Front. Optoelectron. 2018, 11(4): 407–412
https://doi.org/10.1007/s12200-018-0845-6

RESEARCH ARTICLE

Proposal for CEP measurement based on terahertz air photonics

Kejia WANG, Xinyang GU, Jinsong LIU, Zhengang YANG, Shenglie WANG (✉)

Wuhan National Laboratory for Optoelectronics, School of Optical and Electronic information,
Huazhong University of Science and Technology, Wuhan 430074, China

Abstract Single-shot carrier envelope phase (CEP) measurement is a challenge in the research field of ultrafast optics. We theoretically investigate how an intense terahertz pulse modulates second harmonic emission (SH) from a gas plasma induced by a few-cycle laser pulse (FCL). Results show that the modulation quantity of SH intensity has a cosinoidal dependence on the CEP of FCL pulses, based on which we propose a low energy, all-optical method for single-shot CEP measurements via using a known intense terahertz pulse. Moreover, we propose an experimental realization.

Keywords ultrafast measurements, far-infrared or terahertz, ultrafast nonlinear optics, harmonic generation and mixing

1 Introduction

Terahertz (THz) air photonics is one of the most active research areas in THz science during the past two decades, including of generation and detection of ultra-broadband intense THz waves by using laser-induced gas-plasma [1–17]. Recent advances of laser technology have made it possible to generate high-power laser pulses with the duration approaching a single optical cycle, i.e., few-cycle laser (FCL) pulses [18–20]. Thus the emergence of such ultra-short pulse, to our knowledge, leads to the generation of THz waves whose peak electric field strengths exceed a few of MV/cm [16]. Meanwhile, the bandwidth of detected THz pulses reaches from 0.1 to 200 THz via measuring the second harmonic (SH) radiation from the gas-plasma [13]. In 2013, Liu et al. propose an approach for THz coherent detection via using FCL pulse with very low laser energies [15]. Specifically, the SH intensity emitted from the gas plasma can well replicate THz waveform if the laser pulse has a fixed carrier envelope phase (CEP). Here an inverse question emerges: if the detailed information of THz waveform is given, can this fixed CEP of FCL pulse be identified?

In the research field of ultrafast optics, improving the ability to effectively measure and stabilize the CEP of FCL pulse is a key subject [21–24]. Current widely used method is the in-loop f-to-2f interferometer [21]. Alternatively, quantum interference in photocurrents and linear optical interferometry are also invented to derive the CEP's evolution [22,23]. However, the CEP measured by these systems is not a real value but its relative change. In addition, all of these methods are not single-shot measurements. In other words, a large number of laser shots are needed to obtain a single measurement value of the CEP. In 2009, Wittmann et al. performed a single-shot CEP measurement called stereo ATI. By detecting photoelectrons in opposing directions parallel to the polarization of the FCL and comparing their left–right asymmetries at different energies, they can retrieve the real value of CEP without any phase ambiguity [24]. Enlightened by the thought in this work, we propose an all-optical approach for single-shot CEP measurements based on THz air photonics, i.e., retrieving the real values of CEP of consecutive non-phase-stabilized pulses. An experimental realization about our approach will be also proposed.

2 Simulation results and discussion

First, we need introduce three kinds of symmetries between the FCL pulses with different CEP. The electric field of a linearly polarized FCL reads $E_{\omega_0}(t) = E_0(t)\cos(\omega_0 t + \phi_{\mathrm{CEP}})$, where ω_0 is the angular frequency of carrier wave, $E_0(t)$ is supposed to be a Gaussian

