Polarization dependence of resonant magneto-optical Kerr effect measured by two types of figure-8 undulators

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The resonant magneto-optical Kerr effect of an Fe nanofilm at the L-edge was investigated by theoretically and experimentally using the polarization controlled undulator. Large values of the Kerr rotation angle ($\theta_K$) were measured at the $L_2$ and $L_3$ absorption edges for both of s- and p-polarized incident lights. Furthermore, the sign changes of $\theta_K$ depending on the photon energy and the polarization of incident light were also observed.

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1. Introduction

Magneto-optical Kerr effect (MOKE) is one of the popular phenomena where photon and magnetism of magnetic materials interact with each other. The light polarization changes from linearly to elliptically and its plane rotates before and after reflection at a surface of magnetic material resulted from MOKE. Its rotation angle is defined as the Kerr rotation angle ($\theta_K$). Observation of the $\theta_K$ and the ellipticity ($\varepsilon_K$) has been used to obtain magnetic information. The MOKE measurement using visible laser as a light source has been widely performed [1,2] and the $\theta_K$ values of magnetic transition metals, such as Fe, Co, and Ni, typically ranged smaller than 1° [3]. Nevertheless, recently, photon energy of incident light has been tuned to the absorption edges of magnetic elements included in a sample in the vacuum ultraviolet (VUV)-X-ray energy region. This MOKE method, called as resonant MOKE, has been mostly applied to transversal MOKE (T-MOKE) [4,5] that shows only intensity variations of the reflected light depending on magnetization, so the $\theta_K$ and the $\varepsilon_K$ values have not been observed. Resonant MOKE can show not only the element-selectivity but also the resonant enhancement [4,6,7]. Other types of resonant MOKE, polar and longitudinal MOKE (P- and L-MOKE), show variations of $\theta_K$ and $\varepsilon_K$, and the $\theta_K$ value is larger than that obtained using visible light. For example, at the L-edges of Fe, Co, and Ni [8,9], resonant L-MOKE measurements were performed and their $\theta_K$ values were larger than 10°. Comparing with resonant T-MOKE and other single intensity measurements using the resonant enhancement, such as X-ray magnetic circular dichroism (XMCD) and X-ray magnetic linear dichroism (XMLD), resonant P- and L-MOKE enable us to determine the both of real and imaginary parts of the magneto-optical constant completely. Therefore, resonant P- and L-MOKE measurements are very useful methods to get much abundant information about spin and magnetization of magnetic materials. They could open up a new field for the study of magnetism. However, because detecting light polarization is difficult in the VUV-X-ray energy region, a few resonant P- and L-MOKE measurements have been performed [8,13].

Recently, we have developed the experimental apparatuses to measure resonant P- and L-MOKE in the VUV-X-ray energy region. Our previous studies reported the results of resonant P-MOKE for a Ni film at the M-edge [14] and a GdFeCo film at the Fe M-edge [15]. In this paper, we demonstrate the polarization dependence of resonant L-MOKE for an Fe nanofilm at the L-edge by combining the rotating-analyzer ellipsometry (RAE) with the polarization controlled synchrotron radiation (SR) at SPring-8 BL07LSU [16]. The difference of $\theta_K$ between s- and p-polarized incident lights was

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investigated theoretically and experimentally. The measured $\theta_k$ for $s$- and $p$-polarized lights shows the large values at the $L_2$ and $L_3$ absorption edges. We also report the result of the sign change of the $\theta_k$ between $s$- and $p$-polarizations in the soft X-ray energy region.

2. Principle of L-MOKE

Fig. 1 shows the geometric set-ups for L-MOKE using $s$- and $p$-polarized incident lights. The linearly polarized light illuminates a sample at an incident angle, $\phi_i$, with respect to the surface normal. A magnetic field ($B$) is applied along the in-plane direction of the sample surface. L-MOKE is theoretically expressed by the complex Fresnel coefficients [11]

$$r_{ss} = (n_0 \cos \phi_i - n \cos \phi_i)/(n_0 \cos \phi_i + n \cos \phi_i),$$

$$r_{pp} = (n \cos \phi_i - n_0 \cos \phi_i)/(n \cos \phi_i + n_0 \cos \phi_i),$$

$$r_{ps} = \frac{-i n_0 (n_+ - n_-) \cos \phi_i}{(n_0 \cos \phi_i + n_0 \cos \phi_i) \cos \phi_i},$$

$$r_{sp} = -r_{ps} = \frac{-i n_0 (n_+ - n_-) \cos \phi_i}{(n_0 \cos \phi_i + n_0 \cos \phi_i) \cos \phi_i}. $$

