**Review**

# High power terahertz pulses generated in intense laser-plasma interactions*

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Terahertz (THz) radiation has attracted much attention due to its wide potential applications. Though radiation can be generated with various ways, it is still a big challenge to obtain strong tabletop sources. Plasma, with the advantage of no damage limit, is a promising medium to generate strong THz radiation. This review reports recent advances on strong THz radiation generation from low-density gases and high-density solid targets at different laser intensities.

**Keywords:** strong terahertz pulses, intense laser-plasma interactions, relativistic laser pulses

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## 1. Introduction

The electromagnetic waves within the frequency range of 0.1–30 THz, which are located between the microwaves and the infrared light, are typically called Terahertz (THz) waves nowadays. Observation of THz radiation in astronomy has been reported extensively. During the past decades, with the development of new techniques and materials, particularly the invention of the ultrashort lasers, THz radiation has aroused much interest and has been developed rapidly. Numerous applications can be found in a wide range of fields such as physics, chemistry, biology, information, and security. Recent advances of THz physics, technology, and applications have been reviewed by some authors.[1,2] This review will concentrate on how to produce strong THz radiation, particularly by using intense laser-plasma interactions.

Strong THz sources with a power exceeding MW and a field strength exceeding MV/cm are required to extend the THz science and applications to nonlinear regime. Processes associated with the most atoms, molecules, materials, biological and medical systems under strong THz fields are not explored due to the lack of strong THz sources.

Strong THz radiation can be generated by using relativistic electron beams and ultrashort laser pulses. Through the mechanisms such as synchrotron radiation, transition radiation, free electron laser or Smith-Purcell effect, high power THz radiation has been generated by relativistic electron beams from conventional accelerators.[3,4] Compared with conventional accelerators, ultrashort laser-driven THz sources are compact. Tabletop THz sources can be generated by using optical pulses to pump various neutral materials through two general categories, photoconductor and rectification.[5−8] With the tilted laser wavefront scheme,[9−11] THz pulse energies up to 30 μJ have been obtained.

When the energy or focusing intensity of the pump laser pulses is high, the materials may be damaged. In contrast, plasmas can overcome the damage problem of neutral materials. Recent studies have shown that plasmas are promising media to generate strong THz radiation.[12] In principle, the laser intensity can be arbitrarily high for plasmas. The typical intensity of a multi-terawatt laser system is higher

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than $10^{18}$ W/cm$^2$ (up to $10^{21}$ W/cm$^2$ with a Petawatt laser). Using such ultraintense lasers, strong THz radiation with energies even up to mJ is expected. Intense laser–plasma interactions provide a new opportunity to greatly enhance the THz source strength. On the other hand, the THz radiation can also be used as a new way to diagnose the interactions.

So far, plasma-based THz radiation has been excited mainly by using low-density gas (including air). Observations of THz radiation from femtosecond laser-induced plasma filaments in air or in other low density gases have been reported.[13,14] More recently, THz radiation from high-density solid targets has also been demonstrated. In laser–plasma interactions, the electron quiver velocity in a strong laser field approaches light velocity, $c$, when the laser intensity is more than $10^{18}$ W/cm$^2$. In this case, the relativistic effect has to be considered. This paper will review the progress of such a plasma-based THz radiation. The paper is organized as follows: In Section 2, we will present the main progress on THz generation in the nonrelativistic laser interaction with low-density gases. In Section 3, we will extend the laser intensity to the relativistic case. In Section 4, the results from the relativistic laser interaction with high-density solid plasma will be discussed. We finally summarize our review in Section 5.

## 2. THz radiation from nonrelativisic femtosecond laser interaction with low density plasma

When a femtosecond intense laser pulse propagates in low-density gases, for example, in air, plasma filaments can be induced due to Kerr self-focusing effect.[15] The filaments can be much longer than the Rayleigh length. Cheng *et al.* predict that coherent THz radiation can be generated in the air filaments.[16] Tzortzakis *et al.* first observe sub-THz pulses ($\sim$ 0.1 THz), emitted perpendicularly to the laser propagation direction, from plasma filaments in air at an intensity of $10^{13}$ W/cm$^2$.[17] In their following experiment, collimated THz pulses in the forward cone direction are demonstrated. The generation is interpreted by Transition–Cherenkov emission from the plasma space charge moving behind the ionization front at light velocity.[18] The forward THz emission is 100 times more intense than the radial emission.

