COMPACT, PICOSECOND, KW-CLASS THIN-DISK LASER PERLA FOR HI-TECH INDUSTRIAL APPLICATIONS

MARTIN SMRZ[1], MICHAL CHYLA[1], JIRI MUZIK[1,2], SIVA S. NAGISETTY[1,2], ONDREJ NOVAK[1]

[1]HiLASE Centre, Institute of Physics AS CR, Dolni Brezany, Czech Republic

[2]Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic

DOI : 10.17973/MMSJ.2019_12_2019111

martin.smrz@hilase.cz

Ultrashort-pulse, high average power thin-disk lasers matured and became efficient tools for precise material processing and hi-tech laser applications. Hilase centre developed a diode-pumped thin-disk laser platform for Yb:YAG regenerative amplifiers delivering pulse energy >40 mJ, pulse repetition rate up to 400 kHz, nearly diffraction-limited output beam, and average power reaching of >500 W. The platform called Perla is based on a chirped-pulse amplification system (CPA) consisting of a fiber-based front-end, and a thin-disk regenerative amplifier followed by a compact pulse compressor. The system generates pulses <2 ps in duration. A TRL 7 (technical readiness level) version of the system with average power reaching up to 100 W is ready for customers, a 0.5 kW version exists like a laboratory prototype (TRL 4). The Yb:YAG system emitting at 1030 nm can be alternatively equipped by a frequency conversion stages to visible, UV, or mid-infrared (1.5 – 3 um) spectral regions. We demonstrate capabilities and construction details of the Perla platform.

KEYWORDS

Thin-disk laser, picosecond laser, Yb:YAG, high power laser, pulsed laser, CPA

1 INTRODUCTION

High-volume industrial production and advent of new technological processes require increasingly higher performance, lifetime, and reliability of production tools. For industrial lasers this means higher claims for average power, pulse energy, or pulse repetition rate while keeping spatial and temporal light properties highly stable. A rod-type, solid-state laser architecture reached its limits and relay was taken over by a slab architecture allowing to generate high energy pulses, or a thin-disk geometry fitting very well especially the industrial needs, i.e. generation of kW laser beams with low or moderate pulse energy ranging from mJ to sub-1-J level.

Concept of a diode-pumped thin-disk laser was invented in 1994 at the IFSW Stuttgart [Giesen 1994]. Its birth was motivated by an effort to develop an ideal tool for laser manufacturing since a beginning. Thin-disk lasers can reach high peak- and average power, pulse energy, and outstanding beam quality simultaneously, without needs, for example, for cryogenic cooling. After 25 years of their existence have thin-disk lasers undergone hundreds of improvements, power, and energy scaling. Nowadays thin-disk lasers generate radiation from continuous-waves down to few-cycle femtosecond pulses in temporal domain, exceed average power of 12 kW from a single gain medium in a near infrared spectral region, or approach single pulse energy of 700 mJ in a single pulse. Lasers based on garnet, sesqui-oxide, fluoride, or tungstate gain media, both in single-crystalline, and ceramic form were demonstrated. Thin-disk lasers can directly emit radiation ranging spectrally from visible to mid-infrared, and became a versatile tool opening to scientific and industrial users new dimensions. These lasers are responsible for fast progress and breakthroughs in additive manufacturing (3D printing), laser micromachining, multi-beam material processing, x-ray generation, or particle acceleration systems as well.

Hilase centre of the Institute of Physics CAS participates on this exciting story since 2012 by development of an ultrashort-pulse-generating thin-disk laser platform Perla offering currently to its customers >0.5-kW of average output power with prospect of reaching 1-kW in a close future. Advantage of sub-picosecond pulses for material processing and industrial applications lies in the high peak-intensity resulting in fast ablation via nonlinear absorption, preventing material melting and creation of heat affected zones. Unlike few-cycle pulses, picosecond pulses also do not generate unwanted plasma. High pulse energy then enables splitting of laser beams and realization of multi-beam interference or efficient processing by frequency-converted beams, whereas high pulse repetition rate keeps the industrial processes fast and supports high volume production.

In this paper we report on latest results and properties of the Perla platform at the Hilase centre.

