

# A proposed approach for detecting terahertz pulses by using double few-cycle laser pulses with opposite carrier envelope phases

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Previous research shows that few-cycle laser (FCL) pulses with low energy and without a bias field can be used to coherently detect terahertz (THz) pulses. As we know, it is very difficult to stabilize the carrier envelope phase (CEP) of FCL pulses, i.e., there are some random fluctuations for the CEP. Here we theoretically investigate the influence of such instability on the accuracy of THz detection. Our results show that although there is an optimum CEP for THz detection, the fluctuations of the CEP will lead to terrible thorns on the detected THz waveform. In order to solve this problem, we propose an approach using two few-cycle laser pulses with opposite CEPs, i.e., their CEPs are differed by  $\pi$ .

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At present, generation and detection of terahertz (THz) pulses by using laser-induced gas plasma are widely used in the THz field of research<sup>[1-6]</sup>. Thanks to the advent of ultrashort laser pulses with millijoule energy, single-cycle electromagnetic radiation covering the so-called THz gap (0.1–10 THz) and with a MV/cm electric field amplitude, can be obtained from laser-induced gas plasma<sup>[7-11]</sup>. On the other hand, such a gas plasma can also be used as an effective sensor to coherently detect broadband THz waves by “seeing<sup>[10]</sup>” or “hearing<sup>[11]</sup>” the plasma.

For the THz detection process, the ultrashort laser pulses and THz pulses are simultaneously focused in a gaseous medium, so bound electrons in gas molecules (or atoms) are initially stripped off by a laser electric field and form plasma around the focal region. These freed electrons are then accelerated by the electric field of the laser and THz pulses, leading to an oscillating current  $J(t)$ . Using the transient photocurrent (PC) model<sup>[12-16]</sup>, the radiation field from the plasma obeys  $E_{\text{out}} \propto dJ/dt \propto N_e(t)E_{\text{in}}(t)$ , where  $N_e(t)$  is the electron density and  $E_{\text{in}}(t) = E_{\omega_0}(t + \Delta t) + E_{\text{THz}}(t)$ .  $E_{\omega_0}(t + \Delta t)$  and  $E_{\text{THz}}(t)$  are the electric field of the incident laser and THz pulses, respectively, where  $\Delta t$  is the time interval between two such pulses. Measuring the intensities of the second-harmonic (SH) emission from the plasma with respect to  $\Delta t$ , one can obtain the THz pulse<sup>[17,18]</sup>.

For a few-cycle laser (FCL) pulse, the carrier envelope phase (CEP) plays a very important role in gas ionization, electron acceleration, and the subsequent plasma nonlinear emission process<sup>[19-21]</sup>. In 2013, Liu *et al.* proposed a new approach for THz coherent detection based

on an FCL pulse with a fixed CEP and very low laser energies that could be used in remote THz sensing<sup>[22]</sup>.

In the area of ultrafast optics, improving the ability to effectively stabilize the CEP of an FCL pulse is a key subject<sup>[23-25]</sup>. In other words, there are some random fluctuations for the CEP. In principle, the accuracy of THz detection is definitely affected by such an instability. In this Letter, we will numerically investigate this problem and give an approach to solving it. Moreover, an experimental realization is also proposed.

In our simulation, the FCL pulse has a Gaussian formation with a center wavelength  $\lambda_0 = 800$  nm, a full width at half-maximum (FWHM)  $T_{\text{FWHM}} = 6$  fs, a focal beam radius  $w_0 = 10$   $\mu\text{m}$ , and a single pulse energy  $W = 30$   $\mu\text{J}$ . Using a transient PC model, we first calculate the SH intensities  $I_{2\omega_0}^{\omega_0}(\phi_{\text{CEP}}, \Delta t)$  without incident THz waves, as depicted in Fig. 1(a). Next, we obtain the SH intensities  $I_{2\omega_0}^{\omega_0+T}$  with incident THz waves, as shown in Fig. 1(b). By subtracting Fig. 1(a) from Fig. 1(b), one can obtain  $I_{2\omega_0}^T$  versus both  $\phi_{\text{CEP}}$  and  $\Delta t$ , as shown in Fig. 1(c). Extracting four sets of transverse data in Fig. 1(c), we plot four detected THz signals for different  $\phi_{\text{CEP}}$  values [the solid curves in Fig. 1(d)].

