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双色激光偏振夹角对产生太赫兹辐射的影响

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摘　要:基于改进的二维光电流模型,研究了双色激光偏振夹角对太赫兹辐射产生的影响.通过改变基频光以及其对应的倍频光的偏振夹角发现,在激光等离子体中辐射的太赫兹波的强度与双色激光的偏振夹角呈周期性变化,并且最佳偏振夹角和不同激光强度也有关系.在相对较低的激光强度下($\leqslant 2\times 10^{14}$ W/cm^2),当两束激光具备相同的偏振方向,即偏振夹角为 0°时,太赫兹幅值达到最大;然而,当激光强度足够高($>2\times 10^{14}$ W/cm^2)时,最佳的偏振夹角会随着激光强度的增加而变大.从电子密度的角度来分析产生这种现象的原因,并用剩余漂移电流来揭示其潜在的物理机制.研究表明,剩余漂移电流是激光诱导等离子体产生太赫兹波的本质根源,对太赫兹波的产量起着决定性作用.

关键词:太赫兹;激光;等离子体;偏振角;强度
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Terahertz Emission Dependence on the Polarization Angle between Two-color Lasers

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Abstract: The influence of the polarization angle between two-color lasers on the Terahertz (THz) emission was investigated based on a modified two-dimensional transient current model. By changing the polarization angle between the fundamental frequency laser and its second harmonic laser beam, it is found that, the emitted THz amplitude varys periodically with the chaning of the polarization angle in laser plasma, and the optimal angle is also changed with the different laser intensity. Under the comparatively low laser intensity ($\leqslant 2\times 10^{14}$ W/cm^2), the THz amplitude can reach the maximum when the two-color lasers have the same polarization. However, the optimal angle will increase with the increasing of the total laser intensity when the laser intensity is high enough($>2\times 10^{14}$ W/cm^2). The electron density was firstly used to analyze this phenomenon under comparatively low laser intensity and then the residual drift current was utilized to reveal the underlying physical mechanism. It was found that, the residual current density is the essential source of the THz waves and which can determine the intensity of THz emission

Key words: Terahertz; Laser; Plasma; Polarization angle; Intensity
OCIS Codes: 300.6495; 140.3538; 350.4600; 350.5400

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0 Introduction

The intense Terahertz (THz) sources are in great demand due to their great potential applications in many fields, including nondestructive evaluation[1], material characterization[2-3], biomedical and security imaging[4]. A promising method to generate THz waves from gas plasma by focusing an intense femtosecond laser beam into air, which was first observed by Hamster et al.[5-6]. Shortly after, Cook et al.[7] demonstrated that much stronger THz wave can be achieved by using two-color lasers. For this method, ultra-short laser pulses composing of both fundamental and its second-harmonic were simultaneously focused into air to generate plasma by photoionization, emitting an intense THz wave in the forward direction. Compared with the conventional THz emitters employing either nonlinear crystal[8] or photoconductive antenna[9], more intense THz fields over 1.4 MV/cm[10] and ultra-broadband THz radiation up to 200 THz[11] can be obtained by using the two-color method. Moreover, it has other great advantages, such as no damage threshold and easily for the remote generation. Thus, this method has attracted more attentions in the past two decades.

As two laser beams are employed in this method, the relationship between these two lasers, such as their relative phase[12-13], the intensity ratio[14-15] and the incident order[16], can influence the THz generation obviously. Normally, when the two-color lasers were utilized, either parallel polarization or orthogonal polarization was assumed. However, the problem of the influence of the polarization angle between the fundamental and its second harmonic on the THz emission is still unresolved.

In this paper, the effect of the polarization angle between two-color lasers on the THz emission was studied based on the transient photocurrent model[17]. First, the transient photocurrent model (in which the default setting of the polarization angle between two-color lasers was 0°) was modified to the two-dimensional situation by considering the different polarization angle. Then, the influence of the polarization angle between two-color lasers on the THz emission at a certain laser intensity was investigated. Furthermore, the final electron density and the drift current were used to make an explanation. Comparing to the previous investigations which did not consider the polarization angle, the research work of this paper has a certain extend reference meaning for generating intense THz waves.

