Optimizing the rotating point spread function by SLM aided spiral phase modulation

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Outline

1. **Introduction**

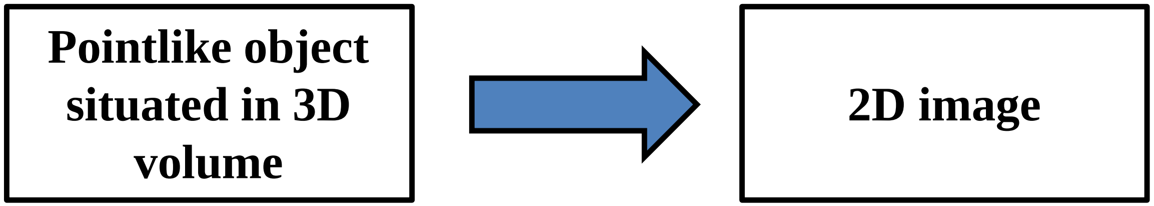
2. New design of the rotating PSF

3. Properties of the rotating PSF

4. Experiment

5. Conclusion

3D particle localization and tracking



How to obtain 3D object position from 2D image?

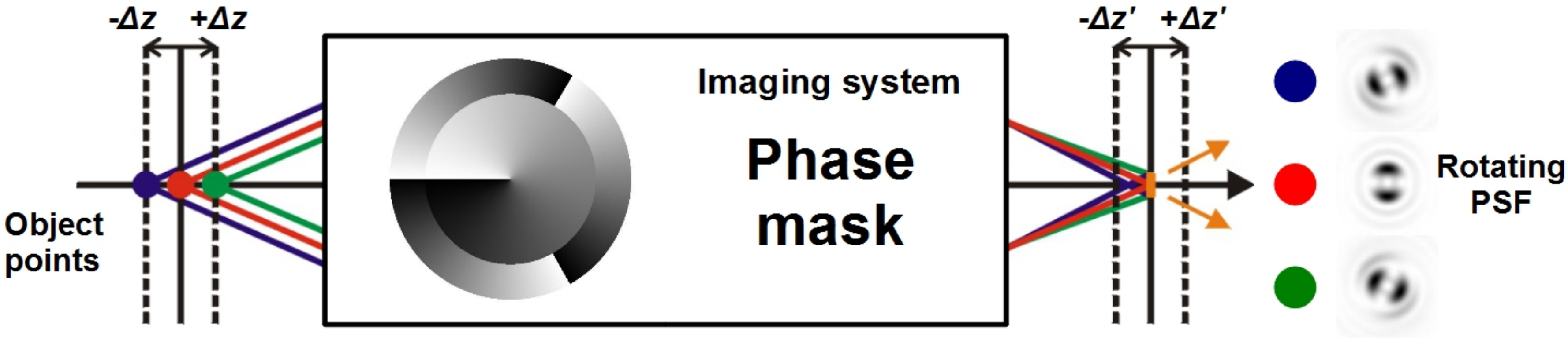
4Pi microscopy
S. Hell, et al., Confocal microscopy with an increased detection aperture: type-B 4Pi confocal microscopy, Optics Letters 19, 222-224 (1994)

Detailed analysis of defocused image
M. Speidel, et al., Three-dimensional tracking of fluorescent nanoparticles with subnanometer precision by use of off-focus imaging, Optics Letters 28, 69-71 (2003)

Introducing of astigmatism by cylidrical lens
H. Kao, et al., Tracking of single fluorescent particles in three dimensions: use of cylindrical optics to encode particle position, Biophysical Journal 67, 1291-1300 (1994)

Rotating point spread function (PSF)
A. Greengard, et al., Depth from diffracted rotation, Optics Letters 31, 181-183 (2006)

Core idea of the rotating PSF



- Image of the object point rotates with defocusing
- Axial position of the pointlike object can be determined from the angle of PSF rotation
- Defocus-induced rotation of PSF can be implemented to standard imaging system by phase modulation

The various methods of rotating PSF implementation

1. Phase mask composed of L-G modes

Double-helix PSF

S. Pavani, et al., Three dimensional tracking of fluorescent microparticles using a photon-limited double-helix response system, Optics Express 16, 22048-22057 (2008)

