Experimental Study on Optical Vortex from a Helical Undulator at UVSOR-III

M. Hosaka

（Nagoya University, Japan）

IPAC16

UVSOR-III storage ring

Collaborators

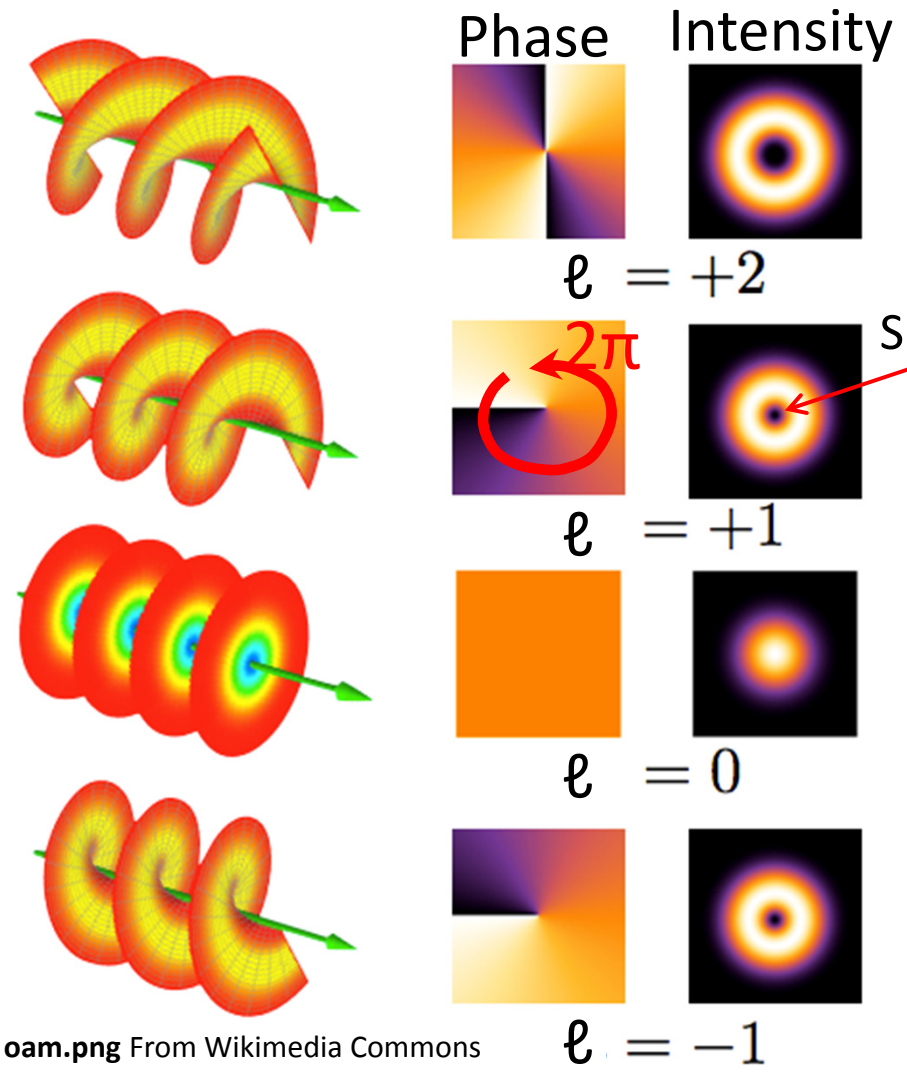
- M. Katoh, N. S. Mirian (UVSOR, IMS)
- N. Yamamoto, T. Konomi (KEK)
- K. Kuroda (ISSP, U. Tokyo)
- A. Miyamoto (Toshiba Co.)
- S. Sasaki, K. Miyamoto (Hiroshima U.)

Outline

- Introduction: Vortex of Lasers
- Optical Vortex from Helical Undulator
- Interference of two Undulators Experiment
- Diffraction Experiments（double slit and knife edge）
- Summary

Introduction: Vortex of Lasers

Studies on optical vortex are originally started with lasers.



Optical vortex is EM wave having vortex wave-front.

Topological Charge : ℓ
phase variation along a closed curve (divide by 2π).

File:Helix oam.png From Wikimedia Commons

Introduction: Vortex of Lasers

Solution of Maxwell equation :

Laguerre-Gauss mode (azimuthal index: l):

$$u_{l,p}(r,\phi,z) = \sqrt{\frac{2p!}{\pi(p+|l|!)}}\left(\frac{\sqrt{2}r}{w(z)}\right)^{|l|} \cdot L_{|l|}^{p}\left[\frac{2r^2}{w(z)^2}\right]$$

$$\cdot \frac{w_0}{w(z)} \exp\left[-\frac{r^2}{w(z)^2}\right] \cdot \exp[il\phi]$$

azimuthal phase dependence

ϕ: azimuthal angle

$$\cdot \exp\left[-i\left(1+2p+|l|\right)\right] \cdot \tan^{-1}\left(\frac{z}{z_R}\right) \cdot \exp\left[-i\frac{kr^2}{2R(z)}\right]$$

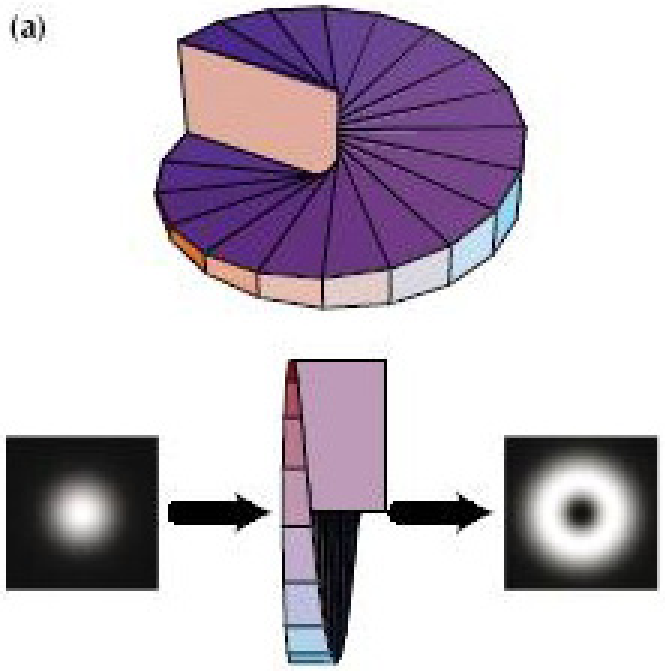
Topological charge: l

Allen et al. , Phys. Rev. A45, 8183-819 (1992).

Optical vortex beam carries orbital angular momentum $l\hbar$ per photon.

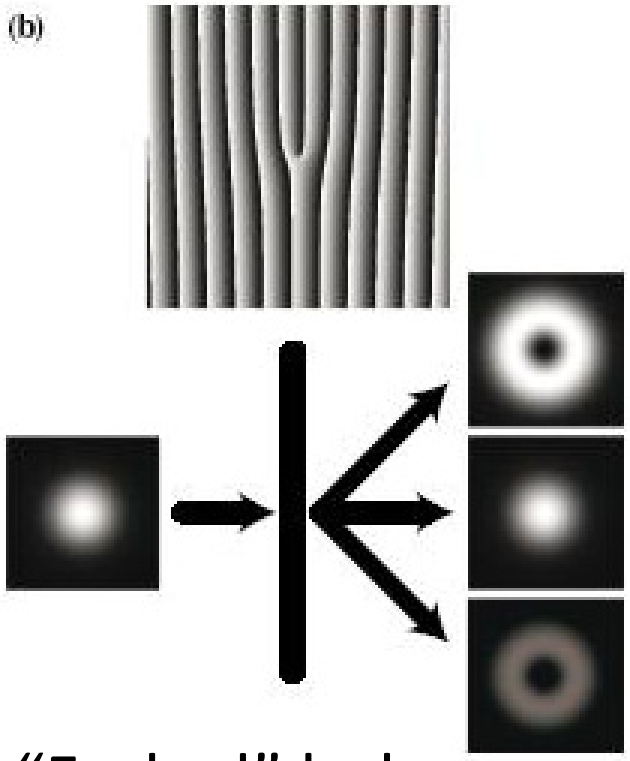
A lot of studies on optical vortex using lasers have been carried out.

Generation of Vortex of Lasers



Spiral phase plate

:Optical media with azimuthal dependence in thickness.



“Forked” hologram

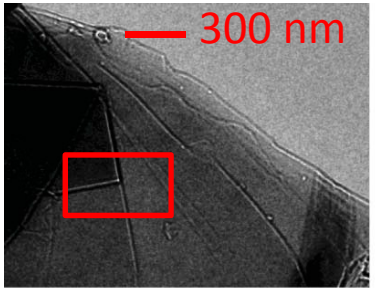
J. Courtial, et. al, Eur. Phys. J. Special Topics 145, 35 (2007)

Vortex Beams

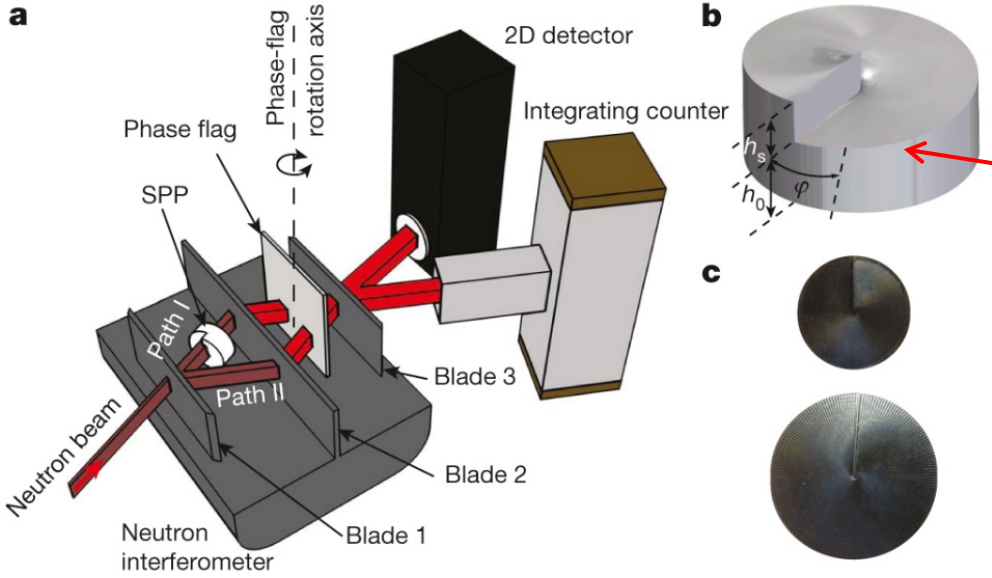
- X-ray vortex beam A.G. Peele, et al. Opt. Lett. **27,** 1752 (2002)
- Electron vortex beam from 300 keV TEM