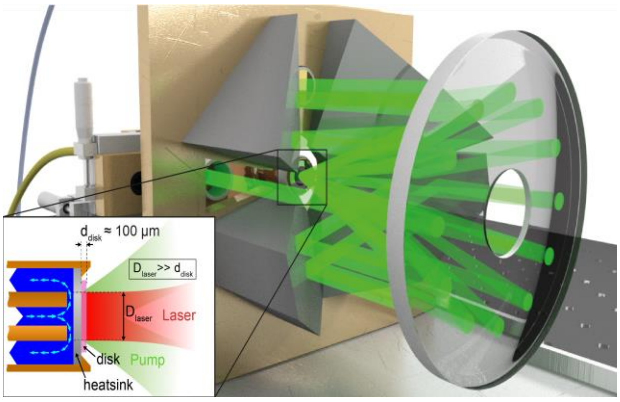

Figure 1. Optical scheme of an optical system for efficient pumping of a thin-disk gain medium. Cross-section of a diamond-bonded thin-disk gain medium is in the inset. Courtesy of Martin Saraceno martin@saraceno.info ; ulp.ethz.ch.

2 THIN-DISK LASER CONCEPT

Thin-disk lasers (Fig.1) have several advantages over rod-type solid state lasers which face serious problems with thermal lensing and material expansion due to huge thermal gradients generated in a volume gain media. When operated in a pulsed regime, pulse propagation in the bulk induces nonlinear response described by an accumulated B-integral resulting, besides other effects, in self-focusing of laser beams inside the rod. Both phenomena can consequence in significant changes in laser behavior and damage on optical components of the laser itself. The thin-disk geometry like a limiting case of a laser diode end-pumped rod with a gain medium diameter of >10 mm and length (thickness) typically of a fraction of mm prevents that behavior. The gain medium is used like a thin, highly-active-ions-doped active mirror with an antireflective (AR) coating on a front side, a highly reflective (HR) one on a

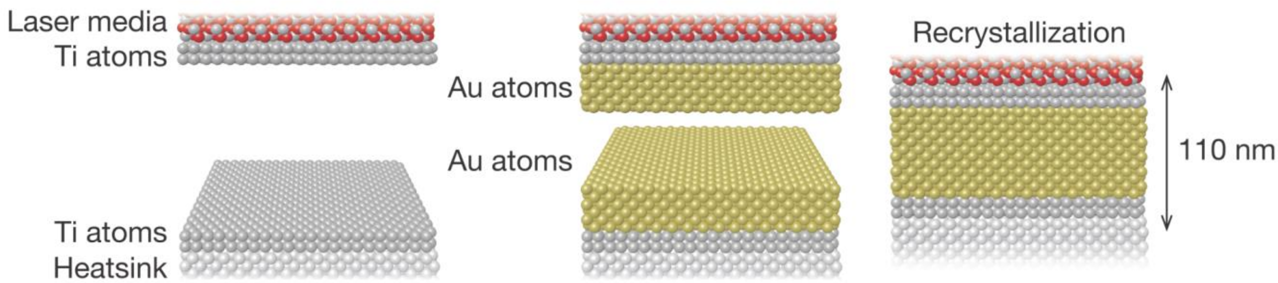

Figure 2. Atomic diffusion bonding (ADB) of thin-disks based on recrystallization of thin layers of sputtered gold. Titanium layers are used for increasing adhesion of the gold layers to the thin-disk gain medium and the heatsink [Nagisetty 2016].

back side (Fig.1, inset), and a water-cooled heat-spreader extracting waste heat in an axial direction of the optical setup bonded to the HR side, unlike a rod-type laser extracting waste heat radially. Thanks to the low thickness of the gain medium is also the accumulated B-integral negligible, even in a multi-pass geometry of the gain medium. On a contrary, low thickness of the gain medium is the most significant drawback of thin-disks because of low single-pass absorption of pump radiation, and low single-pass signal gain, even in highly doped crystals. To overcome this disadvantage, a compact optical image-relaying system consisting of a large parabolic mirror and a set of roof reflectors folding the pump beam path, and allowing to multiply the number of pump beam passes through the gain medium and absorption efficiency was proposed (Fig.1). Nowadays, optical systems allowing up to 72 pump beam passes are commercially available. Achievable size of a pumped area and pump power density on a thin-disk depends on brightness of a pump source, and a focal length of an image-relaying optics, which is usually 50 – 150 mm. Whereas pump radiation reaches the disk surface under an angle, signal is propagating axially and reaches the gain medium through an opened central part of the parabolic mirror. In high power lasers where pump power reaches several kW, all optical components must be water cooled.

