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Strong polarization-controlled terahertz generation by bi-elliptical polarized laser fields

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Terahertz generation from atoms driven by two color linearly polarized (LP) and circularly polarized (CP) laser fields have been well investigated. In this work, based on the photocurrent model, we investigate theoretically the intensity and polarization characteristics of terahertz waves radiated by the bi-elliptical polarized two-color laser fields with orthogonal or parallel major axes. We show that polarization-controlled, including circularly polarized terahertz waves with sufficient intensity comparable to that of co-rotating CP or parallel LP laser field, can be generated by using a longer-wavelength few-cycle bi-elliptical field. Our simulations also show that THz energy and ellipticity can be dramatically improved with dual-color elliptical field with tiny or large ellipticity, compared with that with two-color orthogonal LP field and counter-rotating CP laser field, respectively. Bi-elliptical polarized laser field provides a huge parameter space allowing for far-reaching control of THz emission.

KEYWORDS

terahertz generation, bi-elliptical polarized laser field, photocurrent, polarization, terahertz intensity

1 Introduction

Due to its unique performance, such as high coherence, high intensity, broadband and high orientation, terahertz (THz) wave has brought profound influence to the fields of communications, electronic countermeasures, electromagnetic weapons, radar, astronomy, medical imaging, and so on [1–7]. At present, there are many ways to generate THz radiation, such as free electron lasers [8], vacuum electronics THz sources [9], THz quantum cascade lasers [10], and ultrafast laser pumped photoconductance THz sources [11]. With the development of ultra-short and ultra-strong laser pulse technology, the interaction of intense femtosecond laser with gas target has also become an important way to generate high power, broad THz radiation [12, 13]. How to obtain THz sources with higher strength and controllable polarization is still a challenge of the current THz research.

In the scheme of interaction of intense laser field with gases, the commonly used driving field is a combination of a fundamental linearly polarized pulse and its second harmonic [14, 15], for the linearly polarized THz generation. In order to enhance the THz radiation intensity, the duration of the pump pulse [16, 17], phase delay [14, 15, 18, 19] and intensity ratio between two pulses [20, 21], should be carefully optimized. With these efforts, the THz pulse energy can be increased by at least one order of magnitude. Besides, adjusting the frequency ratio between two components [22, 23], and increasing the number of combing pulses [24, 25], can also increase THz yield. The polarization of pump laser also influences the generated THz pulse energy [26–28]. The recent experimental results of Meng et al. [26] and Tu et al. [28] show that the THz power produced by two-color circularly polarized with the same helicity (CP-S) laser fields is about 5 times (from a thin get) or 8 times (from an air filament) higher than that produced by parallel linearly polarized (LP-P) laser fields. In contrast, the THz radiation from two-color CP-C (circularly polarized pulses with counter helicity) laser fields, which has a much weaker THz yield, is on par with the THz power provided by the orthogonal linearly polarized fields (LP-O).

In some THz applications, effective control of their polarization states is a prerequisite. For example, in materials science, the polarization direction of THz waves plays a key role in optical excitation [29], spectral diagnosis [30, 31], and THz information technology [32, 33]. At the same time, the ellipticity of THz wave is an important parameter in birefringent material imaging [34], and its chirality is very important for the study of chiral rotation of organic molecules and spin dynamics in solid materials [35, 36]. Therefore, it has been an important subject to achieve flexible control of the polarization state of THz pulses over wide band. To this end, many driving laser schemes have been proposed to generate elliptically or circularly polarized THz radiation, such as monochromatic circularly polarized laser pulses [37], combination of circularly polarized and linearly polarized beams [38, 39], and so on. For the attractive CP-S field, the generated THz radiation is always linearly polarized when pulse duration is relatively long, namely, exceeding tens of femtoseconds for 800-nm wavelength. One of our recent works show that CP-S laser pulses can generate elliptically and circularly polarized THz radiations by increasing the wavelength [40].

Compared with linearly and circularly polarized driving fields, the investigation on the THz generation by two-color elliptically polarized driving field are still scarce [27, 41–44], which draws our interest in this work. We focus on whether the strong and polarization-controllable THz waves can be generated with this kind of pump field. In addition, we are curious about how THz radiation changes when a tiny ellipticity is introduced into a LP-O or CP-C laser field. We find that when taking different laser ellipticity, the THz energy generated is comparable with those produced by LP-P or CP-S fields. More importantly, THz radiation with high ellipticity or even circularly polarized can be obtained with longer-wavelength co-rotating bi-elliptical laser fields. Laser ellipticity, intensity ratio and phase difference together constitute a larger parameter space for THz polarization control, compared with other driving field. When an imperfect LP-O or CP-C field is considered, some counterintuitive results are obtained. These results can be partly understood in terms of the generated electric current.

2 Theoretical method

The simulations in this paper are based on the photocurrent model [14, 15]. When the laser pulse interacts with the gas, the electrons in the gas atoms undergo tunneling ionization. The produced free electrons are accelerated by the laser fields. Assuming that the initial density of gas is ρ_0, the electron density $\rho(t)$ of the accelerated electron during its movement can be expressed as

$$\frac{d\rho(t)}{dt} = w(t)\left[\rho_0 - \rho(t)\right] \tag{1}$$

The tunneling ionization rate $w(t)$ can be obtained by Ammosov–Delone–Krainov (ADK) theory [45, 46].

