Journal of
Micro/Nanolithography,
MEMS, and MOEMS

Nanolithography.SPIEDigitalLibrary.org

kW-class picosecond thin-disc prepulse laser Perla for efficient EUV generation

Akira Endo
Martin Smrž
Jiří Mužík
Ondřej Novák
Michal Chyla
Tomáš Mocek

SPIE.

Akira Endo, Martin Smrž, Jiří Mužík, Ondřej Novák, Michal Chyla, Tomáš Mocek, "kW-class picosecond thin-disc prepulse laser Perla for efficient EUV generation," *J. Micro/Nanolith. MEMS MOEMS* **16**(4), 041011 (2017), doi: 10.1117/1.JMM.16.4.041011.

kW-class picosecond thin-disc prepulse laser Perla for efficient EUV generation

Akira Endo,[a,*] Martin Smrž,[a] Jiří Mužík,[a,b] Ondřej Novák,[a] Michal Chyla,[a] and Tomáš Mocek[a]
[a]HiLASE Centre, Institute of Physics Academy of Sciences, Prague, Czech Republic
[b]Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Prague, Czech Republic

Abstract. The technology for extreme ultraviolet (EUV) lithography sources is maturing. Laser produced plasma (LPP) sources with usable power >100 W have been used in high-volume manufacturing (HVM) applications, and 250-W sources are expected to be introduced in HVM soon. However, a further increase of power and cleanness may benefit a powerful picosecond (ps) laser in the near-infrared and wavelength converted spectral region. The HiLASE Centre has been working in thin-disc laser technology and has demonstrated a 0.5-kW platform Perla-C based on a very compact Yb:YAG regenerative amplifier. 100-kHz ps operation has been achieved with a fundamental spatial mode and excellent long-term pointing and energy stability. It is reported on a thin-disc-based ps Yb:YAG solid-state laser technology platform Perla developed in the Czech Republic and the present performance of delivering >4 mJ, <2-ps pulses at a 100-kHz repetition rate with the potential to be upgraded to 1 kW of average power and 1-MHz pulse repetition rate. The ps laser extendibility is important for kW-class LPP sources and controlled free electron laser EUV sources in 10-kW power region. [DOI: 10.1117/1.JMM.16.4.041011]

Keywords: EUV source; laser produced plasma; FEL; prepulse; thin-disc laser.

Paper 17106SS received Jul. 13, 2017; accepted for publication Oct. 24, 2017; published online Nov. 24, 2017.

1 Introduction

Extreme ultraviolet (EUV) lithography is taking off from a long technology development phase to high-volume manufacturing (HVM) in major semiconductor companies. Laser produced plasma (LPP) is the selected method for the required 13.5-nm source for its advantages of scalable output power, narrow spectrum, small source size, and cleanness. The source technology is already fairly advanced in each component level for a 250-W power supply. The next step for extension to the finer line width as a 3-nm node and beyond is based on a high NA imaging system, which requires a further increase of EUV source power to the kW level. A conceptual study based on the present LPP technology on a possible path to the realization of a kW 13.5-nm tin EUV source was reported.[1] There are several key technologies in the LPP source for high average power, and conditioning of the injected micro tin droplet into the mist target is critical for realizing higher conversion efficiency (CE) of up to 6% and full ionization for efficient exhaust in a magnetic field. It was experimentally demonstrated that the resulting mist shape is dependent on the initial laser pulses, and a picosecond (ps) laser can produce a lower density mist distribution rather than nanosecond (ns) pulses. The background physics of this phenomenon is under intensive physical and experimental study.[2,3] The typical repetition rate of the droplet generation is 100 kHz, and a further increase is necessary to kW generation due to the limit of the maximum input main laser pulse energy to keep the CE at 6% level. The requirements for the prepulse laser are relatively critical: a few mJ, good beam quality, a few ps, high pointing accuracy, and pulse-to pulse energy stability at 100-kHz repetition rate.

Further power scaling is considered to apply free electron laser (FEL) technology due to the potential ability of higher average power in the shorter wavelength region.[4,5] Several different FEL methods are evaluated for actual application, and high average power solid-state ps laser technology is also critical in the realization of reliable and robust light sources. The one application is in the photocathode for stable, long-time low emittance operations, and the other one is the seeding of lasing wavelength by harmonics generation.[6,7] The specification of the EUV FEL is still not fixed, and the requirement for the ps laser is also in a preliminary phase. It is estimated that the required average power might be higher than the one for LPP, and further scaling of the ps laser is important.

