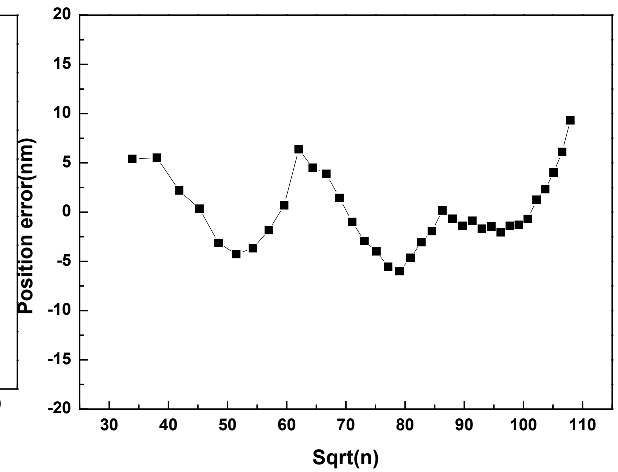




marker layer Position error±40nm→±5nm(PV), 2.9nm(RMS)

The location of each marker layer can be obtained by measuring the thickness of each marker region. In theory, the layer position should be proportional to the square root of the zone number.





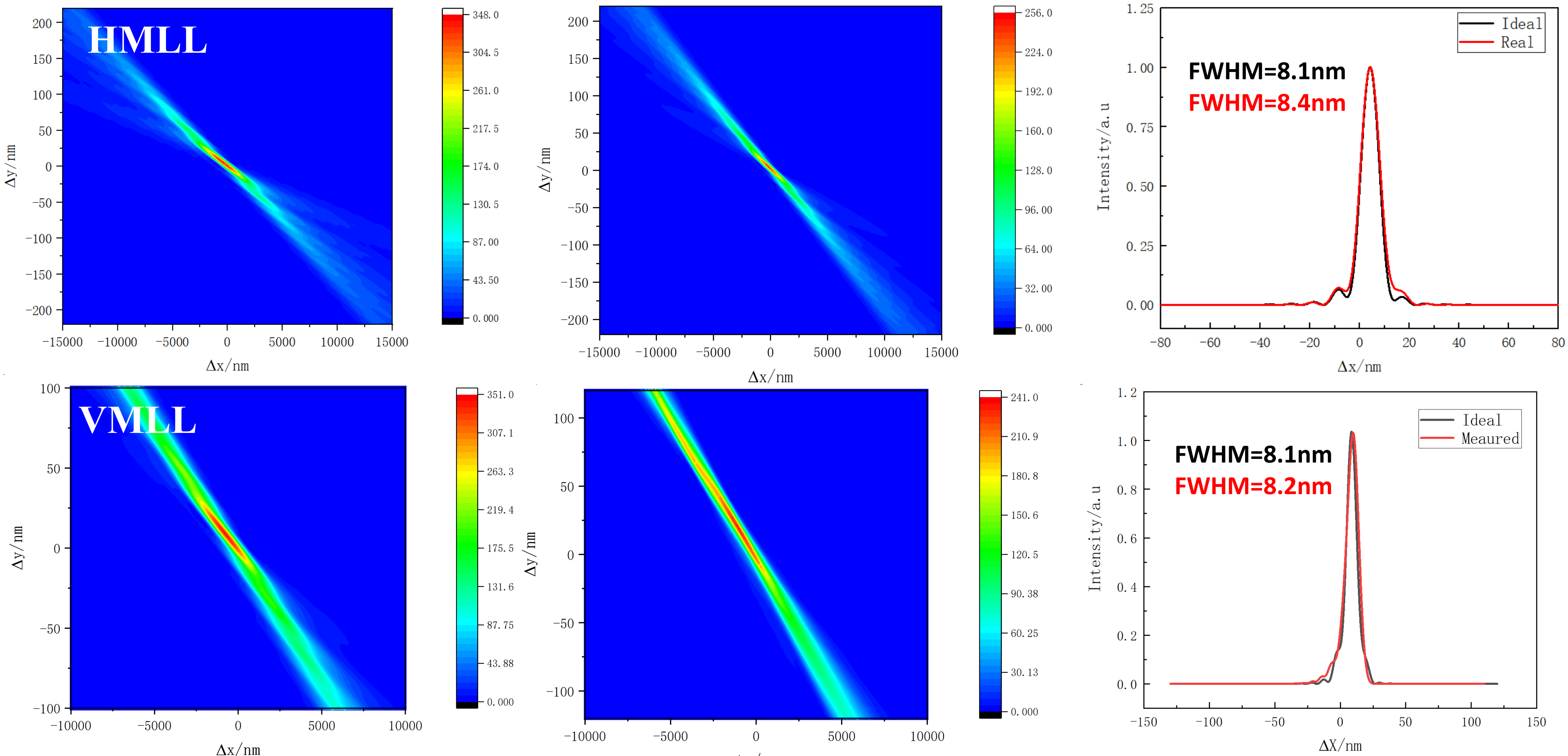
marker layer Position error < ±8nm(PV), 3.70nm(RMS)