Then the electron accelerates under laser field to form the transverse current $\boldsymbol{J}(t)$

$$\boldsymbol{J}(t) = -\int_{-\infty}^{t} e\boldsymbol{v}_e(t,t')d\rho(t') \tag{2}$$

where e is the electron charge and $\boldsymbol{v}_e(t,t')$ is the speed of electron that is released at time t', which satisfies the equation

$$\boldsymbol{v}_e(t,t') = -\frac{e}{m_e}\int_{t'}^{t} \boldsymbol{E}(t'')dt'' \tag{3}$$

Finally, time-dependent photocurrent $\boldsymbol{J}(t)$ radiates electromagnetic waves. After wave filtering, THz radiation in frequency domain is obtained as

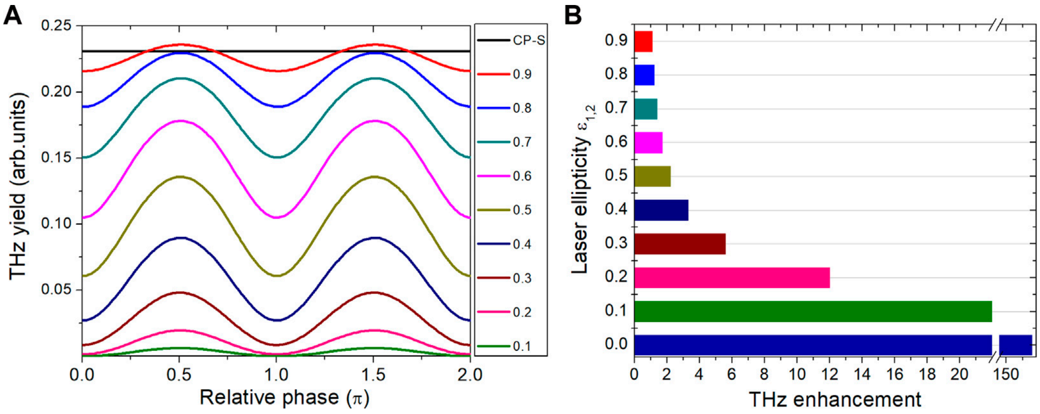

FIGURE 1
Dependence of THz radiation strength on the ellipticity and phase φ_2 of co-rotating 800 nm + 400 nm BEOTC and CP-S fields. **(A)** THz yields (0.1–10 THz) as a function of φ_2. Numbers of 0.1–0.9 denoted in the legend refer to the ellipticity of BEOTC laser field. **(B)** THz enhancement due to phase φ_2: ratio of the strongest THz radiation at 0.5π and weakest radiation at 0.0π shown in **(A)**.

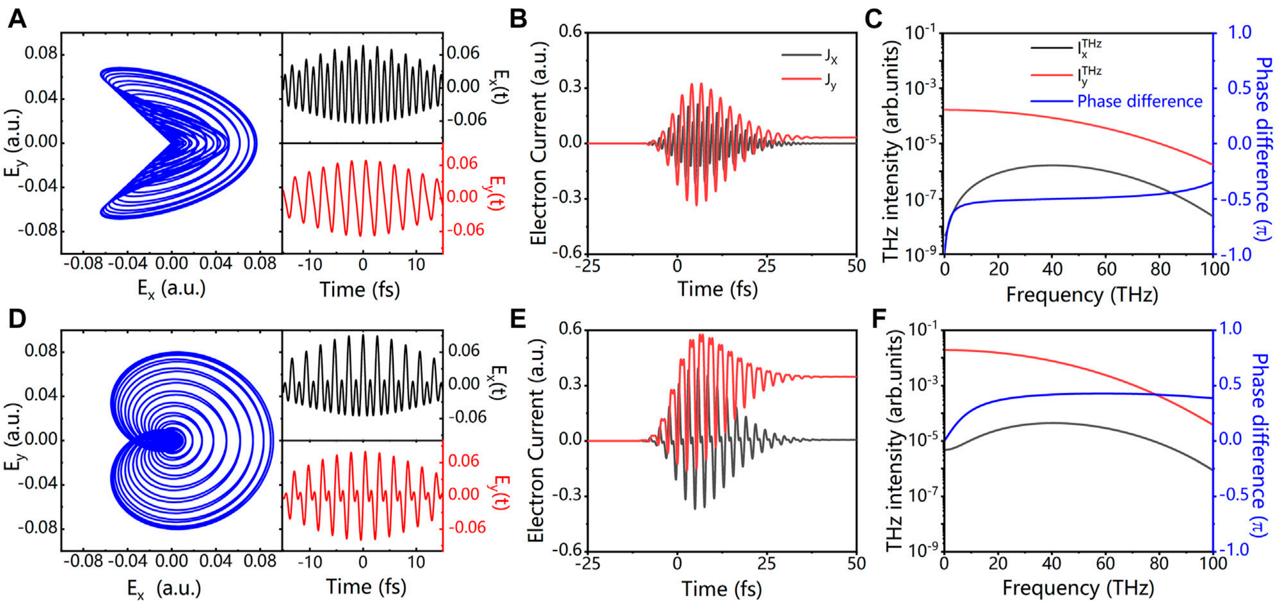

FIGURE 2
Comparisons between $\varepsilon_{L1,L2}$ = 0.2 (upper row) and 0.8 (lower row) for the waveforms of BEOTC laser fields (left column), and generated electric currents (middle column), THz radiation (right column). Laser phase $\varphi_2 = 0.0\pi$.

$$\boldsymbol{E}_{\mathrm{THz}}(\omega) \propto \hat{F}\left[\frac{d\boldsymbol{J}(t)}{dt}\right] \tag{4}$$

where $\hat{F}$ represents the Fourier transform. The THz waveform $\boldsymbol{E}_{\mathrm{THz}}(t)$ of the radiation field in the time domain can be obtained with the inverse Fourier transform on the THz spectrum within a specific frequency range. The parameter ellipticity $\varepsilon_{\mathrm{THz}}$ (defined as the ratio of the THz amplitudes along the short axis and long axis) is used to represent THz polarization degree, which can be obtained from the THz electric field waveform, or THz strengths and phases along two orthogonal directions [47].

