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Abstract. More than 20 years after the first presentation of optical parametric chirped-pulse amplification (OPCPA), the technology has matured as a powerful technique to produce high-intensity, few-cycle, and ultra-short laser pulses. The output characteristics of these systems cover a wide range of center wavelengths, pulse energies, and average powers. The current record performance of table-top, few-cycle OPCPA systems are 16 TW peak power and 22 W average power, which show that OPCPA is able to directly compete with Ti:sapphire chirped-pulse amplification-based systems as source for intense optical pulses. Here, we review the concepts of OPCPA and present the current state-of-the-art performance level for several systems reported in the literature. To date, the performance of these systems is most generally limited by the employed pump laser. Thus, we present a comprehensive review on the recent progress in high-energy, high-average-power, picosecond laser systems, which provide improved performance relative to OPCPA pump lasers employed to date. From here, the impact of these novel pump lasers on table-top, few-cycle OPCPA is detailed and the prospects for next-generation OPCPA systems are discussed. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.53.5.051507]

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1 Introduction

Ultrafast laser amplification was revolutionized in 1985 when chirped-pulse amplification (CPA) was introduced.¹ In CPA, the low-energy sub-1-ps pulses from an ultrafast oscillator are stretched in time to several hundred picoseconds or few nanoseconds. The energy of these pulses is increased in consecutive amplifier stages to the millijoule-(mJ) or even joule-level, while the peak power remains below the threshold of optical damage and pulse distortion in the amplifiers. After amplification, these pulses are recompressed to almost the original pulse duration, allowing to obtain ultrafast pulses with terawatt (TW) peak powers.² Countless major and minor improvements on Ti:sapphire-based CPA have been reported over the last three decades. To date, table-top, high-peak-power systems exceeding 100 TW operate in laboratories around the world and are commercially available. As a result, Ti:sapphire-based CPA systems are currently the dominant driving lasers for ultrafast, high-intensity experiments.

Further increases in performance have been challenging due to two effects. First, the amplification bandwidth of Ti:sapphire systems is limited to ~ 75 nm (FWHM) centered at 800 nm, and gain narrowing associated with amplification over several orders of magnitude further narrows the obtainable bandwidth. Thus, this effect must be compensated for in order to obtain sub-35-fs pulse duration from TW-scale systems. Spectral filtering techniques can be employed to enable compressed pulse durations as short as 15 to 30 fs depending on the level of amplification.³ On the other hand, nonlinear

propagation methods can be utilized to convert a portion of the output of these CPA systems to durations in the few-cycle pulse regime. Such schemes, including spectral broadening in hollow-core fibers⁴⁻⁶ and filamentation-based self-compression,⁷⁻⁹ have been employed to shorten the pulses to quasi-single-cycle duration with up to several mJ-level pulse energies resulting in peak powers at the 1 TW-level. The second limiting effect in Ti:sapphire CPA systems prohibits the output average power to be scaled beyond 30 to 40 W with cryogenically cooled amplifier stages.¹⁰ Compensation of thermal effects and beam distortions become increasingly challenging at this performance level. High repetition rate systems have been presented operating with high average power, such as a system providing 26 W compressed with duration of >50 fs.¹¹

Extending the concept of CPA, the method optical parametric chirped-pulse amplification (OPCPA) was first presented in 1992.¹² Similar to CPA, an ultrashort pulse is first stretched in time, amplified, and recompressed. In contrast to CPA, in which amplification is based on stimulated emission, OPCPA transfers energy from a pump beam to a seed beam in an optical parametric amplifier (OPA). The amplification bandwidth can span almost one octave supporting sub-10-fs pulse durations in the visible spectrum. These pulses are referred to as optical few-cycle pulses since their durations approach the duration of an optical cycle (2.66 fs at 800 nm wavelength). In contrast to traditional amplification via stimulated emission in pumped laser crystals, no energy is directly stored during the amplification process in the nonlinear material due to the instantaneous nature of the OPA process, thereby mitigating typical thermal effects and beam distortions, thereby facilitating power and

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energy scaling of the OPA systems. The pulses from table-top OPCPA systems have been compressed to the few-cycle regime, with the nominal current record durations of 5.0 fs (1.7 cycles) at 0.88 μm ,¹³ 10.5 fs (1.5 cycles) at 2.1 μm ,¹⁴ 67 fs (6.3 cycles) at 3.2 μm ,¹⁵ and 83 fs (6.4 cycles) at 3.9 μm .¹⁶ As will be discussed later, table-top OPCPA systems are primarily limited in terms of pulse energy and average power by the employed pump laser; however, onset of parasitic effects have been reported and will be discussed in Sec. 2.4. The records in terms of peak power [16 TW (Ref. 17)] and average power [22 W (Ref. 13)] indicate that the OPCPA method has matured to a performance level comparable to Ti:sapphire-based CPA systems, with the advantage of shorter pulse durations and wavelength tunability from the visible to mid-IR range.

Here, we give a detailed review of the current performance level and the prospects of table-top, few-cycle OPCPA systems based upon recent developments in table-top, high-energy, high-average-power picosecond laser systems. References 18, 19, and 20 provide excellent overviews on the traditional OPCPA architecture, while the OPA process itself has been reviewed comprehensively in Ref. 21, and essential parameters based on simulations for visible OPCPA based upon beta barium borate ($\beta\text{-BaB}_2\text{O}_4$; commonly referred to as BBO) crystals are presented in Ref. 22. Since the focus in this article is on the recent developments in table-top, few-cycle OPCPA, we intentionally disregard large-scale, petawatt- (PW) level OPCPA laser systems. A few example articles for further reading on PW-scale OPCPA systems include a prospective view in Ref. 23 and a presentation of a full system providing 300 TW in Ref. 24, while Refs. 25, 26, and 27 describe relevant PW-level OPCPA designs.

2 Table-Top, Few-Cycle OPCPA Systems

Several relevant concepts and trends in OPCPA are reviewed in the following sections, starting with an overview on the early pioneering work toward the generation of few-cycle pulses via OPA and OPCPA. The second section introduces the advantages, challenges, and limitations of few-cycle OPCPA, followed by a section highlighting the record performance levels demonstrated to date. The section concludes with a detailed discussion of the performance of representative OPCPA systems and their pump lasers.

