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From terahertz to mid-infrared ultra-broadband radiation generated from few-cycle laser pulse interaction with gas plasma filament

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Abstract: The strong few-cycle laser pulse interaction with the gas plasma filament can generate strong and broadband terahertz radiation. Here, we investigate the detail of plasma current and its terahertz radiation produced by the few-cycle laser pulse interaction with the gas plasma based on the calculations. The ionization during the plasma filamentation is in the transition between the tunnel ionization and the multiphoton ionization. The results show that this scheme can generate ultra-broadband radiation from the range of terahertz to mid-infrared, and its amplitude is a periodic function of the carrier-envelope phase of the few-cycle laser pulse. The frequency of the terahertz pulse is determined by the duration of the laser pulse, the time evolution of ionization and the plasma current, rather than by the density of the plasma. This work might give a useful clue to carry out the experiment of ultra-broadband terahertz generation by the few-cycle laser pulse interaction with the gas plasma filament.

Key words: terahertz, mid-infrared, few-cycle laser pulse, gas plasma, phase evolution

基于少周期激光脉冲与气体等离子体作用的太赫兹到中红外超宽带辐射产生

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摘要：超强少周期激光脉冲与气体等离子体作用可以产生强的宽带太赫兹脉冲辐射。本文以数值计算为主要工具研究了少周期激光脉冲与气体等离子体成丝作用产生的等离子体电流及对应的太赫兹辐射特性。该过程中的等离子体电离处于多光子电离和隧道电离的过渡阶段。结果显示，该机制能够产生从太赫兹到中红外的超宽带辐射，且辐射的电场振幅是少周期激光脉冲载波相位的周期函数。太赫兹脉冲由激光脉冲脉宽和等离子体电离的时间演化确定，而不是由等离子体密度决定。本文为基于少周期激光脉冲与气体等离子体作用产生超宽带太赫兹辐射的实验提供了一定的理论参考。

关 键 词：太赫兹；中红外；少周期激光脉冲；气体等离子体；相位演化

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Introduction

The interaction of ultrashort laser pulses with the gas plasma filament has been used to generate strong and broad terahertz radiation since this kind of source does not have any damaged threshold for the interactive media, especially the two-color laser scheme and the few-cycle laser pulse scheme [1-2]. Many experiments have been carried out to investigate the properties of such terahertz radiation source, and the influences of the pump lasers and the gas targets. Now, it has reached several consensuses: (1) the ionization is necessary in such process;

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(2) the terahertz radiation from the two-color laser scheme is much stronger than the single-color laser scheme, and their physical mechanisms are greatly different; (3) the gas pressure and the laser intensity determine the plasma density, and consequently affect the terahertz yield and its central frequency; (4) the species of the gases also affect the terahertz radiation [3-5].

There are several physical models on the terahertz radiation by the two-color laser pulse interaction with the air/gas plasma filament, in which the plasma current (some are called photocurrent or ionization current) model has shown its qualitative agreement with the experimental results [6-7]. The plasma current, which is generated by the ultrashort laser pulse interaction with the gas plasma and is an ultrafast oscillation process, emits the electromagnetic wave with the frequency in the terahertz region according to this phenomenological model. Furthermore, the particle-in-cell simulations are used to simulate such interaction process to obtain more details of the terahertz generation [8-9].

Until now, there are several mechanisms to explain why the emitted electromagnetic wave frequency is in the terahertz region: (1) when the plasma density is around 10^{18} cm^{-3} (it is determined by the laser intensity and the gas density), the plasma frequency is in the terahertz region, thus the current produced by the laser field oscillates with the same frequency as the plasma frequency, so the emitted electromagnetic wave has the same frequency, thus emits terahertz waves [8-9]; (2) the oscillation of the ultrashort laser pulse makes the current also oscillate rapidly, and generates electromagnetic waves depending on the period and envelope of the laser pulse, rather than the density of the plasma [6-7]. There are several experimental results on the terahertz radiation from the gas plasma with different pressures, which show that the density of the plasma (determined by the ionization of the gas molecules and the gas pressure) changes the central frequency slightly and the amplitude of terahertz pulse[10-13]. Among these experimental reports, the electro-optic sampling detection and the Michelson interference are two common detection methods. The former has a response bandwidth up to several terahertz, and the latter has a much broader response bandwidth up to several tens of terahertz. But the results show that the generated terahertz pulses do not change their central frequencies a lot even the gas pressures are changed greatly from several torrs to several hundreds of torrs. Thus, it is easy to conclude that the frequency of terahertz pulses is determined by the laser duration and the envelope.