2.1 Thin-disk gain medium

Properties of a gain medium acting a role of the active mirror are critical for efficient operation of a thin disk laser. Enormous amount of waste heat approaching in some cases kW level, which is generated in a volume of few cubic millimeters, can be efficiently extracted thanks to the excellent ratio of a disk surface area to a disk volume through the large, highly reflective coated back side of the active mirror. However, front surface temperature of a pumped thin-disk area reaches often >100°C, which generates step-like temperature change and, consequently, high mechanical stress and disk deformation caused by different thermal expansion of a material between the pumped and the unpumped disk regions. A bonding layer fixing the gain medium to a heat spreader must be extremely thin in order not to create high thermal resistance at the interface, and flexible but strong to absorb a different thermal response of both counterparts. Role of the heat spreader is fast and homogenious heat extraction from the gain medium, heat transfer to cooling water, and thin-disk mechanical support because the thin-disk itself is extremely fragile. A popular heat spreader material used to be copper-tungsten soldered to thin-disks by an indium-based solder, however, kW lasers use solely synthetic diamond substrates. The indium solder bonding was exchanged by epoxy gluing because of rigidity and repeatability of thin-disk module production. Low-temperature epoxy bonding also prevents mechanical stress induced by heating and cooling cycles during the soldering procedure. Recently, new approaches using an epoxy-free diffusion bonding have been demonstrated [Nagisetty 2016]. Similar approaches frequently used for a direct bonding of two bulk optical materials cannot be straightforward applied to the thin-disk bonding since two different materials being connected here contain additional amorphous interlayer of a highly reflective optical coatings. Despite this issue we successfully demonstrated the Atomic Diffusion Bonding process based on recrystallization of thin atomic gold layers sputtered on both components being connected (Fig.2). We continue in optimization of this technique since it could get a potential alternative to the epoxy-based bonding, which makes a thermal barrier in the joint by a low thermally-conductive glues.

Many materials with different spectral properties have been tested like a gain medium, however, Yb:YAG is the most frequently used one. It shows several advantages over the other ones. First, Yb:YAG has a broad absorption line centered around 940 nm, and long upper laser level lifetime approaching 1 ms, which makes it ideal for efficient pumping by cheap, high brightness, commercially available AlGaAs-based laser didoes. Second, Yb:YAG is a quasi-three-level gain medium, i.e. it shows a very low quantum defect and waste heat production only around 8 % when pumped at 940 nm. On the other hand, this choice brings a non-zero population at the lower laser level at elevated temperatures, which requires small amount of pumping for bleaching of the gain medium only. Finally, Yb:YAG has relatively high thermal conductivity, excellent mechanical properties, chemical stability, can be grown in large volumes with excellent quality, and technology of its polishing is well developed. A broad emission line centered at a wavelength of 1030 nm also allows for direct amplification of picosecond and sub-picosecond pulses. The Perla platform developed at the Hilase centre is therefore primarily based on Yb:YAG gain medium as well.

2.2 Pumping of Yb:YAG thin-disk lasers

Yb:YAG lasers are usually pumped to a broad absorption line around 940 nm, however, there exists a narrow absorption line close to 969 nm allowing more efficient pumping directly to the upper laser level, so called zero-phonon line pumping. This further reduces a quantum defect [Weichelt 2012], however, efficient zero-phonon line pumping requires narrow-band pump diodes stabilized by volume Bragg gratings to provide a stable flux of desired pump photons. Such didoes have been lately available but their average power is limited to several kW, and their price is higher, so the most powerful lasers must be still pumped conventionally. In [Smrz 2014] we compared the conventional and the zero phonon line pumping, and we described an effect of a nonlinear phonon relaxation responsible for, besides the quantum defect, generation of additional waste heat in Yb:YAG disks. Surface temperature and deformation of the thin-disk was measured under different

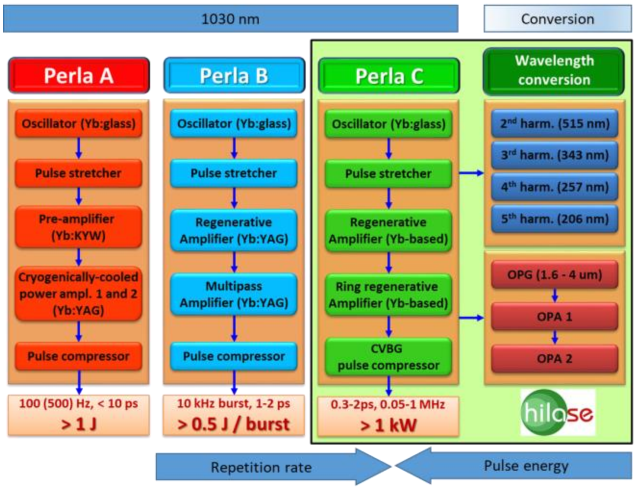

Figure 3. Structure and target parameters of Yb:YAG Perla beamlines at the Hilase centre. The Perla C includes frequency conversion systems.