Received June 25, 2018; accepted August 10, 2018

E-mail: wsl@excellaser.com.cn

envelope function, and ϕ_{CEP} is CEP. Figures 1(a) – 1(e) plot the electric field of FCL pulses with different CEP. Pulses with $\phi_{CEP} = 0$ and π have maximum electric field strength at $t = 0$ and are asymmetric along the positive and negative directions, respectively, while pulses with $\phi_{CEP} = \pm\pi/2$ have two smaller field peaks with opposite sign and retain the field orientation symmetry, as shown in Figs. 1(a) and 1(b). For $\phi_{CEP} = \pi/4$ and $-\pi/4$ (see Fig. 1(c)), the electric field $E_{\omega_0}(t) = E_{\omega_0}(-t)$, implying a time reversal symmetry (TRS). Figure 1(d) gives the polarity reversal symmetry (PRS), i.e., such illustrated two pulses have the same electric field strength distribution but opposite sign. Center symmetry (CS), seeing Fig. 1(e), can be interpreted as a symmetry after a successive time and polarity reversal, i.e., CS = TRS + PRS. Previous research shows that two pulses with one of these three symmetries will usually yield the same electron and harmonic emission, making it difficult to determine the values of CEP [18–20].

Using well-developed photocurrent (PC) model [5,7], we numerically investigate how the FCLs with different CEP influence the SH intensity, see Fig. 2. The simulation parameters can be found in Ref. [15]. Comparing two curves in Fig. 2(a), one can clearly see that THz field effectively modulate the SH intensity. When a strong THz pulse is simultaneously incident on the plasma with a fixed time interval with respect to the FCL pulse, the dependence of SH emission intensity on CEP will be changed (see the blue curve in Fig. 2(a)). Note that this strong THz field can be regarded as static field with a particular polarity since the THz wave pulse width is much longer than that of the FCL pulses. To further manifest the modulation of THz field, we introduce a quantity $\Delta I_{2\omega_0} = I_{2\omega_0}^{\omega_0+T} - I_{2\omega_0}^{\omega_0}$, and plot it versus CEP in Fig. 2(b). When the absolute values of CEP are smaller than $\pi/2$, THz waves enhance the SH intensity. For $|\phi_{CEP}|>\pi/2$, $\Delta I_{2\omega_0}$ is decreased. Fitting calculation shows that $\Delta I_{2\omega_0}$ has a cosinoidal dependence on the CEP, implying that the absolute value (not the real value) of CEP can be retrieved if $\Delta I_{2\omega_0}$ is measured.

To distinguish the contributions from the positive or negative electric field of a FCL pulse, a polarized ionization rate $r(t)$ is defined, i.e., $r(t) = \mathrm{d}N_e/\mathrm{d}t \times E_{\omega_0}/|E_{\omega_0}|$, N_e is the electron density that can be calculated by static tunneling (ST) model [7]. Figures 3(a) and 3(b) show the time dependence of $r(t)$ with and without a positive 1 MV/cm THz field E_T applied on the gas target for $\phi_{CEP} = 0$, π and $\pm\pi/2$, respectively. For FCL pulses with $\phi_{CEP} = 0$, as shown in the insets of Fig. 3(a), the positive polarized electric field contributes more to gas ionization processes than the negative field, while $\phi_{CEP} = \pi$ is on the contrary. So the total increment of SH intensities has a positive extremum for $\phi_{CEP} = 0$ and negative extremum for $\phi_{CEP} = \pi$ (see Fig. 2(b)), showing that the THz field breaks PRS of FCL pulses. As a result, $\phi_{CEP} = 0$ and $\phi_{CEP} = \pi$ can be retrieved. However, for FCL pulses with $\phi_{CEP} = \pm\pi/2$, i.e., TRS pulses, $r(t)$ has same incremental quantity but with opposite sign for positive and negative field of FCL due to the presence of THz fields, as shown in Fig. 3(b). So the TRS of FCL is not broken since they have the same asymmetry and equal THz increment, leading to that $\phi_{CEP} = \pm\pi/2$ cannot be resolved (see Fig. 2(b)). Since CS is a successive action of PRS and TRS, the real values of CEP with CS cannot be also retrieved.

