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EXPERIMENTAL DEMONSTRATION OF VECTOR BEAM GENERATION WITH TANDEM HELICAL UNDULATORS

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Abstract

Vector beam is a light beam with spatially modulated polarization state across the beam. Particular examples of vector beam are radial and azimuthal polarization which have donut-shaped intensity and radially and azimuthally oriented linear polarization state. Vector beam has long been interest in the laser community and it is well known that vector beam can be created by superposing two optical vortex beams which have spiral wave fronts. It has been demonstrated that optical vortex beam can be generated from a helical undulator as harmonics. Therefore, we propose a scheme to generate vector beam by superposing two optical vortex beams from two helical undulators in tandem, based on the principle of the 'crossed undulator'. The experiment was carried out at UVSOR BL1U. In this paper, we describe the principle and the experimental details.

INTRODUCTION

Many researches in the past, homogeneous state of polarization as shown in Fig. 1(a) were dealt with. Figure 1 also show examples of light beams so called vector beams or optical vortices. Vector beams are the lights shown as Fig. 1(b), in which the direction of polarization varies around the beam axis with donuts-shaped intensity. Optical vortices form a donuts-shaped intensity and spiral phase structure as shown in Fig. 1(c), (d). In recent, light which have spatially structured in intensity, polarization and/or phase, called "structured light", stimulate significant interest for a range of applications [1-2]. The research of structured light has long been carried out in the laser community. There are many ways to generate structured light by using spatially inhomogeneous optical devises and lasers or optical fibres with mode discrimination [3-5].

In accelerator-based light sources, several ways to generate optical vortices has been proposed and demonstrated [6-7]. In addition, edge radiation and transition radiation are known as a radial polarization which is included a category of vector beam. In these situations, we devise a scheme to produce a vector beam based on synchrotron radiation technology, which enables the generation of vector beams in the VUV or x-ray range [8]. The scheme is analogous to the idea of "cross undulator" [9] but it is expanded it into two dimensions to superpose second harmonics from tandem helical undulators. In this paper, we present principle and experimental details of this scheme in this presentation.

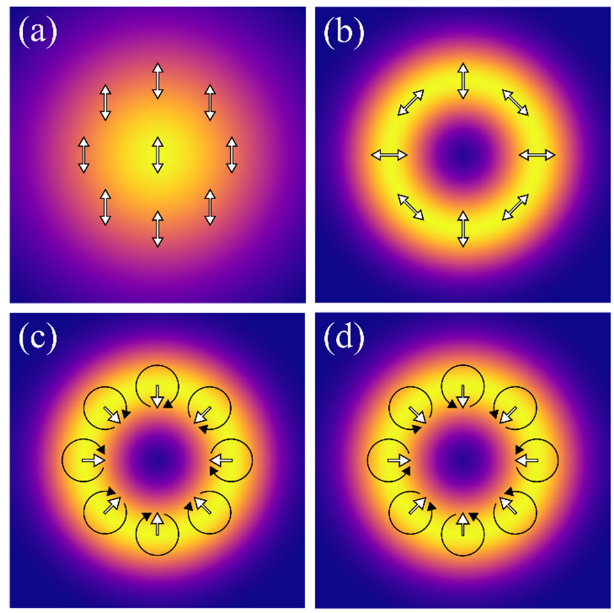

Figure 1: A schematic illustration of a uniform polarization state (a) a vector beam (b) and optical vortices (c) (d). The arrows in (a) and (b) are indicated the polarization directions. The white arrows in (c) and (d) indicate instantaneous electric field vector, and circular arrows indicate the handedness of circular polarization.

PRINCIPLE

Vector beams can be created by superposing two optical vortices. By using the Jones formalism, the polarization state of the superposition of a right-handed circularly polarized optical vortex with a 1st order right-handed spiral wave front (shown in Fig. 1(c)) with an analogous left-handed version (shown in Fig. 1(d)) in polar coordinates (r,ϕ) is written as

$$\begin{aligned}\mathbf{E}(r,\phi) &= E(r)\left(e^{i\phi}\begin{bmatrix}1\\ i\end{bmatrix} + e^{-i(\phi+\alpha)}\begin{bmatrix}1\\ -i\end{bmatrix}\right)\\ &= 2E(r)e^{-i\alpha/2}\begin{bmatrix}\cos(\phi+\alpha/2)\\ -\sin(\phi+\alpha/2)\end{bmatrix}\end{aligned} \quad (1)$$

where α is the relative phase difference between the two optical vortices. The results show that the polarization is linear and its direction rotates toward decreasing azimuthal

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angle. The state of polarization with these features are called anti-vortex modes of vector beams. Figure 1(b) shows the results that the relative phase α is zero.

