THz generation from slow turn-on, rapid turn-off femtosecond laser pulses interaction with gas plasma

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Abstract: The interaction between the femtosecond laser pulses and the gas plasma has been widely used to generate strong and broadband THz pulse radiation. A femtosecond laser pulse with slow turn-on, rapid turn-off shape was used to generate THz radiation by interacting with gas plasma. Based on the plasma current model, the properties of the THz generation from such scheme were investigated in detail. Because the electrons were accelerated to a fast velocity by such specially shaped laser pulses, their motions form a fast oscillation current, which emits electromagnetic wave with frequency in the THz region. The results show that such scheme can generate stronger and broader THz radiation than the normal two-color femtosecond laser scheme, although it loses some energy of the laser pulse. This proposal might offer a new way to develop plasma-based broadband THz radiation source.

Key words: terahertz; shaped laser pulse; gas plasma

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缓慢上升快速下降的飞秒激光脉冲与气体等离子体作用的太赫兹辐射产生研究

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摘 要：飞秒激光脉冲与气体等离子体作用可以产生宽带、强的太赫兹脉冲辐射。采用一种缓慢上升、快速下降的飞秒激光脉冲与气体等离子体作用产生太赫兹辐射,并基于等离子体电流模型计算了这种太赫兹辐射的特性。由于这种特殊整形的激光脉冲能够对电子的加速产生较大的速度,从而可以产生较大的等离子体电流和较强的太赫兹辐射。计算结果显示:尽管这种特殊整形的飞秒激光脉冲能量有所损失,它能够比普通双色飞秒激光脉冲产生更强、更宽的太赫兹脉冲辐射。该项研究为基于激光等离子体作用的太赫兹辐射源提供了新的思路。

关键词：太赫兹； 整形激光脉冲； 气体等离子体

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0 Introduction

Terahertz (THz) waves have increasingly shown their tremendous applications in spectroscopy, imaging, material science, biomedicine, and chemistry[1−4]. Among these applications, intense and broadband THz radiation has its own advantage comparing with the narrow band THz source. Thus, to generate strong and broadband THz radiation, covering all THz range from 0.1-10 THz or even beyond the entire THz gap, is a hot topic in the THz science and technology. With the help of the ultrashort laser pulses, there are some broadband THz sources, including photoconductor antenna, optical rectification, and laser-induced-plasma[5]. Among these methods, the THz radiation from the two-color femtosecond laser pulses interaction with the gas plasma attracts wide attention since it can generate broad, even super-broad THz radiation without any damage threshold for the emitter[6−8] after its demonstration in the experiment[9].

There are several models to explain the complex physical mechanisms under this phenomenon, including the plasma current model proposed by Kim et al[8, 10]. Several groups have proposed similar models meanwhile, and somehow named it photo current or ionization current model[11−14]. Nowadays, this model describes the physics mechanisms well for this ultrafast process although it uses some approximations, since its simulation results have been improved agreeable with the experimental results[15−16].

Several methods have been proposed to change, control, and optimize the THz radiation from the two-color femtosecond laser induced gas plasma based on the simulations or/and the experiments. One way is to change the parameters of the laser pulses, such as the phase difference[14] and the amplitude ratios between the two-color lasers[16], the polarizations[17−18], the chirp of the laser pulses[19], and the shape of the laser pulses[20−21]. The other way is to change the parameters of the gas targets, such as the gas species[22−23] and the gas pressures[5, 23].

Here, we investigate the THz radiation generated from the slow turn-on, rapid turn-off two-color femtosecond laser pulses interaction with gas plasma. These specially shaped laser pulses change the accelerating process of the electrons, and consequently, change the plasma current and its THz radiation from the gas plasma. The calculations based on the plasma current model show that this scheme can generate broader and stronger THz radiation. This study will offer a new way to change and optimize the THz radiation from the ultrashort laser-induced gas plasma.