$r_{ij}$ means a ratio of the incident $j$-polarized electric field and the reflected $i$-polarized electric field. $n_0 (n_0)$ represents the complex refraction constant of the magnetic material (over layer) given by $n \approx (n_0) = 1 - \delta(\omega) + i \beta(\omega)$. It is composed of a real part $1 - \delta(\omega)$ and an imaginary part $\beta(\omega)$ that represent non-magnetic dispersion and absorption, respectively. $n_\pm$ are expressed as $n_\pm = 1 - \delta(\omega) \pm i \beta(\omega)$, where the subscripted sign indicates that the directions of the photon helicity and magnetization are parallel/antiparallel in the sample, and $n = 1/(2(n_+ + n_-)).$ Here $\Delta \delta$ and $\Delta \beta$ denote the magnetic contributions of $\delta(\omega)$ and $\beta(\omega)$, respectively. $\phi_i$ is the angle of refraction. The $\theta_k$ and the $\varepsilon_k$ values for $s$-polarized light ($\theta_k^s$, $\varepsilon_k^s$) and $p$-polarized light ($\theta_k^p$, $\varepsilon_k^p$) in the L-MOKE geometry are expressed by [1]

$$\theta_k^s + i \varepsilon_k^s = -r_{ps}/r_{ss} \approx \frac{-i n_0 n Q}{(n_0^2 - n^2)} \frac{\cos \phi_i \tan \phi_i}{\cos(\phi_i - \phi_i)},$$

$$\theta_k^p + i \varepsilon_k^p = -r_{sp}/r_{pp} \approx \frac{-i n_0 n Q}{(n_0^2 - n^2)} \frac{\cos \phi_i \tan \phi_i}{\cos(\phi_i + \phi_i)}. $$

The Voigt parameter $Q$ for the L-MOKE geometry is given by $Q = (n_+ - n_-)/(n \sin \phi_i)$. When $\phi_i$ is large ($70^\circ \leq \phi_i \leq 90^\circ$) and $\phi_i \approx \phi_i$

[9], the sign changes between $\theta_k^p$ and $\theta_k^s$, $\varepsilon_k^p$ and $\varepsilon_k^s$ are observed due to the sign change of the cosine function in the denominator.

3. Experiment

In this study, the resonant L-MOKE measurement was performed at SPring-8 BL07LSU [16]. Fig. 2(a)-(c) show schematics of a segmented cross-undulator at this beamline which enables us to use SR beam having high energy resolution and high photon flux. It consists of two types of undulators: one is a horizontal figure-8 undulator and the other is a vertical figure-8 (figure-\(\infty\)) undulator, as shown in Fig. 2(a, b). The electron trajectories resemble the figures of eight (8) and infinity (\(\infty\)) in the figure-8 and figure-\(\infty\) undulators, respectively. Four figure-8 undulators and four figure-\(\infty\) undulators line up alternately, as shown in Fig. 2(c). Vertical (horizontal) polarized light is generated by the four figure-8 (figure-\(\infty\)) undulators and their degrees of linear polarization, $P_e$, are 100% [16]. Seven phase shifters are set between the figure-8 and the figure-\(\infty\) undulators, respectively, to make an optical delay between the horizontal and vertical electric fields. They can control the polarization of light not only horizontally and vertically linearly but also skew linearly, circularly, and elliptically. Further details of this beamline can be found in the report by S. Yamamoto et al. [16].

Fig. 2(d) shows a set-up of the resonant L-MOKE measurement. The Ta/Cu/Fe/MgO heterostructure sample was used in this experiment. A 30-nm-thick Fe nanofilm was epitaxially grown on the MgO(001) substrate by magnetron sputtering and it was then capped with Ta (2 nm thick) and Cu (2 nm thick) layers to prevent

![Figure 1](image1.png)

**Fig. 1.** Schematic of the geometries of L-MOKE. The incident light beams are $s$- (a) and $p$-polarized (b) with incident angle $\phi_i$. The polarizations of reflected lights from the sample change to elliptically and these polarization planes are rotated. These rotation angles are defined as $\theta_k^s$ and $\theta_k^p$ for $s$- and $p$-polarized lights, respectively. A magnetic field ($B$) is applied along the in-plane direction of the sample surface.

