EXPERIMENTAL STUDY ON OPTICAL VORTEX FROM A HELICAL UNDULATOR AT UVSOR-III *

M. Hosaka†, Synchrotron Radiation Research Center, Nagoya University, Nagoya, Japan
K. Miyamoto, S. Sasaki, Hiroshima Synchrotron Radiation Center, Hiroshima University Higashi-Hiroshima, Hiroshima Japan
K. Kuroda, Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba, Japan
T. Konomi, N. Yamamoto, High Energy Accelerator Research Organization, Tsukuba, Japan
N. S. Mirian, M. Katoh, UVSOR, Institute for Molecular Science, Okazaki, Japan

Abstract

A relativistic electron in helical undulator emits an optical vortex which carries orbital angular momentum. We have made systematic studies to characterize the optical vortex from a helical undulator at UVSOR-III. Patterns resulting from inferences between two undulator radiation carrying different angular momentums were clearly observed. Diffraction experiments were carried out and specific diffraction patterns due to the phase singularity in the radiation center were clearly observed.

INTRODUCTION

An optical vortex, a light beam with a phase singularity at the center of helical wavefront carries orbital angular momentum (OAM) [1]. Since the discovery, extensive studies not only on vortex of optical beam but also of electron beam [2] and neutron beam [3] have been carried out. These vortices are created by converting plane waves using spiral phase plates, computer-generated holograms and other devices. On the other hand, Sasaki and McNulty predicted theoretically that synchrotron radiation from a helical undulator is naturally optical vortex without any manipulation [4].

The wavelength of n-th harmonics of synchrotron radiation from a helical undulator is

$$\lambda = \frac{\lambda_u}{2n\gamma}(1+K^2+\gamma^2\theta^2) \qquad (1)$$

,

where λ_u, γ, K and θ are period of the undulator, Lorentz factor of the electron beam, deflection parameter of the helical undulator and the observation angle from the radiation axis, respectively. The intensity and phase distributions of 2nd harmonic radiation calculated by means of the computer code SRW [5, 6] are shown in Fig. 1. The harmonics of radiation from a helical undulator exhibits a ring shape vanishing intensity in the center (on-axis direction). The phase changes from 0 to 2π around the center, i. e. the topological charge equal to one and the radiation carries an OAM of $1\hbar$. As described in ref. [4], the topological charge of n-th harmonics of a helical undulator radiation equals to (n-1).

The first experimental verification was conducted by Bahrdt, *et al*. at BESSY II [7]. They observed interference patterns of radiation from two successive undulators: one is tuned to 2nd harmonics and another is tuned to fundamental. The spiral pattern resulting from interference of an optical vortex and plane wave supports the prediction that the second harmonic radiation from a helical undulator carries OAM.

At UVSOR-III, we have carried out systematic studies on optical vortex with a helical undulator radiation [8]. Interference experiment between two undulators as BESSY-II and a diffraction experiment using a double slit was made. In this paper, we report on the latest experimental results at UVSOR-III.

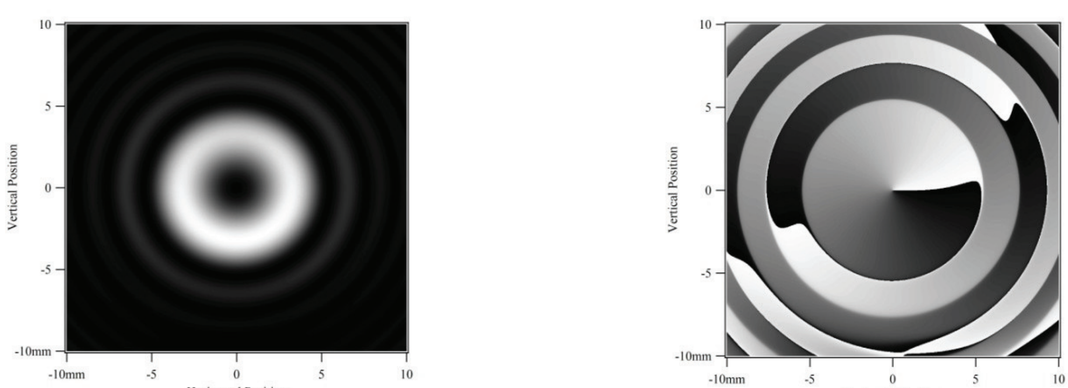

Figure 1: Calculated intensity (left) and phase (right) distribution of 2nd harmonics from a helical undulator. The calculation is done using SRW, under condition of λ = 355 nm, λ_u = 88 mm, γ = 978, and K= 3.8.