Thin-disc configuration is the best type for a solid-state mJ, short-pulse laser with a higher average power of good beam quality. The HiLASE Centre is working to advance the specific laser source for various applications, and the EUV source is the most demanding one. Technical details on the high repetition rate thin-disc laser are described, and further scaling is discussed in the following.

2 Role of High Average Power Picosecond Solid-State Laser in LPP and FEL EUV Sources

This section describes the role of a ps solid-state laser in the scaling of tin-based LPP EUV sources and a further increase of power by emerging FEL technology.

2.1 *Scaling of LPP EUV Source Toward kW Average Power*

The general path to higher average power is to increase all components' efficiency, such as the drive CO_2 laser, conversion from laser to EUV emission, and EUV collection. Each factor is progressing by significant engineering efforts, but

*Address all correspondence to: Akira Endo, E-mail: endo@fzu.cz

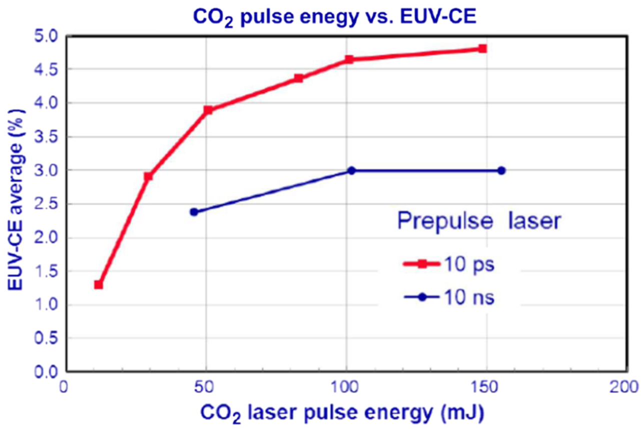

Fig. 1 CE dependent on input CO_2 pulse energy with prepulse of ns and ps.

there are some practical limitations. Higher CO_2 laser pulse energy may cause optics damage and a decrease of laser to EUV CE. Higher collection efficiency needs higher EUV transmission and a large collection angle. A higher repetition rate is favorable for increasing the average power by the same operational parameters, but it is limited by the droplet disturbance by the expanding plasma cloud. A conceptual study was reported to the kW LPP source, where the repetition rate was assumed to be 150 kHz.[1] The laser to EUV CE is increasing and strongly dependent on the physical process in the laser-tin mist interaction, and the physical process of the interaction has been the analytical subject for further higher efficiency. It was experimentally demonstrated that the cluster formation from the tin droplet is critical for higher CE and that a shorter pulse duration laser is more favorable for higher efficiency and less contamination as in Fig. 1. The physical process related to laser irradiation of droplets has been recently studied in detail.[2,3]

The basic architecture of the present LPP sources has been well-described in many research papers.[8–10] The latest achievement of a CE of 6% was reported, and a 375-W in-burst EUV power at low duty cycle was demonstrated on test sources in the development laboratories.[10] The tin droplet generator injects a liquid phase tin microdroplet with a typical diameter of $<20\ \mu$m, and the droplet is irradiated by a controlled, short laser pulse, which initiates a dispersion process of the tin droplet to a mist cloud of atomized Sn in a volume size of >100-μm diameter (Fig. 2). The particle density is reduced from the solid state to the gas state by the dispersion initiated by the impulse of the laser ablation. It was experimentally shown that a shorter laser pulse with a ps pulse length is favorable for generating a tin cloud for higher CE and efficient plasma flow in the guiding magnetic field.[11,12] Recent work presents measurements and theoretical analysis of the deformation and fragmentation of spherical liquid–metal droplets by ps laser pulses.[2,3] 60-μm droplets of Sn–In (tin–indium) alloy were irradiated by Ti:Sa laser pulses with a peak energy fluence of $\sim 100\ \mathrm{J\,cm^{-2}}$. The observed evolution of the droplet shape was shown to confirm the previously reported experiment with ns and ps pulses. It was explained by a two-dimensional hydrodynamic simulation how a liquid droplet is transformed into a characteristic acorn-like expanding shell with two inner cavities due to the specifics of matter dynamics in the liquid–vapor phase coexistence region. The measured shell parameters are related to the details of the equation of state and metastable dynamics and suggest that such a physical process is a new object of thermophysical properties of metals in the region of liquid–vapor phase transition. The resulting shape of the Sn cloud is not a uniformly distributed mist and may offer a further possibility of increased absorption of the driving CO_2 laser energy in the target.

