Simulation on terahertz emission from air plasma induced by circularly polarized few-cycle laser pulses

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We investigate the terahertz (THz) wave emission from air plasma by analyses and simulations. An elliptically polarized THz wave is generated, whereas a circularly polarized carrier-envelope phase (CEP) stabilized few-cycle laser pulse is applied. Its ellipticity and intensity depend on the pulse duration of the driving laser pulse. And the polarization rotates along the CEP of the driving laser pulse. The THz generation is also simulated for different filament lengths. As the filament extends, the polarization of the generated THz wave rotates along the filament.

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The current and potential applications of terahertz (THz) wave in the fields of bioscience, material science, and chemistry inspire the scientists over the world to explore and develop the technologies of THz generation and detection[1–3]. With the developments of laser technologies, for example, synchrotron radiation and material science, since 1990s, more and more practical methods have been invented for THz generation[4–8]. Among these methods, THz waves generated from laser-induced air plasma have many excellent characteristics such as wide spectrum and the remote generation[9]. Therefore, THz generation from laser-induced air plasma has become a hotspot recently[10–16]. The physical mechanism of THz generation by laser is explained by a transient photocurrent model[17] and a four-wave mixing model[18]. According to the photocurrent model, the process can be described with three steps: firstly, the air is ionized to the plasma by the laser pulse, secondly, the ionized electrons are accelerated and form an asymmetric momentary current, and finally, a THz wave radiates from the current. It should be noted that only asymmetric laser field generates asymmetric momentary current; therefore, two-color laser field is used for THz generation instead of single-color multi-cycle laser field[17].

Different from multi-cycle laser pulses, the electric field of a few-cycle laser pulse is highly asymmetric. When it is focused in the air, the intense laser pulse generates strong THz waves[19]. This is a simple but high-performance method for THz generation, and the pure driving laser field benefits the analysis of the physical process. In this letter, we investigate the THz generation from air plasma induced by carrier-envelope phase (CEP) stabilized circularly polarized few-cycle laser pulses. Through theoretical analyses and numerical simulations, the dependence of the characteristics such as the polarization and intensity of generated THz wave on the driving laser pulse are studied: 1) the THz wave is elliptically polarized and the ellipticity relies on the pulse duration of the driving laser; 2) its intensity decreases sharply as the laser pulse duration increasing; 3) its polarization direction relies on the CEP of the driving laser; 4) THz polarization plane rotates along the laser-induced air plasma filament.

The electric fields of a multi-cycle circularly polarized laser pulse are highly symmetrical (Fig. 1(b)). According to the photocurrent model, symmetrical electric field can hardly generate THz wave in the air. However, electric fields are asymmetric for few-cycle laser pulses (Fig. 1(a)). When it is focused in the air, asymmetric photocurrent is generated in the laser-induced plasma and thus intense THz wave is produced.

The electric field of a circularly polarized laser pulse is written as

$$E_{\text{opt}}(z,r,t) = E_{\text{env}}(z,r,t)[\cos(\omega_0 t+\varphi)\vec{x} + \sin(\omega_0 t+\varphi-\pi/2)\vec{y}], \quad (1)$$

where z is the laser propagation direction, r is perpendicular to z, $E_{\text{env}}(z, r, t)$ is the envelope of a Gaussian pulse, ω_0 is the laser frequency, and φ is the initial phase. For simplicity, we only considered the laser field on the z-axis. Thus, the transient photocurrent produced by the laser fields is given by

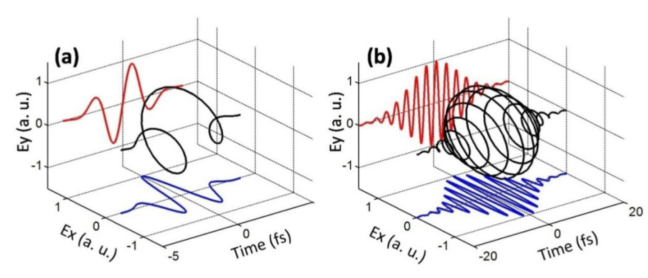

Fig. 1. Electric fields of circularly polarized laser pulses with the pulse duration of (a) 3 and (b) 15 fs. The central wavelength is 800 nm and the CEP is 0. The blue and red lines denote the X and Y components of the electric fields. (color online)

$$\partial_t \vec{J}_{x,y} + \frac{1}{\tau}\vec{J}_{x,y} = \frac{e^2}{m}\rho \vec{E}_{x,y}(t), \quad (2)$$

where τ is the average electron recombination time, ρ is the plasma number density which is given by the Ammosov–Delone–Krainov) model of N_2[20].

