Femtosecond 100 W-level OPCPAs from near-IR to short-wave-IR wavelengths

Riedel, Robert, Schulz, M., Grguraš, I., Golz, T., Buß, J., et al.

Robert Riedel, M. Schulz, I. Grguraš, T. Golz, J. H. Buß, M. J. Prandolini, "Femtosecond 100 W-level OPCPAs from near-IR to short-wave-IR wavelengths," Proc. SPIE 11259, Solid State Lasers XXIX: Technology and Devices, 112591F (21 February 2020); doi: 10.1117/12.2543731

Event: SPIE LASE, 2020, San Francisco, California, United States

Femtosecond 100 W-level OPCPAs from near-IR to short-wave-IR wavelengths

R. Riedel[a], M. Schulz[a], I. Grguraš[a], T. Golz[a], J. H. Buß[a], and M. J. Prandolini[a,b]

[a]Class 5 Photonics GmbH, Notkestr. 85, 22607 Hamburg, Germany
[b]Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

ABSTRACT

A review of current high power (100 W-level), femtosecond, optical parametric chirped-pulse amplifiers (OPCPA) at near IR (NIR) and short-wave IR (SWIR) wavelengths pumped by Yb-based solid-state lasers is presented. OPCPA technology together with white-light-generation (WLG) makes it possible to provide CEP-stable femtosecond broadband or tunable pulses (from 700 nm to 2.1 μm), which are potentially scalable to much high power levels. An important feature of these new OPCPAs is their reliability and compact design, requiring no complex cooling systems.

Keywords: optical parametric chirped-pulse amplifier, nonlinear optics, Yb:YAG pump amplifier

1. INTRODUCTION

High power and high repetition rate lasers are critical for many applications in the physical, chemical, and biological sciences. Previously, laser sources from x-ray to THz were driven by Ti:sapphire lasers at 800 nm with limited bandwidth (Fourier limited pulse of ∼20 fs), and more importantly limited power levels; power levels ∼40 W and above require large complex cooling systems. Optical parametric chirped-pulse amplification (OPCPA) together with bulk crystal white-light-generation (WLG) opens up the possibility high power lasers (well above 100 W), with wavelength tunable and broadband pulses (for example, <10 fs at 800 nm), requiring no complex cooling with a compact design.[1] Previous thermal studies of nonlinear crystal BBO, LBO[2] and KTA[3] demonstrated the possibility of using these crystals for high power applications at 800 nm and 1.5 μm, respectively. Recently, 100 W-level OPCPAs are now commercially available from *Class 5 Photonics GmbH* using BBO at 800 nm[4,5] and KTA with a tunable range 1.45 - 2 μm.[6,7] In a recent development, a CEP, few-cycle 2.1 μm OPCPA laser system is also currently available.

In order to reach these high powers, a suitable picosecond OPCPA pump technology is required. Yb-based solid-state lasers offer sufficient bandwidth and a small quantum defect, which reduces the thermal load, and are commercially available at the kilowatt level. Despite the low quantum defect of Yb-based solid-state lasers, there is still a considerable thermal load. Currently, there are three different laser geometries that dissipate these high thermal loads. First, Yb-doped rod-type fiber amplifier systems can reach kW-level but are limited in pulse energy extraction.[8] This boundary can be overcome by coherently combining individually cooled fiber rods.[9] Second, Yb-YAG thin-disk amplifiers cool only on one side of a thin disk and are scalable to high pulse energies and powers.[10] Third, slab type geometries can be used, where both flat surfaces of a slab are cooled, such as Innoslab technology.[11] Although OPCPA pump lasers are not the subject of this paper, the three different pump technologies allows considerable flexibility for designing OPCPAs.

Another restriction to increasing the average power of OPCPAs is thermal effects within the nonlinear crystals, caused by the absorption of the pump, signal and idler pulses. In this paper, we review the nonlinear crystals that can withstand these high pump powers including associated crystal heating through seed and idler beams. An important advantage of OPCPA is the very high gain (up to 100000) offered by the optical parametric amplification (OPA) process. Thus OPCPA laser architecture has a very short path length between the seed

Further author information: Send correspondence to R. R.
R. R.: E-mail: robert.riedel@class5photonics.com, Tel. +1 650 353 9700

Solid State Lasers XXIX: Technology and Devices, edited by W. Andrew Clarkson, Ramesh K. Shori, Proc. of SPIE Vol. 11259, 112591F · © 2020 SPIE
CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2543731