2.Progress

Calculated Focusing Performance of MLLs

SEM image processing is combined with diffraction dynamics

By substituting the actual layer positions measured by the SEM into the central equations for the CWT method for MLLs This numerical solution allows us to calculate the wavefront of the diffracted wave on the exit surface of the MLL.



Theoretical design **Actual calibration** **At focus**

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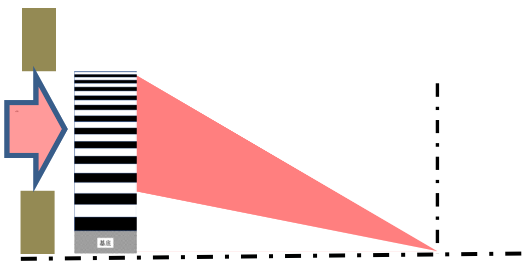
Multilayer Laue lens new design: By Bin Ji

Problem solved: **Remove the OSA which is used to block the high order harmonics. This could increase the working distance of MLL to mm level.**

Solution: **Special structure is designed to suppress high-order harmonics**



Problem

The grating spectrum is impure

↓

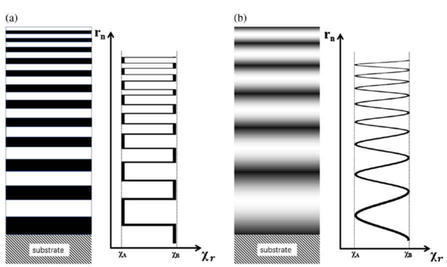
MLL working distance reduced

Effect

Single-order diffraction gratings have no harmonics

↓

Single-Order diffraction MLL with long working distance



Ji B, Yue S, Chang G, et al. Single-order focus multilayer Laue lens[J]. Applied Optics, 2022, 61(27): 8028-8033.

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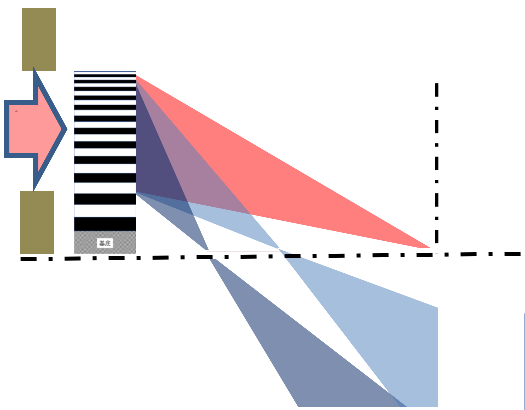

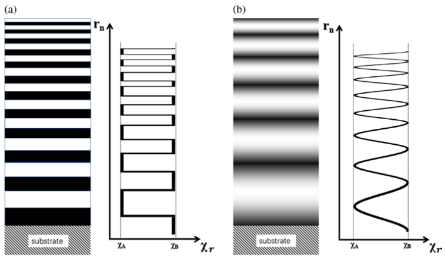

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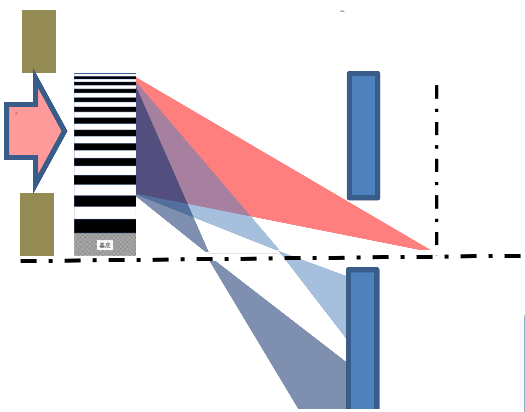