2.1 Pioneering Few-Cycle Optical Parametric Amplification

The OPCPA method was first presented in 1992 by Dubietis et al. with a system incorporating a stretcher, an OPA stage, and a compressor, resulting in energetic 70-fs pulses.¹² This development was followed rapidly with ground-breaking investigations toward the generation of intense few-cycle pulses. The pioneering work of Gale et al. in 1995 resulted in the presentation of the shortest pulse duration from a laser oscillator at this time with 13 fs and nanojoule-level pulse energy.²⁸ The authors also demonstrated the tunability of the sub-20-fs pulses from the megahertz optical parametric oscillator over a range from 590 to 666 nm center wavelength (see also Ref. 29). Hereafter, several groups investigated few-cycle OPA systems based upon BBO pumped by Ti:sapphire CPA systems enabling the generation of intense sub-10-fs pulses with wide tunability. In 1998, Nisoli et al.

employed two OPA stages in collinear configuration to generate 10- μJ -level pulses with 14.5 fs in the near-IR (center wavelength of 1.5 μm),³⁰ and Cerullo et al. used a noncollinear configuration to generate visible sub-8-fs pulses with 2 μJ energy and bandwidth ranging from 510 to 800 nm.³¹ In the same period, Wilhelm et al.³² in 1997 and Riedle et al.³³ in 2000 reported 10- μJ -level, sub-20-fs pulses tunable from 470 to 750 nm and 870 to 1500 nm, respectively. Shirakawa et al. reported in 1998 on a compact noncollinear optical parametric amplification (NOPA) system amplifying pulses with 5 μJ pulse energy and 6.2 fs duration at 630 nm or 8.4 fs at 1.1 μm , respectively,³⁴ and Kobayashi and Shirakawa presented in 2000 sub-5-fs pulses.³⁵ Further improvements on the latter system by Baltuška et al. in 2002 including an ultrashort, white-light, seed pulse and an adaptive pulse compressor enabled the generation of sub-4-fs pulses with 0.5 μJ pulse energy.³⁶ Since most of these pioneering few-cycle OPA implementations were driven by Ti:sapphire-based CPA systems with mJ-level pulse energy and kilohertz repetition rate, the generated few-cycle pulses were limited to the 100 μJ and 0.1 W average power-level. However, the impressive results in the late 1990s demonstrated the potential of energetic few-cycle pulses from OPA (Ref. 21) and lead to the development of few-cycle OPCPA systems driven by a variety of laser technologies, as shown in Sec. 2.6.

2.2 Optical Parametric Chirped-Pulse Amplification

NOPA is capable of supporting the amplification of an almost-octave spanning bandwidth. Several parameters are critical in this process: nonlinear medium, phase-matching conditions, input angle, wavelengths, crystal thickness, and pump intensity. A schematic of the geometry is shown in Fig. 1(a) and a photograph of a laboratory implementation is shown in Fig. 1(b).

The most-commonly used OPCPA architecture for few-cycle pulses in the visible is based on BBO as nonlinear material. This approach has been used to generate the current record performances in terms of peak power and average power. Here, the pump wavelength ranges typically from 343 to 532 nm, depending on the pump lasers. The typical amplification bandwidth ranges from <725 to >1050 nm when pumped at 532 nm wavelength and 3 to 5 mm crystal lengths are employed.³⁷ This bandwidth supports a transform-limited duration of <8 fs or less than three optical cycles.³⁸ Additionally, octave-spanning bandwidth to support quasi-single-cycle pulses can be obtained by pumping consecutive OPA stages with different wavelengths. This is most easily done with different harmonics of the fundamental pump laser, i.e., 532 and 355 nm for Nd:YAG-based pumps or 515 and 343 nm for Yb-based pumps. This concept was introduced in 2010 with mJ-level pulses³⁹ and experimentally verified in a different setup in 2012 with microjoule-level pulse energies and compressed to 4.6-fs duration.⁴⁰

The key parameters determining the parametric gain are the used pump intensity and the length of the crystal. Figure 2(a) shows example calculations for the parametric gain following the assumptions in Ref. 21 for BBO as nonlinear material. Pump intensities from 10 to 100 GW/cm^2 and crystal lengths from 1 to 5 mm are presented. It can be seen that a large parametric gain in excess of 10^6 can

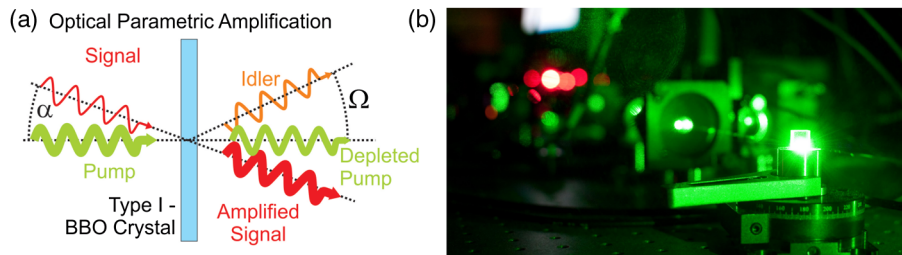


Fig. 1 (a) Schematic of the noncollinear optical parametric amplification (NOPA) geometry showing the geometry for pump, signal, and idler beam. (b) Laboratory picture of an optical parametric amplifier (OPA) setup with the green pump beam visible aligned through a BBO crystal.³⁷

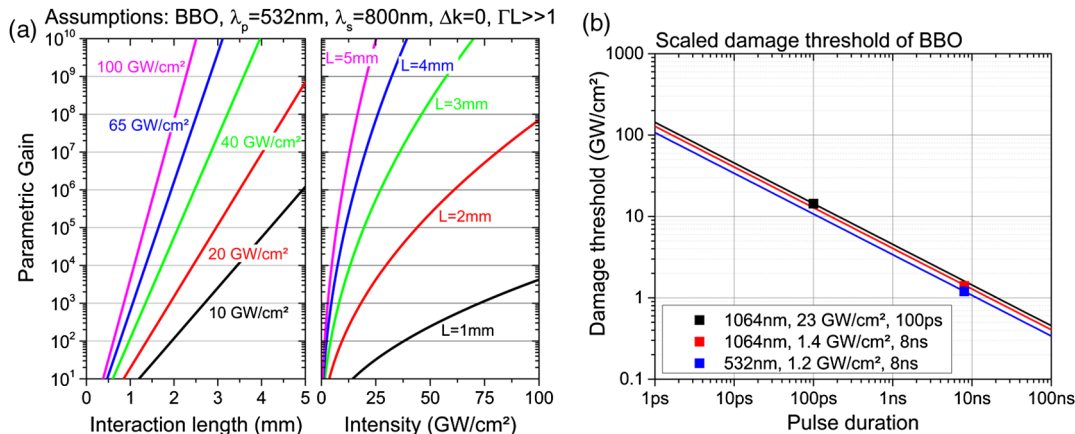


Fig. 2 (a) Calculated parametric gain in dependence of the interaction length and the pump intensity. (b) Scaled⁴⁴ damage threshold^{45,46} of BBO in the femtosecond to nanosecond range.

be obtained in these configurations. Experimentally, high parametric gains of 10^3 (Ref. 17), 10^4 (Ref. 41), or even 10^6 (Ref. 42) are typically employed in the first OPA stage of OPCPA systems, while a parametric gain of up to 10^8 has been experimentally demonstrated from a femtosecond OPA stage.⁴³ Figure 2(b) shows the scaled damage threshold in BBO based on the empirical squared root scaling law of the damage threshold with pulse duration⁴⁴ and values found in the literature.^{45,46} It can be seen that sub-100-ps pulses are necessary to avoid damage and enable pump intensities of 10 GW/cm^2 and above.