Actually, the situation similar to our results, i.e., two pulses with TRS cannot be resolved, is also appeared in

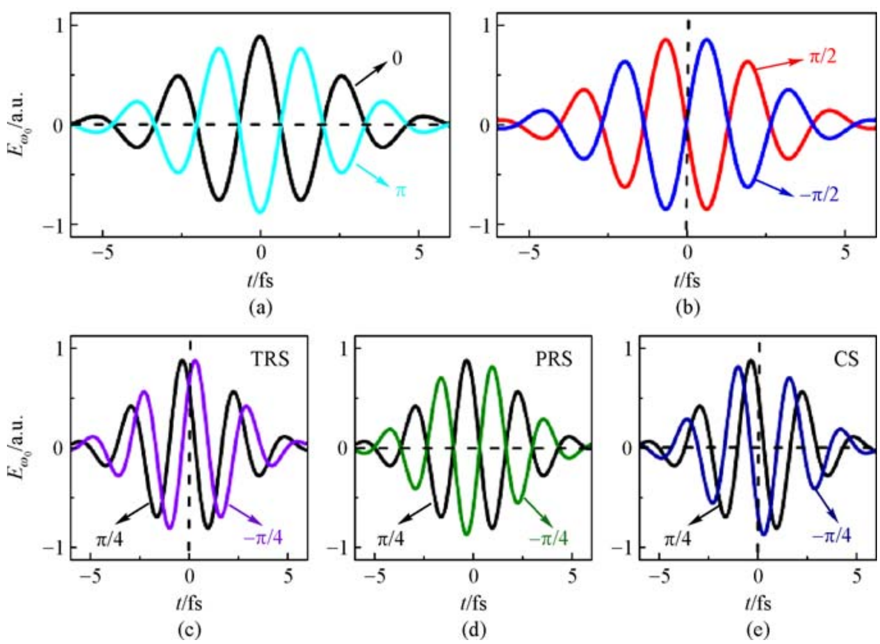

Fig. 1 (a) and (b) Time variation of the electric field of the FCL pulses with $\phi_{CEP} = 0$, π, $\pm\pi/2$, respectively; (c)–(e) illustrations of the symmetries between FCL pulses with different CEP

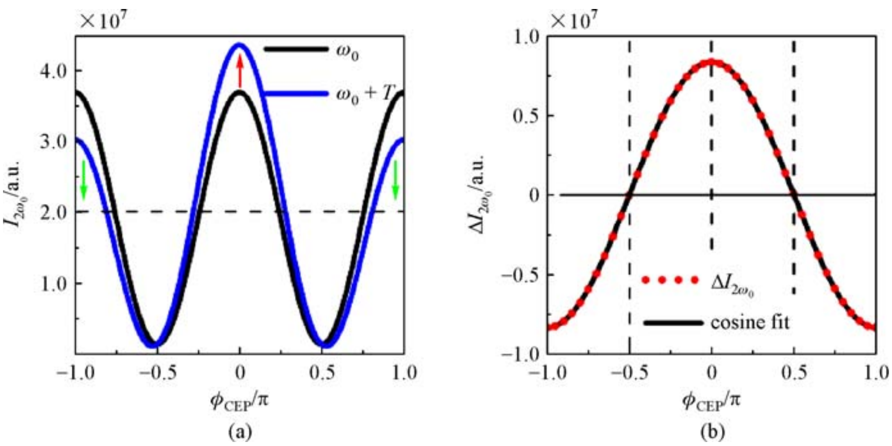

Fig. 2 (a) Dependence of the SH emission intensity on the CEP with and without intense THz pulse irradiation; (b) $\Delta I_{2\omega_0}$ versus CEP

Ref. [24]. To solve this problem, another FCL pulse with a fixed phase shift ϕ_S to the former one is introduced. Referring to this idea, we also introduce another FCL pulse which has shift ϕ_S with respect to that of $E_{\omega_0}(t)$, i.e., $E'_{\omega_0}(t) = E_0(t)\cos(\omega_0 t + \phi_{CEP} + \phi_s)$. To elucidate how to break the TRS, a value of $\phi_S = \pi/4$ is chosen to be an example to distinguish pulses with $\phi_{CEP}= +\pi/2$ and $-\pi/2$. Note that the CEP of $E'_{\omega_0}(t)$ corresponding to former $E_{\omega_0}(t)$ with $+\pi/2$ ($-\pi/2$) is changed to be $+3\pi/4$ ($-\pi/4$) now. It is cleared that the former symmetric $r(t)$ with $\phi_{CEP} = \pm\pi/2$ become negative and positive asymmetric, respectively, as illustrated by the arrows in Fig. 4 (a). Further calculation shows that $\Delta I^T_{2\omega_0}$ is not symmetric about the axis $\phi_{CEP} = 0$, showing that one value of $\Delta I^T_{2\omega_0}$ correspond to two CEP with different absolute values (green line in Fig. 4(b)), instead of former same absolute values (black line in Fig. 4(b)). Therefore, the three asymmetries have been broken, enabling a determination of CEP in the full 2π range without ambiguity.