Table 1. Critical properties of nonlinear optical crystals for NIR (BBO and LBO) and SWIR (KTA) wavelengths: d_{eff} - effective nonlinear optical coefficient, ρ_{P} - walk-off angle, TT- temperature tolerance, and AT - angular tolerance. These values were calculated for BBO and LBO with $\lambda_{\text{pump}} = 515$ nm and $\lambda_{\text{signal}} = 800$ nm, and for KTA with $\lambda_{\text{pump}} = 1030$ nm and $\lambda_{\text{signal}} = 1550$ nm.[15] The nonlinear refractive index (n_2) was taken from Ref. [16] at 780 nm averaged over [100] and [010] directions. The thermal conductivity ($\bar{\kappa}$) is averaged over all crystal axes. The average linear absorption ($\bar{\alpha}$) at 515 nm for BBO and LBO are taken from Ref. [2] In the case of BBO, the three values are from three different manufactures. The values for KTA measured at 1030 nm were also from different manufactures. Note: In the case of KTA, different manufactures quote values from < 200 to < 500 ppm cm^{-1}.

crystal	d_{eff} [pm V^{-1}]	ρ_{P} [mrad]	TT [K cm]	AT [mrad cm]	n_2 [10^{-16} cm^2/W]	$\bar{\kappa}$ [W/(mK)]	$\bar{\alpha}$ [ppm cm^{-1}]
BBO	2.0	55.83	39.69	0.56	3.6	0.97[2]	13, 43, 226
LBO	0.835	7.06	6.80	4.54	2.3	3.43[2]	37
KTA	−2.0	45.03	81.43	1.91	17.0	1.93[17]	700,[3] 102[7]

generation and the final amplified output, usually using only one or two high power OPA stages. Short path lengths reduce sources of jitter and usually require no relay imaging from one amplified stage to the next. In the past, CEP-stable seed generation was achieved with a CEP-stable Ti:Sapphire oscillator.[12] Generation of the seed pulse from bulk crystal WLG, pumped from a single Yb-based solid-state laser, eliminates the need for a separate Ti:Sapphire oscillator, thereby reducing complexity. CEP-stable seeds can be generated as part of the pre-amplification process using difference frequency generation.[13]

2. OPTICAL AND THERMAL PARAMETERS OF HIGH POWER NONLINEAR CRYSTALS

Amongst the wide variety of nonlinear crystals, very few are capable of withstanding high pump powers with broadband seed and idler amplification. In the case of broadband visual to NIR amplification (650 - 1030 nm), both BBO and LBO are suitable.[12,14] A summary of some important parameters is given in Table 1. BBO has a higher d_{eff} compared to LBO, thus providing more amplification over a shorter crystal length. At very high pump powers, BBO has a higher temperature tolerance compared to LBO. This could restrict the use of LBO if there is a significant temperature gradient across the crystal, which would degrade a constant phase matching throughout the crystal. As a compensation, LBO has a higher thermal conductivity, and therefore a potentially reduced temperature gradient at high power levels.

An important parameter, which deserves some attention, is the linear absorption coefficient at 515 nm. Previously, the literature values for the linear absorption coefficients (α_{515}) were given as upper limit estimates: for example, $\alpha < 10^4$ ppm cm^{-1} at 532 nm for BBO, and $\alpha < 10^3$ ppm cm^{-1} at 532 nm for LBO.[18] Up-to-date measurements of the absorption coefficients at 515 nm using the photothermal common-path interferometry (PCI) method have been presented.[2] The results demonstrate that older values were 10 to 100 times larger than the new measured values for both BBO and LBO. In addition, a large local variation of absorption values within and on the surface of the crystals were observed (see Fig. 1 in Ref.[2]), and furthermore, typical protective coatings can also cause a large absorption. In the case of BBO, a large variation was observed between manufacturers (Table 1).

Generally, BBO and LBO are not suited for applications at SWIR wavelengths, because of their poorer phase matching conditions and the large absorption of the idler wave; however, KTA has much better phase matching conditions near 1.5 μm when pumped at 1030 nm.[19] The effective nonlinear optical coefficient (d_{eff}) is relatively high for KTA. However, at 2 μm, BBO and LBO in a broadband degenerate configuration (pumped at 1030 nm and signal at 2060 nm)[20] can be used. For high power OPCPA systems in the wavelength range of 1.5 – 2 μm, pumped at 1030 nm, KTA is most suitable. For all crystals, we expect are large variation in linear absorption both across a single crystal[2,3] and large variations when comparing different crystals both from a single manufacturer and from different manufacturers. In the case of KTA, the measured value of 700 ppm cm^{-1} is much higher than quoted values from manufacturers (see Table 1).