M. Uchida& A. Tonomura, Nature **464**, 737 (2010)

Graphite film as a phase plate →



- Neutron vortex beam from a reactor

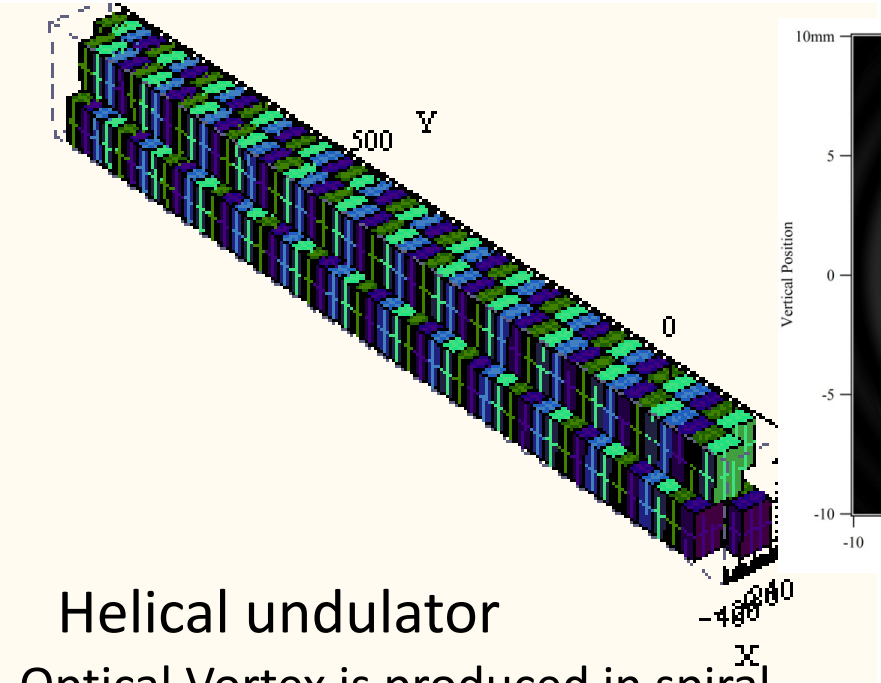


C.W. Clark at al. , Nature **525**, 505 (2015)

Spiral phase plate

Optical Vortex from Helical Undulator

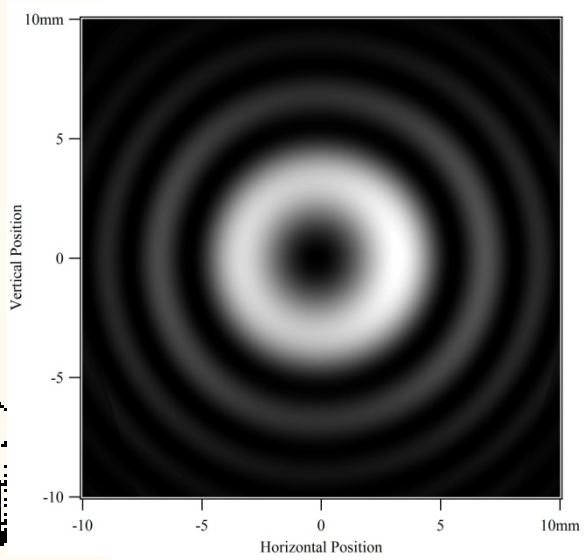
Sasaki &McNulty predicted harmonics from a helical undulator is optical vortex. (PRL 100,12481 (2008))



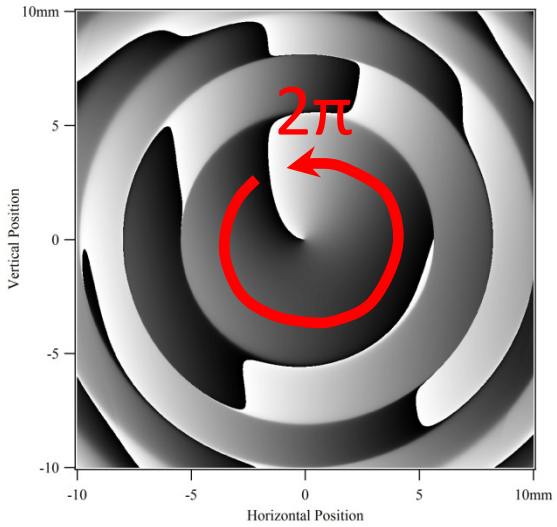
Helical undulator

Optical Vortex is produced in spiral motion of a relativistic electron.

No Spiral phase plate is needed.



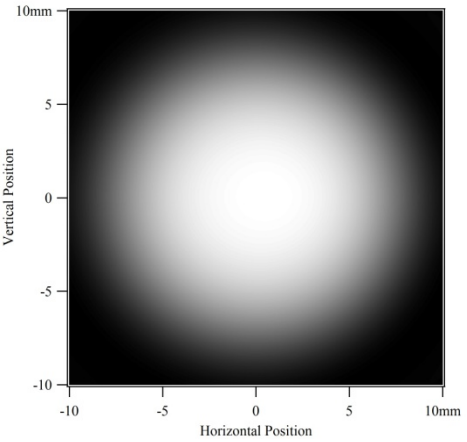
Intensity distribution of 2nd harmonics

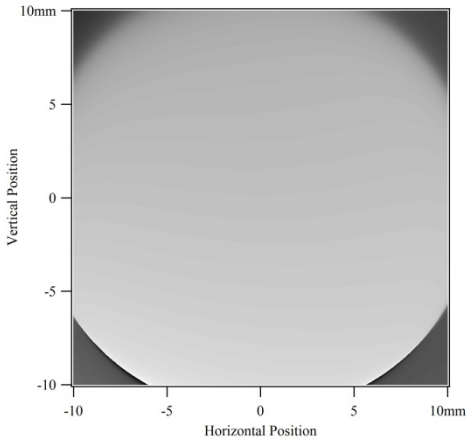


Phase distribution of 2nd harmonics

Simulation using a code SRW :
http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/SRW

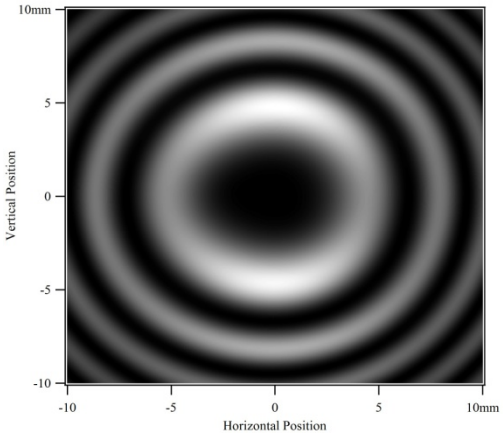
Optical Vortex from Helical Undulator
(SRW calculation)

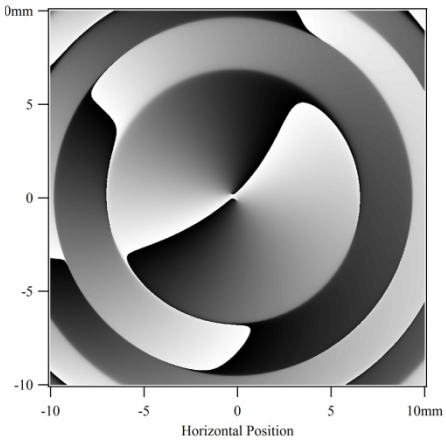




Fundamental: Topological charge : ℓ = 0,

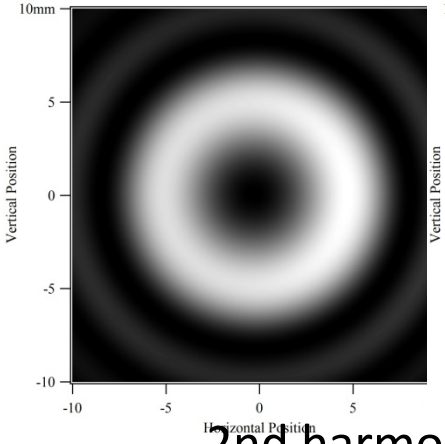
Intensity Phase

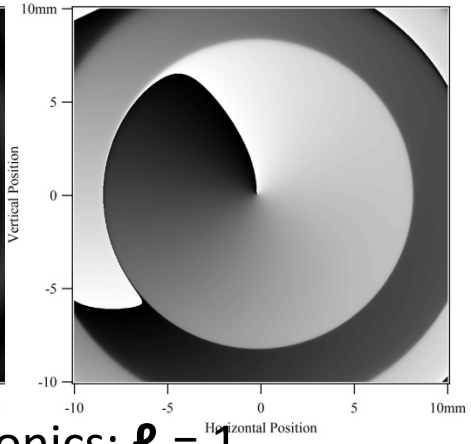




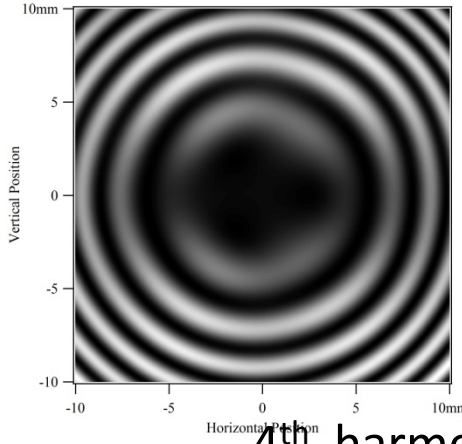
3rd harmonics: ℓ = 2

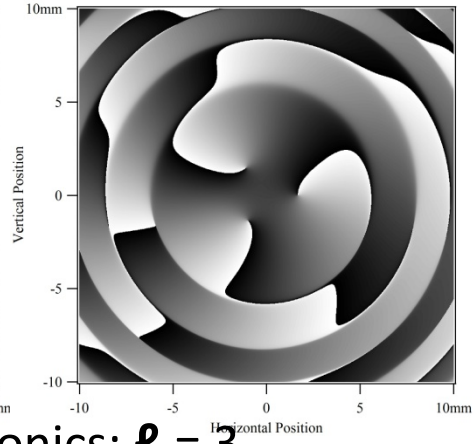
Intensity Phase





2nd harmonics: ℓ = 1



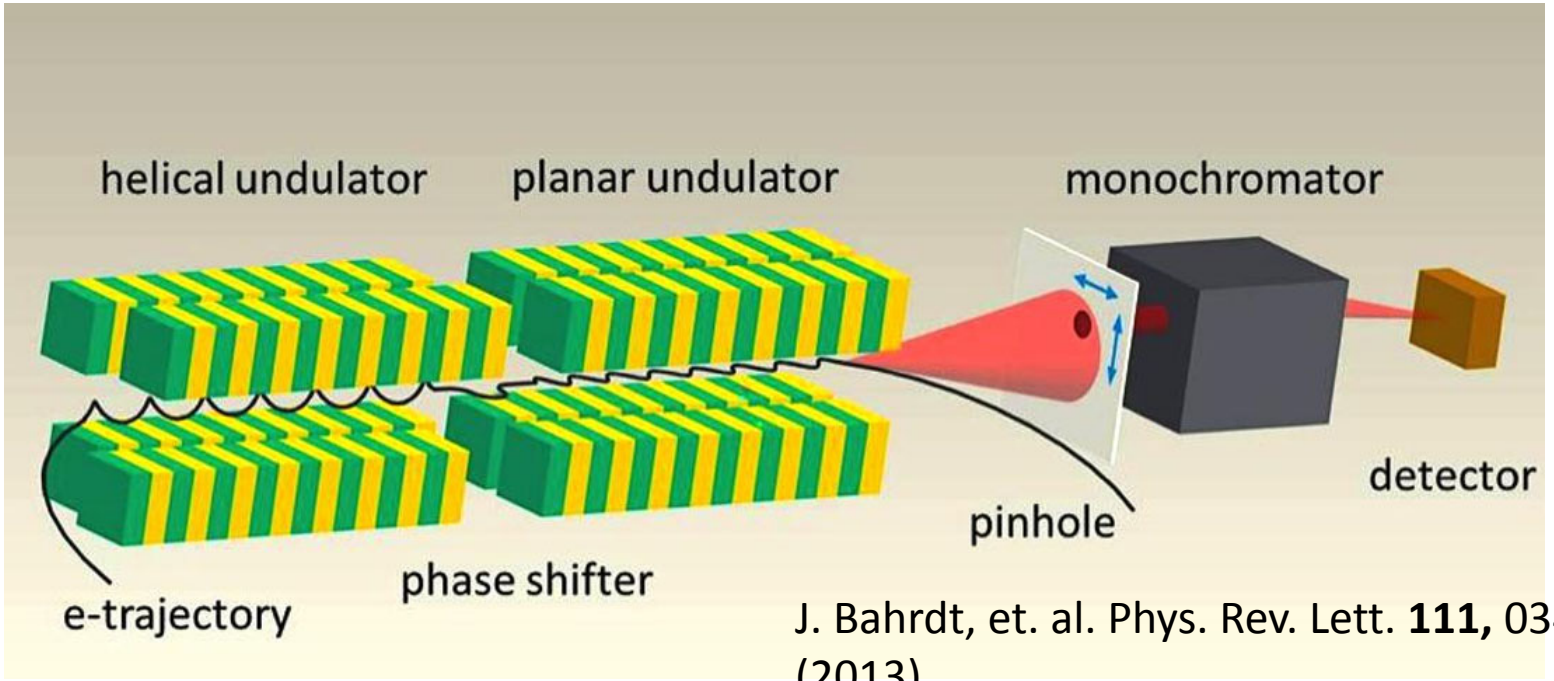


4th harmonics: ℓ = 3

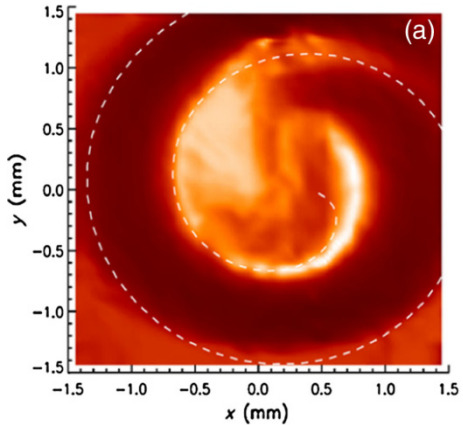
ℓ = order of harmonics -1

An ideal thins lens is used for this calculation.