Corkscrew PSF

M. Lew, et al., Corkscrew point spread function for far-field three-dimensional nanoscale localization of pointlike objects, Optics Letters 36, 202-204 (2011)

2. Sampled spiral phase mask

Azimuthal sampling

M. Baranek, et al., 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, Optics Letters 38, 585-587 (2013)

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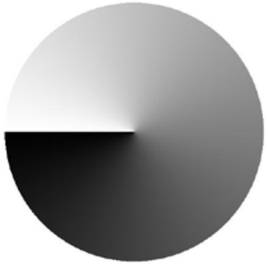
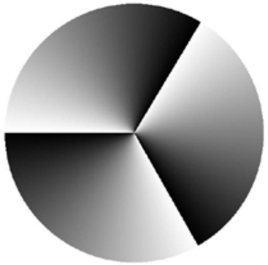
Spiral phase mask parameters

Topological charge – *l*

***l* = 1**



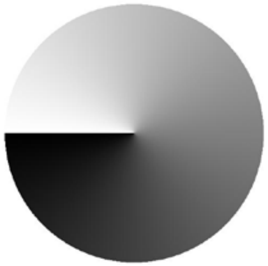
***l* = 3**



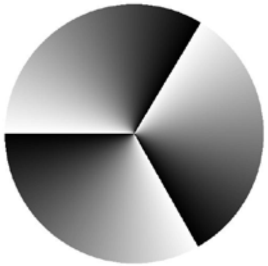
Spiral phase mask parameters

Topological charge – *l*

l **= 1**



l **= 3**



Phase segments number – ***M***

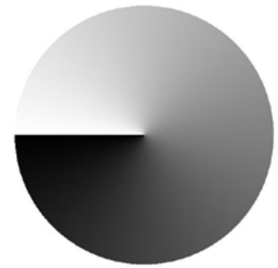
l **= 1**
M **= 8**

l **= 3**
M **= 9**

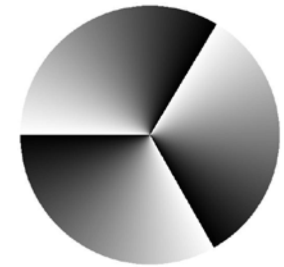
Spiral phase mask parameters

Topological charge – *l*

***l* = 1**



***l* = 3**



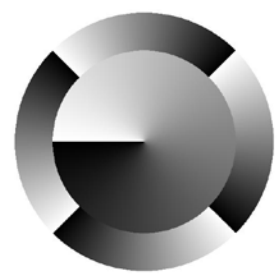
Phase segments number – *M*

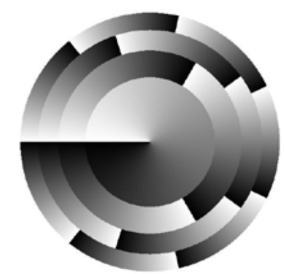
***l* = 1**
***M* = 8**

***l* = 3**
***M* = 9**

Radial zones number – *N*

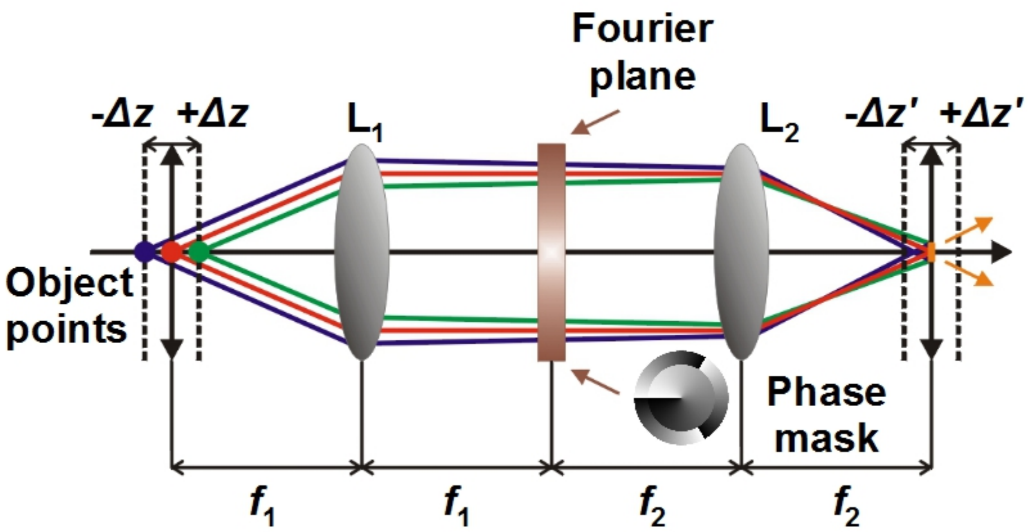
Topological charge
in *n*-th radial zone – l_n