On the other hand, it is well known that employing a shorter crystal has the benefit to relax requirements on the wave-vector mismatch for the OPA process. BBO crystals of several lengths have been utilized in the literature: for example, a single 1-mm-long BBO crystal for the amplification of sub-4-fs pulses³⁶ and two 2-mm-long crystals for the amplification of 5.0-fs pulses to 87- μJ pulse energy.⁴¹ A combination of a 3-mm- and a 5-mm-long crystal has been used to amplify 5.7-fs pulses to 3- μJ pulse energy⁴⁷ and two 5-mm-long crystals to amplify 7.9-fs pulses to 130-mJ pulse energy.¹⁷ In general, shorter crystals enable a wider phase-matching bandwidth and allow OPA stages to support almost-octave spanning bandwidths. In order to obtain the same gain from shorter crystals, higher pump intensities must be employed. A trend from reported OPCPA systems can be found in the utilization of short picosecond pump pulses, enabled by the recent developments in

Yb-based CPA laser technology providing high-energy, high-average-power pumps with 0.5- to 1-ps duration.

The energy transfer efficiency in OPCPA from pump to signal pulse is typically on the order of 10 to 15% and dependent on the amplified bandwidth. Generating the record table-top, few-cycle OPCPA pulse energy of 130 mJ required a pump pulse energy of 1.0 J at 532 nm wavelength,¹⁷ and the record average power of 22 W required a pump laser with 120 W average power at 515 nm wavelength.¹³ For OPCPA at 2.1 μm center wavelength, the current record efficiency is 6.7% with an amplified pulse energy of 0.74 mJ pumped by 11 mJ pulse energy at 1053 nm wavelength.⁴⁸ It is interesting to note that OPCPA compared to Ti:sapphire-based CPA is, in general, less efficient in terms of pump to signal conversion since Ti:sapphire systems operate with conversion efficiencies of 30 to 40%.⁴⁹ In addition, it is worth noting that the required lasers to pump Ti:sapphire are typically commercially available, Nd-based, master oscillator power amplifiers (MOPA) providing high energetic nanosecond pulses (5 to 10 ns). In contrast, OPCPA requires extremely stable picosecond pump lasers with high peak power. The performance of such pump lasers is the primary limitation upon scaling of pulse energy and/or average power in OPCPA systems.

2.3 Traditional OPCPA Architecture

The amplification via OPCPA of few-cycle pulses typically follows the laser architecture^{21,23} as shown in Fig. 3 and described in the following. The front-end of the OPCPA

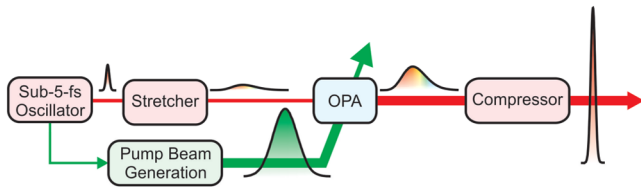


Fig. 3 Traditional optical parametric chirped pulse amplification (OPCPA) architecture in the visible based upon a sub-5-fs oscillator, a pulse stretcher, the broadband amplification in the OPA, and a compressor to retrieve almost the original pulse duration. The pump beam is typically derived from the front-end oscillator to ensure optical synchronization and utilizes in the pump beam generation multiple amplification stages resulting in a high-energetic picosecond pump pulse.

architecture is typically a mode-locked, octave-spanning Ti:sapphire oscillator covering the required amplification bandwidth.⁵⁰ However, a few OPCPA systems have been reported that utilize nonlinear spectral broadening of pulses from either a Ti:sapphire oscillator^{13,40} or a Ti:sapphire-based CPA system¹⁷ to seed the OPA. For center wavelengths different from the visible Ti:sapphire bandwidth, nonlinear frequency conversion based upon the octave-spanning Ti:sapphire bandwidth, typically via difference frequency generation (DFG)^{51,52} or OPA,¹⁶ has been employed to provide the seed pulses at various center wavelengths such as in the mid-IR. In addition, OPCPA systems seeded by stable white light filamentation in bulk material, such as a YAG plate generated by a portion of the typical sub-1-ps pump laser, have been reported.⁵³⁻⁵⁵

Pulse stretching for sub-10-fs pulses in the visible can be achieved with a grism stretcher, based on a combination of grating and prism pairs, an acousto-optical programmable dispersive filter (AOPDF) for phase fine-adjustments and compression in bulk glass compressor. This method has been shown to allow complete dispersion compensation over >300 nm bandwidth in the visible supporting sub-10-fs pulses^{56,57} and has been numerically extended for sub-5-fs pulses.⁵⁸ For wavelengths in the IR, dispersive glasses can be utilized to up or down chirp the pulse and ultrashort pulse shapers such as AOPDF are commercially available.^{14,51} Dispersion management becomes increasingly challenging for wavelengths >4 μm and mainly grating/grism pairs are used without adaptive shaping.⁵⁹

In the traditional OPCPA architecture shown in Fig. 3, the pump laser is typically optically or electronically synchronized to the front-end oscillator. The timing jitter requirement at the OPA stage ranges from sub-picosecond to 10 ps depending on the employed pulse durations, pulse shapes, and output stability requirements. The electronic synchronization has been presented for 60 ps pump pulse durations.⁶⁰ The optical synchronization is commonly preferred since its performance is typically better than the minimum requirement.⁶¹ A jitter of several 100 fs from a pump scheme with sub-1-ps pulse duration has been reported as significant and was actively stabilized, since it otherwise induces fluctuations on the parametric gain, bandwidth, and center wavelength.⁶² Recently, an investigation has shown that the obtainable carrier-envelope phase (CEP) stability also depends on the pump-to-signal timing jitter and a CEP-stabilization with 86 mrad has been realized associated with a residual pump-to-signal timing jitter of 18 ± 4 fs with ~ 500 fs pump pulse duration.⁶³

