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CHARACTERISTICS OF POLARIZED COHERENT RADIATION IN THz REGION FROM A CROSSED-UNDULATOR

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Abstract

A variable polarized THz light source using a crossed-undulator configuration has been developed at Research Center for Electron Photon Science (ELPH), Tohoku University. It consists of two planar undulators of which deflecting planes cross at right angles and a phase shifter for phase adjustment. Polarization of the crossed-undulator has observation angle dependence due to that of radiation wavelength and optical path length difference between two radiations. That limits an angular range maintaining the identical polarization state. Assuming undulator parameters for our experiment (a fundamental frequency 1.9 THz and a number of periods seven) degree of circular polarization larger than 0.9 can be obtained only in the range of 2.2 mrad, i. e. 13% of the radiation angular spread.

INTRODUCTION

THz wave is an electromagnetic wave in frequencies from 0.1 to 10 THz. It is known that biomolecules such as proteins and nucleic acids have vibrational modes in this frequency range. THz circular dichroism is an effective spectroscopy for their chiral structures. However, polarization control technology in THz region is behind compared with the other optical frequency ranges.

We have studied a variable polarized THz light source using a crossed-undulator configuration. Design consideration of the system is underway for an experiment at ELPH, Tohoku University. In addition to those topics, fundamental characteristics of polarization of the crossed-undulator radiation are discussed in this paper.

CONCEPT OF A CROSSED-UNDULATOR

A polarization control method using a crossed-undulator was proposed by K-J. Kim [1]. It consists of two identical planar undulators and a phase shifter for adjustment of phase difference. Deflecting planes of two undulators cross at right angles each other so that arbitrary polarization can be generated by superimposing their linearly polarized radiation. The conceptual configuration is shown in Fig. 1. In our design, the phase shifter is composed of an optical delay line and a bypass electron beam line. Phase difference between two linear polarization components is adjusted by changing the optical path length in the phase shifter. In order to control polarization in such a way, a sufficiently short electron bunch compared with the radiation wavelength is required so that each radiation has coherence.

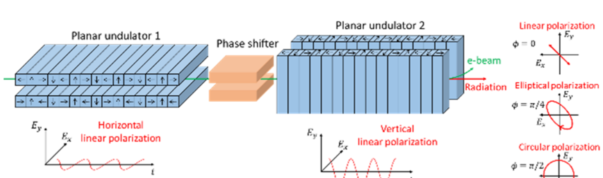

Figure 1: Conceptual configuration of the crossed-undulator.

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PREPARATION FOR AN EXPERIMENT

t-ACTS

We are planning to carry out a demonstration experiment at the t-ACTS (test Accelerator as Coherent THz Source) facility in ELPH, Tohoku University. The t-ACTS linac consists of a thermionic rf gun, an alpha magnet with an energy filter and a 3 m traveling-wave accelerating structure. A velocity bunching scheme is employed to generate ultra short electron bunches. The bunch compression mode operates at beam energy of 22 MeV. Coherent transition radiation of a frequency range up to about 3 THz and undulator radiation ranging from 2.6 to 3.6 THz have been successfully observed [2, 3]. The measured spectrum indicates that the minimum bunch length is approximately 80 fs. This facility is suitable for the demonstration experiment of the crossed-undulator within a few THz.

Planar Undulators

Two identical planar undulators have been designed for the experiment. The parameters were chosen so that the fundamental frequency becomes about 2 THz considering the bunch length and beam energy of t-ACTS. Table 1 shows the designed parameters. The number of periods was set to the small value because of a constraint of the available space for the experiment.

Electric field radiated from a moving electric charge q is calculated from the Lienard-Wiechert potential. Its radiation field term is expressed as [4]

Table 1: Undulator Parameters

Magnet array	Halbach type
Block dimension	70 mm x 23 mm x 20 mm
Period length	80 mm
Number of periods	7
Total length	587 mm
Magnet material	NdFeB
Residual magnetic field	1.22 T
Gap	33 mm
Peak magnetic field	0.471 T
K value	3.52

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$$\vec{E}(\vec{r},t) = \frac{q}{4\pi\varepsilon_0}\left[\frac{\vec{n}\times\left\{(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}\right\}}{Rc\left(1-\vec{n}\cdot\vec{\beta}\right)^3}\right]_{\mathrm{ret}}, \quad (1)$$

where ε_0 is the dielectric constant of vacuum, R the observation distance, c the speed of light, $\vec{\beta}$ the velocity vector normalized by c and $\vec{n}$ the unit vector in the observation direction. Values in the bracket $[\ ]_{\mathrm{ret}}$ are evaluated at the retarded time.

