SCIENCE CHINA
Physics, Mechanics & Astronomy

• **Article** •

April 2012 Vol.55 No.4: 589–592
doi: 10.1007/s11433-012-4665-1

Polarization of terahertz emission out of incident plane from laser interactions with solid targets†

DU Fei[1], LI Chun[1], ZHOU MuLin[1], WANG WeiMin[1], SU LuNing[1], ZHENG Yi[1], LI YuTong[1*], MA JingLong[1], SHENG ZhengMing[1,2], CHEN LiMing[1], LU Xin[1], WANG ZhaoHua[1], WEI ZhiYi[1] & ZHANG Jie[1,2*]

[1] *Beijing National Laboratory of Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China;*
[2] *Key Laboratory for Laser Plasmas (Ministry of Education) and Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China*

Received February 6, 2012; accepted February 15, 2012; published online February 24, 2012

A powerful terahertz (THz) pulse was produced by a p-polarized, 70 fs, 800 nm laser interacting with solid targets at an incident angle of 45°. The polarization of the THz emission was measured out of the laser incident plane. The results showed that it was linearly polarized. We established a surface current model to explain this phenomenon, assuming that the transient current moving along the plasma surface was responsible for the generation of the THz emission. The model expectation and the experimental result were in good agreement.

terahertz emission, laser solid interactions, polarization

PACS number(s): 42.25.Ja, 52.25.Os, 52.38.Kd

Citation: Du F, Li C, Zhou M L, et al. Polarization of terahertz emission out of incident plane from laser interactions with solid targets. Sci China-Phys Mech Astron, 2012, 55: 589–592, doi: 10.1007/s11433-012-4665-1

Terahertz (THz) waves are located between microwave and infrared in the electromagnetic wave spectrum. Its unique wavelength enables numerous applications in many different fields, such as materials science [1], biochemistry [2], biomedicine [3], etc. With the development of femtosecond lasers, the THz science enters a new era. Two main methods, photoconductive switches [4] and optical rectification [5], are widely used to generate broadband pulsed THz emission. However, limited by the material damage threshold, the THz emission power cannot be further increased by applying higher intensity laser. There are two approaches to generate high power THz radiation. One is accelerator-based radiation, such as coherent transition radiation [6], coherent synchrotron radiation [7], free electron laser [8], Cherenkov radiation [9] and Smith-Purcell effect [10], etc. These facilities can provide a high average power output and tunable frequency at a very broad band. The other is laser-produced plasmas. Since plasmas are already "damaged", they can withstand much higher laser intensity. THz emission from a laser produced air filament has recently been reported [11] and a series of improvements are made by adding external fields [12,13]. It is also reported that electron bunches accelerated by laser wakefield can generate THz emission at the plasma-vacuum boundary [14].

With a solid target, powerful THz sources have also been demonstrated [15,16], while the mechanism of the generation is still not fully understood. In our and other groups' previous work, the polarization of the THz emission in the laser incident plane was measured. It was found that the THz polarization was p-polarized in the laser incident plane [15,17,18]. In this paper, we investigate experimentally the

*Corresponding author (LI YuTong, email: ytli@iphy.ac.cn; ZHANG Jie, email: jzhang@aphy.iphy.ac.cn)
†Recommended by NIE YuXin (Executive Associate Editor-in-Chief)

polarization of THz emission from laser-solid interactions not in the laser incident plane. The results show that it is linearly polarized but not p-polarized. To explain this phenomenon, we propose a simple model assuming that the transient current along the target surface produces the THz emission [19]. This model is also successfully used to explain the polarization of THz emission in the laser incident plane.

1 Experimental setup

The experiments were performed at Xtreme Light II (XL-II) Ti: Sapphire femtosecond laser facility at the Institute of Physics, Chinese Academy of Sciences. The laser pulse duration was around 70 fs with the central wavelength of 800 nm in the experiments. Through an *f*/3.5 off-axis parabolic (OAP) mirror, the p-polarized laser pulse was focused onto a 13 μm aluminum foil target with an incidence angle of 45° to the target normal. A 7 μm full width at half maximum (FWHM) diameter laser spot was created by the OAP mirror and contained 35% of total laser pulse energy, monitored and measured by a microscopic system and a beam profile analysis system. With the pulse energy of 180 mJ, the laser intensity on the target is 2.4×10^{18} W/cm^2. There is an amplified spontaneous emission (ASE) pedestal with a contrast ratio of 10^{-6} 5 ns before the main pulse.

