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Soft x-ray polarizer for optical productions of any orthogonal state of the linear and circular polarization modes

Dae-Eun Jeong, Ki-Suk Lee, and Sang-Koog Kim[a)]
Research Center for Spin Dynamics & Spin-Wave Devices (ReC-SDSW) and Nanospintronics Laboratory, School of Materials Science and Engineering, College of Engineering, Seoul National University, Seoul 151-744, South Korea

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An efficient soft x-ray polarizer that is able to optically convert a linear polarization state to any orthogonal state of *not only linear but also circular polarization modes* is found by means of numerical calculations of the intensities of individual orthogonal polarization components in reflected waves. Calculation results, using the known linear-polarization-mode based Kerr matrix as well as a newly derived circular-polarization-mode based Kerr matrix, indicate that a +45° or −45° linearly polarized incident wave can be readily converted to any orthogonal states of both circular and linear polarization modes, i.e., left- and right-handed circular and *s*- and *p*-linear polarizations through reflection, at certain grazing angles of incidence near the critical angle from a simple ferromagnetic thin film of Co(9.0 nm)/Si substrate. The intensities of almost pure circularly or linearly polarized reflected waves are about 10% or less in a certain spectral soft x-ray range just below the absorption edges of constituent magnetic elements. The counterpart orthogonal states of the linear as well as circular modes can be rapidly switched simply by reversing oppositely the orientation of longitudinal magnetizations. These results suggest that the orthogonal polarization states of the circular- and linear-polarization modes converted from such a polarizing optical element through reflection can be practically used in probing the vector quantities of element specific magnetizations in multicomponent magnetic materials. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2200753]

In the research field of magnetic materials and magnetism characterizations, the orthogonal eigenstates of not only the left (L)- and right (R)-handed circular but also the *s*- and *p*-linear polarizations of high photon-flux synchrotron x rays have been widely used as an essential probe to investigate both the magnitudes and orientations of element-specific magnetic moments in multicomponent magnetic materials, and their response to an applied magnetic field, as well as spatial correlations on the multiple-length scales.[1–7] This is because the individual orthogonal states of the linear or circular polarization mode are extremely sensitive differently to the transverse, longitudinal, and polar orientations of magnetizations in the vicinity of the absorption edges for various 3*d* transition metals or 4*f* rare earths in the soft x-ray range roughly from 50 eV to 2 keV.[8]

Therefore, special insertion devices such as an elliptically polarizing undulator (EPU) have been facilitated in order to effectively produce high photon flux, energy tunable, circular, or linear polarization eigenmodes.[9,10] Although the linear and circular polarizations produced from such an EPU have been widely used, optical productions of circularly or linearly polarized soft x rays have also been realized using various polarizing optical elements made of artificially fabricated magnetic thin films suitable in the soft x-ray range. In such optical elements, there are, for example, phase retarders based on transmission multilayer structures,[11,12] and magneto-optical circular polarizing filters employing the magnetic circular dichroism (MCD) effect[13] which convert a linear to circular polarization. As another example, a tunable linear polarizer based on reflecting interference structures of a wedge-typed multilayer rating selectively reflects linearly *s*-polarized waves with high reflectivities in some spectral energy range of interest at Brewster's incidence angle (near 45° incidence). This linear polarizer can thus be also used as an analyzer to determine the degree of a linear polarization P_L in the soft x-ray region.[14–17]

In this letter, we report on a theoretical design of an efficient soft x-ray polarizer that enables to optically convert a linear polarization to any orthogonal states of not only the L- and R-circular polarizations but also the linear *s*- and *p*-polarizations in reflection, using a simple thin-film structure. Numerical calculations reveal that the orthogonal eigenstates of the linear and circular polarization modes of waves reflected from such a polarizer can be produced with the degree of polarizations greater than 0.95 in a certain energy range just below the absorption edges, and are switchable rapidly by reversing the orientation of longitudinal magnetizations, $\mathbf{M}_{\text{long}}$. More interestingly, changing the grazing angle of incidence ϕ leads to a switching between the linear and circular modes.

