Vortex self-imaging experiments on aberration insensitive localization of microobjects

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Outline

1. Introduction

2. Theoretical model

3. Experimental setup

4. Results

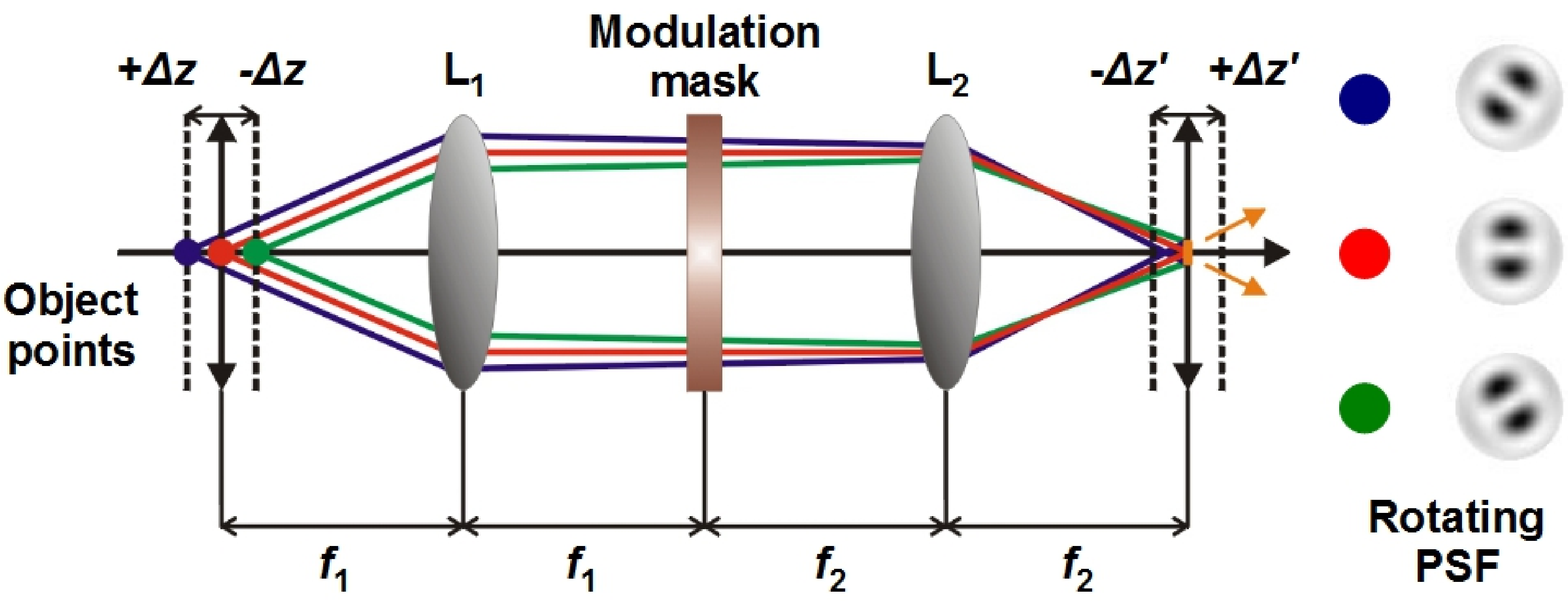
5. Conclusions

Rotating point spread function (PSF)

The rotating PSF has been incorporated into techniques of optical microscopy as a precise tool for three-dimensional localization and tracking of microparticles.

A. Greengard, Y.Y. Schechner, R. Piestun, Depth from diffracted rotation, Opt. Lett. 31, 181-183 (2006).

Principle of the rotating PSF



The axial position of each monitored point-like object is determined from angular orientation of a rotationally asymmetrical image spot, rotating under defocusing.

