Single-cycle megawatt terahertz pulse generation from a wavelength-scale plasma oscillator driven by ultrashort laser pulses

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Terahertz spectroscopy can probe the spectral properties of molecules in a previously inaccessible electromagnetic spectrum [1]. Its applications include the characterization of semiconductors [2] and high-temperature superconductors [3]. T-ray imaging of biomedical tissues [4], cellular structures [5] and dielectric substances [6], and the manipulation of bound atoms [7]. Most applications are based on the techniques of THz time-domain spectroscopy (THz-TDS) [1], where typically coherent broadband THz pulses in the 2-5 THz frequency bandwidth are employed. Most broadband pulsed THz sources are based on the excitation of different materials with ultrashort laser pulses [1], such as through photoconduction or optical rectification, but the output power is limited by the damage threshold of the optical materials used.

So far, there have been no developments in the nonlinear regime due to the lack of sufficiently high-power THz sources [1]. To address this problem a few efforts have been made using ultrashort laser bunches produced by lasers or accelerators through the mechanisms of transition radiation and/or synchrotron radiation [8]. Recently, by four-wave mixing in air with a laser intensity of $\sim10^{14}$ W/cm$^2$, single-cycle THz pulses with a field strength greater than kV/cm can be produced [9], after the laser field-ionization and plasma generation threshold is surpassed. Whether this kind of THz emission will saturate for light intensities $>10^{15}$ W/cm$^2$ is an open question.

For light intensities $\gg10^{14}$ W/cm$^2$, the leading part of the laser pulse can completely ionize the material and the interaction process becomes a pure laser-plasma interaction. Plasma has no thermal damage threshold and can sustain extremely intense light. The peak intensity of lasers today can be as high as $10^{20}$ W/cm$^2$ and in the future is expected to reach $10^{23}$ W/cm$^2$ [10]. Exploring new THz emission mechanisms in the context of intense laser-plasma interactions may produce higher power THz sources. It has been shown that laser wakefields (electron plasma waves driven by the ponderomotive force of a laser pulse) in inhomogeneous plasmas can radiate high-efficiency THz waves at high power through linear mode conversion [11, 12]. The THz pulses produced in this way are generally in multi-cycles and have a negative frequency chirp.

The present work introduces a new THz emission mechanism in laser-plasma interaction, which can directly generate a single-cycle THz pulse with a field strength comparable with our earlier proposal [11, 12]. In addition to the above applications, the single-cycle pulse has special implications for THz propagation physics and seismic surveys [13]. In the one-dimensional (1D) case, an electron plasma wave [14] in a uniform plasma is described by $\delta n = \delta n_p \exp[i(k_p x - \omega_p t)]$, where $\delta n_p$ is the density perturbation amplitude, $\omega_p = \sqrt{ne^2/m_0}$ is the plasma frequency of the background plasma of density $n_e$, $e$ and $m$ are the electron charge and mass respectively, and $k_p = \omega_p/c = 2\pi/\lambda_p$, where $\lambda_p$ is the plasma wavelength. This infinite plasma wave can never emit electromagnetic waves at frequency $\omega_p$, since its displacement current $\varepsilon_0 \partial E/\partial t$ exactly compensates the plasma current ($-env$). However, for a finite plasma wave of length $L \sim \lambda_p$, there could be some electromagnetic radiation. Firstly, for such a few-wavelength plasma oscillator, its displacement and plasma currents cannot completely counteract each other, in particular near the plasma boundaries. Secondly, since the plasma skin depth of the radiation at frequency $\omega_p$ is $k_p^{-1}$, which is comparable to the plasma length $L$, the radiation can tunnel through the plasma into vacuum. Figure 1(a) is a schematic of this THz wave emission mechanism.

