Coherent diffraction radiation of relativistic terahertz pulses from a laser-driven micro-plasma-waveguide

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We propose a method to generate isolated relativistic terahertz (THz) pulses using a high-power laser irradiating a micro-plasma-waveguide (MPW). When the laser pulse enters the MPW, high-charge electron bunches are produced and accelerated to \(\sim 100\) MeV by the transverse magnetic modes. A substantial part of the electron energy is transferred to THz emission through coherent diffraction radiation as the electron bunches exit the MPW. We demonstrate this process with three-dimensional particle-in-cell simulations. The frequency of the radiation is determined by the incident laser duration, and the radiated energy is found to be strongly correlated to the charge of the electron bunches, which can be controlled by the laser intensity and micro-engineering of the MPW target. Our simulations indicate that 100-mJ level relativistic-intense THz pulses with tunable frequency can be generated at existing laser facilities, and the overall efficiency reaches 1%.

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High power terahertz (THz) pulses have attracted significant attention since they can serve as a unique and versatile tool in fields ranging from biological imaging to material science \cite{14}. In particular, at high intensities, such pulses allow manipulation of the transient states of matter, for example giving control over the electronic, spin and ionic degrees of freedom of molecules and solids \cite{5}. Several methods such as two-color laser filamentation \cite{6}, optical reflection in lithium-niobate \cite{7,8} or organic crystals \cite{9}, and relativistic laser irradiated plasmas \cite{10,11,12,13,14}, have been developed for generation of THz pulses with electric fields above 1 MV/cm. However, scaling up such methods towards higher intensities remains challenging, thus representing an active research field.

Relativistic electron beams have also been used to produce THz radiation through a variety of mechanisms that include synchrotron radiation \cite{19}, transition radiation \cite{20,21}, and diffraction radiation \cite{22,23}. Radiation emitted by these mechanisms is coherent if the bunch length is shorter than the radiated wavelength of interest. The radiated energy then scales as the square of the beam charge. Previous studies have also shown that the radiation power decreases significantly with the beam divergence, and the energy radiated in a small cone near-axis would strongly benefit from a high beam energy \cite{24}. Therefore, choosing an electron source with desired qualities (high charge, high energy, and well-collimated) can be crucial for producing intense THz emission that is attractive to a range of applications \cite{5}.

Currently available sources of relativistic electron beams are either linear accelerators or compact sources based on laser-plasma acceleration. The THz radiation energy from linear accelerators has reached \(\sim 600\) \(\mu\text{J/pulse}\) \cite{25}, but such sources are expensive and large and thus can only offer limited accessibility. Laser wakefield acceleration in the nonlinear “bubble” regime can produce multi-GeV electron beams with small divergence (\(\sim 0.1\) mrad), but only small charge (1-100 pC) \cite{26}. Self-modulated laser-wakefield acceleration can produce nano-Coulomb (nC) electron bunches \cite{27} but typically have a temperature of a few MeV, and the beam divergence is large due to direct laser acceleration \cite{28}. Last but not least, hot electrons that arise from laser-solid interaction can reach up to nC-\(\mu\text{C}\) charge, but the electron temperature is typically only a few hundreds of keVs to a few MeVs, and the divergence is usually large (\(\sim 40\)°) \cite{13}. Recently, THz radiation energy above millijoule (mJ) level has been reported in laser-solid interaction \cite{17}, but since a picosecond laser pulse is used, the coherent frequency range is below 1 THz, and the efficiency is \(\sim 0.1\)%.

In this letter, we propose a scheme to generate isolated THz pulses with electric fields beyond 1 GV/cm with high efficiency \(\sim 1\)%. As illustrated in Fig. 1(a), an intense laser pulse is focused into a micro-plasma-waveguide (MPW), leading to electrons being extracted from the wall and accelerated by longitudinal electric fields of the transverse magnetic modes up to a few hundreds of MeVs \cite{29,30,31,32,33}. The divergence is usually a few degrees and the duration is the same as the laser pulse. Typically the electron beam inherits the density of the plasma skin layer \(n_{\text{beam}} \sim n_c\), where \(n_c = m_e\omega_0^2/4\pi e^2\) is the critical density, \(e\) and \(m_e\) are the elementary charge and the electron mass, \(\omega_0\) is the laser angular frequency) from which it is generated \cite{34}. Thus, a total charge of a few tens of nC can easily be obtained with contemporary 100-fs high-power laser systems. Such electron source is suitable for THz generation based on coherent transition radiation and/or coherent diffraction radiation (CDR) as noted above. The simulations demonstrate that when the electron beam exits the MPW, a substantial part of the electron energy \(\sim 20\)% is transferred to electromagnetic energy through CDR, leading to relativistically strong THz pulses up to 10-100 mJ energy.
The electric fields in the simulation with frequency filtering) and spectra produced by laser pulses are shown in (b). The latter is the result of the modulation of the electron beam at 20 fs and 70 fs, respectively. With currently available laser systems, this scheme is capable of generating relativistic pulses with frequencies ranging from near infrared to sub-THz.

