High-energy mid-infrared femtosecond pulses at 3.3 μm directly generated by dual-chirped optical parametric amplification

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Abstract. By employing a dual-chirped optical parametric amplification (DC-OPA) using MgO:$LiNbO_3$ crystals, we generate 31 mJ mid-infrared (MIR) pulses at 3.3 μm with a repetition rate of 10 Hz. After passing through a CaF_2 bulk compressor which has 70% throughput efficiency, these MIR pulses are compressed to 70 fs (6.3 optical cycles), which is close to the transform-limited duration of 66 fs. Thus, the peak power is evaluated to be 0.3 TW. Our results present notable progress in the generation of high-energy MIR pulses and prove that DC-OPA is a superior method for efficiently generating MIR pulses with few-cycle duration and TW-class peak power.

1 Introduction

Currently, there is rapidly growing interest in shifting the ultrafast laser wavelength used for strong-field physics research from the widely employed NIR region (~ 0.8 μm) to the mid-infrared (MIR) region owing to its various advantages, for example, obtaining the current record pulse duration of 43 as [1] in soft x-ray region and 53 as [2] in water window region using MIR pulses which help to extend photon energy and reducing atto-chirp in high-order harmonic generation (HHG). High pulse energy of MIR fs laser is also significant for energy scaling of coherent light source in the sub-keV photon energy region by HHG [3]. For these reasons, we have proposed [4] and demonstrated [5-8] a dual-chirped optical parametric amplification (DC-OPA) scheme. In our previous works, DC-OPA was proved to have an excellent energy scaling ability and obtained 100 mJ class IR fs pulses in the 1–2 μm wavelength range for the first time [8]. Recently, DC-OPA has been numerically analyzed the capability for its energy scalability in the mid-infrared (MIR) [9] and the far-infrared (FIR) wavelength range [7]. In this paper, we experimentally demonstrate the generation of TW-class MIR pulses using MgO:$LiNbO_3$ crystals based DC-OPA. We obtained 21 mJ MIR pulses at 3.3 μm with the duration of 70 fs. Based on our experiment results, we will obtain TW-class MIR pulses in 2-4 μm with a few-cycle duration directly after our DC-OPA system in the near future.

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2 Experimental results

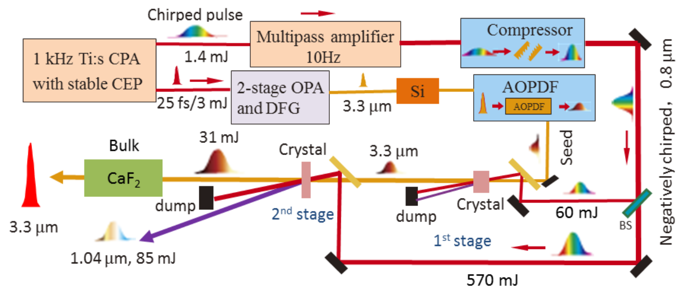

Fig. 1. Schematic of the experimental setup.

Figure 1 shows the schematic of the experimental setup. The pump laser for the DC-OPA is a Ti:sapphire laser with its pulse energy of 630 mJ, a repetition rate of 10 Hz and a central wavelength of ~ 0.8 μm. Its pulse duration is stretched to ~ 6.6 ps by changing separation between two gratings inside a compressor and is employed to pump the two stage DC-OPA. The broadband seed at 3.3 μm for the DC-OPA is provided by the difference frequency generation (DFG) between the signal and idler pulses after a two-stage OPA (TOPAS, Prime). Its pulse is stretched to ~ 5 ps by a 140-mm-thick silicon bulk and an acousto-optic programmable dispersive Filter (AOPDF, Fastlite). MgO: $LiNbO_3$ crystals with thicknesses of 6 mm and 3 mm with type-I phase-match cutting angles (θ = 44.2°) are utilized in the first and second stages of the DC-OPA. The pump intensities on both crystals are adjusted to be approximately 25 GW/cm^2. In both DC-OPA stages, a very small non-collinear angle less than 1 degree is employed to spatially separate the pump and MIR pulses.