The few-cycle laser pulse also can generate strong and broad terahertz radiation via interacting with the gas plasma [14-17], similar to that of the two-color laser scheme. Especially the carrier-envelope phase (CEP) of the few-cycle laser and its duration as short as several femtoseconds give the terahertz radiation some special properties, such as super-broad bandwidth and mid-infrared central frequency. Here, we investigate the ultrabroadband electromagnetic radiation from the few-cycle laser pulse interaction with the gas plasma with the numerical method, and give the details of this ultrafast process, including the ionization, the plasma current, and the phase-dependent evolution of the pulses.

1 The transition between the multiphoton ionization and the tunneling ionization processes

When the ultrashort laser field is strong enough, it will affect and change the Coulomb force between the electrons and the nucleus, even ionize the atoms to free electrons and ions. This ionization process depends on the laser intensity (field strength) and the atom species. Two different physical mechanisms, multiphoton ionization (MPI) and tunnel ionization (TI), are used to describe the ionization interaction between the laser pulse and the atoms, which is characterized by the Keldysh parameter, $\gamma_k = 2.31 \times 10^6 \left(\frac{U_{\text{ion}}[eV]}{\lambda^2[\mu\text{m}] \cdot I[\text{W/cm}^2]}\right)^{1/2}$ [18-20]. Here, U_{ion} is the atom ionization potential energy in eV, λ is the laser wavelength in μm, and I is the laser intensity in W/cm^2. When $\gamma_k<<1$ (the intensity $I>10^{15}$ W/cm^2 for the 800 nm laser pulse), the ionization is induced by TI; while $\gamma_k>>1$ (the intensity $I<10^{12}$ W/cm^2 for the 800 nm laser pulse), the process is MPI. In the intermediate regime, $\gamma_k \sim 1$ (the intensity $I \sim 10^{14}$ W/cm^2 for the 800 nm laser pulse), the ionization is purely neither MPI nor TI. For the plasma filament in the air (pressure at 1 atm) produced by the ultrashort laser pulse, the central intensity is around 10^{13}-10^{14} W/cm^2, thus the ionization during the filamentation is a complex ionization process, including both TI and MPI mechanisms [19].

The rigorous theory of ionization of atoms and molecules induced by the laser field needs to calculate the time-dependent Schrodinger equation of the particles based on the quantum theory [21]. In the TI process, the ionization rate of complex atoms in alternating electric fields is given by Ammosov-Delone-Krainov (ADK) theory as follows [22-23]

$$w = 6.6 \times 10^{16}\frac{Z^2}{n^{9/2}}\left(10.87 \times \frac{Z^3 E_H}{n^4 E_l}\right)^{2n-3/2} \exp\left(-\frac{2Z^3 E_H}{3n^3 E_l}\right)(s^{-1}) \quad , \quad (1)$$

where Z is the charge number of the nucleus, E_H=5.14 × 10^{11} V/m is the electric field strength between an electron and a proton on the first Bohr orbit of a hydrogen atom, $n = Z/\sqrt{E_{ion}(eV)/13.6}$ is the effective main quantum number of the ionized electron, and E_{ion} is the ionization potential in eV, E_l is the laser field strength in V/m. In the MPI process, a valence electron in the atoms usually absorbs several photons to escape the constraint of the nucleus, and the minimum-order perturbation theory can describe it well. The calculation result shows the ionization rate as I^N, where I is the laser intensity and N is the number of the absorption photons [18]. A formula proposed by Kasparian *et al* is also given to calculate the ionization rate in the regime of $\gamma_k \sim 1$, $w(I) = R_T(I/I_T)^{\alpha}$ [24]. R_T and I_T are a pair of experimental values used as a reference point, I is the laser intensity, and α is the power coefficient. For the nitrogen gas, it is $I_{T,N}=10^{13}$ W/cm^2, $R_{T,N}=2.5\times10^4$ s^{-1}, and $\alpha_N\approx7.5$. For a typical infrared femtosecond laser pulse with a wavelength $\lambda=800$ nm, the Keldysh parameter γ_k in the intensity around 10^{14} W/cm^2 is given in Fig. 1(a), and the ionization rate of nitrogen is given in Fig. 1(b). Thus, the ionization is the transition of TI and MPI for a plasma filament in the pure nitrogen gas. Here, the gas target is set pure nitrogen since it is the main constituent of air. Therefore, this fitting formula is used to calculate the ionization rate induced by the laser pulse in the gas plasma.