Undulator radiation was calculated using Eq. (1) assuming designed parameters and electron energy of 22 MeV. The frequency spectrum was obtained by the Fourier transformation and it indicates that the fundamental frequency on the axis is 1.9 THz. Angular distribution of the intensity of the fundamental wave was also calculated by varying observation point. The angular spread is 17 mrad in the x direction (the electron oscillation direction) and 50 mrad in the y direction in HWHM. It should be considered that the angular spread of the crossed-undulator radiation is the narrower one, 17 mrad because deflecting planes of the two undulators are orthogonal.

Phase Shifter

In the phase shifter, electron bunch must be transported such that a six-dimensional phase space distribution at the entrance of the second undulator is identical to that of the first one. Design consideration of a compact (~3 m) beam line satisfying such a requirement is underway. A variable R_{56} chicane or a multi bend type beamline are being considered. However, it was found that when a bending angle per one magnet is large (more than about 10°), bunch lengthening effects due to T_{566} and a finite beam emittance become non-negligible. Therefore it is not simple to realize the required beam line and further investigation is in progress.

CHARACTERISTICS OF THE CROSSED-UNDULATOR RADIATION

It is known that wavelength of undulator radiation has dependence on observation angle. Besides, optical path length difference between two linearly polarized radiations also varies as observation angle changes. Therefore, polarization of the crossed-undulator radiation is dependent on observation angle. In order to evaluate this effect on polarization, angular dependence of phase difference between two linear polarization components and degree of polarization were investigated.

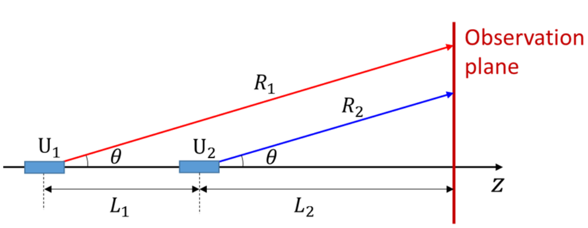

Figure 2: Schematic layout of a simple crossed-undulator configuration.

Angular Dependence of Phase Difference

Expression of angular dependence of phase difference between two linear polarization components was derived assuming a simple layout of the crossed-undulator (Fig. 2). L_1 is a distance between two light sources (the centers of each undulator). L_2 is an observation distance on the axis and supposed to be infinity. θ is an observation angle. R_1 and R_2 are an observation distance at an angle θ from the first source and the second one, respectively. Defining ΔR as path length difference $R_1 - R_2$, its shift from θ=0, $L_\delta(\theta)$ is expressed as

$$L_\delta(\theta) \equiv \Delta R(\theta) - \Delta R(0) = \frac{L_1(1-\cos\theta)}{\cos\theta}. \quad (2)$$

On the other hand, angular dependence of wavelength of undulator radiation is known to be expressed as

$$\lambda(\theta) = \frac{\lambda_{\mathrm{u}}}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\theta^2\right), \quad (3)$$

where λ_{u} is period length of the undulator, γ the Lorentz factor of an electron, and K a deflecting parameter of the undulator. Expression of phase difference is derived from Eq. (2) and (3) as follows.

$$\psi(L_1,\theta) = \psi_0 - \psi_\delta(L_1,\theta),$$
$$\psi_\delta(L_1,\theta) \equiv \frac{2\pi L_\delta}{\lambda} = \frac{4\pi\gamma^2 L_1(1-\cos\theta)}{\lambda_{\mathrm{u}}(1+K^2/2+\gamma^2\theta^2)\cos\theta}. \quad (4)$$

Degree of Circular Polarization

For infinite radiation pulse length In order to evaluate polarization, the Stokes parameters [5] were introduced. Degree of circular polarization (DOCP), P_C can be written as S_0/S_3. Assuming sinusoidal radiation fields, infinite number of cycles of light (undulator periods) N and phase difference of Eq. (4), P_C is expressed by

$$P_C(L_1,\theta) = \sin\psi(L_1,\theta). \quad (5)$$

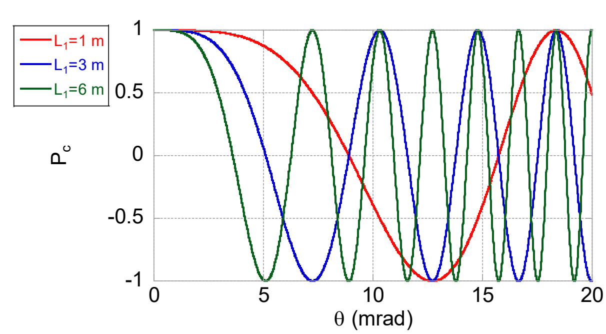

Figure 3: Angular dependence of P_C when L_1=1, 3 and 6 m and ψ_0=π/2. P_C=1, 0 and -1 correspond to right circular, 45° linear and left circular polarization, respectively.