3 Results and discussion

The two-color $\omega + 2\omega$ driving field used in the simulations can be written as

$$\boldsymbol{E}(t) = f(t)\left[\sqrt{\frac{I_1}{1+\varepsilon_1^2}}\begin{pmatrix}\varepsilon_1\cos(\omega t+\varphi_1)\\ \sin(\omega t+\varphi_1)\end{pmatrix} + \sqrt{\frac{I_2}{1+\varepsilon_2^2}}\begin{pmatrix}\cos(2\omega t+\varphi_2)\\ \varepsilon_2\sin(2\omega t+\varphi_2)\end{pmatrix}\right] \tag{5}$$

where $I_{1,2}$ and $\varphi_{1,2}$ are the peak intensity and carrier envelope phase (CEP) for two laser components, respectively. The pulse envelope is Gaussian shape with $f(t) = e^{-2\ln 2t^2/\tau^2}$ and τ is pulse duration (FWHM). For simplicity, we limit the phase $\varphi_1 = 0$ in the following simulations. In general, the field in Eq. 5 is composed of two elliptically polarized fields with aclinic or upright ellipses. Their ellipticities $\varepsilon_{L1,L2}$ are determined by $\varepsilon_{1,2}$. Two kinds of bi-elliptical fields are considered in the following simulations: one with the orthogonal major axes of two ellipses, which are called the bi-elliptical orthogonally polarized two-color (BEOTC) laser fields latter; the other with the parallel major axes of two ellipses (BEPTC). For each case, the ellipticities of ω and 2ω fields are taken as equal. By controlling the parameters $\varepsilon_{1,2}$ (0 or ∞), laser fields with other polarization configurations can be obtained.

3.1 Co-rotating BEOTC and BEPTC fields

3.1.1 800 nm + 400 nm

First, we make a comparison of THz strength radiated by co-rotating BEOTC driving lasers with various ellipticity from 0.1 to 0.9. Figure 1A shows the dependence of THz yields (0.1–10 THz) generated by laser fields with different ellipticity interacting with Ar

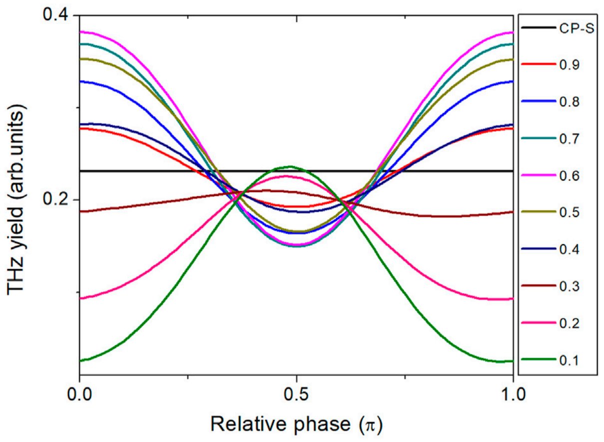

FIGURE 3
The same as Figure 1A, but for co-rotating BEPTC laser field.

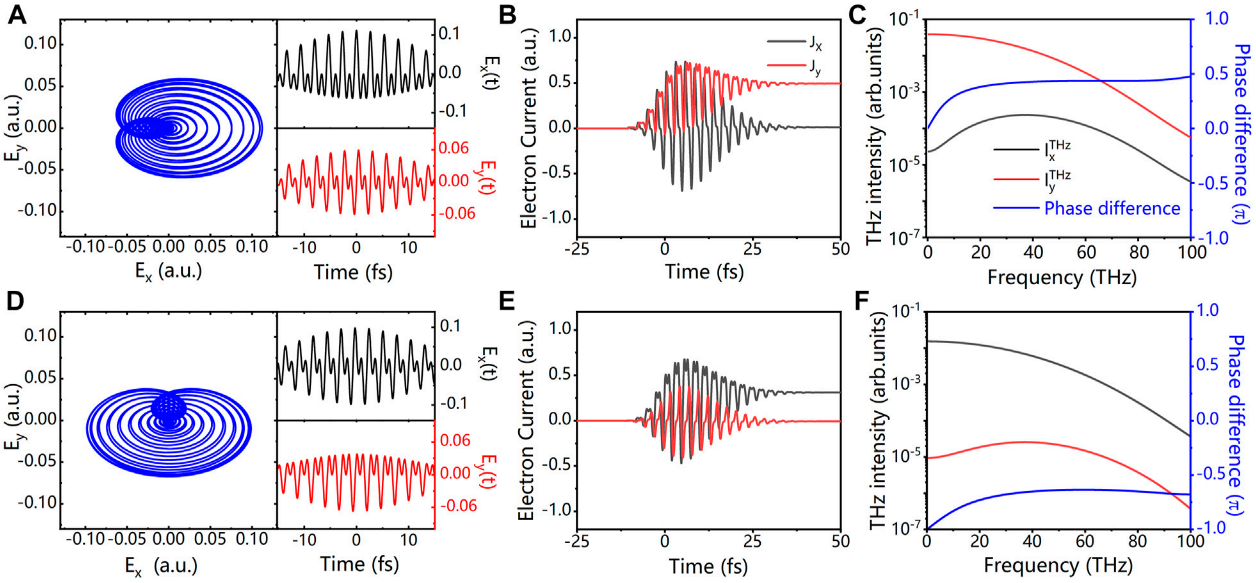

FIGURE 4
Comparisons of the waveforms of BEPTC laser field (left column) with ellipticity of 0.6, and generated electric currents (middle column), THz radiation (right column) for $\varphi_2 = 0.0\pi$ (upper row) and $\varphi_2 = 0.5\pi$ (lower row).

