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Self-imaging of optical vortices for 3D localization and wavefront assessment

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Abstract: The self-imaging of vortices adapted to optical imaging systems is demonstrated and utilized for a long range aberration resistant 3D localization of microscopic objects.
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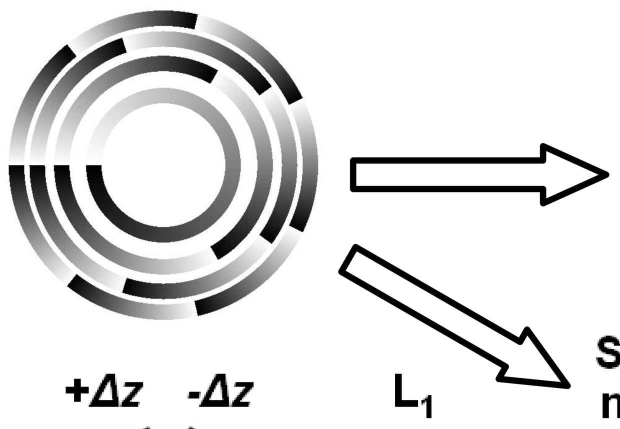
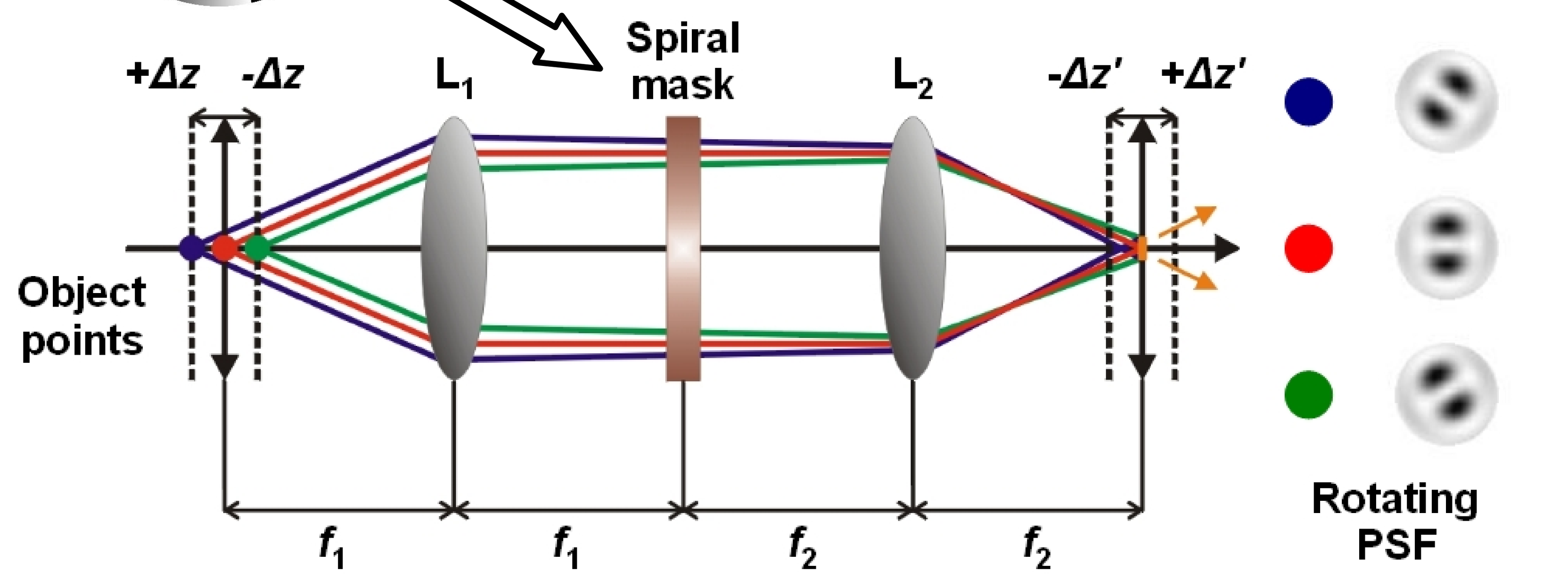
Introduction