First Observation of Optical Vortex in Helical Undulator Radiation



J. Bahrdt, et. al. Phys. Rev. Lett. **111,** 034801 (2013).



BESSY II storage ring: E = 917 MeV

Measured spiral pattern from double undulator interference.
Photon energy : 99 eV
Detail will be explained later.

Experiment at UVSOR-III

- Interference of two undulators experiment.
- Diffraction experiment.

E = 500 MeV or 400 MeV
(nominal energy 750 MeV)

Emittance < 8 nm-rad .

Diffraction limited in UV region (> 100 nm).

UVSOR-III storage ring

Interference of Two Undulators at UVSOR-III

- **Phase distribution of vortex can not be observed directly**
  -> Interference of two undualtors was observed.

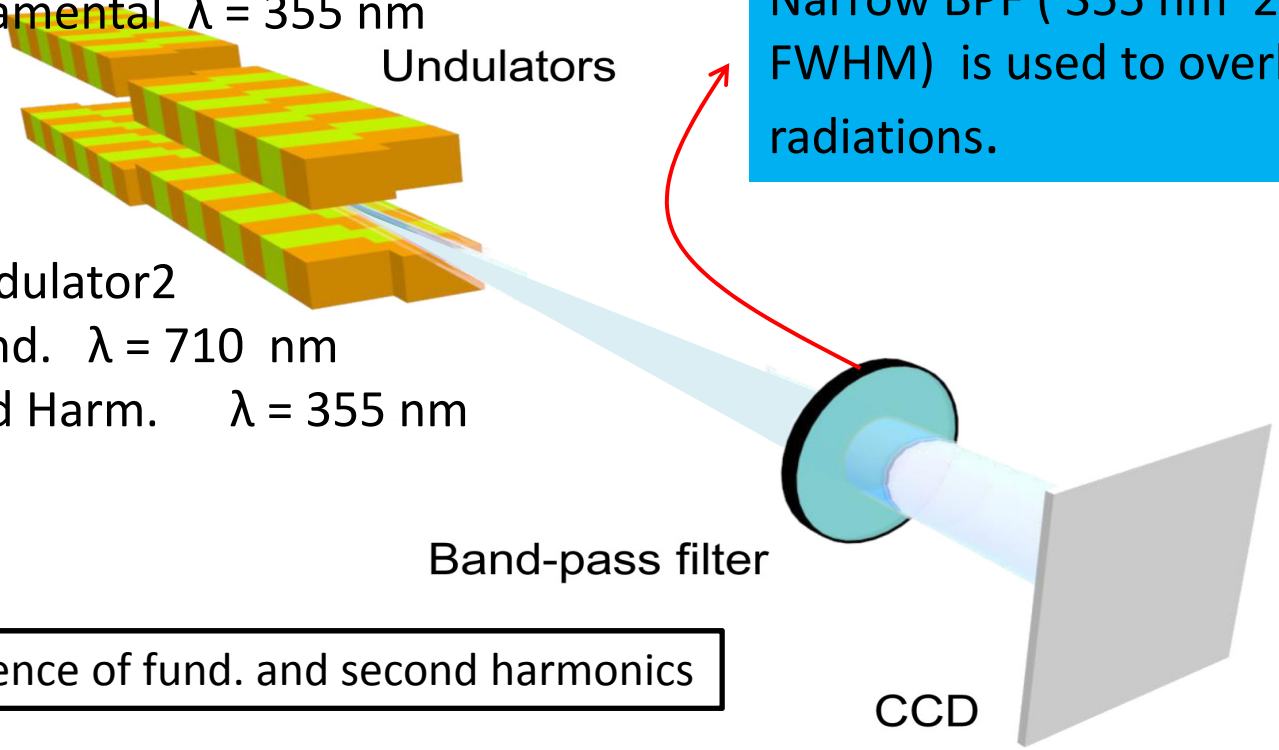
Undulator 1
fundamental λ = 355 nm

Undulators

Double Apple-II undulators

Undulator2
Fund. λ = 710 nm
2nd Harm. λ = 355 nm

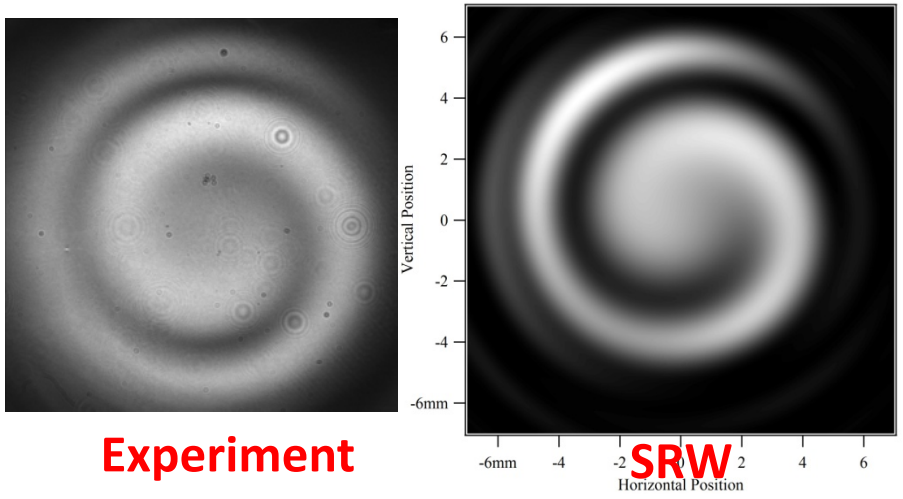
Narrow BPF (355 nm 2.2 nm-FWHM) is used to overlap radiations.



Interference of fund. and second harmonics

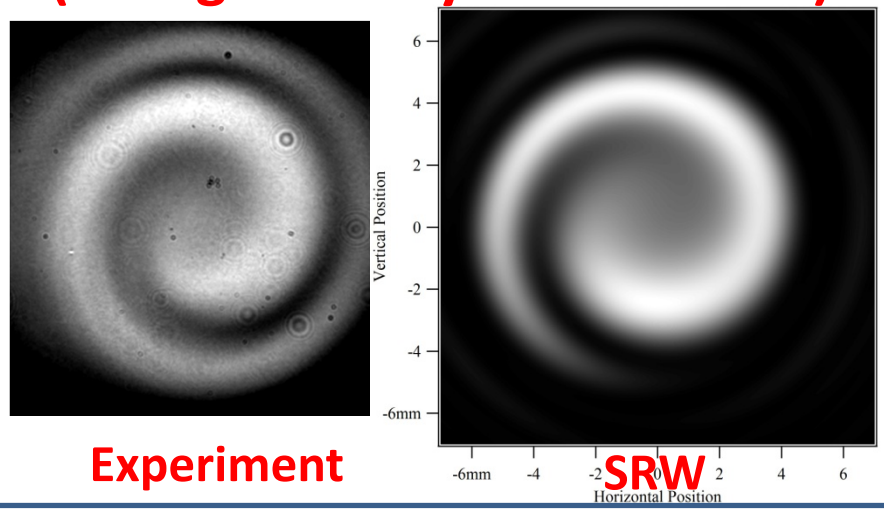
Interference of Two Undulators – results-

ℓ= 0&ℓ= 1



Experiment SRW

ℓ= 0&ℓ= -1
(change helicity of undulator)



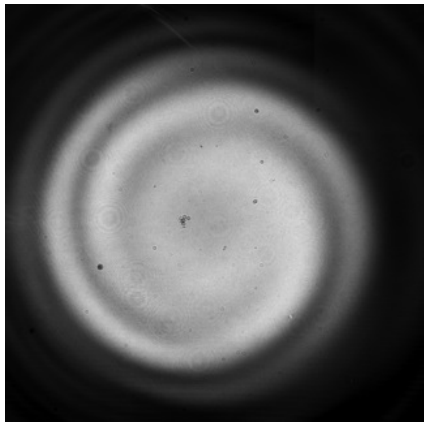
Experiment SRW

Interference of fund. and 2nd harmonic radiation (**ℓ** = 0, 1).

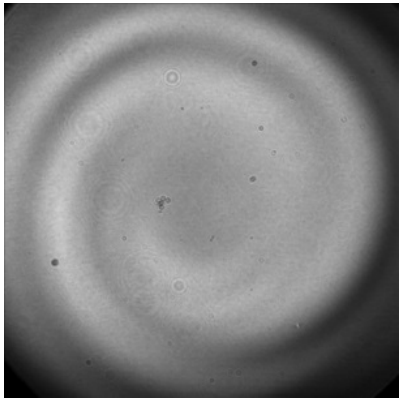
- Single spiral pattern from phase rotation of vortex (**ℓ** = 1) was observed.
- Changing helicilty of the helical undulator, inverse spiral patter was observed.
- SRW calculation reproduces the experiment very well.

Interference of Two Undulators –results-

ℓ= 0&ℓ= 2



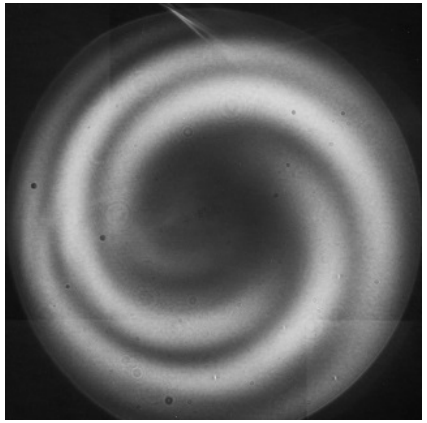
ℓ= 0&ℓ= -2



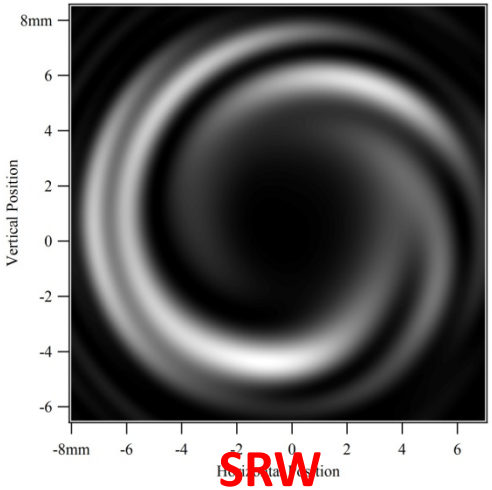
E = 400 MeV

Interference of fund. and 3rd harmonics.
Double spiral pattern was observed from phase rotation of vortex (**ℓ** = 2).

