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Terahertz emission from two-plasmon-decay induced transient currents in laser-solid interactions

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We have studied the generation of terahertz (THz) radiation via the interaction of intense femtosecond laser pulses with solid targets at a small incidence angle. It is found that preplasma with a moderate density gradient can enhance the emission. We also observe saturation of the THz output with the driving laser energy. We find that THz emission is closely related to the 3/2 harmonics of the driving laser. Particle-in-cell simulations indicate that under the present experimental conditions, the THz emission could be attributed to the transient currents at the plasma-vacuum interface, mainly formed by the two-plasmon-decay instability. © 2016 AIP Publishing LLC.

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I. INTRODUCTION

The multitude of frontier applications^{1,2} of terahertz (THz) radiation is driving the exploration of high-power THz radiation sources.³ Laser-plasma interactions provide a unique possibility of achieving tabletop strong-field THz radiation source, since plasma is a medium without a damage threshold. THz radiation from gas plasmas has been studied extensively, both theoretically⁴ and experimentally.^{5–7} Strong THz fields exceeding 1 MV/cm have recently been demonstrated.^{8,9}

THz radiation with higher fields could be generated from solid-density plasmas, in which case the driving laser intensity can be higher than 10^{18} W cm⁻². THz energy of up to hundreds of μ J has been obtained with solid targets irradiated by relativistic lasers.^{10,11} Some models, including transient current-based^{10,12–14} and plasma wave-based^{11,15} models, have been proposed to explain the experiments reported before. For example, when fs laser pulses interact with steep density-gradient solid targets at a large incidence angle, the low-frequency-dominant radiation near the target surface is explained by a surface fast electron current.¹⁴

Here, we study THz radiation under different experimental conditions, where fs laser pulses are incident onto a solid target with a moderate density gradient at a small incidence angle. The THz radiation shows different features from that observed in Ref. 14. The high-frequency-dominant radiation near the target normal is found to increase and then saturate with increasing laser energy and preplasma density scalelengths. Our particle-in-cell (PIC) simulations show that the transient currents induced by two-plasmon-decay

(TPD) at the plasma-vacuum interface could be responsible for the observed radiation.

II. EXPERIMENTAL SETUP

The experiment was carried out using the Beamline 2 A of the advanced laser light source (ALLS) at the INRS-EMT. This laser system can deliver 800 nm laser pulses with a pulse duration of 45 fs and energies up to 300 mJ. Figure 1 shows a schematic view of the experimental setup. The laser pulse was incident onto a polished copper target with an incidence angle of 10°. The focused intensity was $\sim 7 \times 10^{17}$ W cm⁻² for 100 mJ laser energy on the target. The radiation emitted from front of the solid targets was collected using a THz lens, and its energy was measured by two cross-calibrated pyroelectric detectors in the direction of 20° and 65° with respect to the target normal. High-resistivity silicon (HR-Si) was used in the path to shield the scattered laser light and visible light. Meanwhile, the spectrum of the scattered light in the direction of 20° was measured by a fiber optical spectrometer. The preplasma was adjusted by controlling the intensity of prepulses that were 8 ns in front of the main pulse.

III. EXPERIMENTAL RESULTS

The THz signal detected by the detector at 20° was over 5 times stronger than that at 65°. The distinct spatial inhomogeneity indicates that the detected signal is not caused by thermal radiation. We mainly focus on the radiation at 20° in the experiment.

A set of THz low-pass filters were used to estimate the energy distribution in the frequency spectrum. Over 80% of the radiation energy is distributed in the high frequency (>10 THz) region. By checking with a wire-grid polarizer,

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FIG. 1. Schematic of the experimental setup. The THz lens and windows are not depicted.

we find that the radiation is circularly polarized or radially polarized.

Figure 2 shows the measured THz energy as a function of the driving laser energy with different laser contrasts (defined as the ratio I_{pp}/I_{mp} of the prepulse intensity I_{pp} to the main pulse intensity I_{mp}). The radiation increases nonlinearly with the increase of laser energy. At relatively small laser energy, the radiation is found to be stronger for poorer laser contrast (i.e., higher I_{pp}/I_{mp}), which is different from that reported in Ref. 14. As the laser energy increases, the radiation gradually becomes saturated or even slightly decreases, which is observed for the first time in the laser-solid driven THz radiation. The THz radiation after saturation seems independent of the laser contrast.

We have measured the spectrum of the scattered light simultaneously. The upper-left inset in Fig. 3 shows a typical spectrum in the visible region obtained at a laser contrast of 5×10^{-5} . Both $3/2\omega_0$ and $2\omega_0$ can be still observed even at a laser contrast of 3×10^{-7} , where ω_0 is the laser frequency. When the laser contrast worsens (i.e., for higher I_{pp}/I_{mp}), the $2\omega_0$ component weakens and even disappears. Contrary to the observations in Ref. 14, the THz yield is independent of the $2\omega_0$ component, shown in the lower-right inset of Fig. 3. It is interesting, instead, that the $3/2\omega_0$ component shows a very similar dependence on the laser energy and laser

FIG. 2. Dependence of THz radiation on the pump laser energy with different laser contrasts.

