Carrier-envelope phase of single-cycle pulses generated through two-color laser filamentation

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Abstract: Carrier-envelope phase (CEP) control of the pulses from two-color filamentation has been investigated. The CEP variation with the relative phase between the two-color pulses is explained with a four-wave mixing model.

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Passive stabilization of the carrier-envelope phase (CEP) of few-cycle pulses by the use of difference frequency generation (DFG) is a key technology for frequency comb and attosecond science [1, 2]. The CEP control at the passive stabilization scheme can be done by manipulating the relative phase between the two input pulses for the DFG. Similarly, the CEP of the ultrashort terahertz (THz) or mid-infrared (MIR) pulses generated through two-color laser filamentation is also passively stabilized. In this contribution, we report how the CEP of the single-cycle pulses generated through two-color laser filamentation is determined.

There are two basic physical models to explain the THz or MIR generation through two-color laser filamentation. The one is based on four-wave difference frequency generation (FWDFG) of the two-color input pulses and the other is a photocurrent model that accounts for electron motion in the two-color input field [3]. Here we use an one-dimensional plane wave model of the FWDFG. Assuming that the two complex input electric fields are $E_1(t) = \mathscr{E}_1(t)\exp(i\omega_1 t + i\phi_1)$ and $E_2(t) = \mathscr{E}_2(t)\exp(i\omega_2 t + i\phi_2)$, the nonlinear polarization for the process, $P_{\rm NL}(t)$, can be written as

$$P_{\rm NL}(t) \propto E_1^2(t)E_2^*(t) = \mathscr{E}_1^2(t)\mathscr{E}_2^*(t)\exp\big(i(2\omega_1-\omega_2)t + i(2\phi_1-\phi_2)\big) = \mathscr{P}_{\rm NL}(t)\exp(i\omega_0 t + i\Delta\phi) \tag{1}$$

where $\mathscr{P}_{\rm NL}(t)$ is the envelope of $P_{\rm NL}(t)$, $\omega_0 = 2\omega_1 - \omega_2$, and $\Delta\phi = 2\phi_1 - \phi_2$. Assuming that $\ddot{P}_{\rm NL}(t)$ is the far-field source, the generated field, $E_0(t)$, can be written as

$$E_0(t) \propto \ddot{P}_{\rm NL}(t) = \big(\ddot{\mathscr{P}}_{\rm NL}(t) + i2\omega_0\dot{\mathscr{P}}_{\rm NL}(t) - \omega_0^2\mathscr{P}_{\rm NL}(t)\big)\exp(i\omega_0 t + i\Delta\phi). \tag{2}$$

When the variation of the envelope of the FWDFG signal is faster than the difference of the two input frequencies, namely, $\ddot{\mathscr{P}}_{\rm NL}(t) \gg \omega_0\dot{\mathscr{P}}_{\rm NL}(t) \gg \omega_0^2\mathscr{P}_{\rm NL}(t)$, the real field of the FWDFG reduces to $\ddot{\mathscr{P}}_{\rm NL}(t)\cos\Delta\phi$. As a result,

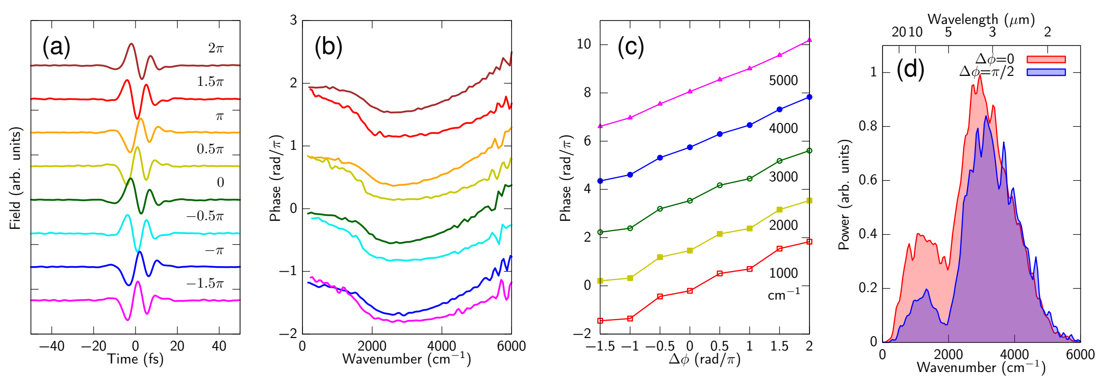

Fig. 1. (a) Waveforms and (b) spectral phases of the generated MIR pulses at each relative phase of the input pulses, respectively. (c) The relative phase dependence of the phases of the MIR pulses for each frequency component. (d) The power spectra of the generated MIR pulses.