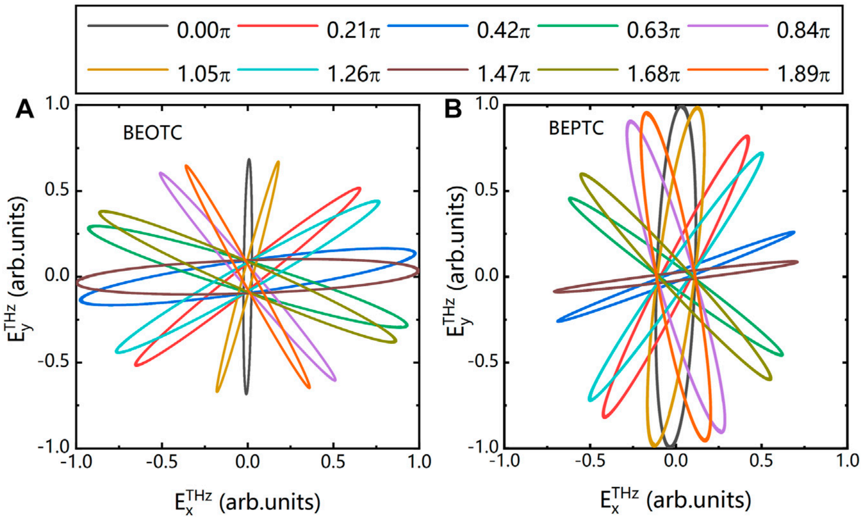

FIGURE 5
Dependence of 30-THz radiation field on the phase φ_2 for co-rotating **(A)** BEOTC and **(B)** BEPTC laser fields. In two cases, $\varepsilon_{L1,L2} = 0.5$ and $I_2/I_1 = 1.0$.

atoms on relative phase φ_2. The pulse duration is 20 fs, the total laser intensity $I_1 + I_2 = 3 \times 10^{14}$ W/cm^2 and the intensity ratio $I_2/I_1 = 1.0$. The wavelength is 800 nm and 400 nm for two components, respectively. As a benchmark, THz yields radiated by two-color CP-S fields are also given. It shows that the THz radiation intensity is modulated by adjusting the polarizations of laser fields. For the bi-elliptical laser fields, the THz yield increases with the increasing of laser ellipticity. As laser ellipticity increases from lower to higher, THz yield is enhanced by more than three orders of magnitude. THz yield also depends on the laser relative phase, which is maximized at $\varphi_2 = 0.5\pi$. For each phase, the generated THz energy is lower than that generated by CP-S field, except for $\varepsilon_{L1,L2} = 0.9$ at some phases around 0.5π, which generates THz radiation even slightly stronger than that of CP-S. It should be pointed out that a very small departure from an ideal CP field may lead to a substantial change in the THz energy [44]. And it is very difficult to get a perfect circularly polarized light in experiments (for instance, see Figure 1B in [26, 28]), which makes it hard to quantitatively compare the simulation results with the experimental ones. Figure 1B quantitatively demonstrate the effect of phase on THz radiation, where we define a THz enhancement factor as the ratio of the strongest THz radiation and the weakest radiation. As laser ellipticity increases from 0.1 to 0.9, THz enhancement monotonously decreases from 20 to 1.2, implying the precise control of the CEP is not required at higher laser ellipticity, which is similar to the case of CP-S field. As a comparison, it is about 190 in the case of LP-P field.

Simulation results show that the ionization level at the end of BEOTC laser pulse increases with the increasing of laser ellipticity, and depends weakly on the relative phase. For $\varepsilon_{L1,L2} = 0.1$, ionization degree is 0.35 and 0.28, respectively, at $\varphi_2 = 0.0\pi$ and 0.5π. Correspondingly, they are 0.46 and 0.49 for $\varepsilon_{L1,L2} = 0.9$ at two phases. For CP-S field, 48% of atoms are ionized. Great difference in the THz strength at these laser phases and ellipticities indicates that the symmetry of laser field plays a more key role in the enhancement of THz generation.

Take $\varepsilon_{L1,L2} = 0.2$ and 0.8 for example, Figure 2 displays the influence of asymmetry of driving BEOTC laser field on the THz radiation strength. Though waveforms of electric field in x direction are different, they are all symmetric in two cases, which generates antisymmetric electron drift velocity and small net current [Figures 2B, E]. As a result, THz emissions in this direction are very weak. For y direction, the electric fields are asymmetrical, especially in the case of higher ellipticity, namely, $\varepsilon_{L1,L2} = 0.8$. Consequently, stronger THz radiation is produced.

When the two major axes of 800-nm and 400-nm elliptical fields are parallel, different THz energy dependence on the laser ellipticity and relative laser phase is observed, which is shown in Figure 3. At $\varphi_2 = 0.0\pi$, THz radiation monotonically increases as laser ellipticity increases from 0.1 to 0.6. Then, it decreases with further increasing of laser ellipticity. At $\varphi_2 = 0.5\pi$, THz radiation displays a weaker dependence on driving laser ellipticity, compared with 0.0π. Considering all laser phases, the strongest radiation occurs at $\varphi_2 = 0.0\pi$, for some laser ellipticities. In addition, the THz energy generated by different lasers varies little, which is modulated weakly around the level produced by CP-S fields. Similar to the case of BEOTC, the THz enhancement induced by laser phase is small, too. Therefore, BEPTC is an attractive driving field, when the higher THz strength and difficulty of generation of perfect CP field are considered.

