Correction of defocusing of object projections in optical diffraction tomography

Warsaw University of Technology

Institute of Micromechanics and Photonics
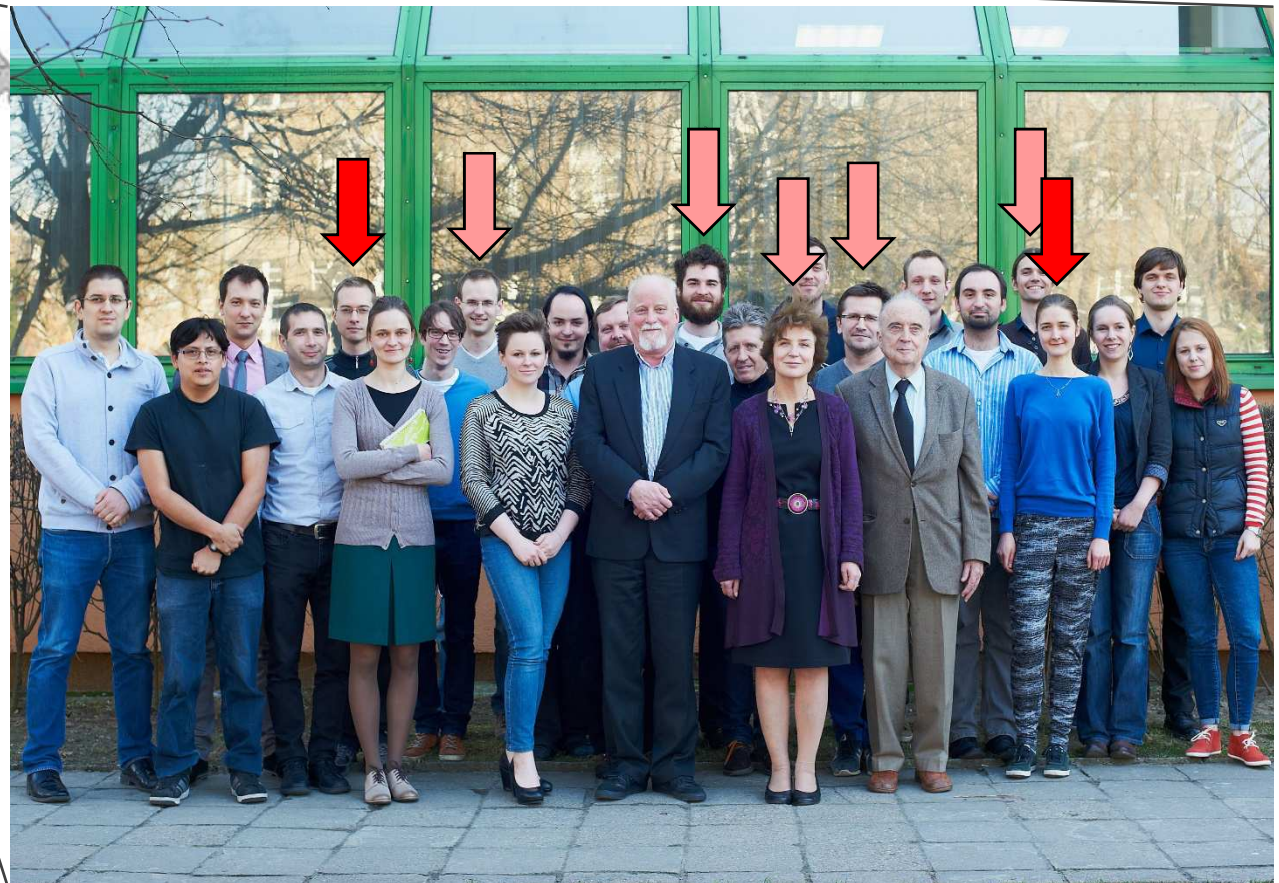
J. Kostencka, **T. Kozacki, M. Kujawińska**

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Warsaw University of Technology
## Photonics Engineering Division

Tomographic Team

Optical diffraction tomograph vs. x-ray tomography

- **probing a sample with visible light (400-700nm)**

- less complicated and less expensive measurmenet systems
- nondestractive inspection, safe for living organisms

- samples have to be transparent to visible light
- spatial resolution dx≈0,5µm
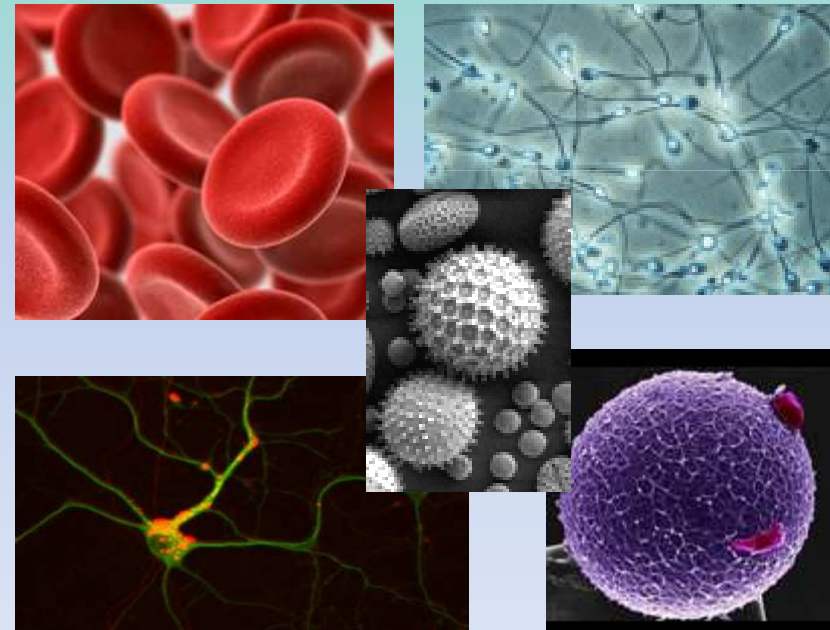- accounting for diffraction is necessary

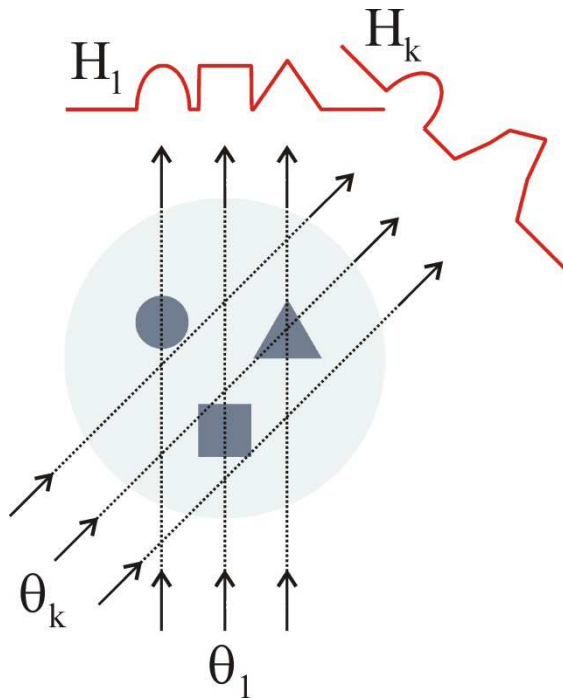# Areas of application

Technical elements
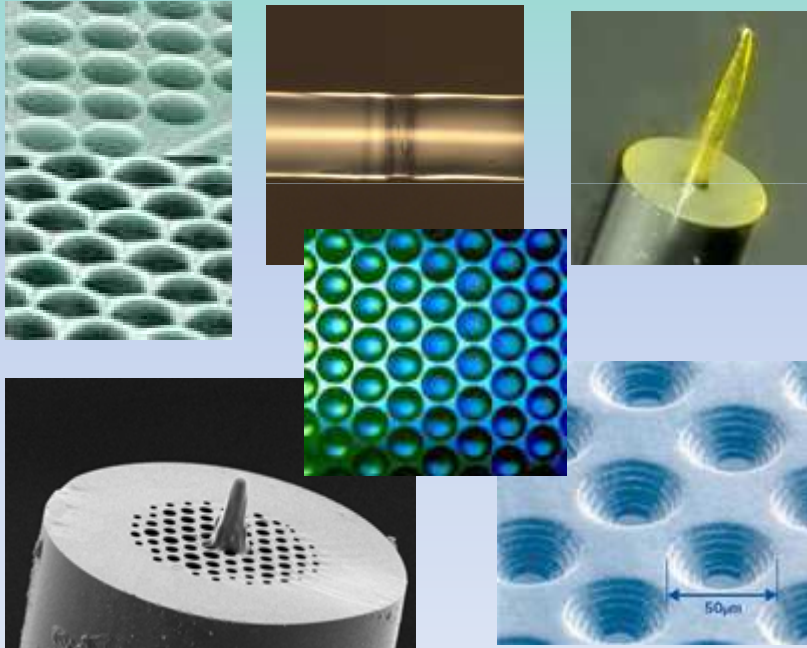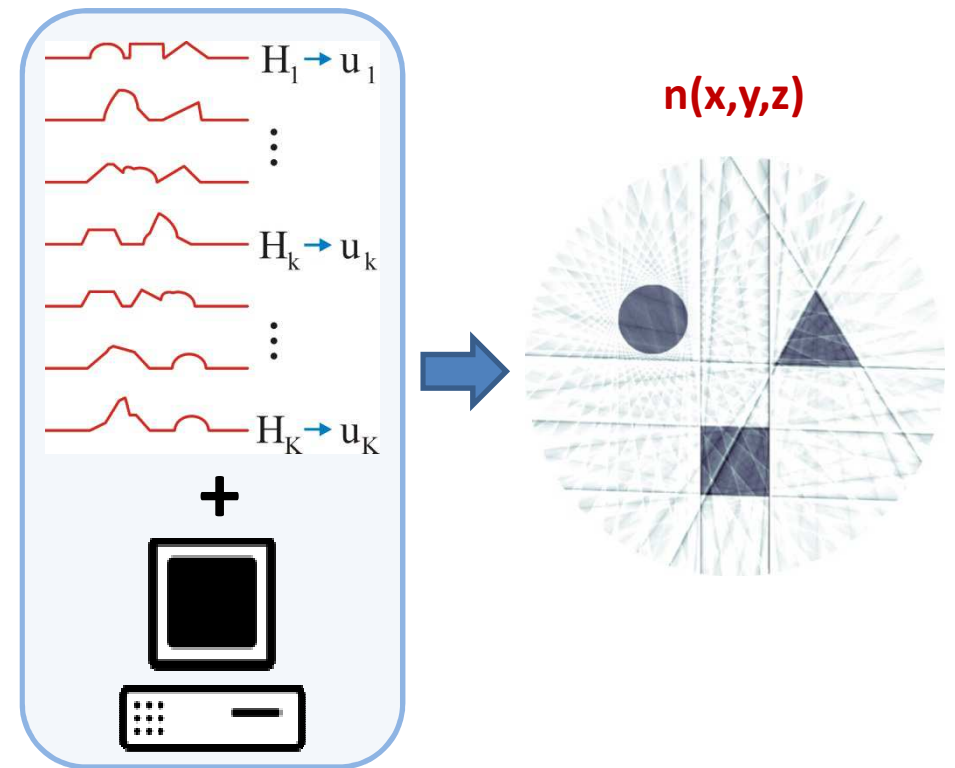

