Generation of 1 mJ, 85 fs, 2.5 µm Pulses from a Cr^{2+}:ZnSe Chirped Pulse Amplifier

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Abstract: We demonstrate the generation of 1 mJ, 85 fs, 2.5 µm pulses with 300 nm of available bandwidth at 1 kHz of repetition rate from a Chirped Pulse Amplifier based on the Cr^{2+}:ZnSe gain medium.

OCIS codes: (320.7090) Ultrafast lasers; (140.5680) Rare earth and transition metal solid-state lasers.

1. Introduction

Recent progress in high-field physics and attosecond science has allowed for the generation of water-window soft X-ray attosecond pulses approaching the time scale of one atomic unit of time [1]. Further scaling of photon energy and bandwidth of these attosecond pulses requires high-energy few-cycle laser sources at longer wavelengths in the short- and mid-wave infrared spectral region [2]. These sources can be enabled via the optical parametric amplification technique. Such technique could produce few-cycle pulses but suffers from a low pump-to-signal conversion efficiency limiting its scalability. Recent advance in the development of Cr^{2+}/Fe^{2+}-doped II-VI materials and suitable pump lasers has provided an alternative way of developing such sources via chirped pulse amplification (CPA), which is more efficient and scalable [3]. However, weak and narrow-band seed sources, coupled with the gain-narrowing effect in the CPA process, have limited output pulses to roughly 200 fs at around 1 mJ of energy [4]. In this paper, we report on the generation of 1 mJ, 85 fs, 2.5 µm pulses at 1 kHz of repetition rate using a µJ-level broadband seed source generated via the difference frequency generation (DFG) in a BIBO crystal and amplified by a two-stage Cr^{2+}:ZnSe CPA.

2. Design of the Cr^{2+}:ZnSe CPA laser

As illustrated in Fig. 1(a), the front-end of the laser system features a Ti:Sapphire CPA setup delivering 2 mJ, 30 fs pulses at 1 kHz. These pulses are spectrally broadened by self-phase modulation in a hollow-core fiber filled with 20 psi of Neon gas, and re-compressed by a subsequent series of chirped mirrors and fused-silica plates. They are then loosely focused into a 0.8 mm-thick type-I phase-matched BIBO crystal for DFG [5]. Generated pulses, having an octave-spanning spectrum covering 1.8 to 4 µm with over 10 µJ of energy, are used to seed the Cr^{2+}:ZnSe CPA.

The main system consists of a standard stretcher-amplifier-compressor architecture. The pulse stretcher employs an all-reflective aberration-free Offner design to stretch each seed pulse to approximately 300 ps. A ruled reflection grating with the groove density of 300 l/mm, whose diffraction efficiency is optimized for 2.5 µm, is used. Throughput efficiency of the stretcher is recorded to be around 50%. Roughly 5 µJ of the 300 ps pulse are available at the stretcher's exit, which are then seeded into a two-stage amplifier.

The first stage is arranged in a 6-pass configuration followed by a single-pass setup in the second stage. Gain medium in the first stage is a 30 mm-long polycrystalline Cr^{2+}:ZnSe crystal cut at the Brewster's angle of 2.4 µm, while the second stage uses a flat-face 40 mm-long polycrystalline Cr^{2+}:ZnSe crystal. Both crystals are water-cooled to the room temperature. Each stage is pumped at 1 kHz by 12 mJ of a 15 ns pulse at 2.09 µm from a Thulium-pumped Ho:YAG Q-switch laser (IPG Photonics). Since the pump's central wavelength is close to that of the crystal's emission spectrum, quantum defect is minimized to approximately 16%. The first stage gives around 900 µJ of pulse energy, which is further boosted to 2 mJ after the second stage yielding a cumulative gain of 400.

Amplified pulses are then sent into an all-reflective pulse compressor. Two ruled reflection gratings used in the compressor are identical to the one installed in the stretcher. Throughput efficiency of the compressor is measured to be roughly 50% resulting in 1 mJ of pulse energy obtained at the compressor's exit. Spectra of the seed pulse after the stretcher and the compressor are shown in Fig. 1(b). We have obtained 1 mJ of pulse energy at the output with a full-width-at-half-maximum (FWHM) bandwidth of around 300 nm - the broadest spectrum ever achieved at 2.5 µm supporting 1 mJ of pulse energy at 1 kHz of repetition rate. At 2.5 µm, such spectrum supports a transform-limited