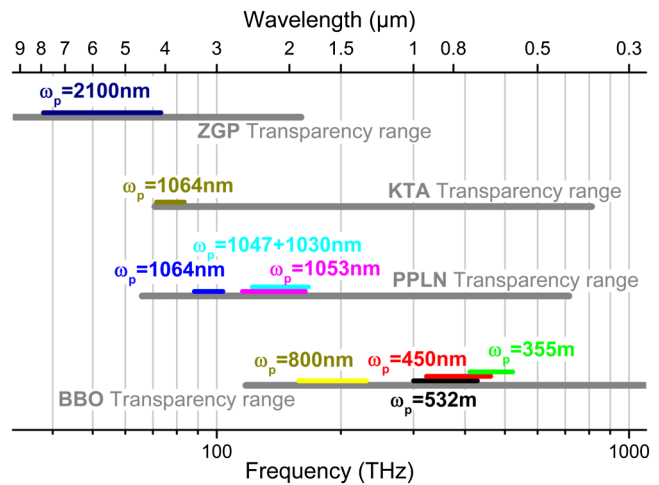


Fig. 4 The colored bars represent the few-cycle OPCPA bandwidth of reported systems for few different crystals, pump wavelengths, and phase matching condition. The gray bars represent the typical transparency range of the employed crystals. Note that the tuning range of the mentioned OPA stages can be larger than the indicated OPCPA bandwidths and extremely wide OPA tuning ranges covering the visible⁵⁵ to near-IR⁶⁵ and mid-IR⁶⁶ have been reported.

2.4 Visible to Mid-IR Few-Cycle Pulses

A major advantage of OPCPA compared to its main competitor, the Ti:sapphire-based CPA, is the possibility to operate at center wavelengths spanning the near-IR to the mid-IR. This is achieved by the choice of a nonlinear crystal, pump wavelength, as well as phase-matching geometry. Several OPCPA systems have been presented operating with few-cycle durations covering almost continuously the spectrum from the visible (0.6 μm) to the mid-IR (8 μm), which are summarized in Fig. 4. The transparency ranges of the employed nonlinear crystals are given, which were found via the freely available software package SNLO (AS-Photonics, LLC, Albuquerque, New Mexico).⁶⁴

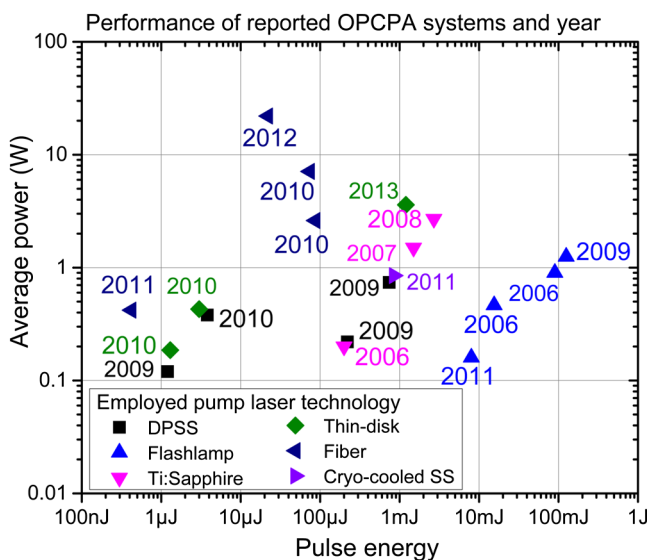
A few crystal and wavelength combinations are detailed in the following. An OPCPA system has been presented in 2011, using MgO:PPLN (periodically poled lithium niobate) pumped at 1049 nm as well as a BBO crystal pumped at 1030 nm, providing parametric amplification from 1.8 to 2.5 μm centered at 2.1 μm .^{15,51} After compression, this produced few-cycle pulses with 0.85 mJ pulse energy at 1 kHz with 32 fs duration (4.5 optical cycles). A comparable system has been presented pumped at 1053 nm with 49 ps using PPLN and BBO crystals.⁴⁸ This system operates with 15.7 fs duration (2 optical cycles) at 2.1 μm center wavelength and 0.74 mJ energy. Further in the IR, a system has been presented operating at 3.2 μm with 67 fs duration (6.3 optical cycles) and generating 3.8 μJ pulse energy at 100 kHz.¹⁵ A system operating at 3.9 μm was presented in 2011, which used KTA (Potassium Titanyl Arsenate, KTiOAsO₄) crystals and produced pulses with 83 fs duration (7 optical cycles) and 8 mJ energy corresponding to 90 GW peak power.¹⁶ The longest-wavelength OPCPA presented to date provided amplification from 4.1 to 7.9 μm centered at 6 μm .⁵⁹

2.5 Current Performance Level of Table-Top, Few-Cycle OPCPA

The performance of the reported OPCPA systems are listed in Table 1 and graphically represented in Fig. 5 with the year

Table 1 List of selected optical parametric chirped pulse amplification (OPCPA) systems reported in the literature, which are graphically illustrated in Fig. 5. See Table 2 for the list of acronyms.

Ref	Pulse energy	Average power	Pulse duration	Peak power	Center wavelength	Pump technology	Pump duration
38	90 mJ	0.9 W	10 fs	9.0 TW	0.8 μm	Flashlamp	60 ps
60	16 mJ	0.47 W	7.6 fs	2.1 TW	0.8 μm	Flashlamp	60 ps
65	200 μJ	0.2 W	15 fs	13 GW	1.5 μm	Ti:sapphire	50 fs
69	1.5 mJ	1.5 W	6.4 fs	230 GW	0.8 μm	Ti:sapphire	100 ps
67	2.7 mJ	2.7 W	5.5 fs	490 GW	0.8 μm	Ti:sapphire	75 ps
52	1.2 μJ	0.12 W	96 fs	13 MW	3.2 μm	DPSS	15 ps
42	220 μJ	0.22 W	23 fs	9.6 GW	2.2 μm	DPSS	12 ps
48	740 μJ	0.74 W	15.7 fs	47 GW	2.1 μm	DPSS	49 ps
17	0.13 J	1.3 W	7.9 fs	16 TW	0.805 μm	Flashlamp	78 ps
15	3.8 μJ	0.38 W	67 fs	56 MW	3.2 μm	DPSS	8 ps
53	0.4 μJ	0.42 W	9.7 fs	43 MW	0.8 μm	Fiber	0.42 ps
70	74 μJ	7.1 W	8.0 fs	9.3 GW	0.8 μm	Fiber	0.78 ps
71	1.3 μJ	0.19 W	8.8 fs	150 MW	0.8 μm	Thin-disk	1.6 ps
47	3 μJ	0.43 W	5.7 fs	530 MW	0.85 μm	Thin-disk	1.6 ps
51	850 μJ	0.85 W	32 fs	27 GW	2.1 μm	Cryo SS	12 ps
41	87 μJ	2.61 W	5.4 fs	16 GW	0.8 μm	Fiber	0.70 ps
16	8 mJ	0.16 W	83 fs	96 GW	3.9 μm	Flashlamp	70 ps
13	22 μJ	22 W	5.0 fs	4.4 GW	0.88 μm	Fiber	0.50 ps
14	1.2 mJ	3.6 W	10.5 fs	114 GW	2.1 μm	Thin-disk	1.6 ps