Methods of the rotating PSF implementation

Wave emitted from microobject → Modulation mask → Interference of optical vortices → Rotating image spot

1. Modulation mask composed of L-G modes

Double-helix PSF

S.R.P. Pavani, R. Piestun, High-efficiency rotating point spread function, Opt. Express 16, 3484-3489 (2008).

Corkscrew PSF

M.D. Lew, S.F. Lee, M. Badieirostami, W.E. Moerner, Corkscrew point spread function for far-field three-dimensional nanoscale localization of pointlike objects, Opt. Lett. 36, 202-204 (2011).

2. Sampled spiral phase mask

Azimuthal sampling

M. Baranek, Z. Bouchal, Rotating vortex imaging implemented by a quantized spiral phase modulation, J. Europ. Opt. Soc. Rap. Public 8, 13017 (2013).

Radial sampling

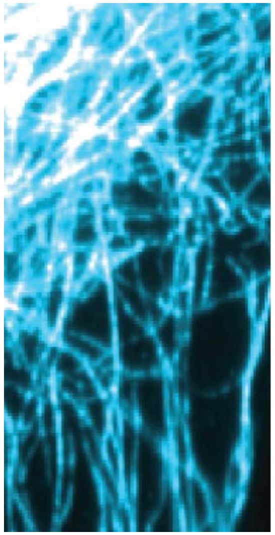
S. Prasad, Rotating point spread function via pupil-phase engineering, Opt. Lett. 38, 585-587 (2013).

Nobel prize in chemistry 2014

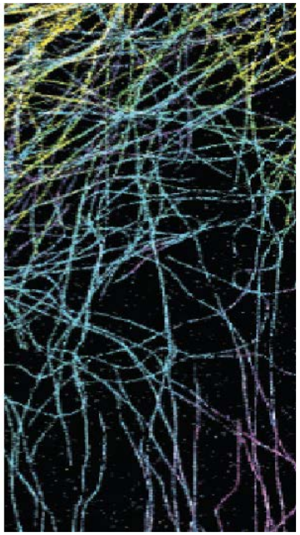
Super-resolution in optical microscopy

S.W. Hell, E. Betzig, W.E. Moerner

Standard imaging



3D STORM



Fluorescence microscopy:

SIM - Structured Illumination Microscopy
STED - Stimulated Emission Depletion

Fluorescence localization microscopy:

STORM - Stochastic Optical Reconstruction Microscopy
PALM - Photoactivated Localization Microscopy

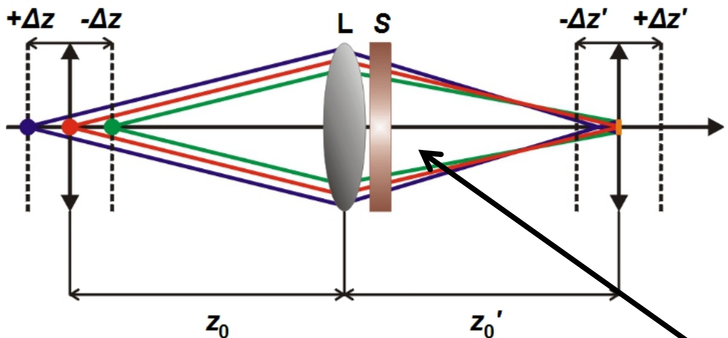
B. Huang, W. Wang, M. Bates, X. Zhuang, Three-dimensional super-resolution imaging by stochastic optical reconstruction microscopy, Science 319, 810-813 (2008).

S.R.P. Pavani, M.A. Thompson, J.S. Biteen, S.J. Lord, N. Liu, R.J. Twieg, R. Piestun, W.E. Moerner, Three-dimensional, single-molecule fluorescence imaging beyond the diffraction limit by using a double-helix point spread function, Proc. Nat. Acad. Sci. USA 106, 2995-2999 (2009).