1 Theoretical model

Considering the relative polarization angle (α) between the two-color lasers, as shown in Fig. 1, the total electric field can be expressed as

$$E_L(t)=[E_{\omega x}\cos(\omega t)x+E_{\omega y}\cos(\omega t)y+E_{2\omega}\cos(2\omega t+\theta)x]\exp(-t^2/2T_0^2) \quad (1)$$

where $E_{\omega x}=E_\omega\cos(\alpha)$ and $E_{\omega y}=E_\omega\sin(\alpha)$ are the amplitude of the fundamental laser electric field component polarized along the x-axis and y-axis, respectively. $E_{2\omega}$ is the electric field of the second harmonic laser, ω is the angular frequency of the fundamental laser. T_0 is the pulse width of the fundamental laser pulse and θ is the relative phase between the two-color lasers.

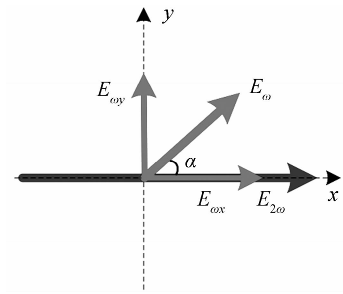


Fig. 1 Electric field of the two-color lasers

When the intense ultra-short two-color laser fields are focused simultaneously into air, a large amount of electrons and ions will be generated as the plasma appeared. The ionization process is rather complicated and has many types, including threshold ionization, multi-photon ionization and tunnel ionization. Normally, the Keldysh parameter is used to define what kind of ionization process happens[18]. As the laser intensity is more than 10^{14} W/cm^2, the Keldysh parameter is $\gamma=[U_{ion}/(2U_p)]^{1/2}<1$, where U_{ion} is the ionization potential of N_2 and U_p is the ponderomotive potential of the laser. Thus, the tunnel ionization will be dominant. In this case, the Ammosov-Delone-Krainov (ADK) model[19] can be employed to calculate the ionization rate, which is expressed as

$$w(t)=4w_0\left(\frac{E_i}{E_H}\right)^{5/2}\frac{E_a}{E_L(t)}\exp\left[-\frac{2}{3}\left(\frac{E_i}{E_H}\right)^{3/2}\frac{E_a}{E_L(t)}\right] \quad (2)$$

where $w_0=\kappa^2me^4/\hbar^3$ is the atomic frequency unit with $\kappa=(4\pi\varepsilon_0)^{-1}$, e and m_e are the electron charge and mass, respectively. $E_L(t)=|E_L|$ is the amplitude of the total laser fields. $E_i\approx15.6$ eV (for N_2 molecules) and $E_H\approx13.6$ eV (for H_2 molecules) are the ionization potentials of the nitrogen and hydrogen. $E_a=\kappa^3m^2e^5/\hbar^4$ is the atomic unit of electric field. Thus, the increasing rate of the free electron density is given by

$$\frac{dn(t)}{dt}=w(t)[n_0-n(t)] \quad (3)$$

where $n(t)$ is the time-varying electron density and n_0 is the initial neutral gas density. Here, $n_0=2.447\times10^{19}$ cm^{-3} as we consider air to be composed entirely of N_2 gas.

Once the air was ionized at the time of $t=t'$, the free electrons will be accelerated under a force coming from the external laser fields, and the time-dependent velocity can be expressed as

$$v(t,t') = -(e/m_e)\int_{t'}^{t} E_L(t'')\,dt'' \qquad (4)$$

Here, the initial velocity of the electron is supposed to be zero. By considering free electrons' movement as classical particles, a transverse electron current will be formed and can be described as

$$J(t) = -\int ev(t,t')\,dn(t') \qquad (5)$$

where $dn(t')$ represents the change of electron density caused by the external laser fields in the interval between t' and $t'+dt'$. As we modified the photocurrent model to two-dimension situation by decomposing the laser electric field into two orthogonal parts, the 2-D transient current density is given by $J=J_e x+J_o y$, where J_e and J_o are the current density component directed along the x-axis and y-axis, respectively. Then, the time evolving electron current radiates an electro-magnetic field, given by $E_{THz}\propto dJ/dt$, which is composed of the two components directed along the x-axis (E_e) and y-axis (E_o). It is clear that the THz electric field E_{THz} is composed of two orthogonal components. Then, by synthetizing these two components, the total THz wave can be obtained.

