Cavity-enhanced similariton Yb-fiber laser frequency comb: 3×10^{14} W/cm^2 peak intensity at 136 MHz

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We report on a passive cavity-enhanced Yb-fiber laser frequency comb generating 230 MW of peak power (3 kW of average power) at a 136 MHz pulse repetition rate. The intracativy peak intensity of 3×10^{14} W/cm^2 for the 95 fs pulse is sufficient to ionize noble gases, such as Xe, Kr, or Ar. The laser system is based on a mode-locked Yb-fiber similariton oscillator in conjunction with a cladding-pumped chirped-pulse fiber amplifier. After recompression, 75 fs duration pulses at a 13.1 W average power are obtained. These pulses are then coherently added inside a passive ring cavity by controlling the fiber oscillator's pulse repetition rate and carrier-envelope offset frequency. This system is well suited for studying high-field phenomena at very high pulse repetition rates. © 2007 Optical Society of America

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Strong-field processes at peak intensities $>10^{14}$ W/cm^2 are actively studied [1] to investigate many interesting phenomena, such as high-order harmonic and attosecond pulse generation in the vacuum UV (VUV) and extreme UV (XUV) spectral region by focusing an intense laser pulse into a gas of atoms [2,3], or electron acceleration and imaging of molecular orbitals by studying the angular distribution of photoelectrons generated by intense laser pulses [4]. The high peak intensities required for studying such processes necessitate the general use of large-scale solid-state amplifiers. This severely limits the pulse repetition rates at which these experiments can be conducted. Typical repetition rates lie in the range of a few hertz up to a few hundreds of kilohertz. All of these studies would greatly benefit from higher pulse repetition rates, since this would not only provide shorter data acquisition times but also allow direct access to the precise frequency comb structure of the femtosecond oscillator. If pulse repetition rates of the order of a few 10 MHz and higher could be reached, high-precision frequency-domain measurements conducted in the VUV and XUV range become feasible by adopting the recently established technique of direct frequency-comb spectroscopy [5]. However, typical mode-locked oscillators produce peak intensities below 1 MW. Hence, even under tight focusing the required intensities cannot be reached. Only with the recent development of thin disk [6,7], extended cavity [8], and chirped-pulse oscillator concepts [9], were peak intensities of the order of 10 MW reached and oscillator-driven noble gas ionization experiments made feasible.

A different concept for achieving high peak intensities at high repetition rates is the coherent addition of femtosecond pulses produced by mode-locked lasers inside passive high-finesse cavities [10]. It was independently demonstrated by Jones *et al.* [11] and Gohle *et al.* [12] that this concept allows the frequency comb to be extended to the VUV spectral region by using intracavity high-harmonic generation in Xe. Because of the use of Ti:sapphire-based solid-state lasers these systems were difficult to scale in average power. Fiber laser systems, on the other hand, provide excellent power scalability via the technologies of cladding pumping and chirped pulse amplification [13] and have the advantages of compact and rugged construction [14] and long-term uninterrupted operation. Recently, it was shown that these concepts are compatible with the phase control requirements of frequency-comb lasers [15]. Also the initially observed large phase noise of early Er-fiber frequency comb lasers has been significantly reduced over the past years, and actively stabilized laser systems with high phase coherence have been demonstrated [16]. Here, for the first time to our knowledge, we combine the concepts of passive cavity enhancement with a similariton Yb-fiber oscillator and a power-scalable, cladding-pumped, femtosecond Yb-fiber chirped-pulse amplifier to perform high-field experiments at high repetition rates.

A schematic of the experimental setup is shown in Fig. 1. An all-fiber Fabry–Perot type similariton Yb-fiber oscillator [17] mode-locked with a subpicosecond lifetime saturable absorber was used as a seed source. The dispersion was compensated by using a chirped fiber grating to achieve a net positive value for operation in the similariton regime [17,18]. The spectral bandwidth of the oscillator output was ~40 nm, centered at 1065 nm and exceeding 100 mW of average power. The pulse train at $f_{\mathrm{rep}}=136$ MHz from the oscillator was stretched in an anomalous