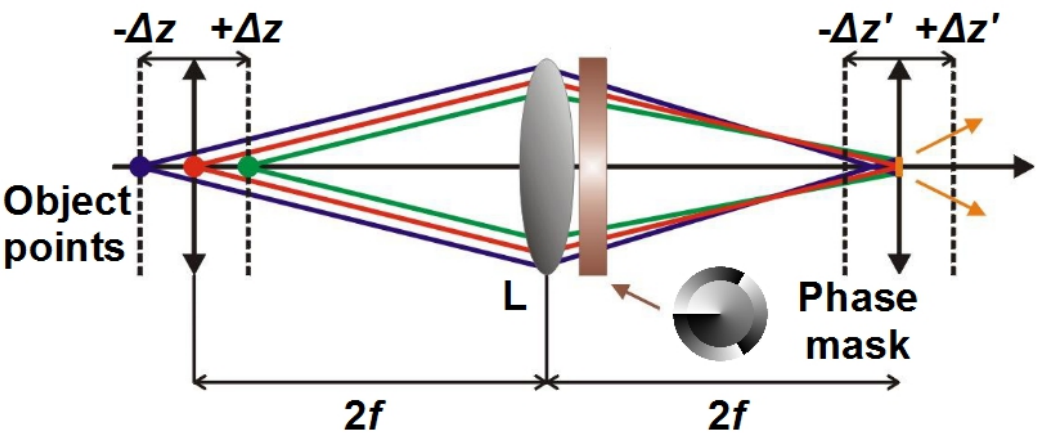
Phase segments number
in *n*-th radial zone – M_n

Theoretical model



4-f optical system

modulation of frequency spectrum



Vortex lens

modulation of complex amplitude

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Computation – continuous azimuthal profile

Optical field in the image plane ↓ | Mask transparency ↓ | Defocus ↓ | Fourier transform term ↓

$$U \propto \int\int_{-\infty}^{+\infty} S(\mathbf{r}_\perp) \exp\left[-i\frac{k\Delta\Phi}{2}|\mathbf{r}_\perp|^2\right] \exp\left[i2\pi\mathbf{r}_\perp \cdot \mathbf{F}'_\perp\right] d\mathbf{r}_\perp,$$

Radial zones approximated to rings

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

$$\alpha = \frac{kR^2\Delta\Phi}{4N}$$

$$I \propto |A|^2 \sum_{n=1}^{N} J_{l_n}^2 + 2|A|^2 \sum_{n=1, n<n'}^{N} \sum_{n'=1}^{N} J_{l_{n'}} J_{l_n} \times \cos\left[(l'_n - l_n)\left(\psi + \frac{\pi}{2}\right) - 2\alpha(n' - n)\right]$$