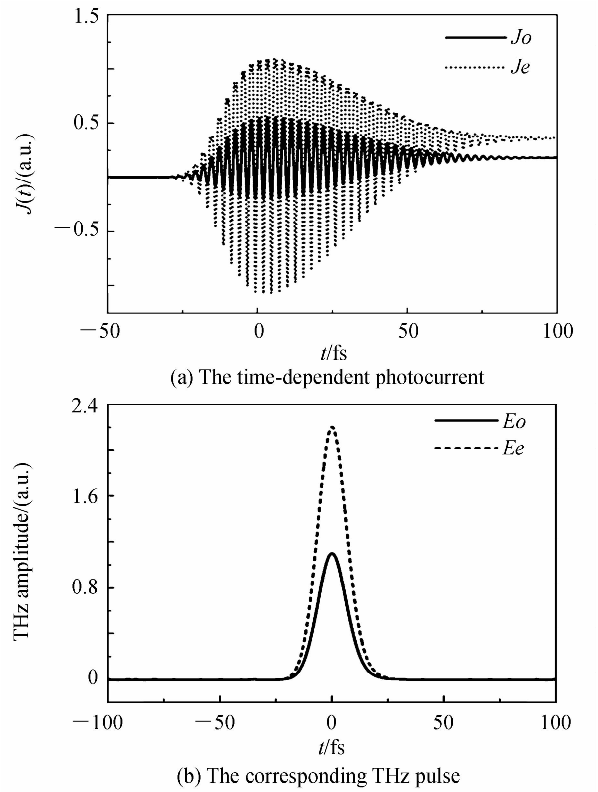


Fig. 2 The time-dependent photocurrent and THz pulse

2 Simulation and discussion

In the simulation, we solved all the equations based on the two-dimension photocurrent model by using the Matlab software. Firstly, we set the parameters of the two-color laser pulses as ω ($\lambda=800$ nm) and 2ω ($\lambda=400$ nm) with the total intensity of $I_t = 2\times10^{14}$ W/cm^2, assuming the intensity ratio between 2ω and ω laser pulses $I_{2\omega}/I_\omega=0.5$, the relative phase of θ is 0.5π, FWHM (Full Width at Half Maximum) of the fundamental laser T_{FWHM} is 50 fs and the relative polarization angle α is 20° in Fig. 2.

Fig. 2(a) shows two orthogonal compenents (J_e and J_o) of the time-dependent photocurrent $J(t)$ calculated from Eq. (5). It can be seen, in addition to the oscillatory feature, both J_e and J_o are asymmetric distribution and non-vanishing Direct Current (DC) appeared. As the electron density changes during the ionization process, a current surge will be produced, leading to a rise of electromagnetic radiation including the frequency range at THz band. Thus, the derivative of $J(t)$ can be calculated and the electromagnetic spectrum, which contains all the frequencies including ω and 2ω, can be obtained by Fourier transform. Furthermore, by filtering out the frequency below 100 THz, THz pulse waveforms can be obtained through inverse Fourier transform shown in Fig. 2(b).

By using the simulation method mentioned above, the total output THz amplitude versus the polarization angle α and the relative phase θ has been achieved, as shown in Fig. 3. With the the total intensity of $I_t=2\times10^{14}$ W/cm^2, it is found that the THz amplitude get the maximum at the relative phase $\theta=90°$, which agrees well with the one-dimensional photocurrent model[17] and the experimental results [13]. On the other hand, THz amplitude varies periodically, getting the maximum at $\alpha=0°$ and the minimum at $\alpha=90°$. It means that the highest THz radiation can be obtained when the polarization of the two-color lasers are parallel, while the lowest THz radiation appears when they are orthogonal. This result agrees well with the previous reports[11, 13] that higher THz intensity can be achieved when the polarization state of the two-color lasers changed from orthogonal to parallel. Initially, the different third-order nonlinear susceptibility tensor (χ) was used to explain this phenomenon as a four-wave mixing process, but it was soon found that the susceptibility is too small to explain the high THz field intensity[20]. However, this physical process can be analyzed by using our modified photocurrent model.