The THz radiation can also be induced by multifilament structure. THz radiation from bifilamentation with femtosecond laser pulses is ten times more intense than the transition-Cherenkov THz emission and with different angular and polarization properties.[19] The typical laser parameters in those experiments are 800 nm in wavelength, tens of femtoseconds duration and several mJ or tens of mJ in energy, which are far below the relativistic laser intensity.

It is found that THz radiation can be much enhanced when an external field is applied on the filaments. The field can be an external static electric field, or another transient laser field. The static electric field, like a "capacitor", can be longitudinal (in the laser propagation axis) or transverse (perpendicular to the laser axis).[20−23] When the pump laser pulse propagates through the capacitor, the static energy of the electric field is converted into the energy of electromagnetic THz waves. In both cases, the energy of the THz radiation increases by two and three orders of magnitude. However, the radiation pattern is different. In the longitudinal case, it is conical angular distribution, in agreement with the transition-Cherenkov radiation. While in the transverse case, the conical pattern gradually converges to a peak along the filament axis for high external field strength. Houard *et al.* propose that the net current excited by the external electric field perpendicular to the laser propagation direction enhances the THz radiation.[22]

Besides the external electric fields, THz radiation can be much enhanced with a frequency-doubled femtosecond laser pulse applied on the filaments. Cook and Hochstrasser found that, by inserting a 100 μm thick BBO crystal just behind the focusing lens, the fundamental 800 nm and second-harmonic 400 nm laser pulses of an Ti:sapphire laser are focused simultaneously to generate plasma filaments.[24] The THz signal is enhanced by a factor of 4000 of that without the BBO crystal. The radiation pattern, polarization, and the dependence on the pulse laser intensity are similar to the results of an external transverse electric field. After this experiment many groups also observed remarkable THz enhancement. This scenario is called two-color field scheme since both the fundamental and second harmonics are applied.[25−29]

Some authors attribute two-color field THz generation to four-wave rectification (FWR). However, Kress *et al.* found that plasma formation is necessary for the THz emission and the FWR cannot give

the THz frequency quantitatively.[25] Recently, Kim *et al.*[30] and Wu *et al.*[31] suggested that transverse drift currents excited by symmetry-broken laser field ionization of gases are responsible for this THz emission. However, their photocurrent model cannot explain the THz emission frequencies and holds only for moderate laser intensities.

Recently, Wang *et al.* propose a mechanism, which can not only explain the THz generation in low-density gases by one or two-color laser fields, but also extend the laser intensity to nearly relativistic regime.[32] In the model, the quasi-static transverse drift currents induced during the field ionization process and sequently modulated by the plasma in the longitudinal direction, are responsible for the THz-wave generation with the plasma frequency.

When a one-color laser pulse is used, the net drift currents are induced by the fluctuation of the electron number generated in the positive and negative half-cycles of the laser pulse. The THz generation is very inefficient and shows some characteristics of noise. While for the two-color scheme, the symmetry of positive and negative half-cycles of the fundamental laser pulse is broken. The ionization causes drift currents in the same direction in every cycle and thus emits THz pulses more efficiently than with one-color laser pulses. If the gases are fully ionized, either one-color or two-color schemes are applied, the net drift current is null and no THz pulses can be generated.

Figure 1 shows the spatial distributions of the transient transverse currents obtained by one-dimensional (1D) particle-in-cell (PIC) simulations. The field ionization of gases is calculated with ADK tunneling ionization formula.[33] The target is composed of only hydrogen gas ($H_2$). A slab target with a gas density $n_{\rm gas} = 1.25 \times 10^{-5} n_{\rm c}$ and a length $L_{\rm gas} = 200\lambda_0$ or $400\lambda_0$ is used, where $n_{\rm c}$ is the critical density, $\lambda_0$ is the laser wavelength. In the simulations we take $a_2 = a_1/2$, and $\theta = \pi/2$, where $a_1$ and $a_2$ are normalized amplitudes for the fundamental and the second-harmonic waves, respectively, and $\theta$ is their relative phase.

