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MUNIPULATION AND MEASUREMENT OF POLARIZATION STATES FOR THz COHRENET UNDULATOR RADIATION

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Abstract

We are conducting research an accelerator-based terahertz source that can produce arbitrary polarization states from linearly polarized coherent undulator radiation (CUR). The polarization manipulation of the CUR can be realized using the Martin Puplett interferometer employed as an optical phase shifter. Variable polarization manipulator (VPM) was demonstrated using the terahertz CUR source based on an extremely short electron bunch at Research Center for Electron Photon Science (ELPH), Tohoku University. The horizontally polarized CUR with a frequency of 1.9 THz was manipulated into variable polarization state, and Stokes parameters were measured to derive the degree of polarization states. Experimental results will be presented in this conference.

INTRODUCTION

A test accelerator as a coherent terahertz source (t-ACTS) is currently under development at ELPH in Tohoku University [1-3], wherein extremely short electron bunches are used to generate intense coherent THz radiation. THz radiation sources have attracted considerable interests because of their potential applications in fields such as material science, medical imaging, and high-speed communication. The coherent THz radiation having polarization control ability can be used for various types of scientific investigation and applications. Vibrational circular dichroism (VCD) measurements in the THz region are extremely sensitive to conformational changes in proteins [4, 5]. A THz source capable of switching left and right circular polarizations with high speed is very useful for biological analysis and is in great demand. Because although a quarter waveplate (QWP) is used to change linearly polarized light into circularly polarized light, no QWP can be used in a wide THz wavelength range. We developed a system that manipulates linearly polarized CUR in the THz region into arbitrary polarization states and measured the degree of polarization.

MANIPULATION AND MEASUREMENT OF POLARIZATION STATE

Polarization Manipulation

As a relativistic electron beam propagates through an undulator, under the condition that the pulse length of the electron beam is sufficiently shorter than the resonance wavelength of the undulator radiation, the radiation will have temporal coherence. The temporal profile of the electric field of the undulator radiation shows an almost sinusoidal wave with a cycle of the number of undulator periods [6].

The polarization state of the CUR is manipulated by exploiting the property of temporal coherence. The variable polarization manipulator (VPM) consists of a wire-grid as beam-splitter and two rooftop mirrors, with one rooftop mirror mounted on a movable stage [7]. The radiation from a planar undulator is linearly polarized, therefore the input polarizer is not necessary. An incident beam of the CUR is split into two orthogonal linear polarizations by the wire-grid splitter, and the reflected and transmitted beams travel to the rooftop mirrors. Polarization of two beams are flipped by 90° using the rooftop mirrors and the round-trip beams are superimposed at the splitter wire-grid. The relative phase (δ) between the two orthogonal linearly polarized beams is adjusted using the movable stage. By using the VPM, it is possible to produce various polarization states by simply adjusting the relative phase. All polarization states can be realized simply by moving the interferometer stage. In other words, the left and right circular polarization can be switched by simply shifting the movable stage by half a wavelength (~150 μm at 1 THz). The VPM can realize high-speed switching the left and right circular polarization at several-hundred-Hz using a piezoelectric actuator stage. In addition, it has the advantage of high transmission efficiency in the interferometer.

Polarization Measurements

The polarization state of light can be expressed by measuring the Stokes parameters (S_0, S_1, S_2, S_3), which are four elements of the Stokes vector. The partial polarization in which polarized and unpolarized lights are mixed can be expressed using polarization degree P $(0 \leq P \leq 1)$ as follows:

$$S = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = (1-P)\begin{pmatrix} S_0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + P\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}. \qquad (1)$$

In the case of complete polarization, $P = 1$, and the degree of polarization P can be defined as:

$$P = \frac{I_{\mathrm{POL}}}{I_{\mathrm{TOT}}} = \frac{\sqrt{{S_1}^2 + {S_2}^2 + {S_3}^2}}{S_0}, \qquad (2)$$

where I_{TOT} is the total intensity and I_{POL} is the intensity of the partial polarization. The four Stokes parameters can be

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measured using a polarizer and a QWP [8]. The linear polarizer follows the QWP, and the transmission intensity of the light to be measured can be expressed as follows by using the rotation angle (θ, ϕ) of the polarizer and QWP.

