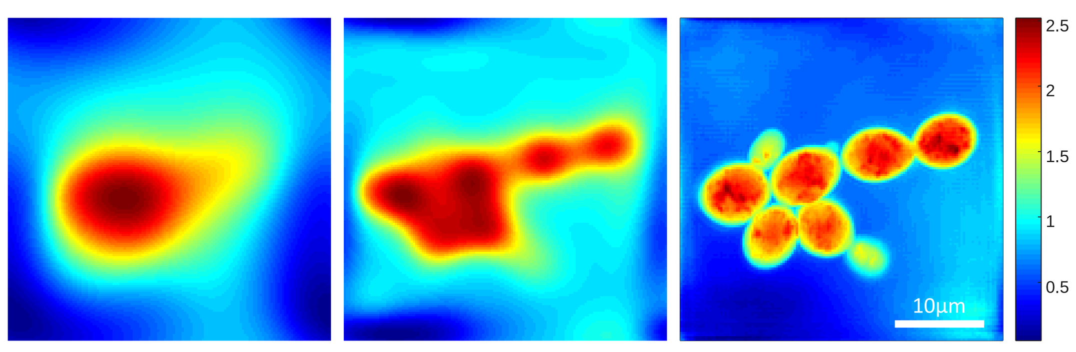
Aberration Correction of an Optical System for High-resolution Synthetic Aperture Imaging

Changsoon Choi, Kyung-Deok Song, Sungsam Kang, and Wonshik Choi
Center for Molecular Spectroscopy and Dynamics, Institute for Basic Science, Seoul 02841, Korea
Department of Physics, Korea University, Seoul 02841, Korea

Introduction

High-resolution optical imaging



- Phase images of yeasts
- Higher resolution uncovers detailed structures

Imaging thick targets with objectives

Oil immersion 

CFI Apo SR TIRF 100X Oil

Mag	NA	WD
100x	1.49	0.12mm

Oil immersion 

CFI Plan 50XH

Mag	NA	WD
50x	0.9	0.35mm

- Large aperture up to 1.49 NA, but limited WD

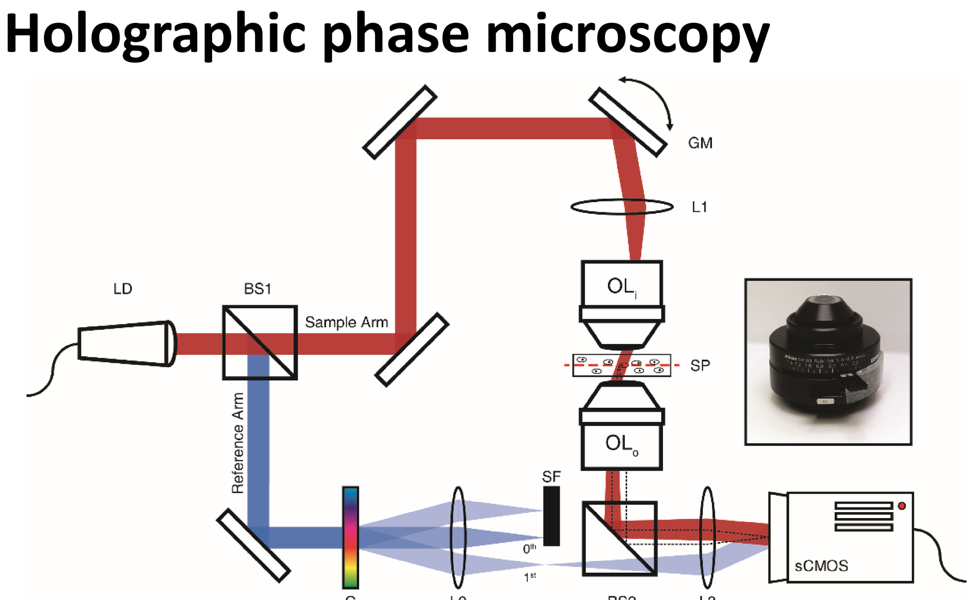
An alternative: microscope condensers

Nikon D-CUO DIC Oil Condenser, 1.4 NA	
Magnification	≈ 40 (depends on tube lens)
NA	1.4
Working distance	1.6 mm