Fig. 5 Graphical overview of the performance of reported OPCPA systems. A color code is employed to emphasize the impact of the pump laser technology on the overall OPCPA performance. See Table 1 for the list of references and Table 2 for the list of acronyms.

of publication noted (see Table 2 for list of acronyms). All of these systems operate with few-cycle pulse duration with center wavelengths ranging from 0.8 to 3.9 μm . A few outstanding record table-top OPCPA systems are listed in the following. The highest OPCPA peak power presented to date is 16 TW corresponding to 130 mJ and 7.9 fs duration with a contrast of 10^{-12} for ± 30 ps.¹⁷ The record pulse energy for repetition rates around 1 kHz is 2.7 mJ with 5.5 fs pulse duration corresponding to a peak power of 490 GW.⁶⁷ The highest average power was reported in Ref. 13 with 22 W at 1 MHz repetition rate and a nominal pulse duration of 5.0 fs corresponding to 1.7 optical cycles. Similar to other OPCPA publications with durations of 5.5 fs (Ref. 67) and 5.7 fs (Ref. 47), the reported central pulse of 5 to 6 fs duration is surrounded by side pulses, which potentially degrade pulse contrast and affect usability for high pulse intensity experiments.⁶⁸

Even shorter pulse durations have been reported recently, employing different pump wavelengths in multiple OPA stages. This method enabled the generation of a waveform with a 4.6 fs duration, where two consecutive OPA stages pumped by the second harmonic generation (SHG) and third harmonic generation of the pump beam, respectively, resulted in an amplified bandwidth covering from 430 to

Table 2 List of acronyms and definitions.

Acronym	Definition
Flashlamp	Based upon flashlamp-pumped amplifiers
Ti:sapphire	Based upon Ti:sapphire-based amplifiers
DPSS	Based upon diode-pumped solid-state amplifiers
Fiber	Based upon Yb-doped fiber-based amplifiers
Thin-disk	Based upon Yb:YAG thin-disk amplifiers
Cryo SS	Based upon cryogenically cooled Yb-based solid-state amplifiers
MOPA	A system in master oscillator power amplifier configuration
CPA	A system in chirped-pulse amplification configuration

1300 nm (−40 dB).⁴⁰ In a similar scheme, two separate OPCPA systems have been employed (covering a bandwidth from 0.75 to 1.1 μm and 1.9 to 2.5 μm) to synthesize a waveform with a central region of 0.8 cycles (FWHM) corresponding to 2.1 fs.⁷² In contrast to these OPCPA systems with quasi-single-cycle pulses, visible sub-10-fs (Ref. 17) and near-IR sub-20-fs pulses^{42,48} can provide a more uniform spectrum, with potentially increased temporal contrast in the femto- to picosecond range. The shortest duration reported from OPA itself is 4.0 fs at a 600 nm center wavelength corresponding to 2.0 optical cycles.³⁶ The lowest number of cycles reported is 1.5 at a center wavelength of 2.1 μm .¹⁴ Most of the record OPCPA performances were achieved when operated in the visible spectrum based upon BBO as a nonlinear medium.

Figure 5 employs a color code that relates the OPCPA performance to the utilized pump laser technology. It can be seen that high pulse energies, exceeding the 10 mJ-level, have only been achieved when pump lasers were employed based on flashlamp-pumped solid-state amplifiers. On the other hand, the highest average power regime demonstrations have utilized fiber and thin-disk pump lasers. For the range in between, several pump technologies have been employed providing comparable performance.

The reported OPCPA systems cover a wide parameter range due to the advantages of OPA and the absences of any stored energy in the nonlinear material (besides the parasitic effects discussed later in this paragraph). The latter is in contrast to traditional laser amplification based upon stimulated emission, in which a high amount of energy can be stored in the amplification medium resulting in thermally induced beam distortions, such as thermal lensing. For OPCPA, it seems that the performance is currently still scalable in terms of pulse energy and average power and that OPCPA is primarily limited by the performance of the employed pump lasers. It has been found recently that parasitic effects in the nonlinear crystal can lead to heat accumulation in the OPA stage of a high-average-power system. In this context, the most dominate parasitic effect in BBO-based visible NOPA, as shown experimentally in Ref. 73, results from absorption of the idler beam. This is due to the limited transparency range, which covers in a 1-

cm-long BBO crystal the range from 0.2 to 2.6 μm for the 0.5 transmittance level, while the linear absorption value at 2.55 μm is significant at 0.5 cm^{-1} .⁷⁴ Thus, for visible NOPA covering the range from 625 to 950 nm, pumped at 515 nm and with generated idler beam ranging from 1.1 to 2.9 μm , the nonvanishing absorption in BBO can become a limiting factor for further power scaling beyond the current level. In addition, the non-negligible linear absorption across the transparency range (for example, in BBO of 0.01 cm^{-1} at 0.532 nm or 0.001 cm^{-1} at 1.0 μm)⁷⁴ or multiphoton absorption results in additional heat accumulation. This heat-affected zone in the OPA stage can impact the phase-matching condition and induce thermal lensing or potentially fracture/damage the OPA material. These novel thermally induced effects in OPA are under investigation in many research laboratories around the world. We expect several approaches to mitigate thermal effects in OPAs emerging from this research.

2.6 Experimentally Demonstrated Pump Laser Schemes

Over the last seven years, several radically different pump laser schemes have been implemented as OPCPA pump lasers. Here, we review the progress of these laser systems and the influence on the OPCPA output performance. The performances of the pump lasers of the OPCPA systems from Fig. 5 are listed in Table 3 and graphically shown in Fig. 6 (see Table 2 for list of acronyms). The latter shows the pulse energy and average power of the employed pump lasers relative to the year of publication.

