Improvement of Coherent Scattering Microscopy by applying Ptychographical Iterative Engine

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Contents

1. **Introduction**

2. **Ptychographical iterative engine (PIE)**

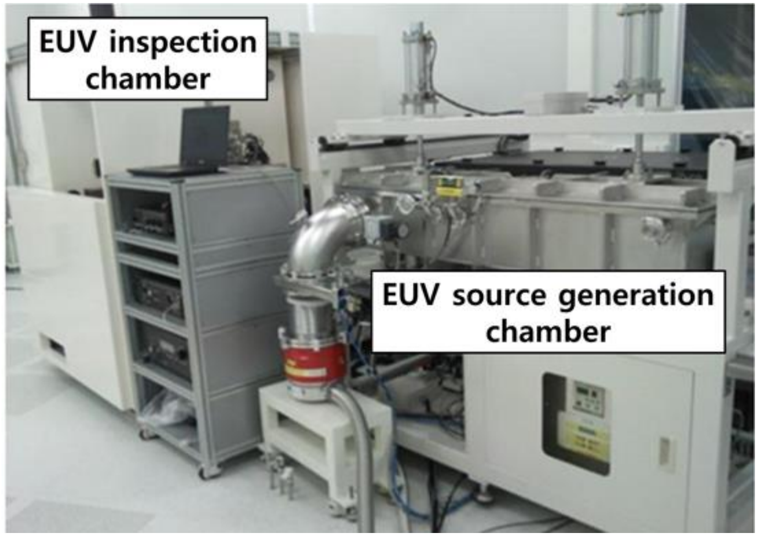
3. **Modified PIE**

4. **Hardware improvement**

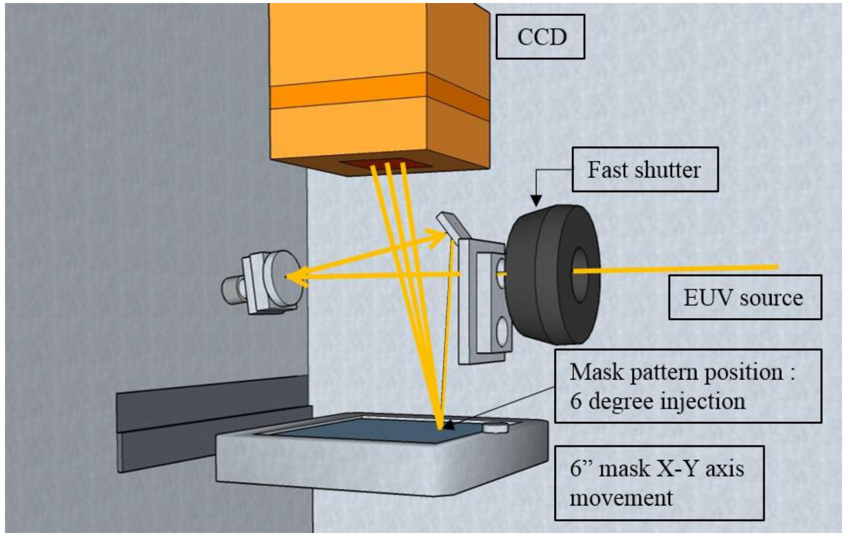
5. **Summary**

Introduction

Coherent Scattering Microscopy (CSM)



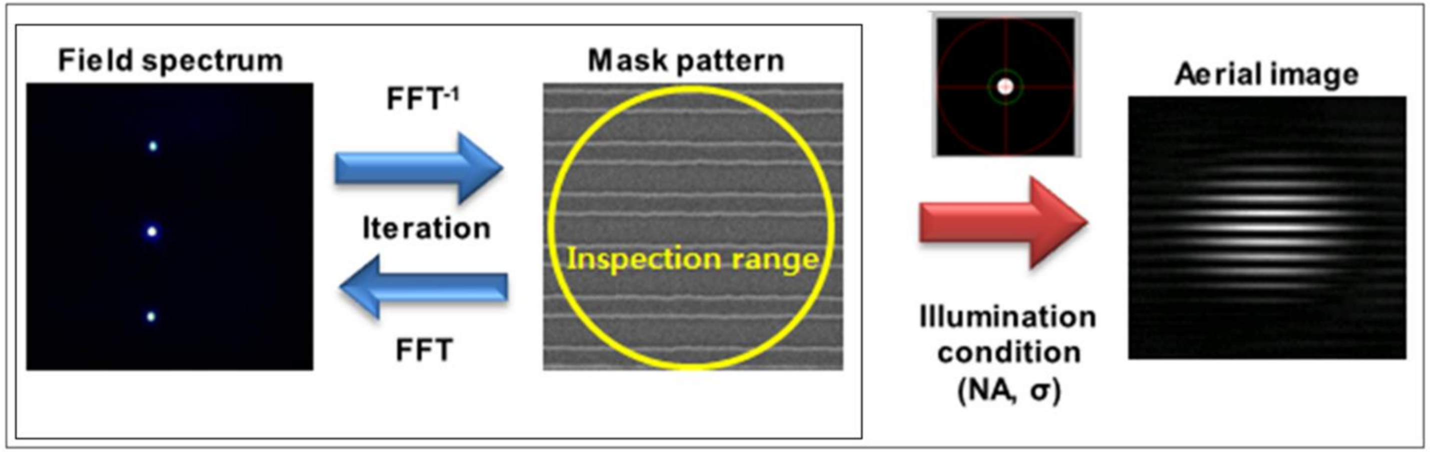
< Coherent scattering microscopy >



< Optic chamber of CSM >

	EUV scanner	CSM
Wavelengths (nm)	13.5	13.5
Incidence angle (˚)	6	6
Numerical aperture	0.33 (NXE:3300)	0.59 (max)
Illumination	Various	Various

< Comparison between EUV scanner and CSM >

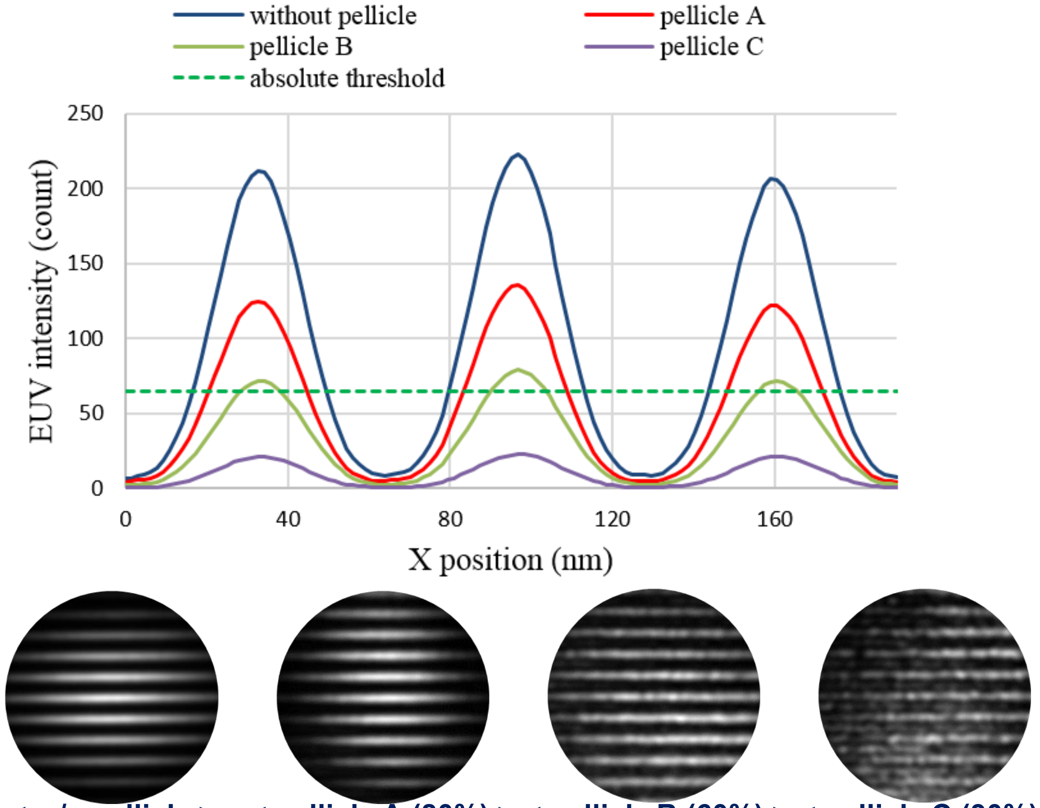


< Image reconstruction method >

- **Evaluation mask imaging performance by actinic inspection**
- **Lensless imaging – free from the errors that occur from lens imperfections**