- High-NA, long working distance
- But, strong aberration degrades resolving power
- Can be useful if its aberration is corrected

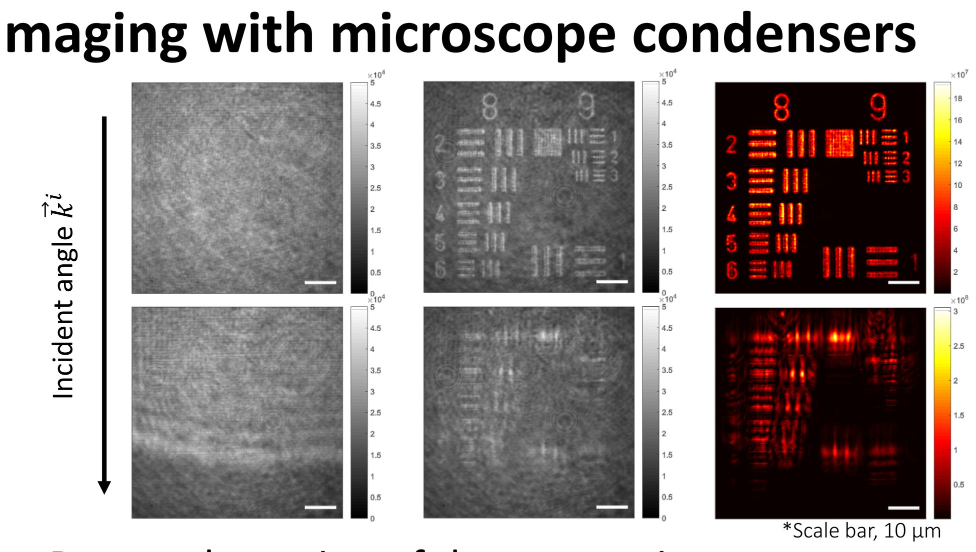
Imaging system

Holographic phase microscopy



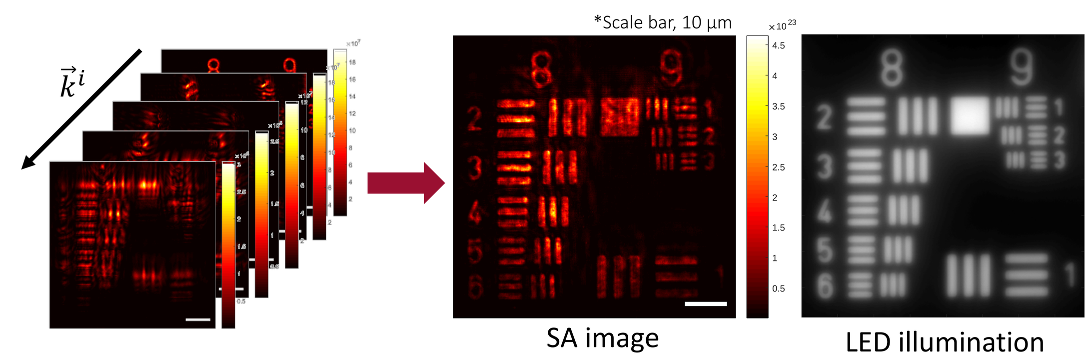
- A Holographic phase microscope [1]
- Detection and illumination NA: 1.4 NA

Imaging with microscope condensers



- Due to aberration of the system, images are distorted as introducing oblique illumination