2.2 *Laser Assistance in EUV FEL Source Technology*

The perspective for further average power increase is regarded to depend on the emerging FEL technology due to its potential possibility for higher average power.[13] There are several proposals for the candidate FEL scheme, and some evaluation works are reported. The evaluation is in an initial phase, and some important characteristics of the suitability have not been tested. The significant difference of the FEL EUV pulse is its pulse length of typically 100 femtosecond compared with several ns of LPP EUV light. The intensity is 100,000 times higher with the same pulse energy in the case of the FEL beam to the LPP EUV light. The FEL beam is also composed of many sharp spikes in the case of SASE operation, and the spatial coherence is higher due to collective electron bunch dynamics in its small beam area.[14] Figure 3 shows examples of FEL and LPP EUV pulses.

The most stable method for generating a temporally coherent smooth pulse is an external seeding. The Italian FEL, FERMI, reported the successful generation of coherent soft x-rays into the water window (2.3 to 4.4 nm) by two-stage frequency upconversion of ultraviolet seed laser pulses using the "fresh bunch" technique.[15] The same method is applicable for the 13.5-nm generation as shown in Fig. 4 with typical parameters. The operation of FERMI has a less than kHz repetition rate, but the EUV FEL should be $>$MHz with 20-μJ pulse energy. The required laser power is >20 W, femtosecond at 324-nm wavelength.

Another application of laser technology is as a driver for photocathodes. Currently, a scientific photocathode is made of a semiconductor for its higher efficiency, but the lifetime is critical in future industrial operations. A metal photocathode is a reliable technology, but it needs higher laser pulse energy like mJ in a deep ultraviolet (DUV), ps pulse. The required average power is the same as for the seeding.

In this section, several reasons are shown for the requirement for a high average power ps laser and wavelength converted light source for scaling of the EUV source toward kW by LPP and further increase by FEL.

3 Thin-Disc Yb:YAG Laser as a High Average Power Picosecond Solid-State Laser in LPP and FEL EUV Sources

The major obstacle to obtaining high average power, high beam quality laser pulses from any laser is the medium distortion, and this is significant in a solid-state laser material due to its small volume and high density compared with a gas laser. A conventional rod type solid-state laser is limited in its operational repetition rate to keep the temperature increase to an acceptable region. Several laser configurations were proposed and tested, and the thin-disc geometry is now proved in its superiority for high average power, high beam quality, and short-pulse laser output with $>$mJ pulse energy. The key

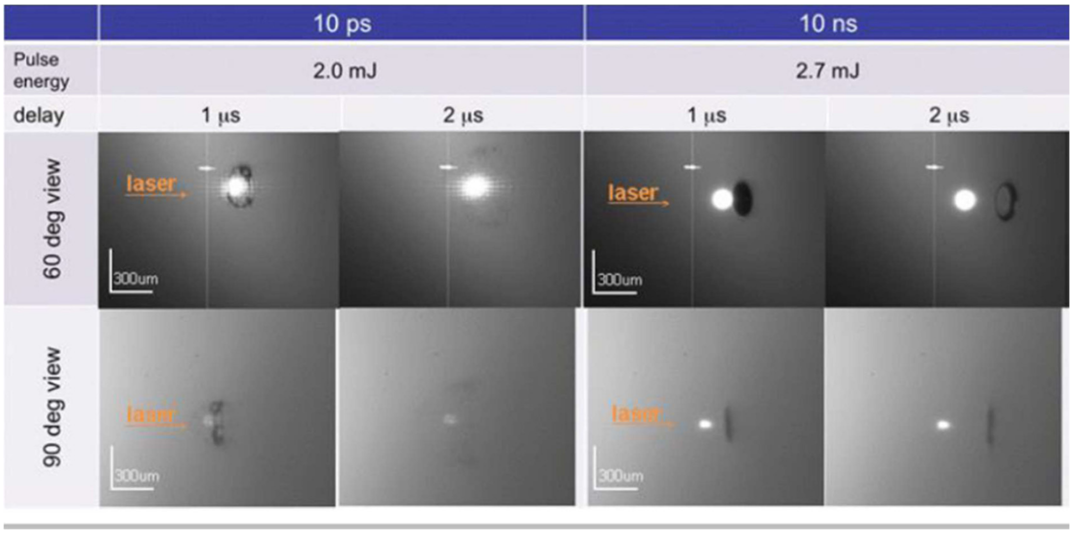

Fig. 2 Dispersion dynamics of tin droplet by ps and ns pulses.