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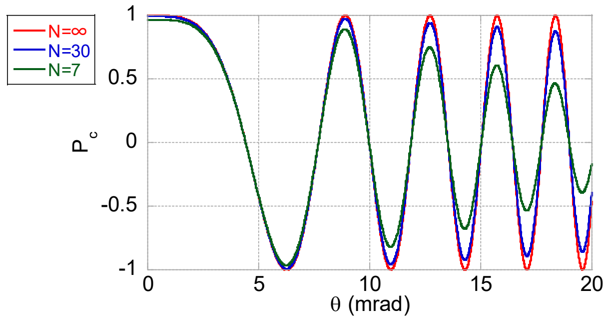

Figure 4: Angular dependence of P_C of finite N when L_1=4 m. The red, blue and green line indicate N=∞, 30 and 7, respectively.

P_C was evaluated by using the designed undulator parameters (table 1) in the following. Figure 3 shows the angular dependence of P_C when L_1=1, 3 and 6 m when $\psi_0=\pi/2$. P_C oscillates by sine function as θ increases. Since ψ depends on L_1 linearly, the period of the oscillation becomes smaller as L_1 increases. A realistic value of L_1 is in the range of several m. Therefore polarization varies significantly within the opening angle of the radiation itself.

For finite radiation pulse length When N is finite, an overlap region of two polarization component becomes shorter compared with the total radiation pulse length. Taking this effect into consideration, P_C can be written as

$$P_C(N, L_1, \theta) = \begin{cases} \left(1 - \frac{|\psi(\theta)|}{2N\pi}\right)\sin\psi(\theta) & (|\psi(\theta)| \leq 2N\pi) \\ 0 & (|\psi(\theta)| > 2N\pi) \end{cases}. \quad (6)$$

Figure 4 shows $P_C(N, \theta)$ when L_1=4 m and $\psi_0=\pi/2$. Amplitude of P_C decreases significantly within the radiation angular spread when N=7. However, the degradation is not significant within a several mrad.

Effective Opening Angle

Only the limited part of radiation with the identical polarization state can be used for general applications. The angular range satisfying $P_C(\theta)\sim P_C(\theta=0)$ was evaluated defining an effective opening angle, θ_{eff}. Here it was defined as an angular range (half width) satisfying $P_C\geq0.9$ and including θ=0.

Figure 5 shows L_1 dependence of θ_{eff} of when N=7 calculated by Eq. (6). L_1 is the sum of an undulator length L_u and that of a phase shifter L_{ph}. θ_{eff} take the maximum value of 5.7 mrad when L_{ph}=0, but that is not realistic. L_1 will be about 4 m and θ_{eff} 2.2 mrad in our experiment. That corresponds to 13% of the opening angle of the radiation itself.

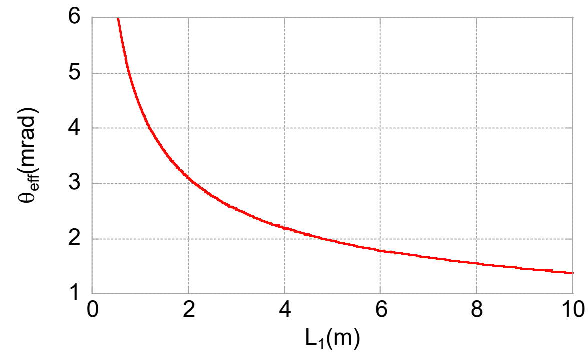

Figure 5: L_1 dependence of θ_{eff} when N=7.

CONCLUSION

A variable polarized THz light source using a crossed-undulator configuration has been studied at Tohoku University. Currently preparation for a demonstration experiment at t-ACTS is underway. Two compact planar undulators have been constructed. Fundamental frequency and angular spread of the radiation are estimated to be 1.9 THz and 17 mrad (HWHM), respectively. Polarization of the crossed-undulator has observation angle dependence due to that of radiation wavelength and optical path length difference between two radiations. Therefore polarization state identical to that on the axis can be obtained only in the limited angular range Assuming the parameters for the experiment and sinusoidal radiation fields, DOCP≥0.9 can be generated in a range of 2.2 mrad (half width), which corresponds to 13% of the radiation spread.

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