Power scaling of a high-repetition-rate enhancement cavity

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A passive optical resonator is used to enhance the power of a pulsed 78 MHz repetition rate Yb laser providing 200 fs pulses. We find limitations relating to the achievable time-averaged and peak power, which we distinguish by varying the duration of the input pulses. An intracavity average power of 18 kW is generated with close to Fourier-limited pulses of 10 W average power. Beyond this power level, intensity-related effects lead to resonator instabilities, which can be removed by chirping the seed laser pulses. By extending the pulse duration in this way to 2 ps, we could obtain 72 kW of intracavity circulating power with 50 W of input power.

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Efforts to resonantly enhance pulsed lasers in an external cavity have recently been boosted by the prospect of intracavity high-harmonic generation (HHG) [1–5]. Traditional methods of generating peak intensities exceeding 10^{13} W/cm^2 required for HHG rely on a largely reduced pulse repetition rate (see, e.g., [6]). The intracavity approach allows HHG with a multimegahertz repetition rate such that individual modes of the resulting frequency comb [7] in the extreme UV (XUV) may be used as cw lasers. Such a laser source would be highly desirable for high-resolution spectroscopy in this hitherto inaccessible wavelength region. Further applications of such a compact and coherent XUV source include lithography or XUV optics characterization. Yet another emerging application, for which compact enhancement cavities constitute a very promising approach, is the generation of high-brilliance hard x-rays via inverse Compton scattering of laser photons by a relativistic electron beam, Doppler upshifting them to the hard x-ray or even gamma-ray range [8,9].

Enhancing a train of pulses in an optical resonator is analogous to the cw case if the mode spacing of the pulse train matches the resonator's frequency-resolved free spectral range. In the time domain this means that, after each round trip, the pulse circulating in the passive cavity interferes constructively with the next pulse from the laser. A power enhancement of a few thousands has been achieved so far with enhancement cavities seeded by Ti:sapphire [1–3] and Yb-doped [4,5] lasers reaching a few kilowatts of intracavity average power and peak intensities exceeding 10^{13} W/cm^2 at the cavity focus. With the advent of high-power ultrafast laser systems [10–12], the power scalability investigation of enhancement cavities becomes crucial to the development of this technique. In this Letter, we explore limiting factors for the intracavity power in a high-repetition-rate, bow-tie cavity employing state-of-the-art commercially available ion-beam sputtered dielectric mirrors (Layertec).

We seed our external cavity with the system presented in [10] [see Fig. 1(a)]. Transform-limited 170 fs sech^2 initial pulses are generated by a passively mode-locked, diode-pumped Yb:KYW oscillator with 78 MHz repetition rate and 220 mW average power. The FWHM bandwidth

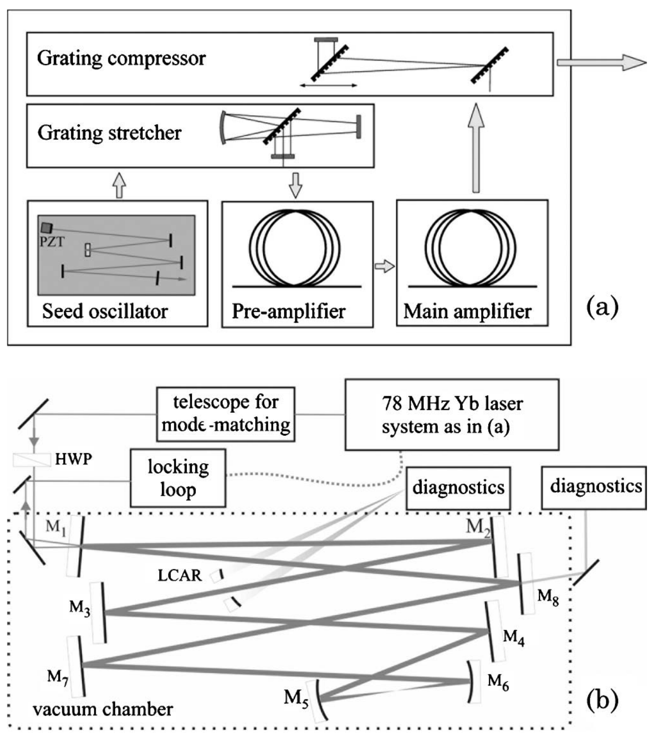

Fig. 1. Experimental setup: (a) seeding laser [10] and (b) enhancement cavity. M2–M8, dielectric mirrors with $R = 99.995\%$ $\pm$ 20 ppm (parts per million) (ring-down measurement); M1, 99.86% reflectivity input coupler. M5 and M6 have a radius of curvature of 150 mm and enclose the 22 μm cavity focus ($1/e^2$ radius calculated at the stability range center). HWP, half-wave plate; LCAR, large circular aperture reflector; diagnostics, photodiode/power meter/spectrometer/autocorrelator/beam profiler.