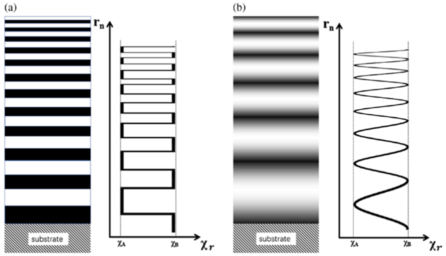

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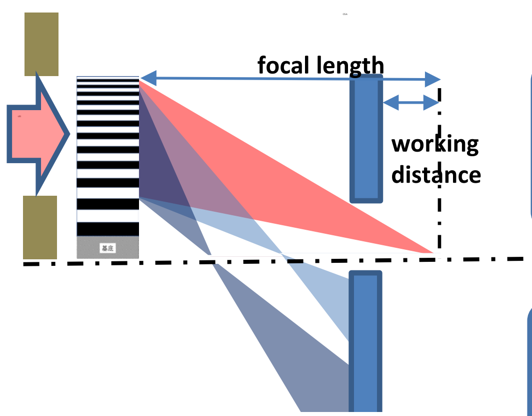

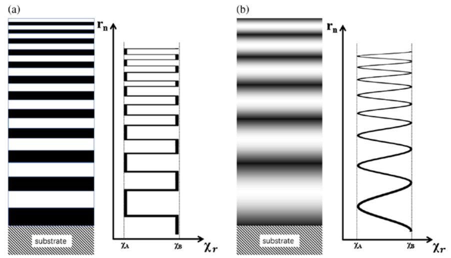

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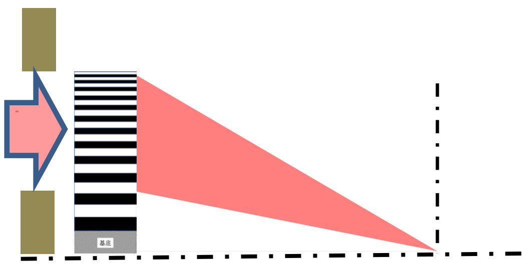

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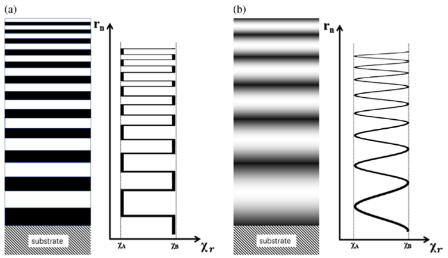

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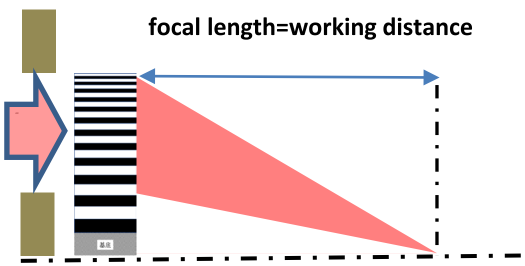
2.Progress

Multilayer Laue lens new design: By Bin Ji

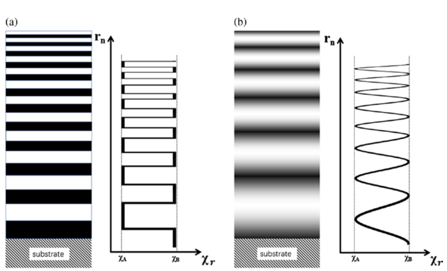
Problem solved: Remove the OSA which is used to block the high order harmonics. This could increase the working distance of MLL to mm level.

