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Tunable few-cycle pulses from a dual-chirped optical parametric amplifier pumped by broadband laser

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ABSTRACT

We propose a dual-chirped optical parametric amplification (DC-OPA) scheme pumped by a broadband laser pulse. The pump pulse is spectrally broadened in a multi-plate system before amplifying the chirped seed in a BBO crystal. The system performance and phase-matching mechanism with different pump bandwidths are investigated thoroughly. It is found that the broadened pump bandwidth benefits the system most effectively when the pump and seed pulses are oppositely chirped. The idler bandwidth is nearly tripled in the broadband pumped system, supporting a transform-limited (TL) duration of 8.4 fs (~1.3 cycles), meanwhile the energy bandwidth product of the idler is 72.6% higher. Furthermore, the idler wavelength is tunable between 1700 nm and 2050 nm, with sub-1.5-cycle TL duration and over 14% conversion efficiency. The proposed scheme provides a suitable approach for the generation of few-cycle pulses varying from near-infrared to mid-infrared regions.

1. Introduction

Few-cycle laser pulses with microjoule to millijoule energy have attracted lots of attentions in the past decades, owing to their utmost importance for applications including strong-field physics, attosecond optics, and ultrafast spectroscopy [1–11]. The special properties of titanium doped sapphire (Ti:sapphire) such as broadband lasing range from 600 to 1050 nm, high stability, and indefinitely long lifetime, make it a suitable material for a femtosecond laser [12,13]. Using Kerr lens mode-locking (KLM) technique accompanied with chirped pulse amplification (CPA) [14], Ti:sapphire laser has become one of the most popular commercially-available sources for energetic ultrashort laser pulses. However, the CPA technology is not capable of producing high-energy femtosecond pulses in >1 μm range, due to the lack of suitable laser material. Optical parametric amplification (OPA) and optical parametric chirped pulse amplification (OPCPA), with their outstanding advantages including broad gain bandwidth, high wavelength tunability, lower accumulation of thermal load and undesired nonlinear effects, have become promising methods to down-convert the Ti:sapphire laser light [15–18].

An ultra-broadband gain is essential for few-cycle pulse generation in OPA. The zero group velocity mismatch (GVM) at degeneracy allows ultrabroad gain bandwidth and few-cycle duration of the output pulses, but the central wavelength is strictly limited with low tunability [19–22]. For non-degenerate signal and idler pulses, the increasing GVM leads to a much narrower gain bandwidth. By using non-collinear geometry, the group velocity (GV) of signal equals the projection of idler GV along the propagation direction, the amplified pulses can therefore be overlapped over a long interacting distance, producing a signal pulse with larger bandwidth [23–27]. Nevertheless, the non-collinear pump-seed angle will result in an idler beam with angular dispersion, which requires energy-consuming dispersion compensation stage for its further use [28,29].

In order to produce few-cycle pulses at non-degenerate wavelength in a collinear OPA, several approaches have been proposed. For example, employing periodically poled crystals to obtain broadband gain in a quasi-phase-matched (QPM) OPA [30–32], broadening the spectral bandwidth of OPA output pulse with a hollow fiber [33,34], or amplifying the pulse in the frequency domain (Frequency-domain OPA, FOPA) [35,36], etc. However, the aperture and damage threshold of periodically poled crystals as well as the hollow core fiber severely limit the available pulse energy, and the FOPA requires complex management of the interacting pulses spatially and temporally.

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A comparatively simpler method to enhance the energy scalability is the dual-chirped OPA (DC-OPA) scheme [37–40]. Zhang et al. proposed DC-OPA scheme in [37]. The authors chirped both pump and seed pulses to decrease the peak intensity of interacting pulses and prevent undesired nonlinear effects. It was found that the DC-OPA scheme is potentially capable of generating IR pulses with the energy of few hundred millijoule. Fu et al. implemented DC-OPA with a 100-mJ pump laser and obtained 20-mJ uncompressed signal at 1400 nm, a total conversion efficiency over 30% is experimentally achieved [38]. Wandel et al. extended the DC-OPA scheme to longer wavelengths and generated narrowband, high-energy, bandwidth-tunable pulses in the mid-infrared (mid-IR) region [40]. Even though the DC-OPA scheme shows excellent energy scalability, the signal or idler bandwidths are not broad enough to support few-cycle output pulses for many important applications, e.g. generation of isolated attosecond pulse (IAP) in extreme ultraviolet range [41,42].

The gain bandwidth in DC-OPA can be increased by introducing the concept of chirp-compensation [43–46]. The time-dependent instantaneous wavelengths of pump and seed pulses are carefully tailored in a way that ensures perfect phase-matching for a wide range of frequency components, thus broadband gain is obtained. Tang et al. implemented a chirp-compensation OPCPA scheme and amplified a spectrum with more than 165-nm bandwidth and less than 15-fs TL duration [43]. In [44], Limpert et al. utilized the chirp compensation scheme for a degenerate signal, with the second harmonic of a Ti:sapphire laser as the pump, the generated signal spectrum covers a range of 630–1030 nm. Similarly, we proposed the dual-pump OPCPA scheme [47] in which two non-degenerate regions of the chirped seed are amplified by two chirped pump respectively, the output spectrum spanning from 1300 nm to 2100 nm is obtained with a TL pulse duration of 9.0 fs. Recently, Yin et al. presented a broadband-pumped DC-OPA system for the generation of high-energy, two-cycle pulses centered at 3.2 μm [48].