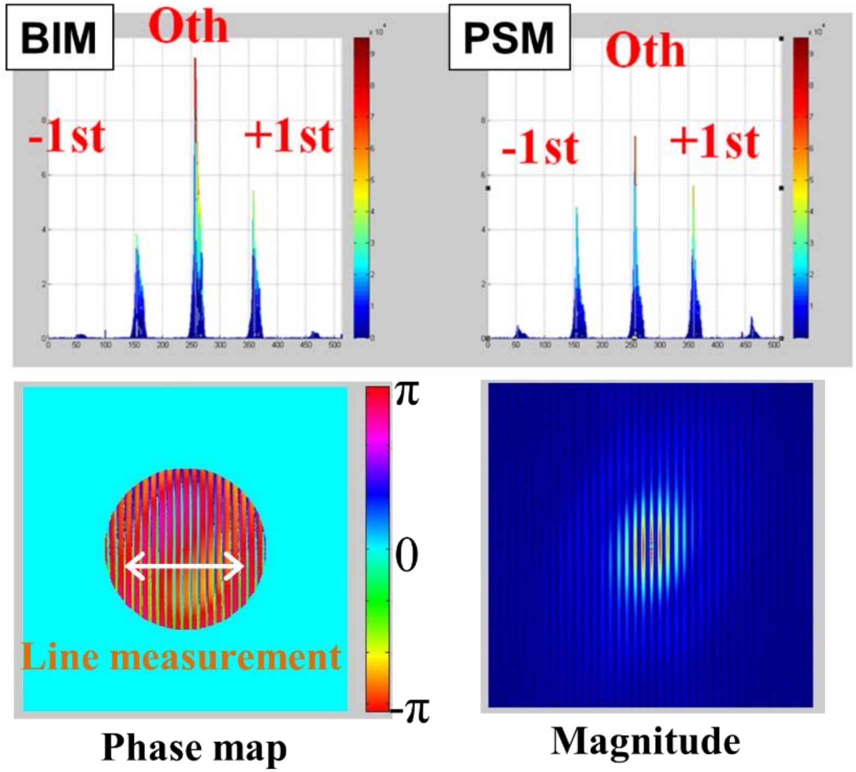
➡ *Limited field of view (FOV)*

Capability of CSM



< w/o pellicle > < pellicle A (80%) > < pellicle B (60%) > < pellicle C (30%) >

< Evaluation of imaging performance of EUV mask with pellicle >



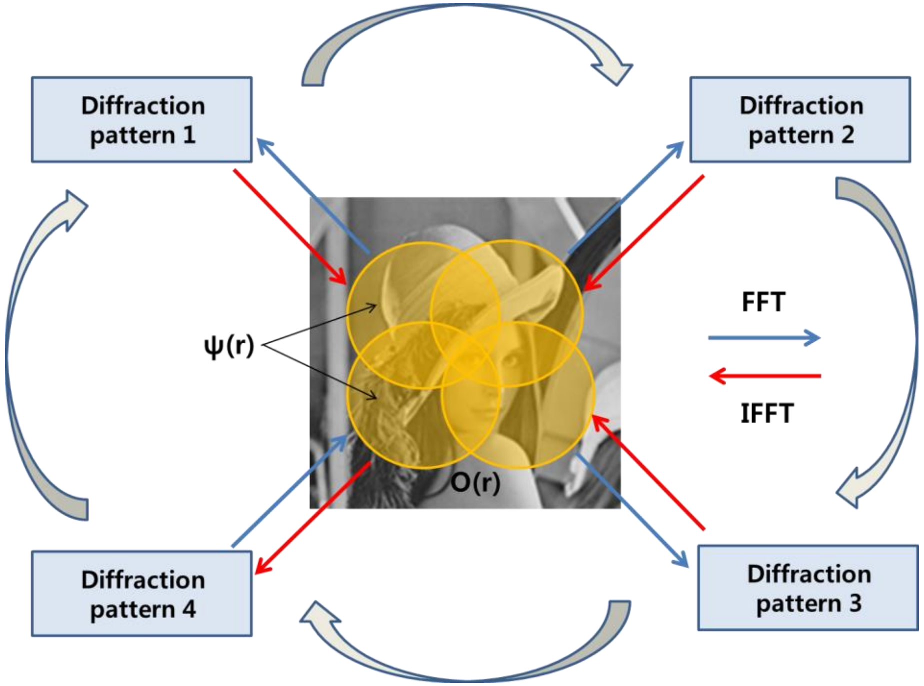
< Extracting phase map of EUV mask >

- **Inspection tool for analyzing the phase shift effect of PSM is insufficient**
- **Field of view is limited as inspection beam size**
  - ➢ **Achieving the large FOV by applying the ptychography to CSM**

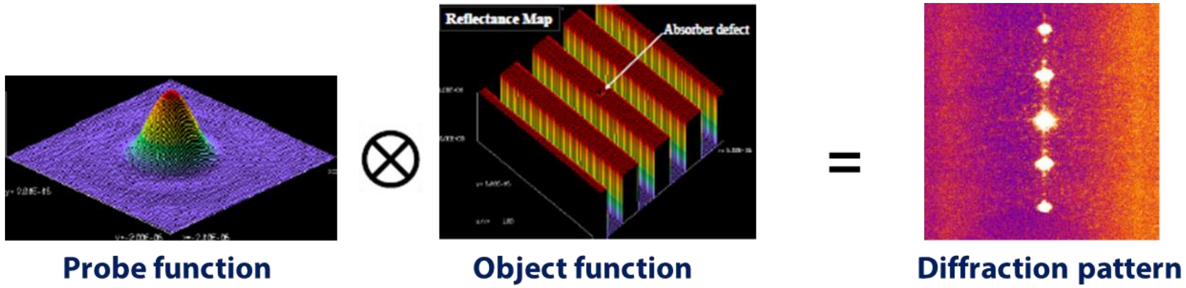
<Ref. D. G. Woo, J. U. Lee, S. Hong, J. S. Kim, and J. Ahn, Optics Express 24(11) (2016)>

Ptychographic Iterative Engine (PIE)

Principle of Ptychography



< Schematic view of ptychographic iterative engine (PIE) >



$$O_{n+1}(\mathbf{r}-\mathbf{R}_l) = O_n(\mathbf{r}-\mathbf{R}_l) + \beta U(\mathbf{r})\left(\Psi_{n,l,\mathrm{new}}(\mathbf{r}) - \Psi_{n,l}(\mathbf{r})\right)$$

$$U(\mathbf{r}) \equiv \frac{|P(\mathbf{r})|}{\max(|P(\mathbf{r})|)}\frac{P^*(\mathbf{r})}{|P(\mathbf{r})|^2+\alpha}$$

$$\boxed{\Psi_{n,l}(\mathbf{r}) = P(\mathbf{r})O_n(\mathbf{r}-\mathbf{R}_l)}$$

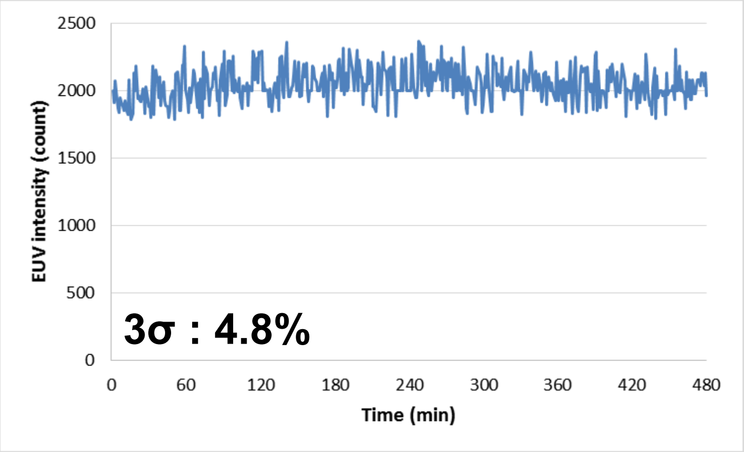
O(r) : object function
P(r) : probe function
R : relative distance between diffraction patterns
α : feedback parameter