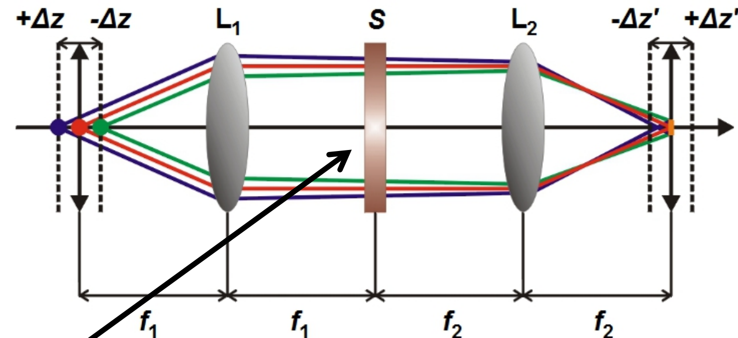
Rotating PSF => 3D super-resolution microscopy

Theoretical model

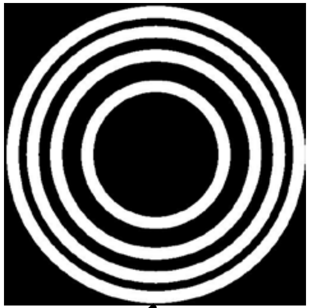
Modulation of complex amplitude



Modulation of spatial spectrum



Amplitude transparency



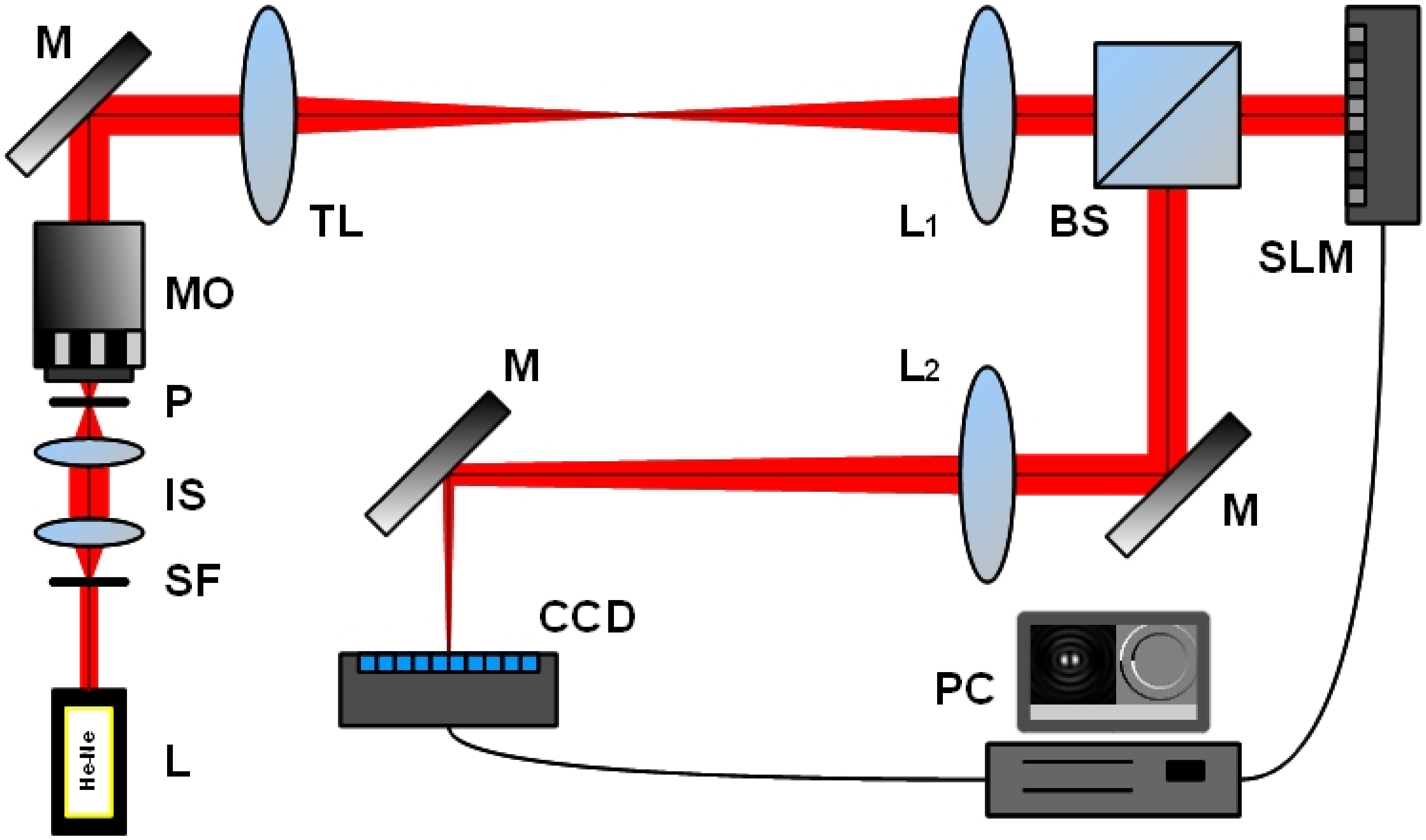
Annular spiral mask

Phase transparency

Narrow rings

Self-imaging of nondiffracting vortices

Experimental setup



L – He-Ne laser (20 mW, 632.8 nm); **SF** – spatial filter; **IS** – illumination system;
P – pinhole (d = 2 µm); **MO** – microscope objective (Newport 20x, NA = 0.4, f_o = 9 mm);
M – mirrors; **TL** – tube lens (f_t = 200 mm); **L_1, L_2** – lenses (f_1 = 200 mm, f_2 = 400 mm);
BS – beam splitter; **SLM** – Hamamatsu (X10468, 600x800 pix); **CCD** – Olympus F-view II