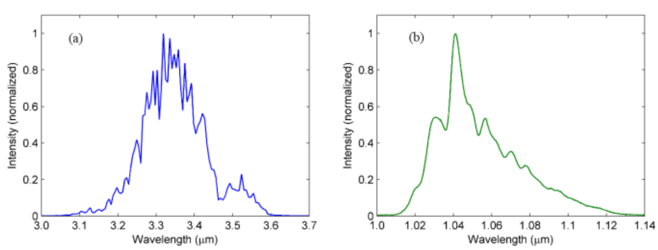

Fig. 2. Typical spectra at (a) 3.3 μm and (b) 1.04 μm.

After the first stage, the seed pulse at 3.3 μm is amplified to 0.67 mJ with a gain of ~1300. In the second stage, the seed pulse is further amplified to ~ 31 mJ which corresponds to an energy conversion efficiency of 5.4% and a photon conversion of 22.3%. A typical spectrum is shown in Fig. 2(a). The energy of pulses at 1.04 μm, which are generated from DFG between pump and seed pulses, after the second stage are measured to be ~85 mJ. Its spectrum is shown in Fig. 2 (b) which supports a transform limited (TL) pulse duration of 33 fs. Thus, the total conversion efficiency after the second stage of our DC-OPA system reaches ~ 20 %. To compress the high-energy 3.3 μm pulses with a high throughput, we employ a bulk compressor consisting of a 60 mm × 60 mm×100 mm^3 and a 60 mm × 60 mm × 50 mm^3 CaF_2 bulks, which are anti-reflection coated in a wavelength range of 2–4 μm. The gross throughput after a total pass length of 600mm (four-pass configuration with 16 times passing bulk surfaces) in the CaF_2 bulks is ~70%. Note that we can obtain a compressor throughput over 95% using single 114-mm-thick sapphire bulk with anti-reflection coatings. The spectral phase is precisely manipulated by controlling the phase of seed using the AOPDF, which is very helpful to correctly compress the amplified pulse. To avoid damage or self-phase modulation (SPM) in the bulk compressor, the beam size of the 3.3 μm pulse is expanded to ~40 mm. In principle, our compressor can accept a pulse energy up to 60 mJ. The pulse duration at 3.3 μm was characterized by the frequency-resolved optical gating (FROG) method. Figure 3 (a) shows the retrieved spectrum and phase as well as the spectrum measured by a spectrometer (Mozza, Fastlite). From the retrieved spectrum and phase, the temporal pulse and phase are reconstructed as shown in Fig. 3 (b). The pulse duration was 70 fs (6.3 optical cycles) which is close to its TL duration of 66 fs.

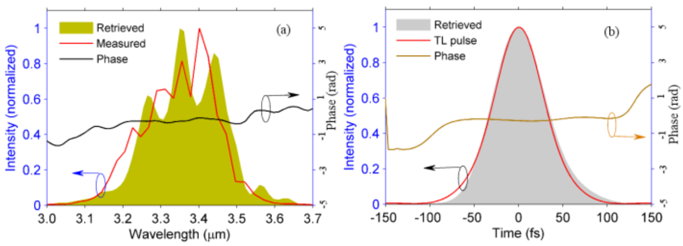

Fig. 3. Spectral phase (a) and pulse envelope (b) characterized by FROG.

Moreover, our MIR DC-OPA can directly generate a two-cycle laser when we employ a broadband seed in 2-4 μm. It is because the spectral bandwidth of our pump laser is sufficiently broad to phase the broad band seed spectrum in $MgO:LiNbO_3$ crystals. More details can be found in our recent paper [10] and another theoretical paper [9].

3 Summary

We have obtained TW-class MIR pulses near 3.3 μm with a duration of 70 fs using the DC-OPA method even though nonlinear crystals in the MIR wavelength region have low damage threshold as well as small apertures. Our demonstration proves that DC-OPA is a superior method that can be universally applied to the scaling of IR pulse energy independent of types of crystals and their aperture sizes. Compared with MIR OPCPA systems, which generally employ post-compensation techniques to obtain 2-cycle or shorter durations, our DC-OPA system can directly generate TW-class, two-cycle, and CEP-stable MIR pulses. The high-energy MIR pulses are helpful for many applications in the strong-field laser science, such as for investigating the scaling law of Keldysh parameter and the effect of the magnetic component of laser fields, generating keV HHs light source, and creating attosecond pulses with durations of 10 attosecond order.

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