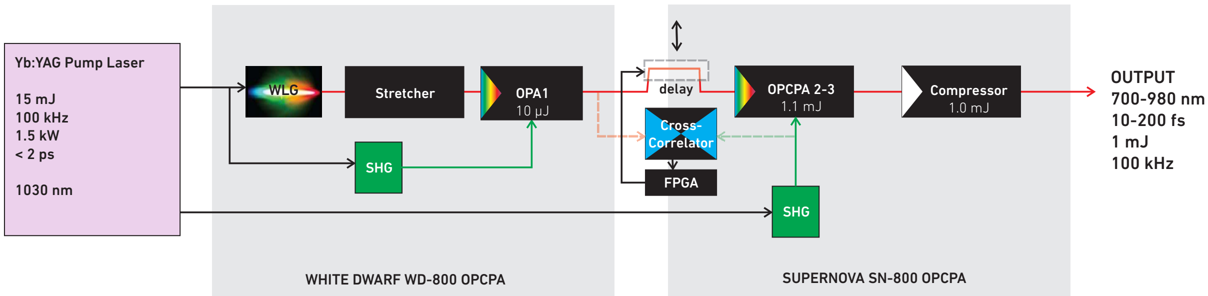

Figure 1. General schematic for a femtosecond, broadband or tunable 100 W NIR (700 – 980 nm) OPCPA with three amplification stages. The OPCPA has two components: a seed generation and pre-amplification stage (*White Dwarf WD-HE-800*) and a high power booster stage (*Supernova SN-800* from Class 5 Photonics). WLG – white-light-generation, SHG - second harmonic generation, OPA – optical parametric amplifier, FPGA – field-programmable gate array.

3. LASER ARCHITECTURES AND KEY RESULTS

Because of the power scaling and bandwidth limitations of Ti:sapphire laser systems at NIR wavelengths and the need to reduce laser complexity, initial development of high power OPCPAs centered on these wavelengths using well established nonlinear crystals of BBO and LBO.[1] Fig. 1 gives a general schematic of a broadband, high power laser system centered at 800 nm. In contrast to a typical Ti:sapphire system, the Ti:Sa-oscillator is replaced with WLG in a bulk crystal, and because pulse stretching/compression is restricted to less than 1 ps, bulk material, chirped mirrors or a prism stretcher can be used, avoiding the use of a lower efficient, stretcher/compressor grating combination, needed for a high power Ti:sapphire system. In addition, the WLG+Preamplifier can be modified to produce CEP-stable pulses to be further amplified. Note: Stretcher/compressor grating combination is usually the main source of CEP jitter,[21] which can be avoided in a OPCPA design. Furthermore, a gain greater than 10^6 is achieved with only three OPA stages, keeping the path length short compared to conventional multilevel laser gain material. Thus OPCPA systems are compact and require less maintenance compared to conventional Ti:sapphire laser systems.

An example of a tunable NIR-OPCPA system is given in Ref. ,[22] although achieving only 100 W in burst mode. In a recent implementation, a 88.6 W system with a pulse duration of 16.96 fs (FWHM) centered at 800 nm was demonstrated, providing 24 hour operation with 1.6% rms (see Fig. 3 in Ref. [4]). Pump at 1030 nm this system achieved a pump to OPCPA output efficiency of 13.1%. Further improvements to the OPCPA pump laser increased the output to 104.1 W (1.3% rms) and 134.8 W (1.8% rms).[7]

For high power, tunable output covering the SWIR range (1.4 – 2 μm), KTA was the chosen material (see Section 2), which is pumped directly at 1030 nm. KTA growth is a mature technology and can be grown in large size with high quality. An example of a typical laser architecture is given in Fig. 2. Pump to output efficiencies are expected to be higher compared to the design in Fig. 1, because the Yb-YAG pump wavelength does not need to be frequency doubled in a SHG stage. Similar to the *Supernova SN-800* design (Fig. 1), a long path grating stretcher/compressor is avoided, because Yb-YAG pump pulse durations are typically less than 2 ps.