Therefore, the far-field THz electric field is further calculated with

$$\widehat{E}^{x,y}_{\text{THz}}(\Omega) \propto \frac{e^{ik_{\text{THz}}R}}{R}\int_{-L/2}^{L/2} A^{x,y}_{\text{THz}}(z,\Omega)\exp\left(i\frac{\Omega}{c}(n_{\text{opt}} - n_{\text{THz}})z\right)\text{d}z, \quad (3)$$

where $A^{x,y}_{\text{THz}}(z,\Omega) \propto \text{FT}[\partial_t J^{x,y}_e(z,t)]$ is the THz spectrum excited by local electric field. THz waveform in time domain is obtained by the inverse Fourier transform of THz spectrum.

Based on the model above, the THz emission driven by laser pulses with different pulse durations is simulated. In the simulation, the laser pulse energy is 0.4 mJ, the initial CEP of driving laser pulses is set as 0, the waist diameter is 50 μm, and the filament length is 10 mm, stepped by 1 μm. As shown in Fig. 2, with the pulse duration getting longer, the asymmetry of laser field reduces, which leads to two results: 1) the ellipticity of the generated THz wave reduces, that is, more close to circularly polarized; 2) the intensity of the THz wave decreases sharply while rising laser duration, for instance, the THz amplitude produced by 5 fs laser pulses is 16700 times of that produced by 20 fs laser pulses.

According to the above simulations, few-cycle laser pulses are needed to generate intense THz wave. In the interaction process of few-cycle laser pulses and air, CEP also plays an important role. For laser pulses with the same pulse duration, different CEPs determine different laser fields. In the laser-induced air plasma, laser electric fields accelerate electrons to form transit photocurrents, and THz waves emit from the transit photocurrent. The CEP determines the direction and strength of the acceleration, and therefore determines the waveform of the generated THz wave. The CEP effect has been demonstrated theoretically and experimentally in the process of THz generation by linearly polarized laser pulses[19]. While for few-cycle circularly polarized laser pulses, the three-dimensional asymmetric electric field causes even stronger CEP-dependent effect in THz generation process. When CEP changes, the electric field of the laser pulse rotates along the propagation direction. As a result, the polarization of the generated THz wave also rotates along the propagation direction with the waveform remaining the same.

The waveforms of THz emission from laser-induced air plasma are shown in Fig. 3. When the CEP of the driving few-cycle laser pulse changes from 0 to π, the polarization of the generated THz waves rotates along the propagation direction, whereas the waveform and amplitude remain the same. Furthermore, when electric field direction of the driving laser pulses is reversed, such as CEP of 0 and π, the polarization of the generated THz wave is also reversed. According to this effect, the THz polarization can be easily controlled by adjusting the CEP of driving laser pulses. On the other hand, the CEP of few-cycle laser pulses can be inferred by measuring the polarization of generated THz waves, which is concerned with attosecond science[21] and other ionization experiments[22].

The CEP of a laser pulse changes when it is focused in the air, which is called Gouy shift[23]. As the preceding discussion, the polarization of generated THz waves changes during the focusing process. In other words, THz waves generated from different parts of the laser-induced air plasma are with different polarizations.