If the target is fully ionized into plasma, instead of gas state, no transverse current is excited. Therefore, no THz radiation is generated (see Fig. 1(a)). However, in a $H_2$ gas target a quasi-static negative transverse current is formed. At a later time the current will have a low-frequency oscillating profile (see Fig. 1(c)) because of the plasma modulation. This shows that ionization of gases is necessary for the THz emission.

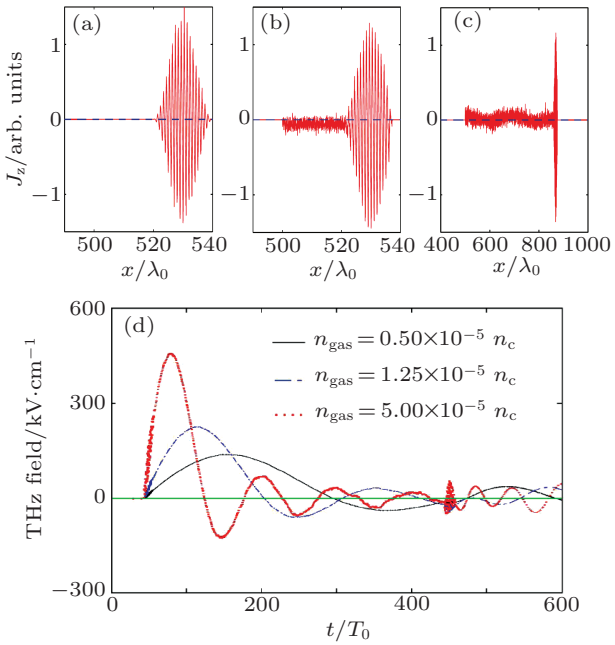



**Fig. 1.** (colour online) Spatial distribution of transverse currents $J_z$ (a) in a preformed plasma at $t = 60T_0$ and (b) in a $H_2$ gas at $t = 60T_0$ and (c) $t = 400T_0$, respectively, where $T_0$ is the laser cycles. The waveforms of the THz pulses for three different gas densities are shown in (d). A two-color laser with $a_1 = 0.06$ and $L_{\rm gas} = 400\lambda_0$ are taken.

For moderate laser intensity, experiments demonstrated that the THz pulse energy increases approximately linearly with the incident laser intensity. While for intense laser pulses, THz wave amplitude does not increase monotonically with the laser intensity since the drift currents will be dominated by uncontrollable field ionization of gases. To extend the laser intensity, Wang *et al.* proposed to use a chirped laser pulse to pump the gas target, so that electrons can get net acceleration in the transverse direction during each laser period. In this way, drift currents can be excited efficiently due to the asymmetric field in each laser cycle and the obtained THz wave amplitude can scale linearly with the incident laser amplitude.

With the two-color field scheme, THz pulses with energies up to several microjoules have been achieved from filaments in low-density gases. To further increase the THz radiation, one has to consider the following effects. When the pump laser intensity is moderate, the THz amplitude increases with the laser energy or intensity. However, it will be saturated if the laser intensity is too high.[32,34] The possible physical process is that the electron number and transverse drift currents can increase with the laser energy for moderate laser intensity, at which the ionization occurs in a few laser cycles. However, for high laser

intensity the gases will be fully ionized rapidly just in a few laser cycles at the front edge of the laser pulses. The laser peak will not contribute to the drift current. As a result, the net drift current will not be enhanced even though the laser intensity is high. Another one is the diffraction effect of the plasma which results in the laser intensity upper limit in filaments to be lower than $10^{15}$–$10^{16}$ W/cm$^2$.[35] In short, the laser intensity will be saturated in filaments when the laser energy is large.

## 3. THz radiation from relativistic femtosecond laser interaction with low density plasma

Recently, several new THz generation mechanisms associated with laser relativistic intensity have been proposed. By using relativistic laser–plasma interactions, high energy, single-cycle, and ultrafast THz pulses can be generated.

