Universität Rostock

Traditio et Innovatio

High-intensity terahertz radiation from microplasma driven by two-color laser pulses

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Abstract

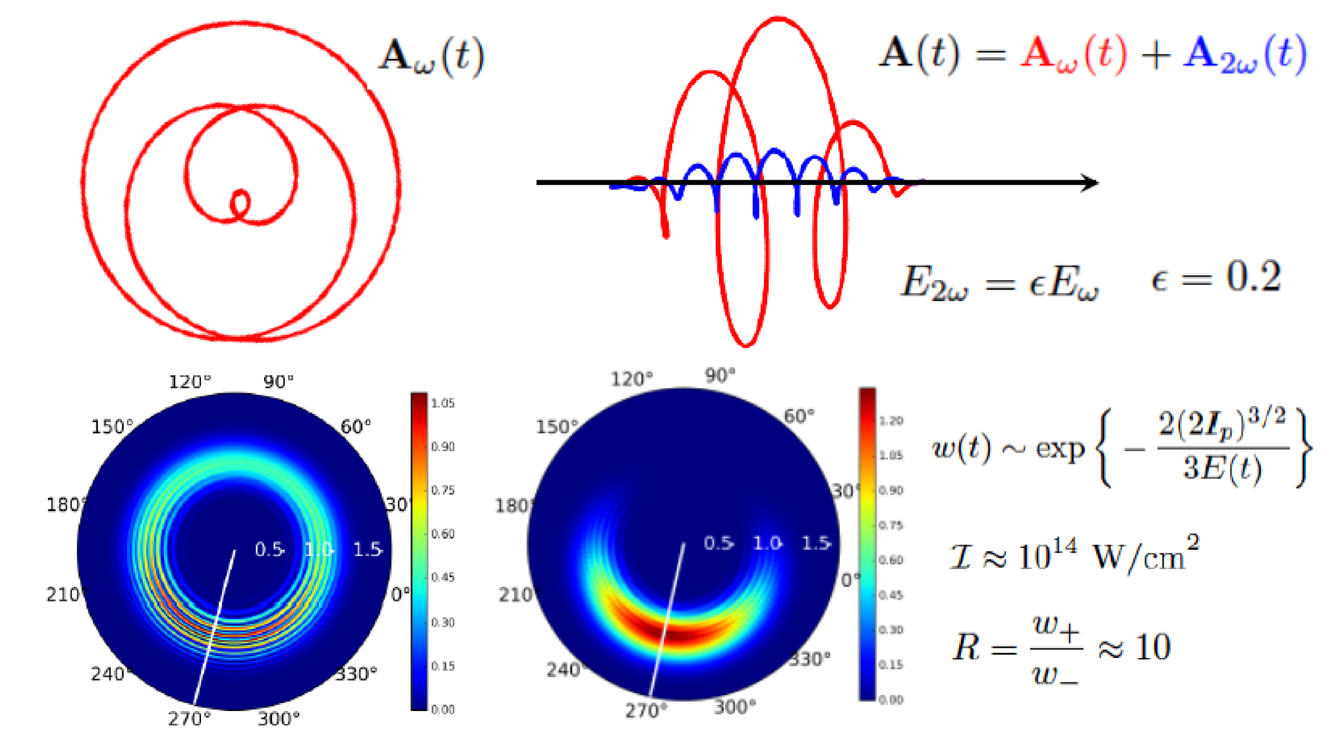
We propose a scheme for the efficient generation of ultrashort intense terahertz waves from a gas irradiated by strong two-color laser pulses. The scheme is based on the use of small gas-filled cells of 20–50μm size, i.e. comparable to the terahertz wavelength. The two-color field consists of a superposition of an intense circularly polarized fundamental pulse of wavelength 0.8μm and its second harmonic with intensity on the level of 5% of the fundamental. The small size of the THz emitters enables the excitation of highly coherent oscillations of the electron plasma which radiates almost as a single dipole. We show that, for the gas concentration $n = 10^{17}$–10^{19}cm^{-3} and the cell size 20μm, a dipole oscillation can be excited leading to the high conversion efficiency. We also analyze the distributions of electromagnetic fields and of electron currents induced inside the plasma and show that quasi-static electric fields with strengths up to 10MV/cm can be excited in the near-field zone.

