Megawatt-scale average-power ultrashort pulses in an enhancement cavity

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Received February 28, 2014; revised March 26, 2014; accepted March 26, 2014; posted March 27, 2014 (Doc. ID 207421); published April 18, 2014

We investigate power scaling of ultrashort-pulse enhancement cavities. We propose a model for the sensitivity of a cavity design to thermal deformations of the mirrors due to the high circulating powers. Using this model and optimized cavity mirrors, we demonstrate 400 kW of average power with 250 fs pulses and 670 kW with 10 ps pulses at a central wavelength of 1040 nm and a repetition rate of 250 MHz. These results represent an average power improvement of one order of magnitude compared to state-of-the-art systems with similar pulse durations and will thus benefit numerous applications such as the further scaling of tabletop sources of hard x rays (via Thomson scattering of relativistic electrons) and of soft x rays (via high harmonic generation).

OCIS codes: (140.4780) Optical resonators; (140.7240) UV, EUV, and X-ray lasers.

http://dx.doi.org/10.1364/OL.39.002595

In a passive optical resonator laser pulses can be coherently stacked, enabling a power enhancement of a few orders of magnitude. These enhancement cavities (ECs) operating at multimegahertz repetition rates are well suited for boosting the overall efficiency of frequency conversion processes that require high intensities and are characterized by low single-pass conversion efficiencies. Among these, high harmonic generation (HHG) in noble gases [1–7] and hard x-ray generation via Thomson (or inverse-Compton) scattering from relativistic electrons [8–10] are prominent examples. For the latter, high intensities of $>10^{14}$ W/cm^2 with picosecond pulses at repetition rates around 100 MHz are targeted, imposing the requirement of megawatt-level average powers [9,10]. However, scaling the power in ECs has so far been limited by intensity-related damage of the mirrors. At 78 MHz, up to 18 kW of average power with 200 fs pulses has been demonstrated [11]. In that work, a further increase of the average power could only be achieved by increasing the pulse duration. Moreover, at the maximum power of 70 kW (achievable only for pulses longer than 2 ps), the cavity mode was considerably deformed due to thermal effects.

In this Letter, we investigate how the thermal deformation of the cavity mirrors affects the operation of an EC in the high-power regime. Using this analysis and design strategies aiming at increasing the spot sizes on all cavity mirrors [12] to avoid intensity-related limitations, we demonstrate the enhancement of 250 fs pulses to 400 kW of average power and the enhancement of 10 ps pulses to 670 kW at a repetition rate of 250 MHz. These results not only will benefit the scaling of hard-x-ray flux from Thomson sources but are also of great interest for further scaling the extreme UV power in intracavity HHG and for coherent pulse stacking to Joule-level energy followed by dumping for extraction as proposed in [13].

To obtain large spot sizes on all mirrors in an alignment-insensitive EC, we recently proposed and investigated the operation of a bow-tie cavity close to the inner stability edge [12]. In a low-power regime, we showed that this EC can be operated with standard optomechanics with a distance between the curved mirrors just 10 μm away from the stability edge without any increase in intracavity power fluctuations at an enhancement of 2000. This observation is supported by simulations showing that the alignment sensitivity in terms of mirror tilts is not necessarily critical at a stability zone edge [12].

The high-power-regime investigations reported here are performed with a similar EC design. We consider a symmetric four-mirror bow-tie cavity of round-trip length L consisting of two identical focusing mirrors with radius of curvature R_{cold} separated by a distance d and two plane folding mirrors (see Fig. 1). Three of the mirrors are highly reflective, and the fourth is the input coupler with transmission T. Absorption in the coating of the mirrors leads to a thermal deformation of the substrate, which can be described by an effective radius of curvature R_{thermal} [14] with

$$R_{\mathrm{thermal}}^{-1} = -\gamma \frac{\alpha}{\kappa} \frac{P_{\mathrm{abs}}}{w_{\mathrm{in}}^2}, \tag{1}$$

where κ denotes the thermal conductivity of the substrate, α its coefficient of thermal expansion, P_{abs} the absorbed power in the coating, and w_{in} the $1/e^2$-intensity radius of the impinging Gaussian beam. The absorbed power relates to the circulating power P_{circ} by the coating absorption factor (assumed to be constant), $P_{\mathrm{abs}} = a_{\mathrm{coat}} P_{\mathrm{circ}}$. From finite-element simulations of the thermal expansion we deduce a proportionality constant $\gamma = 0.1$

