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Ultrashort optical pulse synthesis based on a two-step phase-amplitude hybrid algorithm

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Ultrashort optical pulses with user-desired temporal waveforms are widely applied in the areas of laser control and optical communication. In this paper, by combining the phase iteration and amplitude iteration, a two-step phase-amplitude hybrid algorithm for ultrashort optical pulse synthesis is proposed. Effectiveness of this proposed algorithm is proved by synthesizing two types of ultrashort optical pulses, including a single pulse with different temporal waveforms and a train of pulses with variable intensity envelopes. Compared with the conventional phase-only algorithm, the phase-amplitude hybrid algorithm can effectively reduce the influence of falling into local optimal solution caused by inappropriate initial chosen phase, thus achieving a better accuracy for synthesized pulses.

Keywords: ultrashort optical pulse, pulse synthesize, hybrid algorithm.

1. Introduction

As the development of laser technology, ultrashort pulses with the time scales of below picosecond have been generated and widely applied in many fields. However, the pulse shapes delivered by most lasers are usually fixed, such as Gaussian or Secant shapes [1], which are not suitable for some special applications. For example, triangular pulses are required for optical signal doubling [2], while flat-top rectangular pulses show more advantageous for all-optical sampling [3]. Therefore, manipulating the temporal profile of optical pulses in simple and efficient ways to obtain the user-desired pulse shapes has always been of interest for researchers in the areas of laser control and optical communication [4-5].

Based on their working principles, the methods for synthesizing an ultrashort optical pulse can generally be divided into three categories, including direct time-domain, frequency-to-time mapping and Fourier-transform. By designing versatile photonic differentiator [6] or time-delay optical integrator [7], optical pulses with different shapes are generated by the direct time-domain technologies. However, due to the difficulty in obtaining accurate high-order differentiator and high-order integrator, the shapes of output pulses show obvious deviation from the ideal waveforms. Frequency-to-time -mapping is a linear-optics method, which employs an optical filter to change the spectral envelope of input pulse and a dispersive medium to achieve frequency-to-time mapping. Based on this method, a parabolic pulse with optimized duration and energy is reported [8]. However, quality of the obtained pulse is significantly influenced by the dispersion. Inter-symbol cross interference induced by dispersion may lead to serious distortion as the duration of an optical pulse becomes shorter [9-10]. Compared with above-mentioned direct time-domain or frequency-time mapping, Fourier-transform is the most widely used and commercially adopted approach for shaping an ultrashort optical pulse. The well-known 4f system is the basic setup. By decomposing the spectral components of input pulse into different spatial positions, and then modulating the amplitude and phase of these spectral components by devices, such as liquid crystals spatial light modulators [11], or acousto-optic programmable filter [12], a desired pulse can be obtained after recombining and transforming back to the time-domain.

Since an appropriate amplitude or phase modulation pattern for the spectral components cannot be analytically derived, several optimization algorithms have been proposed, such as genetic algorithm [13], simulated annealing algorithm [14], Fourier iterative algorithm [15], Gerchberg–Saxton [16]. Reference [17] provided a detail comparison between these previous reported algorithms and demonstrated that Fourier iterative algorithm is the most commonly used due to its faster convergence than the other algorithms. However, Fourier iterative algorithm usually shows a large error, which generates serious energy mismatch between the synthesized temporal waveform and the target temporal waveform. In addition, most of these algorithms mentioned above can only design and optimize the spectral phase modulation patterns. Because the amplitude is another important parameter for describing optical pulse besides phase, Ref. [18] recently reported a spectro-temporal algorithm to control the temporal intensity of the shaped waveform. But their method is very complicated, which must use both Fourier transform and short-time Fourier transform. In order to obtain temporal waveform with higher accuracy than those of phase-only optimization algorithms, we propose a novel two-step phase-amplitude hybrid iteration algorithm in this paper. And several ultrashort optical pulses with interesting temporal waveforms are synthesized to verify feasibility of the proposed algorithm.