1 Physical model and simulations

Some nanosecond laser pulses with a slow turn-on, rapid turn-off shape have been produced by using a plasma shutter triggered by the shorter laser pulses[24]. In such experiment, a femtosecond laser pulse with the power higher than the ionization threshold focuses on a gas jet to produce the plasma, and meantime another nanosecond laser pulse with the power lower than the ionization threshold passes the plasma. By adjusting the time delay between these two pulses, the plasma ionized from the gas jet can truncate the shape of the nanosecond pulse at any time as a shutter (so it is called plasma shutter). The plasma shutter can truncate the laser pulse in the temporal domain in the 150 fs, and the residual intensity of the pulse is below 0.4% of the peak intensity[24]. This kind of laser pulse has shown its advantages in the molecular alignment and orientation[25−27], although this process makes the laser pulse lose some energy.

A plasma shutter might work in much shorter time by using a few-cycle laser pulse as the pump laser. In such case, it will truncate the normal femtosecond laser pulses in several femtoseconds, and generate a slow turn-on, rapid turn-off femtosecond laser pulse. Generally, the laser pulse shaping techniques operate in the frequency domain by tailoring the spectral phase and/or the amplitude of the laser field over a given bandwidth[28]. But the slow turn-on, rapid turn-off laser pulse is obtained by truncating the envelope profile of the normal pulse with a plasma shutter in the time domain. After operation, it also has a special shape that are distinction from the normal ultrashort laser pulse. Such laser pulse can be expressed as

$$E(t)=\begin{cases}A_0\exp\left(-\dfrac{t^2}{T^2}\right)\cos(2\pi ft+\phi_0),\ t\leqslant\tau_0\\ 0,t>\tau_0\end{cases}\tag{1}$$

Where A_0 is the amplitude of the laser pulse, T is connected to the laser pulse full-width at half-maximum (FWHM) $T_{\rm FWHM}$ by $T=T_{\rm FWHM}/\sqrt{2\ln 2}$, and τ_0 is an parameter between the turn-on and the turn-off of the pulse shape. In actual experiment, τ_0 is changed by controlling the time delay between the pump lase pulse and the normal femtosecond laser pulse. The laser pulse has a normal shape (Gaussian shape) when $t\leqslant\tau_0$, and falls to zero when $t>\tau_0$. Here a sharply changing from the turn-on to the turn-off profile is used to make the simulation simply. In the actual experiment, this changing will be affected by the plasma shutter. Figure 1(a) shows a 50 fs (FWHM) laser pulse with this slow turn-on and rapid turn-off shape, τ_0=0, including the fundamental laser pulse (blue line), its second harmonic (SH) (red line), and their combined pulse (black line), and (b) shows the detail of curves from −50 fs to −40 fs. The envelope of a normal pulse is plotted by the purple dashed line as a comparison as well. The phase difference between the fundamental laser pulse and its SH is set to zero.

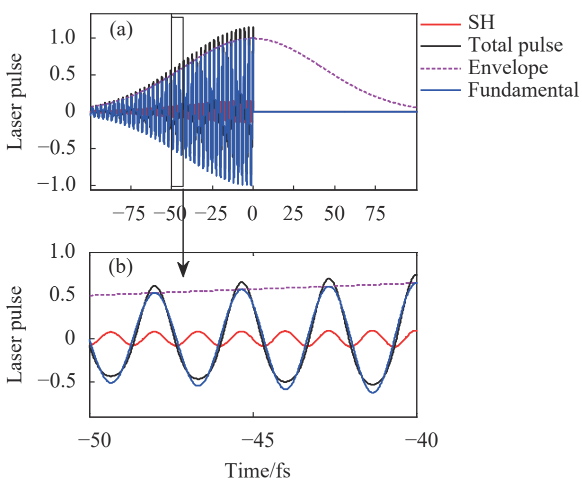

Fig.1 The slow turn-on, rapid turn-off laser pulse (blue line), its SH pulse (red line), their combined pulse (black line), and a normal pulse shape in the temporal domain (purple dashed line). (a) is the whole figure, and (b) is its magnified partition from −50 fs to −40 fs

As shown in the Fig. 1, the parameter τ_0 characterizes the switch from the turn-on to the turn-off of the lase pulse. The shaped laser pulse will have a half-pulse shape when τ_0 is 0. This shaped laser pulse will be shorter than a half-pulse when τ_0<0; and it will be longer than a half-pulse when τ_0>0. It is obvious that the total superposition field (black line) is not symmetric. This asymmetric laser field is the main origin to change the plasma current and the THz radiation from the laser plasma interaction.