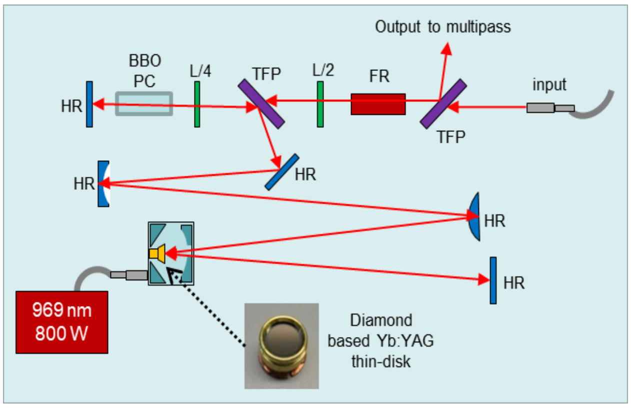

Figure 4. An optical scheme of a standing-wave regenerative amplifier based on the Perla platform (HR – highly reflective mirrors, BBO – BBO Pockels cell, TFP – thin film polarizer, L/2 – a half waveplate, FR – Faraday rotator).

pumping conditions during this experiment. When was the system pumped at the zero phonon line, its behavior corresponded to our expectations with slow linear increase in thin-disk surface temperature. On a contrary, the conventional pumping at 940 nm added an additional component to the heat source, which was causing nonlinear increase in a disk surface temperature with rising pump intensity, both in a fluorescence regime, and a laser operation regime, and consequently led to an elevated deformation of the thin-disk surface. Analysis of a measured wave-front deformation of a conventionally pumped Yb:YAG disk by decomposition into Zernike polynomials, and subtracting spherically-symmetrical defocus, showed an elevated aspherical deformation of the surface. This results correlated with reduced laser output power and worse beam quality from a high power regenerative amplifier under test (for details see [Smrz 2014]). The wave-front change of a signal beam after passing the disk cannot be apparently compensated by cavity spherical mirrors and increases diffraction losses. In addition, lower disk temperature in case of the zero phonon line pumping reduces a thermal population of the lower laser level, and the system works more effectively. All the results, in spite of higher price, strongly support the zero phonon line pumping of high power Yb:YAG thin-disk lasers unlike the cheaper conventional one.

Figure 5. A TRL 7 commercial clone of the Perla C-100 with a front-end module (bottom left), and a GoPico fiber oscillator (bottom right).

3 THIN-DISK PERLA PLATFORM

The Hilase centre [Novak 2015], [Smrz 2017] has been developing a picosecond pulse thin-disk laser platform with average power reaching currently 500 W, a pulse repetition rate up to 400 kHz, pulse energy up to 45 mJ, and a nearly diffraction-limited output laser beam (Fig.3). Several versions of laboratory- or commercial-prototypes working under different conditions, and at various technical readiness level (TRL) ranging from 3 to 7 are currently in operation at our labs. Upgrades reaching average power of up to 1 kW and pulse energy >100 mJ are under development. A spectrum of available laser parameters was chosen to fit a majority of industrial and scientific applications from single or multiple-beam material micromachining, over pumping of femtosecond optical parametric amplifiers, to plasma and x-ray generation, for example for water window microscopy, or semiconductor EUV litography.

3.1 *Chirped pulse amplification*

The Perla platform is based on the chirped pulse amplification technique (CPA) [Strickland 1985]. This technique enabling amplification of ultrashort pulses to high energy was awarded by the Nobel prize in physics in 2018. It uses dispersive systems, a so called pulse stretcher and a pulse compressor, to reduce pulse peak power by chirping it, resulting in dispersive stretching of the ultrashort pulses being amplified below damage threshold of laser amplifiers, and to their re-compression the original pulse duration after amplification by an optical system showing opposite sign of its dispersion. Material dispersion is often insufficient for this purpose. The pulse handling is usually based on angular-dispersion-showing optical components like dispersive prisms, or more frequently, optical gratings, which can in proper configuration change an optical path difference coming from different geometrical paths between them to a temporal chirp and pulse prolongation. Both positive, and negative dispersion can be generated in optical gratings-based dispersive systems.