2. Phase-amplitude hybrid algorithm

According to the signal processing theory, the key task for obtaining an output pulse with user-desired target waveform under a given input pulse is to design the system transfer function so as it can adjust both the amplitude and phase of the input pulse. With the assumption of linear system, the relationship between input and output can be expressed as [15]:

$$\begin{aligned} E_{\text{out}}(t) &= \text{FT}^{-1}\{E_{\text{out}}(\omega)\} = \text{FT}^{-1}\{H(\omega)\cdot E_{\text{in}}(\omega)\} \\ &= \text{FT}^{-1}\{|H(\omega)|\exp[j\varphi(\omega)]\cdot E_{\text{in}}(\omega)\} \end{aligned} \tag{1}$$

where FT^{-1} denotes inverse Fourier transform. $H(\omega)$ is the system transfer function with $|H(\omega)|$ and $\varphi(\omega)$ as its amplitude and phase, respectively. $E_{\mathrm{in}}(t)$, $E_{\mathrm{out}}(t)$ and $E_{\mathrm{in}}(\omega)$, $E_{\mathrm{out}}(\omega)$ are the input pulse, output pulse and their corresponding Fourier spectra.

Figure 1 shows the basic flowchart of phase-amplitude hybrid algorithm for synthesizing ultrashort optical pulse. This algorithm can be divided into two steps: phase iteration and amplitude iteration.

In the step of phase iteration, the goal is to get the phase profile of the transfer function with the amplitude restriction condition: $|H(\omega)| = 1$. To initialize the algorithm, spectral amplitude of the input pulse $|E_{\mathrm{in}}(\omega)|$, the temporal amplitude of the target output pulse $|E_{\mathrm{targ}}(t)|$ and an arbitrarily chosen initial random phase $\varphi_0(\omega)$ are taken as the inputs. We combine the spectral amplitude of input pulse and the initial random phase as a complex spectral function $E_1(\omega) = |E_{\mathrm{in}}(\omega)|\exp\{i\varphi(\omega)\}$ and inverse-Fourier transform it to the time domain. Then, we replace the amplitude of the transformed temporal signal $|B(t)|$ with the amplitude of target output pulse $|E_{\mathrm{targ}}(t)|$ and remain the phase of the transformed temporal signal. Then, this modified temporal signal is

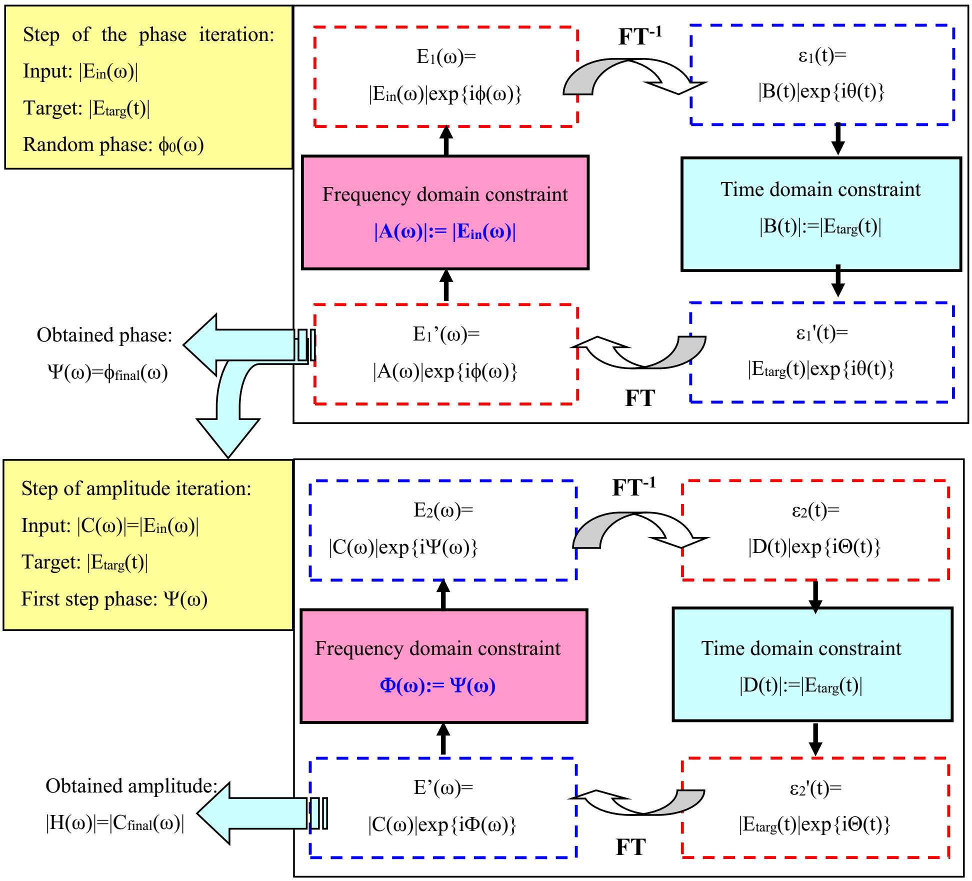


Fig. 1. Flowchart of two-step phase-amplitude hybrid algorithm for synthesizing ultrashort optical pulse.