In order to search for such a polarizing optical element, we employed numerical calculations of total intensities and the individual components of the orthogonal states of either L- and R-circular modes or *s*- and *p*-linear modes in reflected wave, as a function of ϕ for various polarization states of incident waves, as indicated in Fig. 1, from a model system of Co(9.0 nm)/Si substrate. For the calculations, we used the well-known Kerr matrix based on the linear polarization mode, as well as the circular-polarization-mode based Kerr matrix derived in our earlier work.[18]

[a)]Author to whom correspondence should be addressed; electronic mail: sangkoog@snu.ac.kr

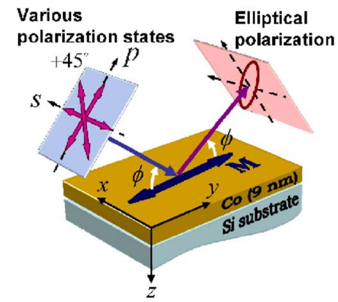

FIG. 1. (Color online) Schematic illustration of a specular reflection geometry of incident and reflected waves for a model system of a 9.0-nm-thick Co film onto a Si substrate with either orientation of the opposite longitudinal magnetizations of Co. Linearly polarized s, p, and +45° states of incident waves are displayed as indicated. The symbols shown in this figure are defined in the text.

Figures 2(a) and 2(b) show calculations of the total intensity $I_{\pm}^{\mathrm{tot}}$ and the individual components of either the s- and p-linear modes $I_{\pm}^{s,p}$ or the R- and L-circular eigenmodes $I_{\pm}^{R,L}$ at a photon energy of $h\nu=770.1$ eV far below the Co L_3 edge ($h\nu=778.1$ eV), for linearly s- and p-polarized incident waves with the opposite $\mathbf{M}_{\mathrm{long}}$, i.e., $m_y=+1$ and -1. As can be seen, extremely large contrasts in intensity between the orthogonal R- and L-circular components are obtained at a specific angle of $\phi=0.66°$, indicating that almost pure circular polarizations can be produced at that angle from both linearly s- and p-polarized incident waves. It is also revealed that the opposite photon helicities of the circular mode can be switched simply by reversing the orientation of $\mathbf{M}_{\mathrm{long}}$. In contrast to that angle, the intensities of the R- and L-components at a different angle of $\phi=1.09°$ are observed to be the same and simultaneously the intensities of the s- and p-components are the same as well, and hence indicating an optical production of either +45° or −45° linear polarization state at that angle. For linearly p-polarized incident waves, the same results are also found at the exactly same angles, as shown in Fig. 2(b). The degree of circular polarization P_c calculated versus ϕ, as shown in the inset of Fig. 2(b), reaches $P_c \simeq +1$ or -1 at $\phi=0.66°$ and $P_c \simeq 0$ at $\phi=1.09°$.

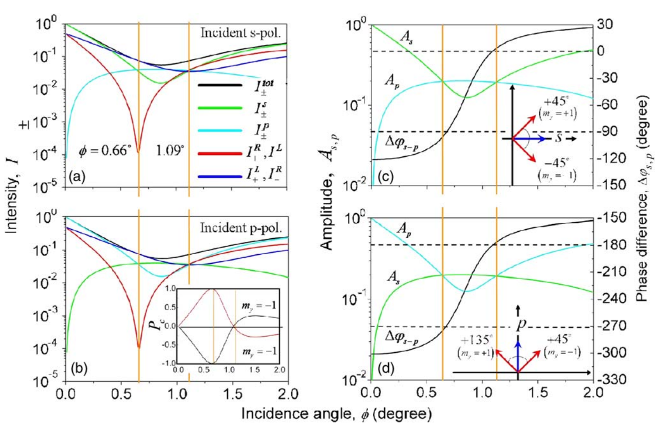

FIG. 2. (Color online) (a) and (b) show the total and individual intensities of the orthogonal components of either the s- and p-linear polarization modes or L- and R-circular modes in reflected waves vs the grazing angle of incidence ϕ from a model system of Co (9.0 nm)/Si substrate with either orientation of longitudinal magnetizations, $m_y=+1$ or $m_y=-1$ for linearly s- and p-polarized incident waves of a photon energy of $h\nu=770.1$ eV. The inset in (b) shows the degree of circular polarization P_C vs ϕ for both the incident s and p polarizations and $m_y=\pm 1$. (c) and (d) show the calculated electric-field amplitudes of the linear s- and p-polarization components, respectively, for $m_y=+1$ and their phase difference. Each inset in (c) and (d) indicates the resulting polarization state of reflected waves for both cases of $m_y=\pm 1$ at $\phi=1.09°$, as noted. The two different vertical lines are drawn at the two different angles of $\phi=0.66°$ and 1.09°, at which pure circular polarizations and ±45° linear polarizations are converted, respectively.