In case of the Perla lasers, ultrashort pulses are generated from a compact Yb-doped fiber oscillators emitting nJ femtosecond pulses in diffraction-limited laser beams. We developed the GoPico and the GoFemto (with a broader spectrum) [Chen 2019] compact oscillators with a nonlinear polarization rotation-based mode-locking scheme fitting well the Perla CPA systems. Generated pulses are stretched to a nanosecond time

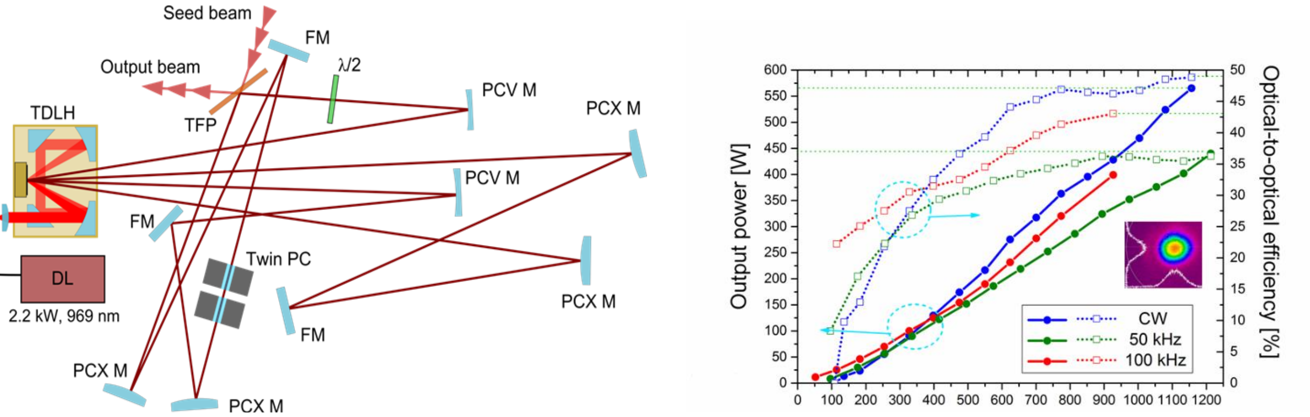

Figure 6. Left: Optical scheme of the Perla C-500 high average power regenerative amplifier with a ring cavity (TDLH – thin disk laser head, DL – pump laser diodes, PCX M – plano-convex mirrors, PCV M – plano-concave mirrors, Twin PC – BBO Pockels cell, TFP – thin film polarizer, λ/2 – half waveplate); Right: Output power and optical efficiency of the Perla C-500 ring cavity regenerative amplifier under different operational regimes with an output near-field beam profile in the inset.

scale, their pulse repetition rate is reduced by an acousto-optics modulator to 1 MHz, and the pulses are pre-amplified in a system of Yb-fiber-based single-mode and double-clad polarization maintaining fiber amplifiers. For pulse stretching in the fiber front-end, chirped fiber Bragg gratings (CFBG) are used. Chirped nanosecond pulses with pulse energy exceeding 1 µJ are seeded to thin-disk-based regenerative amplifiers.

