Polarization Conversion using Diamond X-ray Phase Retarder at BL39XU

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1. Introduction

Polarized x-rays are essential in spin-dependent x-ray absorption spectroscopy and/or diffractometry. For the advantage of polarization tunability and high polarization purity, diffractive x-ray phase retarders (XPR) have been used in place of polarization-tunable insertion devices in several synchrotron radiation facilities [1–3]. The XPR can convert the linear polarization into right- or left-handed circular polarization or rotated linear polarization by producing the appropriate phase shift between the σ and π polarization components [1–4]. It has been proposed that the XPR of light material combined with the small divergent beam such as undulator radiation can convert the polarization states with high efficiency [4]. In this report, we have developed a diamond XPR at the BL39XU undulator beamline [5], and the efficiency of the XPR was confirmed.

2. Experimental

A diamond XPR in the Laue-case 220 transmission geometry [4] was installed just below a beryllium window in the experimental hutch at the BL39XU. The diamond crystal is (111)-oriented and 0.73 mm in the thickness. The (220) plane of the crystal was tilted by 45° with respect to the polarization plane of the incident beam, and deviated from the Laue-case 220 diffraction condition by appropriate angle $\Delta\theta$ to produce 90° or 180° phase shift. The offset angle $\Delta\theta$ was adjusted with an ω-2θ rotation stage with the resolution of 0.72 arc-second/pulse.

Setup of polarization measurements is schematically shown in Fig. 1. The standard Si 111 double crystal monochromator was tuned to select 7.1195 keV photons from the first harmonic of the undulator source (the gap = 11.4 mm and the 1 st peak = 7.14 keV). Adjustable slits (0.5×0.5 mm^2) located at 29 m from the source point allowed us to select the on-axis beam.

Monochromatic and horizontally polarized x-rays are incident on the XPR. The polarization state of the transmitted beam is measured with a linear analyzer of Si 331 channel-cut crystal. The Bragg angle of the Si 331 reflection is 44.435° for E = 7.1195 keV, and the corresponding extinction ratio is estimated to 4×10^{-4}. Integrated intensities of the rocking curve along the ϕ-axis rotation were measured with ionization chambers as a function of the rotation angle χ about an axis parallel to the direction of the incident beam.

3. Results

3-1 *Polarization of monochromatic undulator radiation*

We first measured the degree of linear polarization of the monochromatic beam without XPR. Figure 2 shows the integrated intensities $I(\chi)$ as a function of the azimuthal angle χ (open circles). The $I(\chi)$ is related to the normalized Stokes parameters $P_1 = S_1/S_0$ and $P_2 = S_2/S_0$ (where S_0, S_1, S_2 and S_3 are the components of the Stokes vector),

$$I(\chi) = I_0\,[1 + P_1 \cos 2\chi + P_2 \sin 2\chi]\,, \qquad (1)$$

where $\chi = 0$ corresponds to a vertical diffraction plane of the channel-cut crystal and is representative of the horizontal component of the electric field. The values of I_0, P_1 and P_2 are obtained from

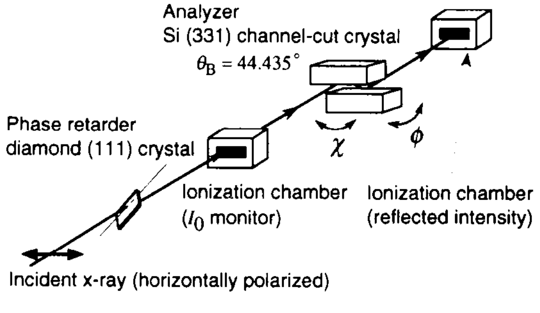

Fig. 1: Experimental setup of polarization analysis.

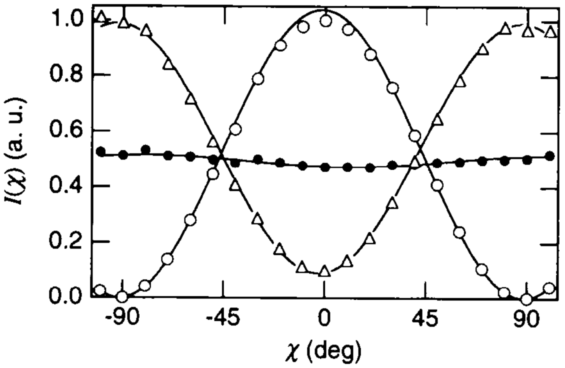

Fig. 2: Integrated intensities $I(\chi)$ as a function of the azimuthal angle χ of the Si 331 channel-cut analyzer. The $I(\chi)$ measured for no phase retarder (open circles), quarter-wave plate, $\Delta\theta = -103$ arcsecond (closed circles), and half-wave plate, $\Delta\theta = -58$ arcsecond (open triangles) are presented. The fitting curves are shown by the solid lines.

the best fit of this expression to the measured integrated intensities. The normalized Stokes parameters obtained from the linear polarization analysis are summarized in Table 1.