Biological specimens

The concept of measurment

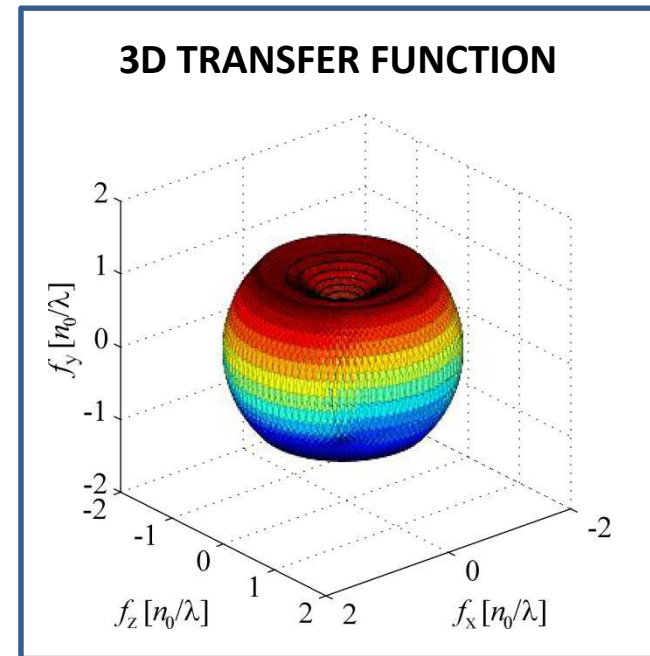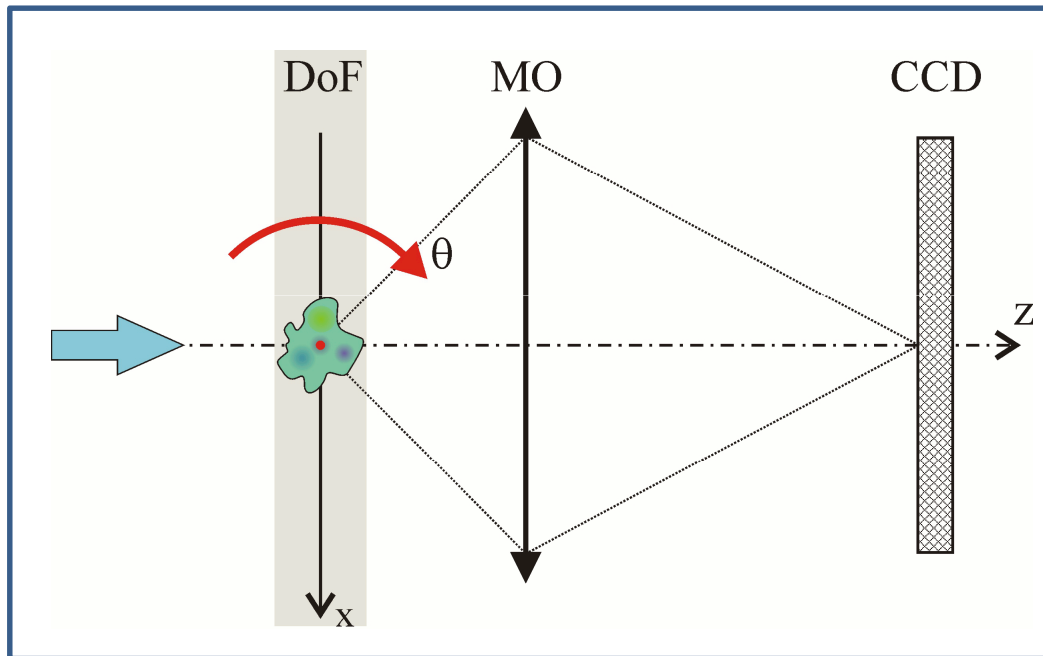**1** **Capturing multiple holograms from various directions**

2 **Computational reconstruction of 3D refractive index distribution**
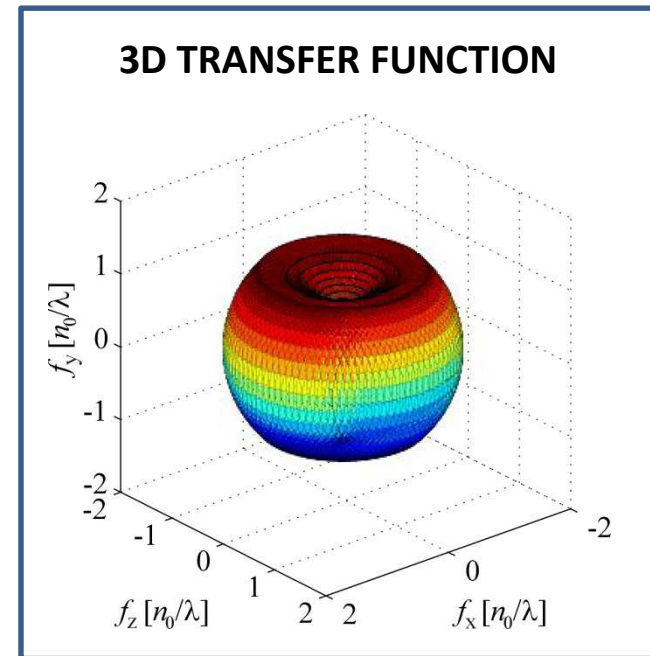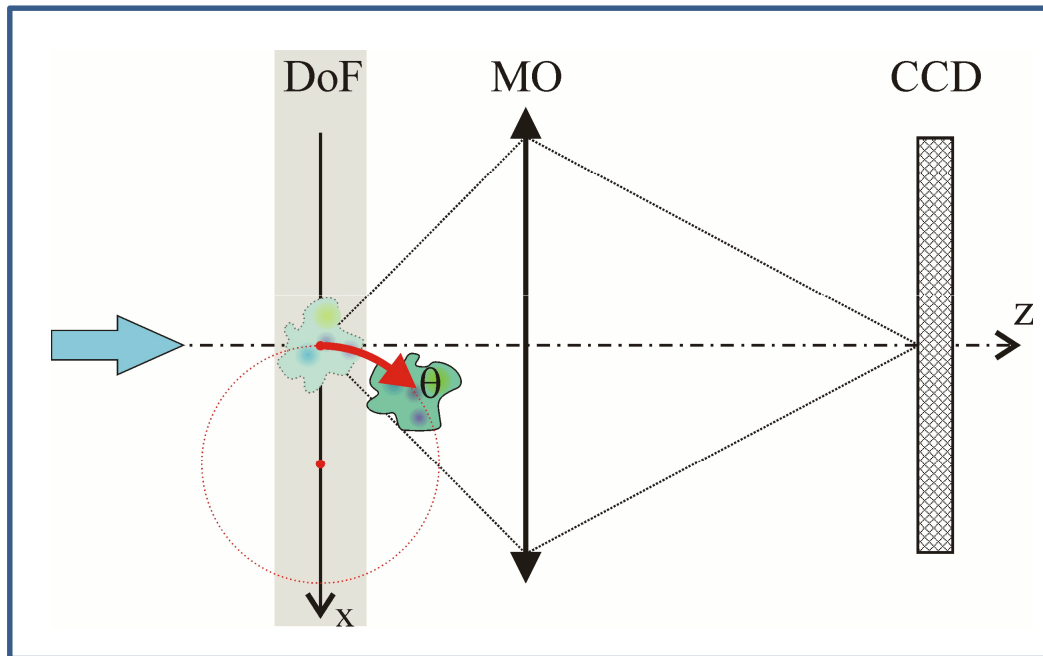
Alternation of the measurement views