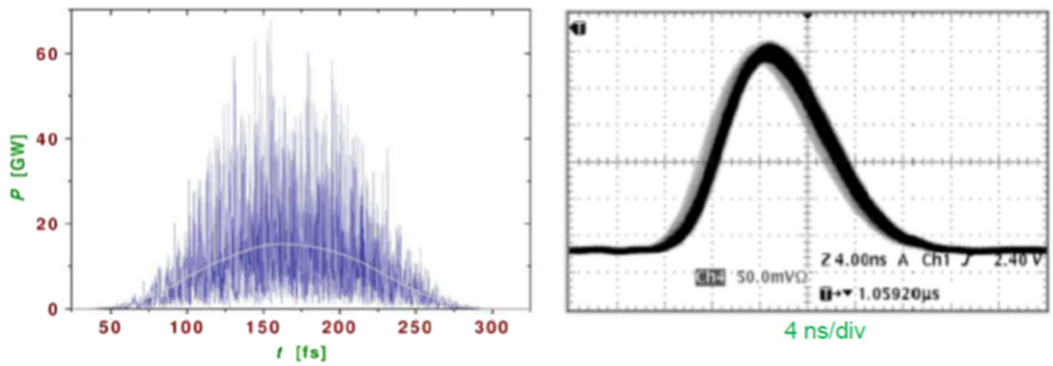

Fig. 3 FEL pulse by simulation and measured LPP pulse of 4-ns FWHM.

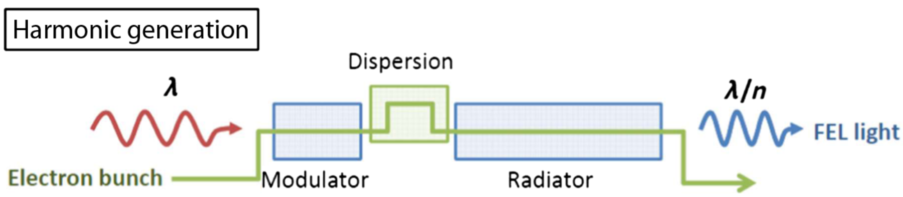

Fig. 4 External seeding for controlled FEL pulses.

concept of the thin-disc laser is the small laser medium thickness for efficient cooling from the backside by water or liquid nitrogen flow. The laser medium is usually bonded to a base structure of high thermal conductivity. The major practical problem is the distortion of thin-disc surface under high average power pumping, which limits the maximum output power. The cross section of thin-disc geometry together with a whole module in operation is shown in Fig. 5.

It has been demonstrated that a thin-disc Yb:YAG laser can generate kW level average power with a high repetition rate in burst mode[16] and continuous mode.[17] In the earlier work by the burst mode, a multipass laser amplifier was developed to operate in a 10-Hz burst mode with 800-μs burst duration and 100-kHz intraburst repetition rate. The total output pulse energy was 44.5 mJ in the single burst pulse with 820-fs compressed pulse duration. The average power of 4.45 kW during the burst was the highest reported in 2012. A larger scale multipass amplifier was employed to generate continuous average power of 1.4 kW in 2015. The pulse length was 8 ps, and the repetition rate was 300 kHz.

The thin-disc laser proved its ability to generate multiple short pulses with high average power, suitable for LPP and FEL EUV source applications. A further requirement is stability and compactness in the actual application field. Intensive study has been performed in the HiLASE Centre to confirm the high beam quality with good pointing stability. Higher CE from pump to amplified pulse energy is the key to realizing these characteristics.[18] A 1-kHz, 45-mJ regenerative amplifier was operated by zero phonon pumping to increase the optical–optical CE, and the resulting increased pulse pointing stability is shown together with a far-field beam shape with M^2 of 1.2 in Fig. 6.