![Figure 2](image2.png)

**Fig. 2.** (a, b) Schematics of the figure-8 undulator (a) and the vertical figure-8 (figure-$\infty$) undulator (b). (c) Schematic of the segmented cross-undulator at SPring-8 BL07LSU. It consists of four figure-8 undulators, four figure-$\infty$ undulators, and seven phase shifters. (d) Set-up of the resonant L-MOKE measurement. SR beam was adjusted to $s$- or $p$-polarizations. The values of $\theta_k$ were measured by RAE composed of a multilayer mirror and a MCP.
the Fe layer from oxidization. The Fe nanofilm has an in-plane easy direction of magnetization. SR beam was incident onto the sample with $\phi_i$ was about 80° respect to the surface normal. Its polarization was adjusted to $s$- or $p$-waves. A magnetic field ($B$) of ±0.3 T, where the magnetization of the Fe nanofilm saturates, was applied along the in-plane direction of the sample surface by the split-coil magnet. The sample temperature was room temperature during the measurement.

The $\theta_K$ values were obtained by the RAE composed of a multilayer mirror and a micro-channel plate (MCP), as shown in Fig. 2(d). Further details of this method can be found in our previous paper [14]. In the RAE, $\theta_K$ for $s$-polarized incident light can be determined from the difference in the ellipsometry curves taken under opposite magnetic fields: $2\theta_K = \theta(-B) - \theta(+B)$, as shown in Fig. 3(a). On the other hand, for $p$-polarized incident light, it should be taken into account that $r_{np}$ includes $n_+ - n_-$, which sign is inverse to $n_+ - n_-$ in $r_{ns}$, as shown in Eqs. (3) and (4). The $\theta_K^p$ value was calculated by $2\theta_K^p = \theta(+B) - \theta(-B)$ based on the Onsager relations.

4. Results and discussion

Fig. 3 shows the results of the resonant L-MOKE measurement for the Fe nanofilm obtained by the RAE. The incident photon energies were chosen at $h\nu = 709$ and 722 eV where the $2\theta_K^p$ spectrum (not shown) has peaks corresponding to the Fe L$_2$ and L$_3$ absorption edges, respectively. From the intensity variation spectra with rotation angle, $\chi$, as shown in Fig. 3, $\theta_K^s$ and $\theta_K^p$ of the Fe nanofilm were determined as $\theta_K^s = -18°$ and $\theta_K^p = 14°$ at 709 eV, and $\theta_K^s = 7°$ and $\theta_K^p = -6°$ at 722 eV, respectively. It is indicated that resonant L-MOKE for $s$- and $p$-polarized incident light shows comparable large values of $\theta_K$ at the L$_2$- and L$_3$-edges and its sign inversions. Moreover, one can also see the sign change of $\theta_K$ between $s$- and $p$-polarized lights both at 709 and 722 eV. These results are consistent with the theory, as shown in Eqs. (5) and (6), and the previous experiment using Co based multilayers with visible light [17]. An absolute value of $\theta_K^p$ is close to that of $\theta_K^s$ when $\phi_i$ is large and $\phi_i \approx \phi_h$. The small difference is derived from the contribution of the incident angle in Eqs. (5) and (6). The $\theta_K^p$ value can be compared with those calculated from Eq. (5) with appropriate parameters. Details of the evaluation are described elsewhere [18].

5. Summary

In the present study, we provide the result of resonant L-MOKE for the Fe nanofilm at the L-edge depending on the incident light polarization fully utilizing the performance of the BL07LSU beamline at SPRing-8. The large values of $\theta_K^s$ and $\theta_K^p$ were observed and showed the sign change between at the L$_2$- and L$_3$-edges. Moreover, we could also report the sign change between the $\theta_K^s$ and the $\theta_K^p$ values at the same photon energies expected by the theoretical calculation, as shown in Eqs. (5) and (6). To the best of our knowledge, observing such sign change is the first demonstration in the soft X-ray energy region. The segmented cross-undulator at this beamline can generate not only $s$- and $p$-polarizations but also the skew linearly polarization that allows one to obtain much detailed information on magnetism of a sample.

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