ℓ= 1&ℓ= -2



Experiment



SRW

Triple spiral pattern was observed in interference of 2nd and 3rd harmonics, with opposite helicity.
SRW reproduces the result.

Diffraction experiment (double slit) at UVSOR-III

Diffraction experiment: another possible technique to observe peculiar phase distribution of vortex.

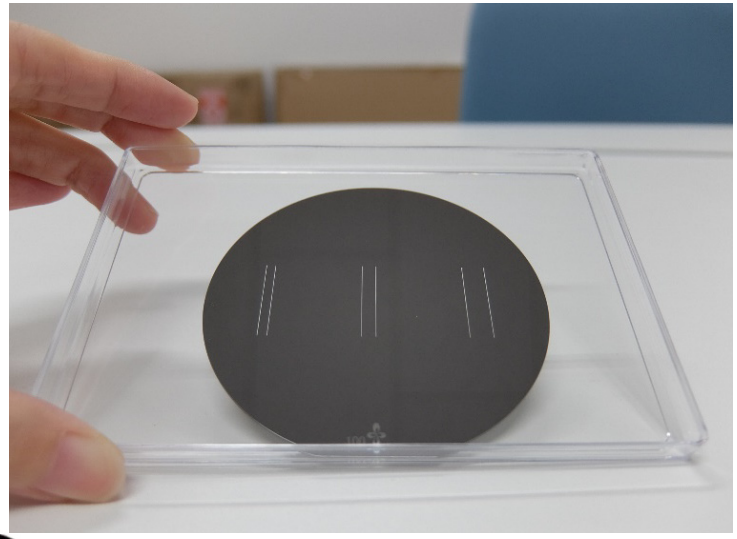
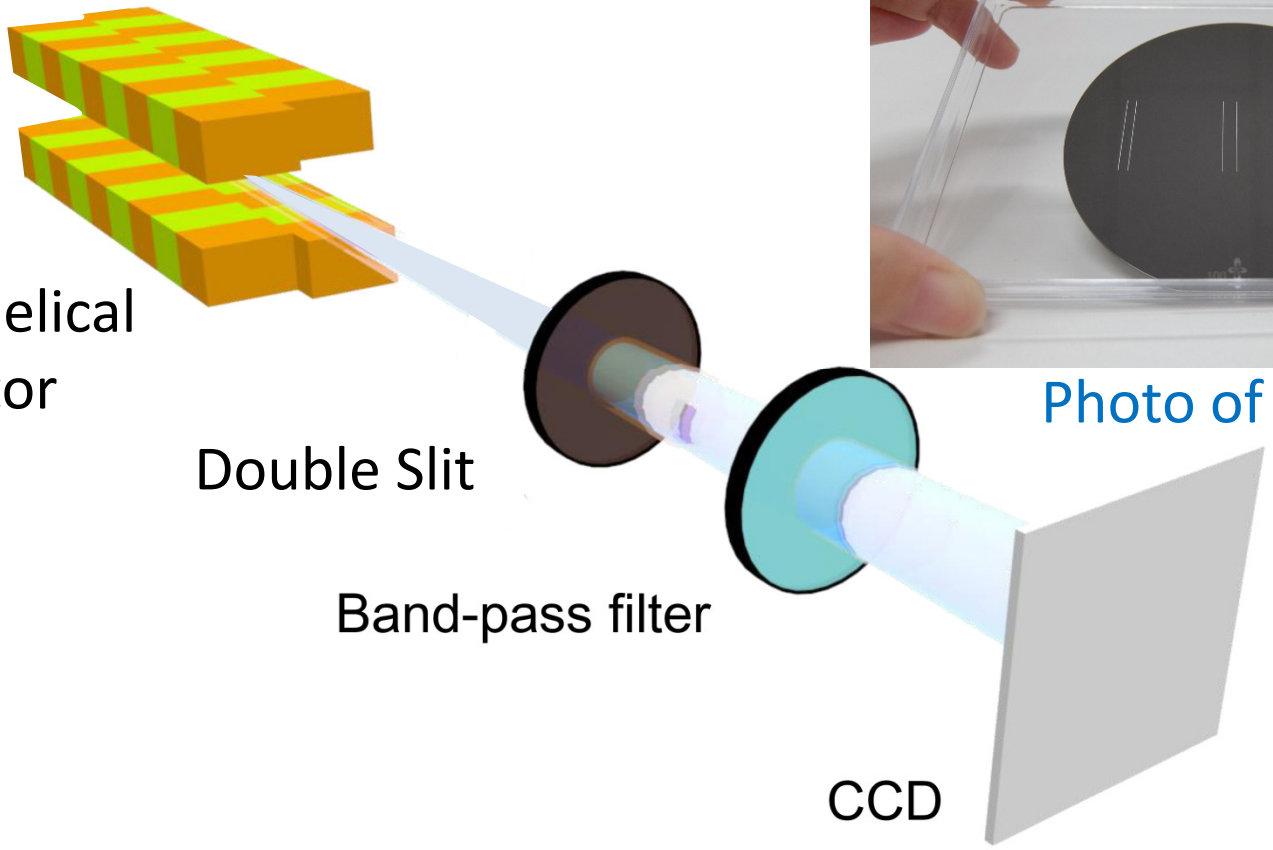
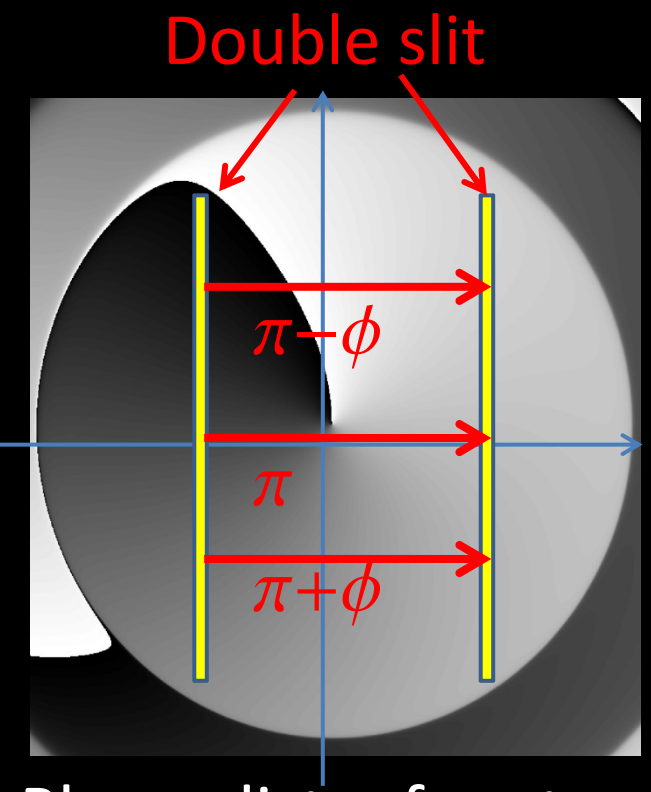


Photo of double slit

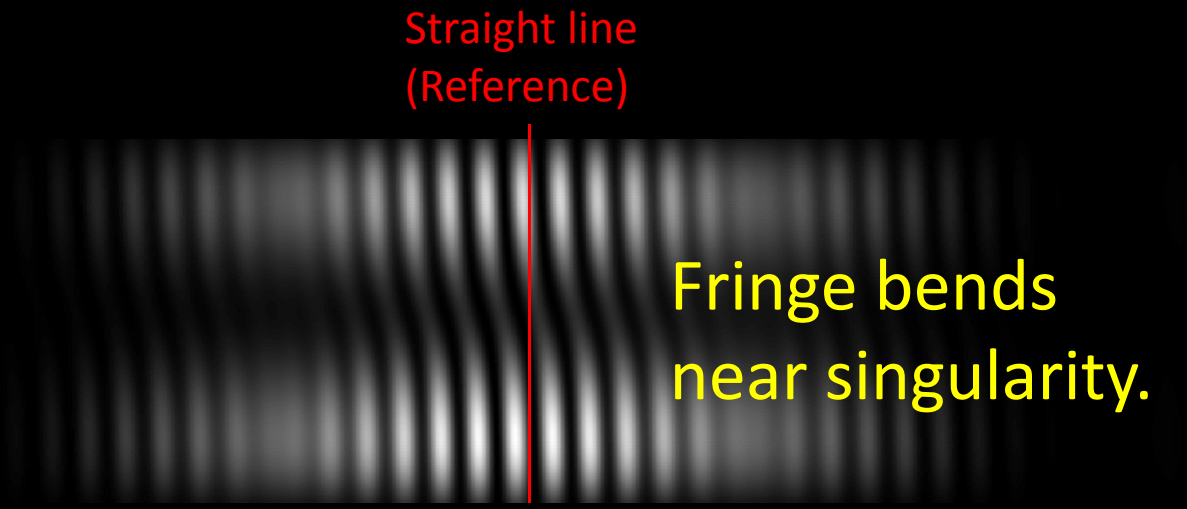


E = 500 MeV 2nd harmonics (ℓ = 1)