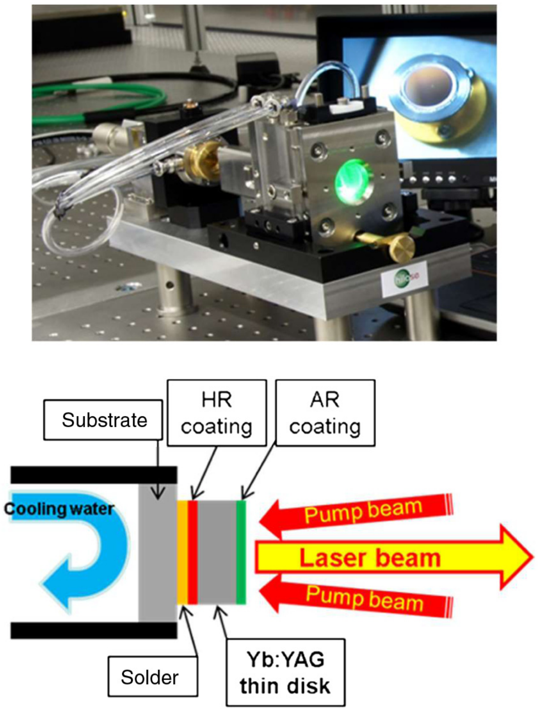

Fig. 5 Thin-disc module and cross section of the thin-disc core region.

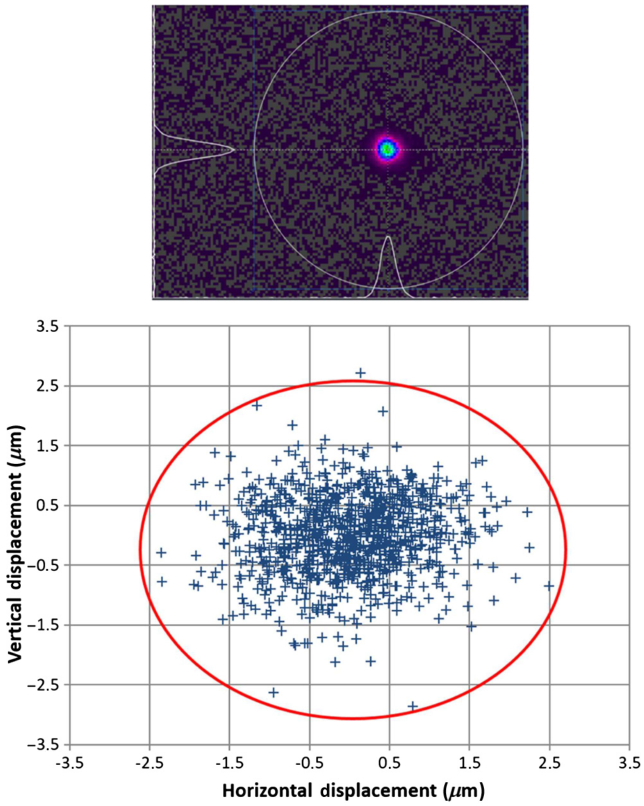

Fig. 6 Beam shape and pointing stability from 1-kHz thin-disc regenerative amplifier.

A compact kW-class thin-disc-based regenerative amplifier, Perla-C, is now under intensive study.[19] Its design is based on the common chirped pulse amplification method. A low-energy Yb-fiber oscillator is followed by fiber preamplifiers, two stage thin-disc regenerative amplifiers, and a chirped volume Bragg grating (CVBG) for both a pulse stretcher and compressor. The design specification of this system is 5-mJ pulse energy at a 100-kHz repetition rate (500 W continuous) with a pulse duration below 2 ps and adjustability of the repetition rate between 50 kHz and 1 MHz while maintaining approximately the same average power. A research trial is to upgrade the system to 1-kW average power level by keeping the same stability.

The thin discs used in the regenerative amplifiers were diamond-bonded Yb:YAG single crystals with a 10-mm diameter, 220-μm thickness, and 7.2 at.% doping concentration, pumped at the zero-phonon-line wavelength (969 nm). The optical setup of the first-stage regenerative amplifier includes a standing-wave cavity, thin-disc laser head with a pump spot diameter of 2.8 mm and pumped by a 500-W pump diode laser, and a dual beta barium borate (BBO) crystal Pockels cell for fast switching of the system. The maximum output pulse energy from this first regenerative amplifier was 1.2 mJ (average output power of 120 W) at a pump power of 430 W in a nearly diffraction-limited beam ($M^2 \approx 1.4$). Compressed pulses were obtained with the CVBG compressor (efficiency 85%) at the duration of 1.3 ps.