Using such shaped two-color femtosecond laser pulses (fundamental pulse and its SH pulse) as the pump laser, the ionization and the net plasma current produced by it can be calculated according to the plasma current model. The ionization rate, w_i, of the gas atoms induced by the laser field is calculated by using the Ammosov-Delone-Krainov (ADK) ionization theory (where i=1, 2,⋯, represents the ionization order)[29]:

$$w_i=6.6\times10^{16}\frac{Z^2}{n^{9/2}}\left(10.87\times\frac{Z^3E_H}{n^4E_l}\right)^{2n-3/2}\exp\left(-\frac{2Z^3E_H}{3n^3E_l}\right)(s^{-1})\tag{2}$$

where 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, Z is the charge number of an ion, $n=Z/\sqrt{E_{ion}({\rm eV})/13.6}$ is the effective main quantum number of the ionized electrons, E_{ion} is the ionization potential of the ion in eV, and E_l is the field strength of the laser pulses. Then, the density of electrons n_e ionized by the laser field can be obtained by:

$$\frac{{\rm d}n_e}{{\rm d}t}=\sum_i w_in_i\tag{3}$$

Here, n_i is the atom (*ion*) density to be ionized. The electrons will be accelerated by the laser field after they are freed from the ions. The ions are much heavier than the electrons, thus the velocity of the electrons is much faster when both are accelerated by the same electric field. Therefore, the current is mainly induced by the motion of the electrons, $J=\sum n_e{\rm eV}$. When the collisions between the ions and the electrons are ignored, the acceleration of the electrons by the laser field can be calculated by:

$$J(t)=\frac{e^2}{m}\int_0^t\left\{\left[\int_0^\tau E_{laser}(t')\mathrm{d}t'\right]\sum_i w_i n_i\right\}\mathrm{d}\tau \tag{4}$$

Thus, the net plasma current could be calculated after the laser pulse is known using the numerical integration. The plasma currents produced by the normal two-color femtosecond laser pulses and the shaped two-color laser pulses are plotted in the Fig. 2. Here, the laser intensity I is using 10^{14} W/cm^2, the central wavelength λ is 800 nm, the duration of the laser pulse is 50 fs, the amplitude of the laser pulse can be obtained from the formula: $I=E_{laser}^2\times1.37\times10^{18}(\mu\mathrm{m}/\lambda)^2\mathrm{W/cm^2}$. The laser shape parameter τ_0 is 0. The gas atoms are nitrogen with a density of $0.000\,5\times n_c$, where n_c is the critical density of the plasma for the fundamental laser, $n_c=4\pi^2m\varepsilon_0c^2/(\lambda^2e^2)$. The gas employs the nitrogen with two reasons: one is that the 78% of the air is nitrogen molecules, using nitrogen as the gas target can offer convenience for the experiment; the other is that the species of the gas targets do not change the physics mechanism in this process although different gas molecules (or atoms) give different efficiencies of THz radiation[8]. This density of the nitrogen makes the plasma transparent for the pump laser and the THz pulses, according to the dispersion relation of the plasma. As shown in the Fig. 2, when the two kinds of laser pulses have the same field in the region of $t<\tau_0$, their currents have same temporal profiles. While the current from the shaped laser pulses increases gradually and then tends to a constant value. Since the laser field is broken off by this rapid turn-off shape, the electrons keep moving after the laser field is truncated off, consequently the currents keep stably in a short time since the recombination of the particles are neglected.