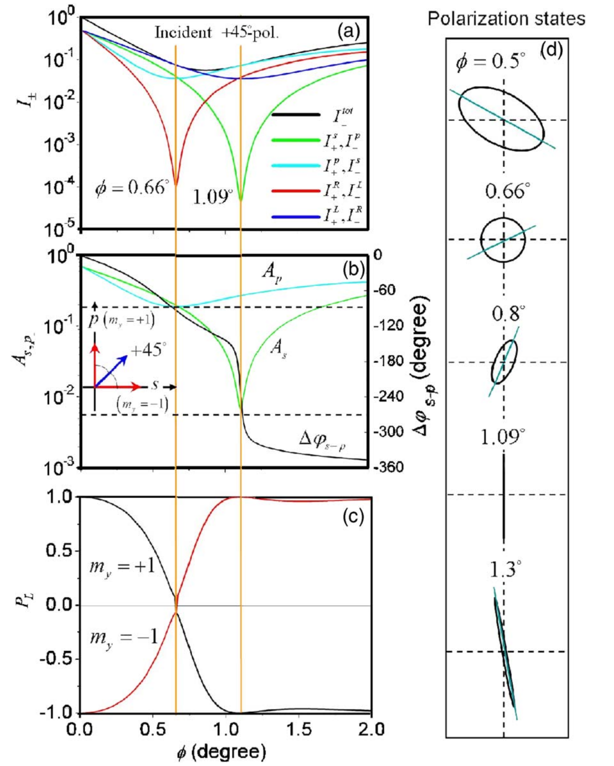

FIG. 3. (Color online) The same calculations as those shown in Fig. 2, but for a +45° linear polarization of incident waves is displayed in (a)–(c). Various polarization states of a reflected wave obtained at different incident angles as noted are illustrated in (d).

To better understand these two contrasting phenomena observed at the two different angles, the amplitudes $A_{s,p}$ and phases $\varphi_{s,p}$ of the electric fields of the orthogonal s- and p-polarization states along with their phase difference, $\Delta\varphi_{s-p}=\varphi_s-\varphi_p$, for reflected waves are plotted, e.g., for both cases of the incident s and p polarizations in Figs. 2(c) and 2(d), respectively. At the angle of $\phi=0.66°$, the orthogonal components have almost an equal amplitude and simultaneously the p polarization leads the other s state in phase, i.e., $\Delta\varphi_{s-p}=-90°$. The resultant polarization state is thus a circular L (R) mode for $m_y=+1(-1)$. At the other angle, $\phi=1.09°$, their equal amplitude value along with their equal phase consequently indicates that the resulting linear polarization is just a +45° (−45°) linear mode for $m_y=+1(-1)$. The photon helicity of the circular mode at $\phi=0.66°$ depends on the orientation of $\mathbf{M}_{\mathrm{long}}$, which also determines whether +45° or −45° linear polarization is converted at $\phi=1.09°$. This indicates that fast switchings between the orthogonal states of the circular mode, and between +45° and −45° linear polarizations can be achieved simply by oppositely reversing $\mathbf{M}_{\mathrm{long}}$ with applying a sufficient magnetic field, as fast as the speed of the $\mathbf{M}_{\mathrm{long}}$ reversal. In addition, the circular and linear polarization states can be possibly switchable just by changing ϕ from $\phi=0.66°$ to 1.09° or vice versa.