is 7 nm centered around 1042 nm. The pulses are stretched to 150 ps with a transmission grating and sent to a two-stage fiber amplifier. The amplifier fibers are pumped at 976 nm by laser diodes delivering up to 25 and 130 W. Subsequent compression down to 200 fs is achieved with two fused-silica transmission gratings. By varying the distance between these gratings, the pulse length can be adjusted between 200 fs and more than 10 ps without affecting the other beam parameters. After compression, the average power exceeds 50 W. The output spectrum is largely independent of the amplification level.

As in the work presented in [1–5], our enhancement cavity is a ring resonator whose round-trip time is adjusted to the inverse of the seeding laser repetition rate [see Fig. 1(b)]. For compactness, the beam is folded several times. The $1/e^2$ beam diameters on the cavity mirrors range between 1.5 and 2.6 mm. To minimize group delay dispersion (GDD) and losses, the cavity is placed inside a vacuum chamber. Its optics exhibit very low dispersion (GDD <20 fs^2 per mirror, according to the manufacturer's specification) over the bandwidth of the 200 fs seed pulses, making further dispersion compensation unnecessary. The frequency of the nth laser mode is given by $f_n = nf_{\mathrm{rep}} + f_{\mathrm{CE}}$, where f_{rep} is the laser repetition frequency and f_{CE} is the carrier-envelope (CE) frequency [1]. Because of the relatively narrow bandwidth of the seeding laser, small variations of f_{rep} and f_{CE} have very similar effects on the structure of the frequency comb. Thus, a stable lock of the seeding laser to the enhancement cavity can be achieved by actively controlling a single comb parameter. In our case, this control is obtained by varying the position of an oscillator cavity end mirror with a fast piezoelectric transducer. The lock is realized with a Hänsch–Couillaud scheme [13]. In contrast to the original scheme, where an intracavity Brewster plate is employed, in our case the necessary polarization discrimination is given by the nonorthogonal incidence on the mirrors. In addition, for optimum enhancement, a coarse CE-offset adjustment is achieved by manually varying the seed oscillator optical pump power. The power enhancement factor P is defined as $P = P_{\mathrm{circ}}/P_{\mathrm{in}}$, where P_{circ} and P_{in} denote the circulating intracavity power and the seeding laser power, respectively. We determine P_{circ} by two different methods. We measure the power P_{leak} leaking through a cavity mirror and divide it by the mirror transmission of 1.65×10^{-6}. To prevent measurement errors due to potential mirror transmission changes at higher powers, we implement a second measurement method for P_{circ} using a large circular aperture around the intracavity laser beam [see Fig. 1(b)]. This aperture does not affect the enhancement but still reflects a measurable portion P_{refl} of the intracavity light. Moreover, by using the leakage through the diagnostic mirror, we record the beam profile with a CCD camera and measure the intracavity autocorrelation and spectrum.

In a first experiment, we investigated the enhancement for various input powers P_{in} while keeping the input pulse duration at 200 fs. For 35 mW $\le P_{\mathrm{in}} \le$ 10 W, we observe a nearly linear dependence of both P_{leak} and P_{refl} on P_{in} [see Fig. 2(a)] in a stable locking regime. The entire spectrum was coupled into the cavity and uniformly enhanced, with the intracavity autocorrelation remaining constant. The reflection from the input coupler indicated an input coupling ratio of ~65%. These results imply a nearly constant enhancement factor $P = 1800$ and are in excellent agreement with the expected values assuming a lossless input coupler and perfect transversal mode matching. For $P_{\mathrm{in}} = 10$ W, a circulating power $P_{\mathrm{circ}} =$ 18 kW was reached. As discussed later in the text, a cavity transverse mode variation was observed with increasing power. For input powers beyond 10 W, the lock became increasingly unstable and, during the short periods of resonance, an intracavity pulse duration between 300 and 400 fs was observed. Operation beyond 10 W of input power invariably led to mirror damage.