→ Bessel functions

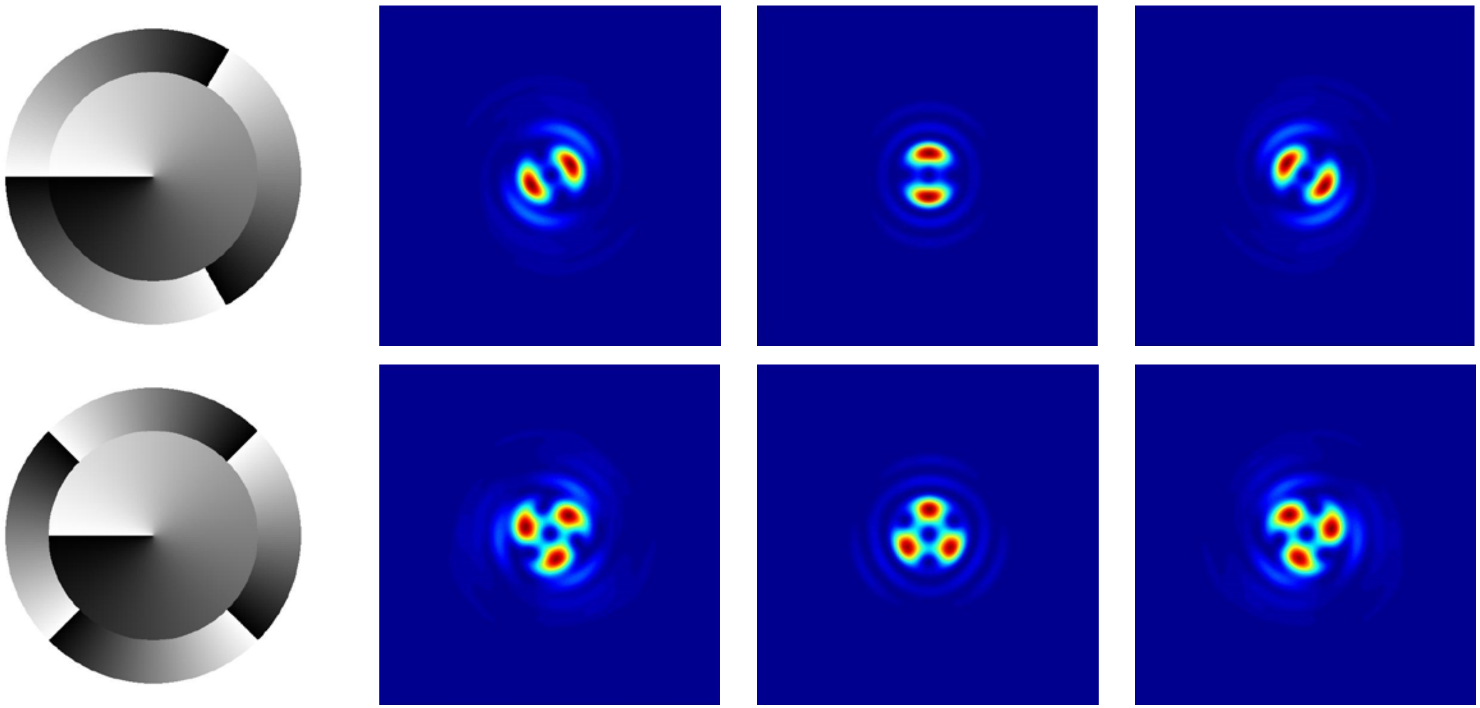
Rotation rate associated to each couple of radial zones

$$\frac{d\psi}{d\alpha} = \frac{2(n' - n)}{l_{n'} - l_n}$$

Topological charge difference between each adjacent radial zones has to be constant

Number of lobes in intensity spot

	Phase mask	PSF (Δz = -80μm)	PSF (Δz = 0)	PSF (Δz = 80μm)