The interfering vortex beams, whose intensity profile rotates due to a defocusing, were successfully applied to a depth estimation and particle localization [1-5]. The 3D localization and tracking of fluorescent and transparent beads using the rotating point spread function (PSF) was also successfully demonstrated in the techniques of coherent and incoherent digital holography [6]. In this paper, the self-imaging of vortices is presented and implemented in optical imaging systems to ensure a 3D aberration resistant localization of microscopic objects.

Implementation of vortex self-imaging



M - number of rings
ρ_m - radius of *m*-th ring
l_m - topological charge in *m*-th ring
$\Delta l = l_{m+1} - l_m$



Defocusing rotation of PSF

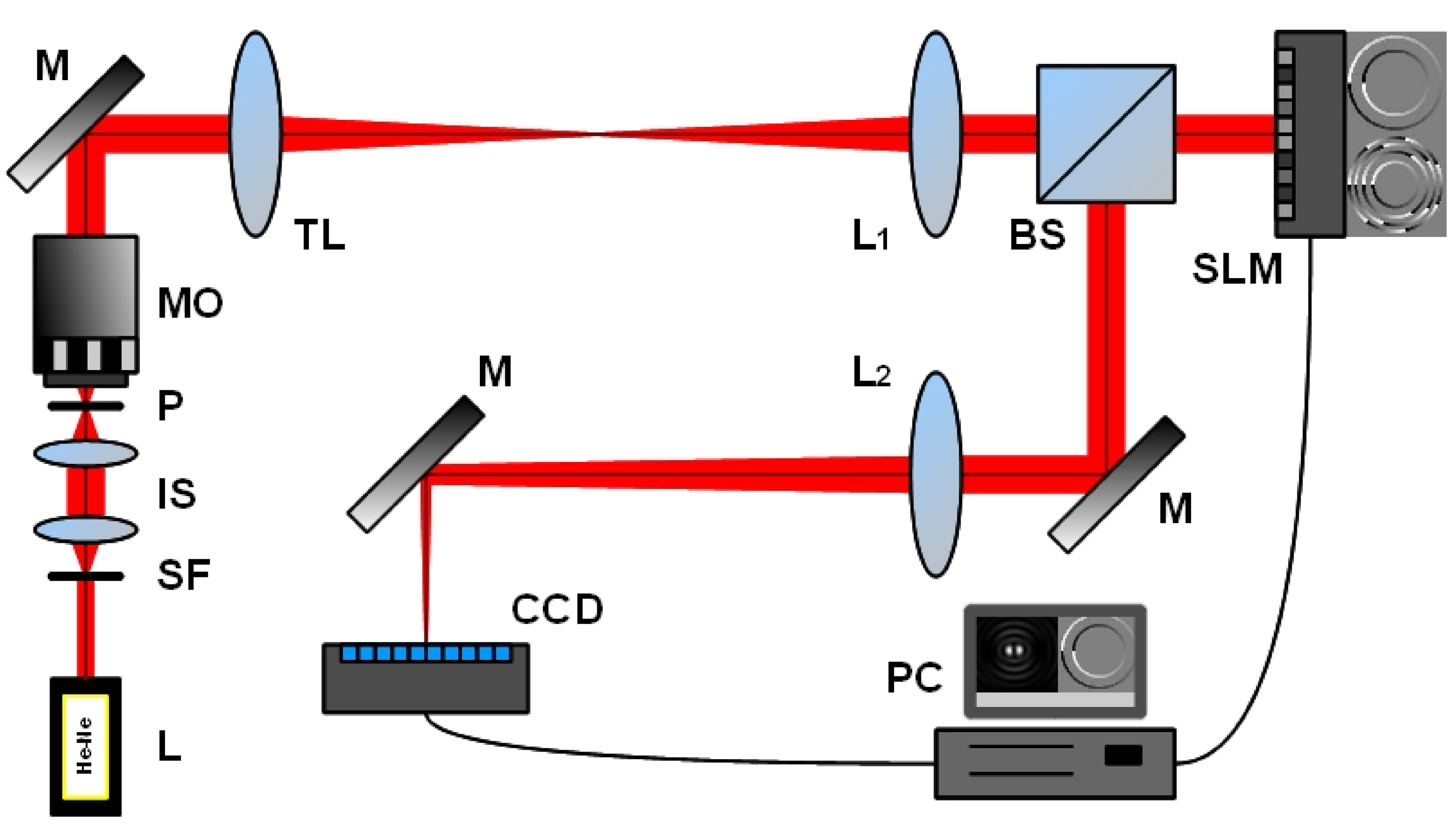
$$\rho_m = \sqrt{\frac{m}{M}}$$ → Self-imaging condition.