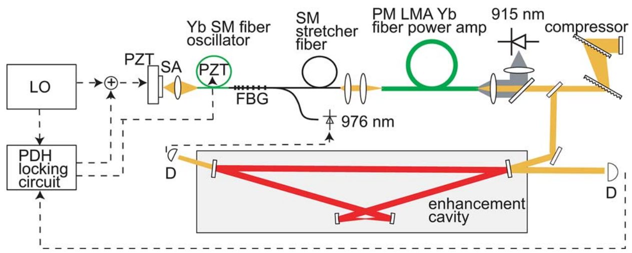

Fig. 1. (Color online) Experimental setup: LO, local oscillator; SA, saturable absorber; PZT, piezo actuator; FBG, fiber Bragg grating; D, photodetector; PM, polarization maintaining; SM, single mode.

third-order dispersion single-mode fiber to ~70 ps. The length of the anomalous third-order stretcher fiber and the normal single-mode fiber output pigtail of the oscillator were carefully adjusted to compensate for the third-order and most of the fourth-order dispersion as shown in Fig. 2(a). The pulse train was amplified at the full repetition rate by using 8 m of 700 μm^2 mode-field area polarization-maintaining double-clad Yb fiber that was end pumped by a fiber-coupled 915 nm diode laser. The amplified pulses were recompressed by using fused-silica transmission gratings. At ~40 W of coupled pump power, a compressed output power of 13.1 W was achieved. The compressed pulse width was measured by frequency-resolved optical gating to be 75 fs at an average output power of 10 W. The central peak of the pulse contains approximately 94% of the energy [Fig. 2(b)]. The fiber amplifier is operated in the linear regime, and we did not observe any significant changes in spectrum or compressed pulse fidelity when scaling the output power to 13.1 W.

The pulse train was mode matched to a high-finesse bow-tie ring cavity consisting of three high-reflectivity mirrors and one input coupler with reflectivities of more than 99.988% and 99.4%, respectively, over the laser output spectral bandwidth. Two of the high reflectors with a 5 cm radius of curvature provided an intracavity focus area of 150 μm^2. The focal area was calculated by using paraxial approximations (*ABCD* matrix method), where the exact curved mirror separation within the stability region was determined by measuring the ellipticity of the fundamental cavity mode. The intracavity dispersion was minimized by use of low-

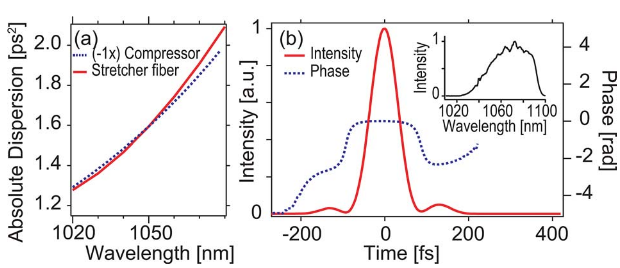

Fig. 2. (Color online) (a) Fiber stretcher–grating compressor dispersion compensation. (b) Amplified pulse retrieved from a frequency-resolved optical gating (FROG) measurement at 10 W of average power. Retrieved intensity FWHM, 75 fs; FROG error, 0.5%. Inset, optical spectrum emitted by the similariton Yb-fiber oscillator.

dispersion mirrors and evacuating the air to $\approx 10^{-6}$ Torr. The input coupler transmission was chosen higher than required for an impedance-matched cavity to limit the bandwidth-reducing effect from residual mirror dispersion. For ionization experiments, noble gas was either injected by using a small-diameter orifice close to the intracavity focus under continuous pumping that maintains a cavity pressure of 10^{-3} Torr or the entire cavity was pumped out and then backfilled at ~750 mTorr. Photoionization was characterized by measuring the current through two Pt electrodes placed across the intracavity waist. The electrodes were separated by 1 mm and biased at 10 V.

To lock the laser comb modes to the modes of the buildup cavity, two degrees of freedom need to be controlled, corresponding to the mode spacing f_{rep} and the offset frequency f_{ceo} of the comb. First, f_{rep} of the oscillator was locked to the cavity free spectral range within a narrow wavelength region. The Pound–Drever–Hall scheme was used for locking, and the phase modulation of the laser output at 1 MHz was achieved by adding a low-amplitude dither signal to the feedback signal driving the fast piezo actuator that translates the saturable absorber mirror. The feedback loop was closed by using this ~70 kHz bandwidth piezo actuator and an additional ~1 kHz bandwidth intracavity fiber stretcher as transducer elements. The total tuning range of the fiber stretcher was sufficient to compensate for thermal drifts of the enhancement cavity over the course of a day. Independently, a slow adjustment of the comb offset frequency of the oscillator was implemented by temperature controlling an oscillator fiber section to permit an optimum spectral overlap between the fiber comb and the enhancement cavity. Here, the power transmitted through one of the high-reflector mirrors was used as input to the control loop. An additional high-bandwidth control of the comb offset frequency was achieved by modulating the oscillator's pump diode current. We maintain the frequency-comb cavity lock for several hours at a time.