The second-stage amplifier was seeded by a part of the uncompressed output of the first stage (~20 W). The thin disc was pumped with a 2.2-kW continuous wave (CW), 969-nm fiber-coupled diode laser on a pump spot with a diameter of 5.2 mm. The disc was located in a compact 6.5-m long ring cavity with two V-passes through the disc per one roundtrip, and the footprint area of the amplifier is only 100×60 cm^2. double Pockels cell with two $10 \times 10 \times 25$ mm^3 BBO crystals in in-house developed holders was operated with a 10-kV voltage and repetition rate of <1 MHz. The maximum CW output power of 565 W was obtained at a 1.21-kW pump power, and the optical-to-optical efficiency was 47%. In a seeded operation with the input pulse energy of 0.2 mJ, obtained pulses were 4 mJ at 100 kHz (400-W average output power) with extraction efficiency of 43% as in Fig. 7(a). Compressed pulses had a duration of 1.8 ps, and the compression efficiency achieved with the CVBG compressor was around 80%. The repetition rate of the laser system was tunable from 50 kHz to 1 MHz. In the 50-kHz regime, a several-hours-long stable operation was achieved with an average output power of 320 W (6.4 mJ) in the fundamental transverse mode in far-field as in Fig. 7(b). The laser was operated for 10 h at 330 W with a power fluctuation with root mean square 1.2% over 2 h. Optimization is continuing in the pulse compression and output pulse shape. The performance of the Perla-C laser system is studied in the entire range of its repetition rates and optimized pulse compression; a concept for a 1-kW, sub-ps upgrade is in the present research subjects.

Nonlinear wavelength conversion is studied as the 100-kHz Yb:YAG thin-disc regenerative amplifier as the initial source.[20] The second (515 nm) and fourth (257.5 nm) harmonics were generated from the first-stage regenerative amplifier with 60 W in pulses of 4-ps duration. 35 W in green light and 6 W in DUV were achieved. The sensitivity of the second harmonic generation efficiency on the lithium triborate crystal temperature was controlled in the experiment. The overall CE from NIR to DUV of 10% was

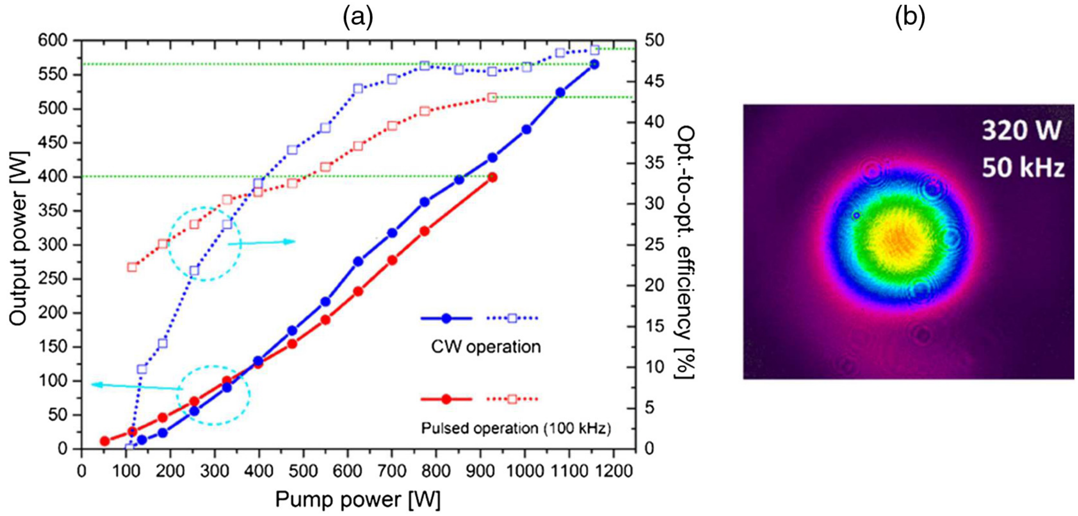

Fig. 7 (a) Average output power and O–O (optical–optical) efficiency of the main regenerative amplifier versus pump power and (b) beam profile at 320 W, 50 kHz.