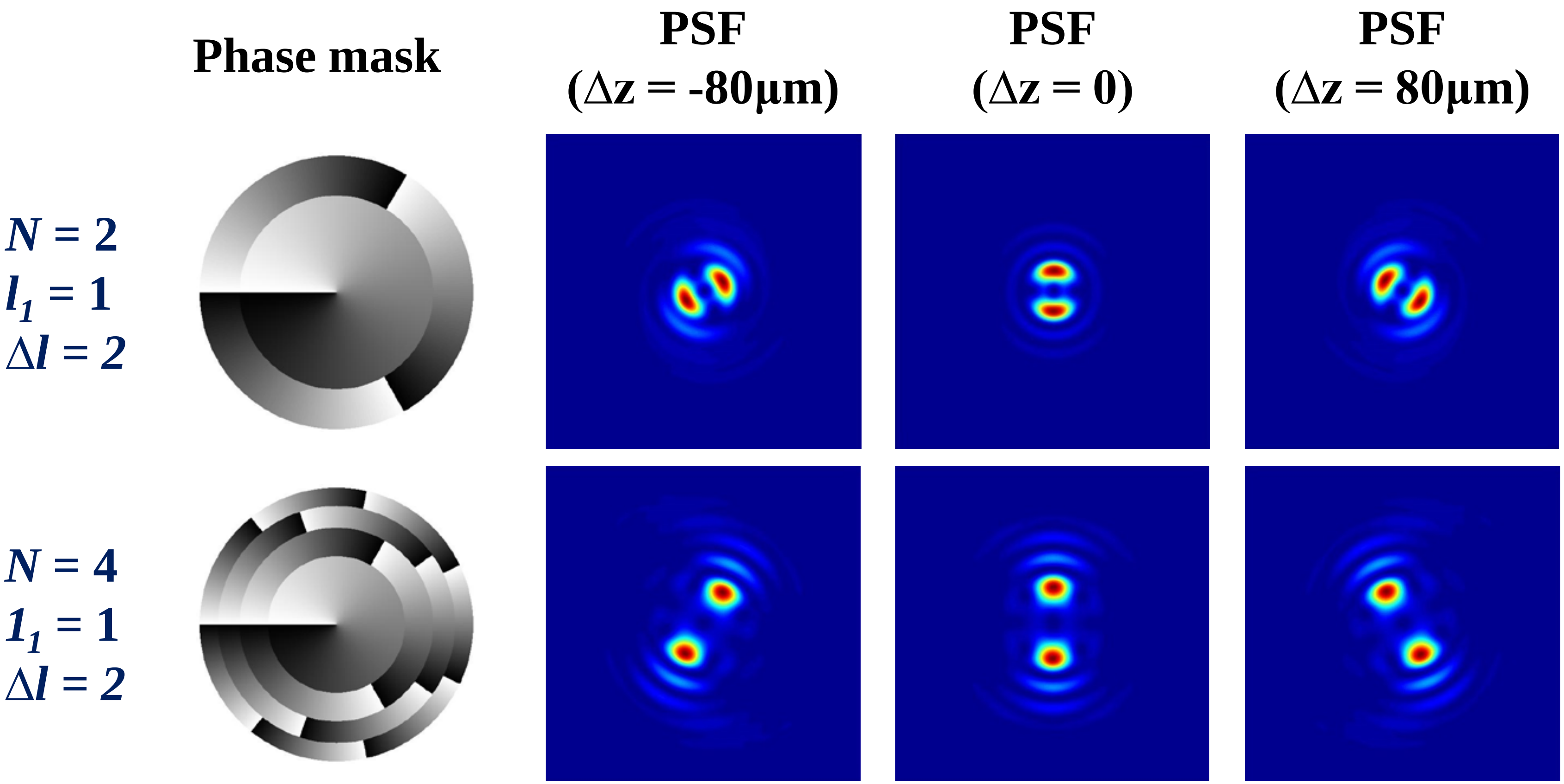
$N = 2$, $l_1 = 1$, $\Delta l = 2$

$N = 2$, $l_1 = 1$, $\Delta l = 3$

Number of lobes in intensity spot is fully determined by parameter Δl

$$I \propto |A|^2 \sum_{n=1}^{N} J_{l_n}^2 + 2|A|^2 \sum_{n=1,n<n'}^{N} \sum_{n'=1}^{N} J_{l_{n'}} J_{l_n} \times \cos\left[(l_n' - l_n)\left(\psi + \frac{\pi}{2}\right) - 2\alpha(n' - n)\right]$$

Rotation rate



Rotation rate can be controlled by spiral mask parameters N and Δl

$$\frac{d\psi}{d\Delta z} = \frac{\pi NA^2}{\lambda N \Delta l}$$

Computation – sampled azimuthal profile

Optical field in the image plane	Mask transparency	Defocus	Fourier transform term
↓	↓	↓	↓

$$U \propto \int\int_{-\infty}^{+\infty} S(\mathbf{r}_\perp)\exp\left[-i\frac{k\Delta\Phi}{2}|\mathbf{r}_\perp|^2\right]\exp\left[i2\pi\mathbf{r}_\perp\cdot\mathbf{F}'_\perp\right]d\mathbf{r}_\perp,$$