ROTATION OF AN OBJECT

Alternation of the measurement views
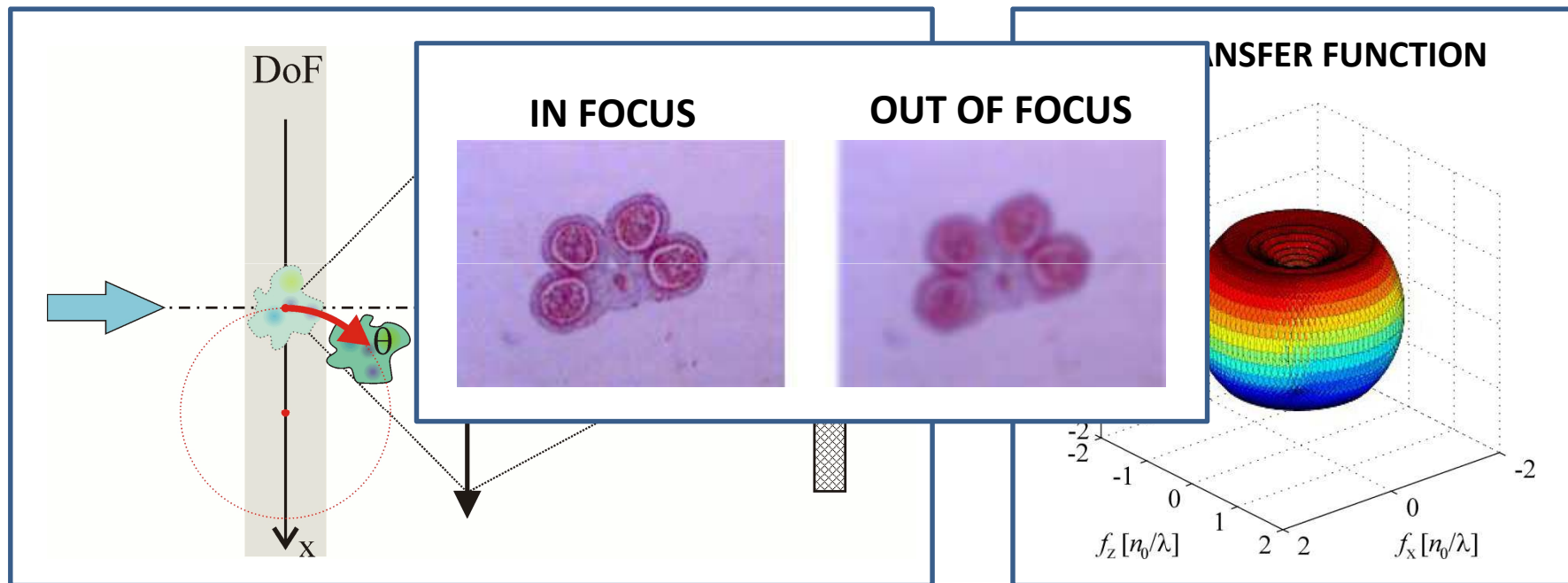
ROTATION OF AN OBJECT

Inevitable inaccuracies of the object rotation ➡ **Errors in a 3D reconstruction**

Alternation of the measurement views

ROTATION OF AN OBJECT

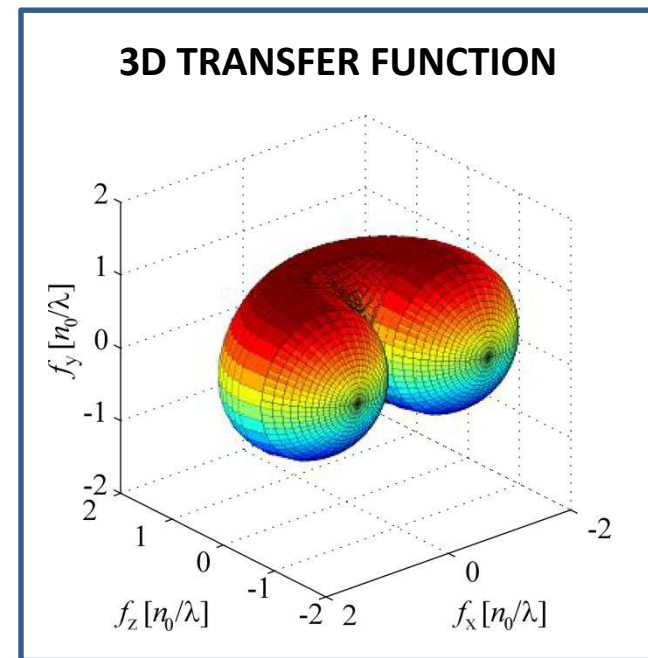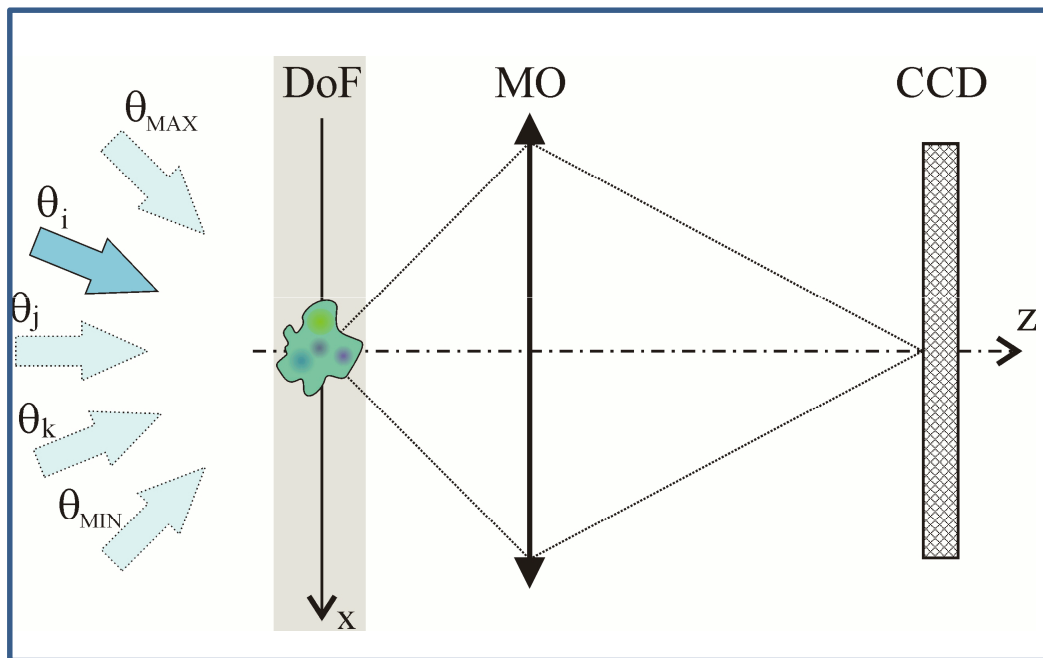**IN FOCUS**   **OUT OF FOCUS**

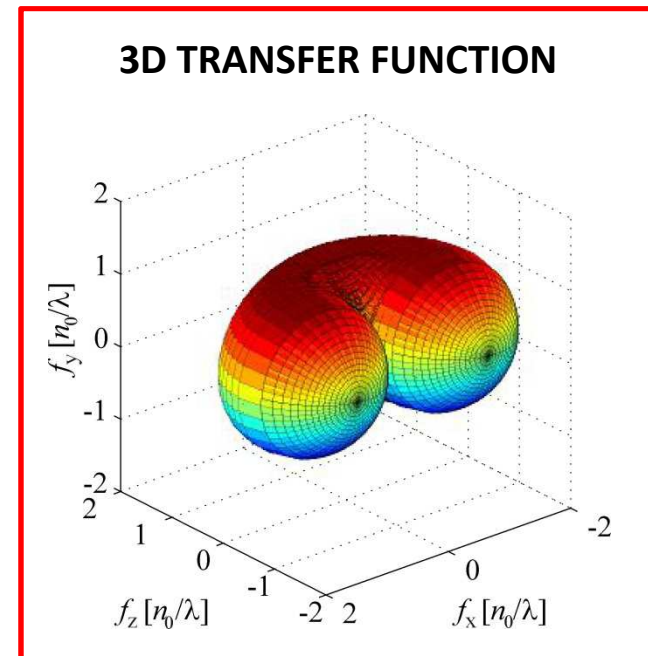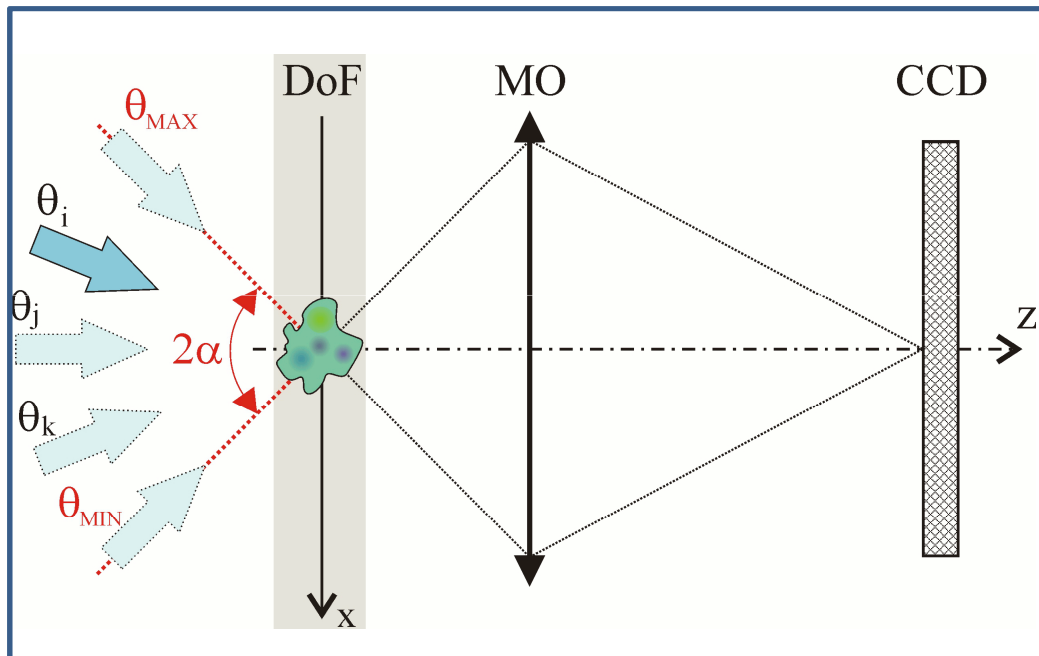**Inevitable inaccuracies of the object rotation** ➡ **Errors in a 3D reconstruction**

Alternation of the measurement views

SCANNING OF ILLUMINATION DIRECTION

Alternation of the measurement views

SCANNING OF ILLUMINATION DIRECTION

3D TRANSFER FUNCTION

Scanning range limited by NA of an objective → **Anisotropic resolution Deformation of a 3D image**