Based on the findings mentioned above, more interesting results are additionally obtained for the cases of +45° or −45° linearly polarized incident waves, as seen in Fig. 3. The

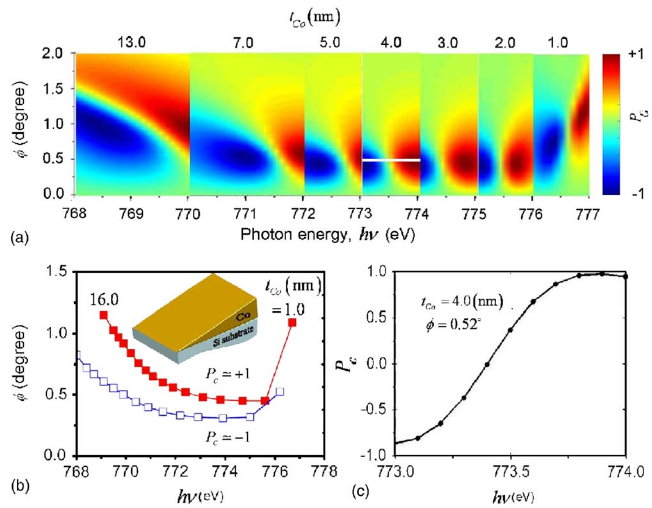

FIG. 4. (Color online) (a) Color-coded contour images of the degree of circular polarization P_c against both ϕ and $h\nu$ for the varying thicknesses of a Co film, t_{Co}, as noted. (b) Plots of the relations of ϕ and $h\nu$ at which the P_c value of each photon helicity is satisfied to be greater than 0.95 for the varying t_{Co}. Each point starts from 1.0 and ends at 16.0 nm at an interval of 1.0 nm. The inset in (b) shows a wedge-type Co film covering its thickness ranging from 0 to 20 nm. (c) shows the dependence of P_c on $h\nu$ for $\phi = 0.52°$ and $t_{\mathrm{Co}} = 4.0$ nm.

intensities of the individual orthogonal components of the circular and linear polarization modes are remarkably contrasting at $\phi = 0.66°$ and $\phi = 1.09°$, respectively, by about two orders of magnitudes. Consequently, a pure circular L or R polarization is optically produced with almost 10% reflectivities at $\phi = 0.66°$, while a pure s or p linear polarization at $\phi = 1.09°$ and their switching by the $\mathbf{M}_{\mathrm{long}}$ reversal. The degree of linear polarization, P_L ($P_L = \pm\sqrt{1-P_c^2}$) in Fig. 3(c) itself proves its remarkable change with ϕ, as $P_L = 0$ at $\phi = 0.66°$ and $P_L = \pm 1$ at $\phi = 1.09°$. As already mentioned in Fig. 2, the counterpart orthogonal states of the linear and circular polarization modes are readily switchable with $\mathbf{M}_{\mathrm{long}}$ reversals. For clearness, the polarization states of a reflected wave as a function of ϕ are illustrated in Fig. 3(d), as example, for a +45° linearly polarized incident wave of $h\nu = 770.1$ eV and $m_y = +1$. These results imply that ±45° linearly polarized incident waves are practically useful for such a polarizing optical element that allows us to produce both pure circular and linear polarization modes with a simple and fast switchability between their orthogonal states in the soft x-ray range.

Next, in order to examine their spectral responses, we also calculate P_c versus both $h\nu$ and ϕ for the different thicknesses of a Co film, t_{Co}, as shown in Fig. 4(a). The value of P_c varies noticeably with $h\nu$ and ϕ, depending on t_{Co}. Therefore, the values of both $h\nu$ and ϕ, where P_c approaches almost ±1, vary with t_{Co}, as shown in Fig. 4(b). This implies that a highly pure circular polarization can be obtained in a certain spectral range by controlling both values of ϕ and t_{Co}, through a wedge-type ferromagnetic film covering such a thickness range shown in the inset of Fig. 4(b). For the other case of the linear mode, similar spectral responses were also observed (not shown here). Although the spectral energy range for optical productions of a pure circular or linear polarization is limited to a certain $h\nu$ range of about 10 eV below the absorption edges of constituent magnetic elements, this partial energy tunability in the optical productions of any polarization states is relatively useful compared to a MCD filter that is limited to the L_3 or L_2 line.