Results

Shape invariant PSF rotation in extended axial range

Modulation mask

$l_1 = -1$

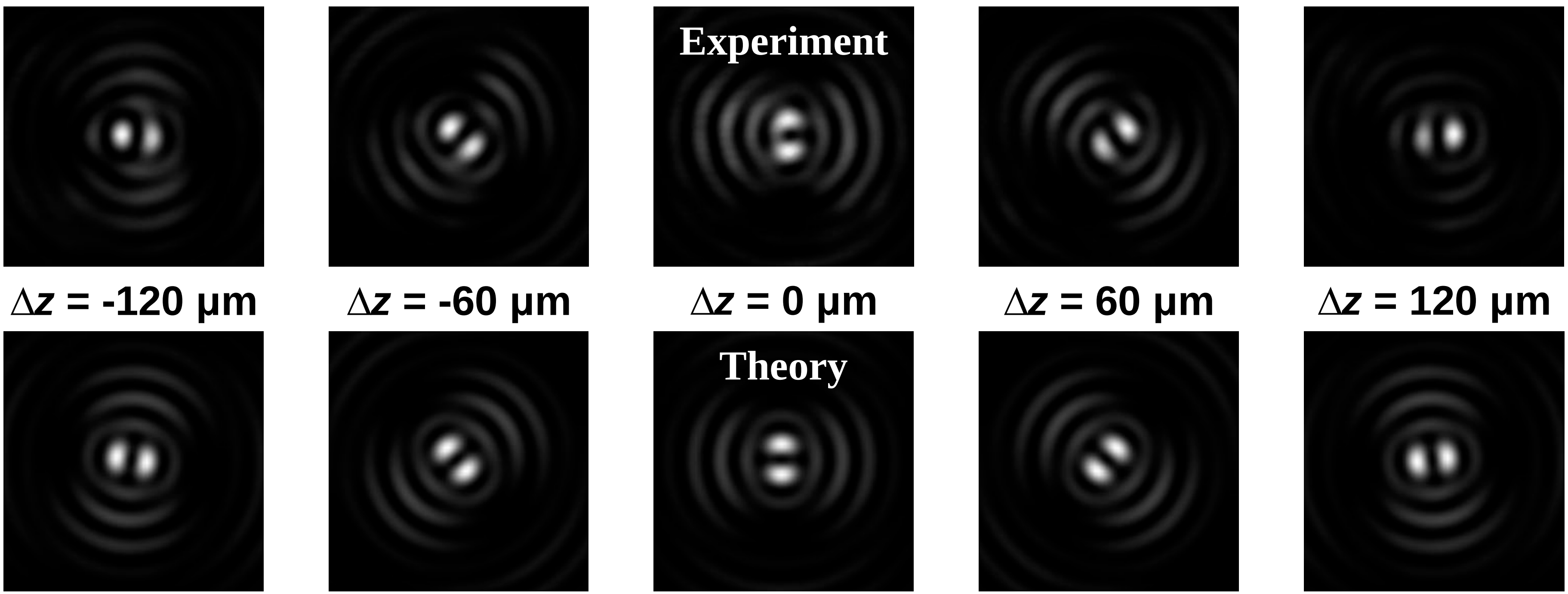
$l_2 = 1$

Numerical aperture: $A = 0.1$

Wavelength: $\lambda = 632.8$ nm

Depth of focus: $\Delta d \approx 32$ μm

Aberration free system: $A_{040} = 0$



M. Baranek, P. Bouchal, M. Siler, Z. Bouchal, Aberration resistant axial localization using a self-imaging of vortices, Opt. Express 23, 15316-15331 (2015).