To further investigate the limits of enhancement, we conducted a second scaling experiment. To distinguish between purely thermal effects and effects involving nonlinear processes in the cavity mirrors, the circulating pulse duration τ_{circ} was varied by chirping the input pulses, while keeping $P_{\mathrm{in}} = 50$ W constant. The results are shown in Fig. 2(b). For $\tau_{\mathrm{circ}} \ge 2$ ps, the locking was stable with an intracavity circulating power of $P_{\mathrm{circ}} =$ 72 kW, which corresponds to an enhancement factor $P = 1400$. The input coupling ratio to the cavity amounted to ~50%. As the pulse duration was decreased from 2 ps toward 640 fs, the lock became increasingly unstable and the enhancement factor decreased. For $\tau_{\mathrm{circ}} < 640$ fs, mirror damage occurred repeatedly. Damages were observed not only on the mirror with the minimum impinging beam size, where the peak intensity reached around 10^{11} W/cm^2, but occasionally, the mirror with the maximum beam size, implying a roughly 3 times lower peak intensity, was also damaged. This behavior is subject to further investigation. Thus, for $P_{\mathrm{in}} = 50$ W, the

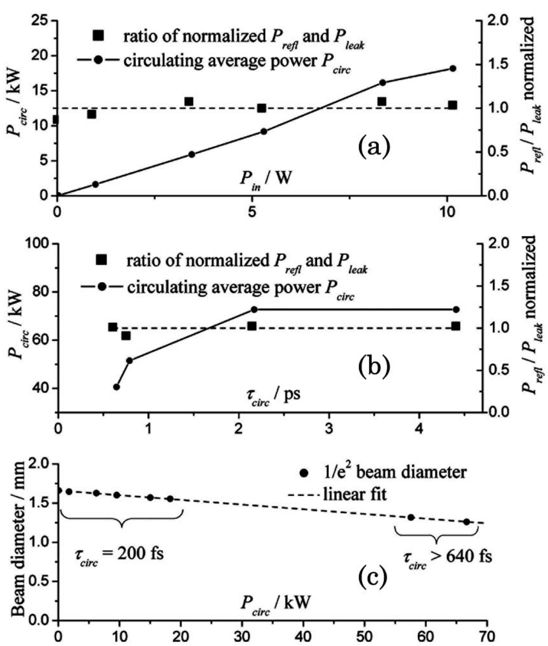

Fig. 2. (a) Circulating power versus input power for a constant intracavity pulse duration of 200 fs. (b) Circulating power versus pulse duration for constant input power of 50 W. The squares show the ratio of the values of P_{refl} and P_{leak} normalized to their average. (c) Beam diameter ($1/e^2$ value, measured behind diagnostic mirror) versus P_{circ} (for different pulse durations).

decrease of both stability and the enhancement factor and mirror damage primarily relate to the peak power. The small variation of the normalized values of P_{leak} and P_{refl}, shown in Fig. 2, implies that the transmission of the diagnostic mirror remained constant during all experiments.

Moreover, we observed a circulating power-dependent variation of the cavity transverse mode with a CCD camera placed behind the diagnostic mirror; see Fig. 2(c). We believe that this effect is due to thermal lensing in the cavity mirrors since it scales with the average circulating power, and is independent of pulse duration. However, the exact physical mechanisms for the change in beam diameter and for instabilities at higher peak powers still need to be investigated. The thermal nature of the beam diameter change is also supported by the observation of a delay of roughly 1 s from the moment the lock is initiated until the intracavity power settled to a steady state. We attribute the reduction of the cavity enhancement from 1800 at low circulating powers to 1400 at the maximum power to changes of the intracavity transverse mode profile due to this effect. This leads to a less than optimum overlap of the incoming and the circulating beam at the cavity input coupler. The decreasing input coupling ratio to the cavity with increasing P_{circ} confirms this assumption.

In conclusion, we have investigated power scaling limitations of a 78 MHz repetition rate, bow-tie enhancement cavity. By comparing the enhancement behavior for constant circulating power and varying the pulse duration, we found that high peak power is the primary cause of mirror damage. Below this damage threshold, in a stable locking regime, pulse duration can be traded in versus circulating power. A maximum circulating power of 18 kW was achieved for the minimum pulse duration of 200 fs, and a minimum pulse duration of 2 ps was measured for the maximum circulating power of 72 kW. In the cavity focus, these peak powers lead to intensities exceeding $10^{14}\ \mathrm{W/cm^2}$, derived with the calculated focus diameter. With the demonstrated peak power, stronger focusing (e.g., as reported in [5]) would increase the peak intensity in the focus by another order of magnitude. This enhancement cavity offers the prospect of HHG as well as hard x-ray generation via inverse Compton scattering at previously unachieved power levels. Further increase of the supported intracavity peak power calls for advances in mirror technology as well as cavity design.

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