$$I(\theta,\phi) = \frac{1}{2}[S_0 + S_1 \cos 2\theta + S_2 \sin 2\theta \cos\phi - S_3 \sin 2\theta \sin\phi] \quad (3)$$

By measuring the four transmission intensities, that is, $I(0,0)$, $I(\pi/2,0)$, $I(\pi/4,0)$ and $I(\pi/4,\pi/2)$, the Stokes parameters can be obtained as follows:

$$\begin{aligned} S_0 &= I(0,0) + I(\pi/2,0), \\ S_1 &= I(0,0) - I(\pi/2,0), \\ S_2 &= 2\cdot I(\pi/4,0) - S_0 \quad \text{and} \\ S_3 &= S_0 - 2\cdot I(\pi/4,\pi/2) \end{aligned} \quad (4)$$

BEAM EXPERIMENT

Experimental Setup

The polarization manipulation of the CUR was demonstrated using t-ACTS, in Tohoku University. The accelerator system consists of a specially designed S-band RF gun [1], alpha-magnet with an energy slit, 3 m-long S-band accelerating structure, the terahertz undulator and a dispersion section with beam dump for energy spectrum measurement. The t-ACTS injector system can deliver small emittance and short electron beams by implementing the velocity bunching scheme, where a traveling wave structure is utilized as a bunch compressor [2]. The short electron bunches were employed to generate a coherent undulator radiation in the THz wavelength region in the present study. The electron beam and undulator parameters are listed in Table 1.

The THz CUR and an electron beam were separated by a bending magnet downstream of the undulator and the CUR passes through the vacuum window made by THz grade crystal quartz (z-cut). The experimental setup of VPM is presented in Fig. 1. Two off-axis parabolic (OAP) mirrors were used to make a parallel THz beam, which was injected to the interferometer. Measurement system of polarization state consists of Fresnel Rhomb waveplate (Quarter wave plate: QWP), wire-grid polarizer (GS57207: wire diameter of 10 m, wire spacing of 25 m) mounted on

Table 1: Electron Beam and Undulator Parameters

Aspect	Parameter	Value
Electron beam	Energy	22 MeV
	Bunch charge	4 pC
	# bunches/pulse	5700
	Bunch length (σ_z)	80 fs
Undulator	Block size	$70\times23\times20$ mm^3
	Period length	80 mm
	# of periods	7
	Total length	587 mm
	Gap	33 mm (fix)
	Peak B field (k)	0.471 T (3.52)

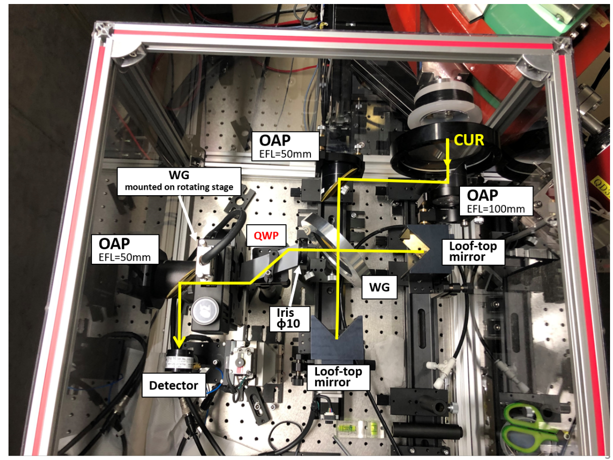

Figure 1: Experimental setup. The VPM system was installed beside the beam line of t-ACTS. (OAP: off-axis parabolic mirror; CUR: coherent undulator radiation; WG: wire-grid polarizer; QWP: quarter wave-plate.)

rotating stage, OAP mirror and pyroelectric detector (THz-10, SLT Sensor- und Lasertechnik GmbH).

The Al coat mirror allows to generate the transition radiation. One Michelson interferometer was installed upstream of the undulator to measure the spectrum of the coherent transition radiation (CTR) emitted from short electron bunches, while the electron bunch length was deduced from the radiation spectrum. The beam injection phase into the accelerating structure was adjusted to produce a short electron bunch by maximizing the radiation power of coherent transition radiation (CTR). From the spectrum analysis of CTR, the electron bunch length was estimated to be compressed to approximately 80 fs.

