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THEORETICAL STUDIES ON POLARIZATION CONTROL OF SEGMENTAL UNDULATOR SYSTEM*

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Abstract

Polarization control of undulator radiation attracts a great attention due to its application prospects in material and biology. Various undulators have been developed to obtain radiation of specific polarization states. In the electron storage ring light source, different methods have been proposed to realize a specific polarization switching. However, there is still a strong demanding to improving the switching speed and/or increasing the available polarization state in a single beam line. This paper gives systematic analysis of simple schemes to obtain the polarization switching by using the segmentation of the undulators with the phase shifter placed between each adjacent undulators. Through switching the polarization state of each undulator and the phase shifts, the polarization state can be fast switched between different polarization states in a same undulator line. The theoretical analysis for the radiation characteristics under different undulator configurations are demonstrated to reveal the basic principle of this simple method.

INTRODUCTION

To control the polarization state of the undulator, several types of undulators, such as APPLE-II [1] and DELTA [2] undulators, have been developed and utilized. With the development of material and biology, users have a great demand for XMCD and XMLD, which have great dependence on polarization control and switching. Through mechanically shifting the magnet array of the permanent-magnet undulator, the polarization state can be easily switched, but the polarization switching speed is limited. The switching frequency between different polarization states can only achieve the level of Hz.

The storage ring light source has attracted more and more attention because of its excellent radiation performance. To realize the fast switching of radiation polarization, many methods have been proposed, such as photon beam line switching, electron beam orbit switching and the nature close orbit switching. However, these methods are faced with different issues and can not ensure a high switching frequency in the normal operation mode of storage ring. Polarization control schemes based on phase shifters and segmental undulators have been paid more and more attention. Fast switching schemes of HLP/VLP or LCP/RCP with segmental planar (helical) undulators have been proposed [3–7].

In this paper, we give the theoretical studies on polarization control of segmental undulator system. Specific examples of polarization control and fast switching have been analyzed to show the power spectrum and polarization state of the radiation from a segmental linear (helical) undulator system. Each undulator is assumed to be the typical APPLE-II undulator, thus both the linear and circular polarization state can be selected. All of the systems analyzed in this paper can be realized in a same undulator line.

PRINCIPLE

We first assuming that the radiation from a single planar undulator is a N-cycle cosine wave. The frequency spectrum of a cosine wave around the certain frequency is obtained by fourier transformation:

$$E_f(\omega) \approx \frac{E_0 T}{2} \mathrm{sinc}\left[(\omega - \omega_1)\frac{T}{2}\right] \tag{1}$$

where E_0 is the amplitude of the electric field, ω_1 is the fundamental frequency, $T = 2\pi N/\omega_1$ is the time duration of the radiation and N is the period number of the undulator. ω_1 is fully depending on the observation angle θ as

$$\omega_1(\theta) = \omega_1(0)\frac{1+K^2}{1+K^2+\gamma^2\theta^2} \tag{2}$$

where K is the undulator strength parameter and γ is the Lorentz factor of the electron .When there are M undulators and the adjustable phase shifter between the (m)th and (m-1)th segment is δ_m, the amplitude of the electric field E_f can be calculated as:

$$E_f(\omega) = \sum_{m=1}^{M} \int_{-\frac{T}{2}}^{\frac{T}{2}} E_m(t) e^{-i\omega\left[t+(m-1)T+\sum_{m=1}^{M}\delta_m\right]} \mathrm{d}t. \tag{3}$$

In order to better analyze the relationship between the polarization state and phase shift of the system, we give the following four typical examples, which are shown in Fig. 1.

Each system is composed of $2M$ undulators, but the polarization state of each segment and the arrangement of different undulators are different, and the relevant analysis will be carried out below. Obviously, adjusting the phase shifts between undulators can change the power spectrum at the frequency we are concerned with. The power spectrum

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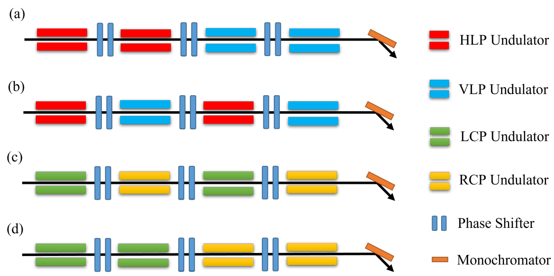

Figure 1: Polarization control and switch of (a) HLP/VLP radiation and (b) LCP/RCP radiation at the segmental linear undulators and polarization control and switch of (c) HLP/VLP radiation and (d) LCP/RCP radiation at the segmental helical undulators

of a M-segment undulator system is:

$$\begin{aligned} I_{Mplanar}(\omega) &= \frac{\sin^2(M\omega(T+\delta)/2)}{\sin^2(\omega(T+\delta)/2)} E_f(\omega,T)E_f^*(\omega,T) \\ &= E_f^2(\omega)\frac{\sin^2[M(2\pi N+\Delta\varphi)\omega/2\omega_1]}{\sin^2[(2\pi N+\Delta\varphi)\omega/2\omega_1]}. \end{aligned} \tag{4}$$