3 A proposed experimental realization

Here we propose an experimental realization, illustrated in Fig. 5(a), to elucidate our approach to measure the real values of CEP. Four detectors (D1 – D4, e.g., photomultiplier tube) are used to measure intensities of SH signals emitted from four gas plasma. Narrow band filter (BNF) is used to block residual FCL and THz waves. Note that four FCLs can be obtained from one laser pulses via using beam splitters. Two fully known intense THz waves are impinged on two gas plasma to modulate the SH signals. The FCLs in C1 and C2 correspond to $E_{\omega_0}(t)$ and $E'_{\omega_0}(t)$, respectively. The shift ϕ_S between $E_{\omega_0}(t)$ and $E'_{\omega_0}(t)$ can be controlled by using a pair of glass wedges [25,26]. To ensure the identical spatial distributions of four plasmas, the lens in front of plasmas must be placed precisely by observing plasmas through CCD camera or microbolometer camera.

We assume that the FCL pulses are generated from a

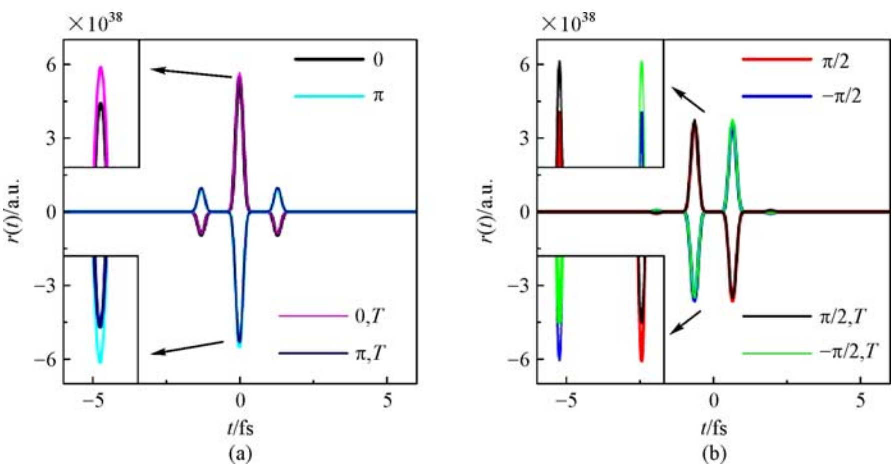

Fig. 3 Time dependence of polarized ionization rates $r(t)$ for the gas plasma induced by FCL pulses without and with a THz field of 1 MV/cm (denoted by *T*) for (a) $\phi_{CEP} = 0$, π and (b) $\pm\pi/2$