The THz emission generated from laser target interaction was first collimated by a polymethylpentene (TPX) lens with a focus length of 150 mm. It passed through the TPX window and was refocused on the detector by another TPX lens. A $LiTaO_3$ pyroelectric detector with a relative flat broadband response from 0.1 to 30 THz was used to measure the power and energy of THz signal. There is a piece of high resistivity float zone silicon (HRFZ-Si) plate placed in front of the crystal in order to screen off the visible light simultaneously generated by the incident laser. A wire-grid polarizer was inserted in the beam line of THz emission by rotating the polarizer axis to measure the polarization of the THz emission.

The schematic experimental setup is displayed in Figure 1, where ***n*** is the target normal. The detection direction ***d*** was 45° with the laser incident plane upward and its project on the incident plane was collinear with the laser mirror reflection direction ***m***. The circle centered at the detection direction represents the polarizer plane which is vertical with ***d*** and 45° to the laser incident plane α. The detailed information is shown in Figure 1(b), which is the top view of the polarizer and sees the interaction area along the inverse detection direction. A polar coordinate system was used. The polar axis was chosen at the intersection line of the polarizer plane and the vertical plane ε containing ***m*** and ***d***. The polar angle θ is positive when the axis of the polarizer is rotated clockwise.

2 Experimental results and discussion

The THz signal after passing the polarizer was measured from the rotation angle of 0 to 180°. The result is shown in Figure 2. It is found that the THz emission is linearly polarized and its maximum signal is not located at the axis of the orthogonal coordinates. To understand the results, we propose a simple transient current model.

THz waves, as a band of electromagnetic wave spectrum, can be generated by acceleration of charged particles such as electrons in the time scale of picosecond. The time scale of electrons in traditional radio frequency (RF) circuit is nanosecond and difficult to be reduced. That's why there are few effective THz antennas in this spectrum band. The

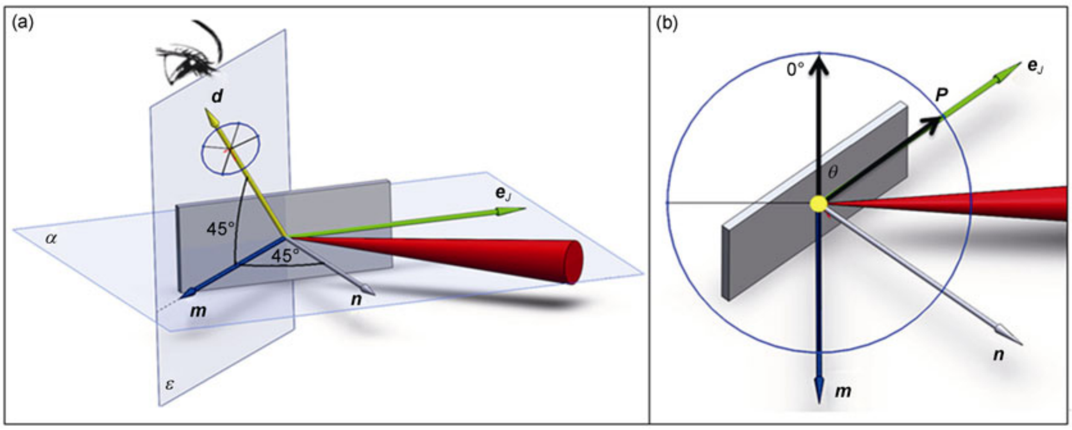

Figure 1 (Color online) Schematic display of the experimental setup and the geometry of incident laser, laser reflection direction ***m***, target normal ***n***, detection direction ***d*** and transient current direction $\boldsymbol{e}_J$. The project of ***d*** on the incident plane α is collinear with ***m*** and the angle between ***d*** and ***m*** is 45°. The vertical plane ε is defined by ***d*** and *m*. The circle centered in ***d*** represents the polarizer. The detailed information is given in (b), which is the schematic display of the top view of the polarizer plane and the polar coordinates. The direction of ***d*** points out of the paper vertically. The rotation angle θ between the polarizer axis ***P*** and the polar axis is positive when rotated clockwise. The polarizer plane is 45° to the incident plane.