< Mathematics in PIE >

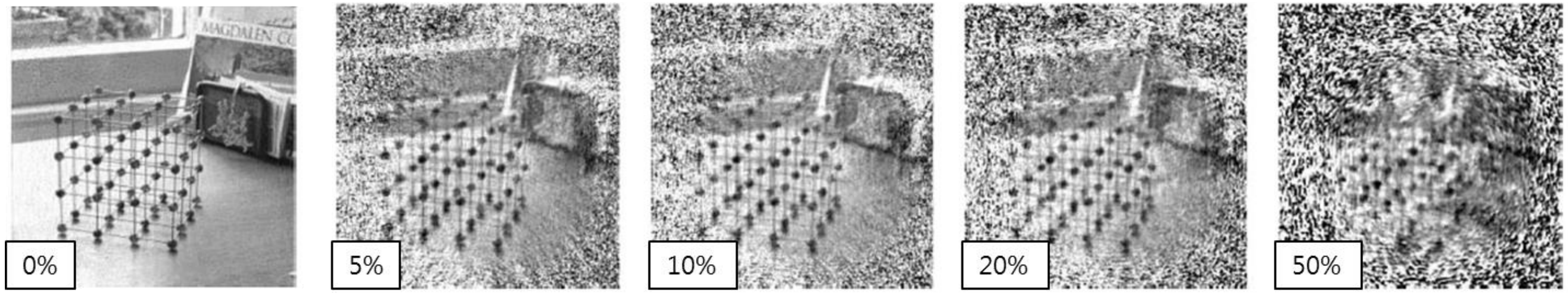
- **Separating the probe and object function from diffraction pattern**
- **Enlargement of FOV by image stitching**
- **Finite probe & constraint determines resolution of reconstructed image**

➡ ***Accuracy of probe function is the key of resolution of reconstructed image***

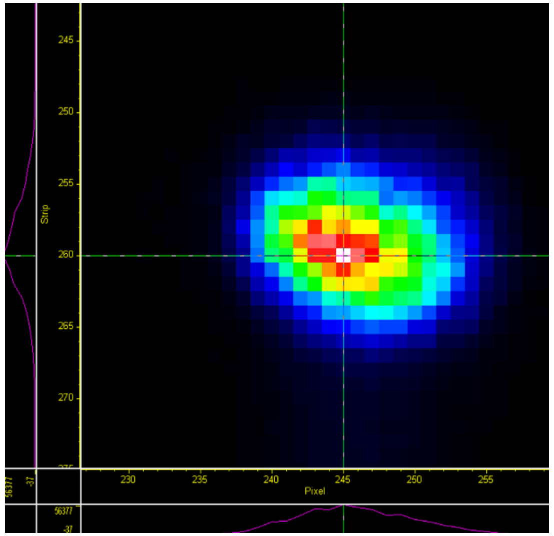
Influence of probe function stability on reconstructed image



< Power stability of inspection source >



< Reconstructed images with random noise in probe function >



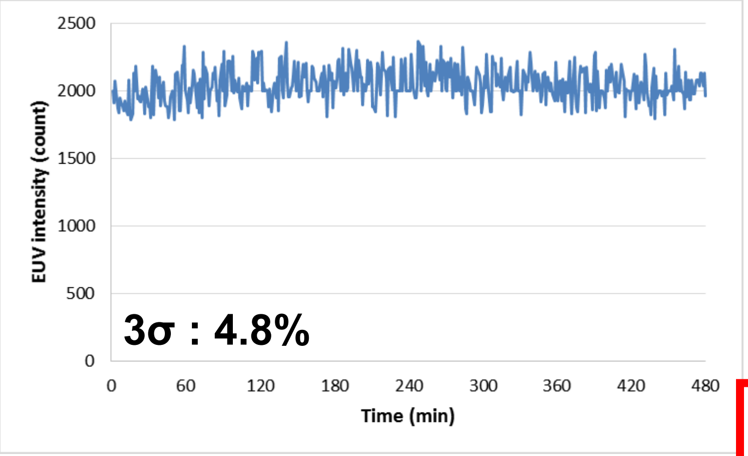
< Shape of inspection source >

- **Stability of inspection source power (8hr) : 3σ 4.8%**
- **Power drop and source shape change occurs due to temperature and humidity**
- **Random noise introduced probe function will degrade the resolution of reconstructed image**

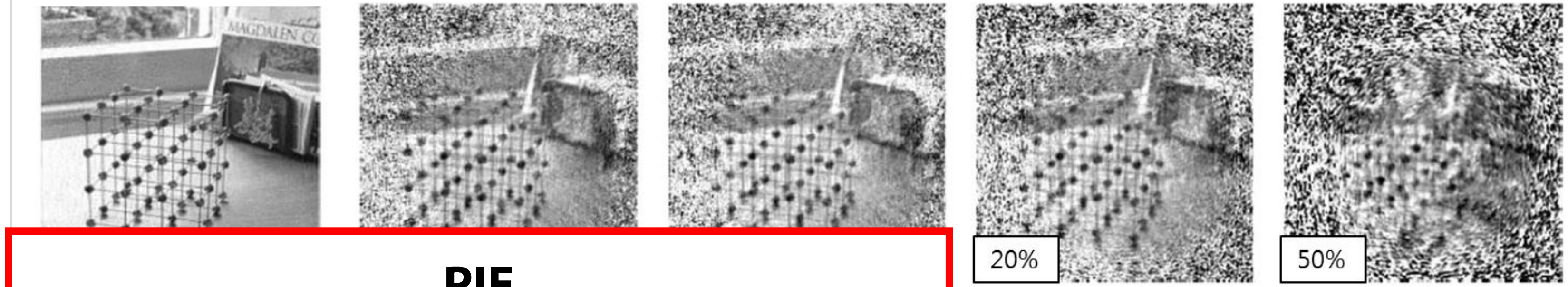
Compensation for probe function error is requried

<Ref. H. M. L. Faulkner, J. M. Rodenburg, Ultramicroscopy 103 (2005)>

Influence of probe function stability on reconstructed image



< Power stability of inspection source >



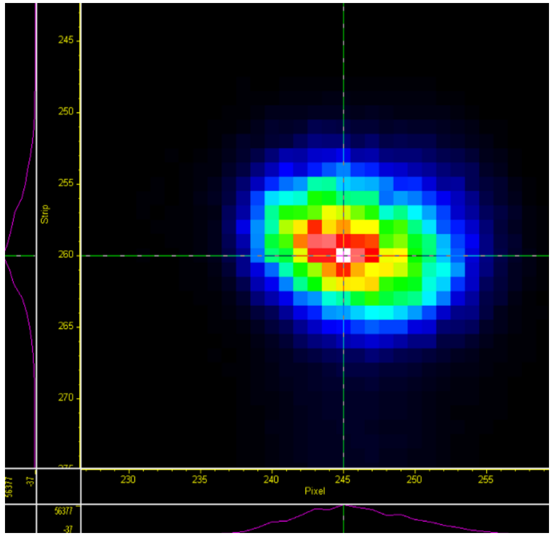
oise in probe function >

PIE

- ✓ **Finite probe function**
- ✓ **Accurate position between diffraction patterns**

%

- **Power drop and source shape change occurs due to temperature and humidity**
- **Random noise introduced probe function will degrade the resolution of reconstructed image**



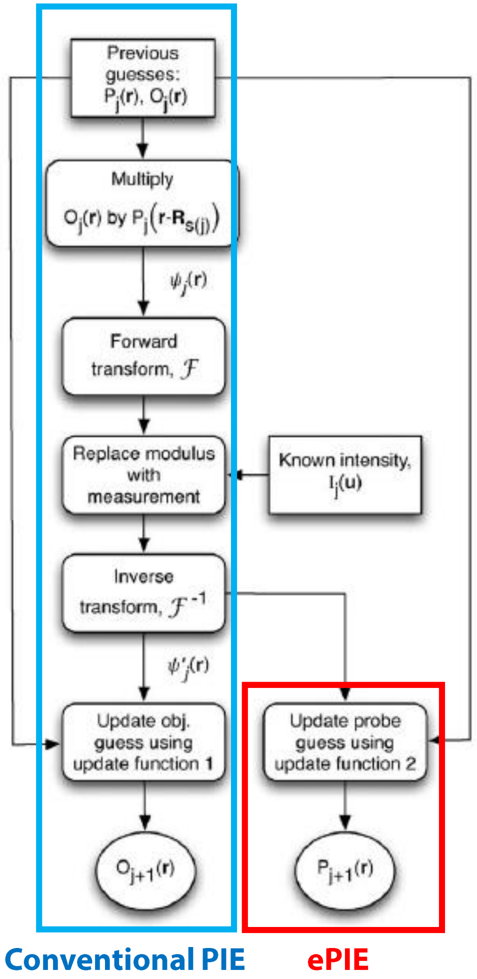
< Shape of inspection source >

➡ *Compensation for probe function error is requried*

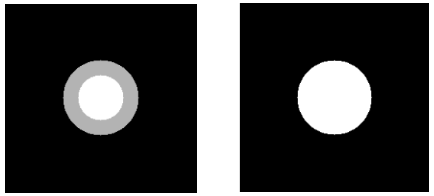
<Ref. H. M. L. Faulkner, J. M. Rodenburg, Ultramicroscopy 103 (2005)>