In the plasma current model, the ionization process and the acceleration process are stimulated nearly simultaneously, where the former is much shorter than the laser pulse duration for a femtosecond laser pulse. Thus, the collision time between the particles (electrons, ions, and atoms) is omitted, which usually lasts several picoseconds or sub-picosecond[29]. The collisions between

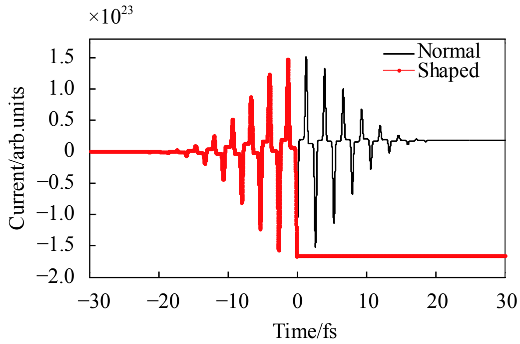

Fig.2 Plasma currents produced by the two-color normal laser pulses and the shaped laser pulses(The other parameters are introduced in the text)

the particles (electrons, ions, and atoms) are omitted, thus the recombination of the electrons and the ions are neglected, which makes the decay of the plasma current not obvious in the end of the laser pulses. Therefore, the current becomes a constant after the shaped laser pulse leaves away. If the pump laser are picosecond pulses or even longer, the recombination of the charged particles would be included, and the equations above also need add some corresponding items. This will improve the model more precise.

This plasma current is not stationary but pulsed with ultrafast oscillations, hence it generates electromagnetic (EM) wave, whose frequency is determined by the oscillation period and the duration of the current. This EM wave far away the origin plasma current has the form:

$$E_{THz}(t)\propto\frac{\mathrm{d}J(t)}{\mathrm{d}t} \tag{5}$$

The frequency of the EM wave is in the THz region for the oscillation of the current is in sub-picosecond, which is determined by the duration of the pump laser pulse. Figure 3 shows the temporal waveforms of the THz pulses in (a) and their frequency spectra in (b) generated by the normal laser pulses and the shaped laser pulses. The other parameters are same to that used in the Fig. 2. Note that the THz pulse from the normal laser pulses is enlarged by one hundred times in order to easily compare both results in the Fig. 3. Therefore, this shaped laser scheme can generate THz radiation one hundred times stronger than the normal laser scheme when both having same power. The shaped laser pulse with a rapid turn-off (this is also a sharp trailing edge) has a large asymmetry in the time domain, and makes the electrons accelerated to a large velocity, thus generating a larger net plasma current with some different profile and a stronger THz radiation. This is similar to the two-color laser scheme, whose asymmetry is broken by the combining the fundamental laser pulse and its SH pulse[10−12]. The decrease of the effective duration of the laser pulse also improves the broadband and the generation efficiency of the THz pulse, since the ionization time of the gas atoms and the sharp of the current become shorter comparing with the normal two-color laser scheme[30]. As shown by the Fig. 1, the shaped laser pulse has a half-shape, much shorter than the normal laser pulse, thus this pulse makes the current oscillate in a short time. This induces the electromagnetic radiation from this current has a shorter period and broader frequency spectrum.

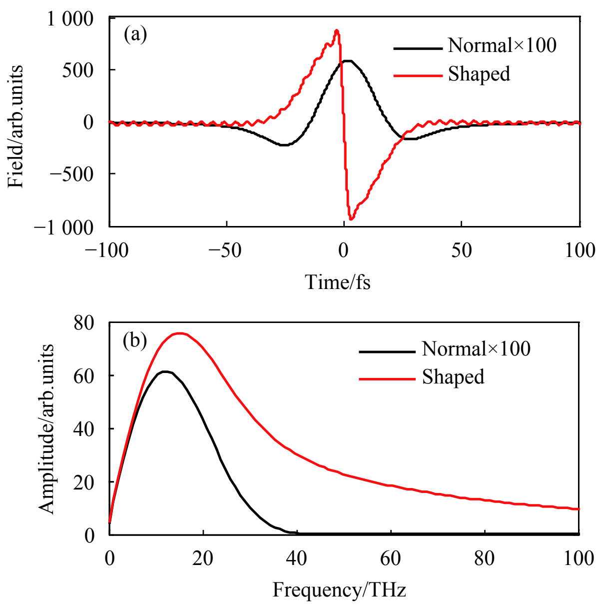

Fig.3 Temporal waveforms of the THz pulses (a) and their frequency spectra (b) produced by the normal laser pulses and the shaped laser pulses