Figure 4 compares the electric field of BEPTC fields with phase $\varphi_2 = 0.0\pi$ and 0.5π, at a fixed laser ellipticity of $\varepsilon_{L1,L2} = 0.6$. It shows that the phase determines the symmetry of laser field in two orthogonal directions. For $\varphi_2 = 0.0\pi$, y-direction field is asymmetric, while it is asymmetric in x-direction in the case of $\varphi_2 = 0.5\pi$. As a result, it is inverse for the relative size of generated residual current and THz radiation between two directions for two phases. Furthermore, net currents generated by $\varphi_2 = 0.0\pi$ are slightly higher than those in the case of 0.5π. Consequently, THz yield in the laser field with phase of 0.0π is higher.

From the THz spectra shown in Figures 2, 4, we can learn that THz radiation in the whole frequency range should be nearly lineally polarized, due to the huge strength difference in two orthogonal directions. To get the THz polarization information generated by bi-elliptical laser field more intuitively, Figure 5A shows the 30 THz electric field waveform changes with more relative phase φ_2 of BEOTC field, for $I_2/I_1 = 1.0$ and $\varepsilon_{L1,L2} = 0.5$. It can be seen that the THz intensity, polarization degree and direction all change with the laser relative phase. In general, however, the THz ellipticity is very low. The maximum ellipticity ε_{THz} is about 0.09 at $\varphi_2 = 0.42\pi$ and 1.47π. Note that THz fields generated by commonly used LP-P and CP-S laser fields can only be linearly polarized, under these parameters. Figure 5B gives the THz field evolution with phase of BEPTC field, and similar behavior can be observed.

3.1.2 1600 nm + 3200 nm

To further improve THz ellipticity generated by co-rotating bi-elliptical field, we increase the wavelength λ_1 and λ_2 to 1600 nm and 3200 nm, respectively, while keeping the pulse width unchanged, according to our previous experience on the generation of THz with large ellipticity by using bicircular laser fields [40]. Figure 6A shows the variation of the ellipticity of THz waves generated by BEOTC fields with $I_2 + I_1 = 3 \times 10^{14}\ \mathrm{W/cm^2}$, $I_2/I_1 = 1.0$, $\varphi_2 = 0$. When laser ellipticity varies from 0.1 to 0.9, the maximal THz ellipticity at a given frequency reaches higher than 0.8, which covers a very broad band. This value could be further increased (>0.98) if we optimize intensity ratio and laser phase, too. Figure 6B shows the electric fields of 30-THz waves corresponding to different ellipticity $\varepsilon_{L1,L2}$ of laser fields. Obviously, the THz polarization can be controlled by choosing an appropriate ellipticity of the laser fields. Thus, in addition to intensity ratio and phase delay, as adopted in other driving fields, bi-elliptical field provides an extra parameter that can control THz polarization. With such a huge parameter space, it is easier to optimize THz polarization state.

Such control over THz polarization can also be achieved when the two major polarization axes of the bi-elliptical laser fields are parallel. Take $\varepsilon_{L1,L2} = 0.6$ as an example, Figure 7 shows the main results in this case. The pulse duration and total laser intensity remain as before. By optimizing the intensity ratio I_2/I_1 and relative phase φ_2, we get the maximum THz ellipticity for a given frequency. Figure 7A shows the THz radiation ellipticity curves obtained for the optimizations at 20 THz and 30 THz. We can see that ellipticity for these two frequencies reaches about 0.90 and 1.0, respectively, with $I_2/I_1 = 0.013$, $\varphi_2 = 0.85\pi$ and $I_2/I_1 = 0.051$, $\varphi_2 = 0.85\pi$. Figures 7B, C show visually the 30-THz electric field. Obviously, THz radiation with controlled polarization can be obtained by just adjusting the intensity ratio at a fixed relative phase. In two cases, THz radiation is circularly polarized and elliptically polarized with a small ellipticity $\varepsilon_{THz} = 0.15$.

3.2 Influence of the small fluctuation of ellipticity of LP-O and CP-C fields on the THz radiation

3.2.1 Non-perfect LP-O field

It is depressing that the THz intensity generated by LP-O field is very low, and these radiations can only be lineally polarized. In surprise, we find that a co-rotating BEOTC laser with a very small ellipticity (<0.1), i.e., an imperfect LP-O field, can improve the performance. In Figure 8A, we give the 30-THz THz electric field waveforms for bicolor laser fields with $\varepsilon_{L1,L2}$ change from 0 to 0.1, with a step of 0.01. The results show that the THz field depends dramatically on ellipticity of the BEOTC laser fields. When the