Solution: **Special structure is designed to suppress high-order harmonics**



Problem → **Effect**

Problem	Effect
The grating spectrum is impure	Single-order diffraction gratings have no harmonics
↓	↓
MLL working distance reduced	Single-Order diffraction MLL with long working distance



Ji B, Yue S, Chang G, et al. Single-order focus multilayer Laue lens[J]. Applied Optics, 2022, 61(27): 8028-8033.

2.Progress

Multilayer Laue lens new design: By Bin Ji

Design Innovations:

- ✓ High order diffraction can be suppressed by MLL structure
- ✓ greatly improve the practicability of MLL system
- ✓ keep the diffraction limit focusing effect

We find that the dynamic effects destroy the suppression ability, by optimizing the aspect ratio to optimize the performance.

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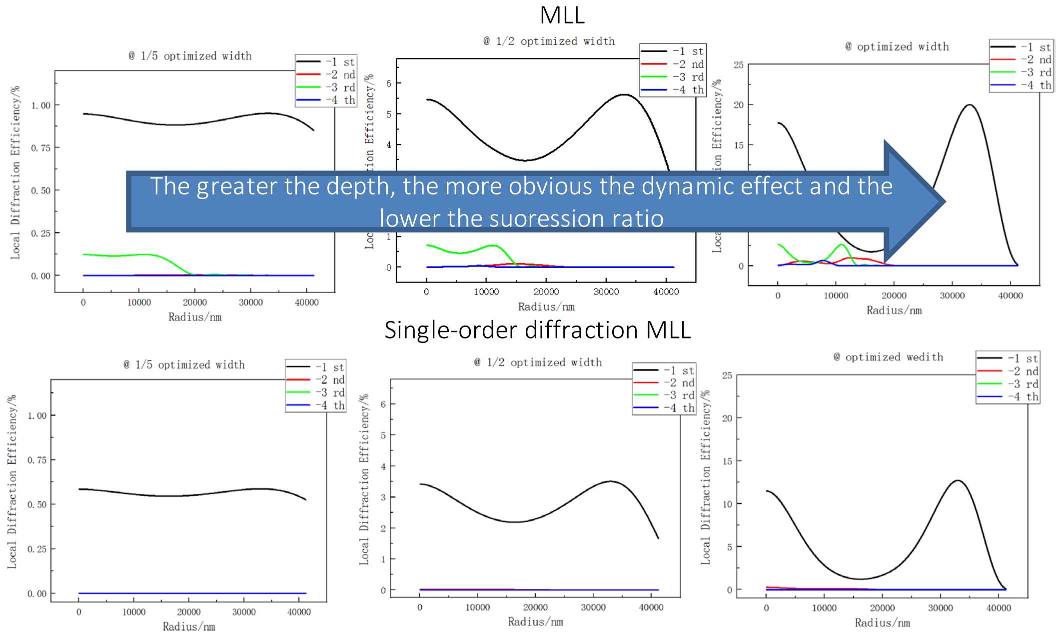