3.2 *High average power amplifiers*

Regenerative amplifiers Perla have been developed in several modifications, however, they differ mainly in a cavity mode size, a cavity length, and an aperture of some components in order to work effectively at different desired output specifications. First amplifiers of the platform, a Perla B-20 and a Perla C-100 [Smrz 2015], are based on a standing wave cavity with a single, diamond-bonded Yb:YAG thin-disk pumped at 969 nm (a zero-phonon line) by a fiber coupled, VBG-stabilized, 0.5 kW laser diodes (Fig.4). A laser head is coupled to the diodes through an industrial fiber with LLK-HP connectors, 0.4 or 1 mm core diameter, and a numerical aperture of 0.15. Pumped area on a thin-disk is given by magnification of an optical system consisting of a laser head parabolic mirror, and a fiber output-collimating lens. In the both above mentioned systems is a pumped spot around 2.8 mm. The Perla C is continuously pumped (CW) because of its high pulse repetition rate operation (100 kHz) and low gain allow it. The Perla B, whose 1 kHz pulse repetition rate is close to the upper laser level lifetime and generates high energy pulses, is pulsed-pumped in order to reduce thermal effects and amplified spontaneous emission (ASE) [Chyla 2014]. Cavity of the regenerative amplifiers is polarization-controlled by electro-optic switches, Pockels cells, based on BBO crystals. BBO, unlike often used RTP crystals, has lower residual absorption at 1030 nm, is less sensitive to thermal effects, and shows significantly lower piezo ringing, which can negatively influence pulse contrast, or even lead to destruction of the Pockels cell itself. A horizontally-polarized pulse injected into the cavity passes twice the Pockels cell (Fig.4) controlled by a quarter-wave voltage. For example, an 8x8 mm aperture of two 25 mm long, z-cut BBO crystals of the Perla C require application of 4 kV for a period of several mili-seconds with repetition rate of 100 kHz. On-time of the Pockels cell defines amplification time, or pulse build-up, in the regenerative amplifier. After reaching gain saturation, the Pockels cell is switched-off, pulse linear polarization rotates by 90 degrees, and the pulse can escape from the cavity. Input and output beams are separated by a Faraday rotator inserted in front of the laser cavity. The Perla C-100 reaches pulse energy of > 1 mJ at a pulse repetition rate of 100 kHz (i.e. > 100 W of average power), beam quality $M^2 < 1.4$ in a compressed beam, and optical-optical efficiency around 30 %. The Perla B-20 is operated up to 20 mJ at 1 kHz repetition rate and an excellent M^2 parameter equal to 1.15. A lately developed TRL 7 platform in a similar configuration can be customized from 100 Hz to 200 kHz in pulse repetition rate, and pulse energy can be scaled up to 20 mJ (Fig.5). This platform offers versatility, is able to work in an industrial environment, and is offered like a commercial product of the Hilase centre.

Amplified pulses can be further amplified in a second-stage regenerative amplifier with a ring cavity (Perla C-500, Fig.6), or a thin-disk-based multipass amplifier (Perla B, Fig.7). The high average power regenerative amplifier Perla C-500 uses advantages of a ring cavity, which seems to be better for large mode area essential for thin-disk laser power and energy scaling. The ring cavity is shorter than a standing-wave cavity for a given mode size, does not need a large Faraday rotator for separation of an input and output beams, and naturally isolates a front-end because of a given propagation direction. A drawback, single-signal-passing of a gain medium per cavity roundtrip can be compensated by a geometrical multi-pass amplification of the pulse inside the thin-disk laser cavity, like the example of the Perla C-500 configuration (Fig.6, left). This cavity is approx. 6.5 m long with a 5.8 mm pump spot (diameter), and is controlled by a pair of 10x10x25 mm^3 BBO crystals operated at a 9.5 kV half-wave voltage when the amplifier is switched-on. The thin-disk in double-pass configuration is like the Perla C-100 pumped by a fiber-coupled diode module at 969 nm (zero-phonon line). The output beam

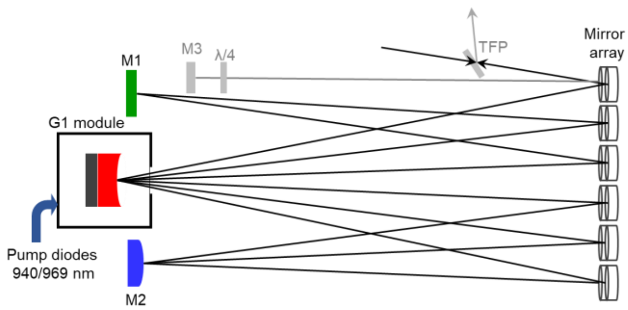

Figure 7. Block scheme of a thin-disk-based multipass amplifier used like a booster amplifier of the Perla B beamline (G1 – thin-disk laser module, M – mirrors, TFP – thin-film polarizer, λ/4 – quarter waveplate).

reaches beam quality given by M^2 = 1.4 at full power and an uncompressed beam. The amplifier was tested at several different repetition rates and in a CW regime with optical efficiency > 40 % at full power, however, it is optimized for 5 mJ of pulse energy and 100 kHz pulse repetition rate (Fig.6, right). A new, fiber-based front-end with µJ pulse energy for seeding of this amplifier is currently under final testing. It will allow independent operation of the Perla C-500, which will also get even more compact (a footprint now is approx. 1.1 x 0.9 m^2 without a pulse compressor).