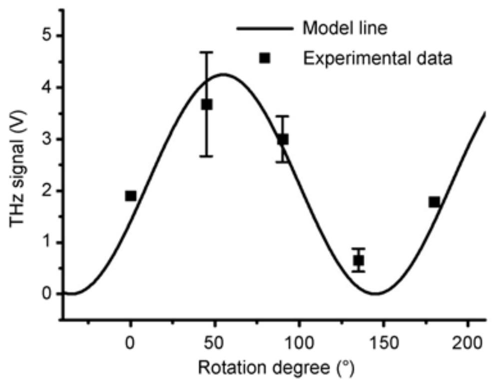

Figure 2 THz signal measured by the detector (squares) and the fitting line induced by the transient current model (line).

fast electrons can be accelerated to near light velocity, *c*, from laser plasma interactions. One electron with a velocity of around *c* passing through 300 μm length plasma will take about 1 ps. Acceleration or deceleration by this plasma may emit THz wave. So we assume that it is the electrons moving along the surface of plasma before escaping that produce THz emission since the THz wave cannot pass through plasma. These electrons generated by intense laser constitute a transient current.

Through measuring the angular distribution of emitted electrons, our previous experimental and theoretical results show that there are a number of electrons emitted along the target surface in the laser forward direction at a relatively large laser incident angle [20]. Even at a relatively moderate incident angle, 45°, there still is electron jet near the target surface under the similar laser condition with this experiment [21]. These electrons propagate along the target because of the confinement of the quasistatic magnetic and electric fields. According to these results, during the following analysis, the transient current along the target produced by laser solid target interactions is assumed responsible for the generation of THz emission.

Because the transient current on the surface of the plasma is only about tens to hundreds of micrometers long [22], it can be assumed reasonably as a point current compared with the detection distance. Its direction $\boldsymbol{e}_J$ is along the target in the laser backward direction inferred from the emitted electrons, as Figure 1 shows. So it can be written as:

$$\boldsymbol{J} = \boldsymbol{e}_J J_0 \delta(\boldsymbol{r}) \exp(-t^2/\tau_0^2), \tag{1}$$

where J_0 is determined by the laser intensity and τ_0 is a constant determined by laser pulse duration. Putting the transient current expression (1) into the retarded potential formula and using the far field approximation, after a series of calculations, we can get the formula of the electric field of the THz emission at the detector:

$$\boldsymbol{E} = \frac{2J_0 t \exp(-t^2/\tau_0^2)}{c^2 \tau_0^2 R_0 (1-\boldsymbol{d}\cdot\boldsymbol{\beta})} \boldsymbol{d} \times (\boldsymbol{d} \times \boldsymbol{e}_J), \tag{2}$$

where R_0 is the distance between the transient current and the detector and $|\boldsymbol{\beta}|$ is the average normalized velocity of the electrons in the current and in the same direction with $\boldsymbol{e}_J$. From eq. (2), the THz emission at the detector is linearly polarized, and its electric field direction is determined by the vector triple product of $\boldsymbol{d}$, $\boldsymbol{d}$ and $\boldsymbol{e}_J$. From this relation, we can get the polarization direction of this experiment. The inferred polarization direction $\boldsymbol{P}$ of THz emission is shown in Figure 1(b), and it is collinear with the project of $\boldsymbol{e}_J$ on the polarizer plane.

The angle θ between the polarization direction $\boldsymbol{P}$ and polar axis is calculated to be 55°. According to Malus' law, the THz signal after the polarizer by rotating its axis should be a function with the form of $\cos^2(\theta-55)$. Considering the magnitude of the measured signal, the model fitting function can be written as:

$$y = 4.25\cos^2(\theta - 55), \tag{3}$$

where 4.25 is a fitting constant. The fitting line is also depicted on Figure 2 (line) and it agrees well with the experimental data. This result shows that the polarization is dependent on the detection direction and it is collinear with the project in the polarizer plane of the transient current. This characteristic conforms to a radially polarized radiation.

By using this model, the polarization in the laser incident plane can also be explained. Sagisaka et al. [17] reported that the polarization was p-polarized at an incident angle of 45°. The same results were also shown by Hamster et al. [23] at 60° and our group at 67.5° [18]. From eq. (2), when the detection direction and transient current are in the laser incident plane, the electric field of THz emission should be also in that plane, that is, p-polarization.

3 Conclusion

We have measured the polarization of THz emission at a direction not in the laser incident plane. The results show that it was linearly polarized with a certain angle to the horizontal direction of the polarizer plane. A surface current model was established to explain these results which assumed that the laser induced transient current along the target surface was responsible for the generation of THz emission. The assumption is based on the experimental and theoretical results that a number of electrons emitting along the target surface were found under similar experimental conditions. The model expectation and experimental results agree well with each other. Considering the measured polarization of THz emission in the laser incident plane, it is believed that these polarization characteristics of the THz waves conform to a radially polarized radiation.