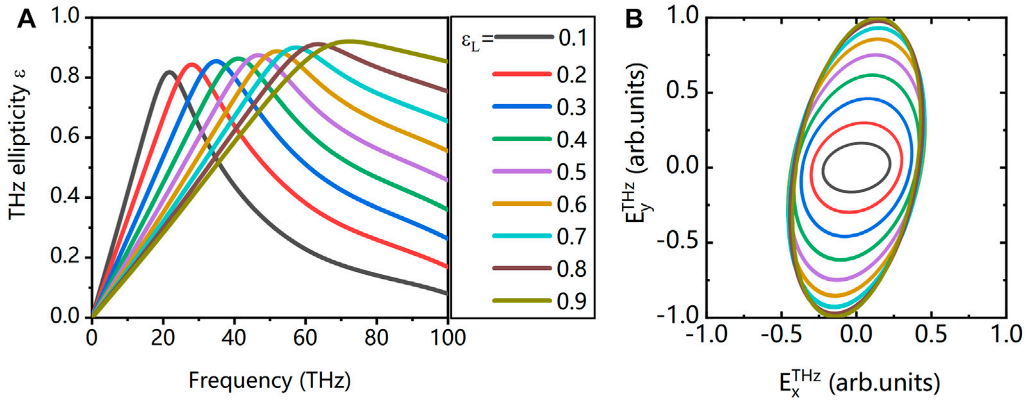

FIGURE 6
(A) The ellipticity of THz waves generated by 20-fs 1600 nm + 3200 nm co-rotating BEOTC laser fields varies with laser ellipticity. **(B)** 30-THz THz wave electric field.

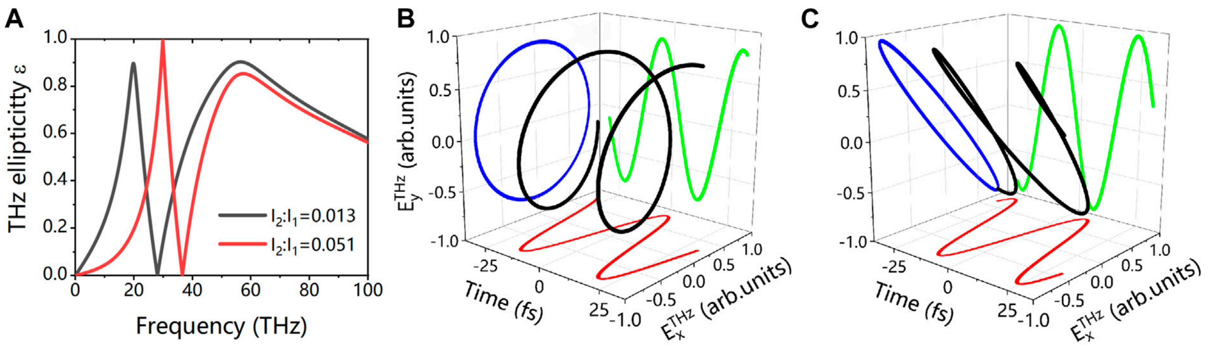

FIGURE 7
THz polarization characteristics radiated by 20 fs, 1600 nm + 3200 nm BEPTC laser fields. **(A)** THz ellipticity varies with the THz frequency for two laser intensity ratios of 0.013 and 0.051 at $\varphi_2 = 0.85\pi$. Laser ellipticity is fixed at 0.60. **(B,C)** THz radiation fields at 30 THz under two intensity ratios.

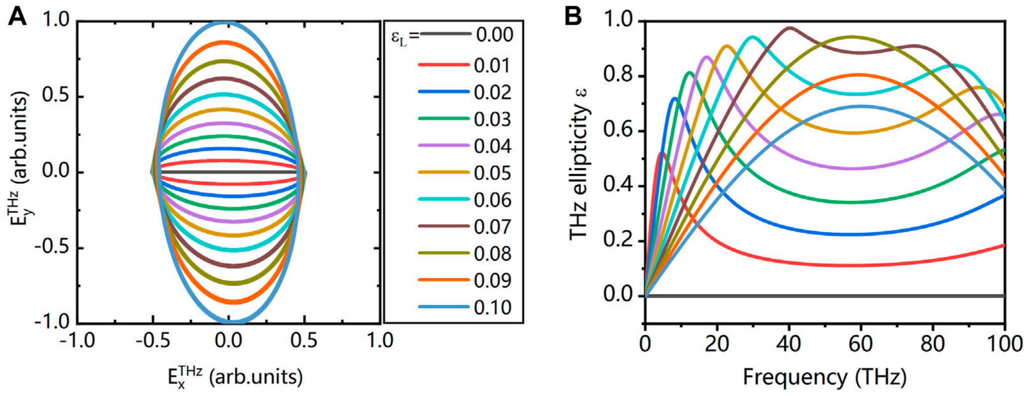

FIGURE 8
(A) Electric field evolution of 30-THz THz waves generated by BEOTC fields with laser ellipticities of $0 \le \varepsilon_{L1} = \varepsilon_{L2} \le 0.10$, for $\varphi_2 = 0$ and $I_2/I_1 = 1.0$. **(B)** Variation of THz ellipticity with laser ellipticity.