Coherent Undulator Radiation

The frequency spectrum of the undulator radiation was measured using the Martin–Puplett interferometer. In this interference measurement, the output wire-grid polarizer was set the angle, at which the horizontal polarized beam passes. Figure 2 (top) shows the measured interferogram, with the shifting of the rooftop mirror in 10 µm steps over 1.2 mm. This sinusoidal interferogram indicates that CUR was being produced. When the phase difference (δ) between the two THz beams in the VPM was zero, the interferogram showed a maximum and the polarization state of CUR was horizontal linear polarization. The spectrum of the CUR was derived by Fourier transform of the interferogram as shown in Fig. 2 (bottom) with a frequency resolution of 0.125 THz. The center frequency of the radiation was approximately 1.9 THz (λ=158 µm).

MEASUREMENT RESULT

Variable polarization states could be produced by changing the stage position of the VPM. The intensities of the THz beam were measured by rotating the output wire-grid polarizer placed in front of the detector. Figure 3 shows the

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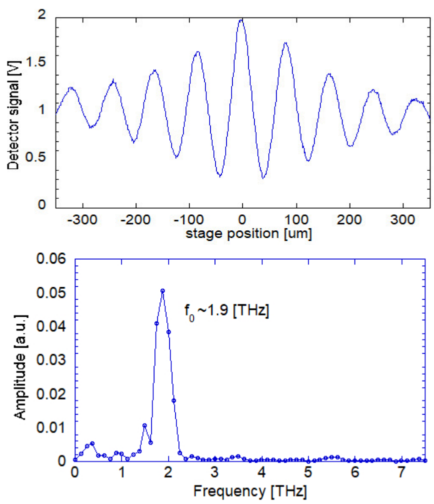

Figure 2: Measured Interferogram and the spectrum of the CUR using the Martin–Puplett interferometer.

measurement result when the phase difference of two THz beams was set to 0 (red solid circle), $\pm\pi$(blue solid and open circles) and $\pm\pi/2$ (green solid and open circles), which correspond stage positions of 0, $\pm 40\mu m$ and $\pm 20\mu m$, respectively. When the phase difference is 0 and π, horizontally polarized and vertically polarized states were produced. Because, in Fig.3, the rotating phase of polarizer for the two conditions was different by 90 degrees. On the other hand, when the phase differences were adjusted to ±π/2, the VPM outputs became left and right circularly polarized beams, respectively. The left and right circularly polarized beams are converted to $\pm\pi/4$ linear polarized beam by the QWP (Fresnel Rhomb waveplate). In Fig. 3, the rotation angle of the polarizer is in opposite phase for left and right circularly polarized light.

From the results of Stokes parameter measurement shown in Fig. 3, we derived polarization degrees using Eqs. (5) and (6) where P_L and P_C are the degree of linear polarization and circular polarization, respectively.

$$P = \frac{\sqrt{{S_1}^2+{S_2}^2+{S_3}^2}}{S_0} = \sqrt{{P_L}^2 + {P_C}^2} \quad (5)$$

$$P_L = \frac{\sqrt{{S_1}^2 + {S_2}^2}}{S_0}, \quad P_C = \frac{S_3}{S_0} \quad (6)$$

We could obtain a degree of circular polarization ($P_C = S_3/S_0$) using the S_3 and left- right- circularly polarization can be distinguished by the sign of P_C. Derived the degree of polarization states are summarized in Table 2.

Table 2: Measured the Degree of Polarization

Pol. state	**δ**	***P***	***P_L***	***P_C***
Hor. Linear	+π	0.707	0.670	0.227
Right circular	+ π/2	0.752	0.039	0.751
Hor. Linear	0	0.88	0.875	0.116
Left circular	- π/2	0.768	0.054	-0.766
Ver. Linear	- π	0.683	0.682	0.043

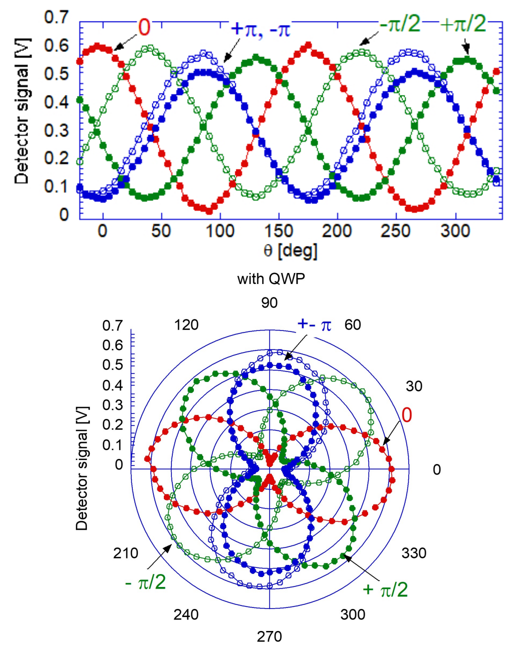

Figure 3: Measured intensity of the coherent undulator radiation as a function of rotating angle of the polarizer wire-grid.