† m-hosaka@nusr.nagoya-u.ac.jp

Copyright © 2016 CC-BY-3.0 and by the respective authors

EXPERMENT

At UVSOR-III, an optical klystron consisting of two APPLE-II helical undulators and a buncher is already installed for FEL and coherent synchrotron light source experiments. In contrast with the BESSY-II experiment in the soft X-ray region (99 eV), we observed the radiation from the helical undulator in the UV region. Therefore we can make the optical vortex experiments using conventional optical apparatus. The radiation from the undulator is extracted directory (without mirror) through a quartz window and is detected using a UV camera.

Although the emittance of UVSOR-III (7.6 nm-rad at an energy of 500 MeV) is not so small as 3rd generation light sources, it is the diffraction limited one in the UV region. The nominal energy of the UVSOR-III is 750 MeV, however, we decreased the energy down to 500 MeV and 400 MeV to adjust the 2nd and 3rd harmonic radiation from the helical undulator to the UV region. The parameters for the experiment is summarized in table 1

Figure 2 shows an example of measured spiral patterns from the interference of two undulators at the wavelength of 355 nm. Fundamental wavelengths for the 1st (upstream) and the 2nd (downstream) undulator are tuned to 355 nm and 710 nm i. e. the wavelength of the 2nd harmonic of downstream undulator is 355 nm. In order to overlap the radiation from the two undulators, a band pass filter with bandwidth of 2.2 nm-FWHM is used and the expected longitudinal overlap is about 80 %. The spiral pattern appears as a result of interference between a spherical Gaussian wave and a spherical vortex wave with different radius of curvature. We carried out a simulation with the same condition as the experiment using SRW and compared with the experimental result. As is shown in Fig. 2 clearly, the spiral pattern is well reproduced by the calculation.

We also demonstrated the phase singular property of the radiation by Young's double slit diffraction. The intensity distribution on a screen of a double slit experiment with a plane wave is

$$I(x) \propto \cos^2\left(\frac{\pi a x}{\lambda d}\right) \tag{2}$$

where λ, d, are the wavelength and distance from the slits to the observation screen, and a and x are the slit spacing and the observation position on the screen in the horizontal direction. In case of the optical vortex with a helical wavefront, the intensity distribution is modified as:

$$I(x, y) \propto \cos^2\left(\frac{\pi a x}{\lambda d} + \frac{\Delta\phi(y)}{2}\right) \tag{3}$$

where $\Delta\phi(y)$ is the additional phase difference between the two slit along the vertical direction [9]. An example of simulation using SRW is shown in Fig. 3.

Table1: Parameters for Experiment

< Electron Beam >	
Beam Energy	500 MeV
Beam Current	~ 1 mA
Natural Emittance	7.6 nm-rad
<Helical Undulator/ Optical Klystron >	
Type	APPLE-II
Period Length	88 mm
Number of periods	10 + 10
K Value	~4.8
<Detecting System>	
Band Pass Filter	355 nm, 2,2 nm-FWHM
Position of UV camera	9.5 m from the center of the optical klystron

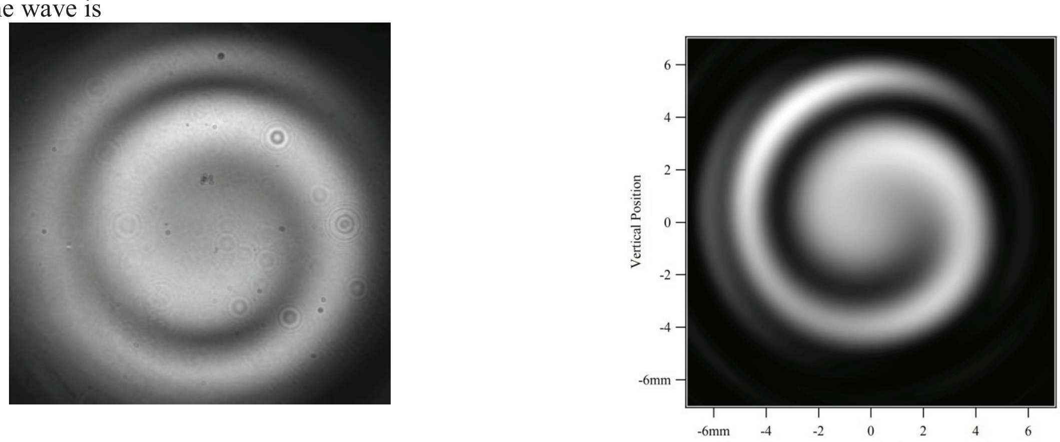

Figure 2: Measured (left) and calculated (right) spiral pattern from double undulator interference.