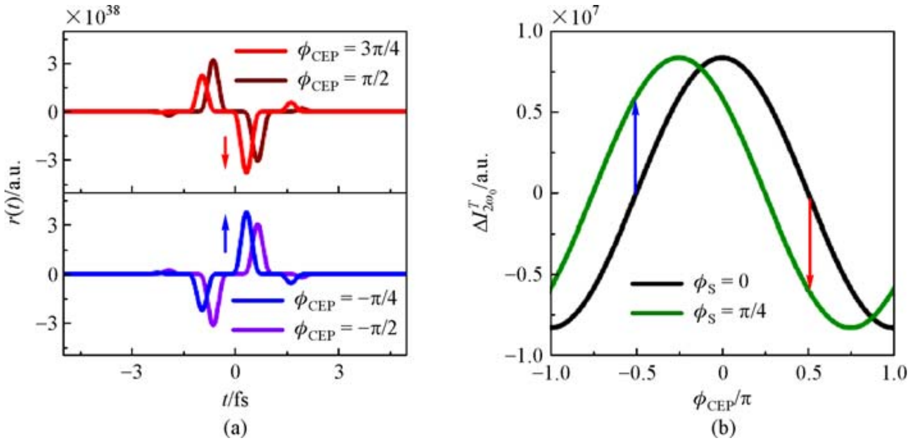

Fig. 4 (a) Time dependence of $r(t)$ for $\phi_{CEP} = \pm\pi/2$ (brown and purple line) and those with a fixed phase shift $\phi_S = \pi/4$ (red and blue line); (b) THz field-induced SH increment $\Delta I^T_{2\omega_0}$ versus the CEP for $\phi_S = 0$ (black line) and $\pi/4$ (green line)

non-phase-stabilized FCL. As also performed in Ref. [24], we can map the CEP of consecutive laser shots on a parametric plot in which the axes are $\Delta I_{2\omega_0}$ and $\Delta I'_{2\omega_0}$, respectively. In this representation, the CEP of each shot can be mapped to one point on the plot. Let's take $\phi_S = \pi/4$ again as an example, calculation results show that a large number of shots will form an oblique elliptic curve, as depicted in Fig. 5(b). Since the horizontal axis is the parameter derived from Cl, i.e., $\Delta I_{2\omega_0}$, the rightmost point represents $\phi_{CEP} = 0$. The leftmost point corresponds to $\phi_{CEP} = \pi$. Considering that $\Delta I'_{2\omega_0}$ is obtained from C2 corresponding to $\phi_S = \pi/4$ shift, the points $\phi_{CEP} = \pm\pi/2$, $\pm\pi/4$ and $\pm 3\pi/4$ are easily identified by referring to the black curve in Fig. 4(b). Other CEP points fall among these special points. For a single shot pulse, once the two signals from the two channels are obtained, i.e., $\Delta I_{2\omega_0}$ and $\Delta I'_{2\omega_0}$, the absolute value of CEP can be calculated according to the cosine relation, $|\phi_{CEP}| = \arccos[\Delta I_1/\Delta I_1(\phi_{CEP} = 0)]$ according to Fig. 2(b). If $0 \leqslant |\phi_{CEP}| < \pi/2$ and $\Delta I'_{2\omega_0} < \Delta I'_{2\omega_0}(\phi_{CEP} = 0)$, as shown in Fig. 5(b), we can derive $\phi_{CEP} = |\phi_{CEP}|$, else $\phi_{CEP} = -|\phi_{CEP}|$. Similarly, the sign of CEP for $\pi/2 < |\phi_{CEP}| \leqslant \pi$ can be recognized by comparing $\Delta I'_{2\omega_0}$ and $-\Delta I'_{2\omega_0}(\phi_{CEP} = 0)$. In this way, the CEP of a single shot can be retrieved without ambiguity. Figure 5(c)

