32nd URSI GASS, Montreal, 19-26 August 2017

Intense THz-Coherent Transition Radiation from Laser Solid Plasma Interaction

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Abstract

We investigate intense broadband terahertz radiation generation based the interaction of high intensity ultrashort laser with solid plasma. THz pulse with electric field of hundreds of MV/cm are generated using laser with intensity of about 10^{18} W/cm^2. Theoretical model, simulations agree well with experiments, and reveal that the THz radiation is coherent transition radiation by hot electrons produced in laser-plasma interaction. We have studied both planar and nanorod array targets, latter of which efficiently enhance the intensity and directionality of the THz source.

1. Introduction

THz radiation has wide ranging applications in imaging, sensing, wireless communication and fundamental science. Laser plasma interaction is a promising technology toward tabletop, powerful THz sources [1]. Firstly, it overcomes the damage limitation of optical material based THz sources [2]. Secondly, huge amount of electrons are involved in laser-plasma interaction comparing to conventional electron accelerator based THz source [3]. Here we present numerical simulations, theoretical model and also experimental investigation on generation of THz radiation with high intensity laser-solid plasma interaction.

2. Theory of coherent transition radiation from hot electrons

Transition radiation is emitted when a charged particle crosses two different materials. We proposed Coherent transition radiation (CTR) theory to explain generation of strong THz radiation from high-intensity ultrashort laser-solid plasma interaction [4]. Theoretically, energy spectrum of transition radiation from an electron beam with N electrons [5, 6], as a function of frequency (ω) and solid angle (Ω), derived from the expression of a single electron, is:

$$\frac{d^2\mathcal{E}}{d\omega d\Omega} = [N + N(N-1)f(\omega)]\frac{d^2\mathcal{E}_{single}}{d\omega d\Omega} \quad (1).$$

where $\frac{d^2\mathcal{E}_{single}}{d\omega d\Omega}$ is the energy spectrum of transition radiation from a single electron. In the incidence plane, it is given by

$$\frac{d^2\mathcal{E}_{single}}{d\omega d\Omega} = \frac{e^2}{\pi^2 c}|S(\beta,\varphi,\phi)|^2 \quad (2).$$

$$S(\beta,\varphi,\phi) = \frac{\beta cos\varphi(sin\phi - \beta sin\varphi)}{(1-\beta sin\phi sin\varphi)^2 - (\beta cos\phi cos\varphi)^2} \quad (3).$$

where e is the electron charge, c is the light velocity in free space, β is the electron velocity normalized to c, φ is the electron injection direction, ϕ is the observation direction.

The term $N(N-1)f(\omega)$ in Eq. (1) represents the coherent enhancement. The form factor $f(\omega)$ is the Fourier transform of the electron distribution $f(\tau,\boldsymbol{\rho},\boldsymbol{v})$, as a function of time, space and velocity, within the beam is

$$f(\omega) = \left|\iint f(\tau,\boldsymbol{\rho},\boldsymbol{v})e^{i\omega\tau - i\boldsymbol{q}\cdot\boldsymbol{\rho}}d\tau d\boldsymbol{\rho} d\boldsymbol{v}\right|^2 \quad (4).$$

The term of coherent transition radiation shows square law dependence on the electron number. In laser-solid plasma interaction, large amount of hot electrons with the charge of a few nC are produced. TR, particularly CTR are generated when the hot electrons cross the plasma-vacuum interface. As the duration of hot electrons resembles that of the laser pulse, the frequency of CTR falls in the THz range. These make CTR from hot electrons in laser-solid plasma an unprecedentedly strong THz source.

3. Simulations and experiments

3.1 THz radiation by planar targets

We performed two dimensional Particle-in-cell (PIC) simulations [7], solving Maxwell equations and Newton-

Lorentz motion equation of charged particles consistently, to model interactions of electromagnetic wave and plasma. In the simulations, a *p*-polarized ultrashort laser with wavelength λ_0=800 nm obliquely incident on a thin solid density plasma target.