Modified PIE

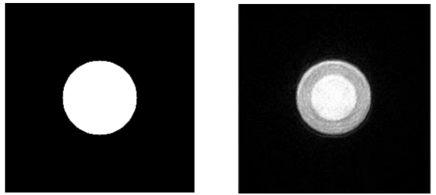
Concept of extended PIE (ePIE)



< Flowchart of ePIE method >



< ground truth & initial guess >

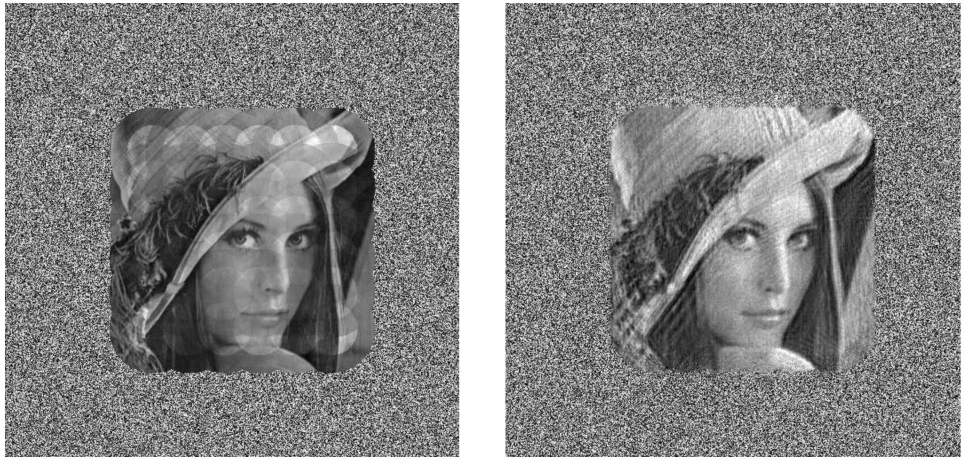


< Reconstructed probe of PIE (left) and ePIE (right) >

$$O_{j+1}(\mathbf{r}) = O_j(\mathbf{r}) + \alpha \frac{P_j^*(\mathbf{r}-\mathbf{R}_{s(j)})}{|P_j(\mathbf{r}-\mathbf{R}_{s(j)})|^2_{\max}}(\psi'_j(\mathbf{r})-\psi_j(\mathbf{r})).$$

$$P_{j+1}(\mathbf{r}) = P_j(\mathbf{r}) + \beta \frac{O_j^*(\mathbf{r}+\mathbf{R}_{s(j)})}{|O_j(\mathbf{r}+\mathbf{R}_{s(j)})|^2_{\max}}(\psi'_j(\mathbf{r})-\psi_j(\mathbf{r})).$$

< Update function of ePIE >



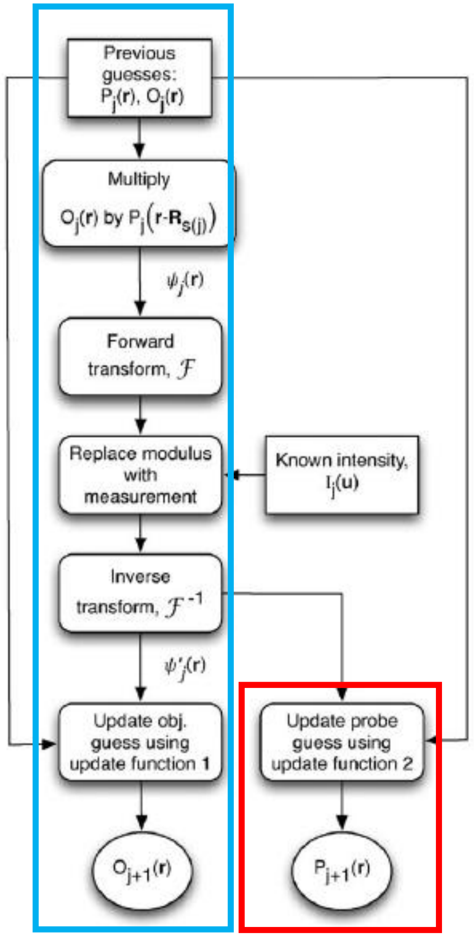
< Reconstructed image of PIE (left) and ePIE (right) >

- **Updating probe and object function simultaneously**
- **Check whether probe function is updated or not**
- **Resolution of final reconstructed image deteriorates**

Insufficient information of redundancy and relative position between diffraction patterns

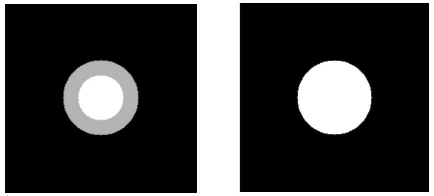
<Ref. F. Hue, J. M. Rodenburg, A. M. Maiden, P. A. Midgley, Ultramicroscopy 111 (2011) >

Concept of extended PIE (ePIE)

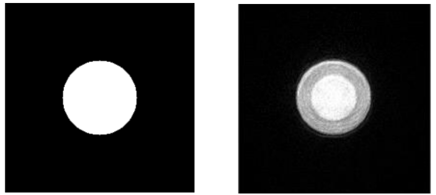


Conventional PIE **ePIE**

< Flowchart of ePIE method >



< ground truth & initial guess >

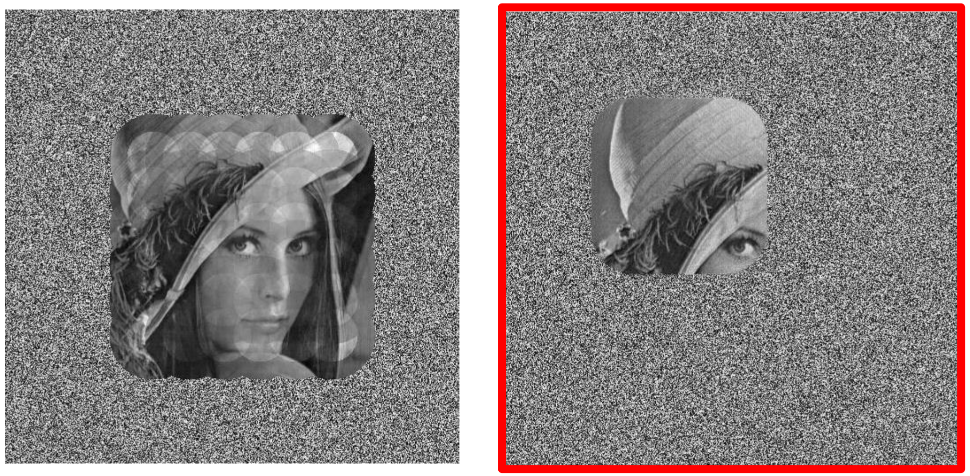


< Reconstructed probe of PIE (left) and ePIE (right) >

$$O_{j+1}(\mathbf{r}) = O_j(\mathbf{r}) + \alpha \frac{P_j^*(\mathbf{r}-\mathbf{R}_{s(j)})}{|P_j(\mathbf{r}-\mathbf{R}_{s(j)})|^2_{\max}}(\psi'_j(\mathbf{r})-\psi_j(\mathbf{r})).$$

$$P_{j+1}(\mathbf{r}) = P_j(\mathbf{r}) + \beta \frac{O_j^*(\mathbf{r}+\mathbf{R}_{s(j)})}{|O_j(\mathbf{r}+\mathbf{R}_{s(j)})|^2_{\max}}(\psi'_j(\mathbf{r})-\psi_j(\mathbf{r})).$$