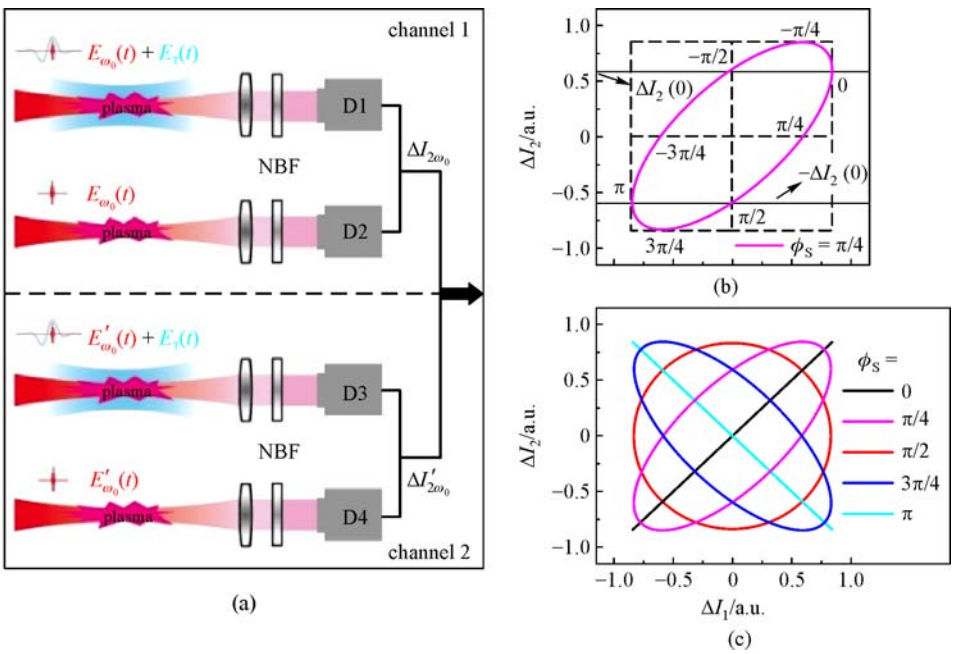

Fig. 5 (a) Experimental realization for our proposed single-shot CEP measurement method; (b) and (c) distributions of a large number of shots from a non-phase-stabilized laser depicted on a two-dimensional parametric plot with THz field-induced increment signals from channel 1 (C1) and channel 2 (C2) for the horizontal and vertical axes, respectively

shows parametric plots for other values of ϕ_S. Since a circular curve is more convenient for the determination of the CEP, we suggest that ϕ_S should be set around $\pi/2$.

4 Conclusion

In conclusion, a method for single-shot CEP measurements is proposed. By detecting the intense THz pulse-induced SH emission increment and adding a similar signal channel, all symmetries between FCL pulses can be broken. Thus the CEP of a single-shot FCL pulse can be retrieved without ambiguity. Our proposed method is all-optical and easily implemented at ambient conditions with only a small fraction of the FCL energy. Although the key physical processes associated with the proposed method have been discussed, other problems such as nonlinear diffraction and propagation phenomena still need to be discussed further, which should use a higher dimensional model. In addition, some technical issues such as signal-to-noise ratio and detection precision and accuracy also need to be addressed in the future.

Acknowledgements We acknowledge the support from the National Natural Science Foundation of China (Grant Nos. 61475054 and 11574105), Fundamental Research Funds for the Central Universities (No. 2017KFYXJJ029). KJ Wang thanks Dr. Hu Wang for his previous calculation about this work.

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Kejia Wang received the B.S. degree in optical engineering from Huazhong University of Science and Technology (HUST) in 2001, and the M.S. degree in physical electronics from HUST in 2004. He received the Ph.D. degree in electronic science and technology from HUST in 2007. He is an associate professor at the Wuhan National Laboratory for Optoelectronics (WNLO), HUST. His research is in the area of terahertz optoelectronics.

Xinyang Gu received the B.S. degree in optoelectronics information engineering from Huazhong University of Science and Technology (HUST) in 2014. He is working toward his Ph.D. degree in Wuhan National Laboratory for Optoelectronics (WNLO), HUST. His research is in the area of air photonic terahertz generation and detection.

Jinsong Liu received the B.S. degree in physics from North-west University in 1982, and the M.S. degree in physical electronics from Xidian University in 1984. He received the Ph.D. degree in physical electronics from Xidian University in 1996. He is a professor at the Wuhan National Laboratory for Optoelectronics (WNLO), Huazhong University of Science and Technology (HUST). His research is in the area of terahertz optoelectronics.

Zhengang Yang received the B.S. degree in optoelectronic from Huazhong University of Technology in 2000, and the M.S. degree in optical engineering from Huazhong University of Science and Technology (HUST) in 2003. He received the Ph. D. degree in optical engineering from HUST in 2007. He is a lecturer at the Wuhan National Laboratory for Optoelectronics (WNLO), HUST. His research is in the area of terahertz optoelectronics.

Shenglie Wang received the B.S. degree in optics and laser from Huazhong University of Science and Technology (HUST) in 1988, and the M.S. degree in optics from Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences in 1991. He received the Ph.D. degree in electronic science and technology from HUST in 2012. He is an associate professor in the School of Optical and Electronic Information, HUST. His research is in the area of terahertz wave generation and detection.