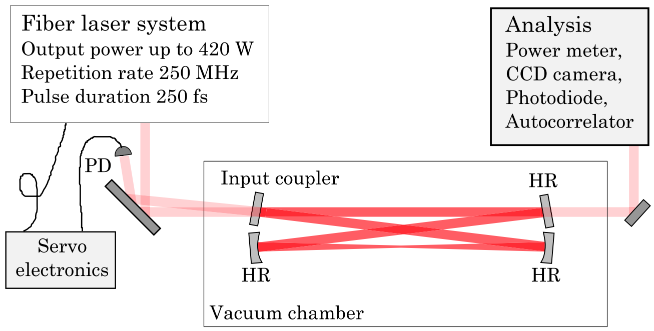

Fig. 1. Schematic of the experimental setup. PD, photodiode; HR, highly reflective.

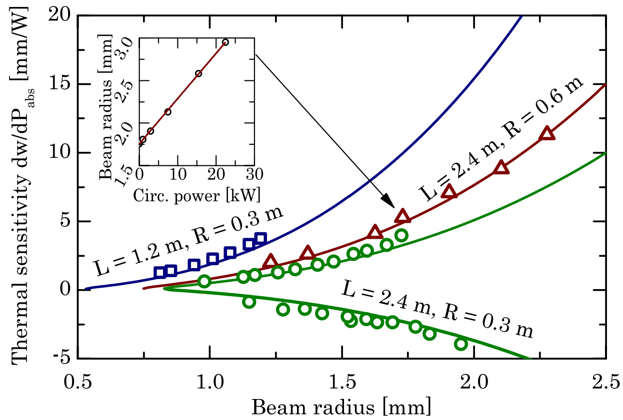

Fig. 2. Thermal sensitivity of three bow-tie cavities over their entire stability range. The measured values (marker points) were fitted to the calculated sensitivities (solid lines) using the coating absorption factor a_{coat} as a single free parameter, yielding excellent agreement.

for fused silica. The total radius of curvature of the warm mirror is then given by $R_{\mathrm{warm}}^{-1} = R_{\mathrm{cold}}^{-1} + R_{\mathrm{thermal}}^{-1}$.

The beam radius on the curved mirrors w_{mirror} can be calculated by means of Gaussian-beam optics. It is determined by the cavity geometry, i.e., it depends on d, L, R_{cold}, and R_{thermal}, which itself depends on w_{mirror}. When the cavity is operated close to the inner stability edge, the defocusing effect of the thermal deformation pushes the cavity further toward the stability edge, leading to an increase of the beam size. This in turn reduces $R_{\mathrm{thermal}}^{-1}$ according to Eq. (1) until a steady state is reached in which $w_{\mathrm{in}} = w_{\mathrm{mirror}}$ holds. Thus, the thermal deformation of the mirrors cannot make the cavity unstable but only increases the beam radius. However, the increase of the beam size can become so strong that it limits the achievable intracavity average power with realistic mirror sizes. Close to the inner stability edge the increase in the mode size is, in very good approximation, linearly proportional to the absorbed power.

To compare the sensitivity of different cavity geometries, we define the *thermal sensitivity* as the derivative of the beam radius on the curved mirrors with respect to the absorbed power $\partial w_{\mathrm{mirror}}/\partial P_{\mathrm{abs}}$. It can be calculated through consideration of the deformation of both the curved and the plane mirrors. This quantity relates to the derivative of the beam radius with respect to the circulating power according to $\partial w_{\mathrm{mirror}}/\partial P_{\mathrm{abs}} = a_{\mathrm{coat}}^{-1}\partial w_{\mathrm{mirror}}/\partial P_{\mathrm{circ}}$, the latter being a quantity that can be measured experimentally.

For the power scaling experiments we use the Yb:fiber-based chirped-pulse amplification system described in [15]. It delivers 250 fs pulses spectrally centered at 1040 nm at a repetition rate of 250 MHz with an average power of up to 420 W (pulse energy 1.7 μJ). The laser is locked to the EC using the Pound–Drever–Hall scheme with an intra-oscillator electro-optical modulator. The cavity is placed in a vacuum chamber (background pressure 10^{-4} mbar). The transmission through one of the cavity mirrors is used to measure the intracavity power (see Fig. 1). For that purpose, we measured the transmission of that cavity mirror using two calibrated power meters, one in front of and one behind the mirror. Furthermore, we measure the pulse duration (via autocorrelation) and the beam profile on one cavity mirror (imaged with known magnification). For all mirrors, we used 6.3 mm thick substrates with a diameter of 25 mm. All highly reflective mirrors have total losses of less than 50 ppm (transmission, scattering, and absorption), and the desired finesse is set by the input coupler transmission. In addition, aberrations induced by thermal deformation of the mirrors can lead to a decrease of the cavity finesse, as discussed later on.