Terahertz radiation: typical parameters and common applications

$$\lambda \simeq 0.001 \div 0.1 \ \mathrm{cm}$$
$$\nu \simeq 0.1 \div 10 \ \mathrm{THz}$$
$$\hbar\omega \simeq 0.001 \div 0.1 \ \mathrm{eV}$$

- distant probing of materials
- medical applications, noninvasive diagnostic
- plasma diagnostics
- excitation of spin waves
- orientation of molecules
- strong-field atomic physics in the presence of high static fields

Two-color scheme with circular polarization



Experiment: C. Meng et al., APL 2016 **Theory:** V.A. Tulsky et al., PRA 2018

FIG.1 *Principal scheme of the two-color ionization setup with circularly polarized strong ω pulse and weak 2ω pulse for excitation of THz currents in a gas target. A weak second harmonic with the relative amplitude $\epsilon \ll 1$ breaks the field symmetry $\mathbf{A}(t+T/2) \neq -\mathbf{A}(t)$ resulting in a strongly asymmetric emission of photoelectrons. Single-atom calculations of the momentum distribution were made by solving numerically the time-dependent Schrdingier equation for a model single-electron atom with ionization potential of argon [V.A. Tylsky et al., PRA (2018)]. In the presence of the second harmonic the momentum distribution $f(\mathbf{p})$ becomes highly asymmetric resulting in the excitation of a nonvanishing net electron current $\mathbf{j}(\mathbf{r},t) \sim -(e/m_e)\int f(\mathbf{p};\mathbf{r},t)\mathbf{p}d\mathbf{p}$.*

During and after the interaction with the laser pulse this asymmetric current excites plasma oscillations with frequencies $\omega_P = \sqrt{4\pi e^2 n_2/m_e} \simeq 10^{11} \div 10^{13}$s^{-1} leading to the emission of radiation into this frequency domain. Typically, only a small fraction of the photoelectron kinetic energy is being converted into coherent radiation of high harmonics (HHG) and of THz waves, while more than 99% of this energy goes to bremsstrahlung or recombination radiation.

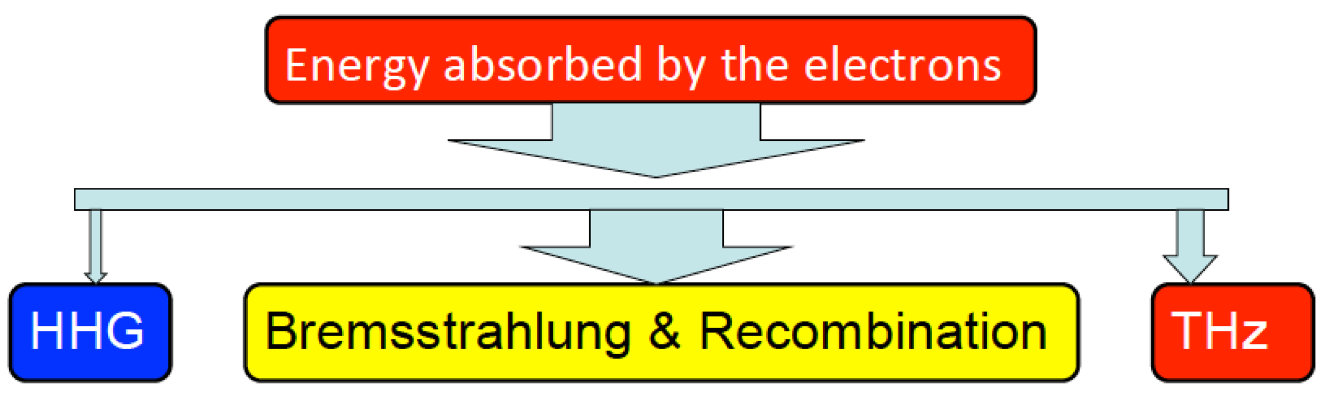
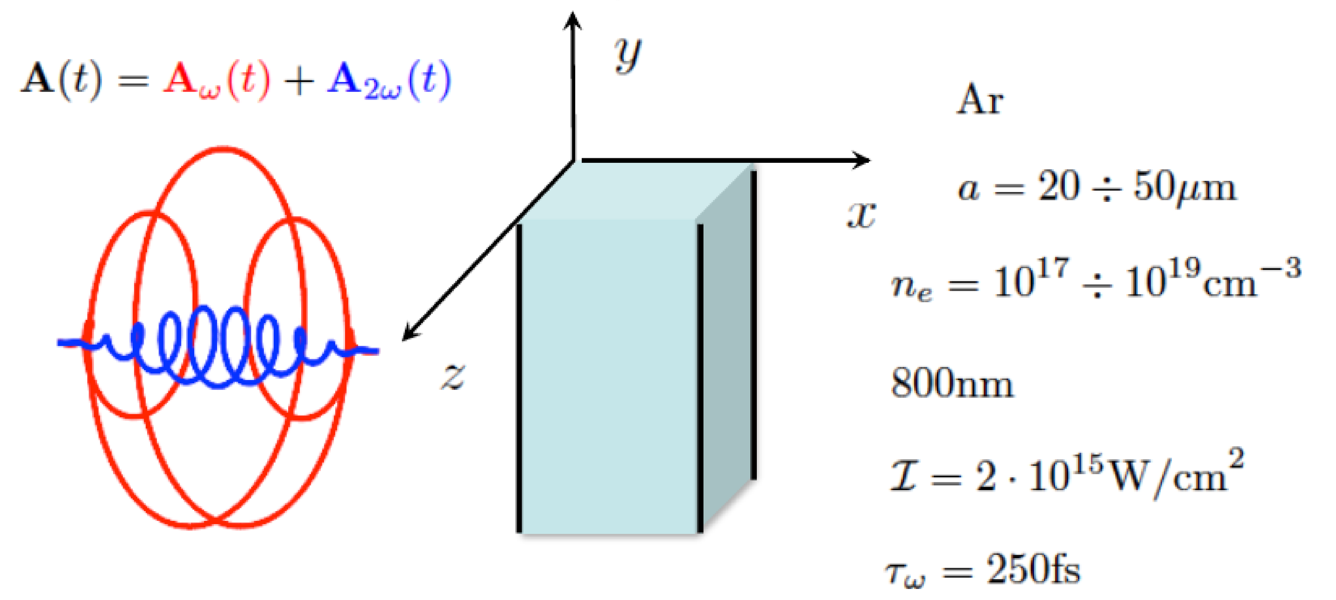