$$l_m = l_0 + m\Delta l$$ → Condition of PSF rigid rotation.

Linear rotation of PSF due to defocusing.

$$\frac{d\varphi'}{d\Delta z} = -\frac{kNA^2}{2M\Delta l}$$ → Controlling rotation rate and localization sensitivity.

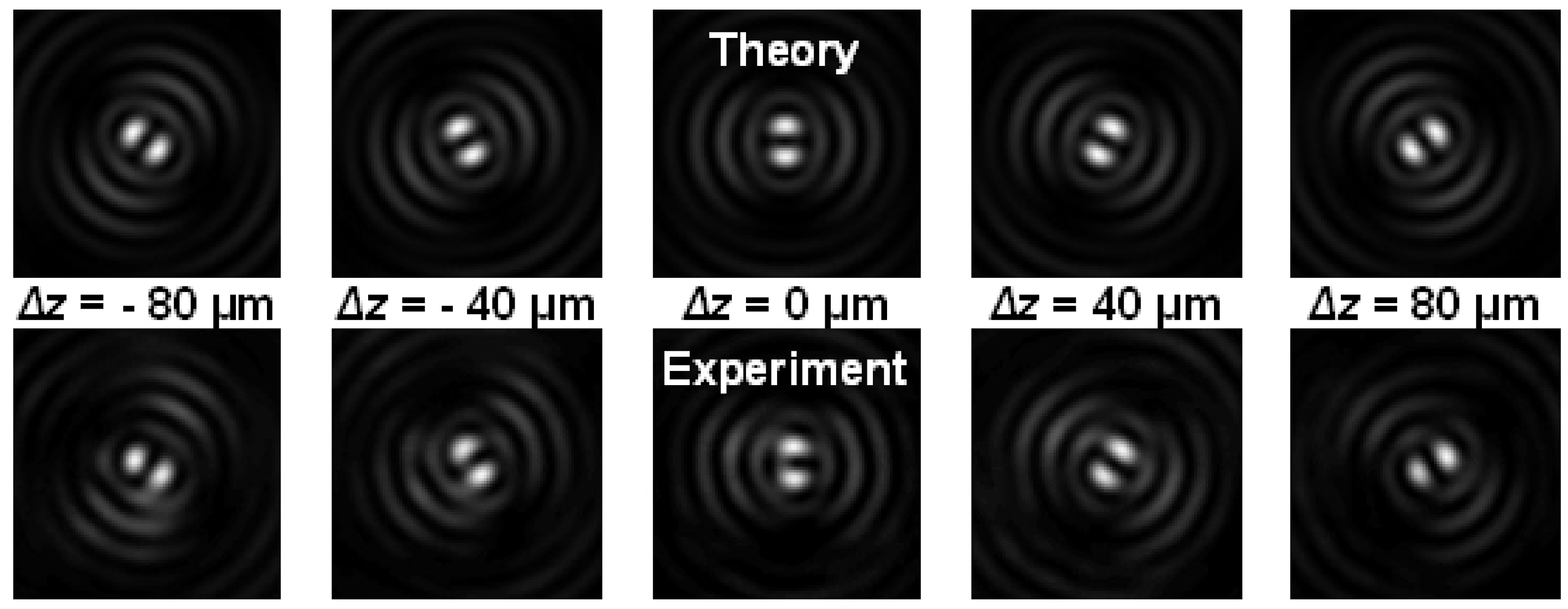
Experimental set-up



L – laser (632.8nm, 20mW), **SF** – spatial filter, **IS** – illumination system, **P** – pinhole (2μm), **MO** – microscope objective (Newport 20x, NA = 0.4, fo = 9mm), **M** – mirror, **TL** - tube lens (f_t = 200mm), **L1** – lens (f_1 = 200mm), **BS** – beam splitter, **SLM** – spatial light modulator (Hamamatsu X10468, 600x800px), **L2** – lens (f_2 = 400mm), **CCD** camera (Olympus F-view II).

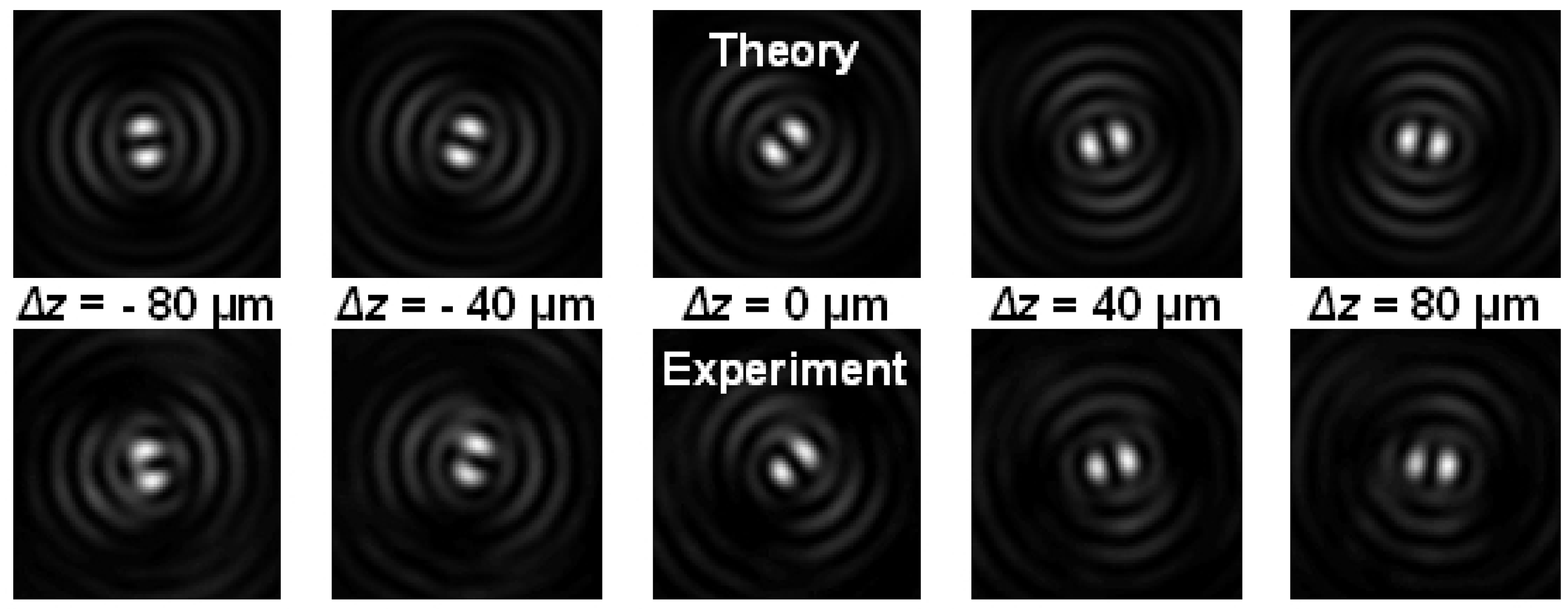
Shape invariant double-helix PSF

λ = 632.8 nm, *NA* = 0.1 (depth of focus 60 μm), l_1 = -1, l_2 = 1, A_{040} = 0 (aberration free case)