A multipass amplifier for the Perla B is under development at the Hilase (Fig.7). This amplifier does not use any optical cavity and results in a slightly worse beam quality. On a contrary, it does not have any limits on a mode size like an optical cavity, which is for large modes extremely long. Therefore such a multipass amplifier can reach even higher pulse energy than regenerative amplifiers. Multipass amplifiers also do not have any optical switches and use only spatial beam multiplexing. The Perla B multipass setup consists of a mirror array reflecting the pulse back to a single, flat thin-disk, of waveplates, and a Faraday rotator. The amplifier was lately tested in a burst mode generating 10 pulses with intra-burst repetition rate of 10 kHz, and a burst repetition rate of 100 Hz. The amplifier reached total burst energy of 220 mJ, however, target value is >> 500 mJ per the burst.

Regardless optical setups of the amplifiers, pulses generated from the Perla lasers are compressed to a pulse duration < 2 ps and typically reach bandwidth of 1.5 nm, i.e. a bandwidth limited pulse is <1 ps long. For average power up to approximately 60 W and mJ pulse energy, the pulses can be successfully compressed by a compact and extremely simple chirped volume Bragg grating (CVBG)-based pulse compressor [Glebov 2014]. It is a single piece of photosensitive glass with a holographically created Bragg grating structure inside. Adoption of this compressor allows us to make the Perla C-100 platform very compact. Despite advantages of the CVBGs at low power, high power pulse compression by CVBGs is complicated. Thermal gradients cause grating deformation with consequent depolarization losses, although original diffraction efficiency is > 95 %. Also beam quality significantly drops and for >200 W of average power exceeds M^2 > 1.8. For high average power and high energy systems we therefore use a standard Treacy-type compressor using a pair of diffraction gratings [Treacy 1969].

The Perla C system can be extended by a harmonic frequency conversion setup consisting of a LBO crystal for second harmonic frequency generation (515 nm, conversion efficiency approx. 60%), third harmonic generation in a BBO crystal (343 nm, conversion efficiency approx. 25% from a fundamental one), fourth harmonic frequency generation in a BBO or a CLBO crystal (257.5 nm, conversion efficiency approx. 10% from a fundamental one when generated like a cascaded conversion via a second harmonic frequency) [Novak 2016], and fifth harmonic frequency generation in a CLBO crystal (206 nm, sum frequency of a fourth harmonic frequency and a fundamental one) [Turcicova 2019].

Alternatively, the Perla platform can be equipped by a tunable mid-infrared source based on an optical parametric generator (OPG) followed by an optical parametric amplifier (OPA). The OPG system is based on a periodically-polled lithium niobate crystal, the OPA on a KTA or KTP crystal pair. A signal beam from the OPA can be tuned from 1.6 to 1.95 µm in case of the KTP crystal, an idler beam from 2.15 to 2.65 µm in case of the KTP (Fig.8) [Vyvlecka 2018], or to 3.2 µm in case of the KTA crystal.

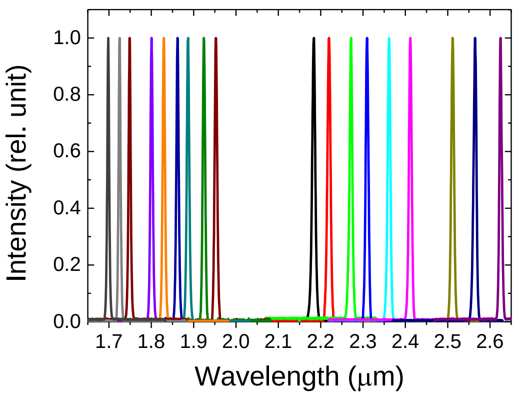

Figure 8. Tunability range of the mid-infrared picosecond optical parametric amplifier (OPA) based on a KTP nonlinear crystal and pumped by the Perla C thin-disk laser.

4 CONCLUSION

Thin disk lasers become widely used tools in many hi-tech industrial laser applications. The Hilase centre developed a versatile thin-disk laser platform Perla covering pulse repetition rates from 100 Hz to 400 kHz and pulse energies up to 45 mJ (220 mJ in pulse bursts). The Perla C-100 system with a TRL 7 is optimized for direct use in an industrial, noisy environment, and is offered like a commercial product. Next upgrades of the Perla platform up to average power of 1 kW and pulse energy exceeding 100 mJ are expected in close future. The Perla C systems can be extended by a frequency conversion to mid-infrared spectral range by a tunable optical parametric amplifier (1.6 – 3.2 µm), or by a harmonic frequency conversion (2^{nd}, 3^{rd}, 4^{th}, 5^{th}) system to visible and UV parts of electromagnetic spectra.