The intracavity parameters were monitored by characterizing the power, spectrum, and autocorrelation function of the transmitted light through a high-reflector mirror. This mirror's transmission was precisely characterized by directly reflecting the 13.1 W output of the laser system at the incident angle used in the enhancement cavity and measuring the transmitted power using a high-sensitivity thermal powermeter (powermeter accuracy ±3%). The maximum intracavity bandwidth is limited by higher-order dispersion of the cavity mirrors. For optimum enhancement, we matched the laser system output bandwidth to the cavity bandwidth by using a birefringent filter between the oscillator and the amplifier. This allowed us to achieve 90% spectral overlap between the spectra measured before and after the enhancement cavity [Fig 3(a)]. At a laser output power of 13 W, a transmitted power of 360 mW was measured through one of the 99.988% high-reflector mirrors, corresponding to 3 kW intracavity power or

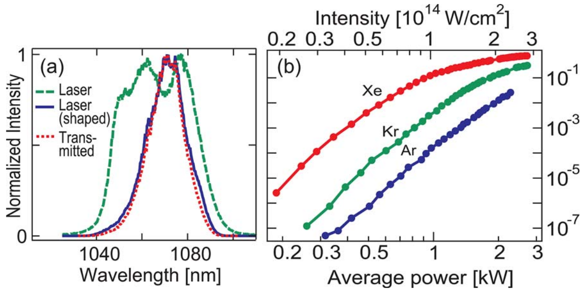

Fig. 3. (Color online) (a) Optical spectrum transmitted through the cavity (dotted, 17.2 nm FWHM) and emitted by the laser system with (solid, 19.3 nm FWHM) and without (dashed, 40 nm FWHM) filtering before the amplifier. (b) Current through plasma for various noble gases at 10 V/mm bias as a function of laser power and peak intensity. The gas pressure was 750 mTorr.

a power enhancement factor of ~230. An interferometric autocorrelation measurement of the transmitted pulse train revealed a 95 fs intracavity pulse duration, the calculated time–bandwidth product is 0.43 (17.3 nm spectral width), very close to the theoretical expected value of 0.44 for a bandwidth-limited pulse of Gaussian shape. This corresponds to 230 MW of intracavity peak power and 3×10^{14} W/cm^2 peak intensity at the intracavity focus, assuming a temporally and spatially Gaussian pulse shape. Those assumptions are justified by measurements of the spectrum, autocorrelation function, and beam profile of the transmitted pulse and by the efficient spatial mode filtering property of the high-finesse cavity.

To confirm the peak intensity we performed ionization experiments in noble gases. Figure 3(b) shows the measured plasma current as a function of peak intensity when photoionizing Xe, Kr, and Ar, showing saturation behavior for Xe and Kr. We also were able to ionize He (not shown). The intensity values found for the ionization thresholds are consistent with the previously published ones [19]. For all data points shown in Fig. 3(b), the intracavity parameters were monitored. Even for saturated ionizations, no degradation of spatial and temporal pulse shapes were observed; all autocorrelation measurements showed a 95 ± 5 fs pulse duration.

In conclusion, we have for the first time (to our knowledge) demonstrated ionization of noble gases with an all-fiber amplification system. Careful higher-order dispersion compensation and modal control of a large-mode-area fiber amplifier allowed us to reach a record peak intensity of 3×10^{14} W/cm^2 at the focus of an external enhancement cavity at the full 136 MHz repetition rate of the oscillator. To our knowledge these are the highest optical intensities ever generated with megahertz fiber laser technology to date. Further scaling to intensity levels beyond 10^{15} W/cm^2 seems possible. This will require high-damage-threshold, low-dispersion mirror coatings in order to overcome currently observed sporadic mirror damages.

We expect cavity-enhanced high-power fiber frequency combs to become an important tool for strong-field experiments at high repetition rates. The high intracavity intensities can be used for XUV precision spectroscopy using an XUV frequency comb via high-harmonic generation.

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