Discrete spiral mask expressed as combination of continuouses masks

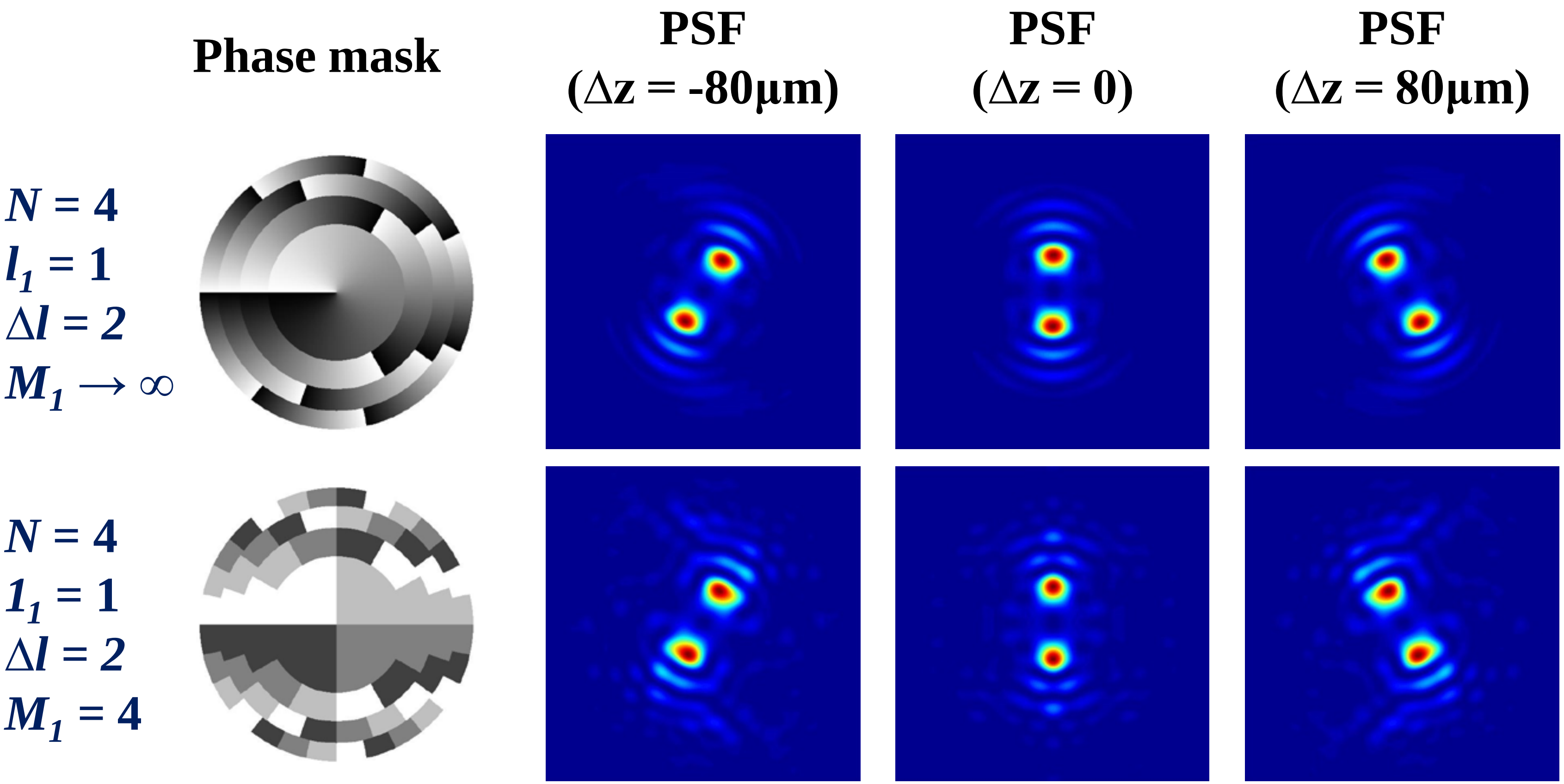
Ch. S. Guo, et al., Optimal phase steps of multi-level spiral phase plates, Opt. Commun. 268, 235-239 (2006)

$$I \propto |A|^2\sum_{n=1}^{N}|c_{l_n}|^2 J_{l_n}^2 + 2|A|^2\sum_{n=1,n<n'}^{N}\sum_{n'=1}^{N}|c_{l_n}c_{l_{n'}}|J_{l_n}J_{l_{n'}}$$
$$\times\cos\left[\left(\psi+\frac{\pi}{2}\right)(l_{n'}-l_n)+\pi\left(\frac{l_{n'}}{M_{n'}}-\frac{l_n}{M_n}\right)-2\alpha(n'-n)\right]$$

↓ Additional rotating

Condition $M_n=M_1(l_n/l_1)$ has to fulfilled to elimination of additional rotation

