# Development of Quarter-wave Plates and Full Polarization Measurement near 400 eV

In the soft X-ray region, many types of undulators were made to provide synchrotron radiation (SR) of various polarization states. Polarization measurement is required to obtain the actual polarization state of these light sources. The polarization state can be measured using a phase shifter and a polarizer. Furthermore, polarization elements can change the polarization state of light, for example, from linear polarization to circular polarization. Expensive undulators specialized for a specific polarization state would not be required to obtain the desired polarization state. In this report, we present the developments of a phase shifter near 400 eV and show the results of full polarization measurement using the phase shifter.

The phase shifter has two important parameters, namely, phase retardation ($\Delta$) and polarizance ($P_Z$). $\Delta$ is the phase difference between p- and s- components retarded by transmitting the phase shifter (Fig. 1). With $\Delta = \pm 90°$, the circularly polarized component of the incident light is changed into a linearly polarized component. A phase shifter with $\Delta = \pm 90°$ is called the quarter-wave plate. The non-polarized component is not affected by the $\Delta$ of the phase shifter. The circularly polarized component is distinguished from the non-polarized component using a phase shifter.

$P_Z$ expresses a polarizer ability and is defined as $(T_S - T_P)/(T_S + T_P)$, where $T_P$ and $T_S$ are the transmittances of p- and s-components. Both the circularly polarized component and non-polarized component are changed into linearly polarized component by this property. An element with a large absolute $P_Z$ value works as a polarizer rather than a phase shifter. $P_Z$ is required to be close to zero for a usable phase shifter. An ideal phase shifter with $\Delta = 90°$ and $P_Z = 0$ can transform circularly polarized light to linearly polarized light and vice versa. It enables the measurement of the $P_C$ of highly circularly polarized light with a high accuracy.

In the soft X-ray region, transmitting-type multilayers are used as phase shifters [1]. Sc/Cr multilayers have a large phase retardation near 400 eV. A freestanding Sc/Cr multilayer was designed as a quarter-wave plate by considering the practical interface roughness of $\sigma = 0.35$ nm from the previous work [2]. The incident angle of the multilayer was optimized to 60°, where the multilayer of $\sigma = 0.35$ nm had the largest phase retardation. The designed parameters were the periodic length d = 3.15 nm, the number of periods N = 300, and the ratio of Cr layer thickness $\Gamma$ (= $d_{Cr}$ / d) = 0.47. Figure 2 shows a photograph of Sc/Cr multilayer samples [3].

The evaluation of the Sc/Cr multilayers was performed at beamline **BL27SU** using a versatile apparatus for polarimetry and ellipsometry [2]. The light source of the beamline is a figure-8 undulator and emits linearly polarized light. The absorption edge of the multilayer was 398.2 eV, which was shifted by -0.5 eV from the Sc 2p absorption edge of bulk state, 398.7 eV. The photon energy was selected to be 398.1 eV, because the phase retardation is the largest at the energy of the absorption edge and degrades rapidly at a higher energy.

A rotating analyzer method (RAM) was performed in the versatile apparatus for polarimetry and ellipsometry. The experimental setup of RAM is shown in Fig. 1. A Sc/Cr polarizer was used as an analyzer and rotated with a detector around the incident beam axis. The outputs of the detector against the azimuth of the analyzer follow the Malus law, which has a cosine squared form. The amplitude of the variation of the outputs indicates the degree of linear polarization ($P_L$) and the phase indicates the azimuth of the major axis of polarization ellipse ($\delta$).

To obtain $\Delta$ and $P_Z$, RAM was performed on the incident light (Fig. 1 without the phase

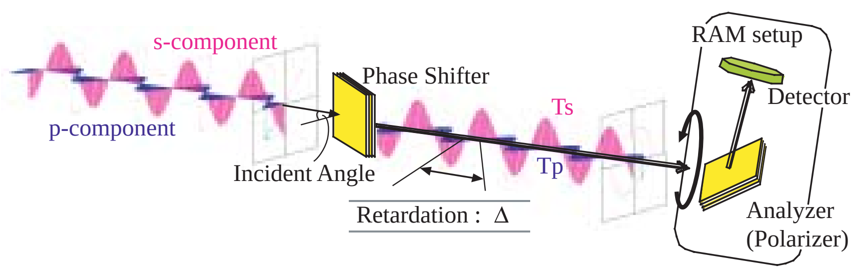


Fig. 1. Schematic view of experimental setup. The polarization state is measured using a phase shifter and a polarizer. The phase shifter changes the phase between the s- and p- components by its phase retardation. The RAM setup contains a polarizer and a detector and is rotated around the incident beam axis.