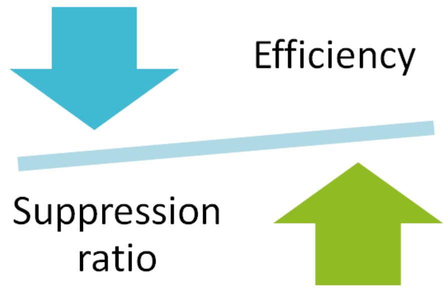

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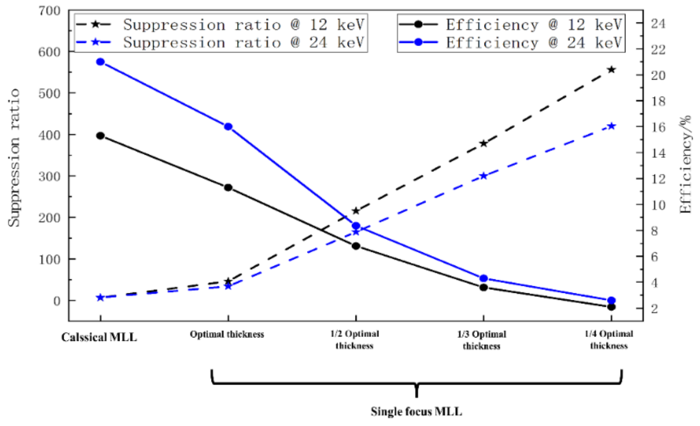
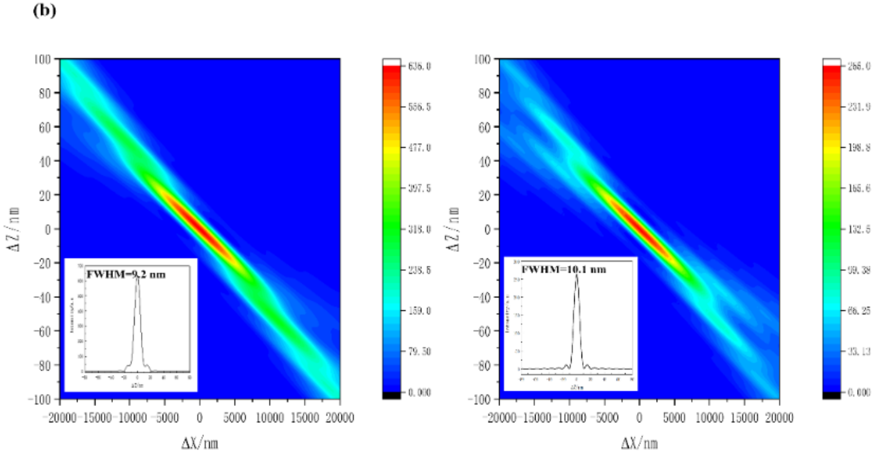


the working distance and practicability of MLL is increased.



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2.Progress

Multilayer Laue lens new design: By Bin Ji

Problem solved: Nearly 100 microns, 10,000-layer graded thickness film, nm level positioning accuracy, increase processing difficulty

Solution: **The mirror figuring method is used for reference to compensate the structural error.**

we propose a method of coating post-processing, lateral etching MLL to compensate the longitudinal structure error, so as to obtain better focusing effect.

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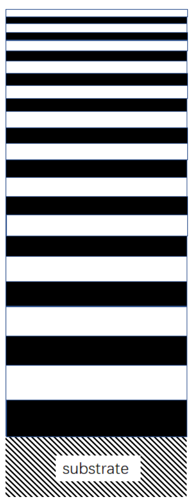
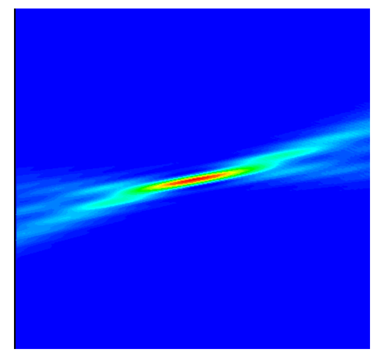


Wave front of the outgoing wave:

$$E = \sum_h E_h \exp[i\vec{k}_0 \cdot \vec{r} + i\phi_h(x)]$$



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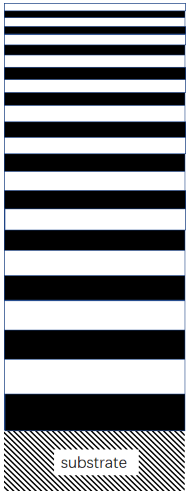

Long time coating leads to structure error

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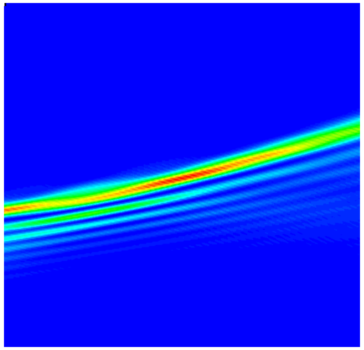

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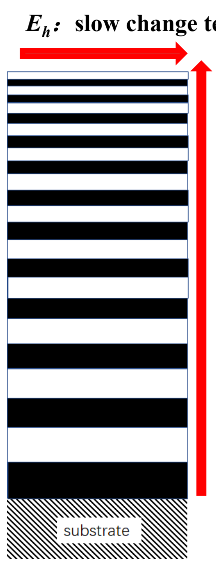