Diffraction experiment (double slit) –results-



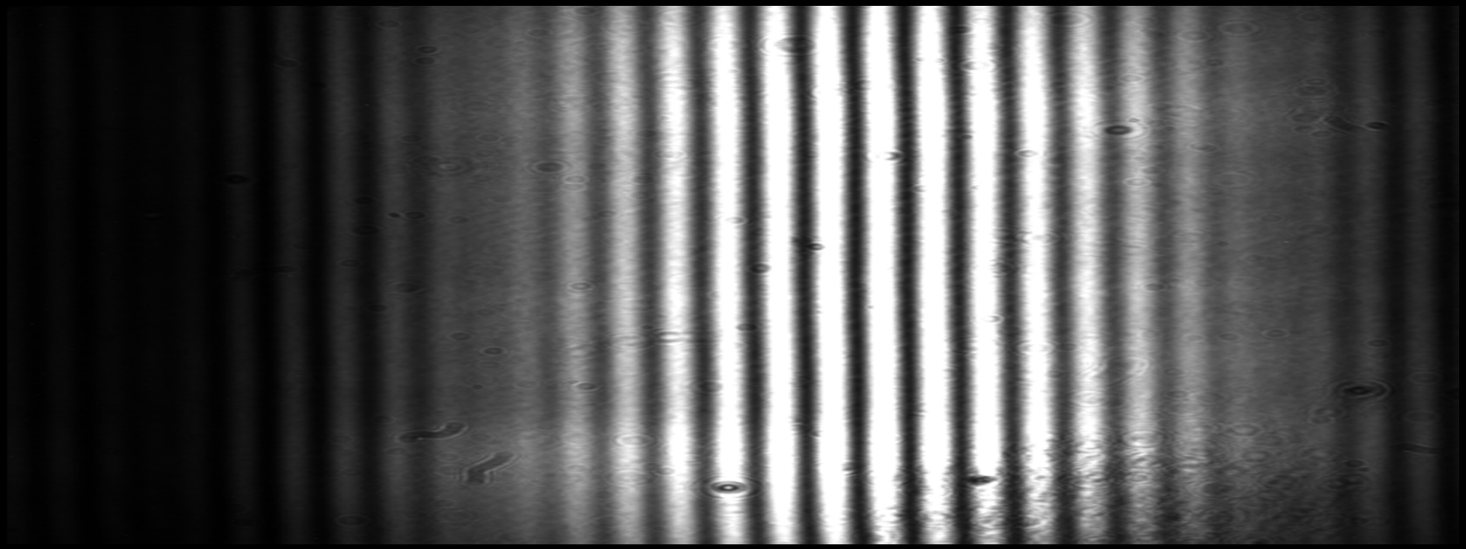
Phase dist. of vortex



SRW simulation

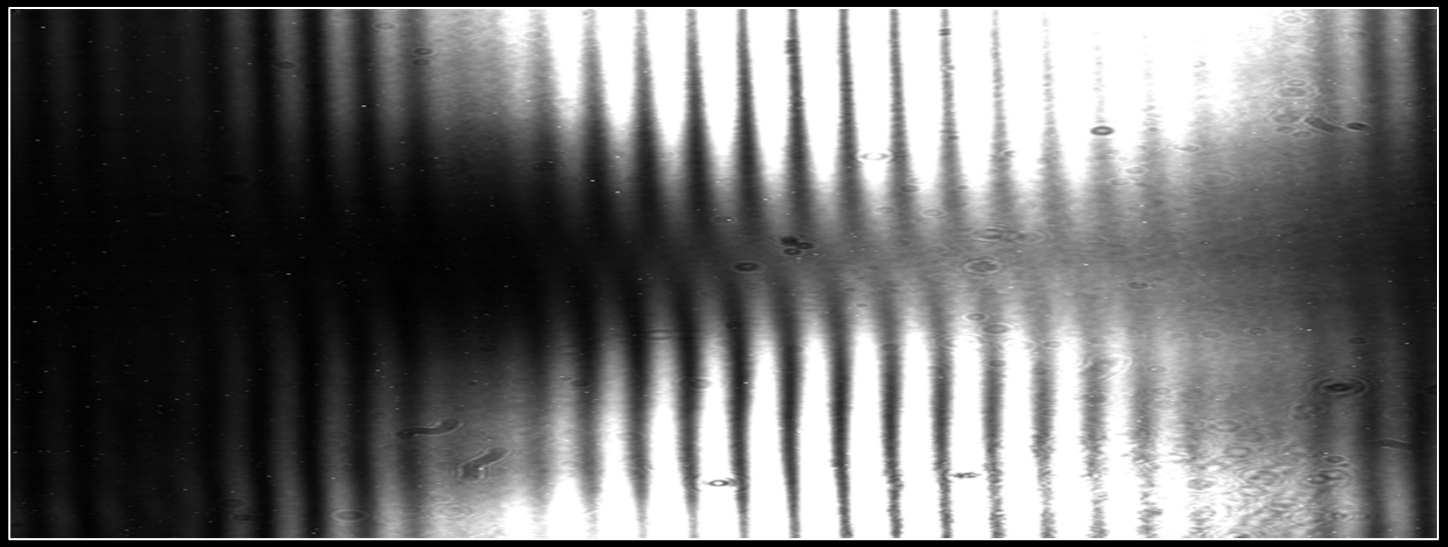
ℓ= 1 Case:
Relative phase depends on vertical position.

Diffraction experiment (double slit) –result-



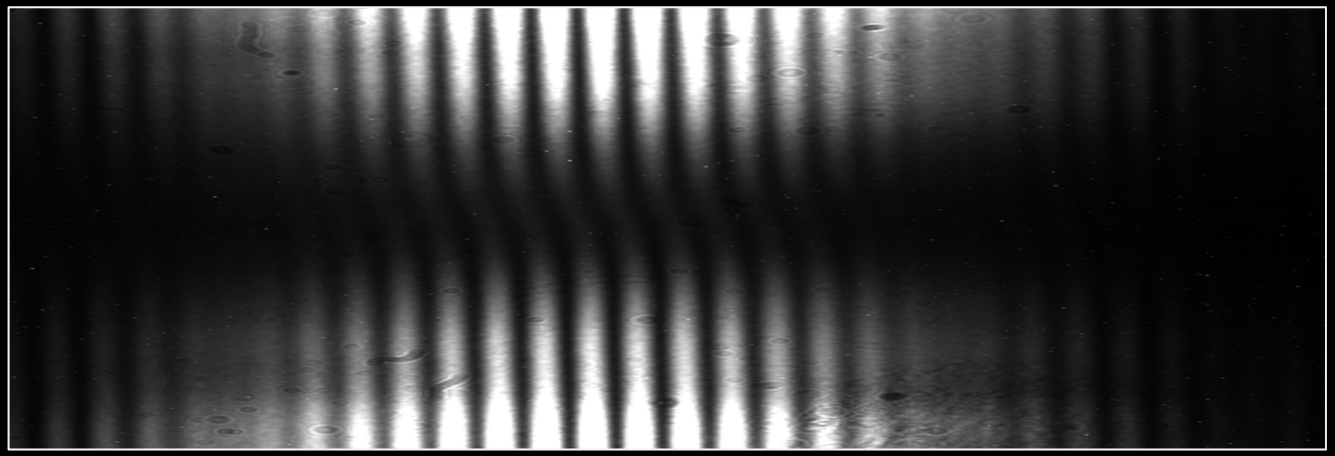
Fundamental Radiation $\ell = 0$

Diffraction experiment (double slit) –result-

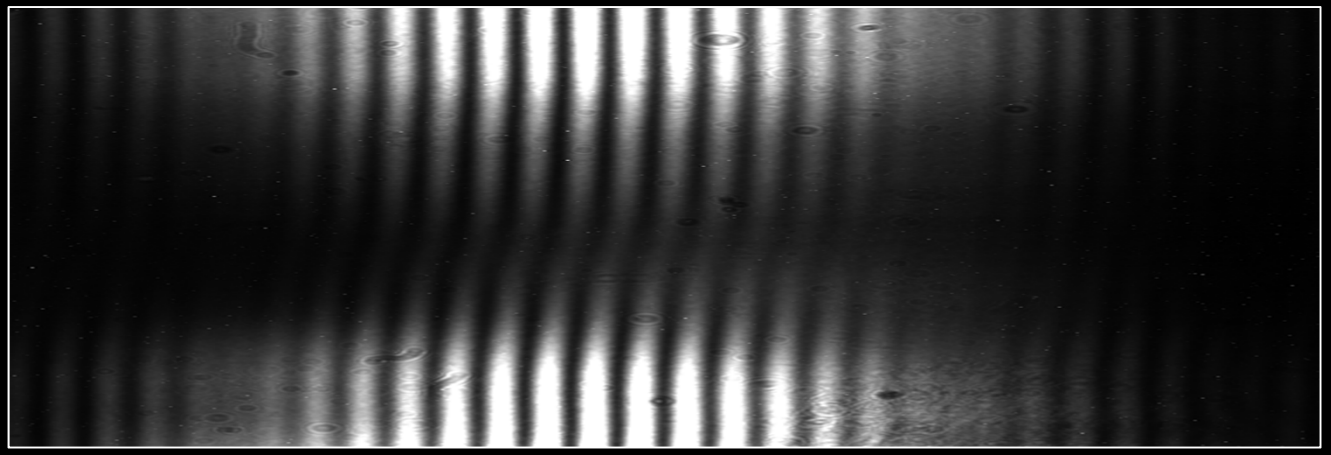


2nd harmonics $\ell = 1$

Diffraction experiment (double slit) –result-



$\ell = 1$



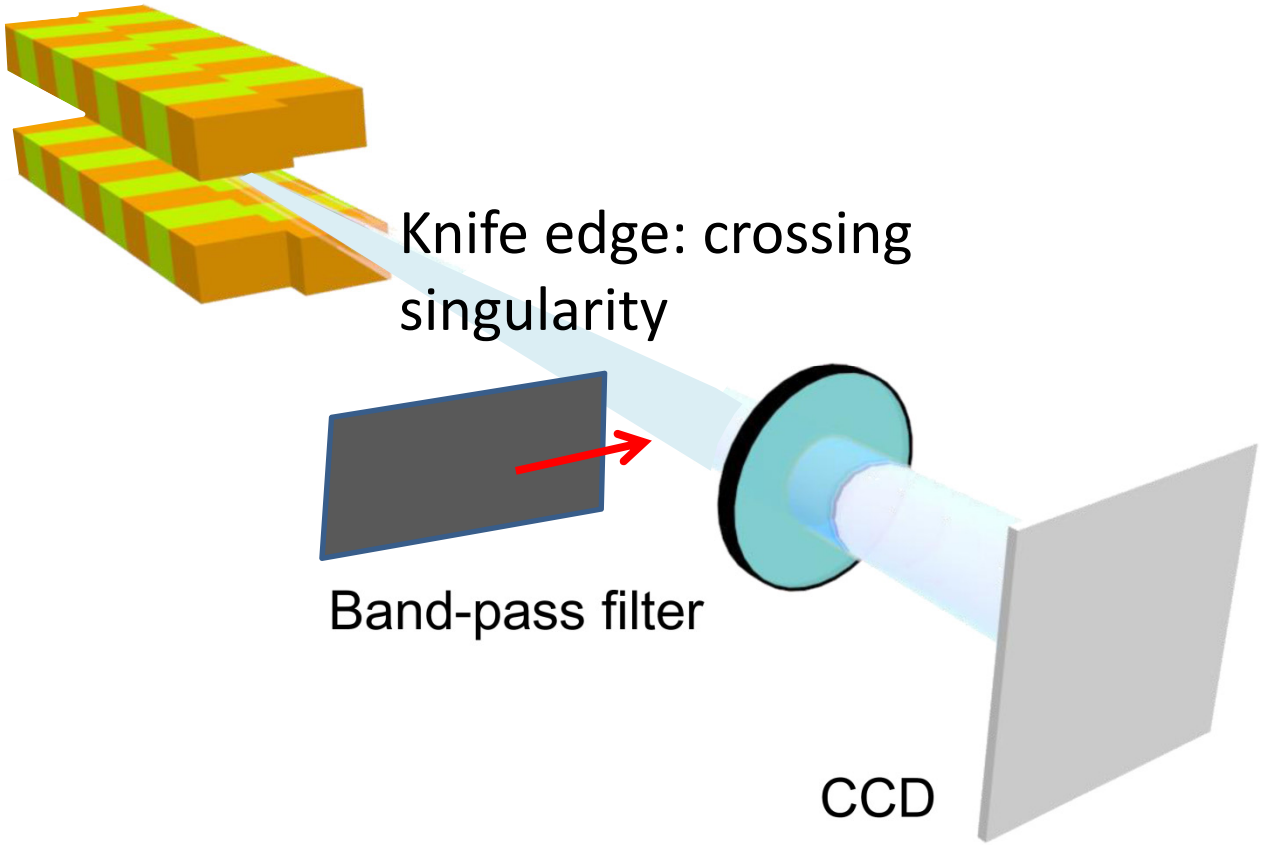
$\ell = -1$

Change helicity : $\ell = 1 \rightarrow -1$

Mirror inverted fringe patter is observed.

