CPC(HEP & NP), 2009, **33**(Suppl. II): 142—145 **Chinese Physics C** Vol. 33, Suppl. II, Jun., 2009

Terahertz emission in tenuous gases irradiated by ultrashort laser pulses*

WANG Wei-Min(王伟民)[1] SHENG Zheng-Ming(盛政明)[1,2;1)] WU Hui-Chun(武慧春)[3]
CHEN Min(陈民)[4] LI Chun(李春)[2] ZHANG Jie(张杰)[1,2] K. Mima[5]

1 (Beijing National Laboratory of Condensed Matter Physics, Institute of Physics, CAS, Beijing 100190, China)
2 (Department of Physics, Shanghai Jiaotong University, Shanghai 200240, China)
3 (Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany)
4 (Institut für Theoretische Physik I, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany)
5 (Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan)

Abstract Mechanism of terahertz (THz) pulse generation in gases irradiated by ultrashort laser pulses is investigated theoretically. Quasi-static transverse currents produced by laser field ionization of gases and the longitudinal modulation in formed plasmas are responsible for the THz emission at the electron plasma frequency, as demonstrated by particle-in-cell simulations including field ionization. The THz field amplitude scaling with the laser amplitude within a large range is also discussed.

Key words Terahertz emission, ionization of gases, plasma formation, particle-in-cell simulations

PACS 52.25.Os, 42.72.Ai, 42.65.Ky

1 Introduction

Intense terahertz (THz) emission has been in wide and increasing demand in nonperturbative THz electro-optics, nonlinear THz spectroscopies, etc.[1]. Such THz emission is usually obtained from accelerator-based sources, which is still limited by bandwidth, peak intensity, and the availability to most users. Therefore “table-top” intense THz sources using gases or plasmas have attracted broad attention recently. Strong THz emission can be produced from the laser wakefield in inhomogeneous plasmas by linear mode conversion[2, 3], or from the transition radiation at plasma-vacuum boundaries using ultrashort electron bunches[4]. Also gases irradiated by ultrashort laser pulses can emit THz pulses[5—13]. Cook et al. proposed and demonstrated that THz pulses can be generated efficiently when two-color laser pulses (one at fundamental and another second-harmonic) co-propagate in air[5]. Several authors attributed this THz pulse generation to four-wave rectification[5—8], and among of them Kress et al. found plasma formation is necessary for this THz emission[6]. Recently, Kim et al.[9] and Wu et al.[10] suggested that transverse drift currents excited by symmetry-broken laser field ionization of gases are responsible for this THz emission. However, their models hold only at moderate laser intensity and cannot explain the THz emission frequencies.

In this paper we present an analytical model describing the mechanism of the THz emission in gases irradiated by high intensity lasers. It is found that the quasi-static transverse drift currents formed during the field ionization process and sequently modulated by formed plasmas in the longitudinal direction are responsible for the THz-wave generation with the frequency ω_p. The THz wave amplitude is proportional to the drift currents formed by the hardly controlled field ionization, which are not necessary to increase with the incident laser intensity.

Received 6 January 2009

* Supported by National Natural Science Foundation of China (10425416, 10674175, 60621063), National High-Tech ICF Committee in China and National Basic Research Program of China (2007CB310406)

1) E-mail: zmsheng@sjtu.edu.cn

2 Analytic model for THz emission

Interaction of ultrashort laser pulses with tenuous gases includes laser field ionization of gases and the interaction of the laser pulses with formed plasmas. The laser field ionization rates can be calculated by the ADK formula[14, 15]. For free electrons, they follow the equation of motion given by

$$\partial \boldsymbol{v}_\perp/\partial t=\partial \boldsymbol{a}_\mathrm{L}/\partial t, \tag{1}$$

where $\boldsymbol{v}_\perp$ is the transverse electron velocity normalized by c, $\boldsymbol{a}_\mathrm{L}$ is the laser vector potential normalized by $m_\mathrm{e}c^2/\mathrm{e}$. Assume the initial velocity of all newly born free electrons is zero and the jth electron is born at place of $x_{\mathrm{j}0}$ and time of $t_{\mathrm{j}0}$. Then the transverse velocity of the electron is $\boldsymbol{v}_{\perp,\mathrm{j}}(x,t)=\boldsymbol{a}_\mathrm{L}(x,t)–\boldsymbol{a}_\mathrm{L}(x_{\mathrm{j}0},t_{\mathrm{j}0})$ in a plane laser field. The average transverse velocity at x and t is given