Several trends can be extracted from Fig. 6: It can be seen that the highest pulse energy has been achieved utilizing flashlamp-pumped solid-state amplifiers. Based on the performance shown in Fig. 6, flashlamp-pumped amplifiers are the only OPCPA-proven technology in this context that result in pump pulse energies $>100\text{ mJ}$, with a record energy of 1.5 J with 15 W average power. The pulse provided by the system had 110 ps duration corresponding to 14 GW

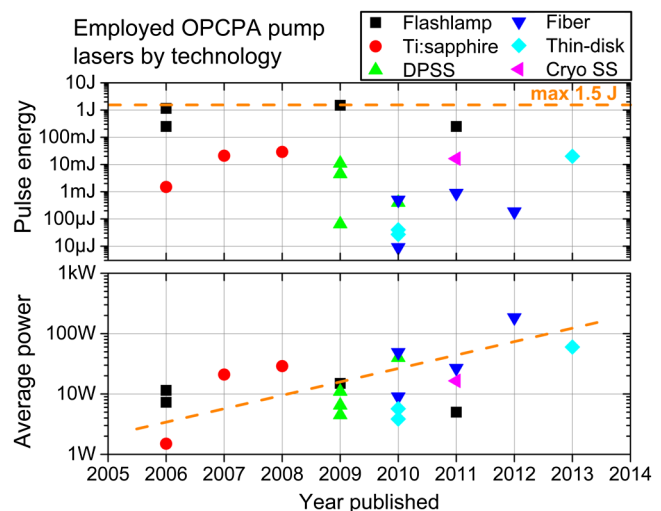


Fig. 6 Performance of OPCPA pump lasers in terms of pulse energy and average power against the year of publication. The pump laser systems are differentiated by color code corresponding to their laser technology. See Table 3 for the list of references and Table 2 for the list of acronyms.

peak power at 1064 nm center wavelength.¹⁷ This pump laser generated the current record performance in terms of pulse energy and peak power for table-top OPCPA systems with an output of 130 mJ and 16 TW, respectively. Other systems have been presented for OPCPA pumping, such as a 250-mJ pulse energy system with 70 ps duration at 20 Hz repetition rate¹⁶ and a system providing 160-mJ, 60-ps pulses at 30 Hz.⁶⁰ It can be seen that high pulse energy is achieved with this technology, but the corresponding average power is limited to the 20 W-level.

On the other side, the highest average power was demonstrated with a fiber-based pump laser system. This system operated at a repetition rate of 1 MHz providing 200 W average power and 200 μJ pulse energy at 1030 nm center wavelength with 0.47 ps duration before SHG to 515 nm to pump an OPCPA system.¹³ This pump laser enabled the record OPCPA average power performance of 22 W with a peak power of 4.4 GW.¹³

Several systems have been presented providing both high pulse energy as well as high average power. The earliest systems were based on narrow-band, picosecond pump systems providing 10 mJ-level pulse energies at kilohertz repetition rate. In 2007, such a pump system based on Ti:sapphire amplifiers provided 4 and 10 mJ at 400 nm with ~70 ps duration.⁶⁹ A Nd:YLF regenerative and multistage amplifiers were used to generate 11 mJ at 1 kHz repetition rate with 49 ps duration.⁴⁸ A similar system of Nd:YLF regenerative and multipass amplifier was used to generate 7 mJ pulse energy with 110 ps duration, which was compressed to 12 ps and 4.5 mJ.⁴² A commercial mode-locked Nd:YVO₄ system (Lumera Laser GmbH, Germany) producing 10 W at

100 kHz with 0.1 mJ pulse energy and 8.7 ps duration was the OPCPA pump laser in Ref. 52.

More recently, Yb-based CPA systems have been introduced as OPCPA pumps allowing significant increases in average power due to their superior thermal handling compared to Nd-based systems and reduction in pulse duration via CPA. A cryogenically cooled solid-state system has been used as OPCPA pump based on a Yb:YAG regenerative amplifier operating at 1 kHz, 13 mJ, 15 ps, 13 W.⁵¹ A Yb:YAG thin-disk system has been used as a pump with 20 mJ at 1030 nm and 3 kHz, 1.6 ps duration.¹⁴ The performance benefits of Yb-based CPA systems are highlighted in Sec. 3.3.

3 Recent Developments on Picosecond, High-Energy, and High-Average-Power Lasers

This section reviews the recent progress in relevant laser technologies that will impact the performance of the OPCPA systems in the near future. The pump laser systems mentioned in Sec. 2.5 are listed in Table 3 and graphically shown in Fig. 7(a) in terms of pulse energy and average power. Similarly, the performances of several recently reported laser systems are listed in Table 4 and graphically shown in Fig. 7(b) (see Table 2 for list of acronyms). These two figures are placed next to one another in order to directly compare the performance of pump lasers that have been employed for OPCPA with that of recently reported picosecond laser systems. In addition, trends are identified in this chapter for the recently reported systems and the direct impact on the performance of OPCPA systems in the near future is discussed.

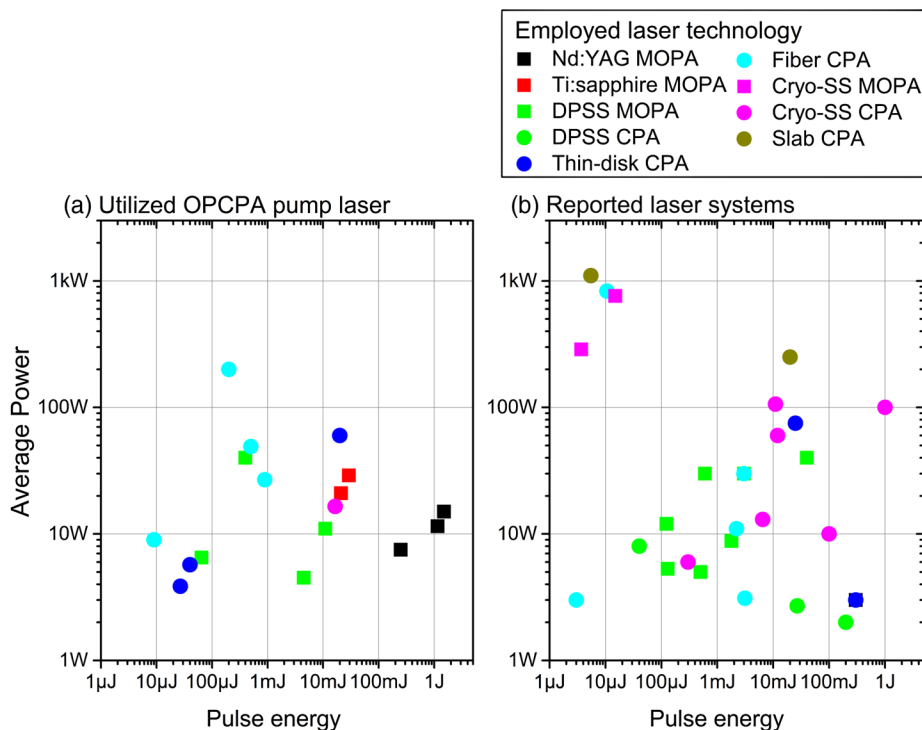


Fig. 7 (a) Performances of the pump lasers of reported OPCPA systems in terms of pulse energy and average power. (b) Performance of recently demonstrated high-energy, high-average-power picosecond laser system. The laser systems are differentiated by color code corresponding to their laser technology. See Tables 3 and 4 for the list of references and Table 2 for the list of acronyms.