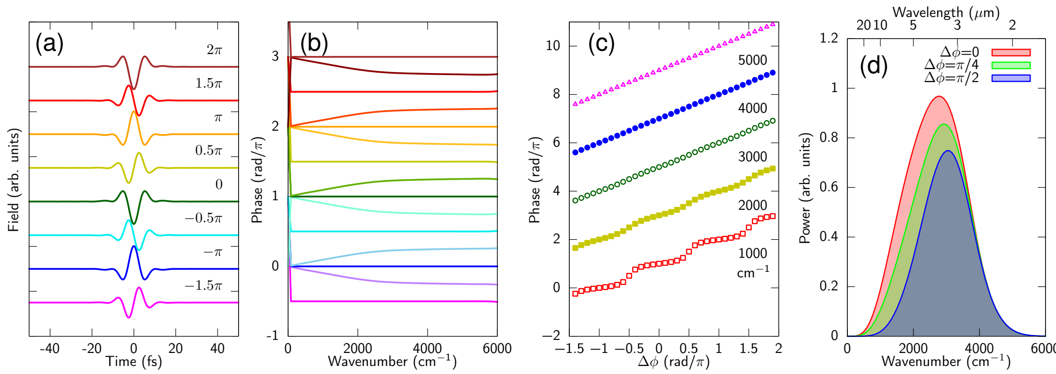

Fig. 2. Results of the numerical simulations. (a) Waveforms and (b) spectral phases of the generated MIR pulses at each relative phase of the input pulses, respectively. (c) The relative phase dependence of the phases of the MIR pulses for each frequency component. (d) The power spectra of the MIR pulses.

$\Delta\phi$ does not contribute to the phase but to the amplitude of the output field. On the other hand, when the variation of the envelope of the FWDFG signal is slower than the difference of the two input frequencies, namely, $\ddot{\mathscr{P}}_{\rm NL}(t) \ll \omega_0 \dot{\mathscr{P}}_{\rm NL}(t) \ll \omega_0^2 \mathscr{P}_{\rm NL}(t)$, the real output field of the FWDFG can be written as $\omega_0^2 \mathscr{P}(t)\cos(\omega_0 t + \Delta\phi + \pi/2)$. In this case, the CEP of the field is $\Delta\phi + \pi/2$, which means that the relative phase between the two input pulses directly affect the CEP of the output pulse.

To experimentally investigate the CEP variation, we generated phase-stable MIR pulses through two-color laser filamentation in nitrogen [4] and characterized the pulse including its CEP information by using FROG capable of CEP determination (FROG-CEP) [5]. Figure 1(a) and (b) shows waveforms and spectral phases of the MIR pulses at different relative phases of the input pulses, respectively. Figure 1(c) shows phase change for each frequency components of the MIR pulses. The phase of the high frequency components (ω_0 >3000 cm^{-1}) changes continuously and linearly with respect to the relative phase. On the other hand, the phase of the low frequency components (ω_0 <3000 cm^{-1}) changes by 0 or π like a step function, which means that $\Delta\phi$ basically affect only the amplitude. The π phase jump means that only the sign of the amplitude (the sign of $\cos\Delta\phi$) changes. Figure 1(d) shows the power spectrum of the MIR pulse. The $\Delta\phi$ dependence is stronger for low frequency components (<2500 cm^{-1}) whereas the high frequency components (<2500 cm^{-1}) are much less sensitive to $\Delta\phi$.

We have also performed numerical simulations for the MIR pulses generated through two-color laser filamentation. The simulations are based on the above mentioned simple theory. The input electric fields were calculated from the fourier-transform of the spectra of the two-color pulses after the filamentation. We assumed no chirp for the both pulses in the simulation. Figure 2 shows the results of the numerical simulations. The stepwise variation of the phase and the phase dependence of the power spectrum is clearly reproduced with the simulations (see Fig. 2(c) and (d)).

At the conference, we plan to show the simulation results based on the photocurrent model and discuss the detail of the physics behind the phase variation.

References

1. A. Baltuška, T. Fuji, and T. Kobayashi, "Controlling the carrier-envelope phase of ultrashort light pulses with optical parametric amplifiers," Phys. Rev. Lett. **88**, 133,901 (2002).
2. G. Cerullo, A. Baltuška, O. D. Muecke, and C. Vozzi, "Few-optical-cycle light pulses with passive carrier-envelope phase stabilization," Laser Photon. Rev. **5**, 323–351 (2011).
3. M. D. Thomson, M. Kress, T. Loeffler, and H. G. Roskos, "Broadband THz emission from gas plasmas induced by femtosecond optical pulses: From fundamentals to applications," Laser Photon. Rev. **1**, 349–368 (2007).
4. T. Fuji and Y. Nomura, "Generation of phase-stable sub-cycle mid-infrared pulses from filamentation in nitrogen," Appl. Sci. **3**, 122–138 (2013).
5. Y. Nomura, H. Shirai, and T. Fuji, "Frequency-resolved optical gating capable of carrier-envelope phase determination," Nat. Commun. **4**, 2820 (2013).