Finally, we suggest that such polarizing optical elements be implemented upstream on synchrotron radiation beamlines to produce the s- and p-linear as well as the L- and R-circular polarization states with almost pure degree of each polarization, fast switchings between them, and their partial energy tunability just below the absorption edges, along with about 10% reflectivity. Since orthogonal polarization eigenstates of the linear and circular modes are extremely sensitive differently to the orientation of magnetizations, such a soft x-ray polarizer could be practically useful to produce and quickly switch various orthogonal polarization states for the investigations of the orientation of magnetizations of specific magnetic elements and oxidation-site specific magnetic moments even under their nonsaturated magnetized states, especially in response to an applied magnetic field.[19,20]

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[1] E. Goering, A. Bayer, G. Gold, G. Schütz, M. Rabe, U. Rüdiger, and G. Güntherodt, Phys. Rev. Lett. **88**, 207203 (2002).
[2] H. Ohldag, A. Scholl, F. Nolting, E. Arenholz, S. Maat, A. T. Young, M. Carey, and J. Stöhr, Phys. Rev. Lett. **91**, 017203 (2003).
[3] J. S. Claydon, Y. B. Xu, M. Tselepi, J. A. C. Bland, and G. van der Laan, Phys. Rev. Lett. **93**, 037206 (2004).
[4] D. J. Huang, C. F. Chang, H.-T. Jeng, G. Y. Guo, H.-J. Lin, W. B. Wu, H. C. Ku, A. Fujimori, Y. Takahashi, and C. T. Chen, Phys. Rev. Lett. **93**, 077204 (2004).
[5] S.-K. Kim, K.-S. Lee, J. B. Kortright, and S.-C. Shin, Appl. Phys. Lett. **86**, 102502 (2005).
[6] K.-S. Lee, S.-K. Kim, and J. B. Kortright, J. Appl. Phys. **96**, 7414 (2004).
[7] K.-S. Lee, S.-K. Kim, and J. B. Kortright, Appl. Phys. Lett. **83**, 3764 (2003).
[8] P. Carra, B. T. Thole, M. Altarelli, and X. Wang, Phys. Rev. Lett. **70**, 694 (1993).
[9] S. Sasaki, K. Miyata, and T. Takada, Jpn. J. Appl. Phys., Part 2 **31**, L1794 (1992).
[10] R. Carr, J. B. Kortright, M. Rice, and S. Lidia, Rev. Sci. Instrum. **66**, 1862 (1995).
[11] J. B. Kortright, H. Kimura, V. Nikitin, K. Mayama, M. Yamamoto, and M. Yanagihara, Appl. Phys. Lett. **60**, 2963 (1992).
[12] M. Yamamoto, M. Yanagihara, H. Nomura, K. Mayama, and H. Kimura, Rev. Sci. Instrum. **63**, 1510 (1992).
[13] J. B. Kortright, S.-K. Kim, T. Warwick, and N. V. Smith, Appl. Phys. Lett. **71**, 1446 (1997).
[14] J. B. Kortright, M. Rice, and K. D. Frank, Rev. Sci. Instrum. **66**, 1862 (1995).
[15] M. Drescher, G. Snell, U. Kleinegerg, H.-J. Stock, N. Müller, U. Heinzmann, and N. B. Brookes, Rev. Sci. Instrum. **68**, 1939 (1997).
[16] J. B. Kortright, M. Rice, S.-K. Kim, C. C. Walton, and T. Warwick, J. Magn. Magn. Mater. **191**, 79 (1999).
[17] F. Schäfers, H.-C. Mertins, A. Gaupp, W. Gudat, M. Mertin, I. Packe, F. Schmolla, S. Di Fonzo, G. Soullié, W. Jark, R. Walker, X. Le Cann, R. Nyholm, and M. Eriksson, Appl. Opt. **38**, 4074 (1999).
[18] D.-E. Jeong, K.-S. Lee, and S.-K. Kim, J. Korean Phys. Soc. **46**, 1180 (2005).
[19] M. Magnuson, S. M. Butorin, J.-H. Guo, and J. Nordgren, Phys. Rev. B **65**, 205106 (2002).
[20] M. Abbate, J. C. Fuggle, A. Fujimori, L. H. Tjeng, C. T. Chen, R. Potze, G. A. Sawatzky, H. Eisaki, and S. Uchida, Phys. Rev. B **47**, 16124 (1993).