Resolving capabilities of tomographic systems

ROTATION OF AN OBJECT
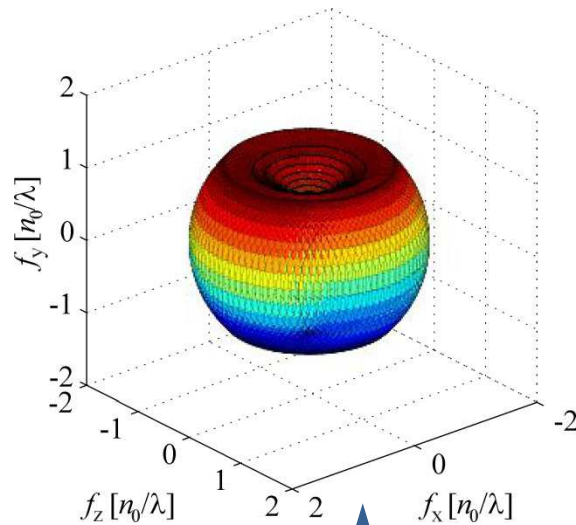
SCANNING OF ILLUMINATION
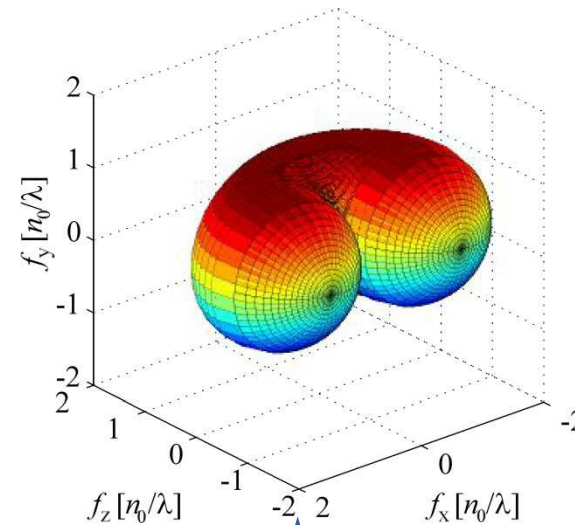
totalvolume	$9.9 \left(\dfrac{n_o}{\lambda}\right)^3$	$7.0 \left(\dfrac{n_o}{\lambda}\right)^3$
$\mathbf{f_x^{MAX}}$	$\sqrt{2}\,\dfrac{n_o}{\lambda}$	$2\,\dfrac{n_o}{\lambda}$
$\mathbf{f_z^{MAX}}$	$\sqrt{2}\,\dfrac{n_o}{\lambda}$	$1\,\dfrac{n_o}{\lambda}$

Resolving capabilities of tomographic systems

ROTATION OF AN OBJECT
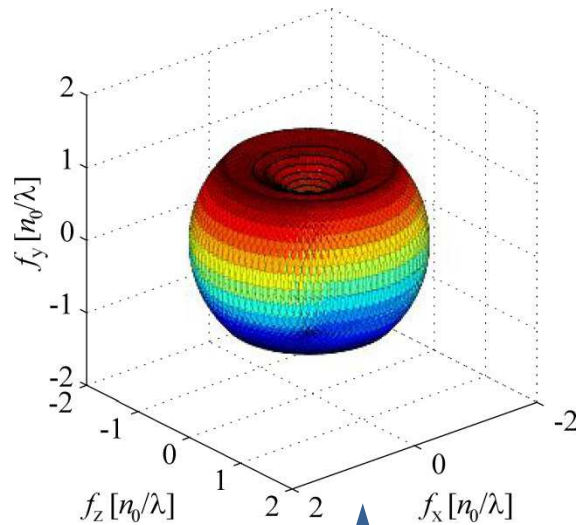
SCANNING OF ILLUMINATION
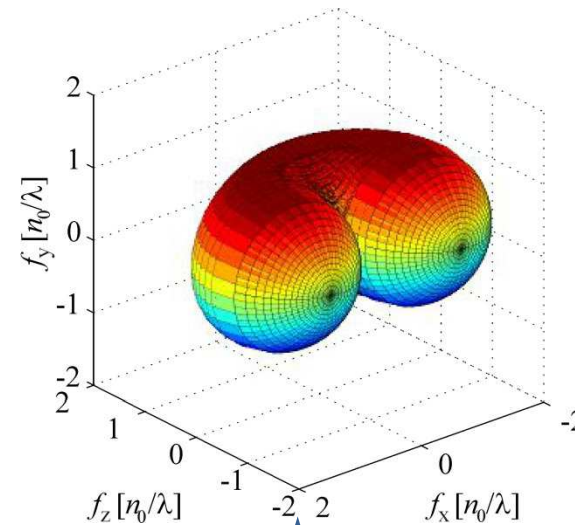
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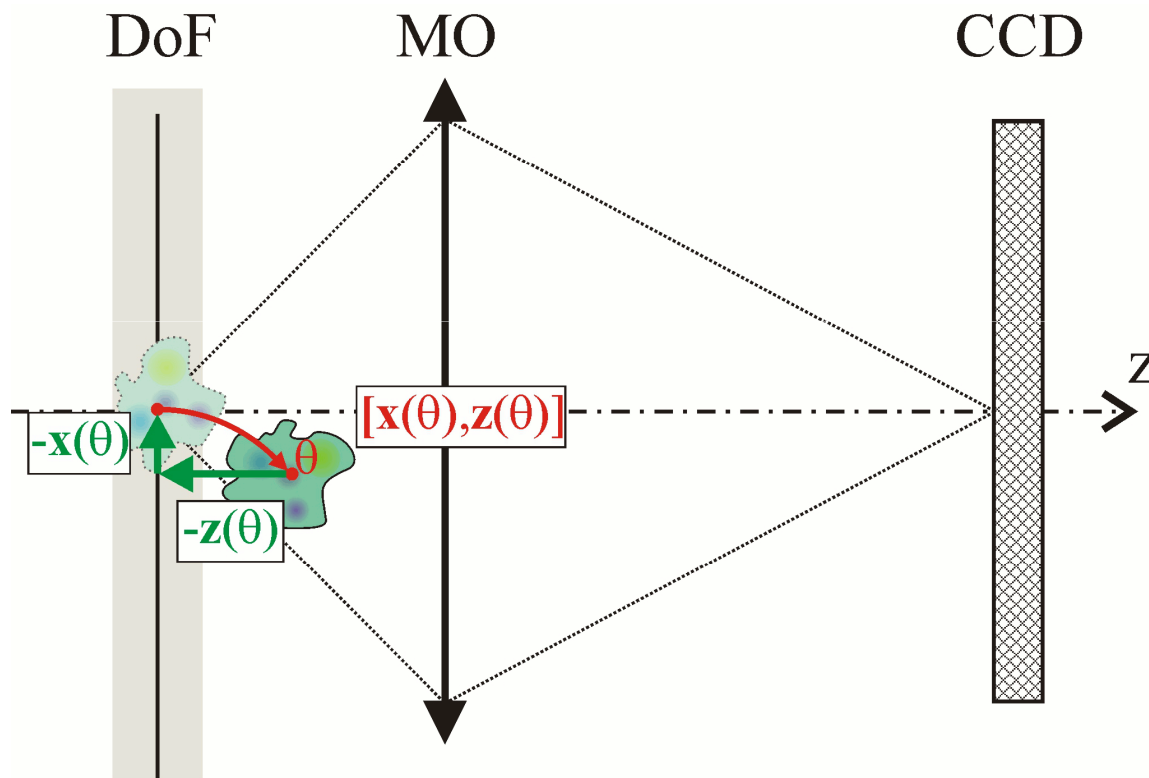# Numerical correction of the rotation error
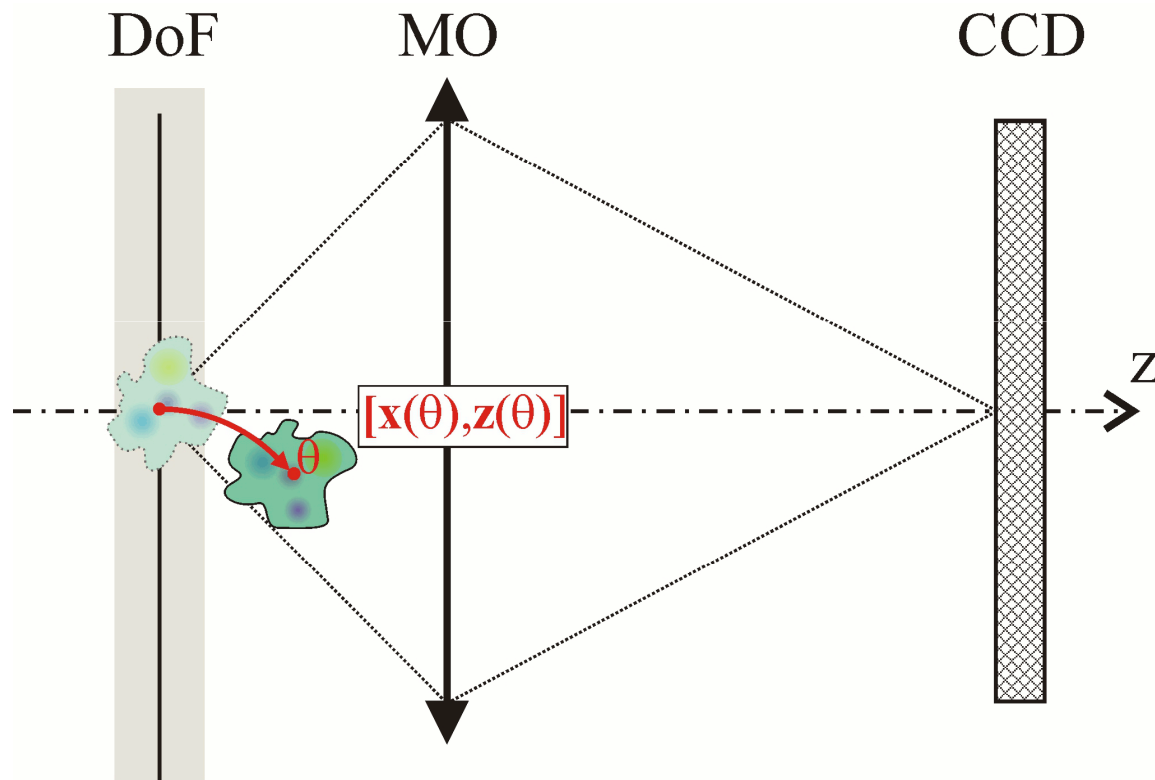
For each angular position θ:

I. Determination of the sample location

Numerical correction of the rotation error

For each angular position θ:

I. **Determination of the sample location**

II. **Correction of the sample displacement**
1. Numerical propagation by a distance **–z(θ)**
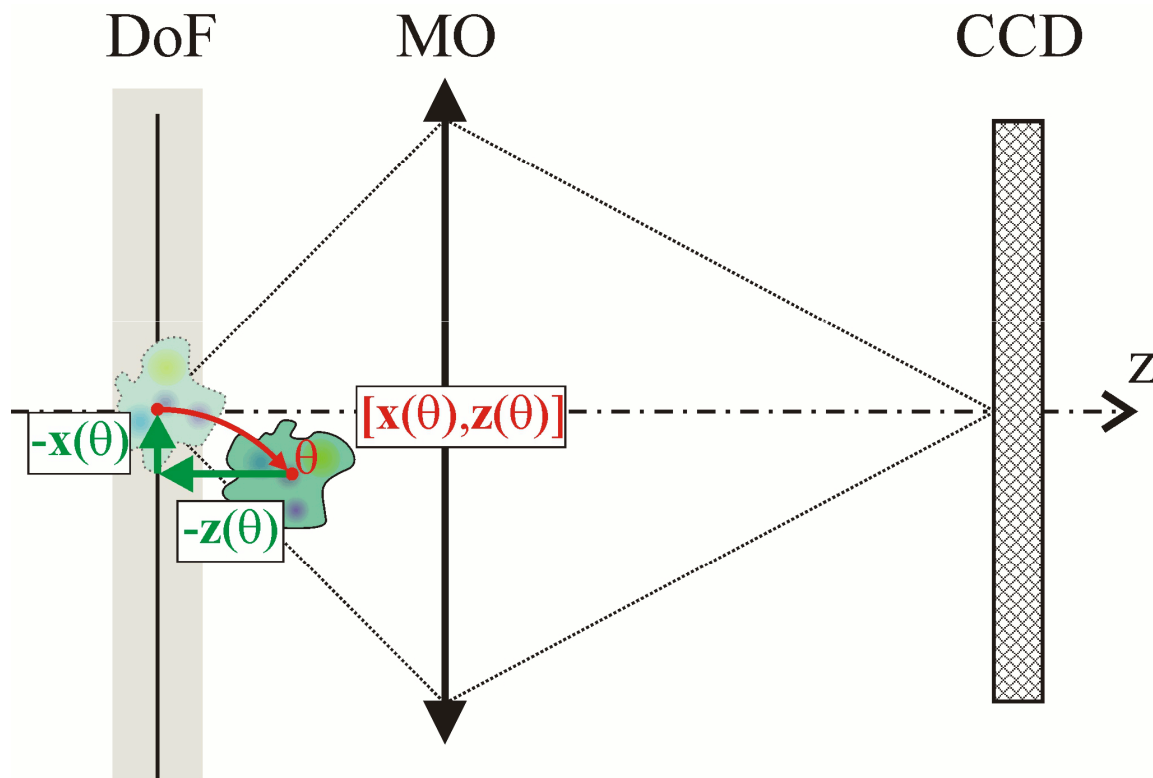2. Transverse shift by **–x(θ)**

Numerical correction of the rotation error

For each angular position θ:

I.   **Determination of the sample location**

II. **Correction of the sample displacement**
     1. Numerical propagation by a distance **–z(θ)**
     2. Transverse shift by **–x(θ)**

MAIN CHALLANGE:
Determination of z(θ)

Autofocusing algorithm
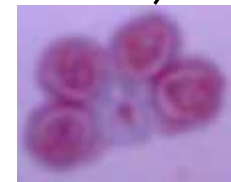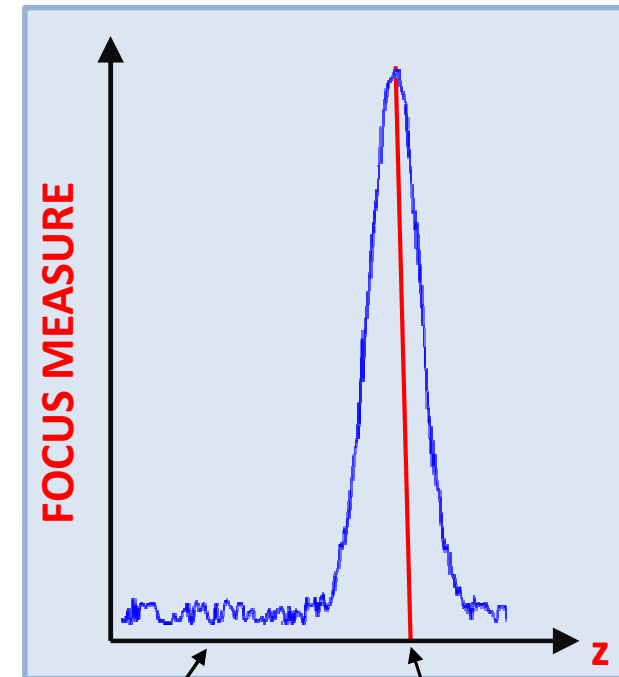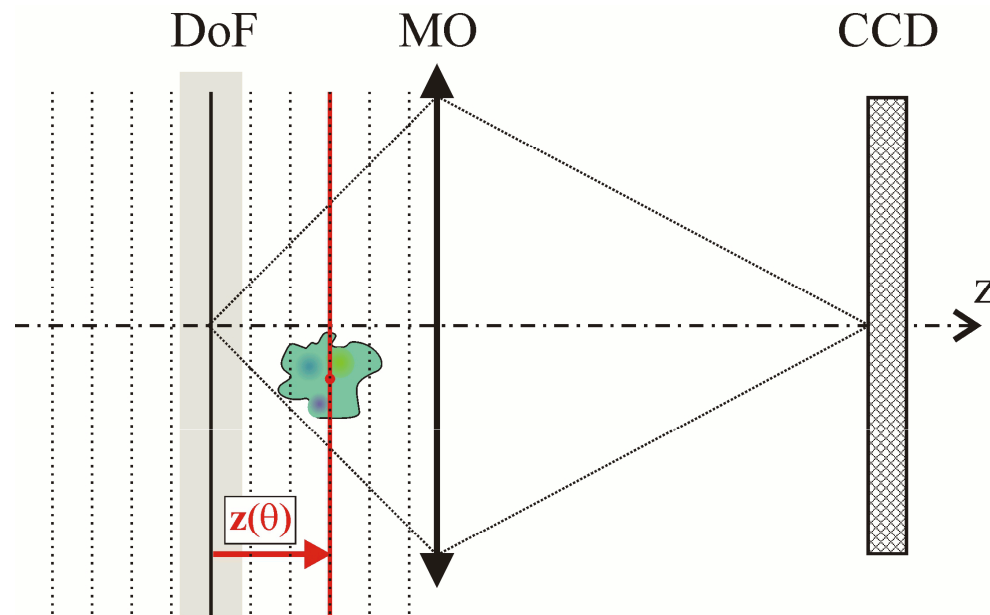
Flaws:
- Low accuracy
- Accuracy dependent on type of a sample
- Method not applicable to samples with mixed amplitude-phase properties

Experimental test

test sample:
FIBER TAPPER
Δn < 0.003
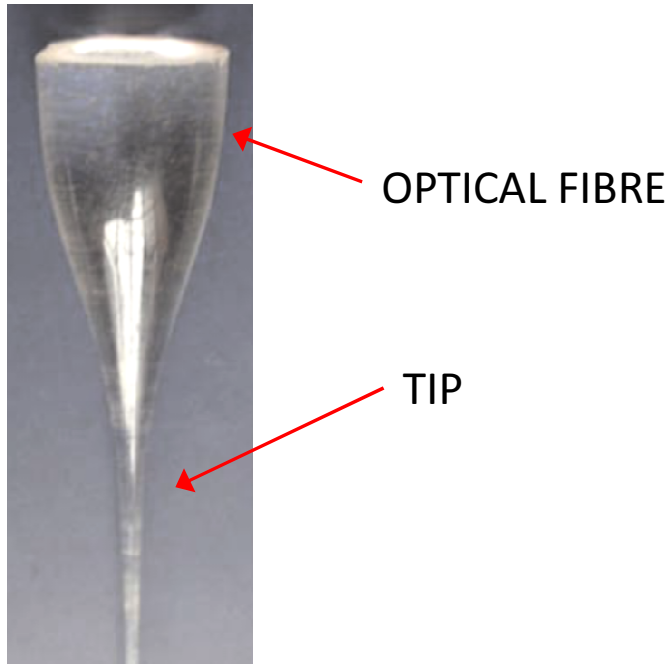
measuerement system:
MACH-ZEHNDER
DIGITAL HOLOGRAPHIC MICROSCOPE
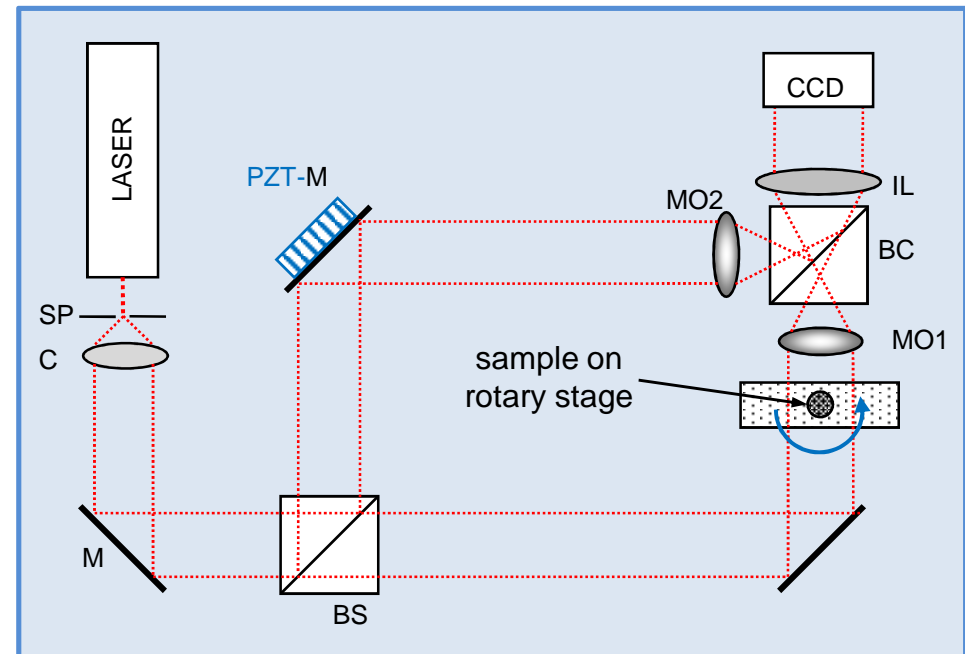
OPTICAL FIBRE