Next, the influence of the phase difference between the fundamental laser pulse and its SH on the THz generation is investigated based on the numerical calculation. As reported before, the plasma current and its emitted THz wave are a period function of this phase difference[13]. And this is in good agreement with the experimental results[10, 31]. Here, Figure 4(a) shows the relation between the THz peak amplitude and the phase difference, and Fig. 4(b) shows the THz pulses evolution with the phase in two-dimension from this shaped laser pulses scheme. The parameter τ_0 is 0 in these simulations. It is found that the period of the THz yield is 90° of the phase difference, as shown in the Fig. 4, which is a half of the normal laser pulse scheme. Thus, it is so short (50 fs FWHM) that the carrier-phase of the shaped pulses is significant for the ionization and the acceleration of the electrons. As a result, the period of THz generation from such scheme is 90°, but not 180°. This is also an obvious distinction between the normal laser pulses scheme and the shaped laser pulses scheme.

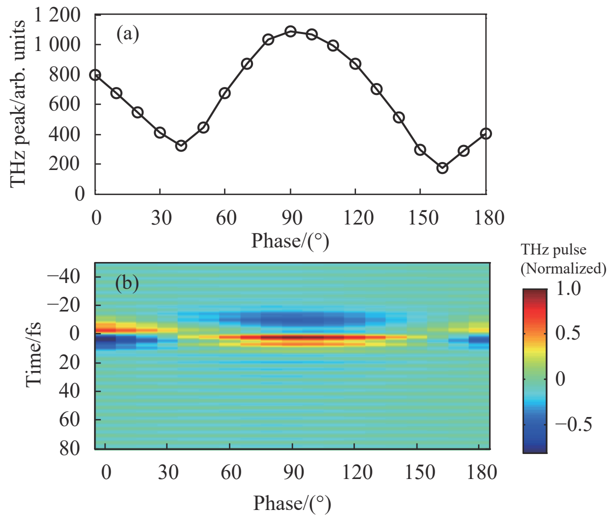

Fig.4 (a) Evolution of the THz peak amplitude with the phase difference; (b) All the THz pulses in the temporal with different phases in two-dimension (Note that the THz pulses are normalized in the (b) in order to show the evolution clearly)

The THz radiation will become stronger when the pump laser becomes stronger. But there is a saturation for the THz yield with the increasing of the pump laser[10]. This is because there is a saturation for the plasma current when the laser is strong enough to ionize all the gas atoms[11−13], and meanwhile the dense plasma induced by the stronger laser pulses absorbs some THz waves[10].

(Here we do not use very stronger laser pulse but focus on the range of 10^{14} W/cm^2, because the ionization process varies when the laser becomes stronger.) However, this change is not observed from the shaped laser pulses scheme, as shown by the Fig. 5 (red). It is found that the THz radiation will become weaker gradually when the pump laser increases slowly. As a comparison, the THz radiation generated from the normal laser pulses scheme is also plotted in the Fig. 5 (black), and it is enlarged by 80 times to shows the difference. Figure 5 indicates that the THz radiation from the shaped laser pulses scheme and the normal laser pulses scheme have different properties. The origin is from the asymmetry of laser field of both schemes because this asymmetry causes the ionization of the atoms and the acceleration of the electrons huge differences, thus makes the THz emission different. This is because the ionization time induced by the laser pulse is different when the laser becomes stronger. Thus, the influence of the shaped laser as an asymmetry field on the plasma current becomes will lose its advantage. This makes the THz generation change not obviously even the laser pulse is stronger in a small range. This asymmetry is characterized by the parameter τ_0, as presented in Eq. (1). The parameter τ_0 directly connects the pulse shape of the pump laser; thus, it decides the yield of the THz radiation. Figure 6 shows the relation between the peak amplitude of THz pulses and the parameter τ_0. The laser pulse duration (FWHM) is 50 fs. In this figure, τ_0 at zero means the laser pulse is a half-pulse, as shown in the Fig.1. The peak amplitude of THz pulses decreases when the τ_0 increase to several ten femtoseconds, in which case the shaped laser pulse treads to normal laser pulse. The interval of τ_0 in the simulations is 5 fs, which is much smaller than the pulse duration of the laser. It is not the multiple of the laser period, thus this sampling interval is small enough to obtain trend of the THz generation.