The highest degree of polarization (P) is obtained when the phase difference is 0. And the degree of polarization decreases as the phase difference increases, because the overlapping of the orthogonally split beam is reduced. With δ = 0 and +π, the output THz beam is expected to be linearly polarized, and the derived polarization degrees were $P_L = 0.875$, $P_C = 0.116$ and $P_L = 0.67$, $P_C = 0.227$, respectively. In contrast, with δ = −π/2 and +π/2, the degrees were $P_L = 0.054$, $P_C = -0.766$ and $P_L = 0.039$, $P_C = 0.75$. When the phase difference is +π/2 and −π/2, the sign of Pc was opposite. This means that the left-right circular polarization was reversed. The measurement results show that various polarization states were realized by the VPM system.

CONCLUSION

We are developing an accelerator-based variable polarized THz source that utilizes the CUR produced from a short electron pulse. The VPM system using the THz-CUR has been demonstrated at Tohoku University. The linearly and circularly polarized beams were obtained using a VPM system by adjusting the relative phase of two orthogonal linearly polarized THz beams generated from the CUR. The results of the polarization measurement using the wire-grid polarizer clearly showed that variable polarized states were produced from the CUR. The development of the measurement system for Stokes parameters in the THz region is also an important issue. A method described in Ref. [9] has been also developed to measure the polarization of vector beams. The VPM using the THz-CUR that can produce various polarization states with extremely simple operation can be expected to be applied to biological analyses such as in VCD.

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REFERENCES

[1] H. Hama *et al.*, "Test-accelerators as coherent terahertz source program (t-ACTS) at Tohoku University", in *Energy Procedia*, vol. 9, pp. 391 – 397, 2011. doi:10.1016/j.egypro.2011.09.042

[2] S. Kashiwagi *et al.*, "Proof-of-principle experiment of velocity bunching for ultra-short electron pulse production", in *Energy Procedia*, vol. 89, pp. 346 – 352, 2016. doi:10.1016/j.egypro.2016.05.045

[3] S. Kashiwagi *et al.*, "Study of Femtosecond Electron Bunch Generation at t-ACTS, Tohoku University", in *Proc. LINAC'14*, Geneva, Switzerland, Aug.-Sep. 2014, paper THPP136, pp. 1178-1181.

[4] G. J. Wilmink and J. E. Grundt, "Invited Review Article: Current State of Research on Biological Effects of Terahertz Radiation", in *Journal of Infrared, Millimeter, and Terahertz Waves,* vol. 32, pp. 1074 – 1122, 2011. doi:10.1007/s10762-011-9794-5

[5] J. Xu *et al.*, "Terahertz circular dichroism spectroscopy of biomolecules", in *Proc. SPIE*, vol. 5268, pp. 19 – 26, 2004. doi:10.1117/12.518533

[6] S. Kashiwagi *et al.*, "Observations of coherent undulator radiation in THz region", in *Infrared Phys. Technol.*, vol. 93, pp. 335 – 339, 2018. doi:10.1016/j.infrared.2018.08.011

[7] A. Catalano *et al.*, "A far infrared polarimeter", in *New Astron.*, vol. 10, pp. 79-89, 2004. doi:10.1016/j.newast.2004.05.002

[8] H. G. Berry, G. Gabrielse, and A. E Livingston, "Measurements of the Stokes parameter of light", in *Appl. Opt.*, vol. 16, no. 12, pp. 3200-3205, 1977. doi:10.1364/AO.16.003200

[9] T. Wakayama *et al.*, "Determination of the polarization states of an arbitrary polarized terahertz beam: vectorial vortex analysis", in *Sci. Rep.*, vol. 5, p. 9416, 2015. doi:10.1038/srep09416