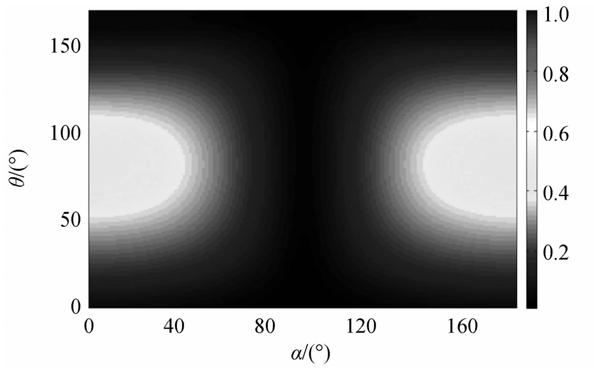


Fig. 3 THz amplitude dependence of the relative phase θ and the relative polarization angle α with the total laser intensity of $I_t = 2\times10^{14}$ W/cm^2

According to the photocurrent model, the movement of the free electrons is very important, and the final ionization rate or the final electron density can influence the THz emission very seriously[21]. By solving Eq. (3), the final electron density ($t=\infty$) ionized by the laser fields with different polarization angle α can be achieved, as shown in Fig. 4. It is clear that final electron density dependence of the polarization angle shows the same variation tendency with THz amplitude dependence of the polarization angle α. That is to say, the final electron density plays the major role in THz emission and can be used to well explain the phenomenon mentioned above. However, it has to be pointed when the total laser intensity is high enough, the final electron density may be saturated at any polarization angle, and in this case, it can not be utilized to explain the situation any more.

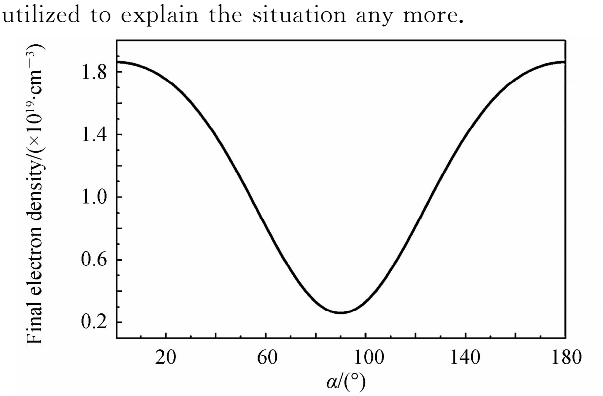


Fig. 4 Final electron density dependence of the polarization angle with $\theta=\pi/2$, $I_t=2\times10^{14}$ W/cm^2

In order to reveal the underlying physical mechanism, we analyze this phenomenon in another way. As discussed above, the free electrons not only oscillate with the laser field but also drift in the transverse direction. As a result, some residual drift current remains in the generated plasma when the laser pulse passed. This residual current density is the essential source of the radiated electromagnetic pulse and determines the intensity of THz emission[22-23]. As described in Eq. (4), the time-dependent velocity of the free electrons can be expressed as

$$v(t,t') = -(e/m_e)\int_{t'}^{t} E_L(t'')\mathrm{d}t'' = -(e/m_e)\left(\int_{-\infty}^{t} E_L(t'')\mathrm{d}t'' - \int_{-\infty}^{t'} E_L(t'')\mathrm{d}t''\right) \quad (6)$$

Eq. (6) describes the time-dependent velocity of the free electrons under the external laser fields. We can see that the free electrons not only oscillate at the laser frequency (the first term) but also drift with a velocity when the laser pulse passed (the second term). Then, the two vertical drift velocity components are given by

$$\begin{aligned} v_{do} &= eE_{\omega y}\sin(\omega t')/(m_e\omega) \\ v_{de} &= eE_{\omega x}\sin(\omega t')/(m_e\omega) + eE_{2\omega}\sin(2\omega t'+\theta)/(2m_e\omega) \end{aligned} \quad (7)$$

where v_{de} and v_{do} are the drift velocity along the x-axis and y-axis, respectively. Thus, the whole velocity v_d can be expressed as