TIP

LovaLite™

Experimental test

Results of autofocusing - z(θ)
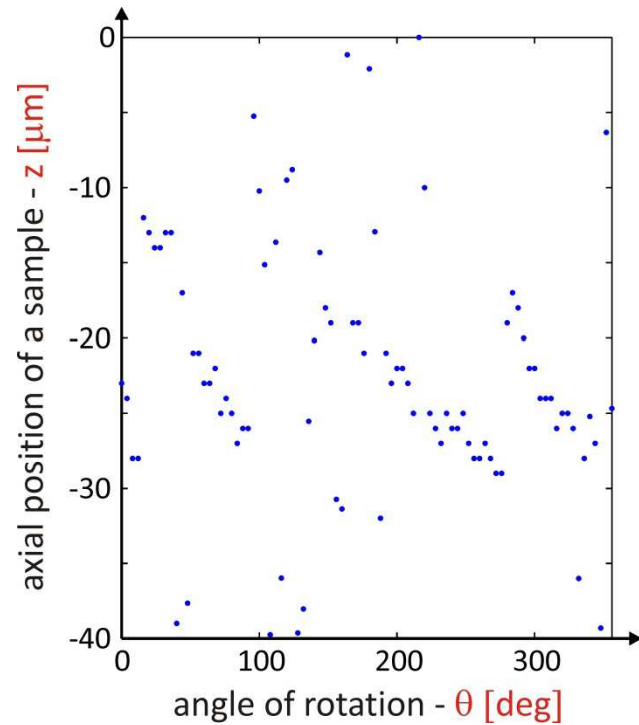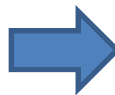
Failure of the autofocusing algorithm ➡ No possibility of correction of rotation error

Experimental test

Results of autofocusing - z(θ)

3D refractive index reconstruction without correcting the rotation error
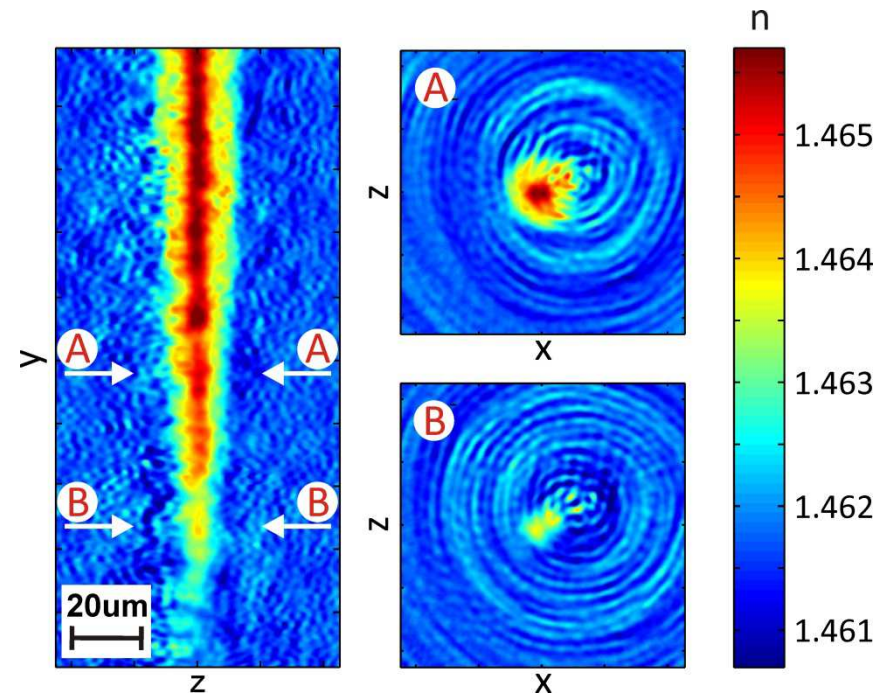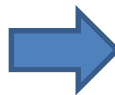
Failure of the autofocusing algorithm ➡ No possibility of correction of rotation error

Novel tomographic configuration

OBJECT ROTATION + OFF-AXIS ILLUMINATION

Autofocusing based on structured illumination
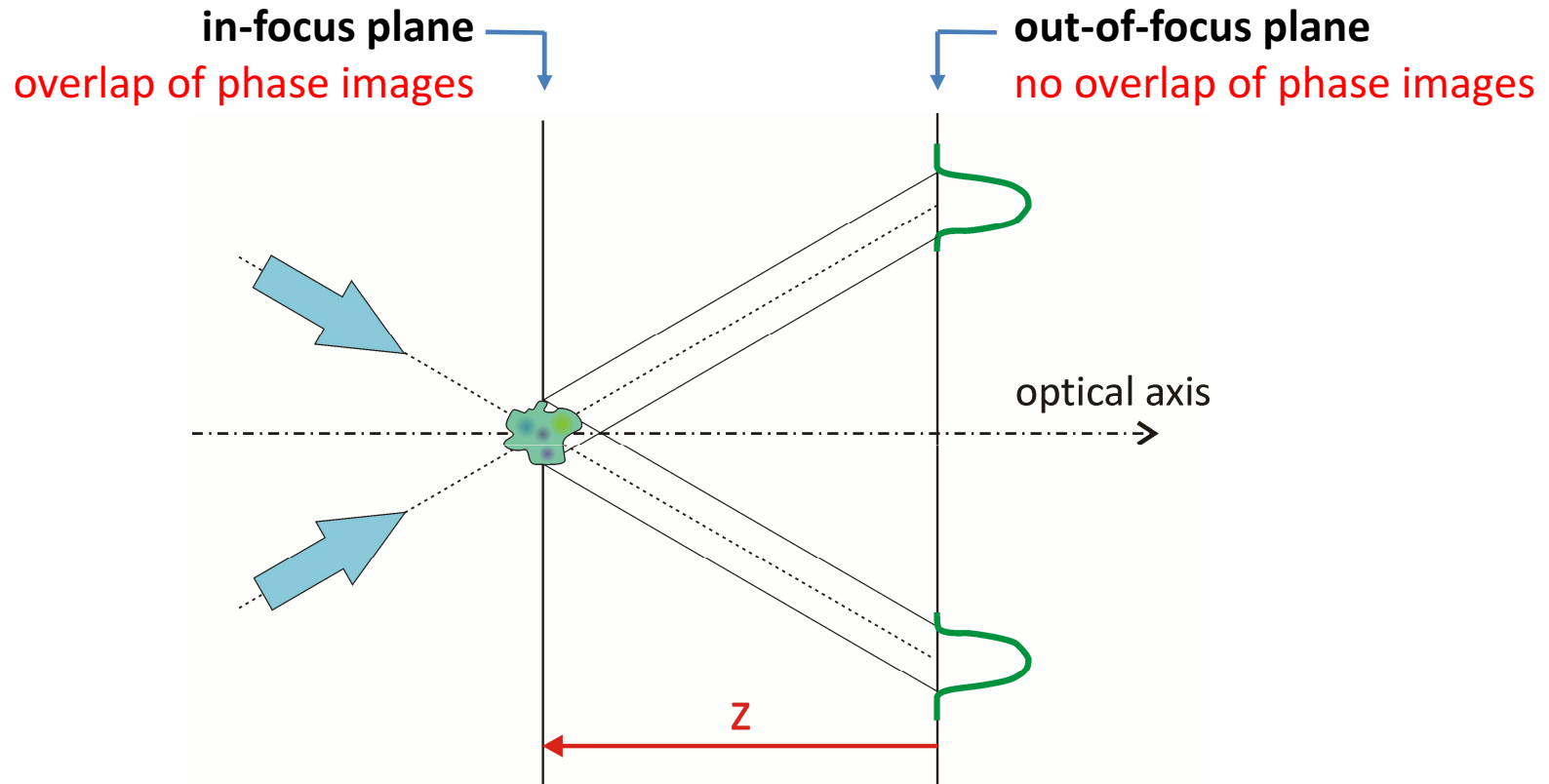
in-focus plane — overlap of phase images
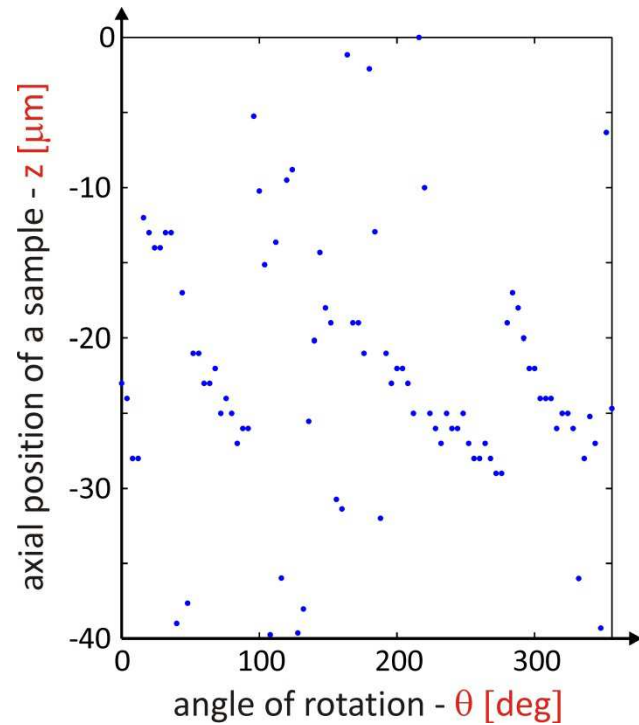
out-of-focus plane — no overlap of phase images

optical axis

z

P. Gao, B. Yao, J. Min, R. Guo, B. Ma, J. Zheng, M. Lei, S. Yan, D. Dan, T. Ye,
„Autofocusing of digital holographic microscopy based on off-axis illuminations,"
Opt. Lett. 37, 3630-3632 (2012).