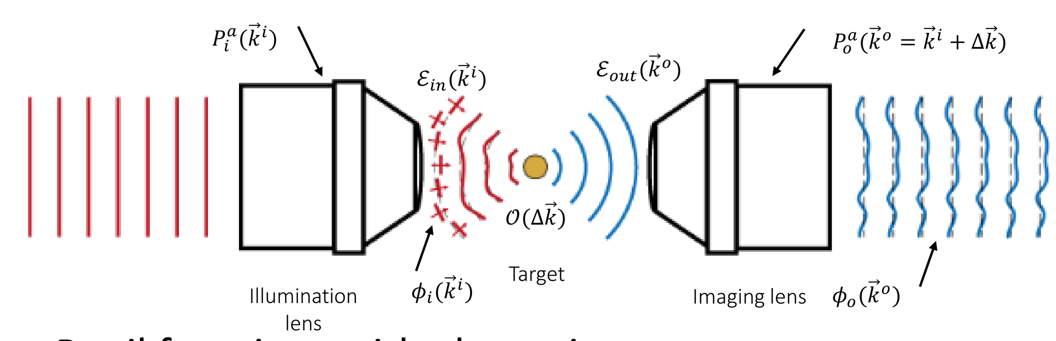
Synthetic aperture (SA) imaging



- Synthetic aperture images [2-3] are acquired by coherently adding individual images

Principle

Aberration: angle-dependent phase delay



- Pupil functions with aberration:

$$P_i^a(\vec{k}^i) = P(\vec{k}^i)\exp[-i\phi_i(\vec{k}^i)]$$
$$P_o^a(\vec{k}^o) = P(\vec{k}^o)\exp[-i\phi_o(\vec{k}^o)]$$

- Images with aberration:

$$\mathcal{E}(\vec{k}^o;\vec{k}^i) = P_o^a(\vec{k}^i+\Delta\vec{k})O(\Delta\vec{k})P_i^a(\vec{k}^i)$$

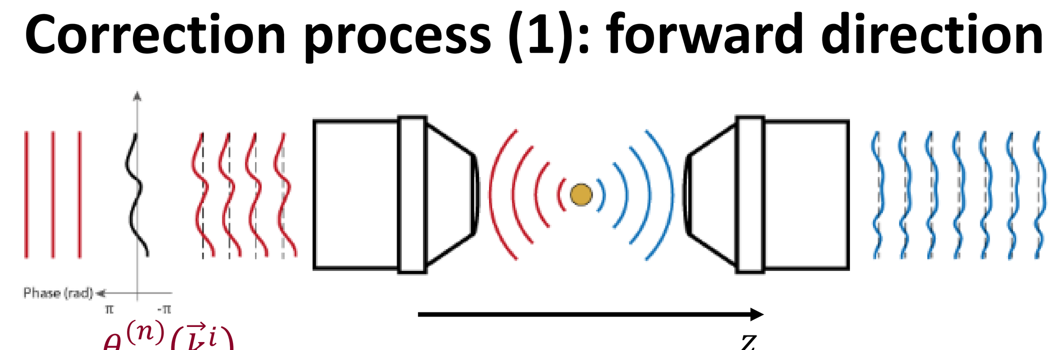
- SA image:

$$\mathcal{E}_{SA}(\Delta k) = \sum_{\vec{k}^i}\mathcal{E}_o(\vec{k}^i+\Delta\vec{k}) = O(\Delta\vec{k})\cdot\sum_{\vec{k}^i}P_i^a(\vec{k}^i)P_o^a(\vec{k}^i+\Delta\vec{k})$$

- Effect of aberration on total intensity of an image

$$\left|\sum_{\vec{k}^i}P_i^a(\vec{k}^i)P_o^a(\vec{k}^i+\Delta\vec{k})\right| \le \left|\sum_{\vec{k}^i}P(\vec{k}^i)P(\vec{k}^i+\Delta\vec{k})\right|$$