In Fig. 2, the thermal sensitivity is shown for three different bow-tie cavity geometries over their entire stability regions, calculated for fused silica substrates. The thermal sensitivity is plotted as a function of the beam radius on the curved mirrors, which directly relates to the position in the stability region. We changed the distance between the two curved mirrors to set the beam radius, while the distance between the two plane mirrors was adjusted to keep the resonator length constant. To verify the simulations, we implemented these cavities experimentally. We measured the beam radius on one curved mirror as a function of the circulating power for several positions in the stability region, as exemplified in the inset of Fig. 2. Each data point in Fig. 2 corresponds to such a curve of the beam radius, with the initial beam radius on the x axis and the slope on the y axis. Using the coating absorption factor a_{coat} as a single fit parameter (assumed to be equal for all four mirrors), the measured values can be fitted to the calculated sensitivities, yielding an excellent agreement for $a_{\mathrm{coat}} = 4$ ppm. Toward the inner stability edge (corresponding to the upper branch in Fig. 2, i.e., $d \gtrsim R$), a significant increase in the thermal sensitivity is observed. However, here the ratio between the intensity on the mirrors and that in the focus is the largest. Thus, in practice, a trade-off between this intensity ratio and the thermal sensitivity needs to be found. This model enables the design optimization of a cavity with respect to this trade-off. From these results, it follows that harder focusing and/or longer cavities exhibit a lower thermal sensitivity.

As the thermally induced radius of curvature R_{thermal} depends on the substrate's α/κ ratio [see Eq. (1)] and the absorbed power, the thermal sensitivity can be reduced by employing substrate materials with superior thermal properties compared to fused silica and low-absorption coatings. One option for the substrate is glass with a thermal expansion coefficient designed to be zero at room temperature, available, e.g., under the trademarks ULE (Corning), Zerodur (Schott), and Clearceram-Z (Ohara). In our experiments we used ULE, which has approximately the same thermal conductivity as fused silica, while the coefficient of thermal expansion is specified to be better by a factor exceeding 17. Apart from these glasses, crystalline materials with high thermal conductivity such as sapphire or YAG can be employed. However, as these materials exhibit a higher coefficient of thermal expansion, the ratio α/κ from Eq. (1) is not significantly improved (e.g., by a factor of 2.5 for sapphire compared to fused silica). We found that absorption in ULE limits its use as an input coupler to about 10 W of input average power. At higher power levels significant thermal lensing impairs efficient coupling of light into the cavity. We therefore use fused silica and sapphire substrates for the input coupler. While sapphire has superior thermal properties, its surface quality is poorer, in general resulting in lower mirror damage thresholds.

For power scaling to the hundreds of kilowatts level with femtosecond pulses, we implemented a 2.4 m long cavity (two circulating pulses) consisting of two curved mirrors with ULE substrates (radius of curvature 600 mm), one plane mirror with a ULE substrate, and a plane input coupler with a fused silica substrate. The footprint of the EC is only $80\ \mathrm{cm} \times 15\ \mathrm{cm}$. In Fig. 3, the increase in the larger beam radius (sagittal plane) of the slightly elliptical beam (see Fig. 4) is depicted for different mirror configurations. Compared to the cavity with all-fused-silica optics and the same coating as in [11], the thermal sensitivity was reduced by more than one order of magnitude due to the ULE mirrors and a low-absorption coating (Layertec). In this configuration the fused silica input coupler dominates the thermal mode change. This configuration allowed up to 400 kW of intracavity average power with 250 fs pulses in the cavity at an input power of 315 W (enhancement factor of 1270). This corresponds to a pulse energy of 1.6 mJ with a peak power of 5.5 GW. These pulses were focused in the cavity to a $25\ \mu\mathrm{m} \times 34\ \mu\mathrm{m}$ focus, resulting in a peak intensity of $4 \times 10^{14}\ \mathrm{W/cm^2}$. Moreover, we implemented the same cavity geometry with a sapphire input coupler.