Fourier transformed back to the spectral domain. Similar to the above, amplitude of the resultant spectral signal $|A(\omega)|$ is replaced by the spectral amplitude of input $|E_{\text{in}}(\omega)|$, while its phase is remained. The process is repeated and after enough iterations, the algorithm converges to a stable spectral phase $\varphi_{\text{final}}(\omega)$, which is used as initial values for the step of amplitude iteration.

In the step of amplitude iteration, although the algorithm still transforms back and forth in the time domain and spectral domain, there are two differences. First, the amplitude restriction condition is removed. Second, as depicted in the red box, phase of the transformed signal in the spectral domain is replaced by the phase finally obtained in the step of phase iteration. And after enough iteration, the spectral amplitude becomes stable and the algorithm converges. Based on the phase-amplitude hybrid optimization algorithm, it is possible to synthesize ultrashort optical pulse with more accurate temporal waveform.

3. Results and discussions

In the followings, we are going to provide some examples to verify the effectiveness and high-accuracy of the proposed phase-amplitude hybrid algorithm. The input is assumed as a transform-limited Gaussian pulse with FWHM time width of 1 ps and the central wavelength of 1550 nm. We intend to synthesize two types of ultrashort optical pulses: a single pulse with different temporal target waveforms (such as rectangular, symmetric or asymmetric triangular) and a train of pulses with interest envelopes (such as multi-pulse with same intensity, ascending intensity, or binary code intensity).

Notice that some ideal waveforms with infinite bandwidth are impossible to obtain in practice, we soften these target output waveforms by using approximate bandwidth-limited mathematical expression. For example, a general raised cosine function can be used to describe the rectangular or triangular pulses [19]:

$$E_{t\,\arg}(t) = \begin{cases} 0.5\left\{1+\cos\left[\dfrac{\pi}{\alpha_1 T_1}\left(-t-\dfrac{1-\alpha_1}{2}T_1\right)\right]\right\}, & -\dfrac{1+\alpha_1}{2}T_1 < t < -\dfrac{1-\alpha_1}{2}T_1 \\ 1, & -\dfrac{1-\alpha_1}{2}T_1 \le t \le -\dfrac{1-\alpha_2}{2}T_2 \\ 0.5\left\{1+\cos\left[\dfrac{\pi}{\alpha_2 T_2}\left(t-\dfrac{1-\alpha_2}{2}T_2\right)\right]\right\}, & \dfrac{1-\alpha_2}{2}T_2 < t < \dfrac{1+\alpha_2}{2}T_2 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

By adjusting the roll-off factors (α_1, α_2) and the pulse time-widths (T_1, T_2) for each side, the target shapes of flat-top rectangular ($\alpha_1 = \alpha_2 = 0$), symmetric ($\alpha_1 = \alpha_2 = 1$ and $T_1 = T_2$) or asymmetric ($\alpha_1 = \alpha_2 = 1$ and $T_1 \neq T_2$) triangular can be obtained.

Firstly, we investigate the performance of algorithm for synthesizing an ultrashort optical pulse with asymmetric triangular temporal waveform. The target asymmetric triangular pulse is assumed to have a FWHM temporal width of 5 ps and asymmetric ratio ($T_1 : T_2 = 1:4$). In order to evaluate the accuracy of the algorithm, an error function is often used to indicate how close the synthesized temporal waveform is to the target waveform during the iterations. Similar to Ref. [20], we use the total deviation between the synthesized temporal waveform from the target waveform at each temporal point as the error:

$$\mathrm{Error}(n) = \sum_{m=1}^{L} \left| \left| E_{t\,\mathrm{arg}}(t_m) \right|^2 - \left| E_{\mathrm{out}}(t_m, n) \right|^2 \right| \tag{3}$$

where n denotes the number of iterations and L denotes the number of temporal points of the pulses.