FIG. 3. Dependence of the $3/2\omega_0$ signal intensity of the scattered light on the THz yield. The upper-left inset shows the typical spectrum of the scattered light. The lower-right inset shows the independence between the THz radiation and $2\omega_0$ component.

contrast to the THz yield. Figure 3 shows the intensity of the $3/2\omega_0$ signal as a function of the THz energy at a laser contrast of 5×10^{-5} . The blue dashed line is a linear fit. The approximately linear relationship between the THz yield and $3/2\omega_0$ intensity is also observed at other laser contrasts. Usually the $3/2\omega_0$ component is an indication of two-plasmon decay (TPD) instability.¹⁶ Therefore, these results imply that the THz emission is closely related with the TPD process.

IV. SIMULATIONS AND DISCUSSIONS

TPD usually occurs when the laser pulse propagates near the $n_c/4$ plasma density region with a moderate density scalelength, where n_c is the critical density. The incident laser pulse (electromagnetic wave, EMW) decays into two plasmons (electrostatic wave) with a frequency of $\omega_0/2$. The $3/2\omega_0$ is generated by the mixing of three $\omega_0/2$ plasmons or a photon ω_0 and a $\omega_0/2$ plasmon.^{16,17} The strong $\omega_0/2$ plasma wave excited by TPD will accelerate electrons through Landau damping or wave breaking.^{18,19}

Limited by the requirement of phase matching, TPD is a two-dimensional (2D) process. Lateral plasma waves will be excited, and correspondingly the electrons could be accelerated laterally. A part of the collectively accelerated electrons transports outward the low-density plasma region and forms a strong transient current at the plasma boundary, which will emit EMW radiation. To confirm this, 2D PIC simulations have been performed using the KLAPS codes²⁰ with similar parameters to the experimental. A p -polarized sine-square-shaped laser pulse with a pulse duration (FWHM) τ_L of $15\tau_0$ and a normalized intensity $a_0 = 0.5$ is incident onto a plasma slab at an incidence angle of 20° , where τ_0 is the laser period. The plasma density is described by an exponential function $n(x)$ along the x -direction from $0.0004 n_c$ at $x = 0$ to $5n_c$. The density scalelength, L , defined by $[-(\partial n/\partial x)/n]^{-1}$ is a variable in the simulations. The spatial resolution is $0.05\lambda_0$ and the temporal resolution is $0.025\tau_0$, where λ_0 is the laser wavelength.

FIG. 4. Spatial distribution of lateral current J_y (a) in high-density regions at $45\tau_0$, where the white arrows show the flowing direction of currents formed by hot and cold electrons, and (b) in low-density ($<0.01n_c$) regions at $65\tau_0$, where the red and black arrows sketch the laser incidence and motion direction of electrons, respectively. (c) Temporal evolution of the peak of lateral current. L in (a)–(c) is $2\lambda_0$. (d) Dependence of the Peak-II of J_{+y} and $3/2\omega_0$ on L . The J_y in (a) is divided by a factor of 10.

In the simulations, a strong transient current is formed after the laser pulse is reflected off the plasma slab. Figure 4(a) shows the snapshot of currents at $45\tau_0$ with $L = 2\lambda_0$. We can see that the lateral current mainly originates from around the density region at $n_c/4$. This indicates that the current is mainly driven by TPD, rather than resonant absorption.¹⁶ Besides the TPD driven hot electron current, a background cold electron return current is also induced simultaneously in the high-density region. Since they almost cancel each other out, the local net current in the high-density region is small. The current transports outward and forms the transient current in the low-density region, as shown in Fig. 4(b). Additionally, since the absorption of THz radiation at high-density region is high due to resonant absorption, the THz field in the high-density region cannot be emitted efficiently into vacuum. Therefore, we will mainly concentrate on the current J_y in low-density ($<0.01n_c$) regions in the following discussions.

Our simulations indicate that the current J_y transports laterally away from the laser focal spot. For $L = 2\lambda_0$, the lateral velocity along the y -direction is about $0.3c$, where c is the light velocity in vacuum. Figure 4(c) shows the temporal

evolution of the peak of the lateral current J_y . The J_y in the $+y$ and $-y$ directions (indicated with J_{+y} and J_{-y} , respectively) are nearly symmetric. Both of them have two peaks. The J_{+y} first increases to a small peak (Peak-I) at $\sim 30\tau_0$ and then decreases. Then, it increases to a strikingly big peak (Peak-II) within about $20\tau_0$ and then drops slowly. We see that Peak-II is over 10 times stronger than Peak-I. The J_{-y} has a similar evolution to the J_{+y} .

We have also varied L and detected the spectrum of scattered light in the simulations. According to our previous simulations,¹⁴ L is set to be in the range of $1-2\lambda_0$. Figure 4(d) shows the peak of J_{+y} and $3/2\omega_0$ as a function of L . We find that both of them increase with L . The lateral current is positively correlated with $3/2\omega_0$. This also indicates that the lateral transient current is mainly driven by TPD.