### 3.1. THz emission from laser wakefield in inhomogeneous plasmas

When a relativistic laser pulse propagates in a low-density plasma, large longitudinal amplitude wakefield can be excited. Since the acceleration gradient is huge in the wakefield, it has been demonstrated that electrons can be accelerated to the magnitude of GeV.[36] Laser wakefield acceleration has become an exciting new frontier in recent years. Besides electron acceleration, since the typical oscillating frequency of the plasma waves is on the THz level, Sheng *et al.* found that the electrostatic wakefield can be converted to electromagnetic emission through linear mode conversion in the THz regime.[12,37] This occurs when the laser pulse is incident obliquely to the density gradient of inhomogeneous plasmas (see Fig. 2). The emission spectrum and conversion efficiency predicted by mode conversion theory are in agreement with the particle-in-cell simulations. The energy conversion efficiency from laser pulses into this low frequency emission scales is proportional to their frequency ratio like $(\omega/\omega_0)^3$, and increases with the laser intensity and the plasma density scalelength, where $\omega_0$ is the laser frequency. By adjusting the laser pulse duration and plasma density profiles, one can control the emission frequency, bandwidth, and duration. In the two- and three-dimensional geometries, conical wake emission is found in the backward direction when the laser pulse propagates along the density gradient. To avoid conical emission, a laser pulse incident obliquely to the density gradient can be deployed so that collimated emission becomes dominant in the "specular refection" direction, suitable for practical applications. Numerical results show that THz radiation with the magnitude of MW and field strengths as large as GV/m can be generated.

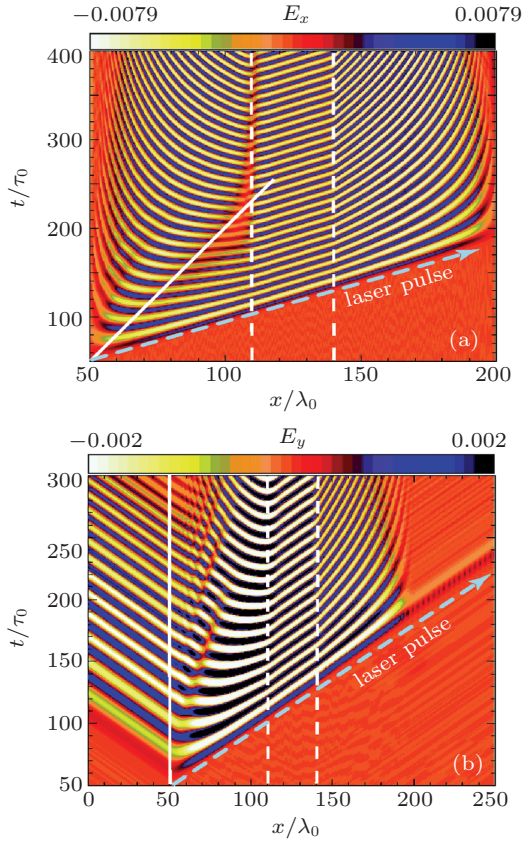



**Fig. 2.** (colour online) Spatial-temporal plots of the longitudinal field (a) and transverse field (b) from one-dimensional PIC simulation.[12]

When an ultrashort intense laser pulse is incident obliquely onto a tenuous plasma foil of few THz wavelengths in thickness, single-cycle powerful THz pulses can be produced due to the net transient current at the plasma surfaces driven by a large amplitude electron plasma wave in the plasma foil.[38] If an external DC magnetic field with a magnitude of a few teslas is applied, the plasma will be magnetized. In inhomogeneous magnetized plasma, strong THz radiation can also be produced through linear mode conversion.[39,40] The laser can be incident either normally or obliquely. By changing the strength and direction of the magnetic field, one can enhance or suppress the THz emission. The maximum energy conversion efficiency in the magnetized plasmas can

be double that in the unmagnetized plasmas. Because these THz emissions are always with a positive chirp, with a proper dispersion compression, single-cycle THz pulses can be generated with higher peak powers and field strengths.

### 3.2. THz emission from laser-produced electron bunches

As mentioned above, relativistic electrons generated by conventional accelerators can be used to produce strong THz pulses. With the rapid development of laser electron wakefield acceleration, the quality of the laser-accelerated electron beams is significantly improved. When the laser-based electron beams pass through the plasma–vacuum interface, THz radiation can be emitted through transition radiation. Leemans *et al.* found that the ultrafast electron bunches produced from laser wakefield acceleration in underdense plasma can result in powerful THz emission with energy about 3–5 μJ/sr per pulse.[41,42]