Influence of azimuthal sampling



Azimuthal sampling does not significantly affect key rotating PSF properties, if condition $\dfrac{l_n}{l_1} = \dfrac{M_n}{M_1}$ is valid

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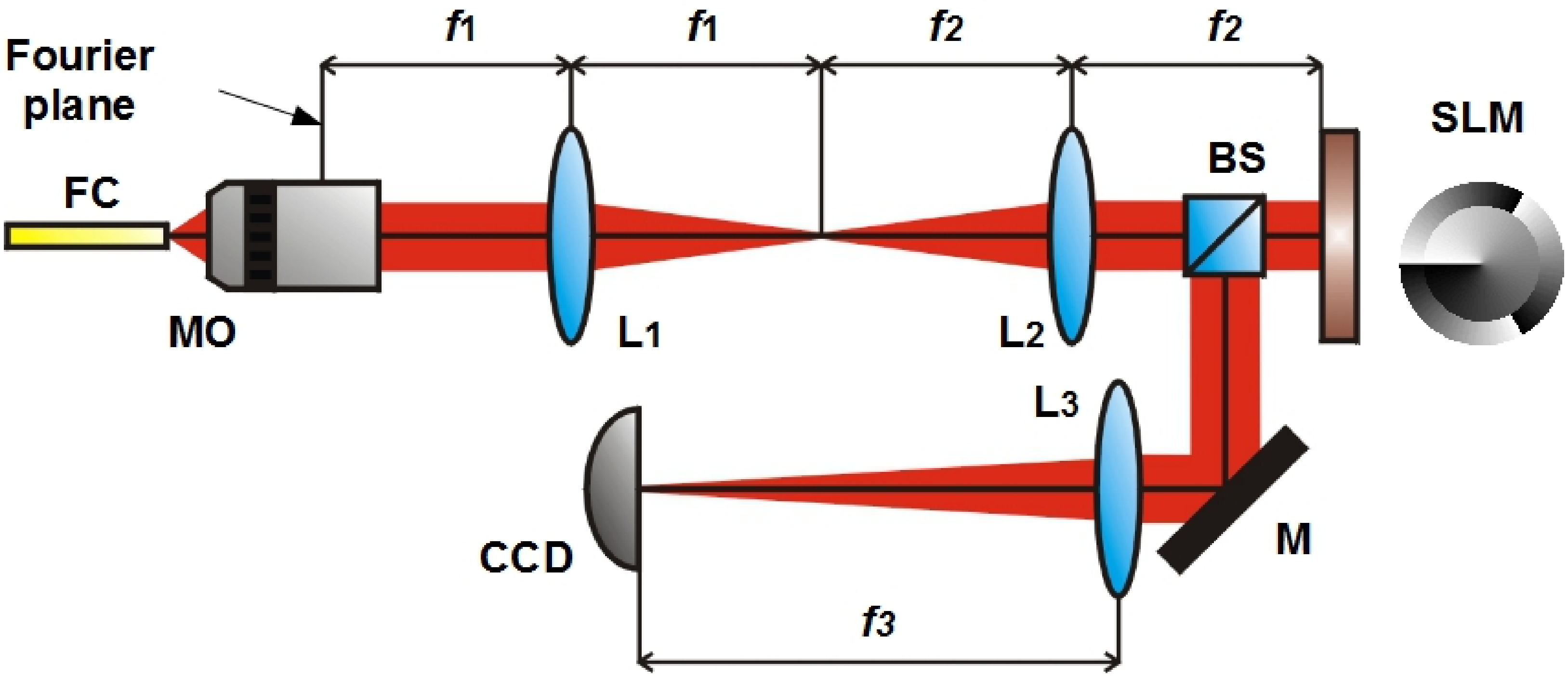
Experimental setup



Experiment:

He-Ne laser (20 mW, 632.8 nm);

MO – microobjektive (Melles Griot-OVI, 50x, NA = 0.55);

SLM – Boulder (512x512 px);