ACKNOWLEDGMENTS

This paper was co-financed by the European Regional Development Fund and the state budget of the Czech Republic (project HiLASE CoE: Grant No. CZ.02.1.01/0.0/0.0/15_006/0000674) and by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 739573. This work was also supported by the Ministry of Education, Youth and Sports of the Czech Republic (Programmes NPU I Project No. LO1602, Large Research Infrastructure Project No. LM2015086), and by the Czech Science Foundation (GACR) under project No. GA16-12960S.

REFERENCES

[Chen 2019] Chen, L. et al. Generating 84 fs, 4 nJ directly from an Yb-doped fiber oscillator by optimization of the net dispersion, Laser Physics, 2019, Vol.29, pp. 065105.

[Chyla 2012] Chyla, M. et al. High energy, picosecond regenerative thin disk amplifier at 1 kHz, High-power, high-energy, and high-intensity laser technology II, Proc. of SPIE, Solid state lasers XXI: Technology and devices, 2012, Vol. 8235, pp. 82351W.

DOI: 10.1117/12.908150

[Chyla 2014] Chyla, M. et al. Optimization of beam quality and optical-to-optical efficiency of Yb:YAG thin-disk regenerative amplifier by pulsed pumping, 2014, Optics Letters, Vol.39, pp.1441-1444.

[Glebov 2014] Glebov, L.B. et al. Volume-chirped Bragg gratings: monolithic components for stretching and compression of ultrashort laser pulses, Optical Engineering, 2014, Vol.53, No.5, pp.051514.

[Nagisetty 2016] Nagisetty, S.S. et al. Lasing and thermal characteristics of Yb:YAG/YAG composite with atomic diffusion bonding. Laser Physics Letters, 2016,Vol.14, No.1, pp.015001-1 – 015001-6.

[Novak 2015] Novák, O. et al. Status of the high average power diode-pumped solid state laser development at HiLASE. Applied Sciences, 2015, Vol.5, pp.637–665.

[Novak 2016] Novák, O. et al., Picosecond green and deep ultraviolet pulses generated by a high-power 100 kHz thin-disk laser, Optics Letters, 2016, Vol.41, No.22, pp.5210-5213.

[Giesen 1994] Giesen, A. et al. Scalable concept for diode pumped high-power solid-state lasers. Applied Physics B, 1994, Vol.58, No.5, pp. 365-72.

[Smrz 2014] Smrž, M. et al. Suppression of nonlinear phonon relaxation in Yb:YAG thin disk via zero phonon line pumping. Optics Letters, 2014, Vol.39, No.16, pp.4919-22.

[Smrz 2015] Smrz, M. et al. Amplification of picosecond pulses to 100 W by an Yb:YAG thin-disk with CVBG compressor, Proc. of SPIE, 2015, Vol. 9513, pp. 951304.

DOI: 10.1117/12.2178900

[Smrz 2017] Smrž, M. et al. Advances in High-Power, Ultrashort Pulse DPSSL Technologies at HiLASE. Applied Sciences, 2017, Vol.7, pp.1016.

[Strickland 1985]

Strickland, D., Mourou, G. Compression of amplified chirped optical pulses. Optics communications, October 1985, pp 447-449.

[Treacy 1969] Treacy, E. Optical pulse compression with diffraction gratings. IEEE Journal of quantum Electronics, 1969, Vol.5, No.9, pp 454–458.

[Turcicova 2019] Turcicova, H. et al. New observations on DUV radiation at 257 nm and 206 nm produced by a picosecond diode pumped thin-disk laser, Optics Express, 2019, Vol.27, No.17, pp.24286-24299.

[Vyvlecka 2018] Vyvlečka, M. et al. High power picosecond parametric mid-IR source tunable between 1.7 and 2.6 µm, Applied Optics, 2018, Vol.57, No.28, pp.8412-8417. [Weichelt 2012] Weichelt, B. et al. Enhanced performance of thin-disk lasers by pumping into the zero-phonon line. Optics Letters, 2012, Vol.37, No.15, pp.3045-47.

CONTACTS:

Ing. Martin Smrz, Ph.D.
HiLASE Centre
Za Radnici 828, Dolni Brezany, 252 41, Czech Republic
martin.smrz@hilase.cz, www.hilase.cz