We gratefully thank Dr. LIU BiCheng for his great contribution in the *experiment. This work was supported by the National Natural Science Foundation of China (Grant Nos. 10925421 and 10734130).*

1 Pedersen J E, Lyssenko V G, Hvam J M, et al. Ultrafast local field-dynamics in photoconductive THz antennas. Appl Phys Lett, 1993, 62: 1265–1267
2 Takahashi M, Ishikawa Y, Nishizawa J, et al. Low-frequency vibrational modes of riboflavin and related compounds. Chem Phys Lett, 2005, 401: 475–482
3 Shen Y C, Upadhya P C, Linfield E H, et al. Temperature-dependent low-frequency vibrational spectra of purine and adenine. Appl Phys Lett, 2003, 82: 2350–2352
4 Auston D H, Cheung K P, Smith P R. Picosecond photoconducting Hertzian dipoles. Appl Phys Lett, 1984, 45: 284–286
5 Auston D H, Cheung K P, Valdmanis J A, et al. Cherenkov radiation from femtosecond optical pulses in electro-optic media. Phys Rev Lett, 1984, 53: 1555–1558
6 Shen Y, Watanabe T, Arena D A, et al. Nonlinear cross-phase modulation with intense single-cycle terahertz pulses. Phys Rev Lett, 2007, 99: 043901
7 Abo-Bakr M, Feikes J, Holldack K, et al. Steady-state far-infrared coherent synchrotron radiation detected at BESSY II. Phys Rev Lett, 2002, 88: 254801
8 Jaroszynski D A, Bakker R J, Vandermeer A F G, et al. Coherent startup of an infrared free-electron laser. Phys Rev Lett, 1993, 71: 3798–3801
9 Takahashi T, Shibata Y, Ishi K, et al. Observation of coherent Cerenkov radiation from a solid dielectric with short bunches of electrons. Phys Rev E, 2000, 62: 8606–8611
10 Korbly S E, Kesar A S, Sirigiri J R, et al. Observation of frequency-locked coherent terahertz Smith-Purcell radiation. Phys Rev Lett, 2005, 94: 054803
11 Cook D J, Hochstrasser R M. Intense terahertz pulses by four-wave rectification in air. Opt Lett, 2000, 25: 1210–1212
12 Bartel T, Gaal P, Reimann K, et al. Generation of single-cycle THz transients with high electric-field amplitudes. Opt Lett, 2005, 30: 2805–2807
13 Xie X, Dai J M, Zhang X C. Coherent control of THz wave generation in ambient air. Phys Rev Lett, 2006, 96: 075005
14 Leemans W P, Geddes C G R, Faure J, et al. Observation of terahertz emission from a laser-plasma accelerated electron bunch crossing a plasma-vacuum boundary. Phys Rev Lett, 2003, 91: 074802
15 Hamster H, Sullivan A, Gordon S, et al. Subpicosecond, electro-magnetic pulses from intense laser-plasma interaction. Phys Rev Lett, 1993, 71: 2725–2728
16 Li C, Zhou M L, Ding W J, et al. Effects of laser-plasma interactions on terahertz radiation from solid targets irradiated by ultrashort intense laser pulses. Phys Rev E, 2011, 84: 036405
17 Sagisaka A, Daido H, Nashima S, et al. Simultaneous generation of a proton beam and terahertz radiation in high-intensity laser and thin-foil interaction. Appl Phys B-Lasers Opt, 2008, 90: 373–377
18 Li Y T, Li C, Zhou M L, et al. Strong terahertz radiation from relativistic laser interaction with solid density plasmas. arXiv:1106.0543v1 [physics.optics]
19 Du F, Li C, Zhou M L, et al. Angular distribution of terahertz emission from laser interactions with solid targets. Sci China-Inf Sci, 2012, 55: 43–48
20 Li Y T, Yuan X H, Xu M H, et al. Observation of a fast electron beam emitted along the surface of a target irradiated by intense femtosecond laser pulses. Phys Rev Lett, 2006, 96: 165003
21 Yuan X H, Li Y T, Xu M H, et al. Effective fast electron acceleration along the target surface. Opt Express, 2008, 16: 81–86
22 Lin X X, Li Y T, Liu B C, et al. Effect of prepulse on fast electron lateral transport at the target surface irradiated by intense femto-second laser pulses. Phys Rev E, 2010, 82: 046401
23 Hamster H, Sullivan A, Gordon S, et al. Short-pulse terahertz radiation from high-intensity-laser-produced plasmas. Phys Rev E, 1994, 49: 671–677