< Update function of ePIE >



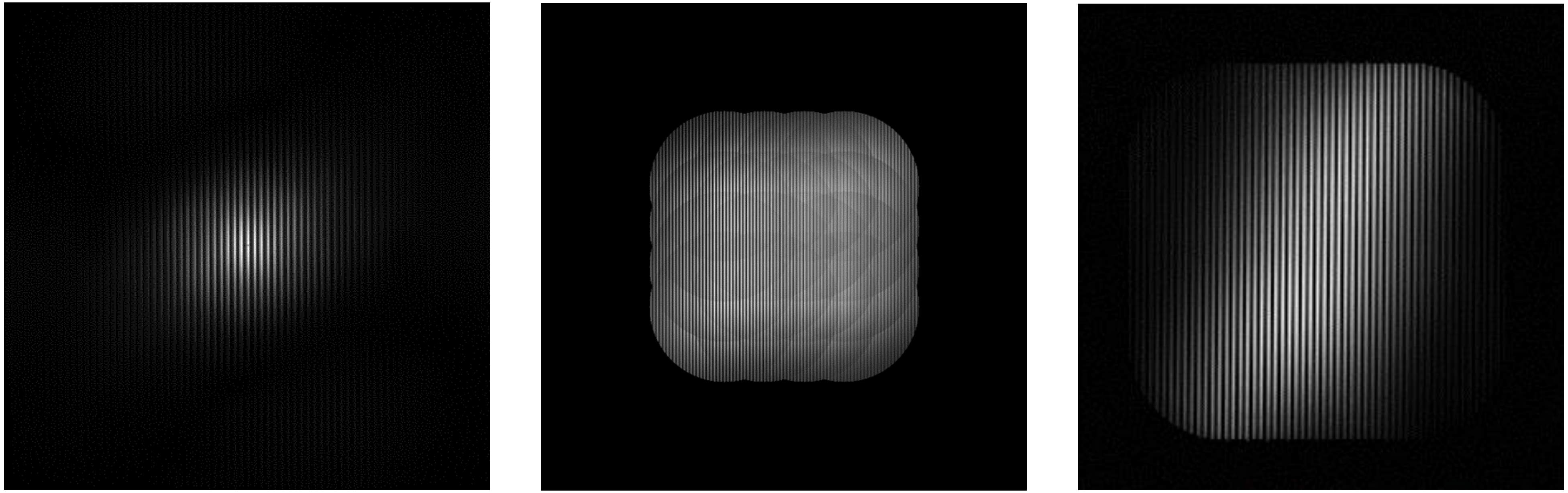
< Reconstructed image of PIE (left) and ePIE (right) >

- **Updating probe and object function simultaneously**
- **Check whether probe function is updated or not**
- **Resolution of final reconstructed image deteriorates**

➡ *Insufficient information of redundancy and relative position between diffraction patterns*

<Ref. F. Hue, J. M. Rodenburg, A. M. Maiden, P. A. Midgley, Ultramicroscopy 111 (2011) >

Comparison between PIE and ePIE

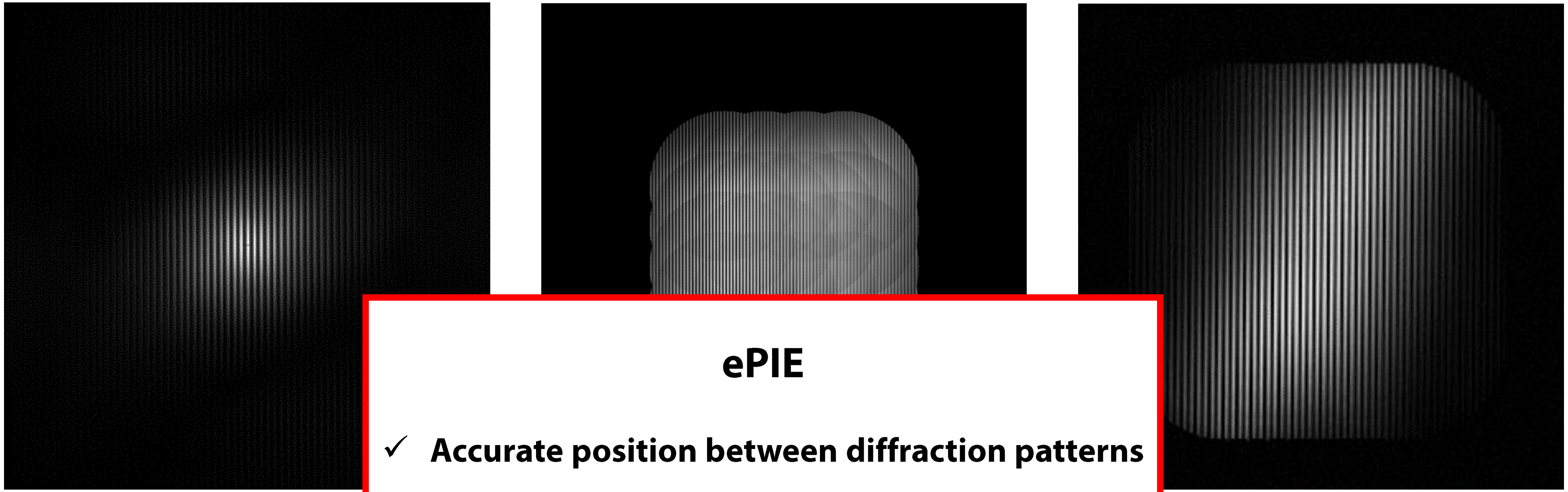


< Reconstructed image of HIO (left), PIE (middle) and ePIE (right) >

- **HIO – Limited FOV as size of inspection source**
- **PIE – deterioration of reconstructed image resolution and boundary occurrence due to inaccurate probe function**
- **ePIE – Improvement of reconstructed image resolution but, still insufficient**

➡ *Should achieve the reliance of relative distance between diffraction pattern*

Comparison between PIE and ePIE



ePIE

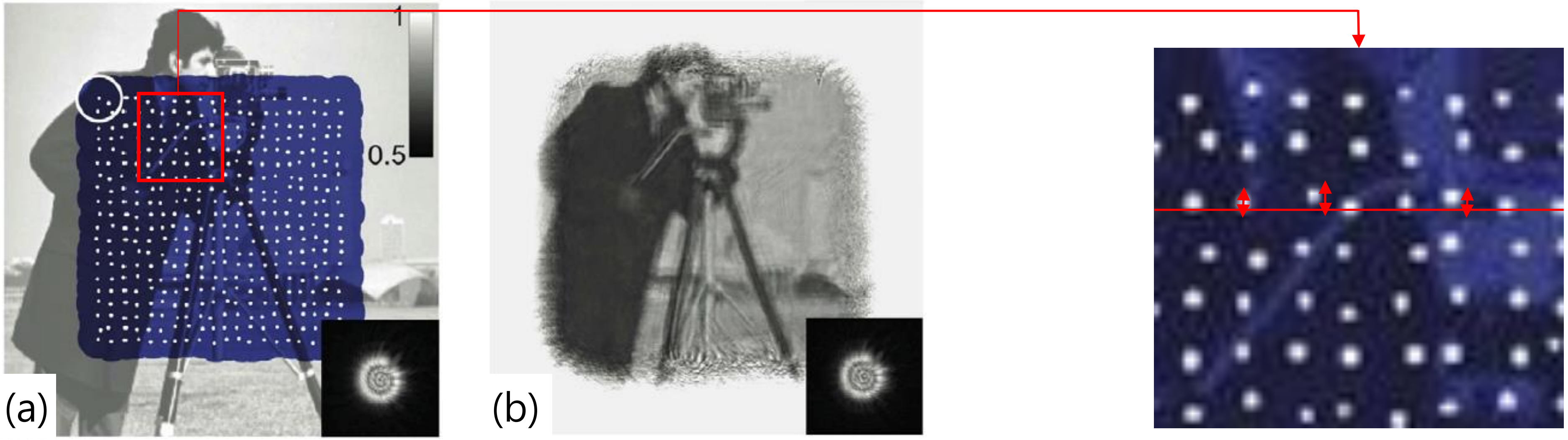
✓ **Accurate position between diffraction patterns**

< Reconstructed image of HIO (left), PIE (middle) and ePIE (right) >

- **HIO – Limited FOV as size of inspection source**
- **PIE – deterioration of reconstructed image resolution and boundary occurrence due to inaccurate probe function**
- **ePIE – Improvement of reconstructed image resolution but, still insufficient**