In the step of phase iteration, the algorithm performance differs greatly depending on the initial conditions. If an appropriate initial phase $\varphi_0(\omega)$ is used as input, the error can decrease rapidly as the number of iterations increasing. As shown in Fig. 2(a), when the initial phase is set as 0, it takes about 18 iterations to reduce the error to a small value. But for the initial phase = $\pi/2$, it takes about only 10 iterations to obtain a significant decrease of the error. For both of the chosen initial phases, after about 50 iterations, the error becomes plateau and the algorithm converges to a stable output phase $\varphi_{\mathrm{final}}(\omega)$. The average time of 50 iterations is about 75 s on our laptop computer with a configuration of intel core i5-1035G1 CPU, which shows the algorithm is fast and effective. Then, we used the obtained phases for modulating the ultrashort optical pulses and the synthesized output waveforms are shown in Fig. 2(b). Although the obtained envelopes are similar to the target waveforms, some obvious fluctuations appear on the descending side of the synthesized output pulses, which are unacceptable for

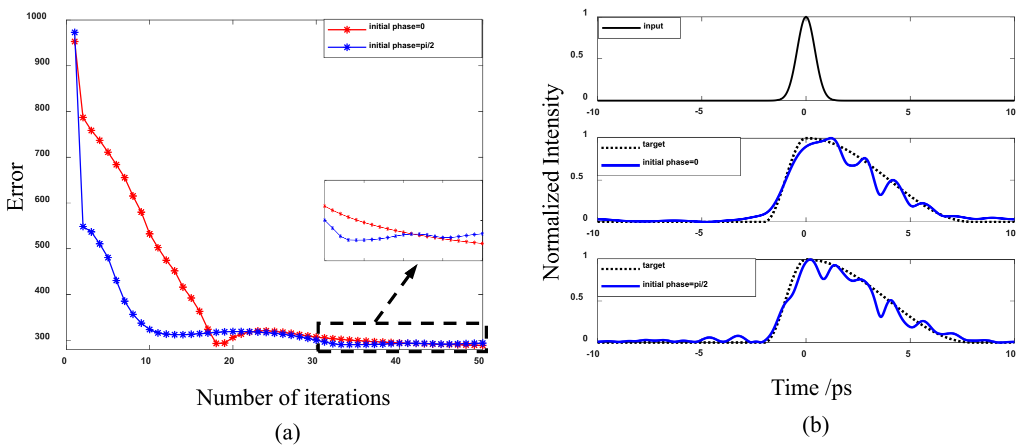


Fig. 2. Influence of initial chosen phase on the accuracy of phase-only algorithm. (a) Iteration error, and (b) synthesized asymmetric-triangular pulse.