Diffraction experiment (knife edge)

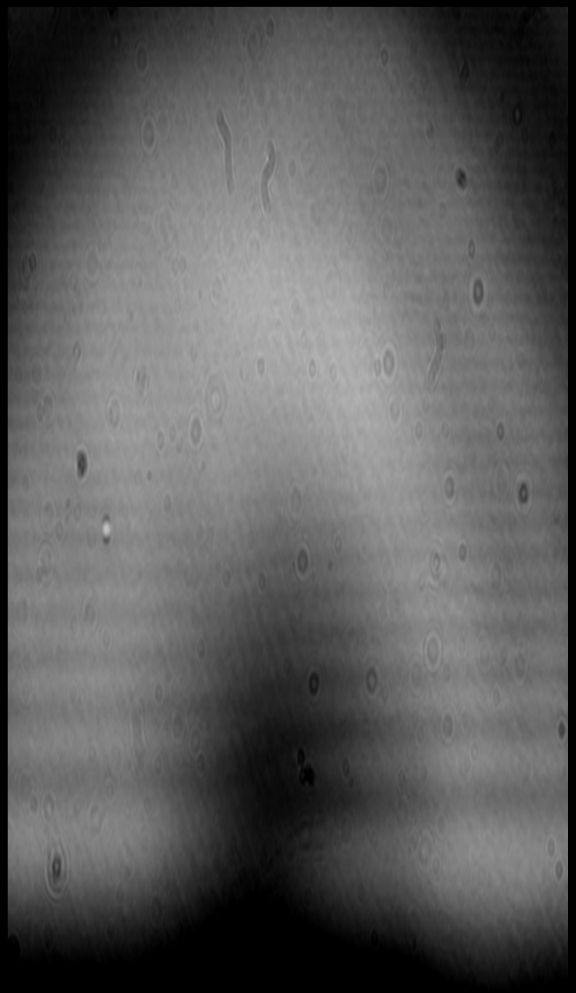
Helical Undulator



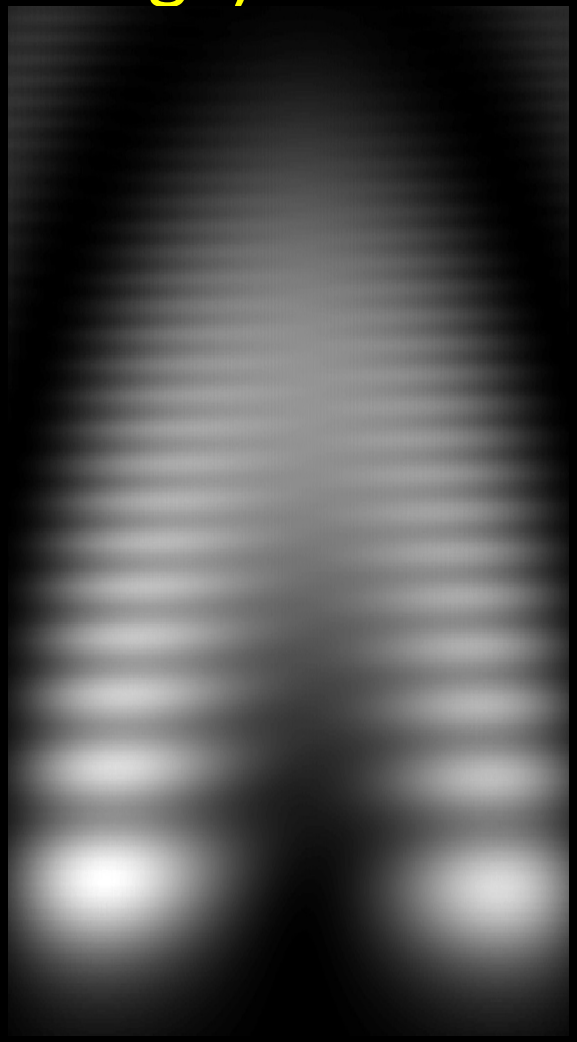
E = 500 MeV 2nd harmonics (λ = 355 nm)

Diffraction experiment (knife edge) –result-

E = 500 MeV
2nd harmonics



Experiment



SRW calculation

Discontinuity of fringe near the center was observed.

Summary

We have conducted systematic experiment on optical vortex from helical undualtor.

- Interference of two undulators (ℓ = 0,1,2).

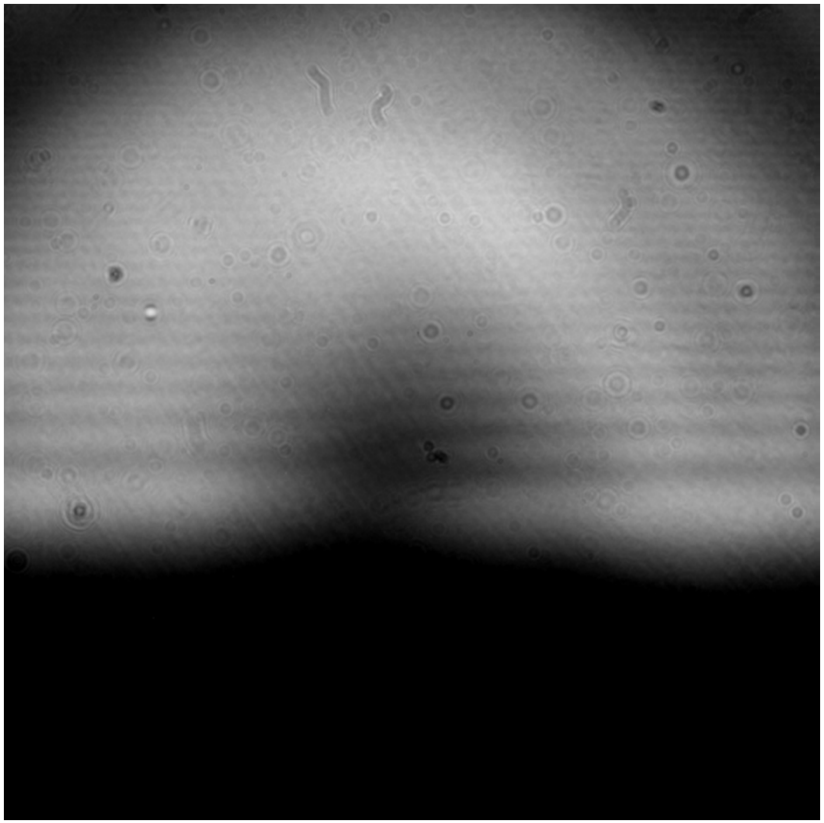
  Single, double, triple spiral patterns were observed.

- Diffraction experiment (ℓ = 1) (single undualtor).

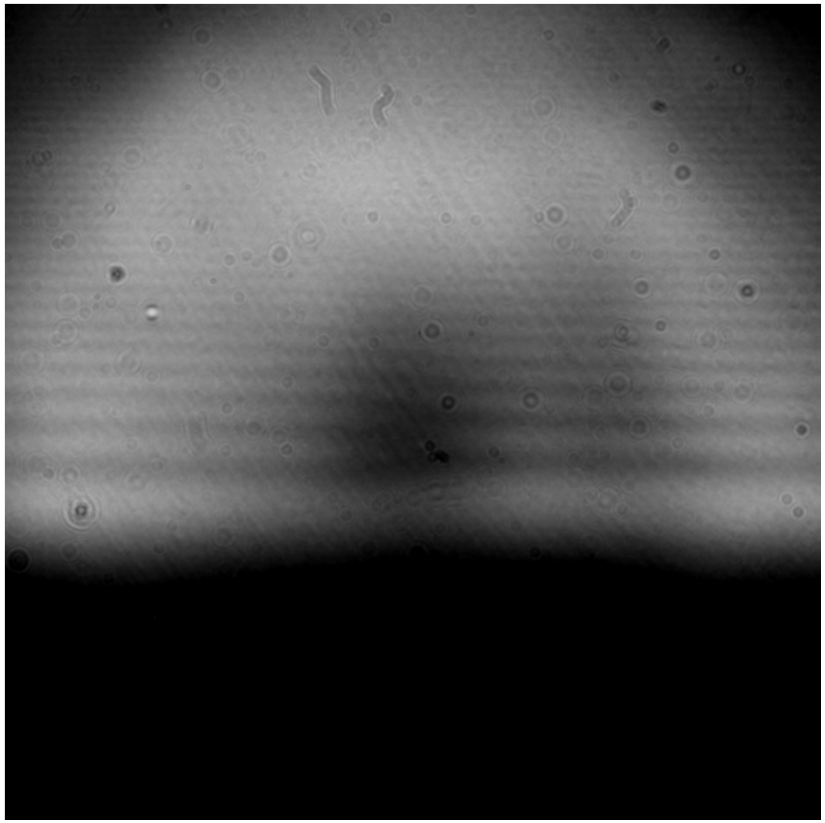
  Specific patterns (bending fringe and discontiniy) were observed.

- SRW calculation reproduces the experiment very well.

Diffraction experiment (knife edge) –result-



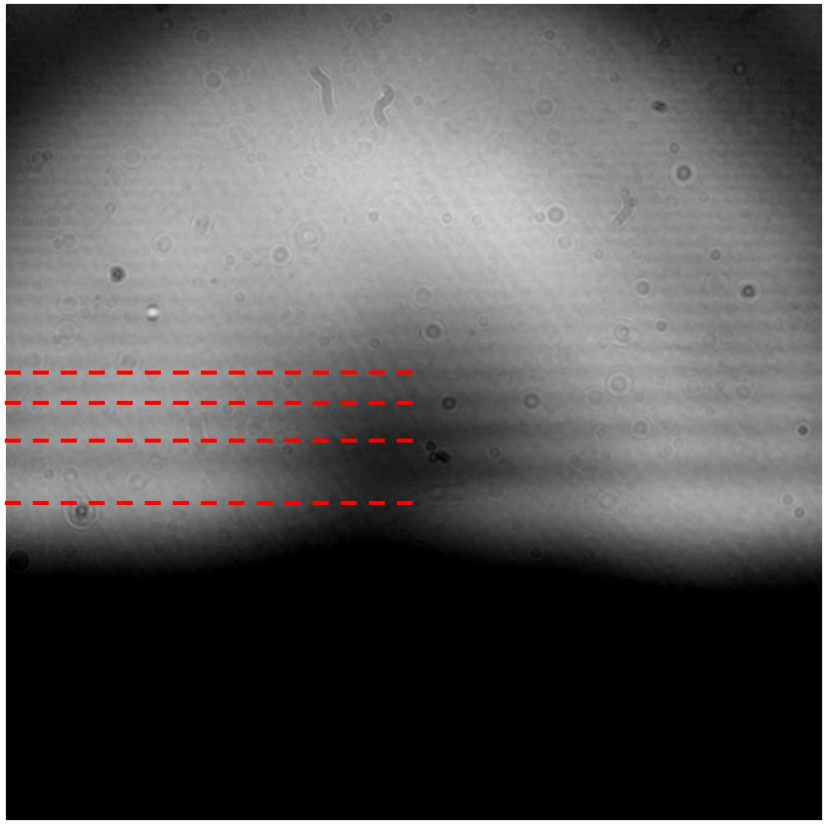
ℓ =1

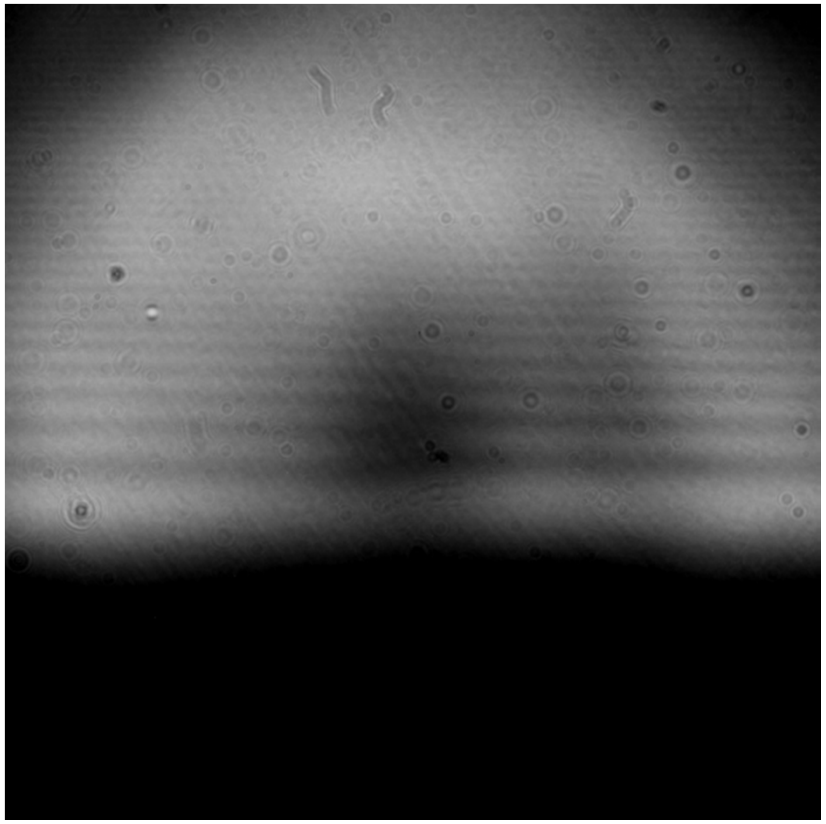


ℓ =-1

Lateral inversion each other.