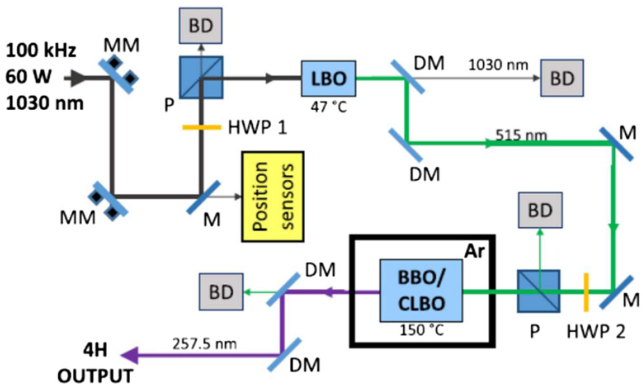

Fig. 8 Optical arrangement in the second and fourth harmonics generation. MM, motorized mirror; M, mirror; BD, beam dump; HWP, half wave plate; DM, dichroic mirror; P, polarizer.

achieved. The β-barium borate and cesium lithium borate crystals were used as green to DUV convertors and compared regarding the efficiency and spectral bandwidths. The achieved output power is unique for DUV ps pulses in 2017. A recently published research paper reports on the femtosecond fourth harmonic generation that an 80-W, 796-kHz ultrafast fiber laser system delivered a 4.6-W average power at 258 nm of 150-fs pulse length, based on two-stage fourth harmonic generation in BBO.[21] Figure 8 shows the experimental setup of the wavelength conversion. The sensitive component of BBO/CLBO was enclosed in an air-filled chamber. A further experiment is scheduled for higher output power with the whole stage thin-disc laser to generate higher fourth harmonics output power.

4 Conclusion

The present status of the Perla-C, Yb:YAG thin-disc laser-based ps regenerative amplifier, which is aimed at applications in LPP and FEL EUV source technology, is reported. The required specification is demanding to the present solid-state laser technology, and the most possible solution is given by thin-disc laser technology. Further research is in progress toward a compact kW-class ps laser, which is robust and stable for EUV sources in the present and coming generations.

Acknowledgments

The authors would like to acknowledge technical discussions with Dr. I Fomenkov of ASML and Dr. H. Mizoguchi of GigaPhoton Inc. Colleagues in the HiLASE Centre are appreciated for their valuable experimental and theoretical works. This work was funded 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 the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 739573. This work was also supported by the Ministry of Education, Youth, and Sports of the Czech Republic (Programs NPU I Project No. LO1602 and Large Research Infrastructure Project No. LM2015086).

References

1. A. Endo, "Extendibility evaluation of industrial EUV source technologies for kW average power and 6× nm wavelength operation," *J. Modern Phys.* **5**, 285–295 (2014).
2. M. S. Krivokorytov et al., "Cavitation and spallation in liquid metal droplets produced by subpicosecond pulsed laser radiation," *Phys. Rev. E* **95**, 031101 (2017).
3. M. M. Basko et al., "Fragmentation dynamics of liquid-metal droplets under ultra-short laser pulses," *Laser Phys. Lett.* **14**, 036001 (2017).
4. C. Pagania et al., "Design considerations of 10 kW-scale, extreme ultraviolet SASE FEL for lithography," *Nucl. Instrum. Methods Phys. Res. A* **475**, 391–396 (2001).
5. E. R. Hosler, O. R. Wood, II, and W. A. Barletta, "Free-electron laser emission architecture impact on EUV lithography," *Proc. SPIE* **10143**, 101431M (2017).
6. T. Nakajyo et al., "Quantum efficiencies of Mg photocathode under illumination with 3rd and 4th harmonics Nd: LiYF4 laser light in RF gun," *Jpn. J. Appl. Phys.* **42**, 1470–1474 (2003).
7. A. Endo, "High-brightness solid-state lasers for compact short-wavelength sources," Chapter 5 in *High Energy and Short Pulse Lasers*, Intech (2016).
8. H. Mizoguchi et al., "Performance of one hundred watt HVM LPP-EUV source," *Proc. SPIE* **9422**, 94220C (2015).
9. H. Mizoguchi et al., "Performance of 250-W high power HVM LPP-EUV source," *Proc. SPIE* **10143**, 101431J (2017).
10. I. Fomenkov et al., "Light sources for high-volume manufacturing EUV lithography: technology, performance, and power scaling," *Appl. Opt. Technol.* **6**(3–4), 173–186 (2017).
11. H. Mizoguchi et al., "LPP-EUV light source development for high volume manufacturing lithography," *Proc. SPIE* **8679**, 86790A (2013).