In the following we give a theoretical analysis of this THz emission mechanism. For the interaction geometry shown in Fig. 1(a), by Lorentz transformations we transform all the physical quantities from the laboratory frame to a moving frame of velocity $c \sin \theta e_y$, where $e_y$ is the unit vector along the $y$ direction. An electromagnetic wave with $\omega^L = \omega'$, $k^L = (\pm k_p \cos \theta, k_p \sin \theta, 0)$...
in the laboratory frame becomes $\omega^M = \omega' \cos \theta$, $k^M = (\pm k' \cos \theta, 0, 0)$ in the moving frame, wherein all the electromagnetic waves propagate along the $\pm x$ directions, i.e. THz emission in the laboratory frame must be in the specular reflection and laser transmission directions. Plasma (electrons and ions) in the moving frame streams along $-\mathbf{e}_y$, with a relativistic factor $\gamma^M = 1/\cos \theta$. Following Ref. [13] and using the quasi-static approximation [10], we obtain the coupled equations (in SI units)

$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}\right) \mathbf{a}_T = \frac{\omega_p^2}{c^2} \mathbf{s}(x, t),$$  

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{\omega_p^2}{c^2} \delta n,$$  

$$\delta n = \frac{1}{2 \cos \theta} \left[ 1 + \left( \frac{\mathbf{a}_L - \mathbf{e}_y \tan \theta}{(1/\cos \theta + \phi)} \right)^2 - 1 \right],$$  

where $\mathbf{s}(x, t) = -\delta n \tan \theta \mathbf{e}_y / \gamma$ is the THz radiation source, $\mathbf{a}_T$ and $\mathbf{a}_L$ are the respective vector potentials of the THz wave and incident laser normalized by $mc/e$, $\phi$ is the scalar potential of the driven plasma wave normalized by $mc/e$, $\delta n$ is the density perturbation of the plasma wave normalized by the initial plasma density $n$, $\gamma = \sqrt{1 + (\mathbf{a}_L - \mathbf{e}_y \tan \theta)^2 + \rho_x^2}$ is the relativistic factor, and $\rho_x$ is the electron longitudinal momentum normalized by $me$.

The generation of the THz radiation is determined by Eq. (1), from which the electric field in the laboratory frame is found to be [13]

$$E_T^L(x, t) = \frac{\omega_p}{2 \omega \cos \theta} \int_0^L \frac{dx'}{k_p^{-1}} \mathbf{s}(x', t - |x - x'|/c),$$  

where $L$ is the plasma length, $\omega$ the laser frequency, and normalization with respect to $mc/e$ has been performed. Equation (4) shows that the THz emission is always $p$-polarized. In the weakly relativistic case $\phi \ll 1$, Eqs. (2) and (3) lead to $\delta n \propto \rho_x^2 \cos \theta$. In the THz emission process, we assume $\gamma \simeq \gamma^M$. Substituting these into Eq. (4) we obtain

$$E_T^L \propto n^{-1/2} a_L^2 \sin \theta$$  

for $L \sim \lambda_p$. From Eq. (5) we can see that there is no THz emission for normal incidence ($\theta = 0$), since there is no transverse electric field component.

To test our proposal and the scaling rule in Eq. (5) we conduct a series of 1D particle-in-cell (PIC) simulations. Taking into account the oblique incidence of the laser beam, our 1D-PIC code adopts a moving frame as discussed above [13] and outputs all physics quantities in the laboratory frame. The initial plasma density is taken to be $n = 0.0001n_c$, where $n_c = m \omega_p^2 / e^2 = 1.1 \times 10^{21} (\mu m/\lambda)^2$ cm$^{-3}$ is the critical density for the laser pulse of wavelength $\lambda$ in vacuum. For $\lambda = 1 \mu m$, $n = 1.1 \times 10^{17}$ cm$^{-3}$. The corresponding plasma frequency is $\omega_p/2\pi = 2.98$ THz, which represents the central frequency of the THz emission. The plasma wavelength is $\lambda_p = \sqrt{n_c/n\lambda} = 100\lambda$. The incident laser pulse has a sine-square profile $a_0 = eE_L/n\omega_c = a_0 \sin^2[\pi(x - ct)/d_L]$ for $0 \leq x - ct \leq d_L$, where $d_L$ is the laser pulse duration. Here $a_0$ is related to the peak laser intensity through $I = a_0^2 \cdot 1.37 \times 10^{18} (\mu m/\lambda)^2$ W/cm$^2$. The relativistic intensity threshold is reached at $a_0 = 1$. The laser pulse enters the left boundary of the simulation box with $s$ polarization in order to distinguish it easily from the $p$-polarized THz emission from the wakefield. For the sine-square laser pulse, the excited wakefield amplitude is maximum when $d_L \approx \lambda_p$ [12]. The simulation results also confirm that the THz emission is strongest for $d_L = \lambda_p$, thus we always set $d_L = \lambda_p$ in the following.