Table 3 List of the performances of the pump lasers employed in reported OPCPA systems (Fig. 5), which are graphically illustrated in Figs. 6 and 7. See Table 2 for the list of acronyms.

Ref.	Laser technology	Scheme	Pulse energy	Average power	Pulse duration	Peak power
38	Flashlamp	MOPA	1.15 J	11.5 W	110 ps	10 GW
60	Flashlamp	MOPA	250 mJ	7.5 W	85 ps	2.9 GW
65	Ti:sapphire	CPA	1.5 mJ	1.5 W	50 fs	30 GW
69	Ti:sapphire	MOPA	21 mJ	21 W	141 ps	150 MW
67	Ti:sapphire	MOPA	29 mJ	29 W	106 ps	273 MW
52	DPSS	MOPA	65 μ J	6.5 W	15 ps	4.3 MW
42	DPSS	MOPA	4.5 mJ	4.5 W	12 ps	380 MW
48	DPSS	MOPA	11 mJ	11 W	49 ps	225 MW
17	Flashlamp	MOPA	1.5 J	15 W	110 ps	14 GW
15	DPSS	MOPA	400 μ J	40 W	12 ps	33 MW
53	Fiber	CPA	9 μ J	9 W	420 fs	21 MW
70	Fiber	CPA	500 μ J	49 W	1.1 ps	460 MW
71	Thin-disk	CPA	40 μ J	5.7 W	1.56 ps	25 MW
47	Thin-disk	CPA	27 μ J	3.85 W	2.3 ps	12 MW
51	Cryo SS	CPA	16.5 mJ	16.5 W	12 ps	1.4 GW
41	Fiber	CPA	890 μ J	26.8 W	990 fs	900 MW
16	Flashlamp	MOPA	250 mJ	5 W	70 ps	3.6 GW
13	Fiber	CPA	120 μ J	120 W	500 fs	240 MW
14	Thin-disk	CPA	20 mJ	60 W	1.6 ps	12.5 GW

3.1 Flashlamp-Pumped and Diode-Pumped Solid-State MOPA Systems

The highest pulse energies from OPCPA systems have been reported when employing flashlamp-pumped solid-state amplifiers. The technology utilizes large-aperture Nd:YAG rods with large amounts of stored energy to reach joule-level pulse energies with repetition rates of 30 Hz and lower. Based on the comparison here, no other laser technology has been used to obtain higher pulse energies. Since this technology offers compact optical setup, it is the most common path for the generation of ultrahigh-energy pulses and moderate average powers. Thus, the current record OPCPA peak power of 16 TW was enabled by flashlamp-pumped amplifiers in the pump beam generation. Higher average powers are generally prohibited by the low efficiency of flashlamp pumping and the associated demands on the high-voltage power supplies/switching electronics. As a consequence, this mature technology has been generally limited to 10 W-level average powers but with ultrahigh pulse energies at the joule-level.

A compromise between pulse energy and average power can be realized with diode-pumped solid-state amplifiers, such as Nd:YAG or Nd:YVO₄. In this case, the average powers are sufficiently high that thermally induced lensing and depolarization must be compensated. A system has been

demonstrated operating at 1 kHz with Nd:YAG amplifiers producing an output energy of 40 mJ, 48 ps duration and a corresponding average power of 40 W.⁹⁴ At higher repetition rates, a system has been presented operating with 33.7 W and 20 kHz with \sim 220 ps pulse duration corresponding to 7 MW peak power.¹⁰³ Another system has been demonstrated based on Nd:YVO₄ slab amplifier with 0.6 mJ pulse energy and 12 ps duration corresponding to an average/peak power between 46 W/38 MW and 30 W/50 MW.⁹⁵ All of these systems offer high performance with compact footprint due to the MOPA architecture.

3.2 Yb:YAG Thin-Disk and Yb:Fiber CPA Systems

Compared to Nd-based amplifiers, the quantum defect is \sim 10% in Yb:YAG whereas it is \sim 25% in Nd:YAG, resulting in higher optical-to-optical efficiency and lower thermal load at comparable operational power. Several novel laser/amplifier configurations have been developed to reduce the thermal distortions. The thin-disk approach is one example in which a Yb:YAG crystal with few hundred micrometers thickness and few millimeters diameter is utilized. This heat removal scheme minimizes thermally induced beam distortions without the need for complex compensation. Extraction of up to 25 mJ at 3 kHz repetition rate with 1.6 ps duration

Table 4 List of the performances of high-energy, high-average-power picosecond laser systems reported over the last years, which satisfy the performance requirements to pump OPCPA. These systems are graphically illustrated in Fig. 7. See Table 2 for the list of acronyms.