12. H. Matsukuma et al., "Correlation between laser absorption and radiation conversion efficiency in laser produced tin plasma," *Appl. Phys. Lett.* **107**, 121103 (2015).
13. M. Goldstein, S. H. Lee, and Y. A. Schroff, "FEL application In EUV lithography," in *Proc. 27th Int. Free Electron Laser Conf.* (2005).
14. A. Endo et al., "Optimization of high average power FEL for EUV lithography application," in *Proc. of the 36th Int. Free Electron Laser Conf.* (2014)
15. E. Allaria et al., "Two-stage seeded soft-x-ray free-electron laser," *Nat. Photonics* **7**, 913–918 (2013).
16. M. Schulz et al., "Pulsed operation of a high average power Yb:YAG thin-disk multipass amplifier," *Opt. Express* **20**, 5038 (2012).
17. J. P. Negel et al., "Ultrafast thin disc multipass amplifier delivering 1.4 kW (4.7 mJ, 1030 nm) average power converted to 820 W at 515 nm and 234 W at 343 nm," *Opt. Express* **23**, 21064–21077 (2015).
18. M. Chyla et al., "Optimization of beam quality and optical-to-optical efficiency of Yb:YAG thin-disk regenerative amplifier by pulsed pumping," *Opt. Lett.* **39**, 1441–1444 (2014).
19. J. Mužík et al., "Development of a variable repetition rate, kW-level, picosecond ring regenerative amplifier," in *CLEO/Europe EQEC 2017*, Munich (2017).
20. O. Noval et al., "Picosecond green and deep ultraviolet pulses generated by a high-power 100 kHz thin-disk laser," *Opt. Lett.* **41**, 5210–5213 (2016).
21. M. Muller et al., "High-average-power femtosecond laser at 258 nm," *Opt. Lett.* **42**, 2826–2829 (2017).

Akira Endo was invited to Jena University as a Zeiss professor during 2009 to 2010, and to FZD research center in Dresden, after successful research projects under METI, Japan "Femtosecond Technology" for "laser-Compton x-ray sources" and "EUVA" as a member of Giga Photon Inc. during 2002 to 2009 to establish the CO_2 laser pumped Tin droplet LPP scheme for >100 W source. He is now a guest professor at Waseda University in Tokyo, Japan, and the research leader of the Thin Disc Laser Program at the HiLASE Centre in Prague, Czech Republic.

Martin Smrž received his PhD in applied physics from the Czech Technical University in Prague, Czech Republic, in 2012. Since 2012, he has been with the HiLASE Centre, Institute of Physics AS CR, where he is a member of the ultrashort pulse thin disk laser development group. His current research focuses on high average power sub-picosecond lasers and nonlinear optics for industrial and scientific applications.

Jiří Mužík is a junior researcher at HiLASE Centre in DolníBřežany, Czech Republic, where he is involved in the development of high-average-power picosecond thin-disk laser systems. He received his master's degree from Czech Technical University, Prague, in 2014, and currently, he is working toward his PhD in physical engineering. His research interests include high-power thin-disk lasers and mid-IR solid-state lasers.

Ondřej Novák: Biography is not available.

Michal Chyla is a senior researcher at HiLASE Centre. He has been working with the thin-disk lasers since 2010. Graduated from Czech Technical University in Prague with a PhD in application of natural sciences in the field of physical engineering. One of the key achievements was to improve the performance of Yb:YAG thin-disk regenerative amplifier with zero-phonon line pulsed pumping. Currently, he is working on a burst thin-disk laser system.

Tomáš Mocek received his PhD in physics from Korea Advanced Institute of Science and Technology in 2000, and in applied physics from the Czech Technical University in 2001. His research expertise includes development of high-average power diode-pumped solid-state lasers for high-tech applications, EUV generation, high-order harmonic generation, mid-IR generation, laser induced periodic surface structures, laser acceleration of particles, dense plasma diagnostics, optical-field ionization, x-ray lasers, and spectroscopy of laser plasma.