➡ *Should achieve the reliance of relative distance between diffraction pattern*

Influence of position accuracy on reconstructed image



✓ **Position error due to position accuracy of stage and thermal drift**

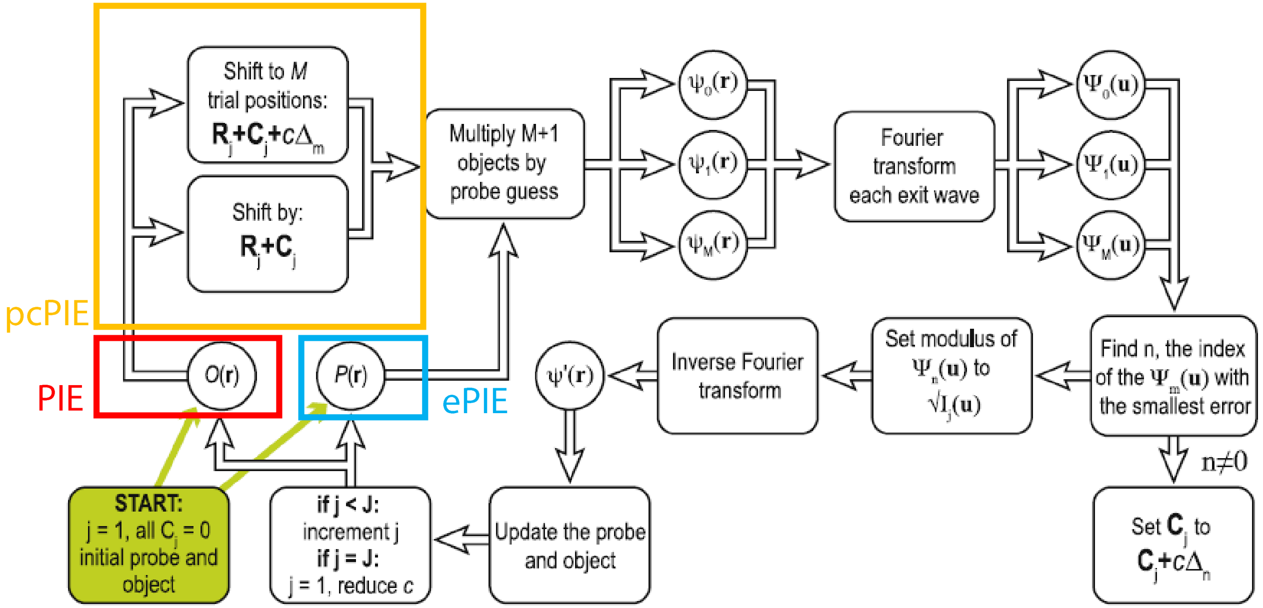
< Image reconstructed by ePIE with position error induced diffraction pattern >

- **Tolerance of position error on PIE and ePIE is 1% of step size**
- **Size of CSM inspection source is 1.5㎛, when secure 60% redundancy its step size is 0.6 ㎛ and to prevent resolution degradation 6nm position accuracy is required**
- **Inevitable error which is out of stage position accuracy specification**

➡ *Compensation method through algorithm improvement should be studied*

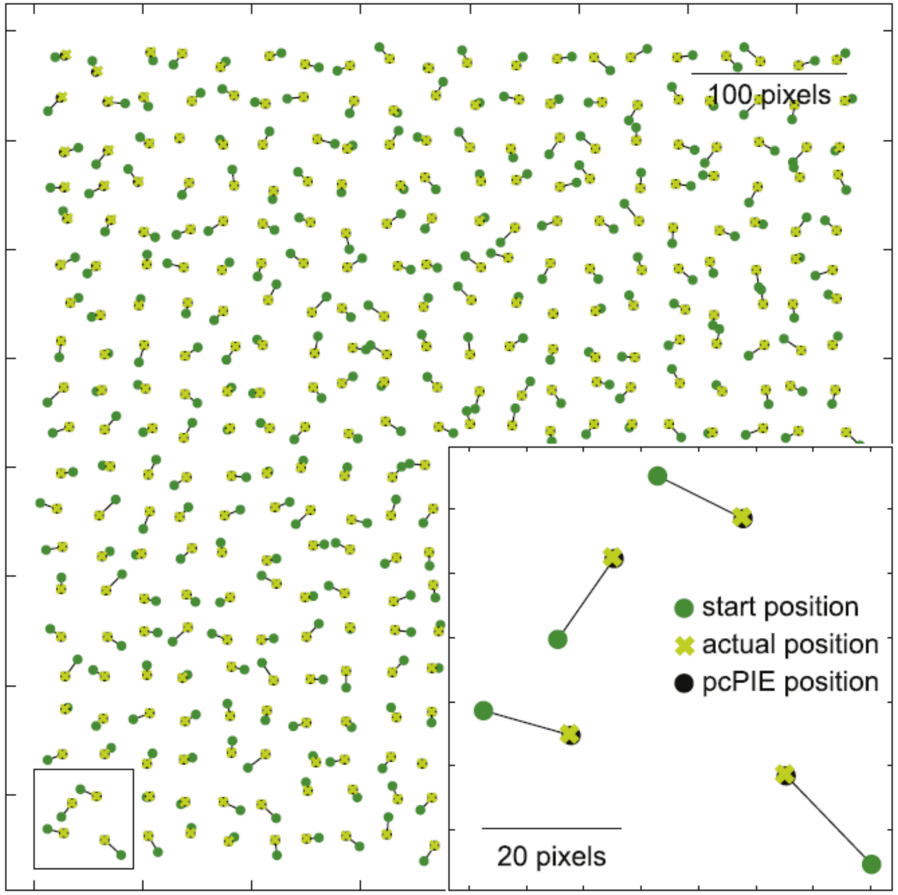
<Ref. A. M. Maiden, M. J. Humphry, M. C. Sarahan, B. Kraus, and J. M. Rodenburg, Ultramicroscopy 120 (2012) >

Concept of position correcting PIE (pcPIE)



< Flowchart of pcPIE >

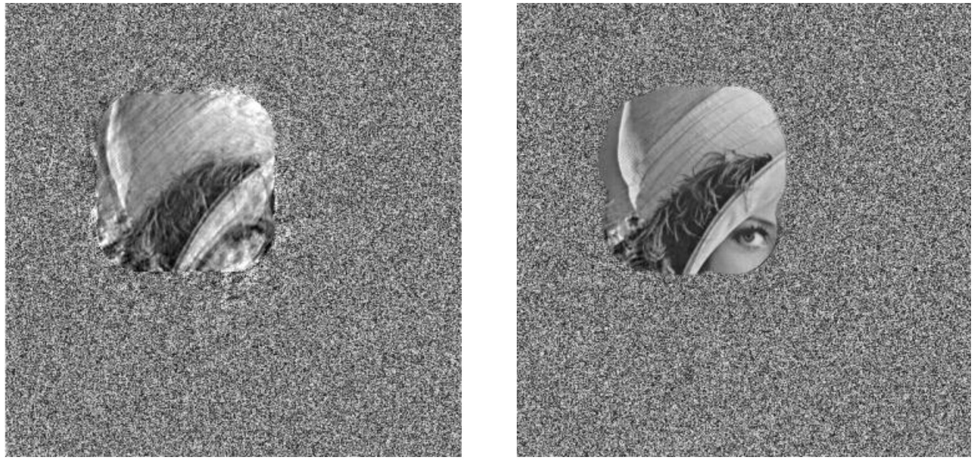
- **pcPIE iteratively updates the initial object and probe like ePIE, and additionally updates the position simultaneously**
- **The resolution and accuracy of ptychographic images are restricted by the precision of the specimen positions**



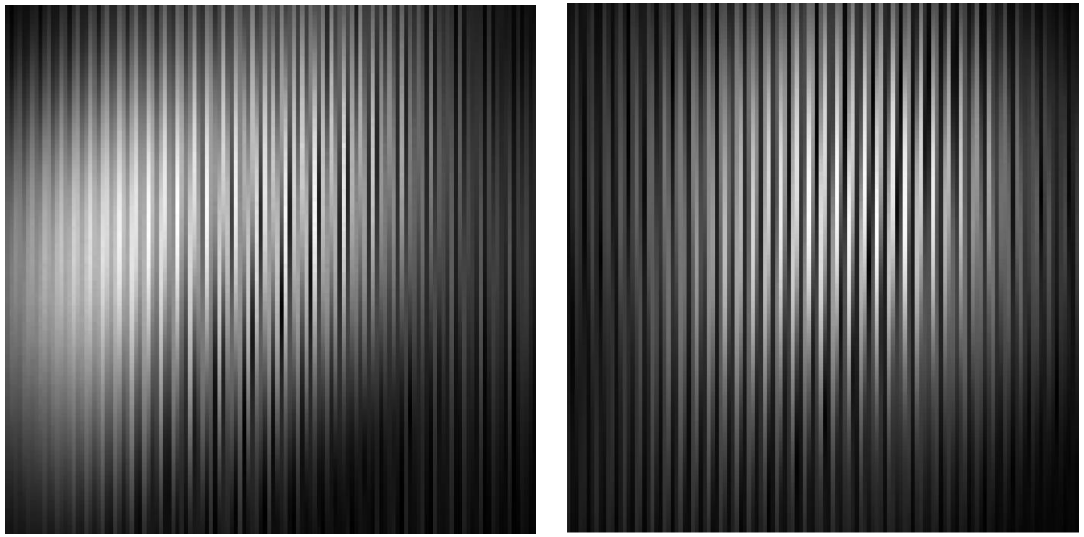
< Position correcting results of pcPIE >

<Ref. A. M. Maiden, M. J. Humphry, M. C. Sarahan, B. Kraus, and J. M. Rodenburg, Ultramicroscopy 120 (2012) >