In a current implementation, a tunable SWIR-OPCPA system was demonstrated with center wavelengths from 1.5 to 2.0 μm, using only a single booster KTA amplification stage.[6] At a center wavelength of 1.75 μm, an output power of 106.2 W with pulse duration of 104 fs (FWHM) was achieved with pump to OPCPA output efficiency of 15.7%. Idler absorption introduces a potential upper limit on the average power scaling for center wavelengths below 1.7 μm, but scaling to many hundreds of watts is possible at center wavelengths greater then 1.7 μm.[6] For further details of thermal effects see Ref. [7]

Another slightly different OPCPA design aims for an even larger wavelength regime centered at 2.1 μm with a sub-25 fs supporting bandwidth including passive CEP stability. The laser system consists of two different pump lasers temporally locked to a common oscillator (c.f. Fig. 3). First, a 30 μJ laser generates a broadband (1.7 μm to 2.5 μm) seed spectrum. This "seeder" is a combination of a standard non-collinear *White Dwarf OPCPA*

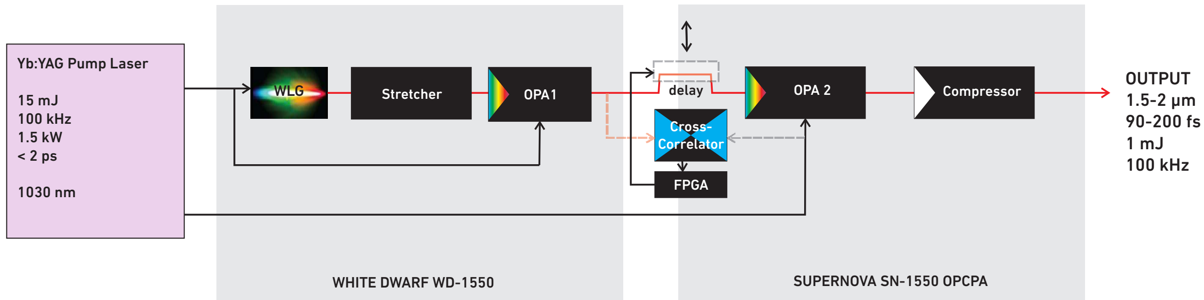

Figure 2. General schematic for a femtosecond, broadband or tunable 100 W SWIR (1.5 – 2.0 nm) OPCPA with a single booster stage. The OPCPA has two components: a seed generation and pre-amplification (*White Dwarf WD-HE-1550*) and a high power booster stage (*Supernova SN-1550* from Class 5 Photonics). WLG – white-light-generation, OPA – optical parametric amplifier, FPGA – field-programmable gate array.

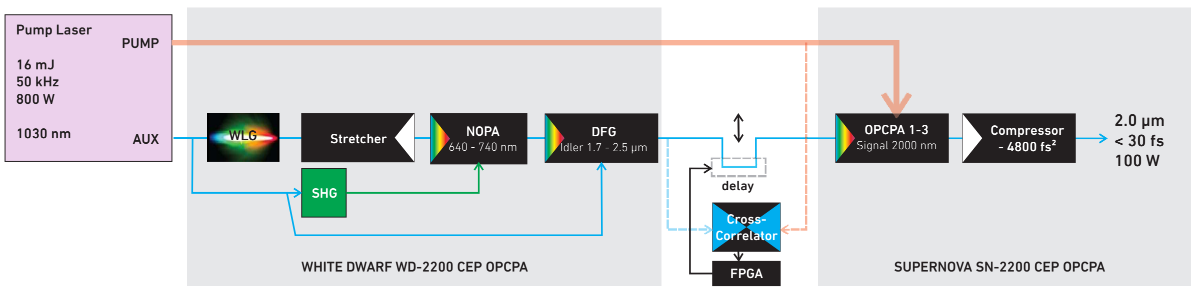

Figure 3. General schematic for a femtosecond, broadband, CEP-stable 100 W 2.1 μm laser. The OPCPA has two components: a seed generation and pre-amplification (White Dwarf WD-2200) and a high power booster stage (*Supernova SN-2200* from Class 5 Photonics). WLG – white-light-generation, SHG - second harmonic generation, NOPA – noncollinear optical parametric amplifier and OPCPA – optical parametric chirped-pulse amplifier, FPGA – field-programmable gate array.