To find the optimum CEP for detection when  $W = 30$   $\mu\text{J}$ , we can extract two sets of longitudinal data versus  $\phi_{\text{CEP}}$  ( $\Delta t = -0.068$  ps and 0.124 ps) from Fig. 1(c) and plot two dashed lines in Fig. 1(e). From Fig. 1(e), one can easily find the maximum and minimum of  $I_{2\omega_0}^T$  corresponding to the best ability to resolve the electric-field polarities of the THz waves. In other words, these two

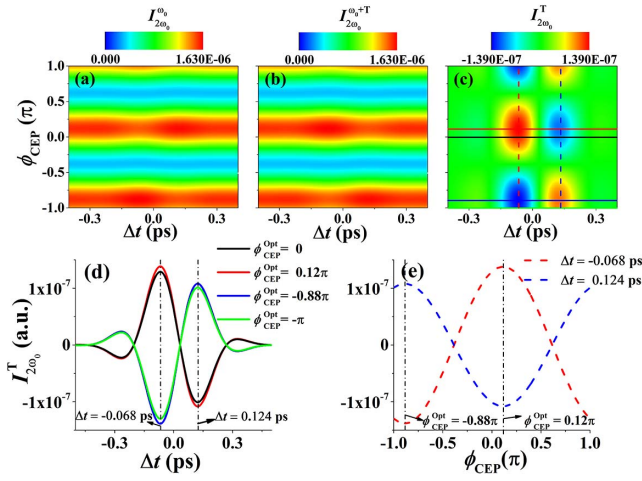


Fig. 1. (a) The calculated SH intensity without the THz field  $I_{2\omega_0}^{0_0}$  as the function of the time interval  $\Delta t$  and the laser pulse  $\phi_{CEP}$  when  $W = 30 \mu\text{J}$ ; (b) the SH intensity with the THz field  $I_{2\omega_0}^{0_0+T}$  versus the CEP and  $\Delta t$ ; (c) the increment of SH intensities due to the THz signals  $I_{2\omega_0}^T$ ; (d) the detected THz signals for different values of CEP; (e) the peak and valley values of the detected THz waveforms versus few-cycle lasers' CEP.

extreme points,  $\phi_{CEP} = 0.12\pi$  and  $-0.88\pi$ , are the best  $\phi_{CEP}$  for an FCL pulse with fixed pulse energy  $W = 30 \mu\text{J}$  to perfectly reproduce a real THz waveform. In what follows, we let  $\phi_{CEP}^{OPT} = 0.12\pi$  in the simulation.

Figure 2(a) plots the evolution of  $I_{2\omega_0}$  with respect to the THz electric field  $E_{THz}$  when the CEPs are chosen to be  $\phi_{CEP}^{OPT}$ ,  $\phi_{CEP}^{OPT} - \pi/4$ ,  $\phi_{CEP}^{OPT} - \pi/2$ ,  $\phi_{CEP}^{OPT} - 3\pi/4$ , and  $\phi_{CEP}^{OPT} - \pi$ , respectively. Performing the simple calculations  $I_{2\omega_0}(\phi_{CEP}^{OPT}) - I_{2\omega_0}(\phi_{CEP}^{OPT} - \pi)$  and  $I_{2\omega_0}(\phi_{CEP}^{OPT} - \pi/4) - I_{2\omega_0}(\phi_{CEP}^{OPT} - 3\pi/4)$ , respectively, we find that the results of the subtractions are linearly dependent on  $E_{THz}$ , as shown in Fig. 2(b). As mentioned earlier, the radiation field from plasma obeys  $E_{out} \propto dJ/dt \propto N_e(t)E_{in}(t)$ , where  $E_{in}(t) = E_{\omega_0}(t + \Delta t) + E_{THz}(t)$ . Therefore the intensities of radiation  $I_{2\omega_0}^{0_0+T}(\Delta t)$  can be written as

$$\begin{aligned} I_{2\omega_0}^{0_0+T}(\Delta t) &\propto E_{out}^2 \propto N_e^2(t)E_{in}^2, \\ &= N_e^2(t)[E_{\omega_0}(t + \Delta t) + E_{THz}(t)]^2, \\ &= N_e^2(t)[E_{\omega_0}^2(t + \Delta t) + E_{THz}^2(t) \\ &\quad + 2E_{\omega_0}(t + \Delta t)E_{THz}(t)]. \end{aligned} \quad (1)$$