Diffraction experiment (knife edge) –result-



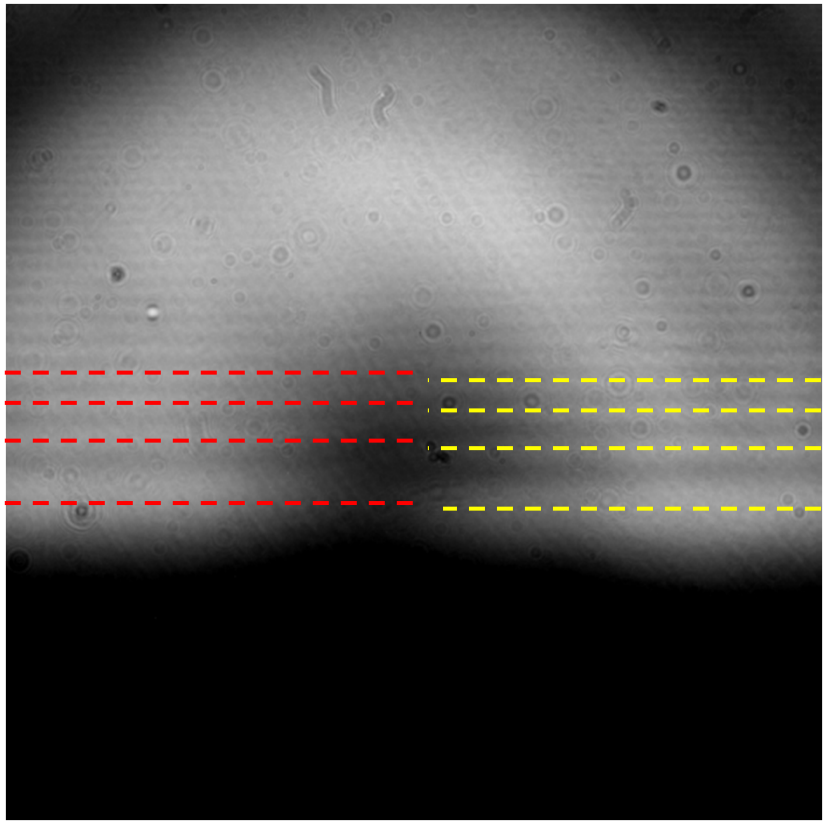


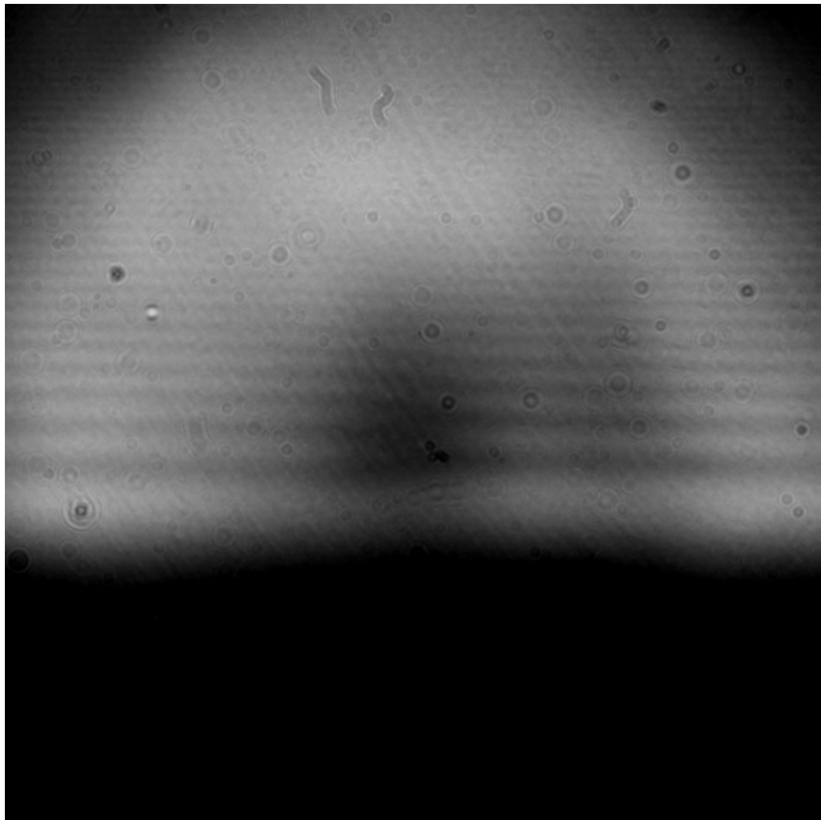
ℓ =1

ℓ =-1

Lateral inversion each other.

Diffraction experiment (knife edge) –result-



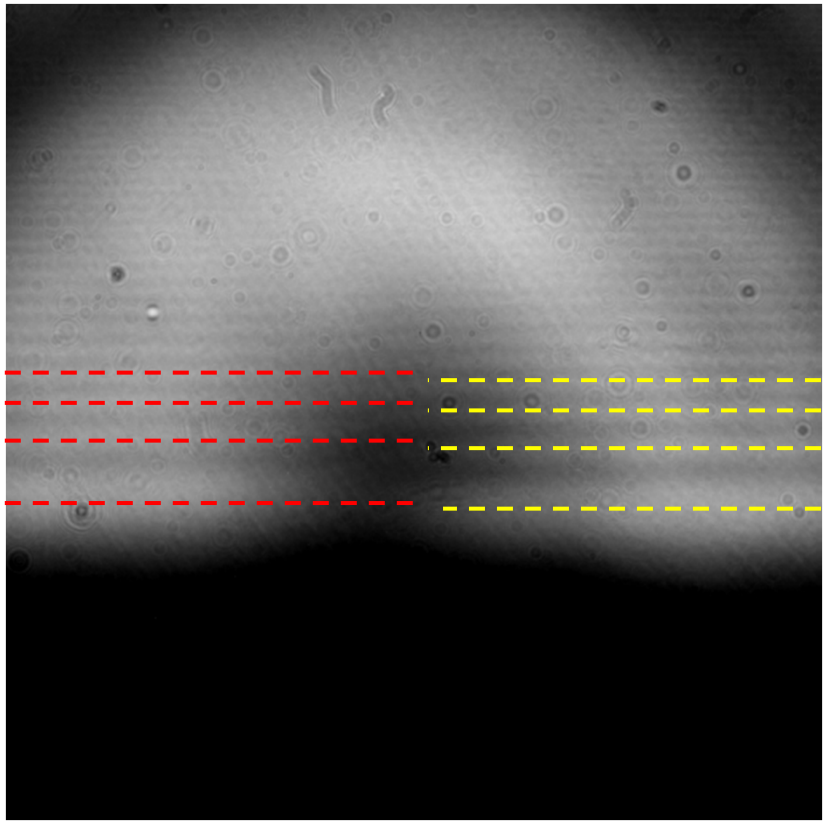


ℓ =1

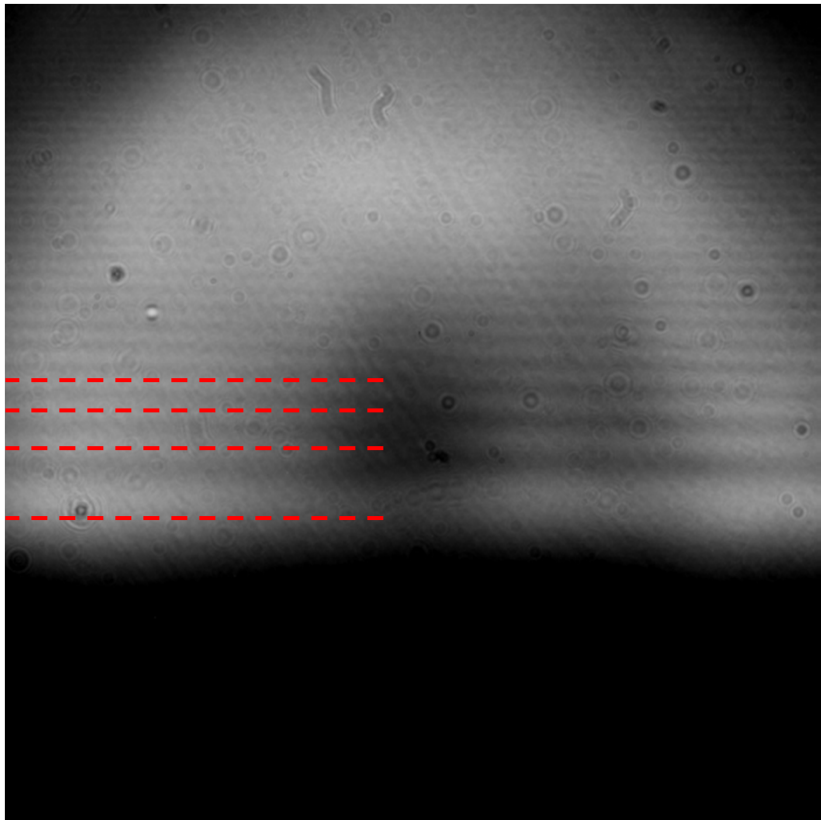
ℓ =-1

Lateral inversion each other.