Results

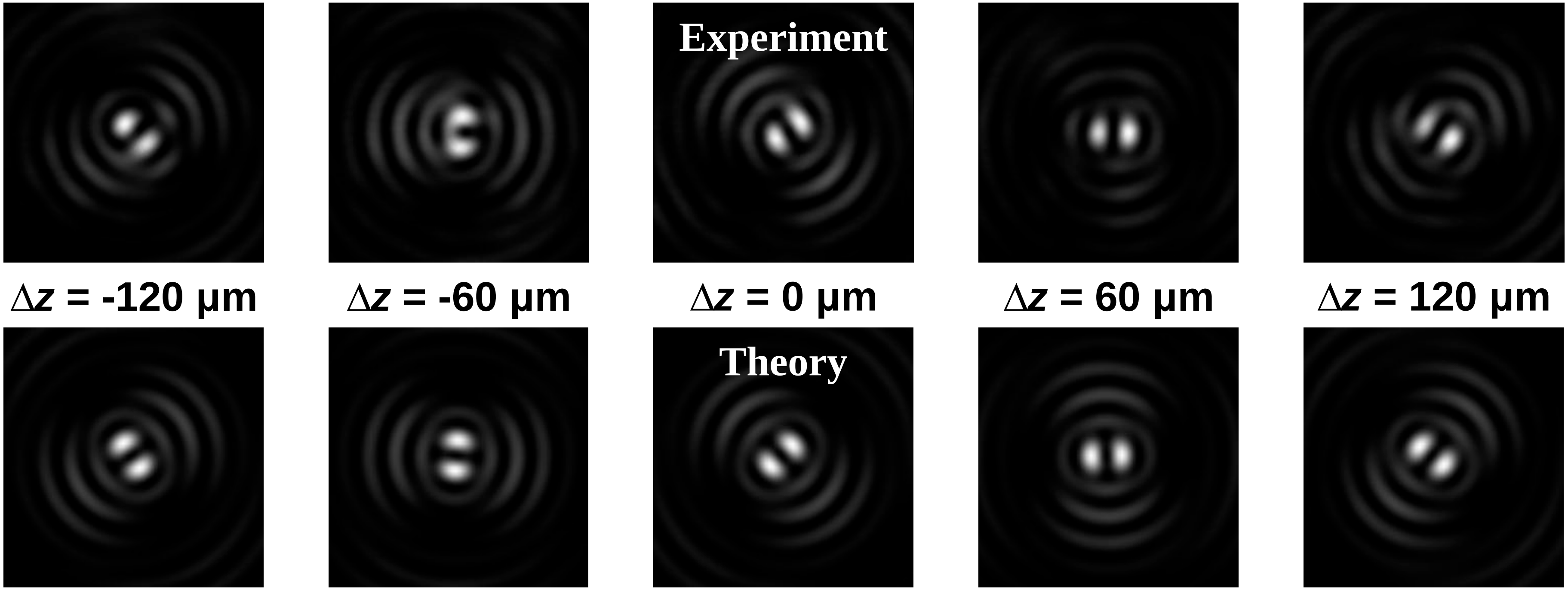
Aberration resistant PSF rotation

Modulation mask

$l_1 = -1$

$l_2 = 1$

Numerical aperture:	$A = 0.1$
Wavelength:	$\lambda = 632.8$ nm
Depth of focus:	$\Delta d \approx 32$ μm
