18-μJ energy, 160-kHz repetition rate, 250-MW peak power mid-IR OPCPA

M. Hemmer[1*], A. Thai[1], M. Baudisch[1], H. Ishizuki[2], T. Taira[2], and J. Biegert[1,3]

[1]*ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, Castelldefels, Spain*

[2]*Laser Research Center for Molecular Science, Inst. for Molecular Science, Okazaki, Japan*

[3]*ICREA-Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain*

**Corresponding author: michael.hemmer@icfo.eu*

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Progresses on the development of a high repetition rate mid-IR laser source suitable for the next generation of high-field physics experiments are reported. The presented optical parametric chirped pulse amplification (OPCPA) source currently delivers carrier-envelope phase (CEP)-stable 67-fs duration optical pulses with up to 18-μJ output energy at 160-kHz repetition rate. The focusability of the output beam (M^2 ~2) enables peak intensities exceeding 10^{14} W/cm^2 and the record output energy stability-below 1% power fluctuation over 4.5 h makes this source a key enabler for the strong field physics community.

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Over the past ten years, optical parametric chirped pulse amplification (OPCPA) has been identified as a complementary approach to the more traditional chirped pulse amplification (CPA) technique to further extend the output parameters of high intensity laser systems[1]. In particular, optical parametric amplification (OPA) enables the amplification of spectral bandwidth spanning hundreds of nanometers–following the amplification of few-cycle pulses– and also permits amplification in spectral region in which no suitable laser gain media are available. Additionally, the instantaneous nature of the parametric amplification process promises simultaneous scalability of output energy and repetition rate.

As an illustration of the versatility of the OPCPA architecture, a number of laser systems have been reported over the past few years, operating in a wide range of output energy, repetition rate, and center wavelength ranges. Systems approaching the petawatt (PW) peak power have been developed providing 24 J of energy in 43 fs pulses at a repetition rate of one shot every 30 min at 910 nm wavelength[2]. Repetition rate scaling of such high peak power systems is ongoing with the development of a PW-class laser system delivering few-cycle pulses at 10-Hz repetition rate[3,4], again in the near-IR spectral region. Simultaneously, OPCPA systems operating at hundreds of kilohertz repetition rate and delivering up to tens of millijoule (μJ) energy have also been developed still in the near-IR spectral region[5,6]. More recently, developments in strong-field physics have triggered large interest in laser systems with center wavelength longer than 800 nm, which resulted in the development of laser systems operating in the 2-μm spectral region. In particular, Hong *et al.* reported on an OPCPA system delivering 850 μJ of output energy at 1-kHz repetition rate with center wavelength at 2 100 nm[7].

Here, we present the latest in our several-year development towards a laser system operating in the true mid-IR spectral range and at high repetition rate. This tabletop system delivers carrier-envelope phase (CEP) stable optical pulses with 67 fs duration, up to 18 μJ of output energy at 160-kHz repetition rate and 3 100-nm center wavelength. Contrary to a number of other reported systems, the long term output power stability was measured and is here reported to be below 1% RMS fluctuations over 4.5 h.

The presented system relies on an OPCPA architecture and can therefore be divided into four building blocks: seed generation, pump, stretcher/compressor assemblies and optical parametric amplifiers. The seed generation building block consists of a commercial fiber-based system (Toptica Photonics AG) providing femtosecond optical pulses with center wavelengths at 1 050 and 1 550 nm and a difference frequency generation stage between those pulses. The fiber-based system consists of an Er-doped oscillator and subsequent amplifiers operating at 100-MHz repetition rate. The 1 550-nm amplified pulses are temporally compressed to 90-fs duration in a prism assembly and a fraction of the output is sampled and fed into a nonlinear fiber to undergo frequency shifting. The pulses resulting from the frequency shifting exhibit a center wavelength of 1 050 nm and pulse duration of 60 fs after compression. The generation of the mid-IR pulses with center wavelength at 3 100 nm is achieved via difference frequency generation (DFG) between the femtosecond optical pulses with 1 050 and 1 550 nm center wavelength in a magnesium oxyde doped periodically poled lithium niobate (MgO:PPLN) crystal. The 10-pJ mid-IR pulses resulting from the nonlinear interaction are stretched to an estimated duration of 3 ps by passing through a 5-cm-long Sapphire rod.

The pump energy for the optical parametric amplifiers is provided by a commercial Nd:YVO_4 based DPSSL master oscillator power amplifier (MOPA) system (Lumera Laser GmbH). The system features three output lines providing 6-ps duration pulses with respectively 100, 280, and 690 μJ energy-corresponding to a total output energy of 1 mJ at 160-kHz repetition rate. The output beam of this pump laser exhibits a measured M^2 of 1.15 on all outputs and the output power stability

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was measured to be greater than 0.8% RMS over 12 h.

The amplification of the pJ-level mid-IR optical pulses is performed in a series of four parametric amplifiers via collinear interaction with the pump pulses in MgO:PPLN crystals. In each stage, the pump and seed diameter are adjusted to provide optimum energy transfer from the pump to the signal and the idler and pump beams are filtered out between each stage using specially designed dichroic filters. The first OPA stage features a relatively limited gain of ~6 000 resulting in an output energy of ~60 nJ and minimal super-fluorescence generation. Additional stretching is performed between the first and second OPAs to maximize the amplified bandwidth and energy extraction. The second OPA stage is therefore operated in the pump depletion regime and delivers up to 2.5-μJ energy. The third OPA stage is also operated in the pump depletion regime and typically delivers 12.5 μJ of energy. The last OPA stage features a large aperture PPLN crystal (5×5 mm^2) and delivers 38 μJ of energy.