Diffraction experiment (knife edge) –result-



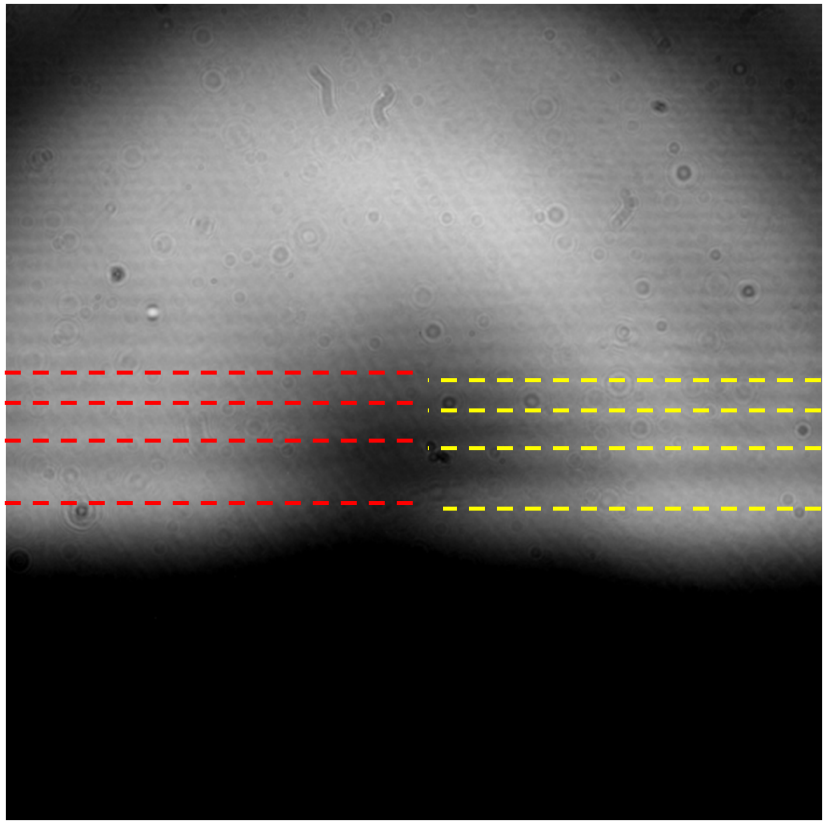
ℓ =1



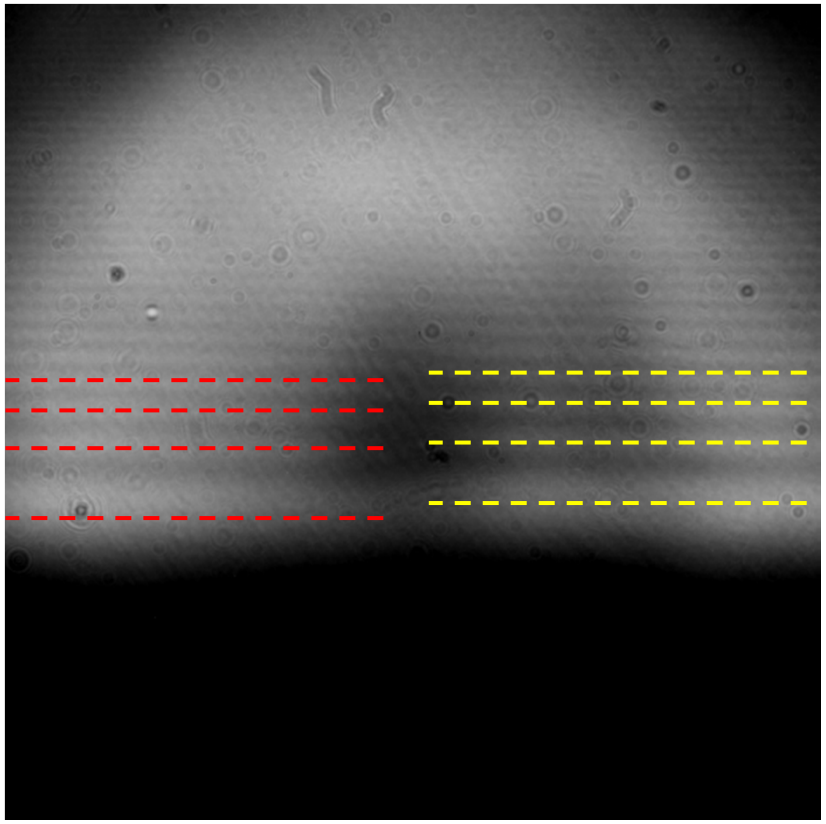
ℓ =-1

Lateral inversion each other.

Diffraction experiment (knife edge) –result-



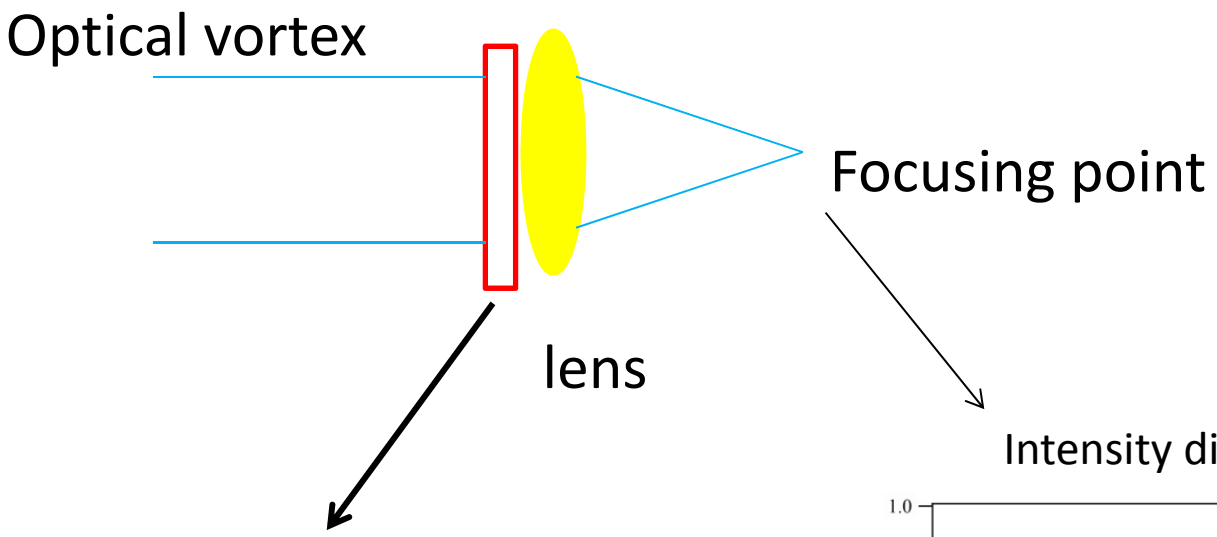
ℓ =1

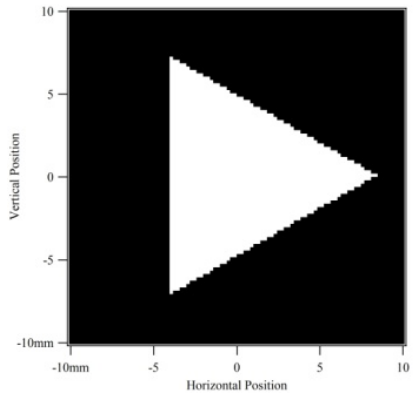


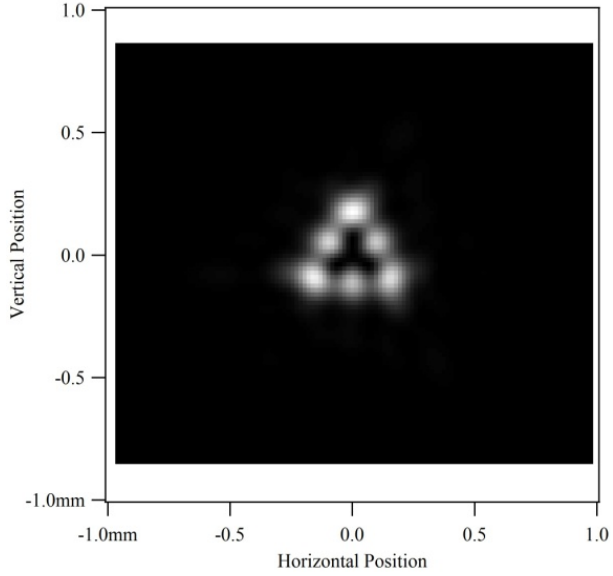
ℓ =-1

Lateral inversion each other.

Diffraction using a triangle aperture



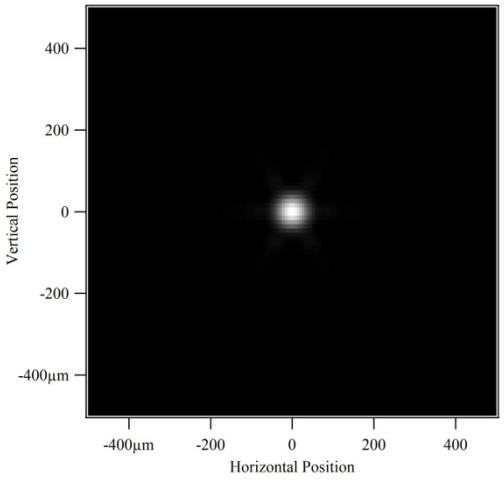




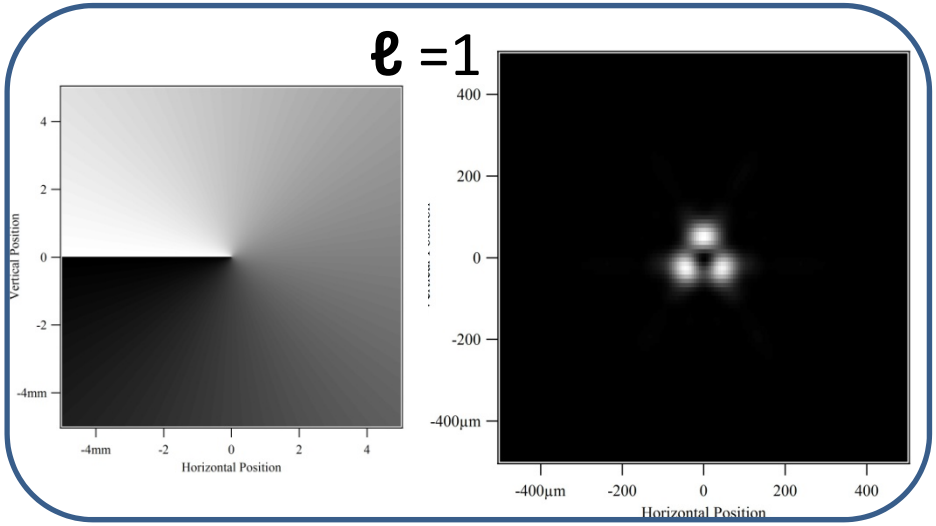
L. E.E . de Araujo, et al,
OPTICS LETTERS Vol.36, No.6 (2011)

Diffraction using a triangle aperture

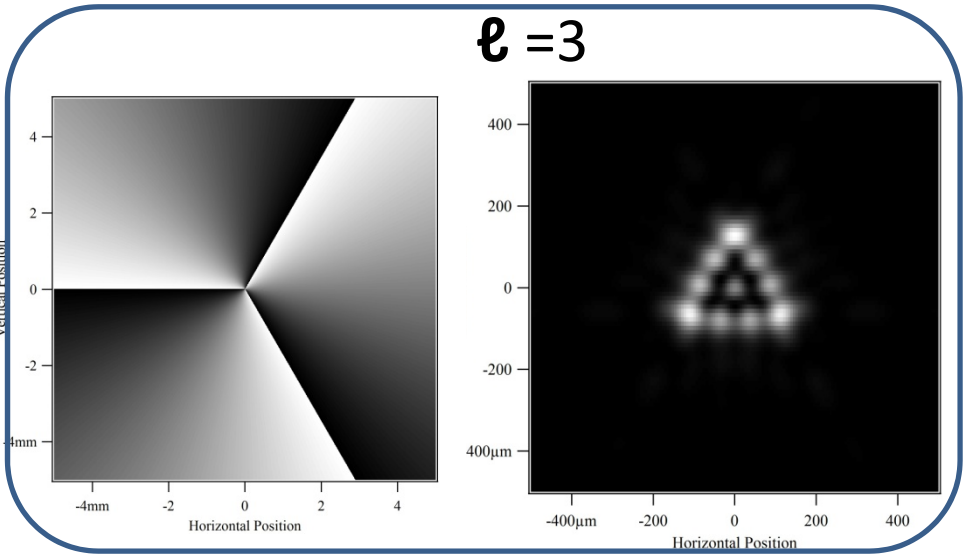
ℓ =0



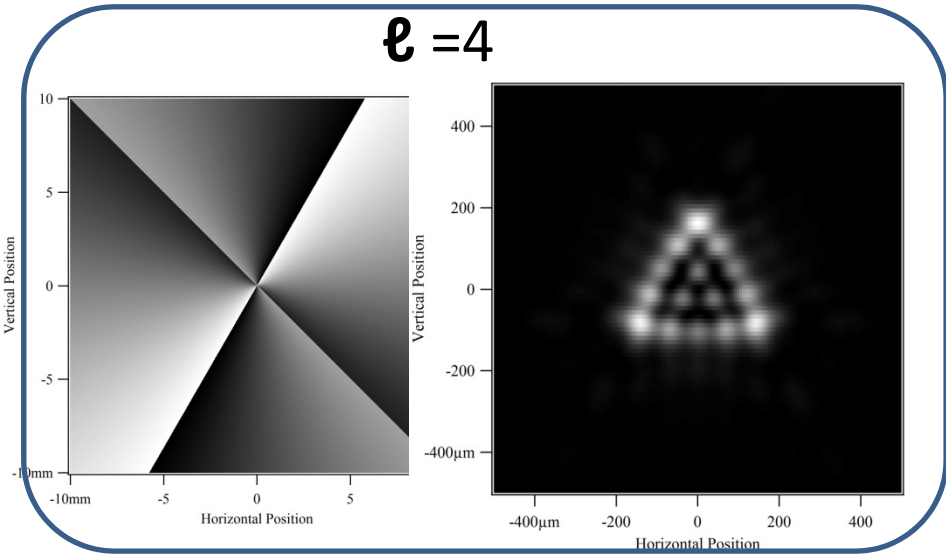
ℓ =1



ℓ =3



ℓ =4



(Topological charge) = (Number of spots in a side) -1