Forward and backward hot electrons [4, 8] are produced in the preplasma of the target by the laser-plasma interaction. Figure 1(b) shows the spatial distribution of electric field after laser reflected from the target. Both backward (reflected) and forward (transmitted) THz radiations are emitted in a broad angular space. Ey can be as high as 400 MV/cm at a distance of 80 μm from the target, even at a moderate laser intensity of around 10^{18} W/cm^2. An empirical scaling of THz pulse intensity as function of laser intensity is also studied. As the electron bunches propagate back and forth through the target [1], multiple radiation pulses are generated. Figures 1(c) and 1(d) show the spectra of the primary pulse of the backward and forward radiation. The radiation is weakest at the emission angle of hot electrons, which is slightly smaller than the reflection angle of the laser 30^{o}, and strongest in large angle near the target surface. Angular distribution of the THz radiation perfectly agree with the theoretical model of transition radiation from a single electron, as seen in Fig. 1(a).

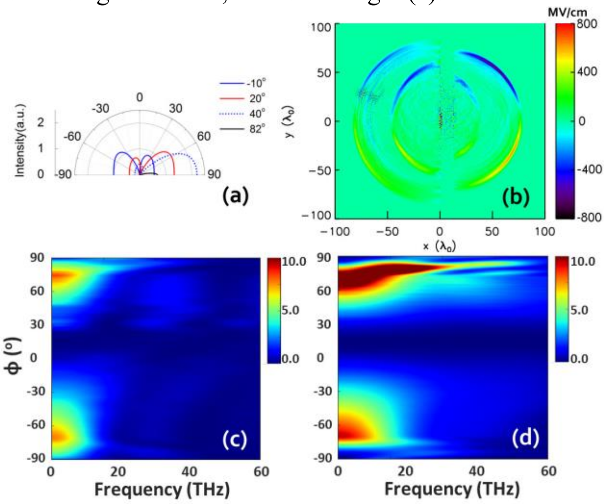

Figure 1. (a) Angular distribution of TR from a single electron by the theory model of eq. (2). Incidence angle of electron is marked with lines of different color. PIC Simulations of laser-solid plasma target interaction: (b) Snapshot of electric field E_y; Spectrum of the (a) backward (reflected) and (d) forward (transmitted) radiations. Laser duration is 80 fs, peak intensity 7.7×10^{17} W/cm^2, spot size 4 μm, incidence angle 30^{o}.

We have also thoroughly investigated the close relation of THz radiation with the parameters of the target and laser, such as scale of the preplasma. Optimum conditions are given in order to generate strongest THz radiations. Good agreement of the theory model and simulation results with experiments by other authors [9, 10, 11] is achieved as well.

3.2 THz radiation by nanorod targets

Nano structures have been found to increase laser absorption rate significantly [12]. Thus we have studied solid targets with nanorod arrays on the front surface, through PIC simulations and experiments. Enhancement on not only intensity but also directionality of the THz radiation are obtained.

Figure 2(a) and 2(b) show PIC simulation results of THz radiation generated using nanorod targets. We can see from Fig. 2(a) that the THz radiation is mainly emitted in the laser reflection direction, which is very different from using planar targets as in Fig. 1(c). This is due to the generation of hot electrons, such as distribution of kinetic energy of hot electrons, are changed because of nanorods. Figure 2(b) shows total energy of hot electrons varies with the length of nanorod. Planar target is marked as length is 0. We can see that with nanorod arrays, more energy are transferred from laser pulse to electrons, and vertical energy of hot electrons E_{ky} are particularly enhanced. In the simulations, intensity of THz radiation has similar trend with the nanorod length. At the optimal nanorod length, which is 4 μm with the given spacing and width of nanorods, an increase of 3.5 times of total electron energy and around 14 times of THz intensity are obtained.