$$\langle \boldsymbol{v}_\perp\rangle=\sum_{\mathrm{j}=1}^{N}\boldsymbol{v}_{\perp,\mathrm{j}}/N=\boldsymbol{a}_\mathrm{L}-\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle, \tag{2}$$

where $\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle=\sum_{\mathrm{j}=1}^{N}\boldsymbol{a}_\mathrm{L}(x_{\mathrm{j}0},t_{\mathrm{j}0})/N$, N is the total electron number at x and t, and $\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle$ should be a function of $x–ct$. Assume the ionization stops at x_f where laser pulses have left or gas atoms have been ionized completely. Then all $\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle$ at $x<x_\mathrm{f}$ should be statistically the same and therefore quasistatic transverse currents are formed in the wake of the laser pulses.

When the laser pulses just leave x at $t=x/c$, the transverse velocity of all free electrons at x is assumed to be $-\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle$. At $t>x/c$, the electron velocity $\boldsymbol{v}_\perp=\delta\boldsymbol{a}-\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle$, where $\delta\boldsymbol{a}$ is the vector potential of newly generated EM waves (THz waves). Here we have assumed $\delta\boldsymbol{a}=0$ at $t<x/c$ since the newly generated EM wave wavelength is much larger than the laser duration, which will be seen below. Thus, the wave equation of newly generated EM waves in plasmas is given by

$$\left(\frac{\partial^2}{\partial x^2}-\frac{\partial^2}{c^2\partial t^2}\right)\delta\boldsymbol{a}=\frac{\omega_\mathrm{p}^2}{c^2}\left[\delta\boldsymbol{a}-\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle\right], \tag{3}$$

where $\omega_\mathrm{p}^2=4\pi\mathrm{e}^2n_\mathrm{e}/m_\mathrm{e}$, the formed plasma electron density n_e is assumed to be uniform since we only consider the case with plasma wavelength $\lambda_\mathrm{p}=2\pi c/\omega_\mathrm{p}\gg\lambda_0$ and $|\delta\boldsymbol{a}|\ll 1$. Solving Eq. (3) by the Laplace transform, one can obtain

$$\begin{aligned}\delta\boldsymbol{a}\ =&\ -\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle[\cos(\omega_\mathrm{p}\tau)-1]+\\ &\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle[\cos(\omega_\mathrm{p}\tau)-1]\otimes\\ &\mathcal{L}^{-1}\left\{\exp\left[\frac{\xi}{2c}\left(s-\frac{\omega_\mathrm{p}^2}{s}\right)\right]\right\},\end{aligned} \tag{4}$$

where $\xi=ct-x$, $\tau=t$, the convolution operator $\otimes$ is defined by $f(\tau)\otimes g(\tau)=\int_0^\tau f(\tau-t)g(t)\mathrm{d}t$, and $\mathcal{L}^{-1}\{F(s)\}=f(\tau)$ is the inverse Laplace transform. The transform $\mathcal{L}^{-1}\left\{\exp\left[\frac{\xi}{2c}\left(s-\frac{\omega_\mathrm{p}^2}{s}\right)\right]\right\}$ cannot be performed analytically, but it is known that the first term in the exponent represents the propagation effect along the x-direction and the second term means the decaying effect. Eq. (4) also shows that the newly generated EM waves include both ω_p and 0−frequency components and have the same polarization as the incident pulses. When the target has a gas-vacuum boundary, the ω_p-frequency part within about λ_p near the boundary can penetrate into the vacuum effectively.

The above analysis is applicable for gas targets irradiated by either one-color or two-color laser pulses with normalized amplitude $a_\mathrm{L}<1$. When one-color waves are incident, the THz pulses will be produced very inefficiently and have some characteristics of noise. While two-color waves are incident, the symmetry of positive and negative half-cycle of the fundamental wave is broken[9]. The two-color-wave ionization causes drift currents in the same direction in every cycle and thus can emit THz pulses more efficiently than with one-color waves. When the target is a fully ionized plasma slab, either one-color or two-color waves are adopted, the net drift current is null, i.e. $\langle \boldsymbol{a}_\mathrm{L}(x_0,t_0)\rangle=0$, and no THz pulses can be generated.

