Characterization of an x-ray diamond phase plate by a polarization analyzer using multiple diffraction

K Hirano¹, Y Ito², Y Shinohara² and Y Amemiya²

¹ Institute of Materials Structure Science, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
² Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa, Chiba 277-8561, Japan

E-mail: keiichi.hirano@kek.jp

Abstract. X-ray transmission phase plates are widely used to control the x-ray polarization at many synchrotron facilities. Although their performance can be calculated from the dynamical theory of x-ray diffraction, it is sometimes necessary to measure the produced polarization for a precise analysis of experimental data. To meet this requirement, we have combined two types of x-ray analyzers: a linear analyzer based on 45° Bragg diffraction and an analyzer based on multiple diffraction. The former was used to adjust a diamond phase plate and the latter for a complete determination of the produced polarization. We successfully obtained elliptically polarized x-rays and determined the Stokes parameters at the vertical-wiggler beamline BL-14B of the Photon Factory. The obtained degree of circular polarization was ~0.70 and 0.95.

1. Introduction

Being able to control the x-ray polarization plays an important role, for example, in x-ray magnetic circular dichroism (XMCD), x-ray anisotropic-tensor scattering (ATS), and x-ray magnetic diffraction studies. One of the most convenient ways to control the x-ray polarization is to use an x-ray phase plate in the x-ray transmission geometry [1-5]. To date, low-absorbing crystals such as diamond [2-4], beryllium [5], and lithium fluoride [3] have been commonly used for this purpose at many synchrotron facilities. Characterization of the polarization converted by the phase plate is also important for precise analysis of experimental data, and this can be done by utilizing an x-ray linear analyzer, the Bragg angle of which is close to 45° (in the x-ray energy region, the Brewster angle corresponds to 45°). Although this method is convenient, there are several disadvantages: the available wavelength is limited by the condition that the Bragg angle must be close to 45°, and the method is not sensitive to either the difference between the circularly polarized and unpolarized components, or the helicity of the x-rays. One way to overcome these disadvantages is to employ an x-ray analyzer that makes use of multiple diffraction in a nearly perfect crystal [6]. Although this is useful, the available signal is usually weak in this method. To exploit the advantages of these two methods, we have used an x-ray linear analyzer to adjust a phase plate and measured the polarization with the multiple-diffraction-based analyzer. In this paper, we show experimental results obtained at the vertical-wiggler beamline BL-14B of the Photon Factory.
2. Principle of x-ray transmission phase plates

When x-rays are incident upon a nearly perfect crystal such as a silicon, germanium, or diamond, birefringence (double refraction) takes place around the diffraction condition due to the effects of dynamical diffraction [2]. X-ray phase plates are based on this diffractive birefringence and are classified into two groups: a reflection type which utilizes the diffracted beam, and a transmission type which uses the forward-diffracted beam. To date, x-ray transmission phase plates have been widely used because of their high throughput and polarization tuneability.

The properties of the x-ray transmission phase plates are described by the phase shift, $\delta$, and the polarization conversion ratio, $R$. The phase shift is given approximately as

$$
\delta \approx -\pi \left[ \frac{r_e^2 \operatorname{Re}(F_h F_h^*)}{\pi^2 V^2} \frac{\lambda^3 \sin(2\theta_B)}{\Delta \theta} \right] l,
$$

where $\lambda$ is the wavelength, $V$ is the volume of the unit cell, $r_e$ is the classical electron radius, $F_h$ is the crystal structure factor, $\theta_B$ is the Bragg angle, and $l$ is the x-ray path length in the phase plate. Note that this equation is valid when the offset angle, $\Delta \theta$, is away from the diffraction condition. If $\Delta \theta$ is in the vicinity of the diffraction condition, the phase shift must be rigorously calculated according to the dynamical theory of x-ray diffraction. When $\delta$ is tuned to $(n + 1/2)\pi$ rad (where $n$ is an integer) through $\Delta \theta$, the phase plate works as a quarter-wave plate. At $\delta = (2n + 1)\pi$, the phase plate works as a half-wave plate. The polarization conversion ratio is defined as the transmittance of the x-ray beam. If $\Delta \theta$ is away from the diffraction condition, the polarization conversion ratio is simply given by

$$
R \approx \exp(-\mu l),
$$

where $\mu$ is the linear-absorption coefficient.

Figure 1 shows the calculated phase shift and polarization conversion ratio for 111 Laue-case diffraction from a 2-mm-thick (001)-oriented diamond crystal slab at a wavelength of 0.1239 nm. At $\Delta \theta \approx \pm 54^\circ$, the crystal functions as a quarter-wave plate with $R \approx 23\%$.

The practical values of $\delta$ and $R$ are in fact slightly different from the calculated values due to defects and strain fields in the phase plate. It is often necessary, therefore, to evaluate the polarization

![Figure 1](image_url)
downstream of the phase plate. One of the simplest ways is to use a linear analyzer, and the intensity, $I$, reflected by the analyzer changes with $\Delta \theta$. As an example, let us assume that the analyzer is arranged so that it reflects only the vertically polarized component. In this case, the intensity of the reflected beam is the highest for vertical polarization, the lowest for horizontal polarization, and an intermediate value for circular polarization. By measuring the $\Delta \theta - I$ curve, we can roughly adjust $\Delta \theta$.