(WD) from Class 5 Photonics tailored to a bandwidth between 660 nm and 725 nm in the visible and a BBO based collinear difference frequency generation (DFG) stage seeded with 2 μJ of 1030 nm light and pumped by the visible WD OPCPA output with 2 – 3 μJ. Subsequently, the 200 nJ CEP stable idler spectrum is pre-amplified to 1.5 W using 20 W of the main pump laser (AMPHOS1000: 50 kHz, 1 kW, 1.3 ps). A typical pre-amplified spectrum centered at 2.1 μm and beam profile is given in Fig.4. After the pre-amplification stage, two high-power stages will amplify the signal > 100 W. At the moment, the *Supernova SN-2200 OPCPA* system is under commissioning achieving more than 47 W (940 μJ at 50 kHz) in the first high power stage pumped by 16 mJ, 1030 nm pulses. The system also comprises a cross-correlator, which monitors the temporal drift of the two laser sources. A PID feedback-loop allows for drift compensation using a linear piezo-stage (c.f. Fig. 3).

4. CONCLUSION

Femtosecond 100 W-level OPCPAs from NIR to SWIR are now commercially available from *Class 5 Photonics GmbH*; options can be chosen, including multiple outputs, broadband or wavelength tunability, as well as CEP-stable output. Originally, these laser systems were developed to service the needs for free-electron laser facilities,[1,22] which require maintenance free, 24/7 operation. OPCPA technology provides a reliable compact design, requiring no complex cooling systems for output powers above 100 W. As an example, a complete OPCPA system fits on a single table of size 6×1.5 m, including an optional HHG output (Fig. 5). In summary, we believe, the key aspects OPCPA are its power – and many cases repetition rate – scalability, wavelength tunability, and its rugged compact design.

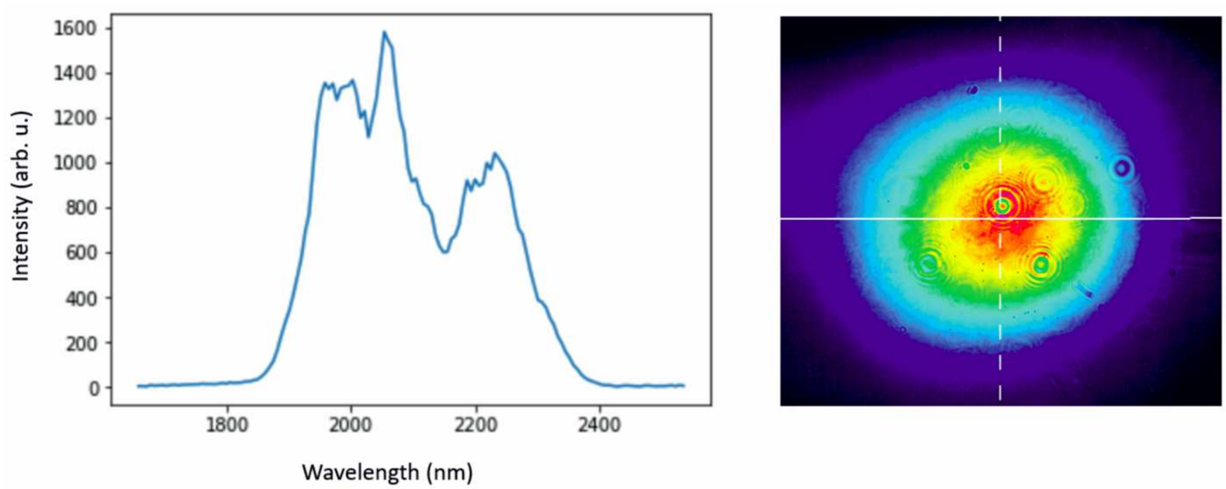

Figure 4. Typical OPCPA pre-amplified spectrum centered at 2.1 μm (left). Gaussian beam profile of the amplified 2.1 μm seed signal (right).