The parameter τ_0 is used to characterize the switch of laser pulses from the turn-on to the turn-off as mentioned before, meanwhile it also decides the laser pulse shape. Thus, the parameter τ_0 decides the THz yield from this special shaped laser pulse scheme, as shown in the Fig. 6.

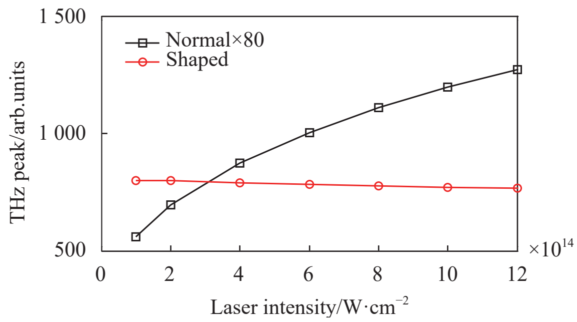

Fig.5 Relations between the THz peak amplitude and the laser intensity (The normal two-color laser scheme and the special shaped laser pulse are plotted together to show their difference)

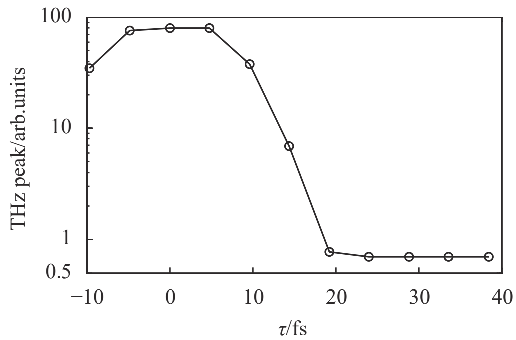

Fig.6 THz peak amplitude changes with the increase of the parameter τ_0 (The other parameters are same to that used in the Fig. 3)

2 Discussions

The THz radiation from the intense ultrashort laser pulses induced gas plasma has been widely used in the broadband THz science. This THz source has its advantages, such as without damage threshold power for the emitter and super-broadband of THz radiation, comparing with other sources based on the ultrashort laser pulses. Thus, the changes for the laser pulses or the gas targets directly change the process of the laser pulses interaction with the gas plasma, and correspondingly change its THz radiation. As specially shaped laser pulses, the slow turn-on, rapid turn-off two-color femtosecond laser pulses changes the acceleration of the electrons in the laser field, and thus changes the plasma current and its THz generation.

The shape of the laser pulse can change the interaction between the laser field and the plasma, thus might improve other plasma-based applications, such as attosecond pulse generation[32]. Although we here only investigate the ionization, the plasma current, and the THz generation from these special shaped laser pulses, these slow turn-on, rapid turn-off laser pulses might have potential applications in the other areas of high-power ultrashort optics.

3 Conclusions

In conclusion, our study shows that the slow turn-on, rapid turn-off two-color femtosecond laser pulses can generate one hundred times stronger broadband THz radiation than the normal two-color laser pulses with the same power. This pump laser pulse is a specially shaped pulse with large asymmetry in the temporal domain. A parameter τ_0 is used to characterize the switch from the turn-on to turn-off of the laser pulse. The properties of the THz radiation, including its relations with the pump laser power, the phase difference between the two-color lasers, and the switch parameter τ_0 are givens as well. These properties show their distinctions from the normal two-color laser pulses scheme. This study might provide a new way to optimize the THz yield from the laser plasma interaction.

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