Table. 1 Measured Stokes parameters

$\Delta\theta$ (arcsecond)	P_1	P_2
no XPR	0.9986 ± 0.0000	-0.046 ± 0.003
-103	-0.039 ± 0.005	-0.016 ± 0.005
-58	-0.827 ± 0.010	0.041 ± 0.009
$+58$	-0.823 ± 0.011	-0.003 ± 0.009

From this analysis the degree of linear polarization of a monochromatic beam of the ID39 undulator was measured to be $P_L = 0.9986$ on-axis.

3-2 Quarter-wave plate

The diamond XPR was next inserted between the monochromator and the linear analyzer. The offset angle from the diffraction condition was tuned $\Delta\theta = -103$ arcsecond to produce the 90° phase shift. This value was previously determined by monitoring the scattered intensities from a polyimide sheet placed between the XPR and the linear analyzer. The $\Delta\theta = -103$ arcsecond gave the same scattered intensities into the vertical and horizontal directions, so that the transmitted beam has equal amplitude of the horizontal and vertical component of the electric vector.

The closed circles show the result for the quarter-wave plate in the Fig. 2. The integrated intensity $I(\chi)$ nearly keeps constant as changing the azimuthal angle χ. The similar analysis gave the normalized Stokes components P_1 and P_2 as shown in the Table 1 of transmitted beam with the quarter-wave plate. We derived the degree of circular polarization from the measured value of P_1 and P_2 according to an equation,

$$|P_C| = \sqrt{P_L^2 - P_1^2 - P_2^2}, \qquad (2)$$

where, $|P_C|$ is the absolute value of the degree of circular polarization and P_L is the degree of linear polarization of the monochromatic beam which is incident on the XPR. The degree of circular polarization was estimated to $|P_C| = 0.9978$. This result shows that nearly perfect circular polarization was obtained with the XPR.

The polarity inversion of an XMCD signal at the Fe K-edge [6] confirmed the helicity inversion of circular polarized photon with changing the offset angle of the XPR on the lower and higher sides of the diffraction condition.

3-3 Half-wave plate

In order to produce 180° phase shift the angle of XPR was deviated by 58 arcsecond on the each side of the diffraction condition. Generation of vertically polarized beam was attempted. The open triangles shows the measured integrated intensity $I(\chi)$ in the Fig. 2.

The value of P_1 obtained for this case was negative, and the value of P_2 was close to zero. That means the beam is elliptically polarized with the long axis along to the vertical direction.

4. Discussion

It is shown that high rate (around 83 %) of linear polarization in the vertical plane could be obtained at both sides of the diffraction condition of the phase retarder. While higher rate of almost 100 % is expected from calculations of the dynamic theory, assuming a well-collimated incident beam. It is necessary to take into account the angular divergence of incident beam.

Figure 3 shows the degree of linear polarization in the horizontal plane, which is represented by the Stokes component P_1, as a function of the offset angle $\Delta\theta$. The measured value were compared with the theoretical value obtained from the convolution by a Gaussian function of 22 arcsecond FWHM. A good agreement is obtained between the experimental results and the calculation. The 22 arcsecond FWHM is close value to the measured rocking curve width (24 arcsecond) of 220 Laue reflection of the phase retarder. The diamond crystal presently used has been confirmed to be nearly perfect. The angular divergence of incident beam could be understood as resulting from the distortion of a pin-post crystal employed for the Si 111 standard monochromator.

Transmittance of the phase retarder was measured to be 15 % at $E = 7.1195$ keV. The trans-

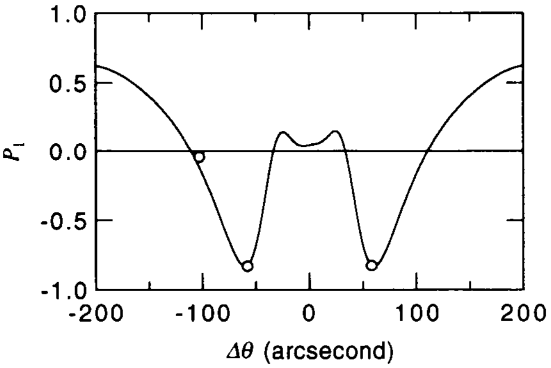

Fig. 3: The variation of the degree of linear polarization P_1 with the offset angle $\Delta\theta$. The experimental values (open circles) are compared with the theoretical curve obtained from the convolution by a Gaussian function of 22 arcsecond FWHM.

mitted photon flux was sufficient for measurements of XMCD or resonant magnetic scattering at the Fe K-edge [6]. The transmittance can be gained by using thinner crystals.

5. Summary

The diamond phase retarder was installed at BL39XU and tested its efficiency with the linear analyzer. It is shown that the on-axis undulator radiation is polarized in the orbital plane and the degree of linear polarization is more than 99 %. Nearly complete circular polarization was obtained with the phase retarder used as a quarter-wave plate. The conversion from the horizontal polarization into vertical one was succeed. To obtain higher degree of linear polarization in the vertical plane, the incident beam must be well-collimated. The diamond phase plate is efficient to be used for XMCD, resonant or non-resonant magnetic scattering experiments.

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