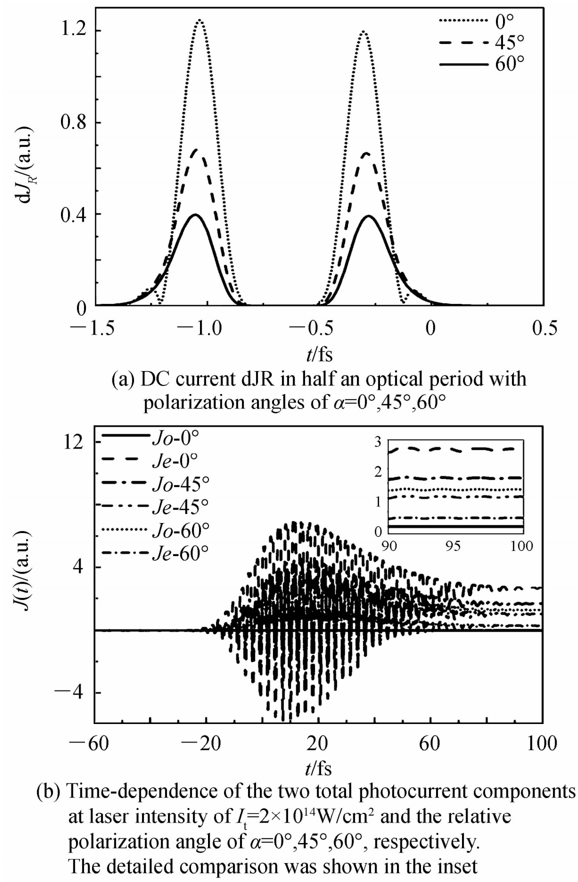
$$|v_d|^2 = v_{do}^2 + v_{de}^2 \quad (8)$$

Therefore, the residual drift current is given by

$$J_R(t') = -e\int_{-\infty}^{\infty}\mathrm{d}J_R(t')\mathrm{d}t' = -e\int_{-\infty}^{\infty}\frac{\mathrm{d}n(t')}{\mathrm{d}t'}v_d(t')\mathrm{d}t' \quad (9)$$

According to Eq. (9), it can be seen that the residual drift current relies on both the increasing rate of the free electron density and the drift velocity. When the polarization angle changed, the increasing rate and the drift velocity may show different variation tendency. Thus, an optimal polarization angle can be found in which the maximum of the drift current can be achieved, corresponding to the highest emitted THz amplitude.

Fig. 5(a) gives the drift current in half an optical period for the total intensity of 2×10^{14} W/cm^2 with the different polarization angles at 0°, 45°, 60°, It is obvious that the drift current $\mathrm{d}J_R$ can reach the maximum value at the angle of $\alpha=0°$. Since the drift current $\mathrm{d}J_R$ shows the same tendency in every optical period at a certain polarization angle, the total drift current achieves the maximum value at the polarization angle $\alpha=0°$, which can radiate the maximum THz emission. On the other hand, we can also intuitively observe the same behavior in the total photocurrent which is oscillating at the laser frequency, as shown in Fig. 5(b). Both J_e and J_o are in the asymmetric distribution and non-vanishing drift current arises with different polarization angle. According to a detailed comparison for different polarization angles to the final drift photocurrent in the inset of Fig. 5, we can clearly see that $J_T^2 = J_e^2 + J_o^2$ gets the maximum value at angle of 0°, which is consistent with the results we obtained above. This is to say, the non-vanished drift current can be perfectly utilized to estimate the THz intensity and explain the phenomenon of the time-varying THz amplitude with different polarization angles.

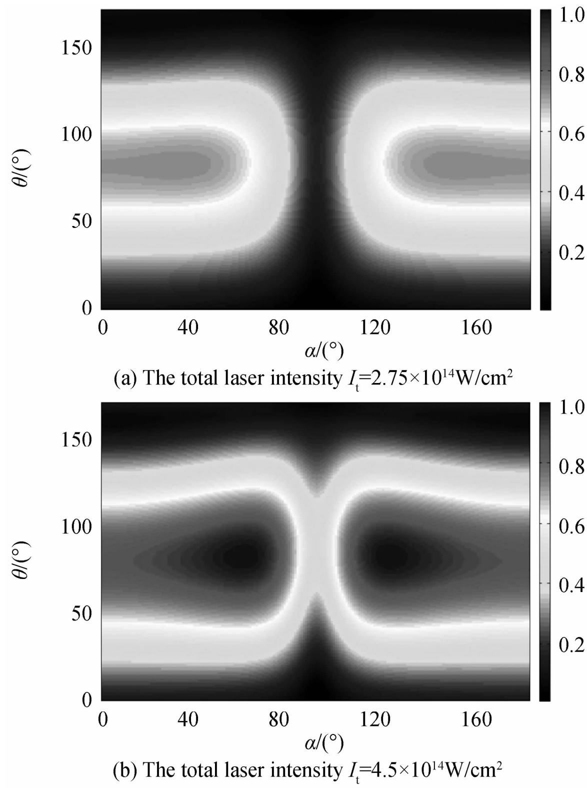


(a) DC current dJR in half an optical period with polarization angles of α=0°,45°,60°