Correction process (1): forward direction

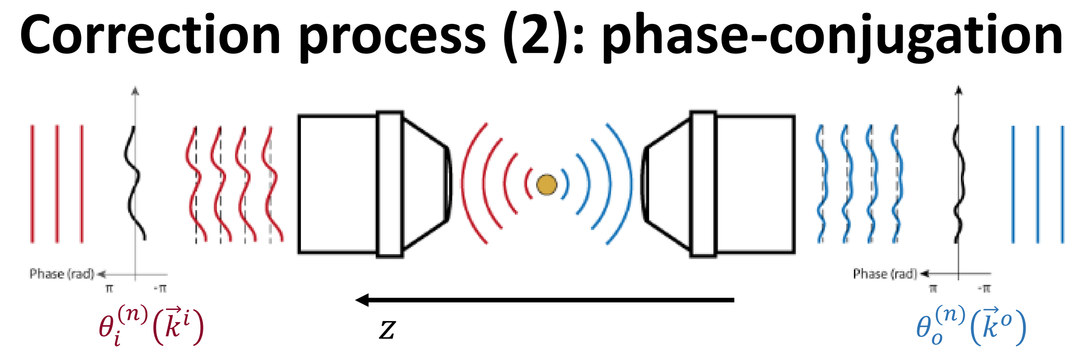


- Add phase correction $\theta_i^{(1)}$ to each incident angles such that maximizes total intensity of SA image

$$\mathcal{E}_{SA}^{(1)}(\Delta\vec{k}) = \sum_{\vec{k}^i}\mathcal{E}(\vec{k}^i+\Delta\vec{k};\vec{k}^i)e^{i\theta_i^{(1)}(\vec{k}^i)}$$
$$= O(\Delta\vec{k})\sum_{\vec{k}^i}P_i^a(\vec{k}^i)P_o^a(\vec{k}^i+\Delta\vec{k})e^{i\theta_i^{(1)}(\vec{k}^i)}$$

- This partly compensates the input aberration

Correction process (2): phase-conjugation



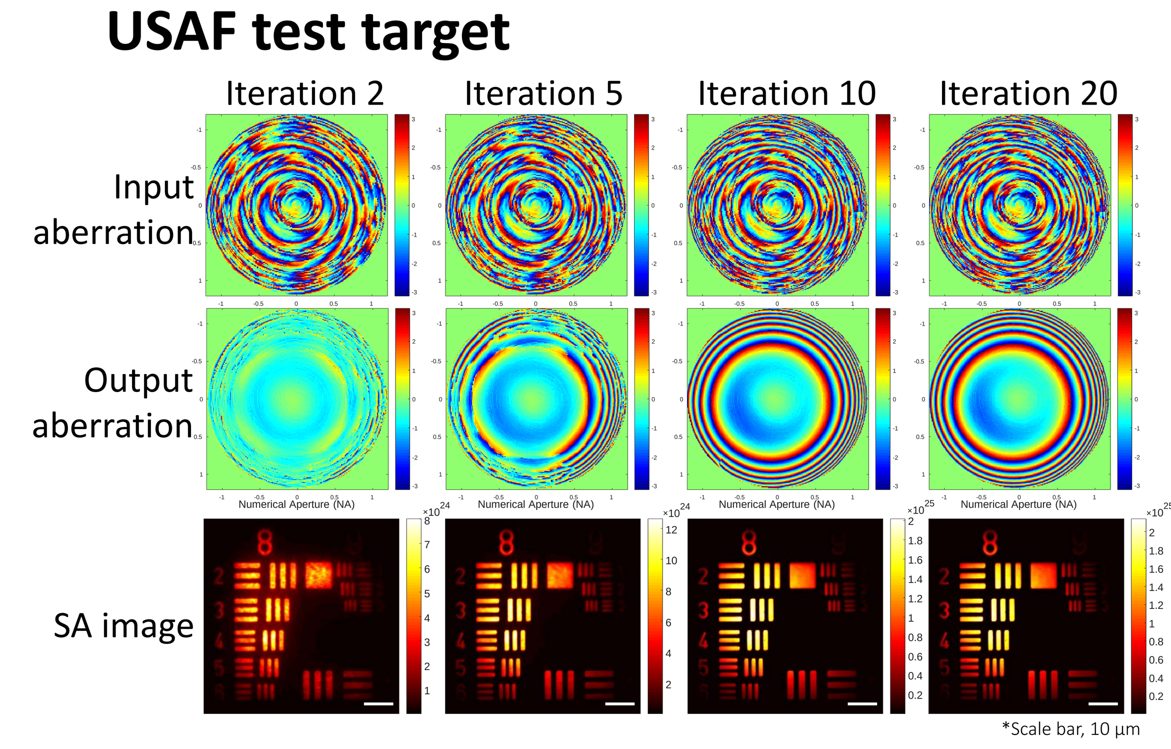
- Direction of propagation is reversed by PC
- Add phase correction $\theta_o^{(1)}$ to each output angles to maximize total intensity of SA image