Spherical aberration:	$\mathbf{A_{040} = 0.4\,\lambda}$

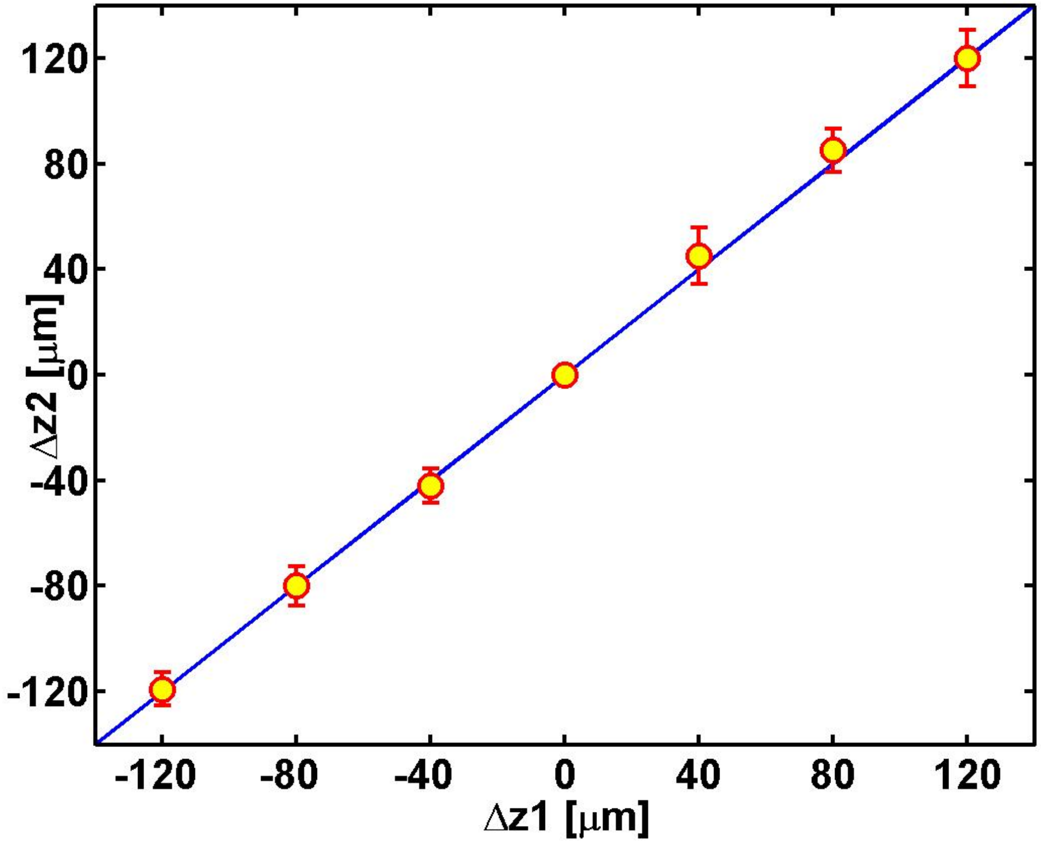


M. Baranek, P. Bouchal, M. Siler, Z. Bouchal, Aberration resistant axial localization using a self-imaging of vortices, Opt. Express 23, 15316-15331 (2015).