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ϕ_h: quick change term

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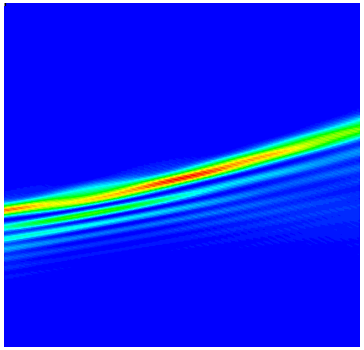

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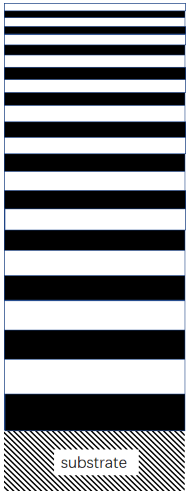

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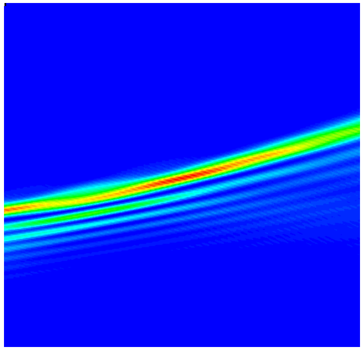

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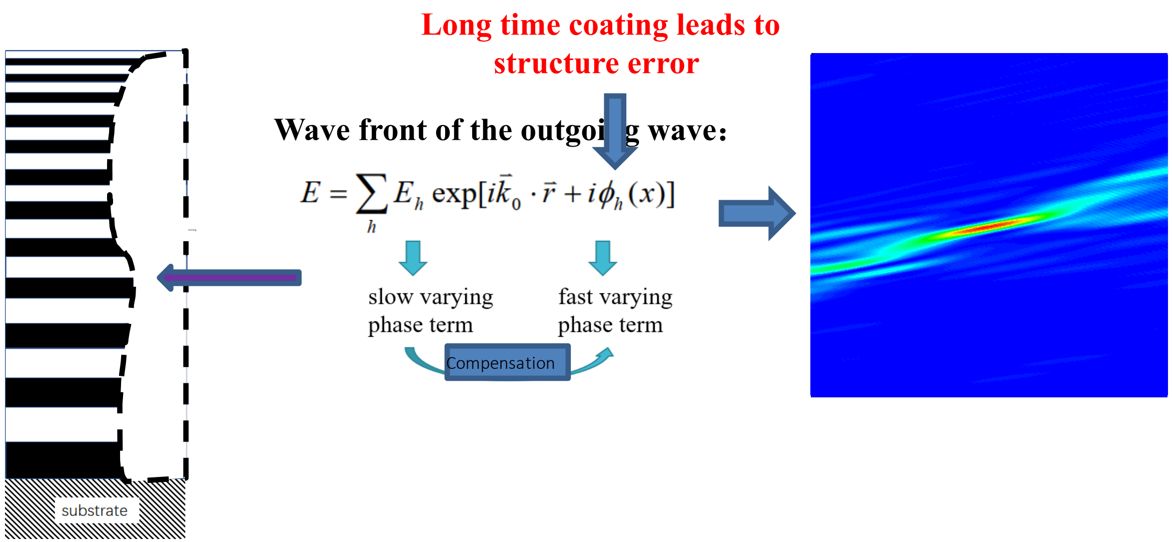

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2.Progress

Multilayer Laue lens new design: By Bin Ji

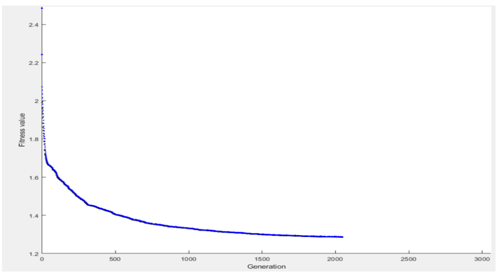
Design Innovations:

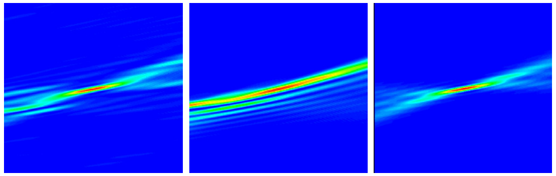
- ✓ The phase compensation effect is better than that of phase plate.
- ✓ The precision requirement of MLL nano-machining can be greatly reduced.