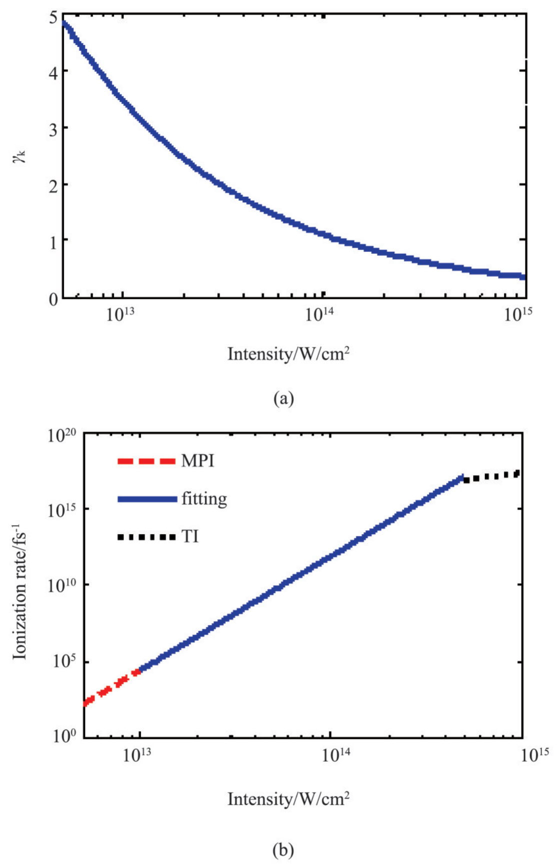

Fig. 1 The Keldysh parameter (a) and the ionization rate (b) with different laser intensities
图1 Keldysh因子(a)和离化率(b)与激光光强的对应关系

As shown in Fig. 1, the laser intensity determines the ionization process and the ionization rate. A typical ultrashort laser pulse generally has a duration from several femtoseconds to several picoseconds, their pulse energy needs to reach several tens of μJ and mJ to generate such intensity. These kinds of laser pulses now can be offered by commercial femtosecond laser amplifier systems.

2 Plasma current and terahertz radiation from the few-cycle laser pulse interaction with the gas plasma filament

2.1 Few-cycle laser pulse and its CEP

The duration of a few-cycle laser pulse is only several femtoseconds, which makes it with only a few (even single) oscillations in a laser envelope. The interaction of such strong laser with the media (including molecules and atoms) is dependent on the oscillation of the pulse rather than its envelope, and the phase of the pulse would not be omitted [25]. Therefore, strong few-cycle laser pulse has a special property of CEP in the interaction with the atoms and the electrons, including the ionization and the high-harmonic generation [26].

The few-cycle laser pulse has a form as

$$\overrightarrow{E(t)} = \overrightarrow{E_0}\exp\left(-\frac{t^2}{T^2}\right)\cos\left(2\pi ft + \varphi_0\right) \quad , \quad (2)$$

where E_0 is the field strength, T is connected with the pulse duration τ (full-width at half-maximum, FWHM) by $T=\frac{\tau}{2\sqrt{ln2}}$, f is the central frequency, and φ_0 is the phase. When the laser is linearly polarized, its strength can be replaced by a scalar. Figure 2 shows two examples of the few-cycle laser pulse with different phases, Fig. 2(a) has a duration (FWHM) of 9 fs and Fig. 2(b) is 5 fs. As shown in the figures, the pulse is so short that its phase will determine the strength of the electric field involving the instantaneous interaction with the molecules and the atoms. Consequently, its field-induced ionization, and acceleration of the particles (including electrons and ions) will have some special adjunction properties with its CEP [27].