We need to explain that in this M-segment undulator system, each planar undulator is the same and each phase shifter between two adjacent undulators is set to the same ($\Delta\varphi_m = \omega_1\delta_m = \Delta\varphi, m \geq 2$). Focusing on the equation above, it is easy to get that the power spectrum only depends on the phase shift between two adjacent undulators if $\omega = \omega_1$, only considering about the fundamental frequency on axis. The period of the function is 2π, and there are $2M + 1$ extreme points, of which $M + 1$ are analytic, respectively, and $M - 2$ are non-analytic. If $\Delta\varphi = 2\pi/M$and $\Delta\varphi \neq 2\pi, 0$ (M is an even number), the energy spectrum at $\omega = \omega_1$ is vanished. It is only when the phase shift is 2π or 0 that the power spectrum gets the maximum. Each nonanalytic point is located between two adjacent minimum points in the period, corresponding to an extreme value, not a maximum value. As shown in Fig. 1(a), the first M segments are HLP undulators and the next M undulators are VLP undulators. HLP (VLP) radiation can be collected if the phase shifts between HLP undulators are set to 0 (π) while the phase shifts between another VLP undulators are set to π (0).

By setting the phase shifts between HLP undulators to 0 and the same with VLP undulators, the segmental undulators can be viewed as a long HLP undulator and a long VLP undulator. Both HLP and VLP radiation can be collected. If we set the phase shift between the last HLP undulator and the first VLP undulator to 0 (π), RCP (LCP) radiation can be collected finally, realizing the fast switching of RCP/LCP. In this mode, the source points of HLP and VLP radiation are different and the distance of two source points is approximately half the total length of the undulator system, which possibly result in a sharp reduction on polarization degree.

Of course, if we set the first M segments to LCP and the next M segments to RCP, we get the system in Fig. 1(d). But the power spectrum doubles because circular polarization can be viewed as a superposition of two cross linear polarizations.

$$I_d(\omega) = 2E_f^2(\omega)\frac{\sin^2[M(2\pi N+\Delta\varphi)\omega/2\omega_1]}{\sin^2[(2\pi N+\Delta\varphi)\omega/2\omega_1]}. \tag{5}$$

If the phase shifts between LCP undulators are set to 0 while the phase shifts between another RCP undulators are set to π, RCP radiation has few flux on the axis and LCP radiation can be collected. Obviously, LCP and RCP radiation can be mutually switched when we swap the phase shifts of LCP and RCP segments.

For the helical undulator system in Fig. 1(c), each helical undulator segment has an opposite polarization state to its adjacent segments. Particularly, if M is an even number, $I_c(\omega)$ can be described as:

$$I_c(\omega) = 4E_f^2(\omega)\frac{\sin^2[M(2\pi N+\Delta\varphi)\omega/2\omega_1]}{\sin^2[(2\pi N+\Delta\varphi)\omega/\omega_1]}. \tag{6}$$

We need to further analyze the polarization depending on phaseshifts. The relationship between E_x and E_y is:

$$\begin{aligned} E_y(\omega) &= E_x(\omega)\frac{1-\cos[(2\pi N+\Delta\varphi)\omega/\omega_1]}{\sin[(2\pi N+\Delta\varphi)\omega/\omega_1]} \\ &= E_x tan[(2\pi N+\Delta\varphi)\omega/\omega_1] \\ &= E_x tan(\varphi). \end{aligned} \tag{7}$$

The period of the power spectrum is π, It's only when the phaseshift is π or 0 that the power spectrum gets the maximum, but the polarization states of π and 0 are different.

And as for the system of cross-planar undulators shown in Fig. 1(b), the adjacent two undulators can be merged into a whole which equals to a helical undulator. LCP or RCP radiation can be selected by adjusting the phase shift between these two undulators. So that a $2M$ system of planar undulators equal to a M system of helical undulators in Fig. 1(c) or Fig. 1(d).

To clearly demonstrate the above theoretical analysis of the system in Fig. 1, we perform the corresponding qualitative analysis with the basic undulator parameters, as shown in Fig. 2. The helical undulator parameters given in Table. 1 are taken as the examples. The systems in Fig. 1(c) and Fig. 1(d) are analyzed. The corresponding qualitative analysis of systems in Fig. 1(a) and Fig. 1(b) are not shown because they are similar to the helical undulator system. Here we keep the total period number equal to 80 and choose $N = 10$ and $M = 4$. The normalized angle Θ is set to $\gamma\theta/\sqrt{1+K^2}$. For the system in Fig. 1(c), the polarization angle increases linearly from 0° (horizontal) to 90° (vertical) with the phase shift increasing from 0 to π, while the on-axis energy spectrum achieves the maximum at 0° and 90° polarization angle. At the phase shift of $\Delta\varphi = 2\pi/M$ and $\Delta\varphi \neq 2\pi, 0$, the on-axis energy spectrum is vanished. For the system in Fig. 1(d),