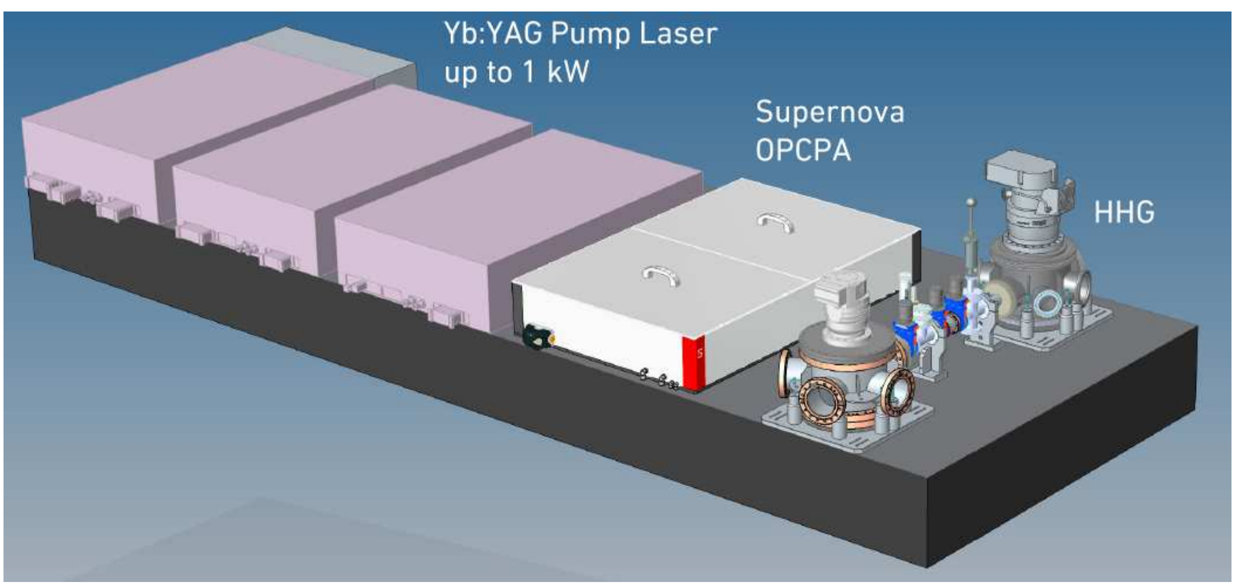

Figure 5. Schematic of a complete 100 W OPCPA system from *Class 5 Photonics GmbH*, with an optional HHG output.

ACKNOWLEDGMENTS

The authors would like to thank the Helmholtz Association for their support for the spin-off project *Class 5 Photonics GmbH.*

REFERENCES

[1] Prandolini, M. J., Riedel, R., Schulz, M., and Tavella, F., "A review of high power OPCPA technology for high repetition rate free-electron lasers," in [*Proceedings: Proc. 36th Int. Free-Electron Laser Conf., Basel, Switzerland*], *TUA02* (2014).

[2] Riedel, R., Rothhardt, J., Beil, K., Gronloh, B., Klenke, A., Höppner, H., Schulz, M., Teubner, U., Kränkel, C., Limpert, J., Tünnermann, A., Prandolini, M. J., and Tavella, F., "Thermal properties of borate crystals for high power optical parametric chirped-pulse amplification," *Opt. Express* **22**, 17607–17619 (2014).

[3] Mecseki, K., Olgun, H. T., Windeler, M., Schulz, M., Riedel, R., Tavella, F., and Prandolini, M. J., "Investigation of the critical parameters for CEP stabilized high power 1.5 mum OPCPA," in [*Solid State Lasers XXVI: Technology and Devices*], Clarkson, W. A. and Shori, R. K., eds., **10082**, 265 – 270 (2017).

[4] Mecseki, K., Windeler, M. K. R., Miahnahri, A., Robinson, J. S., Fraser, J. M., Fry, A. R., and Tavella, F., "High average power 88W OPCPA system for high-repetition-rate experiments at the LCLS x-ray free-electron laser," *Opt. Lett.* **44**, 1257–1260 (2019).

[5] Mecseki, K., Windeler, M. K. R., Robinson, J. S., Fraser, J. M., Fry, A. R., and Tavella, F., "Thermal effects in a high repetition rate 88 W average power OPCPA system at 800 nm," in [*High Power Lasers for Fusion Research V*], Awwal, A. A. S. and Haefner, C. L., eds., **10898**, 67 – 73 (2019).

[6] Windeler, M. K. R., Mecseki, K., Miahnahri, A., Robinson, J. S., Fraser, J. M., Fry, A. R., and Tavella, F., "100 W high-repetition-rate near-infrared optical parametric chirped pulse amplifier," *Opt. Lett.* **44**, 4287–4290 (2019).