Copyright © 2016 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-147-2

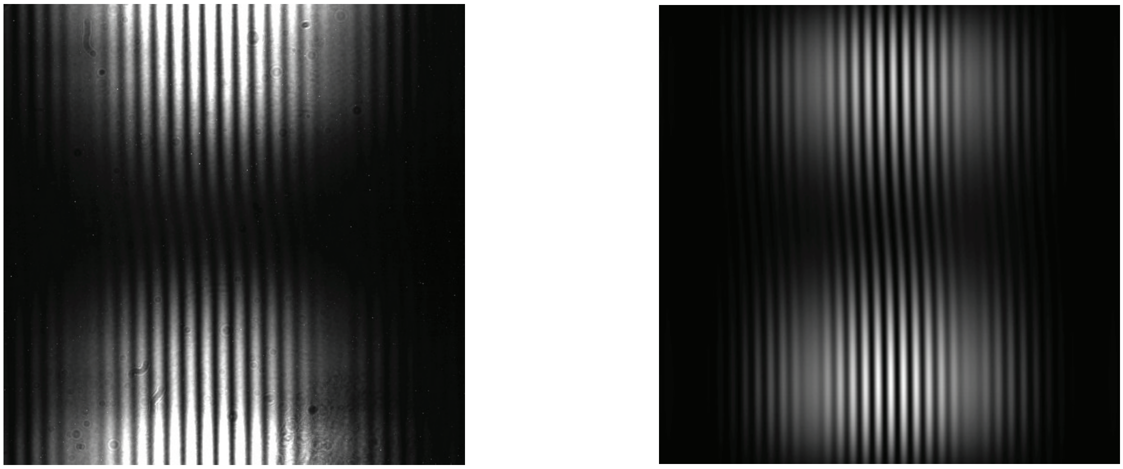

Figure 3: Measured (left) and calculated double slit pattern from 2nd harmonic radiation.

The double slit interference experiment on helical undulator radiation was carried out with almost the same setup as the double undulator inference experiment, except that only the 2nd undulator is used. The fundamental wavelength of the 2nd undulator is tuned to 710 nm and the 2nd harmonic radiation is selected by the 355 nm band pass filter and detected by the UV camera placed 6.5 m from the center of the second undulator. In order to reduce radiation from the bending magnets and edge radiation, which smear out the diffraction image, a linear vertical polarizer is used. An example of the experimental results is shown in Fig. 3 with a SRW simulation. The interference fringes are shifted from the left to the right looking at from top to bottom. We also observed reversion of the diffraction pattern by switching the helicity of the helical undulator to invert the sign of topological charge. The measured pattern was the mirror inversion of the former one and is consistent with the SRW calculation.

SUMMARY AND OUTLOOK

We have made experimental studies on an optical vortex from a helical undulator. The experimental results are well reproduced by SRW calculations. However, these experiments were limited to 2nd harmonic radiation (topological charge equal to one) case. Actually we tried some experiments on 3rd harmonic radiation, but no clear evidence of higher topological charge could be obtained. We think that the limitation is caused by weaker intensity around the center region as increasing harmonic number. We are thinking about another diffraction method which is more sensitive to the topological charge. One candidate is an experiment using a triangular aperture [10], with which the number of a topological charge can be directly measured.

REFERENCES

[1] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, J. P. Woerdman, *Phys. Rev. A* 45, p. 8185, 1992.
[2] M. Uchida and A. Tonomura, *Nature,* 464, p. 737, 2010.
[3] C.W. Clark *et al., Nature,* 525, pp. 504, 2015.
[4] S. Sasaki and I. McNulty, *Phys. Rev. Lett.*, 100, pp.124801, 2008.
[5] O. Chubar and P. Elleaume, in *Proc. EPAC98*, 1998, pp. 1177, available at http://www.jacow.org
[6] O. Chubar, P. Elleaume, A. Snigirev, *Nucl. Instr. Meth. A* 435, p. 495, 1999.
[7] J. Bahrdt *et al.*, *Phys. Rev. Lett.* 111, p. 034801, 2013.
[8] S. Sasaki *et al.*, Presentation at 12th Int 'l Conf. on Synchrotron Radiation Instrumentation, New York, July 2015.
[9] H. I. Sztul and R. R Alfano, *Opt. Lett.,* 31, p. 999, 2006.
[10] L. E. E. de Araijo and M. E. Anderson, *Opt Lett* 36, 787 (2011).

Copyright © 2016 CC-BY-3.0 and by the respective authors