Upon amplification, the optical pulses are directed to a Martinez-type compressor featuring dielectric reflective optics and a gold coated 20-cm-focal-length mirror, an Al coated deformable mirror as folding mirror and a 200-lp/mm diffraction grating. The deformable mirror enables fine tuning of the high order dispersion, enabling tight control of the spectral phase over hundreds of nanometers of spectral bandwidth. The sub-optimum diffraction efficiency of the grating and reflectivity of the metal coated optics still result in a ~50% throughput for the compressor assembly. The overall layout of the system is shown in Fig. 1.

Upon compression, the output beam is diagnosed to evaluate its spectral, spatial and temporal properties and therefore confirm the suitability of the system as a source for driving high-field physics experiments. The output spectrum was measured using a Fourier transform infra-red (FTIR) spectrometer featuring a liquid nitrogen cooled mercury cadmium telluride (MCT)

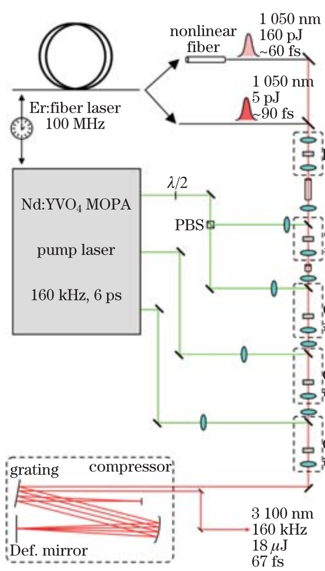

Fig. 1. Layout of the OPCPA system featuring a seed Er:fiber laser, a Nd:YVO$_4$ MOPA pump laser, a series of four MgO:PPLN-based optical parametric amplifiers and a Martinez-type compressor. The system delivers up to 18-μJ energy at 160-kHz repetition rate at mid-IR wavelength.

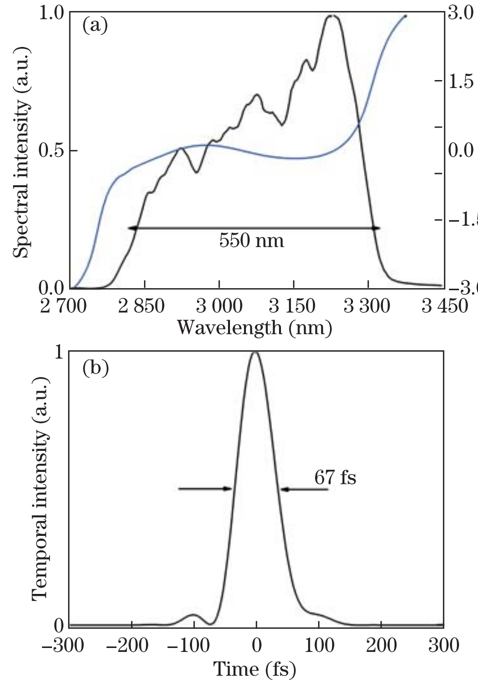

Fig. 2. (Color online) (a) Measured spectral intensity at the output of the OPCPA system (black curve) featuring a total spectral extend approaching 600 nm and retrieved spectral phase (blue curve) from FROG measurement; (b) retrieved temporal intensity profile revealing a 67-fs pulse duration.

detector and exhibited a total spectral width approaching 600 nm (Fig. 2(a)), potentially leading to compression to the few-cycle regime. The shape of the spectrum is inherited from the strong depletion regime in which the OPAs are operated. Temporal investigations–using a frequency resolved optical gating (FROG) apparatus specifically designed for measuring mid-IR wavelength femtosecond pulses[8]–revealed output pulses with a duration of 67 fs (Fig. 2(b)), affected by slight residual third order dispersion (Fig. 2(a)–blue curve). In the temporal domain, the residual third order spectral phase results in a slight asymmetry of the pulses.

The output energy of the system was measured to be 18 μJ, resulting in a peak power of 250 MW at 160-kHz repetition rate. Spatially, the M^2 of the output beam was measured to be ~2. Consequently, the output pulses were successfully focused to FHWM diameters smaller than 10 μm which resulted in intensities in the 10^{14} GW·cm^{-2} range, suitable for high field physics experiments. The output power stability over time was measured and revealed sub-1% rms fluctuation over 4.5 h (Fig. 3).

Finally, the CEP stability of the system has been measured and reported previously[9] to be greater than 250 mrad rms over 30 min. Such stability at 160 kHz corresponds–in terms of CEP stable laser shots–to 30 h of operation on a typical kHz repetition rate system.

In conclusion, we report on a mid-IR laser systemsuitable to drive the next generation of high-field physics experiments. The system delivers up to 18 μJ of output energy at 160-kHz repetition rate. The measured duration of the output pulses is as short as 67 fs and exhibits CEP stability greater than 250 mrad RMS over 30 min. In addition, the long term output power stability of the

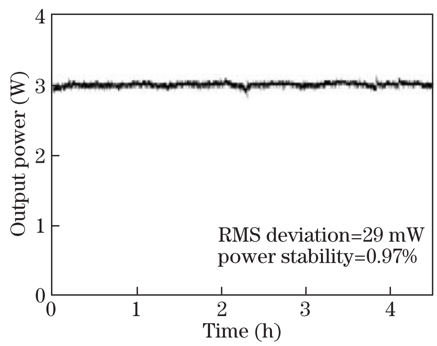

Fig. 3. Measured output power stability over 4.5 h exhibiting a 3-W average power with a standard deviation of 29 mW, corresponding to sub-1% power fluctuations.

OPCPA system is measured to be better than 1% RMS over 4.5 h.

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