Autofocusing based on structured illumination

in-focus plane
overlap of phase images

out-of-focus plane
no overlap of phase images

optical axis

z

Accurate correction of rotation error
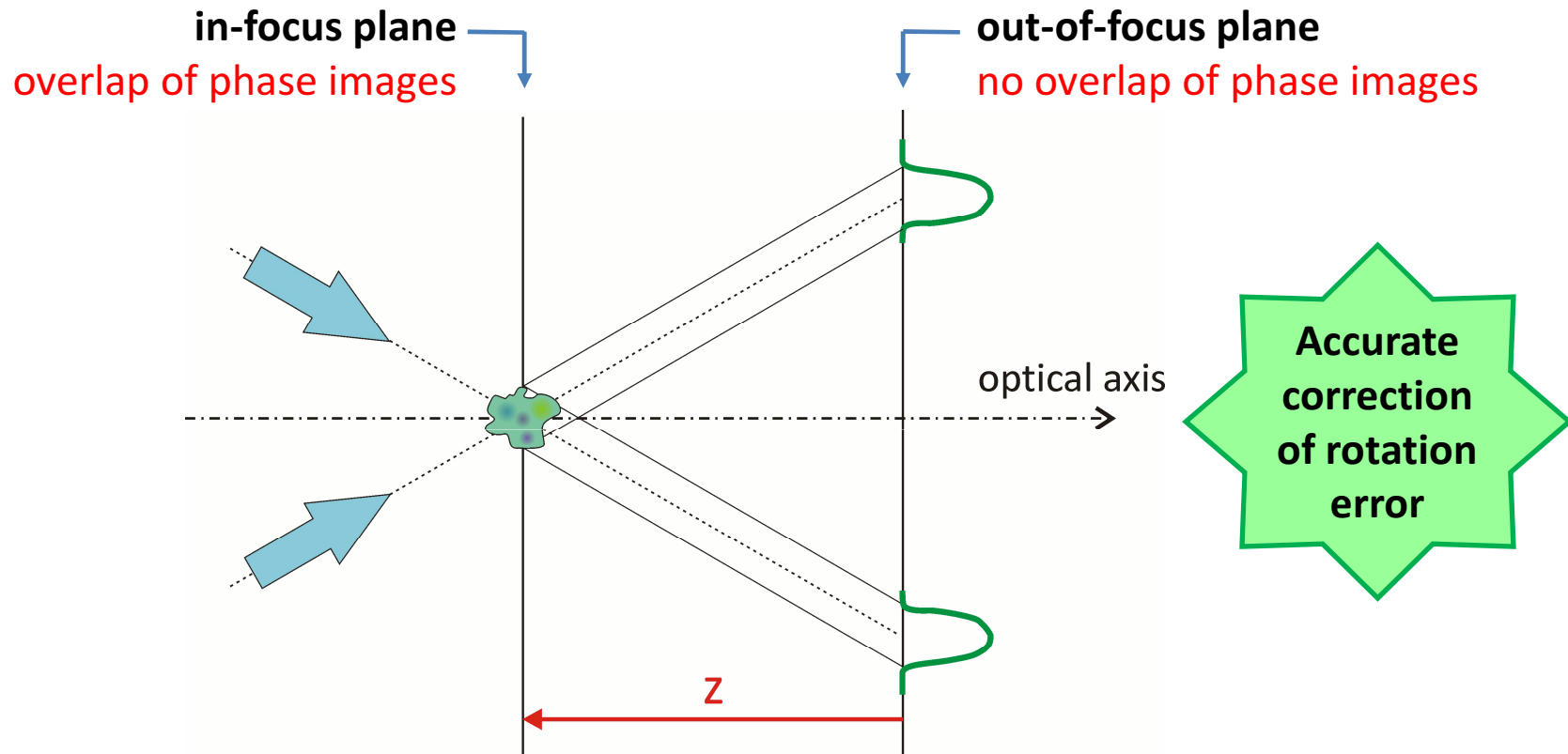
P. Gao, B. Yao, J. Min, R. Guo, B. Ma, J. Zheng, M. Lei, S. Yan, D. Dan, T. Ye,
„**Autofocusing of digital holographic microscopy based on off-axis illuminations,**"
Opt. Lett. 37, 3630-3632 (2012).

Autofocusing results for the test sample

Results of tracking the sample for successive angular positions

Fiber tapper

Standard autofocusing method

Structred illumination autofocusing

Autofocusing results for the test sample

Results of tracking the sample for successive angular positions

Fiber tapper

Standard autofocusing method

Structred illumination autofocusing

3D refractive index reconstructions

Standard tomografic configuration
Correction not possible
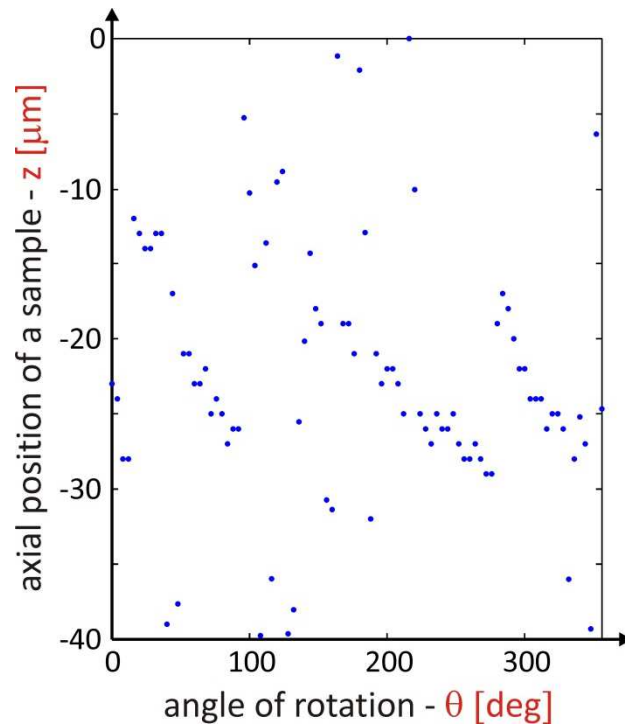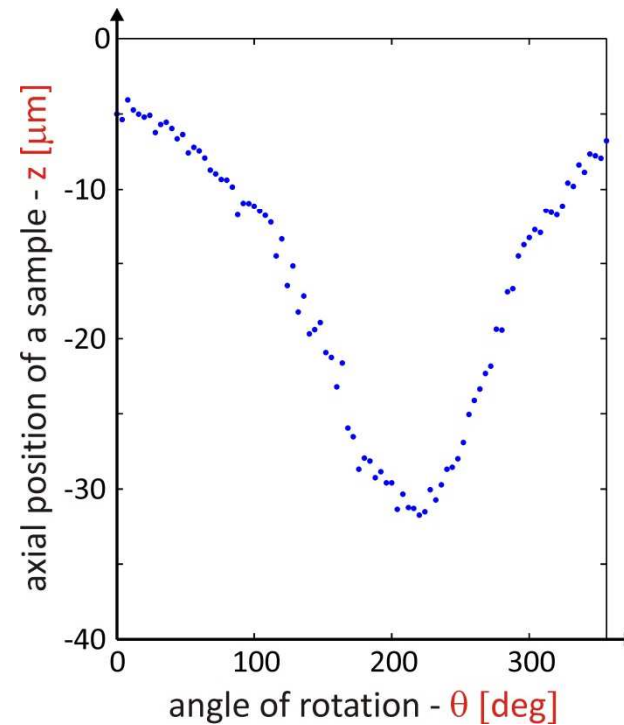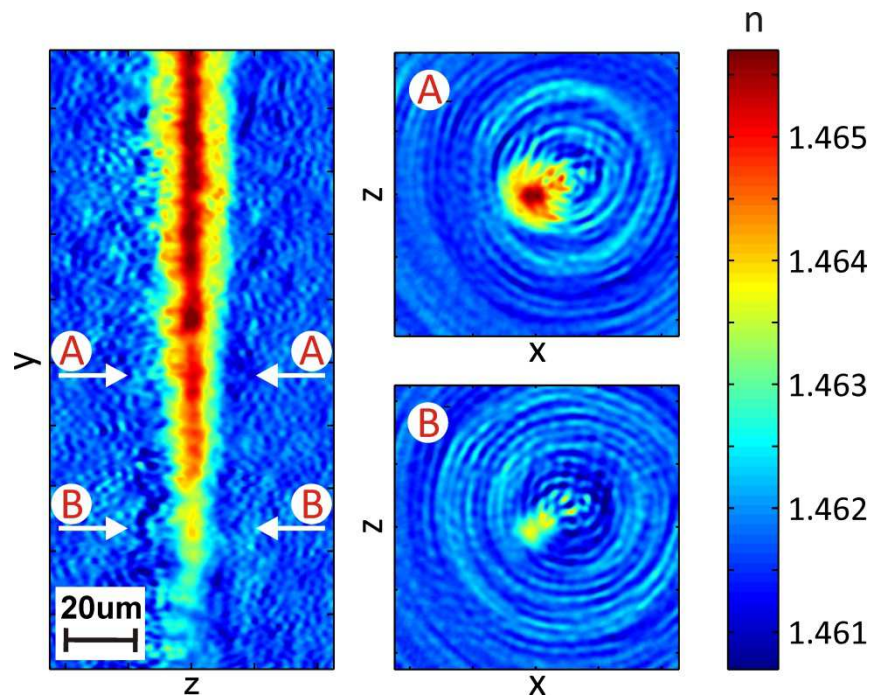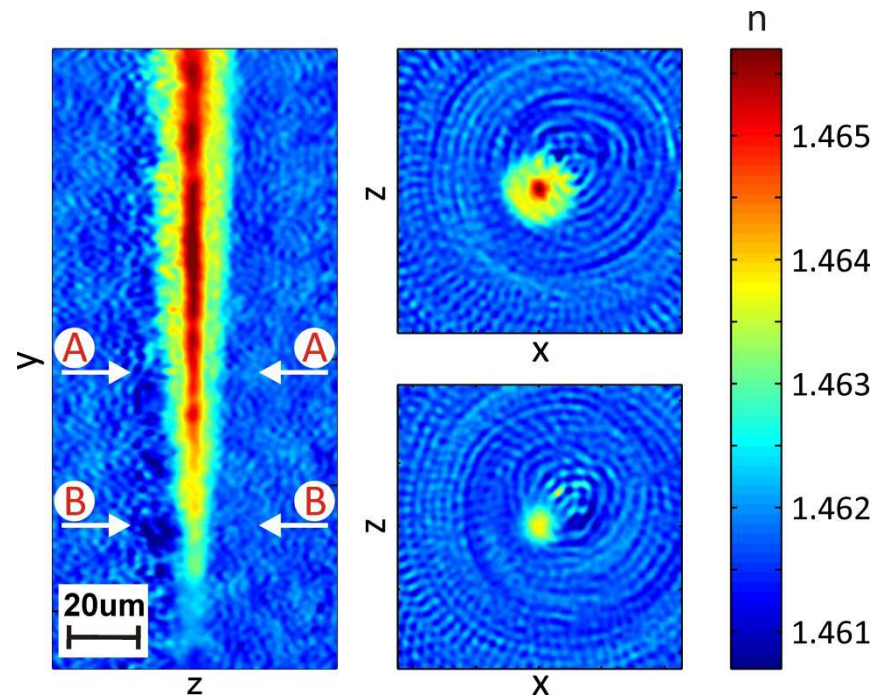
Structured illumination configuration
Correction of the rotation error