The properties of the laser-produced plasmas depend on the laser parameters. By controlling the laser conditions, THz radiation can be greatly enhanced. Using a chirped laser pulse, the THz wave amplitude can be increased with the laser intensity up to near the relativistic regime in the two-color field scheme. If the duration of the pump laser pulses is as short as a few laser cycles, theoretical studies predict that the THz amplitude scales linearly with the laser amplitude as well as with the sine of the laser carrier-envelope phase. In particular, it increases exponentially with the decrease of the laser duration.[43] In this way, the THz amplitude increases by near 2 orders of magnitude as the laser duration decreases from one and a half cycles to one cycle. A single-cycle laser of 200 TW can drive the THz radiation of 1 GW with the energy conversion efficiency higher than $10^{-4}$. The laser wavelength is another important factor affecting the THz radiation. It is found that THz amplitude can be enhanced by 35 times as the laser wavelength increases from 1 μm to 4 μm.[44] A 4-μm mid-infrared laser pulse at $10^{15}$ W·cm$^2$ can produce 5 MV/cm THz radiation.

On the other hand, from the target design point of view, besides the low-density gases, the plasma can also be produced by atomic clusters. The average density of clusters is similar to that of gases. However, a single cluster has a density like liquid, even solid. Therefore, higher laser energy deposition into the clusters can be achieved. A recent cluster experiment show that THz radiation from argon clusters irradiated by intense femtosecond laser pulses in the energy range of 10–70 mJ is two orders higher than that from argon gas.[45]

## 4. THz radiation from relativistic femtosecond laser–high density plasma interactions

The laser intensity in the plasma filaments in low-density gases is typically lower than $10^{15}$–$10^{16}$ W/cm$^2$, while laser intensity as high as $10^{18}$–$10^{21}$ W/cm$^2$ is available for the present multiterawatt ultrashort intense lasers. In contrast to neutral materials and plasma filaments in low density gases, almost arbitrarily high laser energies and intensities can be used in laser-solid interactions.

Hamster *et al.* first demonstrated the generation of THz pulses with energies of 1 μJ/sr from solid aluminum targets irradiated by laser pulses at an intensity of about $10^{19}$ W/cm$^2$.[46] The THz radiation is observed in the specular direction and the peak power is higher than 1 MW. They also observed THz radiation from low-density gas targets. Combining with the X-ray measurement, Hamster *et al.* believed that the THz radiation originated from the charge separation fields arisen from the longitudinal ponderomotive force on the critical density surface. This understanding can explain their observation of the THz from low-density gases. However, they did not explain the solid target results.

THz pulses with 0.5 μJ/sr were also observed by Sagisaka *et al.* from Ti solid foil targets at a little bit lower laser intensity $10^{17}$ W/cm$^2$.[47] They proposed an "antenna" model to explain the observation, which assumes that the electrons spread over the whole target and the target acts like an antenna. According to the model, the source of the THz radiation is a time-dependent current whose lifetime is equal to the ratio of half of the target size to the velocity of the electrons. Sagisaka *et al.* predicted that a target with a width of 5 mm will generate a THz pulse at 0.12 THz. The spectrum of THz radiation from laser driven plasmas generated on a copper wire is measured using free-space electro-optic sampling by Gao *et al.*[48] However, no clear evidence was found that the target size affects the THz radiation spectrum. These observations show the feasibility to produce strong THz sources

with solid targets irradiated by high intensity laser pulses, though the generation mechanisms are still not well understood.

Recently, energies up to 50 μJ/sr per THz pulse is observed by Li *et al.* when an intense laser pulse is incident onto a copper foil at relativistic intensities larger than $10^{18}$ W/cm$^2$.[49−52] The experiments were carried out using the Xtreme Light II (XL-II) Ti: sapphire laser system at Institute of Physics, Chinese Academy of Sciences. A calibrated thermoelectric detector aligned in the laser specular direction was used to measure the THz pulse energy. The temporal waveform was measured by a modified, single-shot electro-optic method with a chirped laser pulse, while a 1-mm thick ZnTe was used as the sampling crystal. It is found that the THz peak frequency is about 0.5 THz. The frequency can be tuned by changing the laser incidence angle and the plasma conditions.