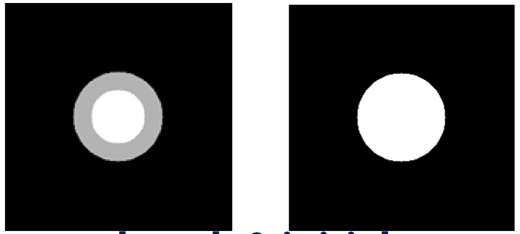
Reconstructed images using pcPIE



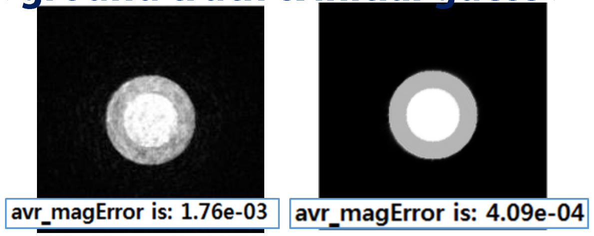
< Image reconstructed by ePIE (left) and pcPIE(right) with position error induced diffraction pattern >



< Image reconstructed by ePIE (left) and pcPIE(right) with diffraction pattern captured by CSM, 128 nm hp L/S EUV mask>



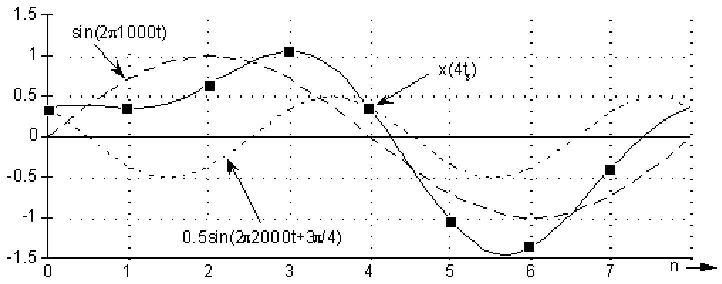
< ground truth & initial guess >



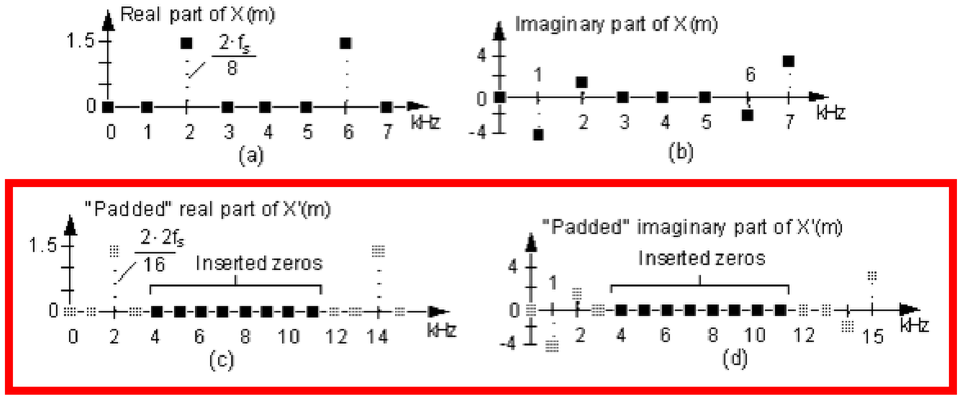
< Reconstructed probe of ePIE (left) and pcPIE (right) >

- **Improvement of reconstructed image resolution by compensating inaccuracy of translation stage**
- **Noise of reconstructed probe function is also alleviated**
- **Tolerance of position accuracy could be relieved from 1% to 15% of step size**

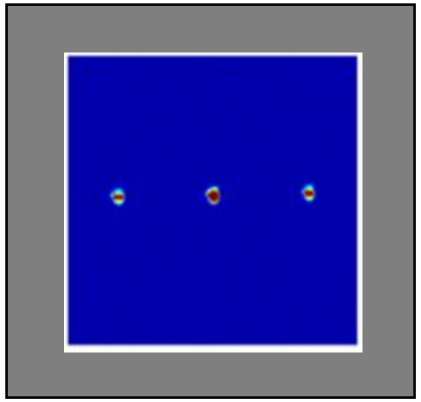
superresolution PIE (SR-PIE)

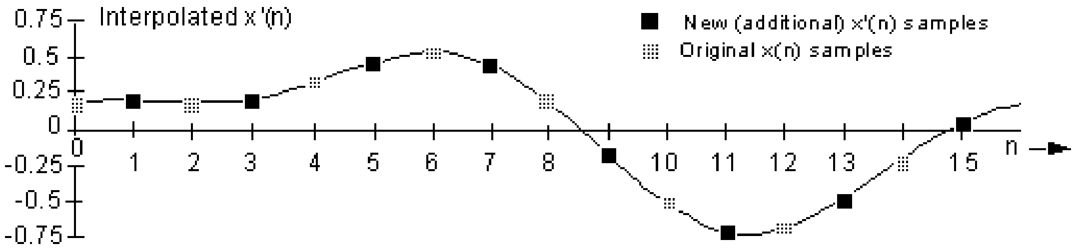


< Signal in time-domain >

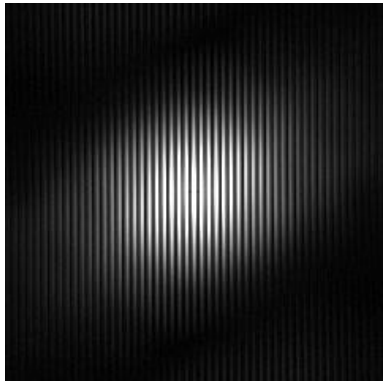


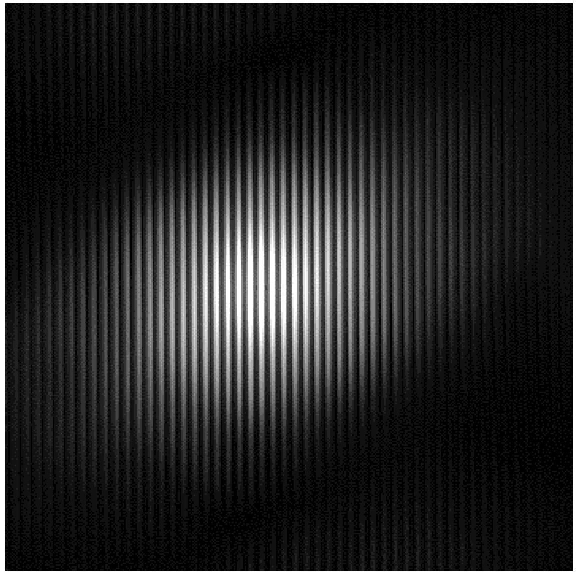
< Signal in frequency-domain >





< Interpolated time sequence >



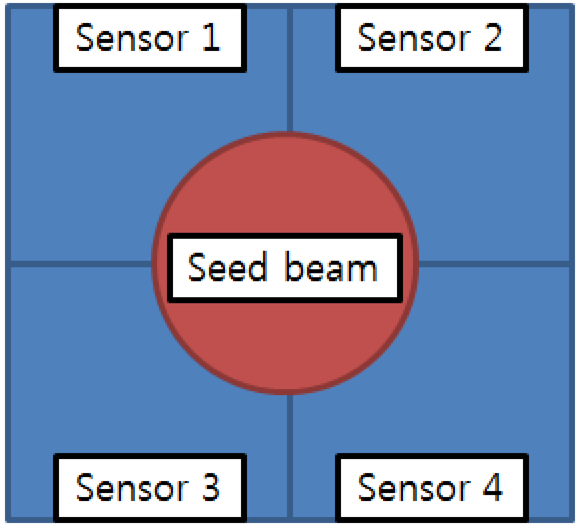


< Reconstructed image applying interpolating>

- **Interpolating the recorded diffraction patterns beyond the aperture of the detector is considered to enhance resolution of ptychography**