shifter) and the light transmitted through the phase shifter (Fig. 1 with the phase shifter). The $P_L$ and $\delta$ of the incident and transmitted light were obtained. The differences in $P_L$ and $\delta$ between the incident and transmitted light were changed according to the $\Delta$ and $P_Z$ of the phase shifter and the degree of circular polarization ($P_C$) of the incident light. These $\Delta$ and $P_Z$ were derived from the results of RAM at two different azimuths of the phase shifter [4]. Figure 3 shows the measured $\Delta$ and $P_Z$ as a function of the incident angle from the normal. The maximum and minimum of $\Delta$ values exceeded ±90°. At the incident angle of 59.77°, $\Delta$ was 90°, and $P_Z$ was nearest to zero. The phase shifter can therefore be used as a quarter-wave plate at this incident angle. $P_Z$ was -0.19, and the transmittance of the p-component was 0.4% at the angle. With this quarter-wave plate, we can obtain circularly polarized light from linearly polarized light of $\delta$ = 34.2°.

Next, the Sc/Cr multilayer quarter-wave plate was used for the full polarization measurements of the highly circularly polarized light from the undulators [5]. The experiment was carried out at **BL25SU**. The beamline has twin helical undulators as light sources. The measured $P_C$ values of the right- and left-hand circularly polarized light at the photon energy were 0.96±0.03 and -0.97±0.03, respectively. The twin undulators produced symmetrically circularly polarized light, because the right- and left-handed circularly polarized light have the same absolute $P_C$ values. The $P_L$ values of such light were also measured as 0.10±0.01 and 0.08±0.01, respectively. The degree of polarization ($V = \sqrt{P_C^2 + P_L^2}$) was derived from $P_C$ and $P_L$ as 0.97. The light source was designed to generate circularly polarized light having $|P_C|$ as high as 0.9998. $P_L$ was not sufficient high to explain the degradation of $P_C$ by the transformation of circularly polarized light into linearly polarized light. The investigation of the causes of non-polarization is required to obtain a higher $P_C$.

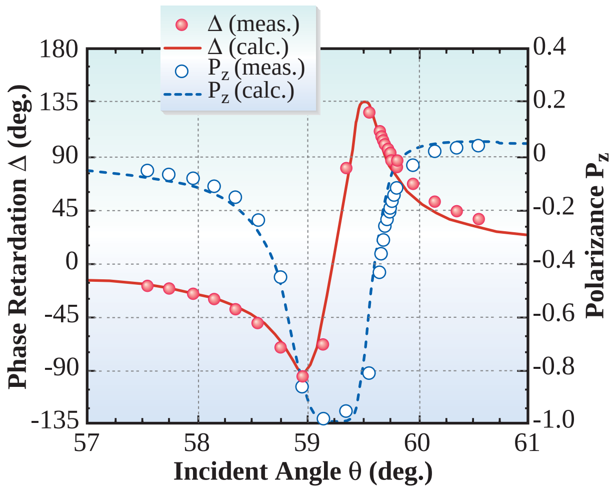


Fig. 3. Measured $\Delta$ and $P_Z$ of Sc/Cr multilayer at 398.1 eV as a function of incident angle from normal. The circles indicate the measured data and the lines indicate the result of fitting with the parameters of photon energy = 398.1 eV, optical indices for Cr = 0.995254 – 0.001006i and for Sc = 1.003401 – 0.000286i, d = 3.05 nm, N = 300, $\Gamma$ = 0.47, $\sigma$ = 0.4 nm, and beam divergence = 0.2°.

Fig. 2. Transmitting-type Sc/Cr multilayers fabricated by X-ray Co., Ltd. [3]. The front and back surfaces of the phase shifters are shown. The central part transmits light where there is no substrate.

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## References

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