Figure 3 shows the dependence of the THz pulse energy on pump laser energy.[53] Each data point is taken by an average of about 10 shots. The energy of the THz radiation monotonically increases with the laser energy. For the laser energy of 130 mJ, the THz energy is up to 5.5 μJ in 0.11 sr, which corresponds to 50 μJ/sr. They found that the radiation is dependent on the preplasma density scale length.[50] Unlike laser-gas interactions,[30] no saturation effect was observed. With the measured energy and angular distribution of the THz pulse, the total conversion efficiency from laser energy to THz pulse is estimated to be more than $10^{-3}$. Higher THz pulse energy could be achieved if the laser energy or intensity was further increased.

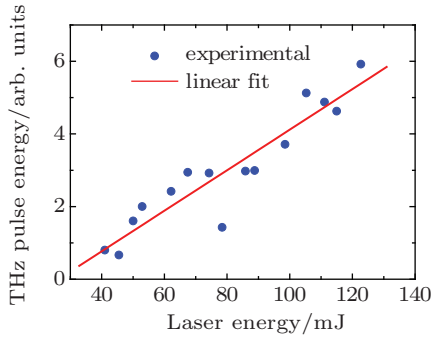



**Fig. 3.** (colour online) THz pulse energy as a function of the pump laser energy when the laser pulse is p-polarized. The THz pulse energy increases with the laser energy, which reaches 5.5 μJ in a solid angle of 0.11 sr for the pump laser energy of 130 mJ.[53]

The strong THz radiation observed indicated that a net current should have been excited in the plasma. In the interaction of a relativistic laser pulse with a solid foil, energetic (fast) electrons with a temperature from several hundreds keV to several MeV can be generated.[54,55] These fast electrons will form a transient current. There are two kinds of currents that can be formed in the interaction. One is a longitudinal current generated by the ponderomotive force of the relativistic laser pulse in the laser propagation direction. This kind of current basically exists in the high density region. Another is the lateral current, which comes from the fast electrons propagating nearly along the target surface due to the confinement of the spontaneous quasistatic magnetic and electrostatic fields on the surface.[56−59] The lateral current will be strong when the laser incidence angle is large. In the experiments, it is found that the dependence of the THz radiation on laser conditions (polarization, intensity, etc.) is quite similar to that of the lateral current. Therefore, the THz radiation observed may be originated from the lateral current. Two-dimensional PIC simulations clearly show the presence of the surface current. This self-organized transient fast electron current model can describe most of the measured THz features.

If the MeV fast electron current is transported near a grating structure, THz radiation may also be excited by Smith–Purcell effect. Recently, near-infrared radiation generated from a high-density MeV electron current is demonstrated with a grating target. The advantage of this scheme is that the terahertz radiation is tunable by changing the grating parameters.[60]

## 5. Summery and perspectives

The development of THz sources is closely related with the development of ultrafast lasers. The peak power of the present ultrafast intense lasers is up to Petawatt, giving the focused laser intensity in vacuum to $10^{21}$ W/cm$^2$. Any materials will become plasma at such a high intensity. To achieve high power pulsed THz sources, plasma-based THz radiation has become a research focus during the past years. THz radiation from femtosecond laser-induced plasmas in low-density gases and high-density solid targets has been demonstrated at non-relativistic and relativistic laser intensities.

In low-density plasmas, the two-color laser filed scheme using plasma filaments is quite efficient. The conversion efficiency of from the laser energy to THz

radiation is as high as $10^{-3}$. The THz energy can be on the order of μJ, even tens of μJ.

To fully use the power of the intense laser, THz generation from the relativistic plasma has been proposed. Theoretical studies show efficient generation of single-cycle strong THz pulses with field strength higher than MV/cm. Recent experiments show the feasibility to produce high energy THz pulses from relativistic laser–plasma interactions. It is believed that the energetic electrons play an important role in THz pulse generation. With relativistic plasma, it is possible to increase the THz pulse energy to more than 100 $\mu$J. Further work is required to understand the generation mechanisms and develop THz diagnostic techniques, which can run well in single-shot mode.

Despite the low repetition rate of the relativistic lasers, high peak power and energy of the THz pulses from relativistic plasmas show prospects for many rich nonlinear optical studies in the THz range,[61] single-shot THz imaging,[62] and THz pump-probe measurement of some ultrafast dynamics, etc. Recently, Kerr birefringence effect has been demonstrated using single-cycle THz pulses, instead of optical pulses, in liquids.[63] Such THz nonlinear optics will pave a new way for numerous physical, biological and chemical progresses.

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