The duration of the THz field coincides with the laser pulse, and the cut-off frequency is determined accordingly, as shown in Fig. 2, where the green and blue dashed lines represent the radiation field (after frequency-filtering) and spectra produced by laser pulses with τ0 of 36 fs and 72 fs, respectively. With currently available laser systems, this scheme is capable of generating relativistic pulses with frequencies ranging from near infrared to sub-THz.

The mechanism of the electron beam generation, i.e. the electron injected into the channel (vacuum core of the MPW), is crucial for understanding the THz radiation power. The production of electron bunches at a...
plasma-vacuum interface when irradiated by an intense laser pulse can be attributed to the counterstreaming electrons percolating through the laser nodes, as the laser pushes the surface electrons inwards [34]. In the MPW, the underlying physics is similar, but the mechanism that pushes the surface electrons (towards the plasma cladding), and the associated radial counterstreaming, depends on the ratio of the laser focal spot size ($w_0$) and the effective MPW radius ($r_c$), which results in different injection behaviour.

To show this, we perform 2D PIC simulations of lasers having different focal spot sizes propagating in a long waveguide (240 µm). The laser and plasma parameters are the same as in the 3D simulation unless otherwise described. The resolution is 50 and 20 cells per laser wavelength in longitudinal and transverse directions, respectively. The third dimension is assumed to be 4 m and $N_{ph}$ per unit time is 

$$N_{ph} = n_c\pi r_c^2\beta c k_n / k_T,$$

where $k_T$ and $k_n$ are the transverse and longitudinal wavenumber in the MPW, $\beta'$ is the radial velocity of counterstreaming electrons normalised by $c$. These electrons are reflected back on the plasma-vacuum interface due to the interaction with the photons ($N_{ph}$ per unit time). We assume the number of electrons percolating through the laser nodes as well as the number of the photons absorbed are negligibly small during this process. According to momentum conservation $2N_{ph} k_T = N_e (\gamma \beta' + \gamma' \beta') m_e c$, where $\gamma' = (1 - \beta'^2)^{-1}$, $\gamma$ and $\beta$ are the relativistic gamma factor and the normalised radial velocity of the electrons that being pushed back (after the interaction).

Here we are only interested in the maximum counterstreaming electron energy that can be achieved. Substituting $\beta_r \approx \beta'$ due to quasi-neutrality, we find that when the longitudinal velocity of the surface electrons vanishes after interaction, $\gamma'$ reaches its maximum,

$$\gamma_m' \approx \frac{\Gamma + \sqrt{\Gamma^2 + 4}}{2}$$

where $\Gamma \equiv (x^2 a_m^2)/(k_0^2 r_c^2)$, $k_0 = \sqrt{k_T^2 + k_n^2}$, and $a_m$ is the normalised intensity of the waveguide mode. For $w_0 \geq r_c$,

FIG. 2: (Color online) The radiation fields $E_0$ (a) and their spectra (b) observed at $\Theta = 17^\circ$ and $\Phi = 90^\circ$, the black and red lines represent the CDR with and without a low-pass filter (frequency below 60 THz) for laser FWHM duration $\tau_0 = 54$ fs. The green and blue dashed lines show the cases driven by the full-spectrum (0-1000 THz) for $\tau_0 = 72$ fs and $\tau_0 = 36$ fs, respectively. The inset in (b) is $0 < r < r_c$.

FIG. 3: (Color online) The electron yield vs propagation distance, for different $w_0/r_c$ ratios.
effective MPW radii (with $a_0$, and for $w_0 < r_c$, $a_m = a_0 w_0 / r_c$. We have assumed the radius of MPW is sufficiently large ($k_T \ll k_0$), and only the fundamental mode exists inside the MPW, so that $k_T = x_1 / r_c$ and $x_1 = 2.4$ is the first root of eigenvalue equation [38].