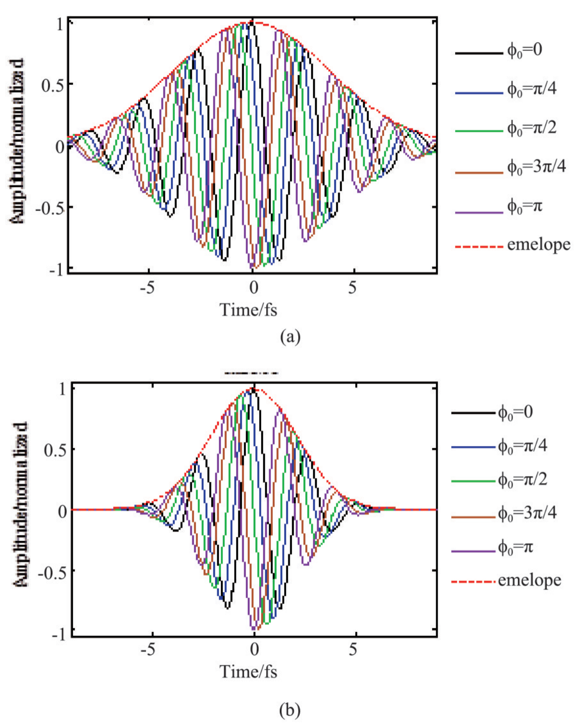

Fig. 2 Two few-cycle laser pulses with durations of 9 fs (a) and 5 fs (b), respectively, with several different phases
图2 含有多个不同相位的、脉宽分别为9 fs(a)和5 fs(b)的少周期激光脉冲

2.2 The plasma current and its terahertz radiation induced by the few-cycle laser pulse interaction with

nitrogen plasma

In this section, we give the detail of the calculations of the plasma current and its terahertz radiation from the few-cycle laser pulse. The strong ultrashort laser pulse ionizes the gas molecules to generate free electrons (plasma), the density of the electrons n_e is determined by the density of the gas molecules n_0 and the ionization rate $w(t)$ as

$$\frac{dn_e}{dt} = \sum_i w_i(t) n_0 \quad . \quad (3)$$

The subscript i=1, 2, ⋯ in the equation means the order of the ionization. The nitrogen atoms are mainly one-order ionized and excited by a laser pulse with the intensity around 10^{14} W/cm^2. Figure 3 shows the ionization rate of the few-cycle laser with phases at 0, π/4, and π/2 at the intensity of 10^{14} W/cm^2.

The gaseous molecules in the air have a rough density of 1 mol/22.4 L=2.688×10^{19} cm^{-3} in the pressure of one standard atmosphere. Thus, the density of electrons released from the nitrogen can be calculated from Eq. (3) when the gas target is assumed to be pure nitrogen. Figure 4 shows the plasma densities produced by the few-cycle laser pulses with three different phases. It can be seen clearly that the last densities tend to be a same value even with different phases, but their time evolutions are different. This is because the density is an accumulating process, the cycles in the laser pulse with different phases have different strength, consequently, different ionization rates. Therefore, every cycle will release (ionize) different number of electrons. But the accumulation of all electrons from different cycles makes the last total density. Thus, the formation of the electron density has a different time evolution depending on the instantaneous field strength and the ionization rate. The plasma frequency is $\omega_p = \sqrt{n_e e^2 / m\epsilon_0} \approx 5.64$ THz for this density.

The electron will be accelerated to form the current in the laser field after ionization, its velocity v_i is given by

$$\frac{dv_i}{dt} = \frac{eE_i(t)}{m} \quad , \quad (4)$$

where $E_i(t)$ is the instantaneous field when the electron is ionized, e is the charge of the electron, and m is the mass of it. Then, the total plasma current is

$$J(t) = \sum_i n_i(t) e v_i(t) \quad . \quad (5)$$

Because the field of the few-cycle laser is not symmetry as that of the two-color laser scheme, the electrons are accelerated to a velocity in the laser cycle to form a net current [6]. The collisions between the particles are neglected since they are usually in the picosecond range, which is much longer than the duration of the few-cycle laser pulse. When the laser pulses and the gas targets are known, the current $J(t)$ as the function of the time can be obtained by solving the equations above with the numerical methods. Figure 5 is the time evolution of plasma current with the laser pulses at different phases. It shows that the oscillations of the current are different since the ionization and the acceleration in the laser pulse are different, which consequently induces the currents with small differences in the end.