FIG.2 *Schematic share between coherent (HHG+THz) and incoherent radiation emitted out of the target. The initial kinetic energy of photoelectrons can be comparable to that of the pump laser pulse or much smaller, depending on ionization rates, gas density and pulse duration. Typically only 10^{-3} or even less of this energy goes into high harmonics and/or THz waves.*

We show here that a significant fraction of incoherent radiation can be transmitted to the coherent THz domain. For that we are looking at conditions making THz emission fast, so that a significant fraction of the electron energy is radiated out within a single THz cycle or even faster.

Modeling

To calculate the ionization-induced distribution of electric currents and electromagnetic fields inside the gas cell and their evolution we apply the self-consistent system of Maxwell-Vlasov equations and solve them numerically with a 2D3V PIC code with ionization included.



Time-dependent fields inside the plasma and radiation spectra

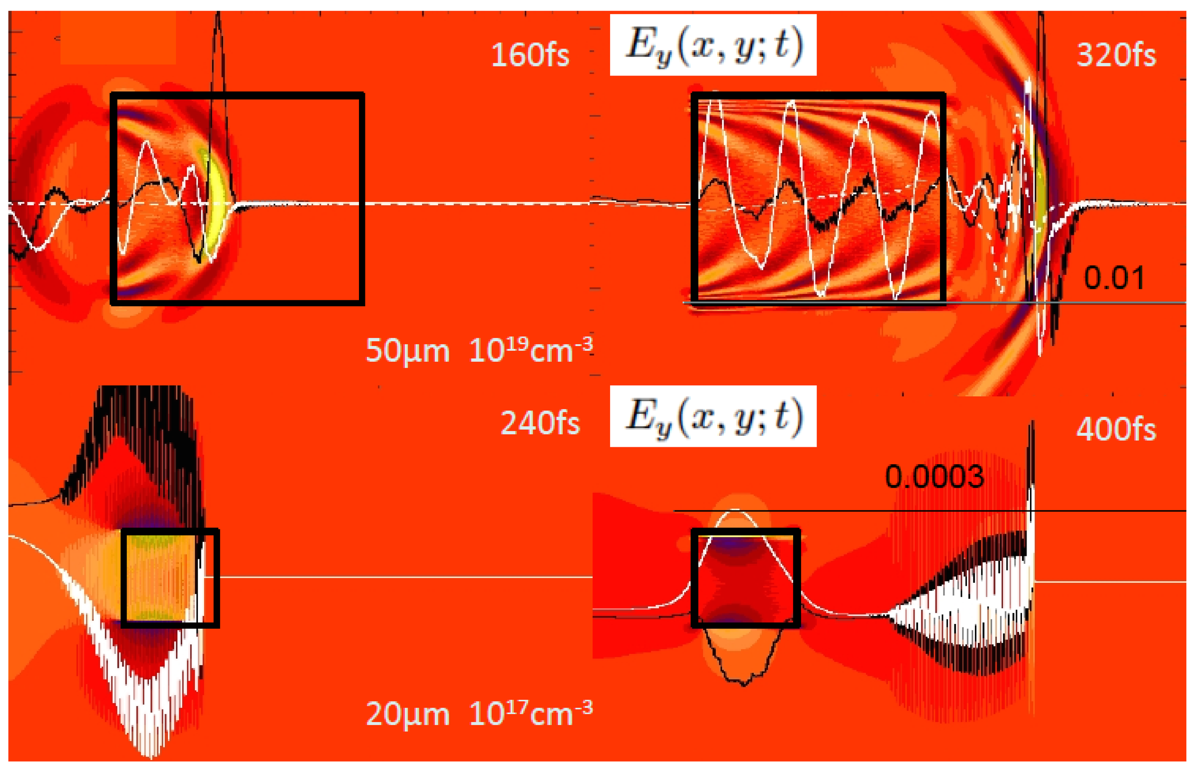
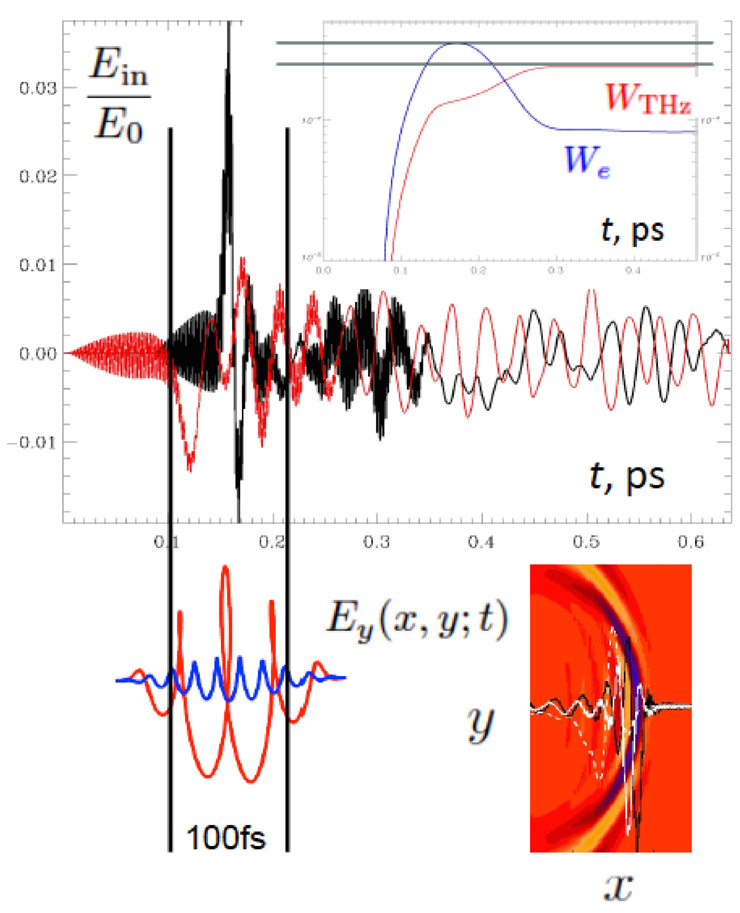


FIG.3 *Distributions of the electric field in the plane (x,y) with x the pulse propagation direction for a 50μm cell and concentration $n = 10^{19}$cm^{-3} (upper row) and a 20μm cell and concentration $n = 10^{17}$cm^{-3} (lower row) taken at different time instants. White line