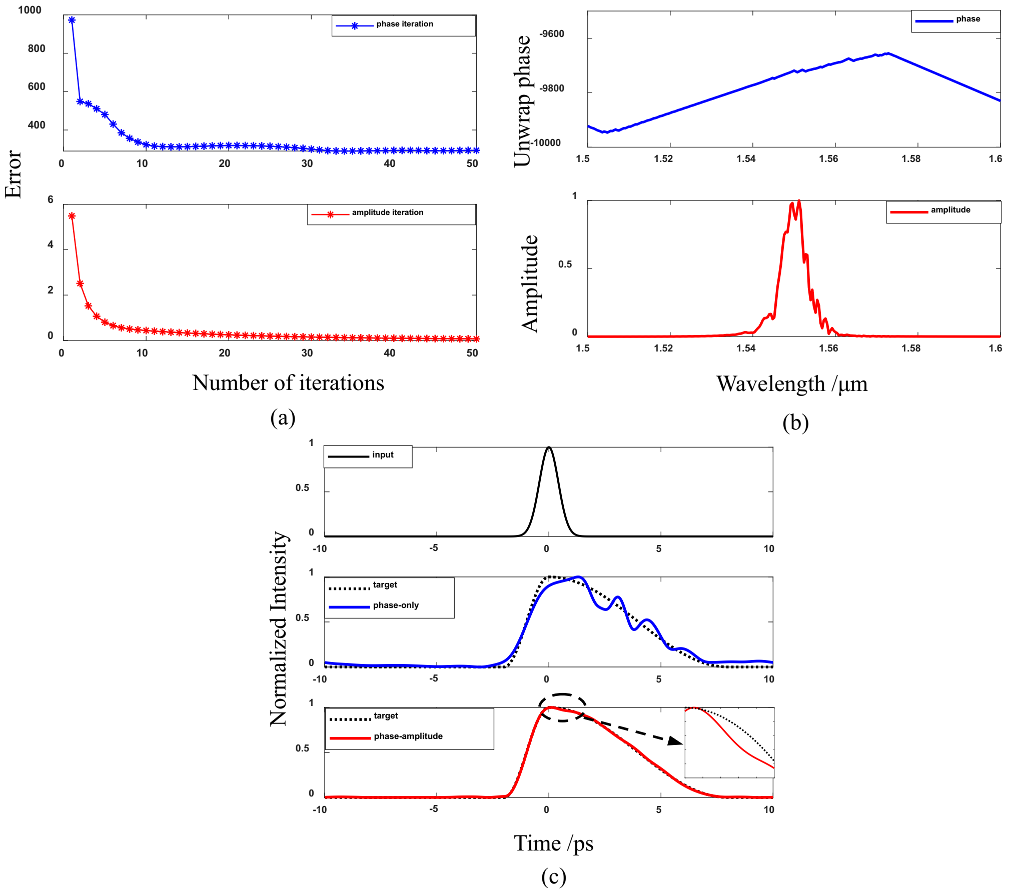
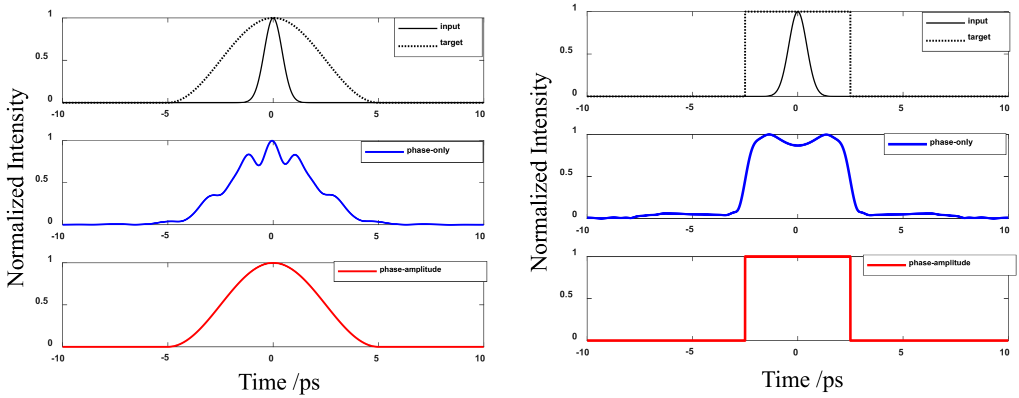


Fig. 3. Synthesis of ultrashort optical pulse with asymmetric-triangular temporal waveform. (a) Error for the phase iteration step (upper) and amplitude iteration step (lower). (b) Obtained phase (upper) and amplitude (lower) of the transfer function. (c) Comparison between phase-only algorithm (middle) and phase -amplitude hybrid algorithm.

practical applications. Even worse, if an inappropriate initial phase is used, it may fall into a local optimal solution or fail to converge at all for the phase-only algorithm. However, if amplitude iteration is used after phase iteration, the error will be further reduced and the accuracy of the synthesized pulse will be greatly improved, as depicted in Fig. 3.

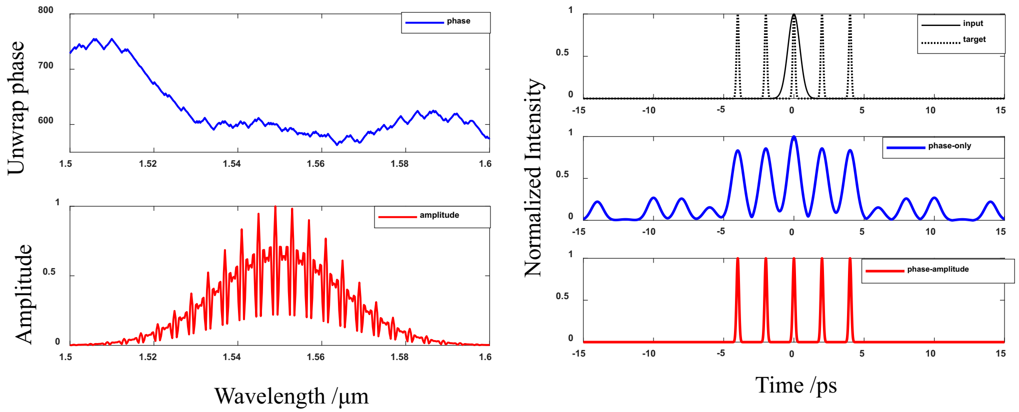
Besides the asymmetric triangular waveform, a symmetric triangle pulse and a rectangular pulse are also synthesized by using the phase-amplitude algorithm, as shown in Fig. 4. Compared with the phase-only algorithm, the ripples of the synthesized pulse are decreased significantly and the difference from the target waveform is almost negligible.