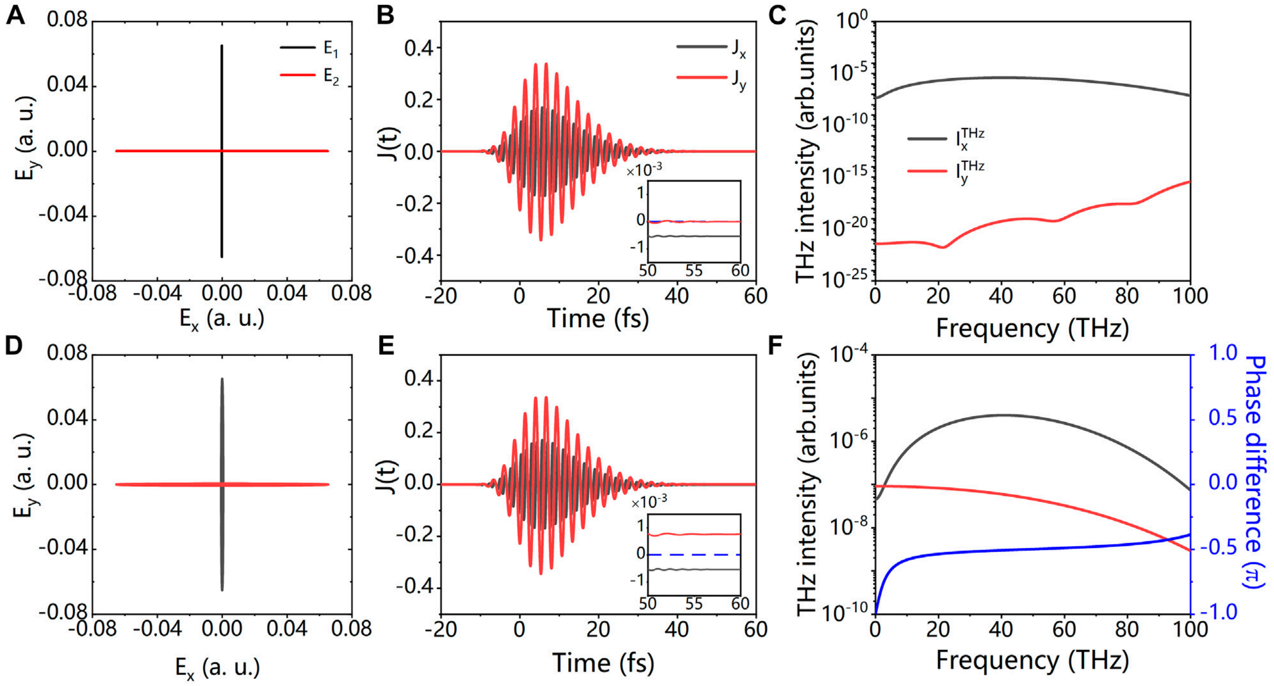

FIGURE 9
Waveforms of laser fields (left column), the electric currents (middle column, where the inset shows an enlarged view of the residual current), and generated THz radiation (right column) for LP-O (upper row) and BEOTC laser fields with $\varepsilon_L = 0.01$ (lower row).

ellipticity of the laser fields changes from 0 to 0.06, the THz wave changes from linear polarization to nearly circular polarization ($\varepsilon_{THz} = 0.93$). Figure 8B further shows the ellipticity of THz waves over a broad range of 100 THz changes with the laser ellipticity. Obviously, such a flexible control over THz ellipticity can be achieved in the whole frequency range by altering a small laser ellipticity.

Such sensitivity of THz polarization and intensity on the small fluctuation of ellipticity of driving laser is incomprehensible. However, we note that similar phenomenon has also been observed in other strong field process, namely, the generation of high order harmonics [48, 49]. In Milošević et al simulations, they observe a dramatic dependence of harmonic ellipticity on the ellipticity of BEOTC field even in a level of one part in one thousand. The explanation behind these phenomena is difficult. Here, we give a qualitative analysis from the view of residual current. In Figure 9 we show the laser waveforms with the ellipticity $\varepsilon_L = 0$ (LP-O) and $\varepsilon_L = 0.01$, the generated currents and THz spectra. It shows that the differences between two laser waveforms and total currents are barely visible, but difference in residual current is significant [see enlarged insets in Figures 9B, E]. For $\varepsilon_L = 0$, the residual current in the y direction is almost zero, while the current in the x direction exhibits asymmetry. Therefore, the resulting linearly polarized THz radiation is along the x direction. For $\varepsilon_L = 0.01$, the residual currents in both x direction and y direction are all not zero. In particular, the current in the y direction is increased by a factor of over 1000, compared with the case of LP-O. So, THz radiation in y direction is enhanced dramatically, reducing the intensity difference between it and x-direction THz radiation. Besides, phase difference in two directions is close to $\pi/2$, except at 0 frequency. As a result, the radiated THz wave is elliptically polarized. When the two major axes of the bi-elliptical laser fields are parallel, similar phenomena can be found, too (not shown here). That is to say, BEPTC field with tiny ellipticity can generate THz radiation with high ellipticity, and THz intensity is comparable to that of produced by the LP-P laser field.

3.2.2 Counter-rotating bi-elliptical polarized laser fields with high ellipticity—imperfect CP-C field

For a CP-C driving laser field, it can produce high-ellipticity THz waves, but the intensity of the THz emission is very weak. Tailliez et al [44] has showed that a very small departure from an ideal CP-C configuration, that is, a BEOTC field with high ellipticity may lead to a substantial increase in the THz energy. Here, we give a similar demonstration with BEPTC field. We find that such a small deviation could lead to recovering THz performances comparable with those reached with a LP-P or CP-S field. Figure 10 compares the laser field waveforms, electric currents, and radiated THz spectra of the CP-C and the counter-rotating 800 nm + 400 nm BEPTC laser field with ellipticity $\varepsilon_L = 0.95$. The intensity ratio I_2/I_1 is 12.0 in two cases. At first glance, the difference between two laser waveforms is very small. However, the resulting residual currents and THz intensities are very different in two cases. As shown in Figures 10C, F for the THz spectra, when the laser field changes from CP-C by an ellipticity of 0.05 to the counter-rotating bi-elliptical polarization fields, the intensity of the THz radiated changes by more than ten orders of magnitude. From the comparison of