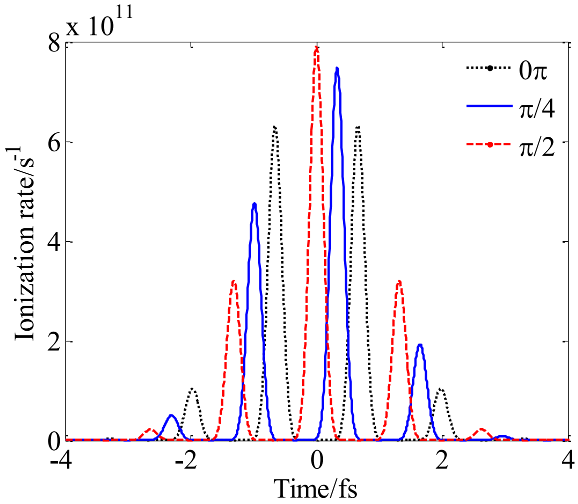

Fig. 3 The ionization rate induced by the few-cycle laser pulses with different phases
图3 不同相位的少周期激光脉冲产生的离化率

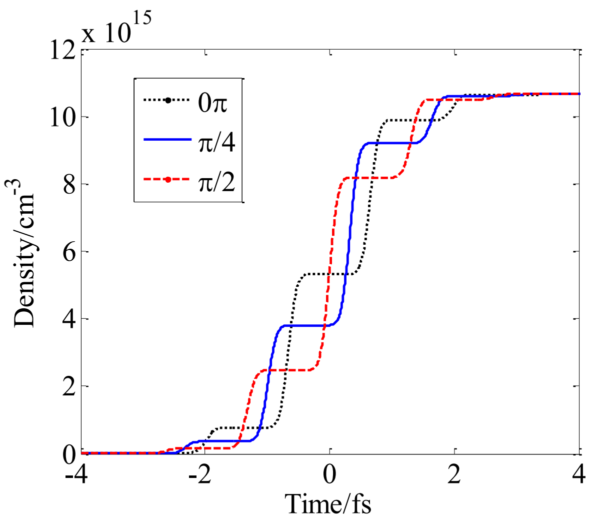

Fig. 4 The plasma density produced by the few-cycle laser pulses with different phases
图4 相位不同的少周期激光脉冲电离产生的等离子体密度时间演化规律

The electromagnetic radiation from the plasma current is calculated after obtaining the time evolution of the current. Here, the electric field from phase 0 is calculated from the formula $E(t) \propto \frac{dJ(t)}{dt}$, as shown in Fig. 6(a) with terahertz time waveform, and Fig. 6(b) with its frequency spectrum. As shown in Fig. 6(b), the frequency has a central frequency of around 80 terahertz and a bandwidth up to several tens of terahertz. This is because the laser pulse is so short (9 fs) that its plasma current also oscillates very fast, which generates high frequency electromagnetic waves. As discussed above, the plasma frequency is around 5.64 THz, which is much lower than that in Fig. 6. The frequency of terahertz pulse is not decided by the density of the plasma, but by the duration of the laser pulse. Therefore, the few-cycle

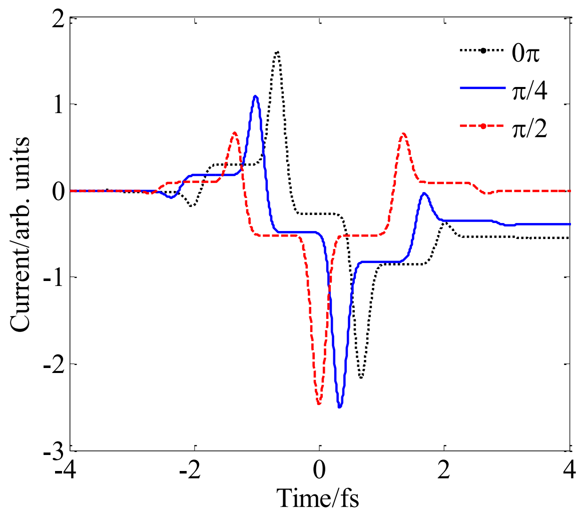

Fig. 5 Plasma currents produced by the few-cycle laser pulses with different phases
图 5 不同相位的少周期激光脉冲产生的等离子体电流

laser can generate super-broadband terahertz radiation, close to the mid-infrared regime, as reported by Matsubara *et al* [15-16].