(b) Time-dependence of the two total photocurrent components at laser intensity of I_t=2×10^14^W/cm^2^ and the relative polarization angle of α=0°,45°,60°, respectively. The detailed comparison was shown in the inset

Fig. 5 DC current dJ_R and time-dependence of the two total photocurrent components

For further investigation, we aim to find the relationship of the optimal polarization angle with different laser intensities. Fig. 6 shows the contour plot of THz amplitude dependence on the relative phase θ and the polarizaion angle α with the total laser intensities of $I_t = 2.75 \times 10^{14}$ W/cm^2 and 4.5×10^{14} W/cm^2, respectively. It is clear that higher THz amplitude can be obtained with higher laser intensity (For comparison, the same color bar has been utilized in Fig. 3 and Fig. 6). However, the maximum THz amplitude occurs at the polarization angles about α = 0°, 31° and 60° for the laser intensity of 2×10^{14} W/cm^2, 2.75×10^{14} W/cm^2 and 4.5×10^{14} W/cm^2, respectively. In other words, the optimal angle increases with the total laser intensity increasing. Moreover, it indicates that once we change the polarization state of the two-color lasers from orthogonal to parallel, the emitted THz amplitude can be enhanced remarkably. However, if we aim to get the highest THz amplitude, a proper polarization angle should be selected in different laser intensity.



(a) The total laser intensity I_t=2.75×10^14^W/cm^2^

(b) The total laser intensity I_t=4.5×10^14^W/cm^2^

Fig. 6 THz amplitude dependence of the relative phase θ and the polarization angle α at a certain total laser intensity

Finally, we investigate the optimal polarization angle as a function of the total laser intensity as shown in Fig. 7. It presents that optimal polarization angle increases promptly with the increasing laser energy at the lower pump energy and gets to be saturated at around 61° when the laser intensity is higher enough. The saturation characteristic is mainly due to the saturation of the final electron density as discussed above.

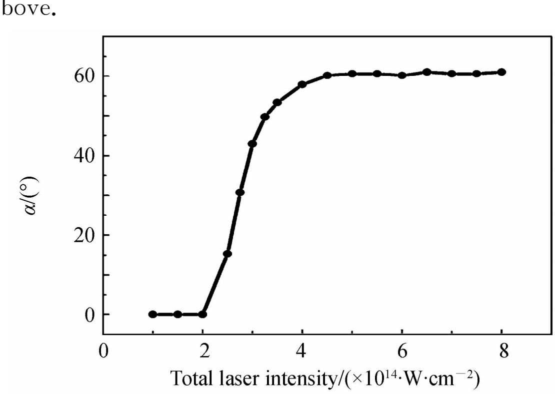


Fig. 7 The optimal polarization angle α as a function of the total laser intensity

3 Conclusions

In conclusion, the influence of the polarization angle between the fundamental and its second harmonic on the THz emission was investigated based on a modified two-dimensional transient current model. It shows that when the total laser intensity is comparatively low ($\leqslant 2 \times 10^{14}$ W/cm^2), the THz amplitude reached the maximum when the polarization of the two-color lasers are parallel, while the minimum appeared when they are orthogonal. However, when the laser intensity was high enough ($> 2 \times 10^{14}$ W/cm^2), the optimal polarization angle increased with the increasing of the total laser intensity and finally get saturated. The final electron density can be used to explain this phenomenon in the low laser intensity as it shows the same variation tendency with the THz amplitude dependence of the polarization angle. Then, the residual drift photocurrent, which was the essential source of the THz radiation, was utilized to explain this phenomenon. It shows that the value of the residual drift photocurrent can be used to estimate the THz yield. This investigation will be very useful to generate the intense THz waves for further applications.

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