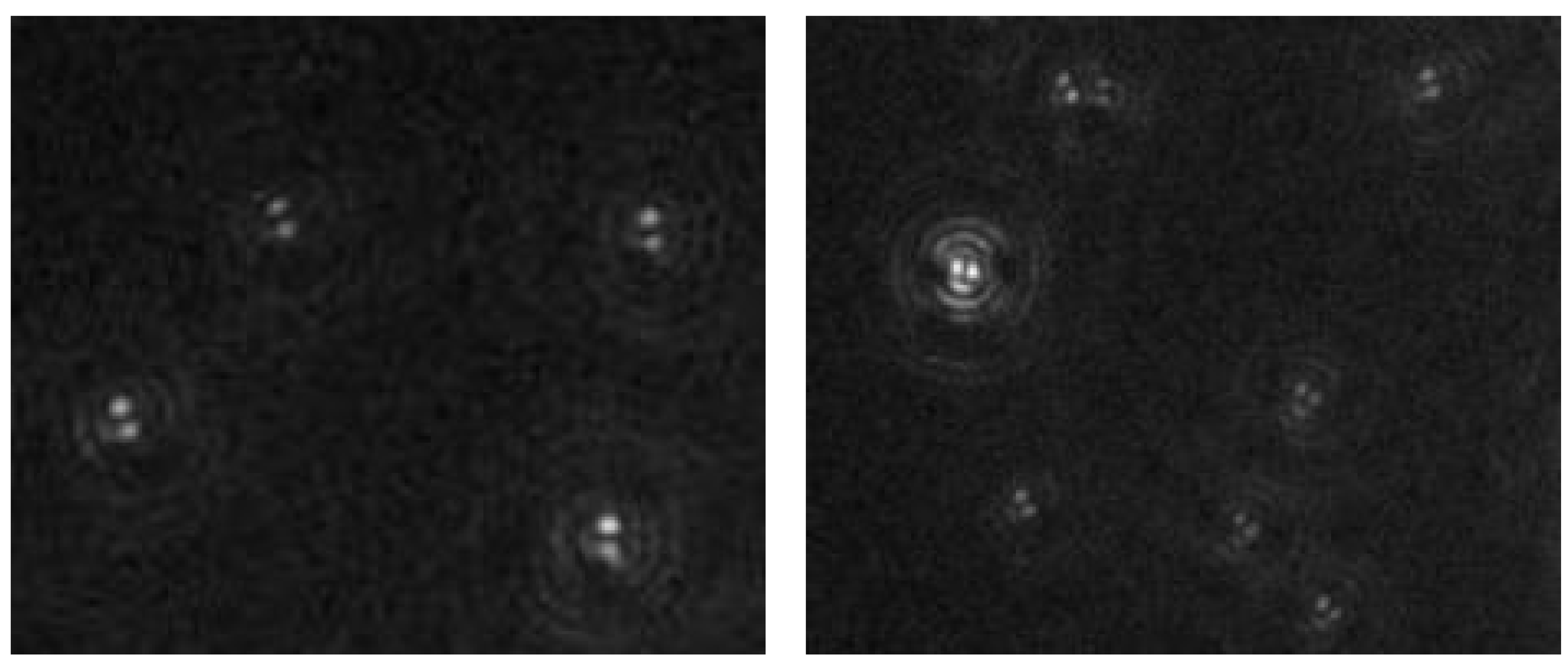
Aberration resistant double-helix PSF

$A_{040} = 0.4\lambda$
(spherical aberration controlably created by SLM)



Spherical aberration causes constant additional rotation only and its effect can be completely eliminated in axial localization.

Defocusing rotation of microparticles



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

Conclusions

The self-imaging of vortices was presented and experimentally demonstrated and its use for the 3D localization of microscopic objects discussed. 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.**

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