Helical undulator radiation contains harmonic components as optical vortices [6,7]. The directions of the circular polarization and the helical phase front coincide. Therefore, the second harmonic component become as shown in Fig. 1(c) and (d).

The superposition of polarization with tandem undulators was realized by the "cross undulator". Two wave packets from tandem undulators are lengthened by a monochromator. After the monochromator, two wave packets are longitudinally overlapped and superposed. The bump orbit between undulators can control the relative phase of superposition.

Therefore, the superposition of second harmonics of right and left handed helical undulators become a vector beam.

EXPERIMENTAL SETUP

The experimental demonstration was carried out at the BL1U beamline of UVSOR-III. To obtain clear experimental results, the energy of storage ring was decreased to 500 MeV from 750 MeV. The emittance was estimated to be 8 nm in this condition. Figure 2 shows the experimental setup. BL1U consists of two APPLE-II-type variable-polarization undulators, and a phase shifter composed three magnets. In the experiment, the upstream and downstream undulators were set to the right handed and left handed circularly polarized mode respectively. The phase shifter retards the light pulse from the downstream undulators respect to the that of upstream undulator by making a bump orbit. The undulator radiation is directly extracted into the air only through a quartz window, without passing through any other optical elements. The undulator was set to 496 nm as first harmonic, and the 248 nm as second harmonic.

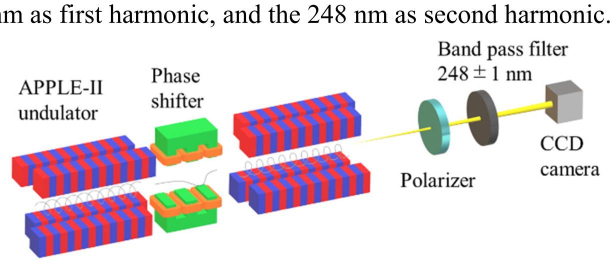

Figure 2: Schematic illustration of the experimental configuration. This figure is reproduced from ref [8].

The two dimensional intensity was obtained with a CCD camera. A band-pass filter with a center wavelength of 248 ± 1 nm FWHM, a rotatable wire-grid linear polarizer and neutral density filters for prevention of saturation was placed in front of the camera. Two-dimensional intensity distributions were measured while rotating the polarizer direction to analyse the polarization.

RESULTS AND DISCUSSION

Figure 3 shows the intensity distribution of a superposed light beam observed without polarizer and with polarizer for the transmission axis at 0° and 90° by experiment and simulation. Simulations are done by the Synchrotron Radiation Workshop [10].

The intensity distribution without polarizer is the same as optical vortices. However, double spiral patterns are appeared in the intensity distributions in the intensity distribution observed through the linear polarizer. And the spiral pattern rotates clockwise as the polarizer direction rotates counterclockwise. This result indicates that the direction of linear polarization varies with position. The experimental results are well reproduced by the simulation.

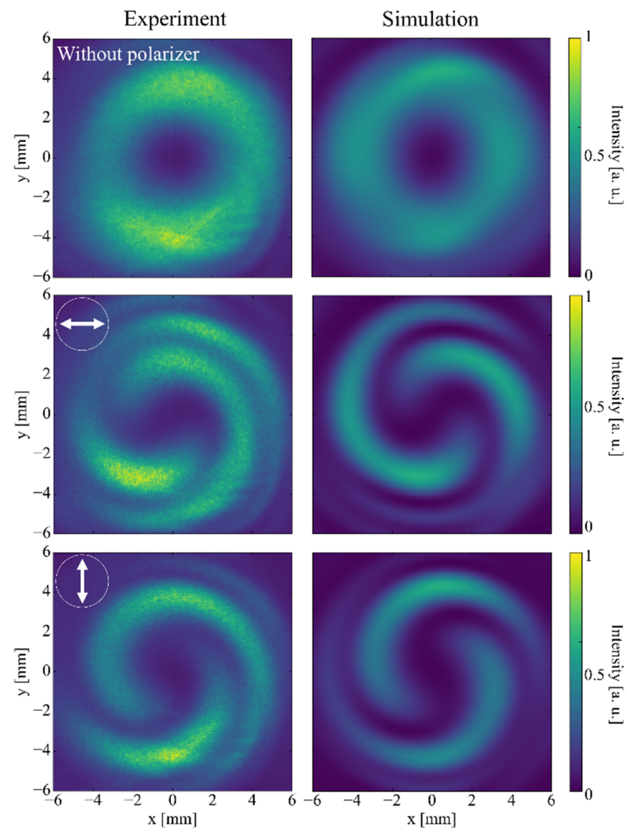

Figure 3: Obtained intensity distributions in experiment (left column) and simulation (right column). Top row shows intensity without polarizer. Middle and bottom rows show intensity through horizontally and vertically oriented polarizer.