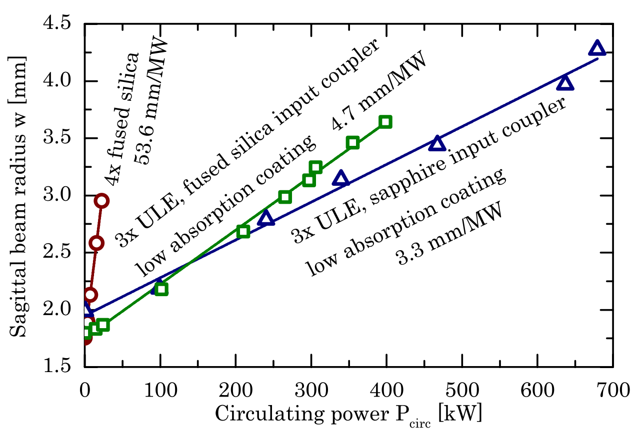

Fig. 3. Increase in the beam radius on one cavity mirror with respect to the circulating power. The straight lines are linear fits. The slope (given in mm/MW) is reduced by more than one order of magnitude when employing ULE substrates for the highly reflective mirrors.

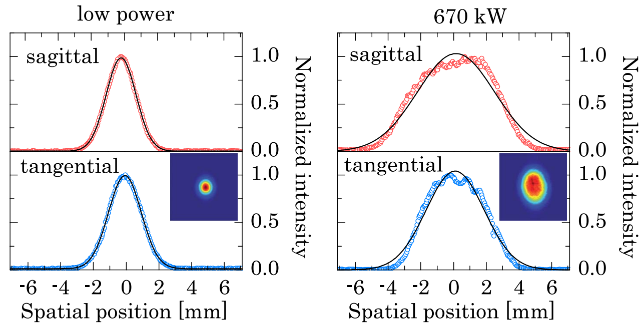

Fig. 4. Linecuts of the cavity mode at low power (left panel) and at 670 kW (right panel) with corresponding Gaussian fits (solid lines). At high power, there is a deviation from a purely Gaussian shape due to resonant coupling to higher-order Gauss–Hermite modes.

With 10 ps pulses, an average power of 670 kW was obtained. However, reaching higher average powers or the same power with shorter pulses was repeatedly prevented by optical damage of the input coupler. We attribute this to the inferior surface quality of the sapphire substrates compared to that of fused silica.

These results were limited by a decrease in the power enhancement due to resonant mode coupling [16] close to the inner stability edge. For example, with the fused silica input coupler, the enhancement decreased from 2000 at lower powers to 1270 at 400 kW. Higher input powers did not lead to higher intracavity powers. In general, all perturbations in the cavity, such as spherical aberrations, thermally induced aberrations, or mirror imperfections, result in a coupling among the transverse modes (mode numbers n, m). If the higher-order modes have different round-trip Gouy phases, this corresponds to a constant loss factor. However, toward the inner stability edge, the Gouy phase of all modes with even $n + m$ (including the TEM_{00} mode) converge to the same value, i.e., these modes are almost degenerate. Then the coupling becomes resonant, which leads to a reduction in the cavity finesse [16]. As higher-order modes are also resonant here, the spatial profile of the intracavity beam changes from a purely Gaussian shape to a slightly flattened profile (see Fig. 4). The mode coupling can, in principle, be reduced by minimizing the perturbations or by increasing the difference in Gouy phase of the higher-order modes, e.g., by increasing the cavity length.

In conclusion, we have investigated power scaling of ultrashort-pulse ECs theoretically and experimentally. With the thermal sensitivity model presented here and the alignment sensitivity metric introduced in [12], large-mode ECs supporting high peak and/or average powers can be designed. We have demonstrated the enhancement of 250 fs pulses to an average power of 400 kW and of 10 ps pulses to 670 kW at a repetition rate of 250 MHz. To the best of our knowledge this represents an improvement of around one order of magnitude over the previously reported highest average power at similar pulse durations [11]. Further scaling can be expected by increasing the cavity length, as this improves both the thermal sensitivity (Fig. 2) and the transverse mode discrimination. In addition, the intensity on the mirrors can be decreased by compensating for the beam ellipticity (see Fig. 4), e.g., with cylindrical or deformable mirrors [12]. The results presented here pave the way toward intracavity HHG at an average power level of 100 kW of the driving field, which is about a factor of ten more than in current experiments [3–6]. For Thomson scattering, enhancement factors on the order of 1000 for intracavity powers on the 1 MW level with picosecond pulses can be envisaged [8–10]. With the methods described here and in conjunction with state-of-the-art kilowatt-level average power laser systems [17–19], these parameters come within reach for the first time.