shows the electric field strength in units of the external laser field amplitude measured in the center of the cell, black line – the same for the cell edge. Laser intensity is $\mathcal{I}_\omega \approx 2\cdot 10^{15}$W/cm^2.*



$$\ddot{x} = -\frac{e}{m_e}E_L(t) - \omega_P^2 x$$
$$F_{\rm rad} = \frac{2Q^2}{3c^3}\dddot{x} \qquad Q = eN_e$$
$$\ddot{x} = -\frac{e}{m_e}E_L(t) - \omega_P^2 x - \gamma\dot{x}$$
$$\gamma = \omega_P N_e \frac{\omega_P}{\omega_0}$$
$$\omega_0 = \frac{mc^3}{e^2} \simeq 10^{23}\mathrm{s}^{-1}$$
$$\omega_P \simeq 10^{13}\mathrm{s}^{-1}$$
$$N_e \simeq 10^{11} \div 10^{15}$$

FIG.4 *Electric field inside the 50μm cell as a function of time averaged over the time interval of several laser periods. The inset shows the energy of electrons and that emitted into the THz domain. Formulas in the right column introduce a simple model of a laser-driven oscillator with an extreme radiation damping.*

Conclusion & Outlook

- When a gas cell is sufficiently small, with a size comparable to the emitted THz wavelength, highly coherent dipole oscillations of the electron plasma can be excited leading to a gross increase in the conversion efficiency from photoelectrons to THz waves.
- The damping of dipole oscillations results from a coherent multi-particle effect of the radiation reaction force.

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