To determine the direction of polarization at each position on the transverse plane, the intensity distributions were measured for polarizer angles from 0° to 330° with 30° steps. The intensity at selected positions as a function of polarizer orientation was fit with a sinusoidal function and a constant background. After, we determine the direction of polarization as the angle where intensity is maximum. The degree of linear polarization was also determined by the ratio between the amplitude of the sinusoidal function and the sum of this amplitude and the constant background.

The analysed results of the direction of polarization are shown in the Fig. 4. These results show that the light forms an anti-vortex-mode vector beam. Since the phase of an undulator light depends on the radial angle of radiation, the

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polarization vector also rotates slightly in the radial direction. The difference in the distance from the centers of the undulators to the point of observation produces the radial angle difference, which are 8.0 and 9.6 m respectively in our case. Bottom column of Fig. 4 shows the results with bump orbit which make the relative phase retardation about 180 degrees between the radiations from undulators. The relative phase retardation is estimated from the results of the magnetic-field calculation of the phase shifter. The lengthening of electron path between undulator was estimated to be approximately 0.12 µm. In this case, the orientation of all vector arrows is rotated theoretically by 90°. The results of experiments and simulations are consistent with the theory.

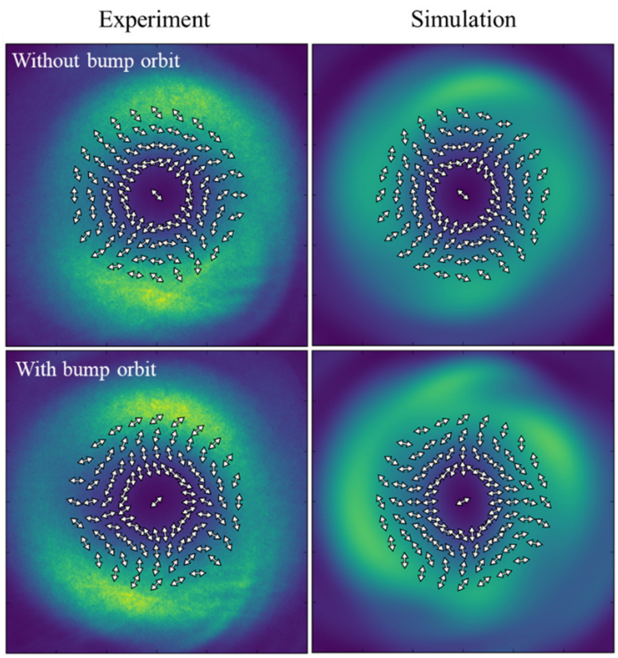

Figure 4: Distributions of directions of polarization on observing plane. Upper figures are analysed results of Fig. 3. This figure is reproduced from ref [8].

The degree of linear polarization is shown in Fig. 5. The degree of linear polarization in experiment are distributed in the range of 60%–80%. The results roughly agree with a simulation results, which contain the effect of monochromator as 15 % constant reduction of degree of linear polarization described in ref [9]. More study need to understand the remaining discrepancy and degree of circular polarization.

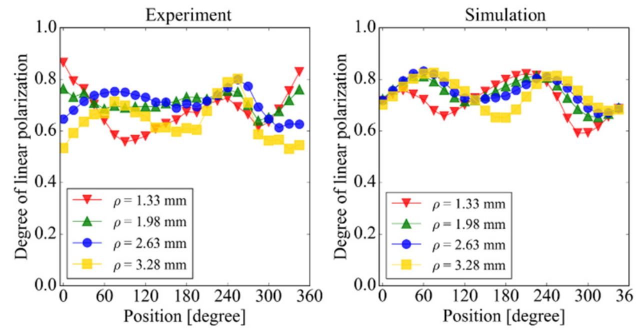

Figure 5: Degree of linear polarization at analysed position in top row figures of Fig. 4. The horizontal axis and ρ indicate the position as azimuthal angle and distance from center. This figure is reproduced from ref [8].

CONCLUSION

A vector beam is generated by superposing second harmonics from tandem helical undulators operated in right- and left-circular modes. In this scheme, the electron beam should be diffraction limited to obtain high degree of linear polarization. This scheme may be applied in diffraction-limited synchrotron light sources in future.

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