In the last item  $2N_e^2(t)E_{\omega_0}(t + \Delta t)E_{THz}(t)$  in Eq. (1) THz information can be encoded into  $I_{2\omega_0}^{0_0+T}$ [26]. For simplicity, we let  $\Delta t = 0$ , i.e., the zero delay between the laser and the THz pulse. Substituting  $E_{\omega_0}(t) = E_0(t) \cos(\omega_0 t + \phi_{CEP}^{OPT})$  and  $E_{\omega_0}(t) = E_0(t) \cos(\omega_0 t + \phi_{CEP}^{OPT} - \pi)$  into Eq. (1), respectively, and after some simple algebraic derivations, one can obtain

$$\begin{aligned} I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT}) - I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT} - \pi) \\ \propto 4N_e^2(t)E_0(t) \cos(\omega_0 t + \phi_{CEP}^{OPT})E_{THz}(t), \end{aligned} \quad (2)$$

which shows that  $I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT}) - I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT} - \pi)$  is linearly dependent on  $E_{THz}$ . Similarly, one can also obtain

$$\begin{aligned} I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT} - \pi/4) - I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT} - 3\pi/4) \\ \propto 2\sqrt{2}N_e^2(t)E_0(t) \cos(\omega_0 t + \phi_{CEP}^{OPT})E_{THz}(t), \end{aligned} \quad (3)$$

which shows that  $I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT} - \pi/4) - I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT} - 3\pi/4)$  is also linearly dependent on  $E_{THz}$ , and it is  $\sqrt{2}/2$  times the value of  $I_{2\omega_0}(\phi_{CEP}^{OPT}) - I_{2\omega_0}(\phi_{CEP}^{OPT} - \pi)$ . Note that we assume that  $E_{THz}$  has no contribution to  $N_e(t)$ , since it is too weak to strip off the bounded electrons.

In practice, the instability of the CEP for FCL pulses is unavoidable. Next, we will investigate how it affects the accuracy of THz detection. Assuming the amount of the CEP's random fluctuations is one percent of  $\phi_{CEP}^{OPT}$ , we re-calculate the SH intensities  $I_{2\omega_0}^T$ , shown in the black curve ( $\phi_{CEP}^{OPT}$ ) and red curve ( $\phi_{CEP}^{OPT} - \pi$ ) in Fig. 3(a), on which a few thorns appear. If the amount is raised to be five percent of  $\phi_{CEP}^{OPT}$ , the fluctuations of the CEP will lead to terrible thorns on the detected THz waveforms, as shown in Fig. 3(d). Thus, a single few-cycle laser with an unstable CEP could not be used to detect THz waves perfectly.

Linear dependence, i.e., Eq. (2), enlightens us to resolve this problem. The results of  $I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT}) - I_{2\omega_0}^{0_0+T}(\phi_{CEP}^{OPT} - \pi)$  are plotted in Figs. 3(b) and 3(e), respectively. Although the thorns still exist, their scale is significantly reduced. Using a Fourier transform, we obtain the spectra of the detected THz waveforms [see Figs. 3(c) and 3(f)], which also demonstrate the feasibility of our method.

Based on these simulation results, we propose an experimental scheme, as shown in Fig. 4. Two collinear few-cycle laser pulses ( $\omega_0$ ), whose CEPs differ by  $\pi$ [27,28], are alternately focused into gas to generate the plasma, meanwhile the THz waves are impinged on the plasma.