$$\mathcal{E}_{SA}^{pc(1)}(\Delta\vec{k}) = O^{-1}(\Delta\vec{k})\cdot\sum_{\vec{k}^o}P_o^a(\vec{k}^o)^*\,P_i^{(1)}(\vec{k}^o-\Delta\vec{k})^*\,e^{i\theta_o^{(1)}(\vec{k}^o)}$$

- This partly compensates the output aberration
- Iteratively compute $\theta_i^{(n)}$ and $\theta_o^{(n)}$ to compensate the system aberration [4]

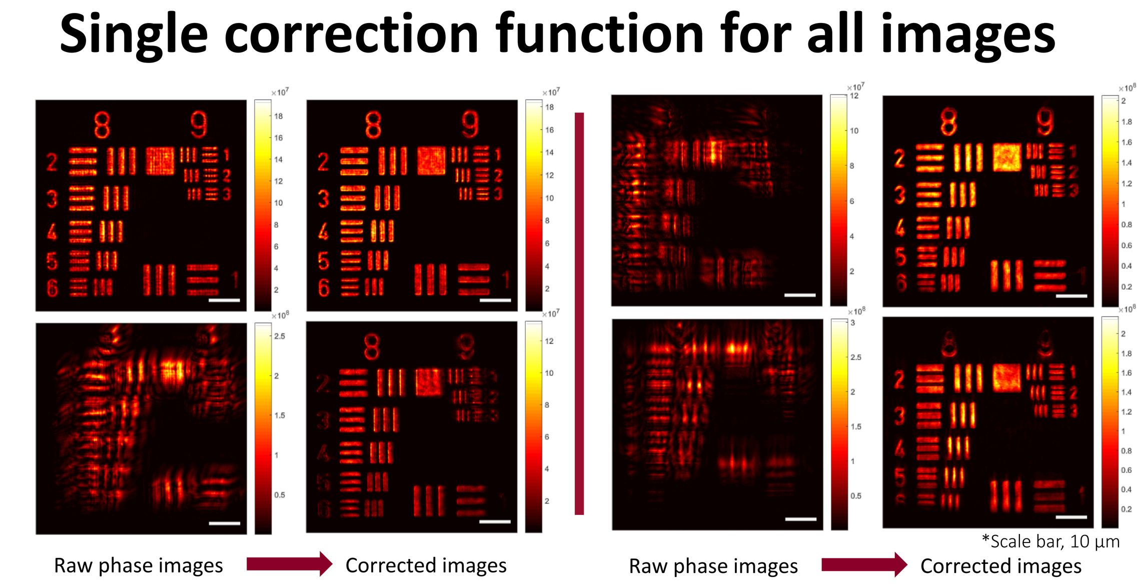
Results: Iterative AC

USAF test target



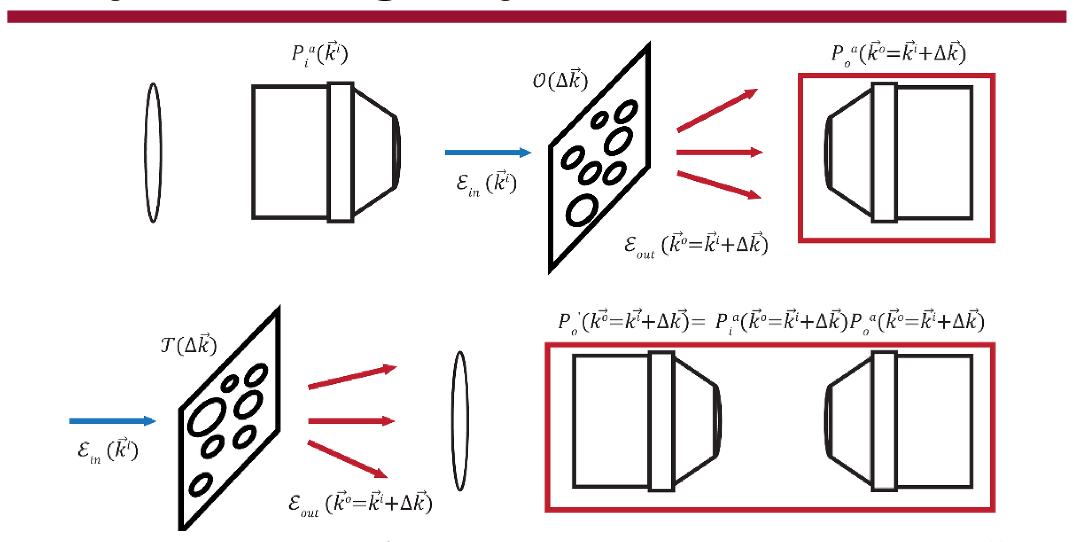
- After a few iterations, sharp images along with aberration can be measured
- The aberration map converges to a spherical shape

Single correction function for all images

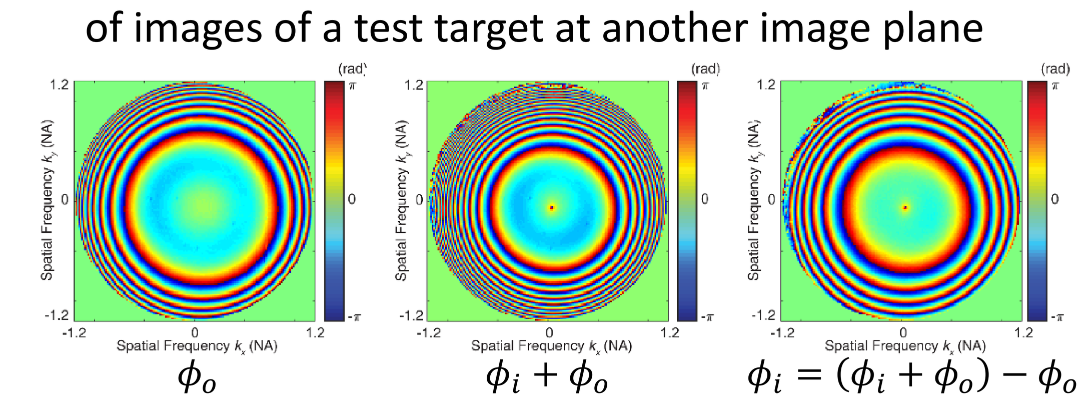


- Single output aberration correction function can correct all individual images

Separating input Aberration



- Input correction function is noisy due to uncontrolled phase drift of the system
- To separate this from input aberration, one more set of images of a test target at another image plane



- Input aberration successfully separated from the drift

Conclusion

- Input/output aberration of an optical system are separately measured to numerically correct them
- High-resolution images are acquired by exploiting microscope condensers as objectives

Reference

[1] Choi, W., *et al.* Tomographic phase microscopy, *Nat. Methods* **4**, 717-719 (2007)
[2] Kang, S., *et al.* Imaging deep within a scattering medium using collective accumulation of single-scattered waves, *Nat. Photon.* **9**, 253-258 (2015)
[3] Choi, Y., *et al.* Synthetic aperture microscopy for high resolution imaging through a turbid medium, *Opt. Lett.* **36**, 4263-4265 (2011)
[4] Kang, S., *et al.* Simultaneous suppression of scattering and aberration for ultra-high resolution imaging deep within scattering media, *Nat. Commun*. In press. (2017)
[5] Choi, C., *et al.* Optical imaging with long working distance and high spatial resolution by correcting the aberration of a large aperture lens, manuscript in preparation.

CMSD Center for Molecular Spectroscopy and Dynamics, IBS-Korea University
KOREA UNIVERSITY