The electrostatic field near the MPW wall can be estimated using Gauss’s law, $E_C = 2Q / r_c c \gamma_0$, where $Q$ is the charge that is lost from the wall (i.e. injected into the channel). Further injection can only happen when the kinetic energy of counterstreaming electrons overcomes the electrostatic potential within the skin layer, i.e. $(\gamma_m' - 1)m e^2 \sim \sqrt{\gamma_m' e E_C c / \omega_0}$, which yields the saturation charge,

$$Q \approx \frac{(\gamma_m' - 1) k_0 r_c m e c^3}{\sqrt{\gamma_m'}} \frac{2}{e} \tau_0. \quad (2)$$

As an order-of-magnitude estimate, for a micro-sized channel, $k_0 r_c$ is typically around unity. This means that a $10^{20} \text{ W/cm}^2$, 50-fs laser system could produce $10 \text{ nC}$ electron beams, which agrees with simulations. From Eq. (2) the scaling of the charge with the normalised laser intensity can be estimated: for weakly-relativistic cases ($\gamma \ll 1$) $Q \propto a_0^2 / r_c$, while for strongly-relativistic cases ($\gamma \gg 1$) $Q \propto a_m$. Note, that the energy of CDR scales as $W_r \propto Q^2$, it is therefore important to control these scalings by 3D PIC simulations to guide future experiments. In the analysis above we neglected the azimuthal dependence, which is strictly valid only for circular polarization. However, 3D PIC simulations presented in Fig. 4 show that the obtained scalings are valid also for linear polarization.

In Fig. 4(a), we plot the electron charge produced by the MPW and the total THz energy (below 60 THz) as functions of $a_0$, where $r_c = 3.35 \mu m$ and $w_0 = 4 \mu m$ are fixed, and the MPW length is $L = 30 \mu m$. The parameters are the same as in Fig. 1 unless otherwise stated. It is shown that the charge increases quadratically with the normalised laser intensity ($Q \propto a_0^2$) when $a_0$ is small, and the scaling becomes linear ($Q \propto a_0$) for $a_0 > 8$, where $\Gamma$ exceeds unity. In addition, the simulation results indicate that the THz energy can be fitted by $W_r \propto a_0^4$ in the weakly-relativistic regime, where the transition efficiency increases linearly with the intensity. In the strongly-relativistic regime, the THz energy can be fitted by $W_r \propto a_0^2$, where the conversion efficiency saturates at $\sim 1\%$. Note, that this also demonstrates that the radiation is coherent ($W_r \propto Q^2$). Our numerical results suggest that TW-class, 100-mJ-strong THz emission can be produced by a 10-1/250-TW laser system, which is within reach of the existing laser facilities.

In Fig. 4(b), we consider the effects of varying the MPW radius variation when the laser parameters are fixed ($a_0 = 10$ and $w_0 = 4 \mu m$), and the MPW length is extended to $L = 120 \mu m$ to ensure sufficient distance for injection. In this case, Eq. (2) leads to $Q \propto r_c^{-1}$ in the strongly-relativistic regime,ystem, and $Q \propto r_c^{-3}$ in the weakly-relativistic regime, which agrees with our simulations. Since the radiation is coherent, it results in a quenching effect: the radiation energy drops dramatically ($W_r \propto r_c^{-6}$) as the effective radius exceeds a threshold near $\Gamma \sim 1$. This is verified by a sharp decrease of the THz energy at the separatrix of the two regimes around $r_c \approx 4.3 \mu m$, when the counterstreaming electrons become weakly-relativistic (i.e. $\Gamma \approx 0.7$).

Finally, we note that Eq. (2) does not consider the effects of high-order waveguide modes (which give a higher transverse light pressure) and strong diffraction at the entrance (so that the charge produced at the entrance may already exceed the saturation limit suggested by Eq. (2), especially in large MPW). In fact, the value from Eq. (2) should be treated as the minimum charge that can be produced by laser-MPW interaction, as the interaction between the lowest-order mode and MPW is the weakest. A detailed study of these effects is left for future work.

In conclusion, we proposed a scheme to generate relativistic isolated THz pulses based on the interaction of a laser pulse with a micro-plasma-waveguide. 3D PIC simulations show the energetic electron beam with a few tens of nC charge can be produced inside the channel. As the beam exits the waveguide, a substantial part of the electron energy is transferred to an intense THz emission through coherent diffraction radiation. We demonstrated with 3D PIC simulations that the overall efficiency reaches 1%, the radiation power 1 TW and the energy 100 mJ. We obtain scaling laws for THz generation energy in different regimes that are characterised by the maximum gamma factor of the counterstreaming electrons induced by the fundamental mode. The proposed scheme can be easily extended to other frequency ranges by varying the driving laser duration, allowing the generation of radiation from infrared to sub-THz range with relativistic intensities. This opens a new avenue towards high-power light matter interaction beyond the
state of the art.

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