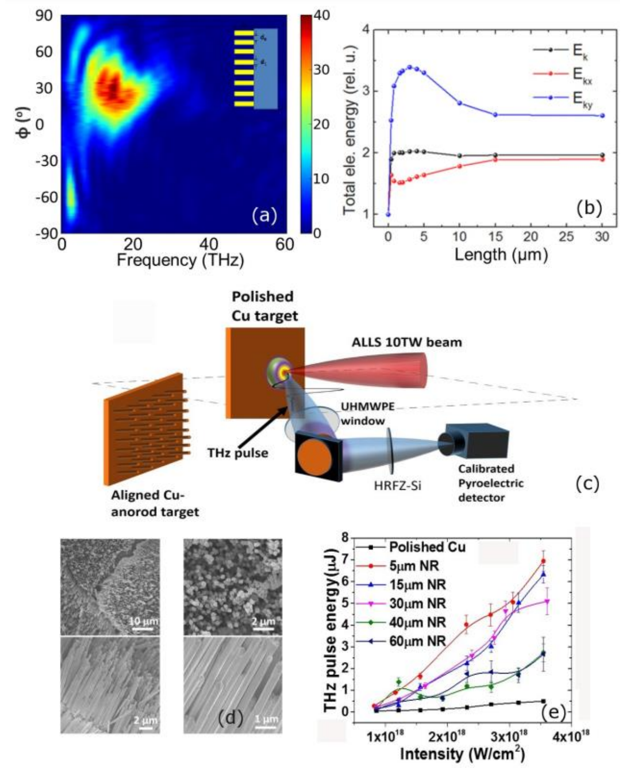

Figure 2. THz radiation generated from nanorod targets. PIC simulation results: (a) Spectrum of reflected radiation, inset is the schemetic of the target; (b) Total electron energy as a function of nanorod length h. h=4 μm in (a). laser duration is 40 fs, peak intensity 3.5×10^{18} W/cm^2. Experiment results: (c) Schemetic of the experimental setup; (d) SEM images of Cu nanorod arrays; (e) THz pulse energy for different targets as a function of laser intensity.

Spacing and width of nanorods are $d_0=d_1=0.2$ μm in simulations and experiments.

Figure 2(c) shows the schematic setup of the experiments. We use 10 TW femtosecond laser pulses from the 10 Hz beam line of the Advanced Laser Light Source (ALLS) at INRS-EMT. The laser is focused on a copper target (size: 5cm×5cm×3cm), to a circular spot of 20 μm in diameter. The laser pulses have energy of 240mJ maximum with duration of 40fs, which results in a peak intensity of 3.5×10^{18} W/cm^2, same as in simulations. Broadband THz and infrared pulses are generated by the laser-plasma interaction. The generated THz are collimated by a gold-blended off-axis parabolic mirror and then guided out of the vacuum chamber through a THz window made of ultrahigh molecular weight polyethylene (UHMWPE).

Figure 2(d) shows SEM images of the rough Cu targets with nanorod arrays. We compare the THz energy for medium frequencies (≤ 20 THz) from Cu targets with polished and rough surfaces in Fig. 2(e). Comparing to polished Cu targets, nanorod targets with different nanorod length all increase THz pulse energy significantly. A 13.8 times enhancement in the THz pulse energy is obtained when nanorod length h=5 μm. Same trend of THz energy on nanorod length are observed in simulation in Fig. 2(b). The slightly reduction and saturation of THz pulse energy with longer nanorod length is different from x-ray generation [13], which increases with longer nanorod length.

4. Summary

High field broadband THz radiation, with electric field of sub GV/cm is generated from interaction of femtosecond laser with solid plasma targets, even at a moderated laser intensity of a few times of 10^{17} W/cm^2. The THz radiation is attributed to coherent transition radiation by hot electrons produced in laser-plasma interaction. The square law dependence of CTR on electron number makes this method generate the strongest THz source so far. Characteristics of the THz radiation has close relation with the parameters of the laser and the target. Planar and nanorod arrays targets are both studied. It is revealed that THz pulse is enhanced significantly by nanorod targets in energy and directionality. A 13.8 times enhancement in the THz energy is obtained with nanorod targets comparing to planar targets. Theoretical model, particle-in-cell simulations and experimental results match perfectly.

5. Acknowledgements

Z.M.S. and J.Z. acknowledges the support by the National Basic Research Program of China (Nos 2014CB339801 and 2013CBA01504), the National Science Foundation of China (No. 11421064), a MOST international collaboration project (No. 2014DFG02330), and a Leverhulme Trust Research Grant.

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