Secondly, we investigate the ability of the phase-amplitude hybrid algorithm for synthesizing a train of ultrashort optical pulses. After convergences of phase iteration



(a) (b)

Fig. 4. Comparison between phase-only algorithm and phase-amplitude hybrid algorithm for synthesizing. (a) Symmetric-triangular pulse, and (b) rectangular pulse.



(a) (b)

Fig. 5. Synthesize of a train of ultrashort optical pulses with binary code '11111' (same intensity). (a) Obtained phase (upper) and amplitude (lower) of the transfer function. (b) Comparison between phase-only algorithm (middle) and phase-amplitude hybrid algorithm.

and amplitude iteration, the obtained spectral phase and amplitude patterns for synthesizing five pulses with a gap of 2 ps and same peak intensity (binary code '11111') is shown in Fig. 5(a) and the corresponding temporal waveform is shown in Fig. 5(b). If only the phase iteration algorithm is used, significant peak variation in each pulse can be seen. In addition, there are large fluctuations at the base outside of the five pulses, which may cause serious interference. However, these adverse effects can be removed by using the phase-amplitude hybrid algorithm.

Then, we further synthesize a train of ultrashort optical pulses with binary code '10111' peak intensity and a train of ultrashort optical pulses with ascending peak in-

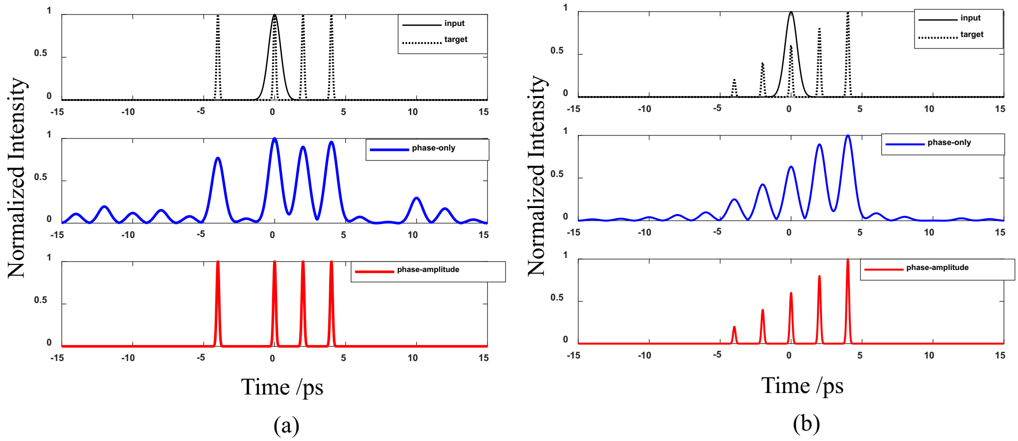


Fig. 6. Synthesize of a train of ultrashort optical pulses with the profiles of (a) binary code '10111' (same intensity), and (b) ascending intensity.

tensity. As depicted in Fig.6(a) and Fig.6(b), it is demonstrated that the phase-amplitude hybrid algorithm can achieve better accuracy than the phase-only algorithm.

4. Conclusions

In this paper, we propose a two-step phase-amplitude hybrid algorithm for synthesizing ultrashort optical pulse. Several interesting pulse shapes, including a single pulse with different temporal waveforms (such as symmetric or asymmetric triangular and rectangular) and a train of pulses with variable intensity envelope (such as multi-pulse with same intensity, ascending intensity, or binary code intensity) are obtained from a Gaussian input pulse. Compared with the phase-only algorithm, the effectiveness and higher accuracy of the proposed phase-amplitude hybrid algorithm is demonstrated, which is promising for synthesizing ultrashort optical pulses with more complicated temporal waveforms in the future.

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Availability of data
Data underlying the results presented at this paper are not publicly available at this time, but may be obtained from the corresponding author upon reasonable request.

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