Results

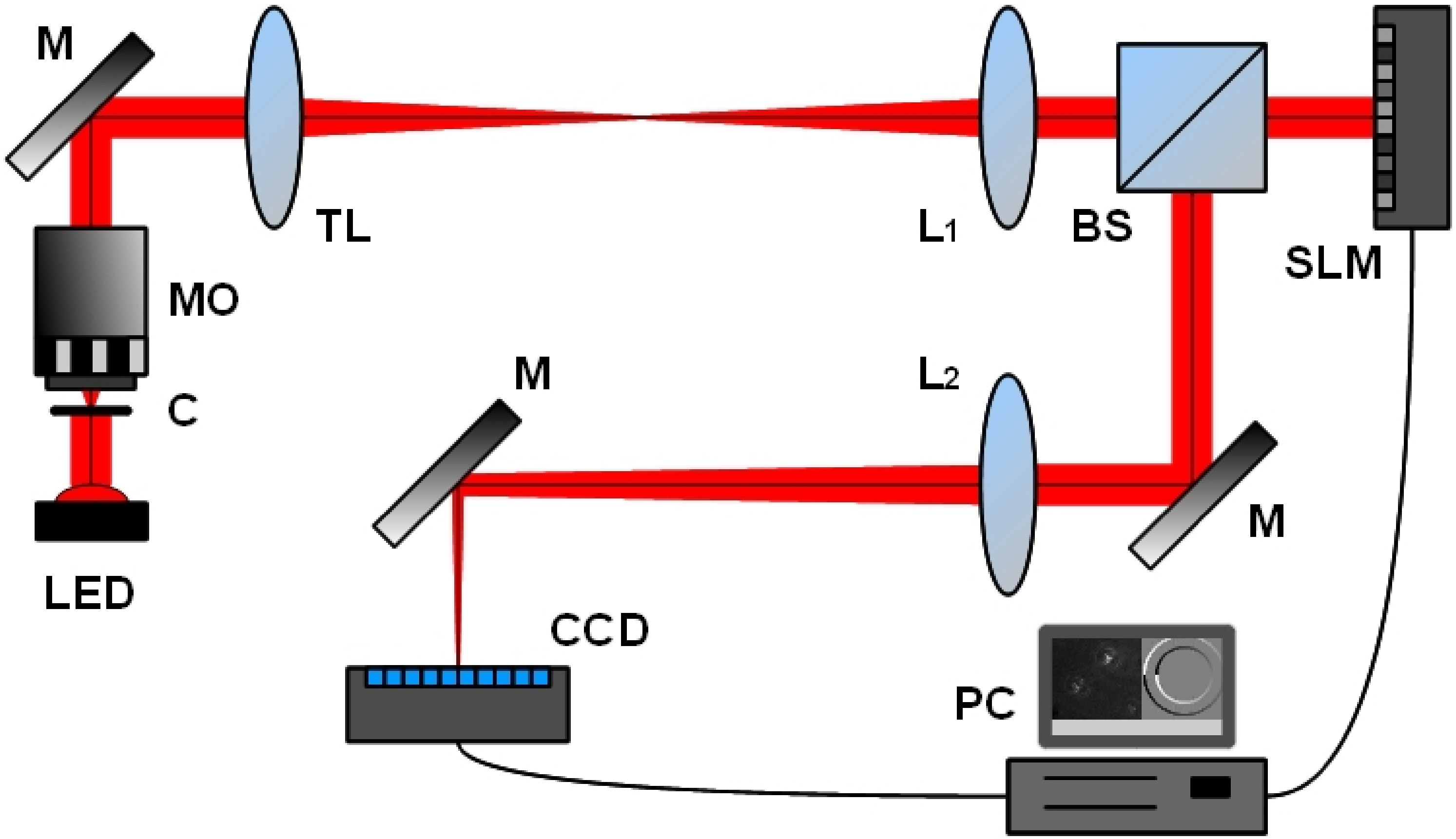
Evaluation of the pinhole axial position