Ref.	Laser technology	Scheme	Pulse energy	Average power	Pulse duration	Peak power
75	DPSS	MOPA	130 μ J	5.3 W	19 ps	7 MW
76	DPSS	MOPA	123 μ J	12 W	6.8 ps	18 MW
77	Cryo SS	MOPA	3.7 μ J	287 W	5.5 ps	670 kW
78	Cryo SS	CPA	300 μ J	6 W	195 fs	1.5 GW
79	Thin-disk	CPA	25 mJ	75 W	1.6 ps	15 GW
80	Thin-disk	CPA	300 mJ	3 W	2 ps	150 GW
81	Cryo SS	MOPA	15 μ J	760 W	12 ps	1.2 MW
82	Cryo SS	CPA	6.5 mJ	13 W	15 ps	433 MW
83	DPSS	MOPA	3 mJ	30 W	25 ps	118 MW
84	DPSS slab	CPA	5.5 μ J	1.1 kW	610 fs	9 MW
85	Fiber	CPA	3.1 μ J	3.1 W	140 fs	22 MW
86	Fiber	CPA	11 μ J	830 W	0.64 fs	12 MW
87	Cryo SS	CPA	100 mJ	10 W	5 ps	20 GW
88	Cryo SS	CPA	12 mJ	60 W	1.6 ps	7.5 GW
89	DPSS	CPA	27 mJ	2.7 W	560 fs	48 GW
90	DPSS ceramic	CPA	130 mJ	1.3 W	450 fs	290 GW
91	DPSS	MOPA	1.8 mJ	8.8 W	28 ps	62 MW
92	DPSS	CPA	200 mJ	2 W	900 fs	222 GW
93	DPSS	MOPA	500 μ J	5 W	85 ps	5.8 MW
94	DPSS	MOPA	40 mJ	40 W	48 ps	833 MW
54	DPSS slab	CPA	20 mJ	250 W	830 fs	24 GW
95	DPSS slab	MOPA	600 μ J	30 W	12 ps	50 MW
96	Fiber	CPA	3 mJ	30 W	470 fs	6.4 GW
97	Fiber	CPA	2.2 mJ	11 W	500 fs	4.4 GW
98	Cryo SS	CPA	11 mJ	106 W	865 fs	12.3 GW
99	Cryo SS	CPA	1 J	100 W	5 ps	200 GW
100	DPSS	CPA	40 μ J	8 W	180 fs	220 MW
101	Fiber	CPA	3 μ J	3 W	50 fs	60 MW
102	Flashlamp	MOPA	300 mJ	3 W	141 ps	2.1 GW

has been presented.⁹² However, due to the small thickness of the disk, the scheme has to overcome low pump absorption and low small signal gain (on occasion <1.1) with a high number of passes for pump and signal, such as 20 passes of the pump and 300 bounces in the case of regenerative amplifier reported in Ref. 92. A 15-pass amplifier was presented based on a thin-disk to amplify a 10-Hz burst of 80 pulses at 100 kHz repetition rate with 25 mJ per pulse.¹⁰⁴

Recent progress in large-pitch photonic crystal fibers has allowed the increase of pulse energy in fiber amplifier systems to impressive levels. CPA systems based on such fibers have been already used as OPCPA pump with up to 200 W average power resulting in the current record OPCPA average power.¹³ A similar performance has been shown from a system providing up to 830 W average and 10.6 μ J pulse energy with sub-picosecond pulse duration.⁸⁶ For higher

pulse energies, a similar fiber system has been employed to generate 2.2 mJ pulse energy with sub-ps duration⁹⁷ and 3 mJ when beam combining is utilized.⁹⁶ Thus, fiber amplifier based systems offer high average power performance in highly stable and compact architectures.

3.3 Yb-Based Cryogenically Cooled Solid-State and Slab Systems

Several relevant properties of Yb:YAG improve when operating at cryogenic temperatures. The level scheme becomes an almost four-level minimizing reabsorption, the stimulated cross-section improves by ~ 5 , while the thermal conductivity increases 2.5 to 4 times depending on the dopant level.⁸¹ However, the emission linewidth and thus, the amplification bandwidths of these systems reduce to typically < 1 nm, corresponding to a transform-limited pulse duration of ~ 5 ps. A few cryogenically cooled systems have been presented, such as a system generating 287 W average power with 5.5 ps duration pulses corresponding to 3.7 μ J pulse energy.⁷⁷ Another system has been reported based on cryogenically cooled, thick-disk, Yb:YAG producing up to 100 mJ at 100 Hz with a compressed duration of 5 ps.⁸⁷ The performance of the system has been further scaled to generate an output of 1 J pulse energy with 5 ps duration corresponding to 100 W average power.⁹⁹ A system with a double- and single-pass amplifier was presented based on multiple thick Yb:YAG disks generating up to 15.2 μ J pulse energy with 760 W average power and 12 ps duration.⁸¹

Another scheme to reduce thermally induced aberrations is a slab amplifier. The beam multipasses through the slab offering lower thermal aberration compared to rod-type designs, high small signal gain as well as a compact design. One such system based on a Yb:YAG slab generated 0.64 ps pulses with up to 1.1 kW average power at 20 MHz corresponding to a peak power of 80 MW.⁸⁴ At 12.5 kHz repetition rate, a similar amplifier scheme has been used to generate 20 mJ pulse energy with 0.83 ps after postcompression corresponding to an average power of 250 W.⁵⁴

3.4 Trends and Impact for Few-Cycle OPCPA

The mentioned laser technologies are employed with a wide range of output parameters. Figure 7 shows the performance in terms of pulse energy and average power for some potential pump systems in contrast to those already employed for OPCPA pumping. It can be seen that novel laser technologies offer an order of magnitude improvement in average power relative to the performance employed to pump OPCPA systems to date. Although many of these new systems have not been characterized for the strict OPCPA requirements in terms of low noise, fluctuations, and jitter, the implementation of higher-average-power pump lasers is within reach.

A few notable pump lasers have been presented. For example, if the cryogenically cooled, Yb:YAG, thick-disk amplifier producing 1 J pulses with 5 ps duration⁹⁹ were employed as an OPCPA pump, few-cycle pulses could be generated with 100 mJ at 100 Hz corresponding to 10 W average power. Similarly, if the Yb:YAG slab amplifier producing 0.83 ps pulses with 20 mJ energy⁵⁴ were employed, an OPCPA output of 2 mJ at 12.5 kHz could be obtained. As a consequence, we expect to see a sharp increase of available pump power in the next years, enabling OPCPA with

energies from 1 to 100 mJ and repetition rate from 100 Hz to 10 kHz outperforming Ti:sapphire-based CPA systems.

4 Summary and Outlook

In this article, we have reviewed the concepts behind table-top, few-cycle OPCPA as well as the current performance level obtained in research laboratories around the world. The current performance level of table-top OPCPA is primarily limited by the performance of the employed pump laser. Today, the OPCPA method has reached a performance level comparable to Ti:sapphire-based CPA technology with multi-10 TW peak power, mJ-level pulse energy at several kilohertz repetition rate, or ultra-high repetition rates with > 20 W average power. Although thermal effects have been observed in the OPA, this is not yet a significant limit on average power scaling.

We also have presented an overview of recently reported high-energy, high-average-power, picosecond laser systems. Several promising laser systems have been presented, producing > 100 W average power with high pulse energy and picosecond pulse duration. Thus, it seems feasible to obtain in the near future few-cycle pulses with multi-mJ-level energy in the visible, near-IR, or mid-IR via OPCPA at the 10 W average power level.

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