According to the characteristic of each layer coupling of MLL, we use GA algorithm to optimize the figuring by choosing proper subdivision mode

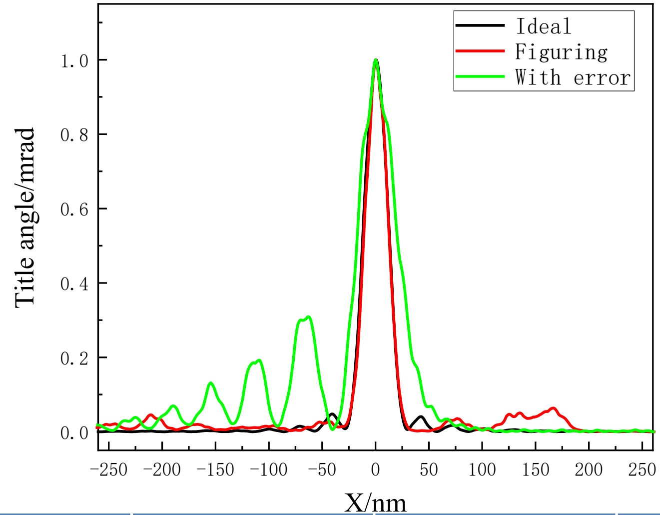
Mean phase difference of exit surface before figuring: 0.87π

Mean phase difference of exit surface after figuring: 0.22π





Figuring With error Ideal



	Efficiency	Focus resolution	Sidelobe suppression
Ideal	100%	25 nm	None
Figuring	49%	26 nm	Partial restrain
With error	29%	39 nm	Worse

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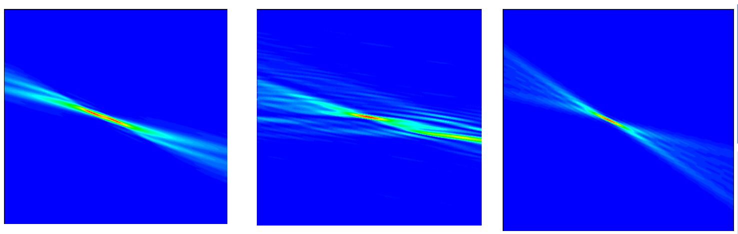
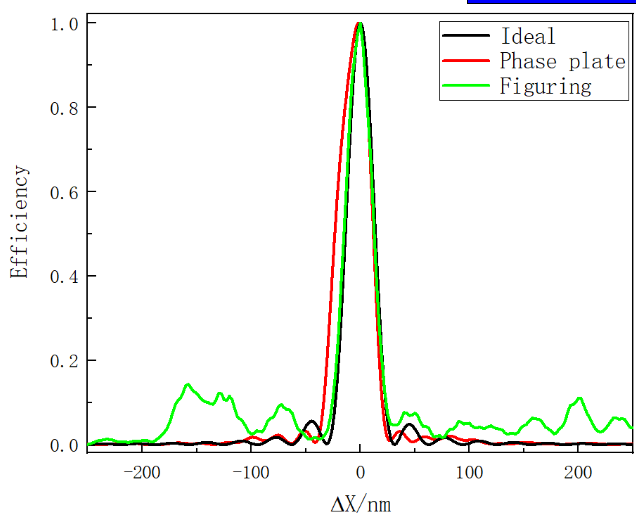
Compared with the traditional phase plate compensation, the simulation results show that the figuring can get better compensation effect in efficiency and focusing resolution

Phase plate Figuring Ideal





	Efficiency	focusing resolution	Sidelobe suppression
Phase Plate	38%	30 nm	Perfect
Figuring	49%	26 nm	Better

The possibility of MLL figuring is verified theoretically the effect is better than phase plate.

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3.Conclusion

- Nano-focusing MLLs are successfully prepared and measured, and 8 nm 2D focusing performance is calculated

- All of the above new designs of MLLs will be carried out in the future, and will be used in the beamline station.

Thank you for your attention