Hardware improvement

Source stabilizer system


Sensor 1

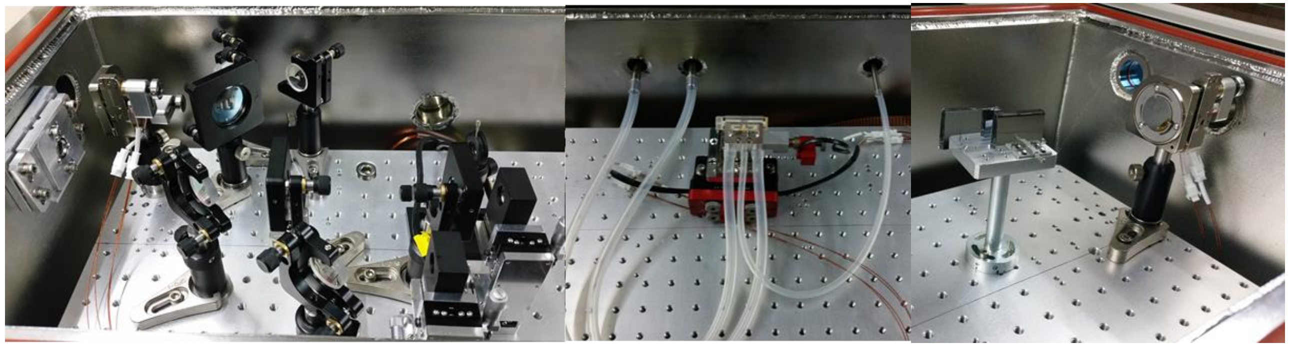
Sensor 2

Seed beam

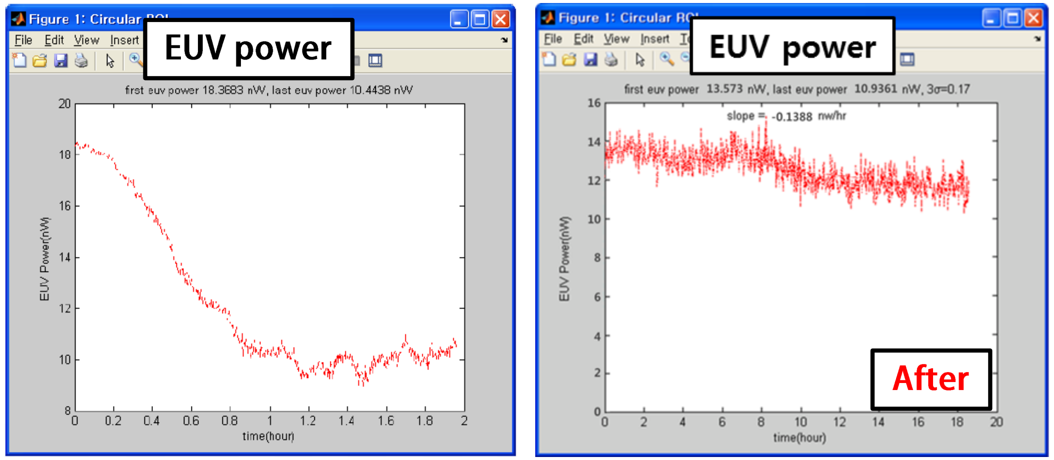
Sensor 3

Sensor 4

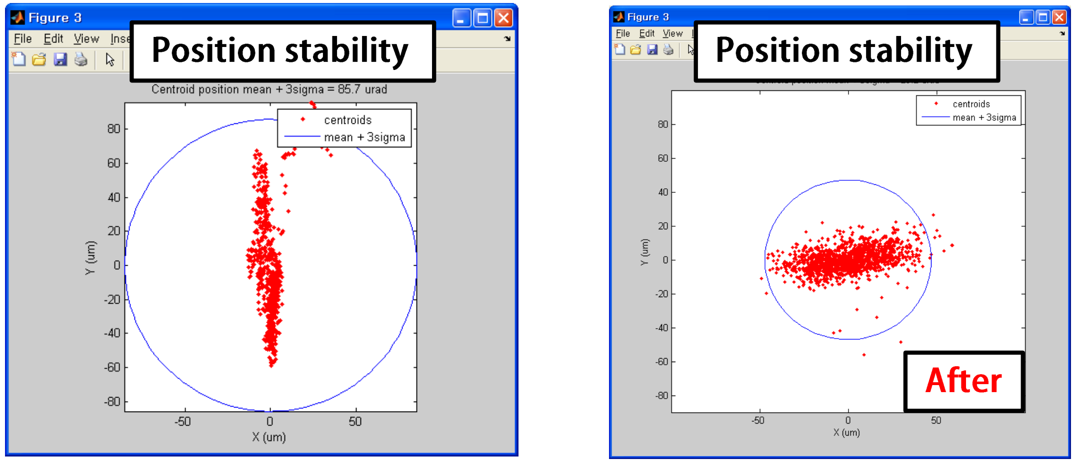
< Concept of EUV stabilizer system >



< EUV stabilizer system >

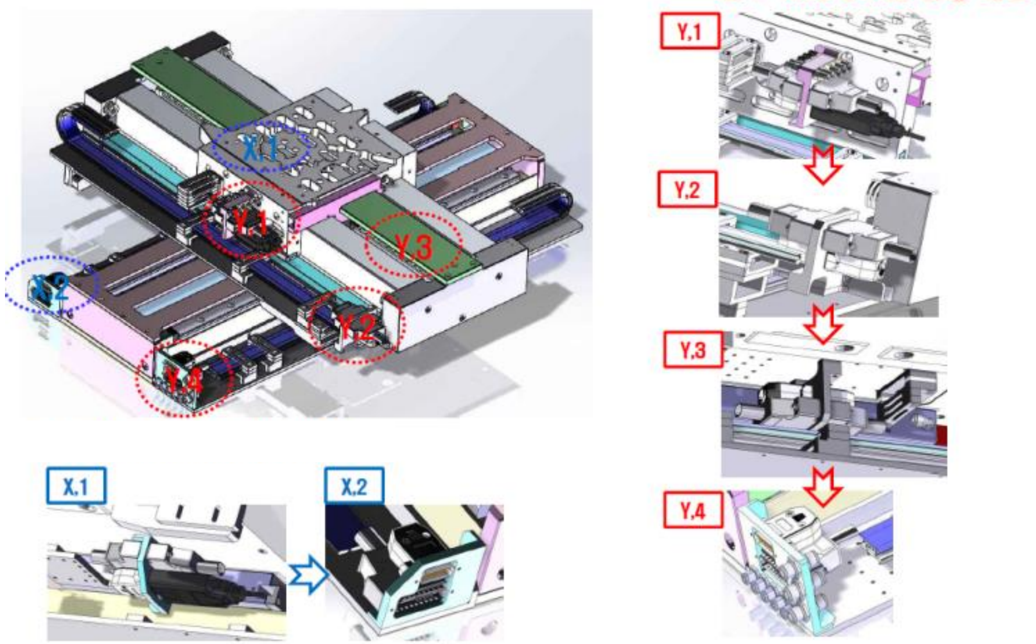


< Long-term stability after applying EUV stabilizer system >

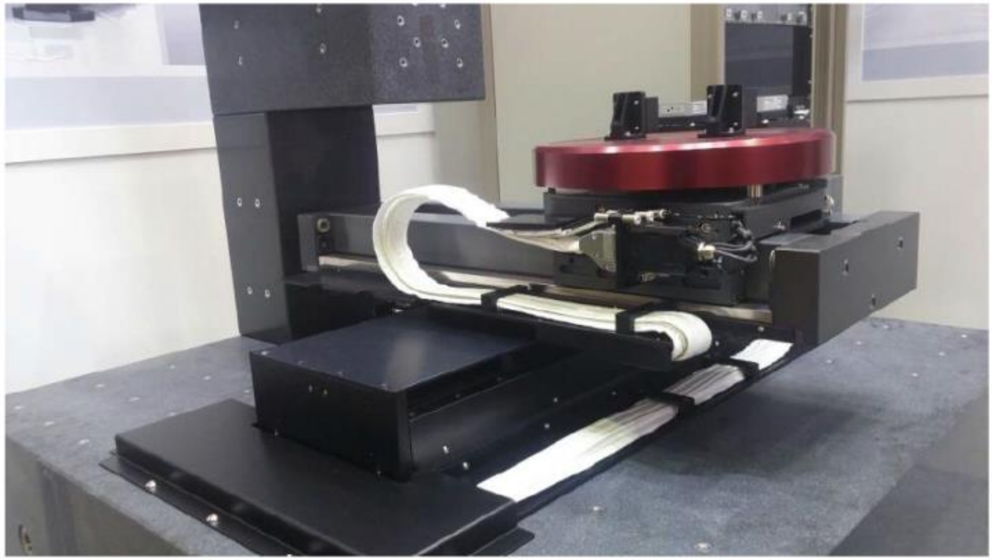


< Long-term position stability after applying EUV stabilizer system >

High precision stage



< Schematic of the designed stage >



< Proto-type of high precision stage >

- **Designing precision stage to minimize the physical position error**
- **Position accuracy within in 100 nm to achieve reliance of relative distance between diffraction pattern**
- **Sub micron resolution to achieve enough redundancy**

Summary

- **Coherent Scattering Microscopy (CSM) is verified actinic inspection tool for evaluating the imaging performance but, it is limited by its field of view**
- **Ptychography is applied to CSM to enlarge field of view**
- **Using ePIE, accuracy of reconstructed probe function is improved.**
- **Experimental error such as beam instability and position inaccuracy has been compensated by using modified PIE (1% → 15% tolerance of position error)**
- **High precision hardware have been established to minimize the mechanical error**

Thank you for your attention.

Question and Answer