Complete determination of the polarization is realized by using an analyzer based on multiple diffraction [6]. A convenient way to satisfy the multiple diffraction condition is to perform a Renninger scan [7]. When the crystal is in the vicinity of the multiple diffraction condition, the detoured reflection, $L$, is excited as well as the main reflection, $H$, which causes interference and polarization mixing inside the crystal. Using these effects we can determine all three components of the Stokes parameters.

3. Experiment and results

The experiment was carried out at the vertical-wiggler beamline BL-14B of the Photon Factory. The x-ray wavelength was tuned to 0.1239 nm by a pair of Si(111) crystals, and Figure 2 shows a schematic of the experimental setup. Higher harmonics in the incident beam were first removed by a Si(220) crystal, and then x-rays linearly polarized in the vertical plane were directed onto a phase plate, for which a 2-mm-thick (001)-oriented diamond crystal slab was used. The (111) plane of the diamond crystal was tilted by 45° with respect to the horizontal plane in order to coherently excite both the $\sigma$- and $\pi$-components with equal amplitude. The polarization of the transmitted beam was controlled through the offset angle, $\Delta \theta$, from the 111 Laue-case diffraction condition.

![Figure 2. The experimental setup for the polarization analysis.](image)

We initially used a Si(620) crystal as the linear analyzer ($\theta_B = 46.22^\circ$) because this is the simplest way for adjusting $\Delta \theta$. The analyzer was mounted on a compact precise goniometer. Figure 3 shows the dependence of $I$ on $\Delta \theta$. The obtained profile is asymmetric with respect to $\Delta \theta$ because of defects and strain fields in the diamond crystal and the slight deviation of the incident polarization from vertical polarization. From this profile and the data shown in Figure 1, we expect that right-handed circular polarization (RHC) is produced at around $\Delta \theta = 0.014^\circ$ and left-handed circular polarization (LHC) at around $\Delta \theta = -0.03^\circ$.

![Figure 3. Observed $\Delta \theta - I$ profile.](image)

We then replaced the linear analyzer with a GaAs (222) crystal in order to perform a complete
determination of the polarization at $\Delta \theta = -0.03^\circ$, 0.014$^\circ$, and 0.25$^\circ$. The glancing angle of the GaAs analyzer crystal, $\theta$, was adjusted to excite the main reflection, $H = (222)$, and the azimuth angle, $\phi$, was rotated to excite the detoured reflections $L = (11\bar{3})$, $(\bar{1} \bar{1} \bar{5})$, and $(\bar{5} \bar{1} \bar{1})$ while maintaining the main reflection. At each $\phi$, the intensity integrated over $\theta$ was measured with an x-ray photodiode detector. The Stokes parameters were determined for each $\Delta \theta$ from the experimental data. Figure 4 shows the polarization ellipses for $\Delta \theta = -0.03^\circ$, 0.014$^\circ$, and 0.25$^\circ$. The polarization was close to LHC at $\Delta \theta = -0.03^\circ$, RHC at $\Delta \theta = 0.014^\circ$, and vertical polarization at $\Delta \theta = 0.25^\circ$. The degree of circular polarization was $-0.70$ at $\Delta \theta = -0.03^\circ$ and $+0.95$ at $\Delta \theta = 0.014^\circ$.

4. Summary
To adjust and characterize an x-ray transmission phase plate, we have used a linear analyzer based on the 45$^\circ$ Bragg diffraction condition and an analyzer based on multiple diffraction. By using the Si(620) linear analyzer, we could adjust the offset angle, $\Delta \theta$, of the diamond phase plate to produce elliptically polarized x-rays. A complete successful determination of the polarization by a Renninger scan of the GaAs(222) analyzer revealed that the degree of circular polarization was $-0.70$ at $\Delta \theta = -0.03^\circ$ and $+0.95$ at $\Delta \theta = 0.014^\circ$.

Acknowledgment
This work was performed under the approval of the Program Advisory Committee of the Photon Factory (2012G046).

References
[1] Hirano K, Izumi K, Ishikawa T, Annaka S and Kikuta S 1991 Jpn. J. Appl. Phys. 30 L407
[2] Hirano K, Ishikawa T and Kikuta S 1993 Nucl. Instrum. Methods Phys. Res. A 336 343
[3] Hirano K, Ishikawa T and Kikuta S 1995 Rev. Sci. Instrum. 66 1604
[4] Giles C, Malgrange C, Goulon J, de Bergevin F, Vettier C, Dartyge E, Fontaine A, Giorgetti C and Pizzini S 1994 J. Appl. Cryst. 27 232
[5] Giles C, Malgrange C, de Bergevin F, Goulon J, Baudelet F, Fontaine A, Vettier C and Freund A 1995 Nucl. Instrum. Methods Phys. Res. A 361 354
[6] Shen Q and Finkelstein K D 1992 Phys. Rev. B 45 5075
[7] Cole H, Chambers F W and Dunn H M 1962 Acta Cryst. 15 138