The waveforms of THz waves generated from air plasma of different parts are shown in Fig. 4. In the simulation, the initial CEP of driving laser pulses is set as 0. As the filament gets longer, the polarization of

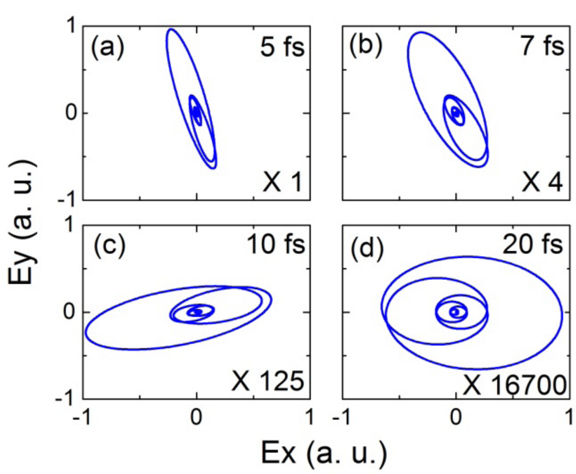

Fig. 2. THz waveforms generated from air plasmas produced by laser pulses with pulse durations of (a) 5, (b) 7, (c) 10, and (d) 20 fs.

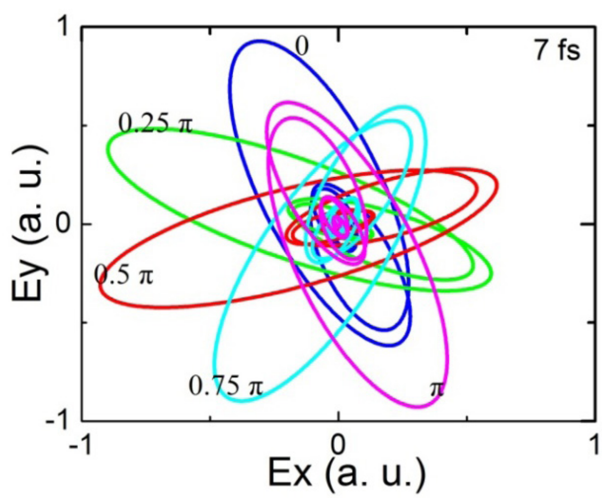

Fig. 3. THz polarization direction changes with the CEP of the driving laser pulse. The driving laser is circularly polarized with its pulse duration of 7 fs and a central wavelength of 800 nm.

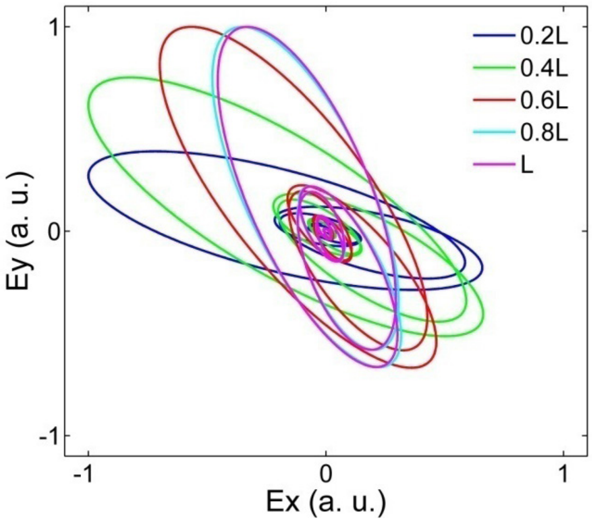

Fig. 4. THz waves generated from different parts of laser-induced air plasma. L is the length of the filament.

induced THz waves rotates as the CEP changes. Since the compositions of THz emission are from different parts of the filament, the ellipticity of the polarization also changes along the filament. The waveforms shown in Fig. 4 are normalized results, and most of the THz waves are generated from the central part of the filament. Therefore, it can be seen that, as the filament gets longer, the THz polarization rotates a bigger angle in the front part than in the back part of the filament.

In conclusion, we investigate THz waves generated from air plasmas induced by circularly polarized CEP stabilized few-cycle laser pulses by analyses and simulations. According to the simulation results, the intensity and polarization of the generated THz waves are related to the pulse duration and the CEP of the driving laser pulses. Laser pulses with shorter pulse duration can induce more intense THz waves and the THz polarization is closer to linearly polarized laser pulses. When the CEP of driving laser pulses changes, the polarization of the generated THz wave rotates along the propagation direction with the same THz amplitude. This study is meaningful for THz enhancement, THz polarization control, and CEP measurement of few-cycle laser pulses.

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