This time-dependent transient current will emit EMW.²¹ A detection plane for the emission is set at $x = -30\lambda_0$ in the simulations. Fast-Fourier-transform (FFT) algorithm is applied to calculate the EMW spectra and filter the laser light and harmonics. Two types of emissions are observed. A weak few-cycle radiation (Type-I) is emitted after the laser

FIG. 5. (a) Spatial snapshot of the EMW radiation field B_z at $t = 40\tau_0$. (b) Temporal profile and (c) frequency spectrum of the radiation field B_z detected at the point A ($-30\lambda_0, 130\lambda_0$) in $50-80\tau_0$. (d) Spatio-temporal profile of B_z detected at the plane $x = -30\lambda_0$. (e) Calculated angular distribution of THz emissions. (f) and (g) Temporal profile and spectrum comparison of the B_z , detected at the point A, with $-dJ_{+y}/dt$. L in the simulations is $2\lambda_0$.

pulse is incident into the inhomogeneous plasma. Figure 5(a) shows a snapshot of the EMW field B_z at $t = 40\tau_0$. The radiation is conical and nearly symmetric relative to the laser incidence point. The high-frequency field within the red dashed region is the reflected laser field. Figures 5(b) and 5(c) show the temporal profile and the spectrum of B_z detected at the point A $(-30\lambda_0, 130\lambda_0)$, respectively. The central frequency is at $0.052\omega_0 = 20$ THz, close to the inverse of the laser pulse duration $1/\tau_L$ (25 THz). The radiation is generated from the transient current at Peak-I shown in the inset of Fig. 4(c), driven by the laser ponderomotive force at the plasma-vacuum interface.²²

Following the reflected laser pulses, a strong half-cycle radiation (Type-II) is emitted. Figure 5(d) shows the spatio-temporal profiles of B_z detected at the plane $x = -30\lambda_0$. The radiation field is about 10 times higher than that of Type-I. The spatial or angular distribution of THz emissions obtained is shown in Fig. 5(e). The two emission lobes peak at $y = 130\lambda_0$ and $88\lambda_0$, in the vicinity of the direction of laser specular reflection.

The THz temporal waveforms and frequency spectra at the point A $(-30\lambda_0, 130\lambda_0)$ are shown in Figs. 5(f) and 5(g), respectively. The asymmetric THz pulse increases to its peak within $\sim 10\tau_0$ and the pulse duration (FWHM) is $\sim 10\tau_0$ (close to the laser pulse duration τ_L). Considering the retardation from the laser interaction point to the observation point, the field peak moment at $t \sim 90\tau_0$ in Fig. 5(f) corresponds well to the moment $t \sim 50\tau_0$ in Fig. 4(c), when the current J_y varies the fastest. For a current J emitting the EMW, the magnetic component $B \propto$ the electric component $E \propto \frac{\partial A}{\partial t} \propto \frac{dJ}{dt}$, where A is the vector potential. To confirm that the TPD driven current J_y emits the Type-II radiation, we have also calculated the $-dJ_y/dt$ and its spectrum. The results are shown with the dashed lines in Figs. 5(f) and 5(g). The waveform and spectrum of $-dJ_y/dt$ are similar to the radiation field B_z , indicating that the strong half-cycle radiation is mainly generated by the TPD driven lateral current J_y at the plasma-vacuum interface.

For the two types of transient currents driven by either the laser ponderomotive force or TPD, the characteristic times are both close to the laser pulse duration τ_L . Hence, the induced emission peaks around $1/\tau_L$ in the frequency spectra, as shown in Figs. 5(c) and 5(g). This explains why the detected radiation is dominated by the high-frequency (>10 THz) component in our experiment. The simulated THz emission is p -polarized in the 2D geometry. In the 3D space, however, due to the axial symmetry of the lateral currents excited at a small laser incidence angle,²³ the induced THz electric field would be radially polarized. This also agrees well with the experimental measurement.

The preplasma dependence and the energy saturation of the detected THz radiation could be understood qualitatively by the TPD related model. Preplasmas in a suitable range will enhance the TPD, since the laser intensity threshold for TPD is lower at larger density scalelengths.¹⁶ When the laser intensity increases to a relativistic level, the plasma density modulation around $n_c/4$ by the laser ponderomotive force and the competition with stimulated Raman scattering will result in the saturation of TPD.¹⁶ The similar effects of pre-pulses and laser energy on the electron lateral transport have

also been observed in the previous experiments,²⁴ which might imply the underlying relation between the lateral current and THz radiation.

V. CONCLUSIONS

We have studied the THz radiation emitted from solid targets with a moderate preplasma scalelength irradiated by intense fs laser pulses at a small incidence angle. The radiation is found to be closely related with the preplasma scale length and $3/2\omega_0$. PIC simulations reproduce the main features observed in the experiment. It shows that the conically emitted half-cycle THz radiation is mainly originated from the transient current at the plasma-vacuum interface, which is mainly driven by TPD under the current experimental conditions.

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