[7] Mecseki, K., Windeler, M. K. R., Prandolini, M. J., Robinson, J. S., Fraser, J. M., Fry, A. R., and Tavella, F., "High-power dual mode IR and NIR OPCPA," in [*High-Power, High-Energy, and High-Intensity Laser Technology IV*], Hein, J. and Butcher, T. J., eds., **11033**, 65–75 (2019).

[8] Eidam, T., Hanf, S., Seise, E., Andersen, T. V., Gabler, T., Wirth, C., Schreiber, T., Limpert, J., and Tünnermann, A., "Femtosecond fiber CPA system emitting 830 W average output power," *Opt. Lett.* **35**, 94–96 (2010).

[9] Limpert, J., Klenke, A., Kienel, M., Breitkopf, S., Eidam, T., Hädrich, S., Jauregui, C., and Tünnermann, A., "Performace scaling of ultrafast laser systems by coherent addition of femtosecond pulses," *IEEE J. Sel. Topics Quantum Electron.* **20**, 0901810 (2014).

[10] Giesen, A. and Speiser, J., "Fifteen years of work on thin-disk lasers: Results and scaling laws," *IEEE J. Sel. Topics Quantum Electron.* **13**, 598–609 (2007).

[11] Russbueldt, P., Mans, T., Weitenberg, J., Hoffmann, H. D., and Poprawe, R., "Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier," *Opt. Lett.* **35**, 4169–4171 (2010).

[12] Riedel, R., Schulz, M., Prandolini, M. J., Hage, A., Höppner, H., Gottschall, T., Limpert, J., Drescher, M., and Tavella, F., "Long-term stabilization of high power optical parametric chirped-pulse amplifiers," *Opt. Express* **21**, 28987–28999 (2013).

[13] Baltuška, A., Fuji, T., and Kobayashi, T., "Controlling the carrier-envelope phase of ultrashort light pulses with optical parametric amplifiers," *Phys. Rev. Lett.* **88**, 133901 (2002).

[14] Prandolini, M. J., Riedel, R., Schulz, M., Hage, A., Höppner, H., and Tavella, F., "Design considerations for a high power, ultrabroadband optical parametric chirped-pulse amplifier," *Opt. Express* **22**, 1594–1607 (2014).

[15] Smith, A. V., *SNLO nonlinear optics code (Ver. 73).* AS-Photonics, Albuquerque, USA (2019).

[16] Li, H. P., Kam, C. H., Lam, Y. L., and Ji, W., "Femtosecond Z-scan measurements of nonlinear refraction in nonlinear optical crystals," *Opt. Mater.* **15**, 237–242 (2001).

[17] Ebbers, C. A. and Velsko, S. P., "Optical and thermo-optical characterization of KTP and its isomorphs for 1.06-um-pumped OPOs," *Proc. SPIE 2700, Nonlinear Frequency Generation and Conversion* **2700**, 227–239 (1996).

[18] Nikogosyan, D. N., [*Nonlinear Optical Crystals: A Complete Survey*], Springer (2005).

[19] Mücke, O. D., Ališauskas, S., Verhoef, A. J., Pugžlys, A., Baltuška, A., Smilgevičius, V., Pocius, J., Giniūnas, L., Danielius, R., and Forget, N., [*Toward TW-Peak-Power Single-Cycle IR Fields for Attosecond Physics and High-Field Science*], ch. 13, 279–300, INTECH (2010).

[20] Shamir, Y., Rothhardt, J., Hädrich, S., Demmler, S., Tschernajew, M., Limpert, J., and Tünnermann, A., "High-average-power 2 μm few-cycle optical parametric chirped pulse amplifier at 100 kHz repetition rate," *Opt. Lett.* **40**, 5546–5549 (2015).

[21] Kakehata, M., Fujihira, Y., Takada, H., Kobayashi, Y., Torizuka, K., Homma, T., and Takahashi, H., "Measurements of carrier-envelope phase changes of 100-hz amplified laser pulses," *Appl. Phys. B* **74**, s43–s50 (2002).

[22] Höppner, H., Hage, A., Tanikawa, T., Schulz, M., Riedel, R., Teubner, U., Prandolini, M. J., Faatz, B., and Tavella, F., "An optical parametric chirped-pulse amplifier for seeding high repetition rate free-electron lasers," *New J. Phys.* **17**, 053020 (2015).