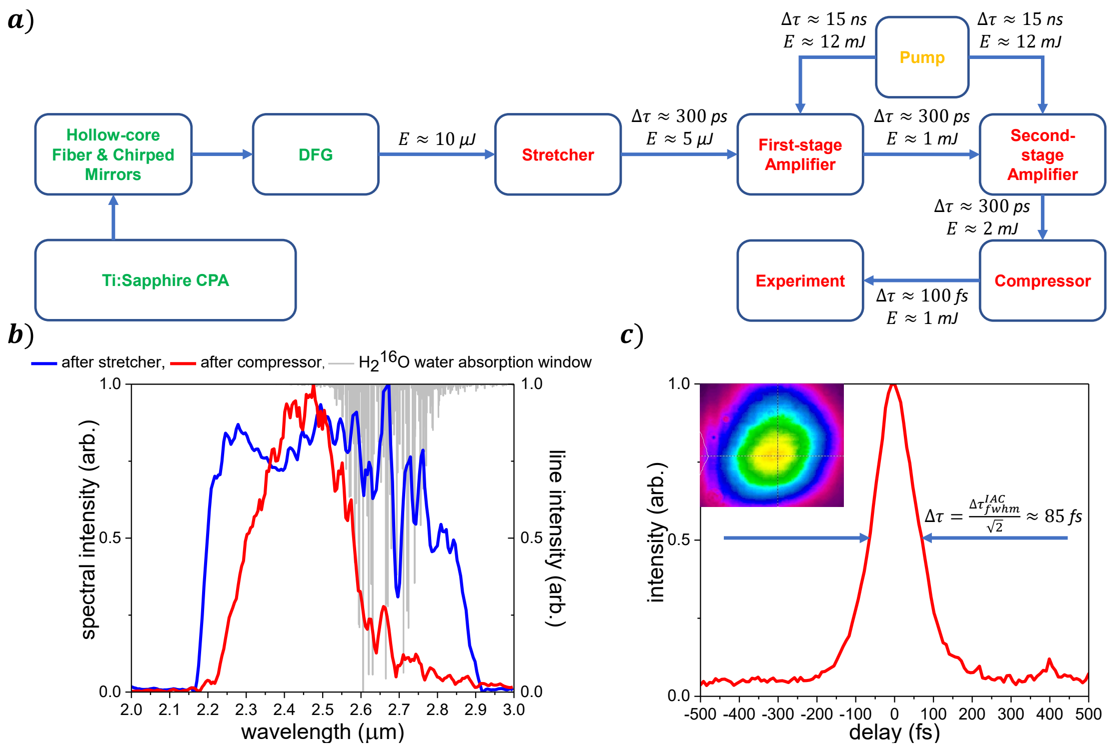

Fig. 1. a) Schematic layout of the Cr^{2+}:ZnSe CPA laser. b) Power spectra of the seed pulse after the stretcher and the compressor plotted along with the absorption window of water vapor [6]. c) Intensity autocorrelation and spatial profile of the seed pulse at the compressor's exit.

pulse duration of 30 fs corresponding to 4-cycle pulses. From Fig. 1(b), the reduction of bandwidth on the short-wavelength side is due to the gain crystal's absorption, while the water vapor's absorption limits the long-wavelength side of the spectrum. A proper enclosure purged with dry air should allow the bandwidth beyond 2.6 µm to be recovered potentially yielding even shorter pulses.

From the intensity autocorrelation shown in Fig. 1(c), temporal width of the output pulse is estimated to be about 85 fs. Since the CPA's seed source is generated from a DFG process, carrier-envelope phase (CEP) of output pulses should be passively stabilized, which is important for the generation of isolated attosecond pulses. However, grating-based stretchers and compressors are known to add instabilities to the CEP; thus, the actual CEP noise of output pulses needs to be verified.

3. Summary

We demonstrate the generation of 1 mJ, 85 fs, 2.5 µm pulses with 300 nm of available bandwidth at 1 kHz of repetition rate from a CPA based on the Cr^{2+}:ZnSe gain medium. Further scaling of pulse energy is possible by adding more amplification stages. Such system will be an ideal driving source for the generation of attosecond pulses whose spectrum approaches keV photon energy. This work has been supported by the Army Research Office (W911NF-14-1-0383, W911NF-15-1-0336); the Air Force Office of Scientific Research (FA9550-15-1-0037, FA9550-16-1-0013); and the DARPA PULSE program via a grant from AMRDEC (W31P4Q1310017). This material is also based upon work supported by the National Science Foundation (NSF 1506345).

References

1. J. Li *et al.*, "53-attosecond X-ray pulses reach the carbon K-edge," Nat. Commun. **8**, 186 (2017).
2. S. Bing and Z. Chang, "Dramatic extension of the high-order harmonic cutoff by using a long-wavelength driving field," Phys. Rev. A **65.1**, 011804 (2001).
3. S. B. Mirov *et al.*, "Progress in mid-IR Cr^{2+} and Fe^{2+} doped II-VI materials and lasers," Opt. Mater. Express **1.5**, 898-910 (2011).
4. E. Slobodchikov *et al.*, "High peak power ultrafast Cr^{2+}:ZnSe oscillator and power amplifier," Proc. SPIE **9726**, 972603 (2016).
5. Y. Yin *et al.*, "Generation of octave-spanning mid-infrared pulses from cascaded second-order nonlinear processes in a single crystal," Sci. Rep. **7**, 11097 (2017).
6. L. S. Rothman *et al.*, "The HITRAN 2012 molecular spectroscopic database," J. Quant. Spectrosc. Ra. **130**, 4-50 (2013).