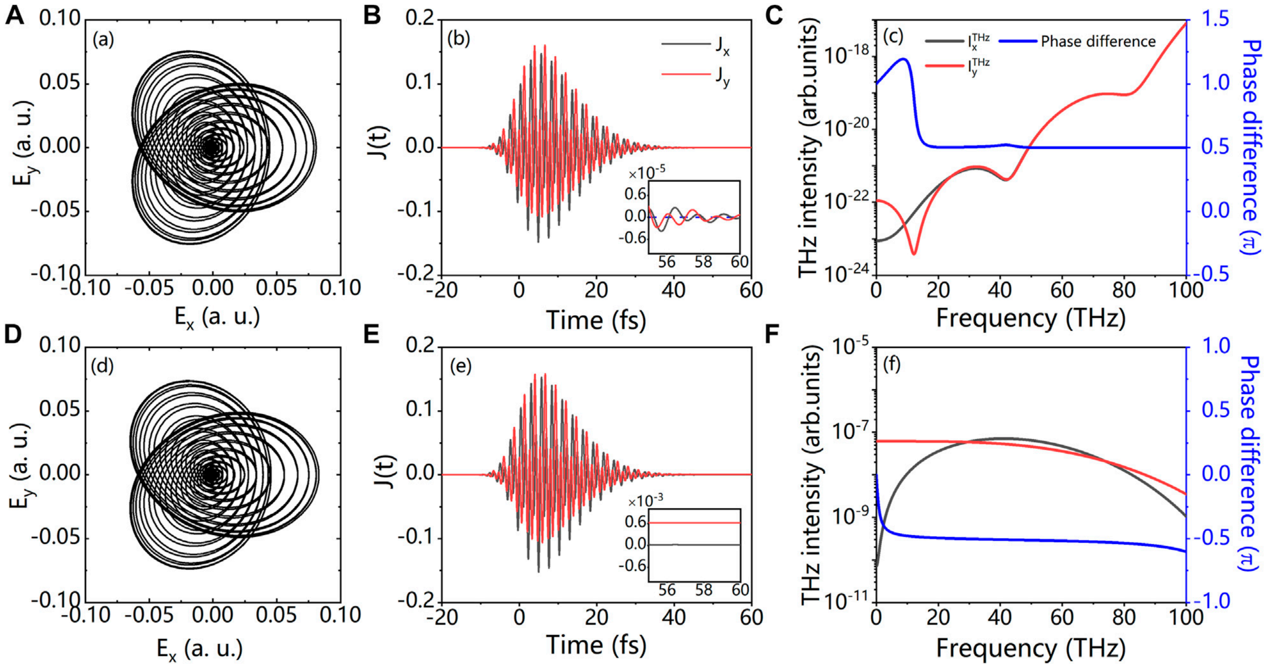

FIGURE 10
Waveforms of laser fields (left column), the electric currents (middle column), and generated THz radiation (right column) for CP-C field (upper row) and counter-rotating BEPTC field with $\varepsilon_L = 0.95$ (lower row).

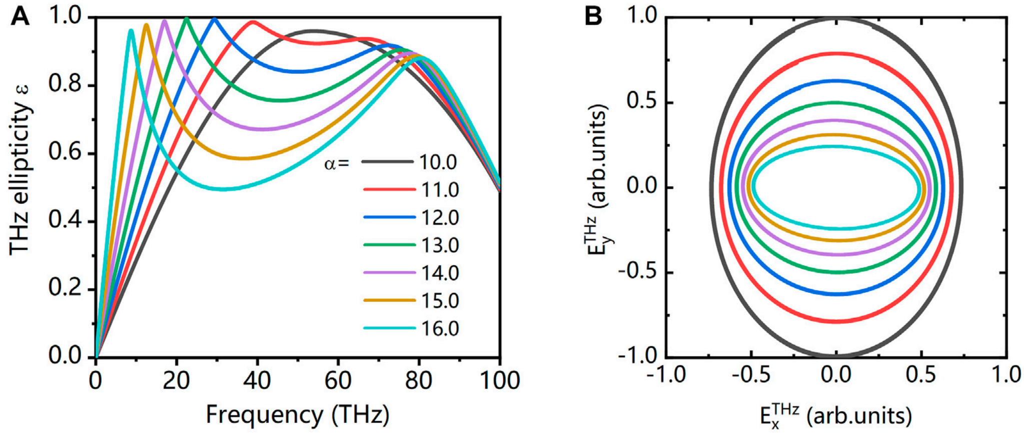

FIGURE 11
(A) The ellipticity of THz waves varies with the intensity ratio α of counter-rotating BEPTC laser fields with $\varepsilon_L = 0.95$ and $\varphi_2 = 0$. **(B)** Corresponding electric field at 30 THz.

photocurrents shown in Figures 10B, E, we know this is mainly due to the increase of net current in y direction in BEPTC field. A convincing explanation for the enhancement of THz radiation with higher frequency is still to be expected.

For the polarization state, Figure 10C indicates that THz radiations above 20 THz are nearly circularly polarized for the CP-C field, while they are elliptically polarized with high ellipticity at most frequencies with elliptical field [Figure 10F]. In Figure 11, we further show that we can control the THz polarization by adjusting the intensity ratio of a counter-rotating bi-elliptical field. Obviously, elliptical and circular THz field can be generated with the optimization.

4 Conclusion

In conclusion, we have shown that the bi-elliptical $\omega + 2\omega$ polarized laser field is a promising driving pulse for THz emission. Based on the photocurrent model, the process of THz radiation produced by bi-elliptical laser fields interacting with gas is simulated. When the laser pulse is long, it can generate nearly linearly polarized THz radiation as strong as those generated with two-color circularly polarized with the same helicity laser fields or parallel linearly polarized laser fields. What's more, elliptically and circularly polarized THz waves can be produced with this kind of driving laser field with appropriate parameters. Compared with other laser fields, bi-elliptical field provides more parameters for the optimal control of THz generation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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