3 Particle-in-cell simulations

To check the above results, we use one-dimensional (1D) particle-in-cell (PIC) simulations. In our PIC code the field ionization of gases is included with tunnelling ionization rates calculated by the ADK formula[14, 15]. For simplicity, only hydrogen gas (H_2) is used which generates one kind of plasma density only. A slab target with the gas density $n_\mathrm{gas}=1.25\times10^{-5}n_\mathrm{c}$ and the length $L_\mathrm{gas}=200\lambda_0$ or $400\lambda_0$ is used starting from $x=500\lambda_0$, where $n_\mathrm{c}=m_\mathrm{e}\omega_0^2/4\pi e^2$ is the critical density and $\omega_0=2\pi/T_0$ is the laser frequency. A laser pulse is incident along the $+x$ direction with the vector potential $\boldsymbol{a}_\mathrm{L}=\hat{\boldsymbol{e}}_z a_\mathrm{L}$, where $a_\mathrm{L}=\sin^2(\pi\xi/L_\mathrm{t})\cdot[a_1\cos(k_0\xi)+a_2\cos(2k_0\xi+\theta)]$, $k_0=\omega_0/c$, L_t is pulse duration, a_1 and a_2 are the normalized amplitudes for the fundamental and the second-harmonic waves, respectively, and θ is their phase displace. In the following simulations we take $L_\mathrm{t}=20\lambda_0$, $a_2=a_1/2$, and $\theta=\pi/2$.

Figure 1 is the spacial distribution of transverse currents in a preformed plasma and a H_2 target, respectively. One can see that in the preformed plasma no transverse current is left after the incident pulse. However in the H_2 target a quasi-static negative transverse current is formed. Therefore, in this case only gases can emit THz pulses. The excited transverse current in the H_2 target has a low-frequency oscillating profile at a later time [see Fig. 1(c)] because of the formed plasma modulation. It is indicated that ionization of gases is necessary for the THz emission in this case.

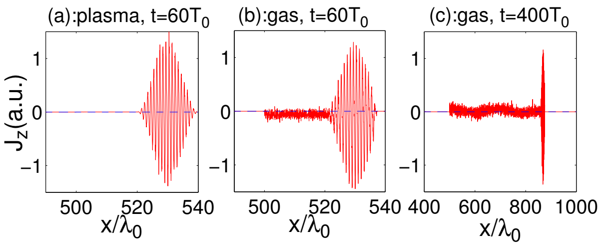

Fig. 1. Spacial distribution of transverse currents in a preformed plasma (a) at $t=60T_0$ and in a H_2 target at $t=60T_0$ (b) and $t=400T_0$ (c), respectively. A two-color laser with $a_1=0.06$ and $L_{\text{gas}}=400\lambda_0$ is taken.

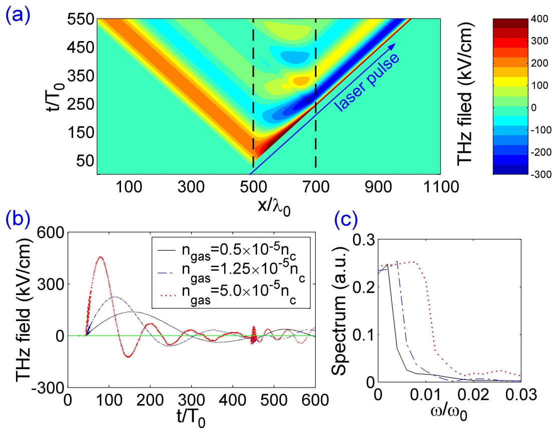

Fig. 2. (a) Temporal and spacial distribution of THz pulses from a H_2 gas target with the density $n_{\text{gas}}=1.25\times10^{-5}n_{\text{c}}$. Waveforms (b) and spectra (c) of THz pulses from H_2 targets with different initial gas densities. A two-color laser with $a_1=0.06$ is taken.

Figure 2(a) shows the temporal and spacial distribution of THz pulses generated by a H_2 target. One can see that there are two THz pulses, one going along the $+x$ direction and the other along the $-x$ direction. Both THz pulses in the vacuum are weaker than their sources within the H_2 plasma because they have to go through a distance of plasma. During radiation of THz pulses these sources decay so the first cycle in the vacuum is the strongest, which can be seen in Fig. 2(b) more clearly. Fig. 2(b) is temporal evolution of THz pulses observed at $20\lambda_0$ in front of the left gas-vacuum boundary and their corresponding spectra are plotted by Fig. 2(c). One can see that THz pulses have frequencies of $0.003\omega_0$ (1 THz), $0.005\omega_0$, and $0.01\omega_0$, equal to their individual ω_{p}. Note that there is the 0−frequency component because of the asymmetry of the positive and negative peaks of the THz pulse. These are consistent with the previous analysis.