The CEP of the few-cycle laser pulses also has its influence during the ionization, as reported by *Chetty et al*[27]. Then, the influence of the phase on the terahertz radiation is given in Fig. 7(a) with the evolution of the time waveforms, and Fig. 7(b) the frequency spectra. As shown in Fig. 7, (1) the mutation in these figures is at the phase of π/2, including the time waveform and the spectrum; (2) the time waveforms have nearly the same duration, but their crest and trough are changed from π/2; (3) the frequency spectra, including the central frequency and the bandwidth, are nearly the same. Then the peak strengths of terahertz pulses are calculated to obtain its trend, as plotted in Fig. 8. It shows that the peak of terahertz pulses is the period function of the phase of the few-cycle laser pulse, its minimum is at π/2. In the two-color scheme, the strength of terahertz is also the function of the phase difference of the two-color laser pulses [28], similar to Fig. 8. These phases determine the ionization instantaneous time and then the acceleration time of the electrons, which consequently determines the plasma current and terahertz radiation. Thus, the phase of the lasers is a key parameter to control the terahertz radiation in the gas plasma-based terahertz sources [14, 17].

2.3 Discussions

The dispersion relation of the electromagnetic wave in the plasma is $\omega^2 = \omega_p^2 + c^2k^2$, where ω is the angular frequency of the wave, c is the speed of the light, and k is the wavevector of the wave. If the electromagnetic wave can propagate in the plasma, its frequency must be higher than the plasma frequency. Thus, the terahertz pulse shown in Fig. 6 can propagate inside the plasma. During the formation of the plasma filament, the focused beam of the laser pulse propagates in the gas for a long distance and ionizes the atoms meanwhile. In this process, the moving electrons in the current act like oscillat-

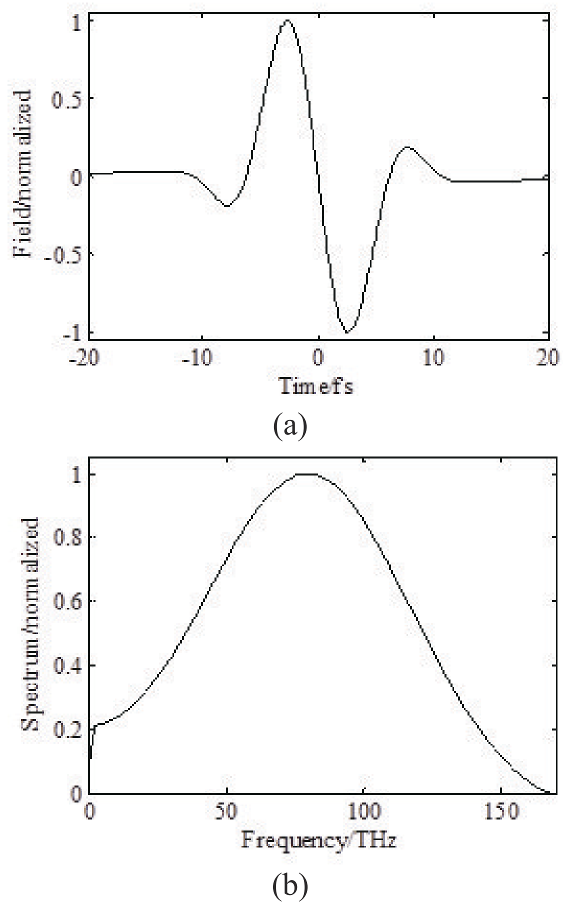

Fig. 6 The ultra-broadband radiation in the terahertz to mid-infrared range generated by the plasma current, (a) the time waveform, (b) its frequency spectrum
图 6 (a)等离子体电流产生的从太赫兹到中红外超宽带电磁辐射的时域波形,(b)其频谱分布

ing dipoles and emit electromagnetic waves. The duration and the oscillation of the current directly decide the duration and the frequency of the electromagnetic pulse. Shaping the profile of the laser pulses can also change the duration and profile of the plasma current, and thus its terahertz radiation [28].

By increasing the laser intensity from 0.1×10^{14} W/cm^2 to 5×10^{14} W/cm^2, the ultra-broadband radiation is found to have the same properties as above. Then, similar results are obtained when the width of the few-cycle laser pulse is changed from 9 fs to 5 fs. Thus, our results are ubiquitous for this radiation from the plasma filament induced by the few-cycle laser pulse. This ultra-broadband radiation from the terahertz to mid-infrared range can also be generated by a two-color laser interacting with a gas plasma [29-30].