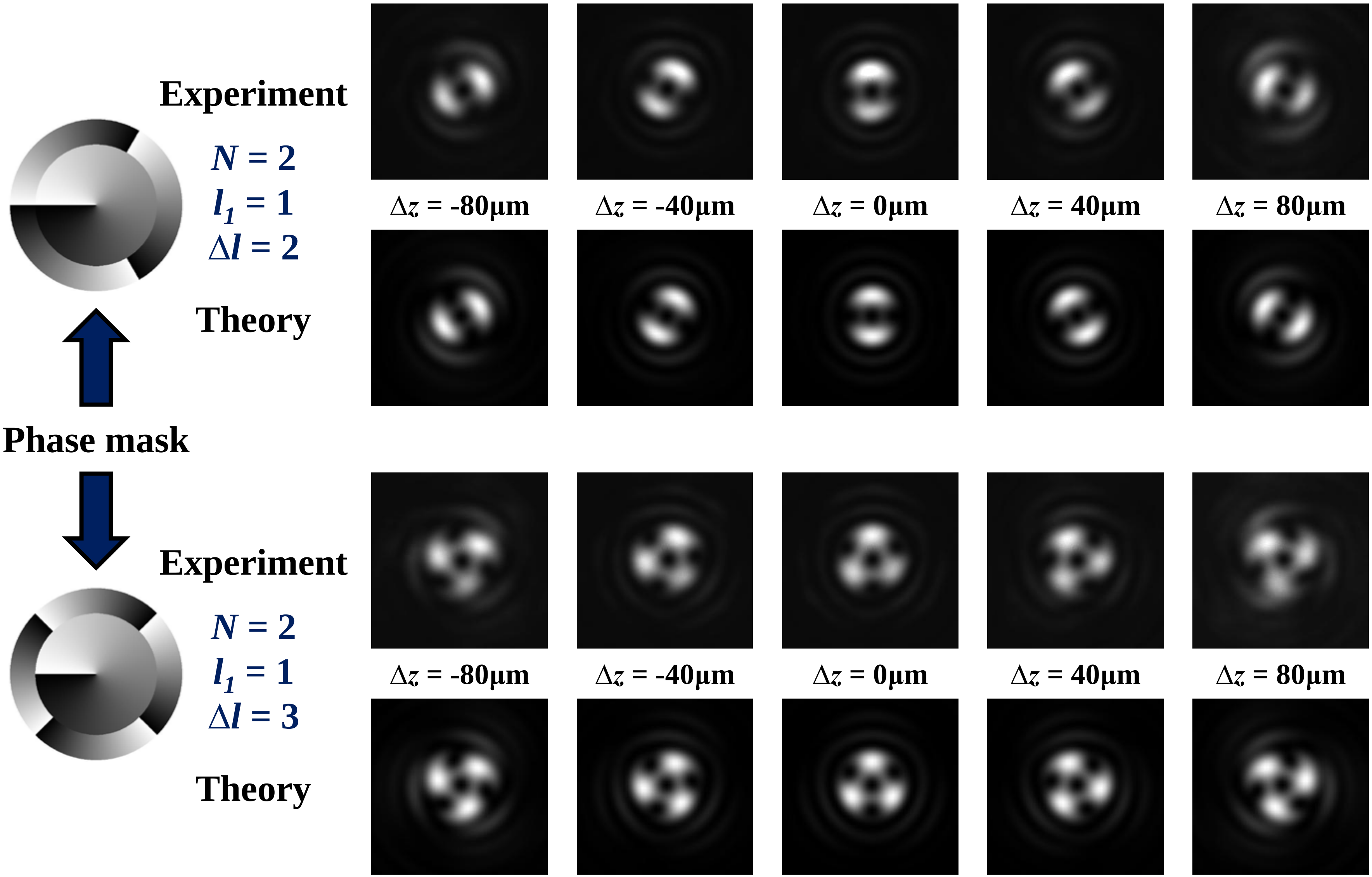
L_1, L_2, L_3 – lenses (f_1 = 200 mm, f_2 = 200 mm, f_3 = 400 mm)

FC – fiber core (NA = 0.1)

BS – beam splitter

M – mirror

Experimental results



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Summary

We presented the new method for rotating PSF generation

- Presented technique has high energy efficiency and can be easily implemented to standard imaging systems
- The PSF was described mathematicaly in dependence on the parameters of the spiral mask
- PSF transverse profile and rotation rate can be controlled by two independent parameters of the phase mask
- Continuous azimuthal change of the helical phase profile can be satisfactorily replaced by just a few phase levels used in practical implementation

Outlook

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

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Thank You for Your attention