For moderately intense incident pulses, experiments in Refs. [5—9] demonstrate that the THz pulse intensity increases almost linearly with the incident pulse intensity. At even intense incident pulses, however, it is not clear whether this still holds. By PIC simulations, we are able to study the THz pulse amplitude as a function of incident laser amplitude within a large range. As shown in Fig. 3(a), at $a_1\leqslant0.06$ the THz pulse amplitude increases with growing a_1, which agrees with previous experimental results. However, when one increases a_1 further, the THz pulse amplitude does not increase with a_1 monotonically. The reason is that when a_1 is very small, the ionization process lasts for many laser cycles [see Fig. 3(b)] and the produced electron number and the drift current increase with growing a_1. When a_1 is not small, the ionization process only occurs in the first few cycles and the leading edge of the incident pulse can ionize the gas completely [see Fig. 3(c)]. When a_1 is increased further, the drift current may not increase because the part of the incident pulse, which ionizes the gas, is shifted forwards [see Fig. 3(d) and (e)]. Therefore, for intense incident pulses it is

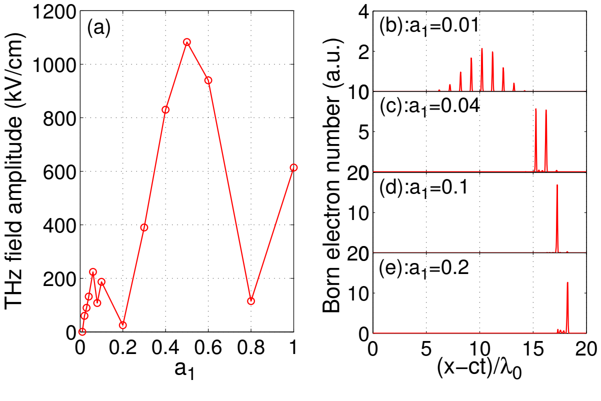

Fig. 3. (a) THz pulse amplitude as a function of a_1. (b)—(e) Number distribution of electrons, produced by laser field ionization, with $x-ct$ at different a_1. Two-color lasers and a H_2 target are taken.

difficult to control the born places of free electrons and produced drift currents, and consequently the THz amplitude does not scale with a_1 monotonically. This is unfavorable for powerful THz emission. At the moment, there is not yet any experiment conducted in such a high laser intensity regime. On the other hand, it would be interesting to seek new schemes to overcome this limit.

4 Summary

In summary, we have studied the mechanism of THz pulse generation from gas targets irradiated by ultrashort intens laser pulses at either one color or two colors. The quasi-static transverse currents created by laser field ionization and sequent modulation in formed plasmas are responsible for the THz emission. The THz pulse amplitude scales linearly with the incident laser amplitude only when the latter is moderately large in the well-studied two-color laser scheme. This presents a significant limitation for high power THz emission.

References

1 Cole B E, Williams J B, King B T et al. Nature, 2001, **410**: 60—63

2 SHENG Z M, WU H C, LI K et al. Phys. Rev. E, 2004, **69**: 025401(R)

3 SHENG Z M, Mima K, ZHANG J et al. Phys. Rev. Lett., 2005, **94**: 095003

4 Leemans W P, Geddes C G R, Faure J et al. Phys. Rev. Lett., 2003, **91**: 074802

5 Cook D J, Hochstrasser R M. Opt. Lett., 2000, **25**: 1210—1212

6 Kress M, Loffler T, Eden S et al. Opt. Lett., 2004, **29**: 1120—1122

7 Bartel T, Gaal P, Reimann K et al. Opt. Lett., 2005, **30**: 2805—2807

8 XIE X, DAI J, ZHANG X C. Phys. Rev. Lett., 2006, **96**: 075005

9 Kim K Y, Glownia J H, Taylor A J et al. Opt. Express, 2007, **15**: 4577—4584

10 WU H C, Meyer-ter-Vehn J, SHENG Z M. New J. Phys., 2008, **10**: 043001

11 Hamster H, Sullivan A, Gordon S et al. Phys. Rev. Lett., 1993, **71**: 2725—2728

12 D'Amico C, Houard A, Franco M et al. Phys. Rev. Lett., 2007, **98**: 235002

13 LIU Y, Houard A, Prade B et al. Phys. Rev. Lett., 2007, **99**: 135002

14 Ammosov M V, Delone N B, Krainov V P. Sov. Phys. JETP, 1986, **64**: 1191—1194

15 Penetrante B M, Bardsley J N. Phys. Rev. A, 1991, **43**: 3100—3113