Defining fields $F_{\pm} = (E_y \pm cB_z)/2$ in the moving frame, we see that $F_+$ and $F_-$ represent the forward and backward $p$-polarized electromagnetic waves, respectively. Tracing $F_+$ and $F_-$ at the right and left boundaries of the simulation box, we can obtain the temporal profile of the radiated THz pulses in the reflection and transmission directions. Figure 1(b) shows the peak field strengths $|F_{\pm}|_{\text{max}}$ of the THz pulses as a function of the plasma length $L$. The laser pulse parameters are $a_0 = 0.5$, $d_L = 100\lambda$ and $\theta = 45^\circ$. The incident laser intensity is about $3.4 \times 10^{17}$ W/cm$^2$ ($\lambda = 1 \mu m$). We find that the plasma length $L$ should be within $[0.25\lambda_p, 2.7\lambda_p]$ for intense THz pulses to be generated. When $L \geq 3\lambda_p$, the THz pulse amplitude decreases dramatically.

We also find that the radiated THz pulse is single-cycle. Figures 1(c) and 1(d) show the time evolution of field components $E_x$ and $B_z$ in the $x$ space for $L = 100\lambda$. The field $E_x$ in Fig. 1(c) includes the longitudinal field of the wakefield and the electric field of the $p$-polarized THz emission. The wakefield is completely localized in the plasma region, while the electric field of the THz wave is mainly outside the plasma slab. In Fig. 1(d) $B_z$ is the pure magnetic field of the THz wave. It is obvious that two single-cycle THz pulses are radiated from the plasma region. Due to the propagation delay of the laser pulse, the pulse in the backward (reflection) direction is generated earlier than that in the forward (transmission) direction. For the specific laser wavelength $\lambda = 1 \mu m$ in Fig. 1(d), the field strength is found to be above 10 MV/cm. When $L \geq 3\lambda_p$, the THz pulse is no longer single-cycle.

Figures 2(a) and 2(b) illustrate the temporal profiles of the THz pulses shown in Figs. 1(c) and 2(d) together with two other incident angles of $30^\circ$ and $60^\circ$. The shape of the transmitted THz wave $F_+$ is the same as that of the reflected $F_-$. For $\theta = 30^\circ$, the THz pulses have two cycles. Single-cycle THz emission is produced when $\theta \geq 45^\circ$. With increasing incident angle, the number of cycles included in the THz pulse decreases. Figure 2(c) displays the power spectra of the THz pulses $F_-$. The central frequency is at 3 THz ($\lambda = 1 \mu m$). The spectrum width increases with the incident angle, because of...
the shorter THz duration for the larger $\theta$. The bandwidths approach 3-6 THz, meeting the requirements for the THz-TDS system. Figure 2(d) shows that the peak field strengths $|F_\parallel|_{\text{max}}$ are proportional to $\sin \theta$, which agrees with Eq. (5). There is no THz emissions for $\theta = 0$.

Figures 3(a) and 3(b) show that the THz field strength is proportional to both the laser intensity, i.e. $a_L^2$, and the square root of the plasma density $n$. At lower intensities of $10^{14}$-$10^{15}$ W/cm$^2$, the THz field strength is several tens of kV/cm, comparable to that generated through four-wave mixing in air [9] under the same intensities. The above 1D theoretical analysis and 1D-PIC simulations are valid as long as the laser spot size is large compared with the plasma wavelength. For a laser beam with a Gaussian profile $\exp(-r^2/w_L^2)$ in transverse space, the 1D model applies for $w_L \gg \lambda_p$. It is easily understood that, for $w_L < \lambda_p$, the radiation source size is smaller than the radiated wavelength, so that the generated THz wave will diffract dramatically. In order to have collimated THz emission, $w_L \gg \lambda_p$ should be maintained.