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) Cluster of Excellence, Munich Centre for Advanced Photonics (MAP) (www.munich-photonics.de), by the Bundesministerium für Bildung und Forschung (BMBF) under Photonische Nanomaterialien (PhoNa), contract number 03IS2101B, and by the Fraunhofer-Max Planck project MEGAS. T.Eidam acknowledges financial support from the Carl-Zeiss-Stiftung, and D. C. Yost from the Alexander von Humboldt Foundation.

References

1. C. Gohle, T. Udem, M. Herrmann, J. Rauschenberger, R. Holzwarth, H. A. Schuessler, F. Krausz, and T. W. Hänsch, Nature **436**, 234 (2005).
2. R. J. Jones, K. D. Moll, M. J. Thorpe, and J. Ye, Phys. Rev. Lett. **94**, 193201 (2005).
3. I. Pupeza, S. Holzberger, T. Eidam, H. Carstens, D. Esser, J. Weitenberg, P. Rußbüldt, J. Rauschenberger, J. Limpert, T. Udem, A. Tünnermann, T. W. Hänsch, A. Apolonski, F. Krausz, and E. Fill, Nat. Photonics **7**, 608 (2013).
4. T. K. Allison, A. Cingöz, D. C. Yost, and J. Ye, Phys. Rev. Lett. **107**, 183903 (2011).
5. D. R. Carlson, J. Lee, J. Mongelli, E. M. Wright, and R. J. Jones, Opt. Lett. **36**, 2991 (2011).
6. A. K. Mills, T. J. Hammond, M. H. C. Lam, and D. J. Jones, J. Phys. B **45**, 142001 (2012).
7. A. Ozawa, A. Vernaleken, W. Schneider, I. Gotlibovych, T. Udem, and T. W. Hänsch, Opt. Express **16**, 6233 (2008).
8. Z. Huang and R. D. Ruth, Phys. Rev. Lett. **80**, 976 (1998).
9. J. Bonis, R. Chiche, R. Cizeron, M. Cohen, E. Cormier, P. Cornebise, N. Delerue, R. Flaminio, D. Jehanno, F. Labaye, M. Lacroix, R. Marie, B. Mercier, C. Michel, Y. Peinaud, L. Pinard, C. Prevost, V. Soskov, A. Variola, and F. Zomer, J. Instrum. **7**, P01017 (2012).
10. W. S. Graves, W. Brown, F. X. Kaertner, and D. E. Moncton, Nucl. Instrum. Methods Phys. Res. A **608**, S103 (2009).
11. I. Pupeza, T. Eidam, J. Rauschenberger, B. Bernhardt, A. Ozawa, E. Fill, A. Apolonski, T. Udem, J. Limpert, Z. A. Alahmed, A. M. Azzeer, A. Tünnermann, T. W. Hänsch, and F. Krausz, Opt. Lett. **35**, 2052 (2010).
12. H. Carstens, S. Holzberger, J. Kaster, J. Weitenberg, V. Pervak, A. Apolonski, E. Fill, F. Krausz, and I. Pupeza, Opt. Express **21**, 11606 (2013).
13. S. Breitkopf, T. Eidam, A. Klenke, L. v. Grafenstein, H. Carstens, S. Holzberger, I. Pupeza, E. Fill, T. Schreiber, F. Krausz, A. Tünnermann, and J. Limpert, Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany, are preparing a manuscript to be called "Concept for multi-terawatt fibre lasers based on coherent pulse stacking in passive cavities."
14. W. Winkler, K. Danzmann, A. Rüdiger, and R. Schilling, Phys. Rev. A **44**, 7022 (1991).
15. C. Jocher, T. Eidam, S. Hädrich, J. Limpert, and A. Tünnermann, Opt. Lett. **37**, 4407 (2012).
16. T. Klaassen, J. de Jong, M. van Exter, and J. P. Woerdman, Opt. Lett. **30**, 1959 (2005).
17. T. Eidam, S. Hanf, E. Seise, T. V. Andersen, T. Gabler, C. Wirth, T. Schreiber, J. Limpert, and A. Tünnermann, Opt. Lett. **35**, 94 (2010).
18. P. Russbueldt, T. Mans, J. Weitenberg, H. D. Hoffmann, and R. Poprawe, Opt. Lett. **35**, 4169 (2010).
19. J.-P. Negel, A. Voss, M. A. Ahmed, D. Bauer, D. Sutter, A. Killi, and T. Graf, Opt. Lett. **38**, 5442 (2013).