Comparison of 3D transfer functions

SCANNING OF ILLUMINATION **ROTATION OF OBJECT** **OBJECT ROTATION +
STRUCTURED ILLUMINATION**
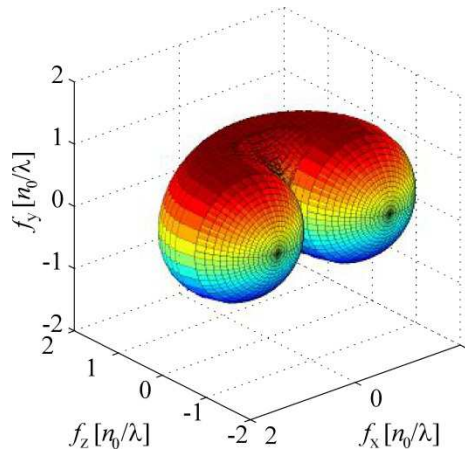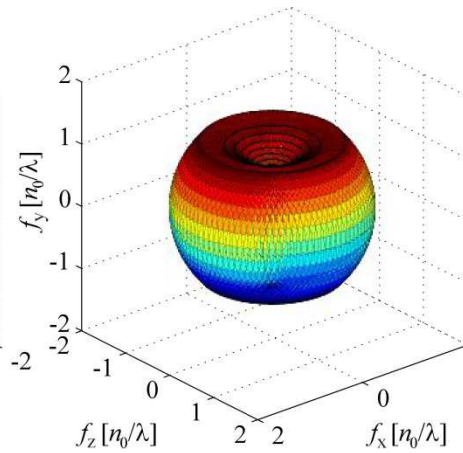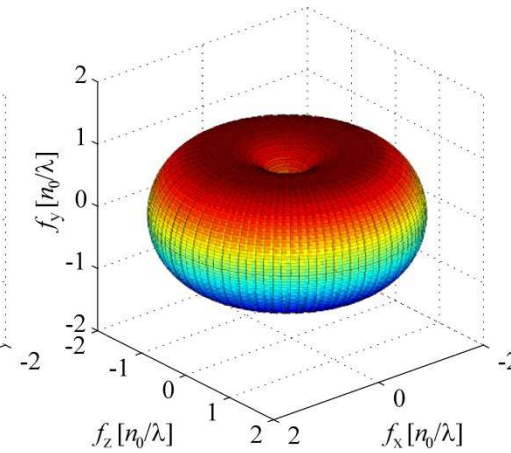
	SCANNING OF ILLUMINATION	ROTATION OF OBJECT	OBJECT ROTATION + STRUCTURED ILLUMINATION
totalvolume	$7.0 \left(\dfrac{n_o}{\lambda}\right)^3$	$9.9 \left(\dfrac{n_o}{\lambda}\right)^3$	$19.7 \left(\dfrac{n_o}{\lambda}\right)^3$
$\mathbf{f_x}^{\mathbf{MAX}}$	$2 \dfrac{n_o}{\lambda}$	$\sqrt{2} \dfrac{n_o}{\lambda}$	$2 \dfrac{n_o}{\lambda}$
$\mathbf{f_z}^{\mathbf{MAX}}$	$1 \dfrac{n_o}{\lambda}$	$\sqrt{2} \dfrac{n_o}{\lambda}$	$2 \dfrac{n_o}{\lambda}$

High and isotropic 3D resolution

Novel tomographic configuration - conclusions

OBJECT ROTATION + OFF-AXIS ILLUMINATION
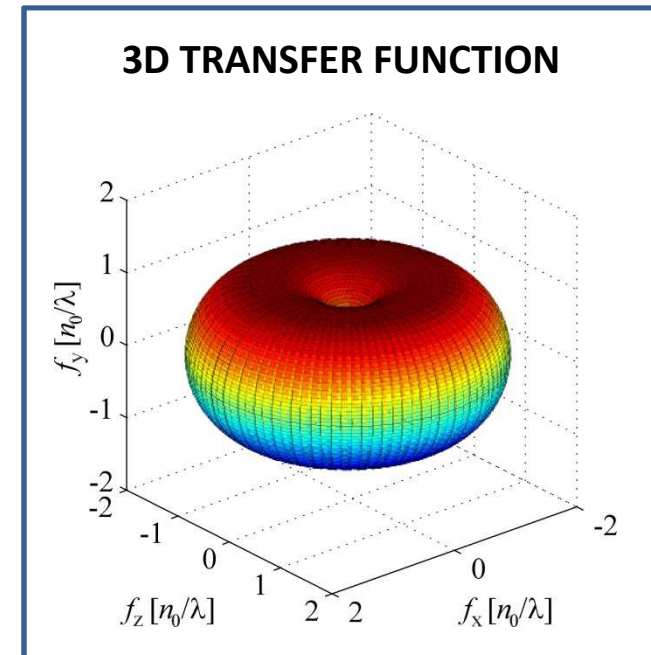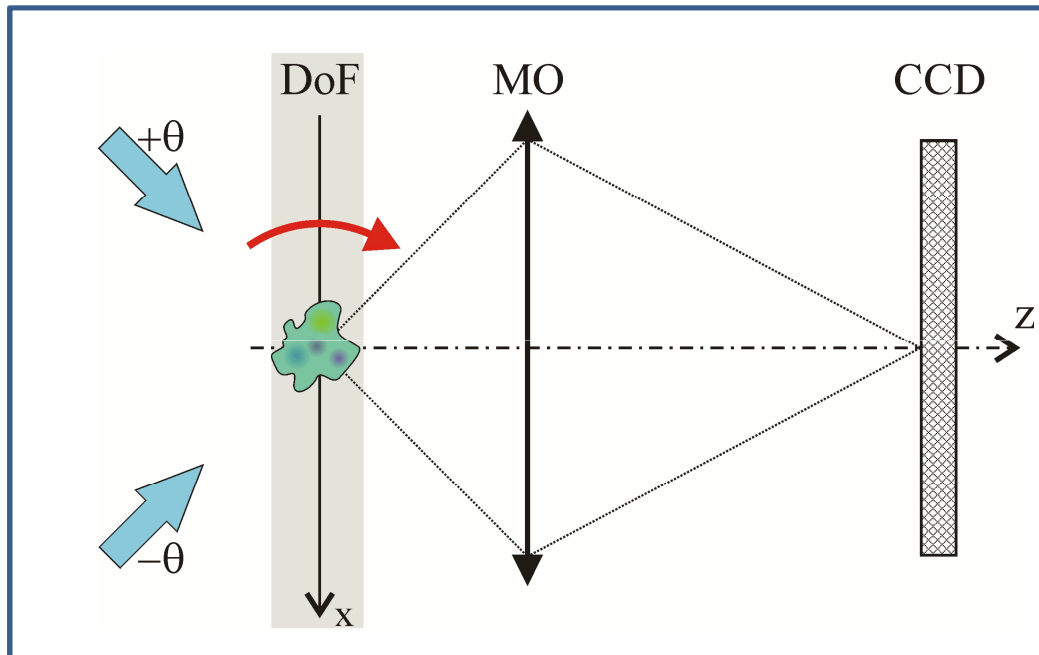
ADVANTAGES:
- Correction of rotation errors
- Gain in 3D resolution

Acknowledgment

References

- Kou, S. and Sheppard, C. J., "Imaging in digital holographic microscopy," Opt. Express 15, 13640-13648 (2007).

- Kostencka, J., Kozacki, T., Dudek, M. and Kujawińska, M., "Noise suppressed optical diffraction tomography with autofocus correction," Opt. Express 22, 5731-5745 (2014).

- Kostencka, J., Kozacki T., Dudek, M. and Kujawińska, M., "Time efficient method for defocus error compensation in tomographic phase microscopy," Photonics Letters of Poland 6, 102-104 (2014).

- Langehanenberg, P., Bally, G. and Kemper, B., "Autofocusing in digital holographic microscopy," 3D Research 2, 1-11 (2011).

- Liżewski, K., Tomczewski, S., Kozacki, T. and Kostencka, J., "High precision topography measurement through accurate in-focus plane detection with hybrid digital holographic microscope and white light interferometer module," Applied Optics 53, 2446-2454 (2014).

- Górski, W. and Osten, W., "Tomographic imaging of photonic crystal fibers," Opt. Lett. 32, 1977-1979 (2007).

- Gao, P., Yao, B., Min, J., Guo, R., Ma, B., Zheng, J., Lei, M., Yan, S., Dan, D. and Ye, T., "Autofocusing of digital holographic microscopy based on off-axis illuminations," Opt. Lett. 37, 3630-3632 (2012).

- Kostencka, J. and Kozacki, T., "Computational and experimental study on accuracy of off-axis reconstructions in optical diffraction tomography," Optical Engineering, 54, 024107 (2015).

- Kostencka, J., Kozacki, T., Kuś, A. and Kujawińska, M., "Accurate approach to capillary-supported optical diffraction tomography," Optics Express 23, 7908-7923 (2015).