To illustrate the multi-dimensional properties of the THz emission, Fig. 4 shows the THz emission in a 2D-PIC simulation. It is found that there are indeed two single-cycle THz pulses in the reflection and transmission directions. For $\lambda = 1$ $\mu$m, the THz field strength is 42 MV/cm, i.e. an intensity of $2.5 \times 10^{12}$ W/cm$^2$. Since the radiation radius is about $30\mu$m, this is equivalent to a peak power of 70 MW.

A uniform plasma slab several tens of microns long can be readily formed from the gas jet targets commonly used in high-harmonic generation experiments [17]. Meanwhile, our numerical simulations show that THz pulses emitted from a nonuniform plasma with a trapezoid density profile are similar to those from a uniform plasma slab, provided that the ascending and decending parts of the trapezoid are also at the THz wavelength scale. This suggests that the density homogeneity of the plasma slab is not necessary.

To conclude, we have presented a method for producing single-cycle high power THz radiation from wavelength-scale plasma oscillators ($L \sim \lambda_p$). It is emitted by the transient net currents induced at the plasma surfaces while building-up the plasma oscillators. This mechanism together with that for THz emission by linear mode conversion in inhomogeneous plasmas ($L \gg \lambda_p$) [11, 12] provide a complete picture for interpreting the early experimental observation of THz emission in intense laser plasma interaction [18].

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FIG. 2 (color online). Temporal profile, frequency spectrum and field amplitude of the THz emission. (a) Temporal profiles of the THz waves $F_+$ for incident angles of $\theta = 30^\circ$, $45^\circ$ and $60^\circ$. (b) Temporal profiles of the THz waves $F_-$. Other parameters are the same as in Fig. 1(c,d). (c) The power spectra of $F_-$ in (b). (d) The peak field strengths $|F_\pm|_{\text{max}}$ of the THz pulses as a function of $\sin \theta$ with $\theta \in [0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ]$.

FIG. 3 (color online). The scaling rule of the THz emission. (a) The peak field strengths $|F_\pm|_{\text{max}}$ of the THz pulses as a function of the laser intensity. The plasma parameters are $n = 0.0001n_c$, $L = 50\lambda$ and the laser pulse parameters $d_L = 100\lambda$ and $\theta = 45^\circ$. (b) $|F_\pm|_{\text{max}}$ of the THz pulses as a function of the electron density $n$. The laser pulse parameters are $a_0 = 0.5$ and $\theta = 45^\circ$. For a given plasma density $n$, we take $L = d_L = \lambda_p$. The dashed lines are fitted curves.

FIG. 4 (color online). 2D spatial plot of the pure THz magnetic field $B_z$ from 2D-PIC simulation. We take $n = 0.0025n_c$, corresponding to $\lambda_p = 20\lambda$ and $\omega_p/2\pi = 14.9$ THz. The plasma length is $L = 25\lambda$. The laser pulse is s-polarized, focused on the plasma slab surface, and has parameters $a_0 = 0.5$, $w_L = 30\lambda$, $d_L = 20\lambda$ and $\theta = 50^\circ$. The dashed rectangle shows the plasma region, the solid arrow marks the laser propagation axis, and the dashed arrows the THz emission directions, one along the laser propagation and another along the specular reflection direction.
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http://arxiv.org/ps/physics/0702007v1
Figure 2
Figure 3

(a) Laser intensity ($\mu m/\lambda$)$^2$ (W/cm$^2$) vs. $F (\mu m/\lambda)$ (MV/cm)

(b) $n (\mu m/\lambda)^2$ cm$^{-3}$ vs. $F (\mu m/\lambda)$ (MV/cm)
This figure "fig4.JPG" is available in "JPG" format from:

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