According to our study on the dual-pump OPCPA scheme, the gain bandwidth of the system can benefit from a broader pump bandwidth [47]. However, most of the existing OPAs utilized the pump pulse directly from a laser system with a TL duration of >30 fs. Energetic 800-nm pulses with broader bandwidth and shorter TL duration are readily available with current technique. Lu et al. generated an intense super-continuum by focusing a high-power laser pulse into several pieces of strategically placed fused silica plates [49]. In [50], He et al. also performed the multi-plate scheme and achieved 800-nm, 0.68-mJ, 5.4-fs pulse with a near-single-cycle TL duration of 3.5-fs. It is naturally inferred that if the high-energy, broadband pulses are utilized to pump an OPA, the gain bandwidth of the system can be remarkably improved.

In this paper, we propose a DC-OPA system pumped by a broadband femtosecond laser. Instead of pumping the system directly from a Ti:sapphire laser source, the pulse is sent into a multi-plate system for spectral broadening. The broadband pump and seed pulses are both chirped to manipulate their time-dependent wavelengths and improve the gain efficiency. The amplification mechanism at different pump bandwidths and chirp combinations is investigated and discussed, and the system performance is optimized correspondingly. The spectral-temporal property of the idler pulse from a broadband pump OPA is specifically analyzed and the wavelength tunability is confirmed. The rest of this paper is arranged as follows. In Section 2, we introduce the concept and numerical model of the proposed scheme. In Section 3, the gain mechanism of DC-OPA is analyzed. In Section 4, the results of broadband pumped and narrowband pumped DC-OPAs are compared. Finally in Section 5, the conclusions are drawn and the prospect is discussed.

2. Concept and theory

The schematic of the proposed scheme is presented in Fig. 1. The initial pulse is produced in a commercially available Ti:sapphire laser with a pulse duration of 50 fs and a repetition rate of 1 kHz. The laser beam is divided into two beams. The beam with higher pulse energy is spectrally broadened in a multi-plate system, and then temporally chirped in the pump stretcher. The less energetic beam passes through a dual-crystal OPA (DOPA) system to produce a broadband seed centered at 1400 nm [51,52]. The seed pulse is chirped in a seed stretcher. In order to compare different systems with different pump bandwidths, we simulate the amplification process using Gaussian-shaped pump pulses with TL durations of 10 fs, 20 fs, 30 fs, and 50 fs, respectively. The shorter the TL duration is, the broader the pump bandwidth is. The pulse energy is fixed at 300 μJ. For simplicity and clarity in the following article, the 50-fs pump pulse will be referred to as the narrowband pump (although the bandwidth is considerably large), in comparison to the broadband pump with 10-fs to 30-fs TL duration. It is noteworthy that, since all existing bandwidth-broadening methods inevitably stretch the pulse temporally and the recompression requires deliberate dispersion management, the broadband pumps will not be used as TL pulses here. Instead, each broadband pump pulse is chirped and stretched to a designed pulse duration, varying from 50 fs to 120 fs. The seed spectrum is obtained from our recent experiment [52], with a full width at half maximum (FWHM) bandwidth over 200 nm. The TL duration of the seed is 13 fs and the pulse energy is approximately 1 μJ. Both the radii of the pump and seed beams are 5 mm.

To quantitatively investigate the influence of pump bandwidth on OPA system, we numerically solve the coupled wave equations including the nonlinear interaction and up to fourth order dispersion of each pulse, which are written as follows:

$$\frac{\partial}{\partial z}A_p + \sum_{j=2}^{n}\frac{(-i)^{j-1}}{j!}k_p^{(j)}\frac{\partial^j}{\partial \tau^j}A_p = \frac{id_{eff}\omega_p}{n_p c}A_s A_i e^{i\Delta kz},$$

$$\frac{\partial}{\partial z}A_s + \left(\frac{1}{v_{gs}} - \frac{1}{v_{gp}}\right)\frac{\partial}{\partial \tau}A_s + \sum_{j=2}^{n}\frac{(-i)^{j-1}}{j!}k_s^{(j)}\frac{\partial^j}{\partial \tau^j}A_s = \frac{id_{eff}\omega_s}{n_s c}A_p A_i^* e^{-i\Delta kz},$$

$$\frac{\partial}{\partial z}A_i + \left(\frac{1}{v_{gi}} - \frac{1}{v_{gp}}\right)\frac{\partial}{\partial \tau}A_i + \sum_{j=2}^{n}\frac{(-i)^{j-1}}{j!}k_i^{(j)}\frac{\partial^j}{\partial \tau^j}A_i = \frac{id_{eff}\omega_i}{n_i c}A_p A_s^* e^{-i\Delta kz},$$

in which A_m ($m = p$, s, and i) is the field amplitude of the pump, signal and idler pulses, respectively, v_{gm} is the group velocity, k_j denotes the jth-order dispersion coefficient, j is calculated up to 4, d_{eff} is the nonlinear coefficient for the parametric amplification, and n_m is the refractive index of each pulse evaluated from the Sellmeier equations. The equations are solved through split-step Fourier-transform algorithm, in which the dispersion is calculated in the frequency domain and the amplification is calculated in the time domain with 4th-order Runge-Kutta numerical method. The interacting pulses are treated with slowly varying envelope approximation (SVEA), which is a reasonable approximation in the investigation because all the involved pulses are stretched to pulse durations longer than 50 fs. Since the input pulses contain spectral bandwidth up to several hundred nanometers, the 3rd-order and 4th-order dispersions are included. However, higher order dispersions show very little influence to the results, therefore neglected in the simulation. Since one-dimensional (1D) numerical model is valid to reveal the spectral-temporal properties in the parametric process, and the spatial distribution of the beams is beyond the scope of this paper, we perform a simple 1D simulation in the following investigation.