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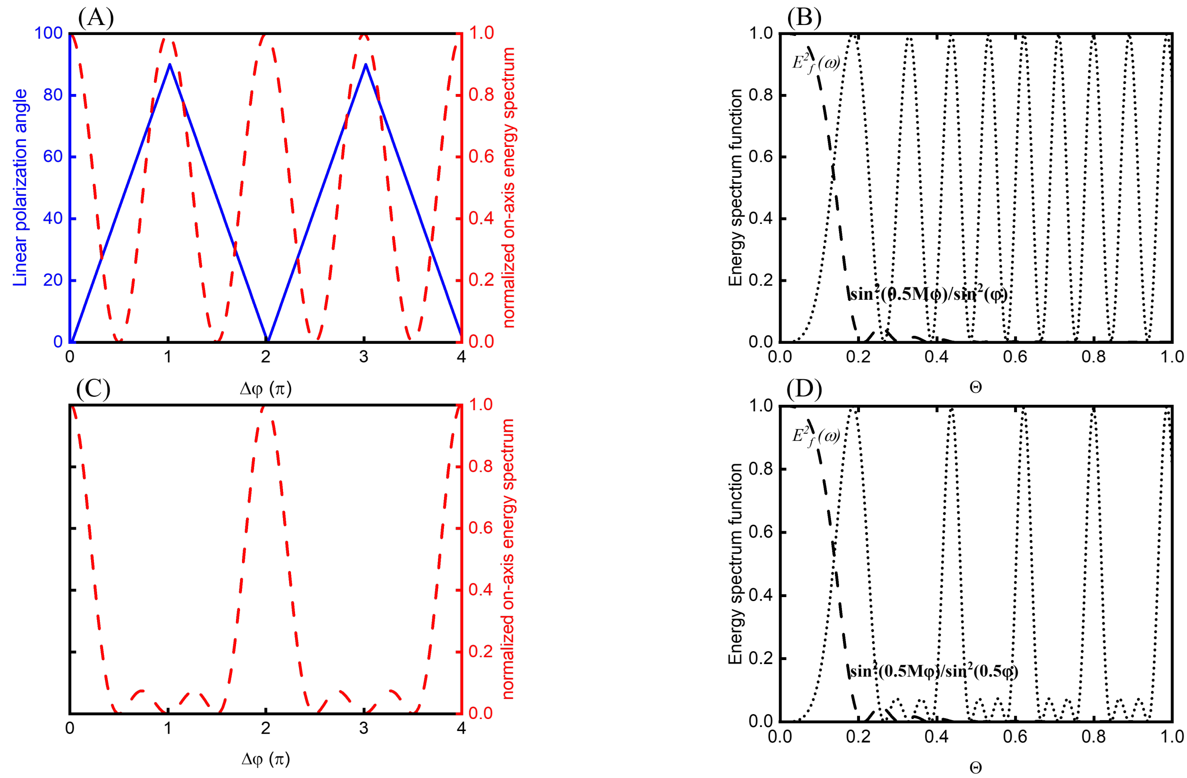

Figure 2: The qualitative analysis of radiation characteristic for the systems in Fig1.(c) and Fig1.(d) with $M = 4$. (A) The polarization angle and normalized on-axis energy spectrum depend on the phase shift of system (c). (B) The energy spectrum function in Eq. (6) depends on the normalized observation angle with $\Delta\varphi = \pi$ of system (c). (C) The normalized on-axis energy spectrum depends on the phase shift of system (d). (D) The energy spectrum function in Eq. (5) depends on the normalized observation angle with $\Delta\varphi = 2\pi/M$ of system (d).

if the phase shifts of the LCP (RCP) undulators are 0 and the phase shifts of the RCP (LCP) undulators are $2\pi/M$,RCP (LCP) radiation is vanished and LCP (RCP) undulators equal to a long LCP (RCP) undulator, the radiation collected is LCP (RCP). Note that here we only analyze the system which consists of M same helical undulators , i.e., the first M undulators in Fig. 1(d). The phase shifts are set to $\pi/2$, then the polarization angle is not changed in this system.

Table 1: The Basic Parameters used in Analysis

Parameter	Specification	Unit
Period number per segment N	10	–
Segment number M	4	–
Period length	25	mm
Undulator strength parameter K	0.916	–
Target photon energy	1000	eV
Lorentz factor γ	4305	–

CONCLUSION

In this paper, we give a summary and the theoretical studies on polarization control of segmental linear (circular) undulator system, four typical systems have been analyzed. Both the segmental planar undulators and segmental helical undulators can achieve the switching of HLP/VLP and LCP/RCP by adjusting the phase shift between the adjacent undulators or the position of the undulators. The specific feature of each system is analyzed in details and compared with each case. It shows a good potential on controlling and switching different polarization state in a same undulator line.

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