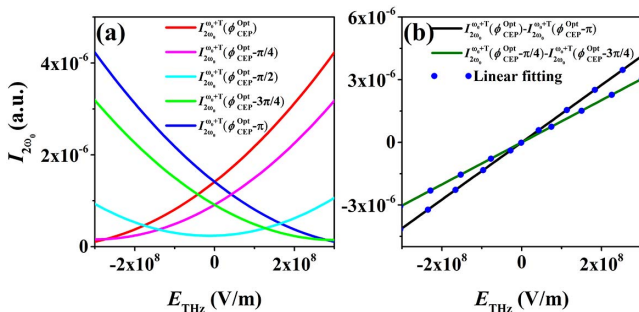


Fig. 2. (a) Dependence of SH signal intensity on the THz pulse peak field with probe pulses of some special CEP points relative to the optimum one. (b) The subtraction results of the curves in (a).

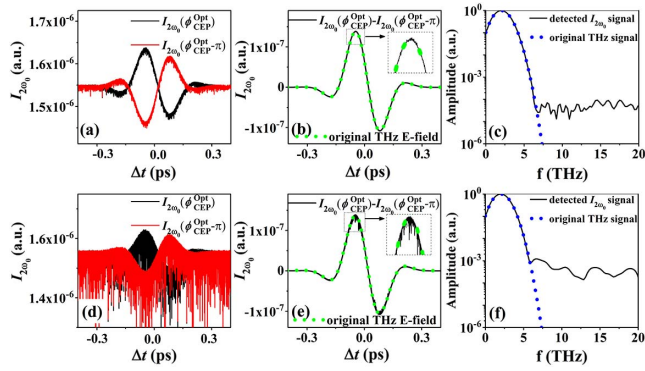


Fig. 3. (a) The THz SH signal waveforms detected by probe pulses when the amount of fluctuations is 1% of  $\phi_{\text{CEP}}^{\text{OPT}}$ ; (b) the difference signal waveform and the original THz waveform; (c) the THz spectrum from the Fourier transform of the THz waveforms in (b); (d) the THz SH signal waveforms detected by the probe pulses when the amount of fluctuations is 5% of  $\phi_{\text{CEP}}^{\text{OPT}}$ ; (e) the difference signal waveform and the original THz waveform; (f) the THz spectrum from the Fourier transform of THz waveforms in (e).

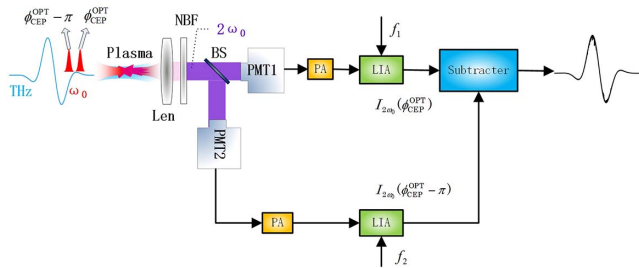


Fig. 4. Proposed experimental scheme for the coherent detection of a THz pulse via using two few-cycle laser pulses.

The generated SH signals ( $2\omega_0$ ) are collected by two lenses. A narrowband filter (NBF) is used to isolate the residual  $\omega_0$  laser beam and the other emissions from the plasma. Then the SH signal is separated into two beams by a beam splitter (BS) and detected by two photomultiplier tubes (PMTs), respectively. The small signals are first amplified by preamplifiers (PAs) and input into the lock-in amplifier (LIA). In order to distinguish the colinear detected  $I_{2\omega_0}(\phi_{\text{CEP}}^{\text{OPT}})$  and  $I_{2\omega_0}(\phi_{\text{CEP}}^{\text{OPT}} - \pi)$ , one can set two chopping frequencies for the two incident FCL pulses, i.e.,  $\phi_{\text{CEP}}^{\text{OPT}}$  is  $f_1$  and  $\phi_{\text{CEP}}^{\text{OPT}} - \pi$  is  $f_2$ . By inputting  $f_1$  and  $f_2$  into the two LIAs as trigger signals, the different SH signals can be detected<sup>[18]</sup>. Finally, the two detected SH signals are input into a subtractor, and the THz waveforms are obtained.

In conclusion, we propose an approach to eliminate the influence of the CEP's instability on THz detection via using two FCL pulses with opposite CEPs.

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