Δz$_1$ **–** pinhole axial position – **set by precise microtranslation.**
Δz$_2$ **–** pinhole axial position – **obtained from rotated image.**



Δz$_1$ **[μm]**	***Δz***$_2$ **[μm]**
-120±1	-118.8±6.1
-80±1	-79.7±7.4
-40±1	-42.0±6.5
40±1	44.5±10.7
80±1	84.8±8.0
120±1	119.4±10.7

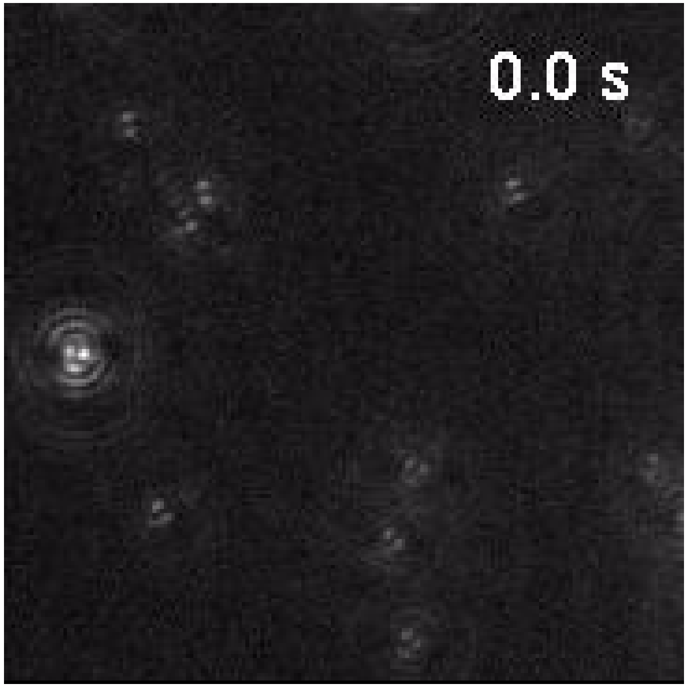
Experimental setup



LED – Thorlabs (625 nm, FWHM 10 nm); **C** – capillary tube with polystyrene beads (1 μm);
MO – microscope objective (Melles Griot 10x, NA = 0.28, f_o = 20 mm); **M** – mirrors;
TL – tube lens (f_t = 200 mm); $\mathbf{L_1}$**,** $\mathbf{L_2}$ – lenses (f_1 = 200 mm, f_2 = 400 mm);
BS – beam splitter; **SLM** – Hamamatsu (X10468, 600x800 pix)

Results

Defocusing rotation of microparticles



Vortex self-imaging applied to 3D localization of freely moving 1 μm polystyrene beads.

M. Baranek, P. Bouchal, M. Siler, Z. Bouchal, Aberration resistant axial localization using a self-imaging of vortices, Opt. Express 23, 15316-15331 (2015).

Conclusions

Summary

New technique for rotating PSF generation was presented.
The advantages of the method are:

- **resistance against aberrations,**
- **localization in a large axial range substantially exceeding the depth of field of the microscope objective used,**
- **shape and size invariance of the PSF during rotation,**
- **possibility to control the rotation sensitivity and the energy efficiency by SLM addressing.**

Outlook

Our future research is focused on application potencial of designed rotating PSF.

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Thank You for Your attention