The coherent detection techniques for broadband terahertz radiation include the photoconductor antenna, the electro-optic sampling, and the air coherent detection, with different response bandwidths [31]. As shown in Fig. 6(b), the bandwidth of the electromagnetic pulse from the few-cycle laser is much broader than the detection response of the electro-optic sampling and the air coherent detection techniques [32]. Thus, Michelson inter-

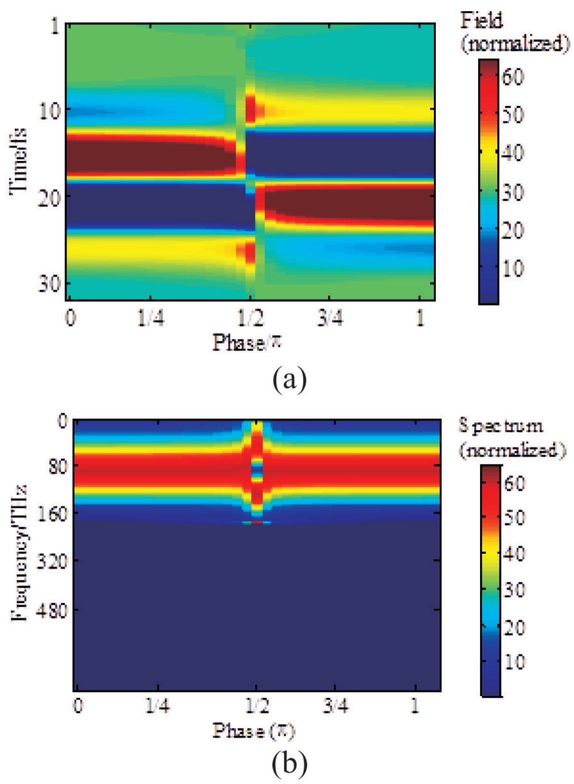

Fig. 7 The phase evolution of electromagnetic pulse depending on the phase of few-cycle laser pulses, (a) the pulse waveforms, (b) the frequency spectra
图7 (a)依赖少周期激光脉冲相位演化的电磁脉冲电场时域波形,(b)频谱分布

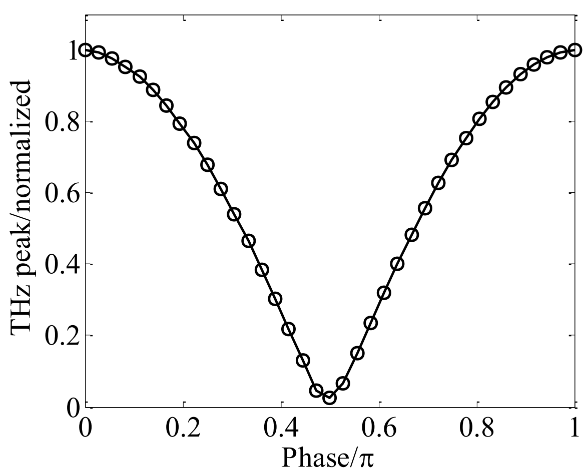

Fig. 8 The amplitude of electromagnetic pulse as a function of the phase of the few-cycle laser pulse
图8 电磁脉冲振幅与少周期激光脉冲相位的关系

ference might work well at this bandwidth since its detector is sensitive from the mid-infrared to the far-infrared regime. Although only numerical results are given here, it offers a reference for the experiment of terahertz generation by the few-cycle laser pulse.

There is no propagation effect of the laser beam and the plasma filament in the plasma current model, therefore the spatial distribution of this ultra-broadband radiation cannot be given at present, only the ultrafast microscopic process of current and emission can be given. These results will help to understand the physical mechanism behind. This ultra-broadband pulse will extend its duration in gases (including air) after generation from the plasma. Thus, the propagation path of the terahertz pulse needs to be set in the vacuum environment.

3 Conclusions

In summary, the detail of the electromagnetic radiation from the terahertz to mid-infrared range generated by the interaction of the few-cycle laser pulse with the gas plasma filament is investigated based on the simulations. The ionization is mainly at the transient between the multiphoton ionization and the tunneling ionization for the laser intensity in the formation of the filament. Thus, a fitting formula is used to calculate the ionization rate. The free electrons are accelerated to form a plasma current, which oscillates rapidly during the laser pulse propagation. This current emits electromagnetic waves with the frequency determined by the laser duration and plasma current. The simulation results show this ultra-broadband radiation pulse has a bandwidth up to tens of terahertz, which is close to the mid-infrared regime. The pulse strength is dependent on the phase of the few-cycle laser pulse. In this case, the frequency spectrum is not determined by the density of plasma, but by the duration of the laser cycle. Thus, the few-cycle laser pulse can generate super-broadband radiation from the terahertz to mid-infrared range by interacting with the gas plasma filament. Our work will offer useful reference for the development of relevant experiments.

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