Generation of millijoule-level soft-x-ray laser pulses at a 4-Hz repetition rate in a highly saturated tabletop capillary discharge amplifier

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Received March 8, 1999

Laser pulses with energies of as much as 1 mJ were generated at a wavelength of 46.9 nm by single-pass amplification in a 34.5 cm-long Ne-like Ar capillary discharge plasma. The large gain–length product of this plasma column allows for soft-x-ray amplification in a highly saturated regime, resulting in efficient energy extraction. Average laser output pulse energy of 0.88 mJ and peak power of 0.6 MW were obtained at a repetition rate of 4 Hz. With an estimated peak spectral brightness of $\approx 1 \times 10^{23}$ photons/(s mm^2 mrad^2 0.01% bandwidth) this tabletop laser is one of the brightest soft-x-ray sources to date.

OCIS codes: 140.7240, 140.3280, 140.1340.

A characteristic that distinguishes soft-x-ray lasers from other sources of coherent soft-x-ray radiation is their potential to generate high-energy pulses. Undulators at modern sychrotron facilities generate high average power beams of soft-x-ray radiation. However, they operate at very high pulse repetition rates [e.g., 5×10^8 Hz (Ref. 1)], and the energy per pulse is typically of the order of nanojoules. In the case of soft-x-ray pulses that result from the generation of high-order harmonics of optical lasers, the highest pulse energy that has been reported is 60 nJ.[2] The average power obtained by this method was recently increased to the microwatt level as a result of the demonstration of phase-matched harmonic conversion.[3] In contrast, soft-x-ray lasers pumped by large optical lasers have produced output energies of as much as several millijoules.[4–6] The largest pulse energy reported to date is 8 mJ and was obtained at a wavelength of 15.5 nm in a collisionally excited Ne-like Y laser pumped by the Nova laser.[4] This laser can operate at a repetition rate of approximately one shot per hour. A more compact $\lambda = 18.2$ nm H-like C recombination laser pumped by a 300-J CO_2 laser generated laser pulses with an energy of 3 mJ at a rate of one shot every 3 min.[6] Recently important progress has been achieved in the development of tabletop soft-x-ray amplifiers.[7–17] In particular, the high efficiency with which capillary discharges can pump soft-x-ray amplifiers with large gain volumes can potentially produce large laser pulse energies at high repetition rates.[8,14–16]

In this Letter we report what is to our knowledge the first demonstration of millijoule-level soft-x-ray laser pulses with a tabletop device. Efficient energy extraction from the laser amplifier was achieved by operation at intensities well above the gain-saturation intensity. Tabletop discharge pumped soft-x-ray amplifiers that exceed the saturation intensity were previously demonstrated,[14,15] and recently the generation of a laser output pulse energy of 0.135 mJ at 46.9 nm in a capillary discharge Ar plasma column 18.2 cm in length[16] was reported. However, in all those saturated capillary discharge soft-x-ray laser experiments the amplifier length was only slightly greater than the 12–15 cm at which gain saturation was observed. Therefore energy was efficiently extracted only from the last few centimeters of the plasma column. Increased laser output energy can be achieved by double-pass amplification by use of a mirror placed in close proximity to the end of the plasma column.[5,14] However, rapid damage to the mirror by the plasma makes this solution unsuitable for high-repetition-rate operation.[14] Instead we obtained the results reported herein by increasing the length of the plasma column to 34.5 cm, which is more than twice the saturation length. The length-to-diameter ratio of this plasma column exceeds 1000:1. Operation in this highly gain-saturated amplification regime has allowed us to efficiently extract the energy stored in the population inversion from the majority of the amplifier volume. Laser pulses with an average energy of 0.88 mJ ($>2 \times 10^{14}$ photons/pulse) were generated at a wavelength of 46.9 nm at a repetition frequency of 4 Hz; the energy of the most intense pulses exceeded 1 mJ. The average power obtained was 3.5 mW, to our knowledge the highest reported to date for a tabletop soft-x-ray laser.

The experiments were conducted with aluminum oxide capillary channels 3.2 mm in diameter filled with preionized Ar gas at an optimized pressure of $\approx$460 mTorr. The plasma columns were excited by current pulses of $\approx$26-kA peak amplitude with a 10–90% rise time of approximately 40 ns. The setup was similar to that used in previous experiments reported in Ref. 16. The excitation current pulse was produced by discharge of a water capacitor through a spark gap switch connected in series with the capillary load. The water served as a liquid dielectric for the capacitor and also cooled the capillary. The capacitor was pulse charged by a compact four-stage Marx generator enclosed in a separate box and connected to the laser head with a coaxial cable. The capillary discharge-pumped laser used in this experiment occupies an area of approximately 0.4 m × 1 m on the top of a table, a size comparable with that of many widely utilized visible or ultraviolet gas lasers. The laser output pulse energy and power were measured with a vacuum photodiode placed 87 cm from the exit of the laser, and the data were recorded and stored by a 2-Gbit/s digitizing oscilloscope. The quantum efficiency of the Al photocathode had previously been calibrated with respect to a Si photodiode of known quantum yield.[14] The laser output was attenuated with several stainless-steel meshes of measured transmissivity to avoid saturation of the photodiode. A measurement performed with the soft-x-ray laser beam verified that the transmittivity of the stack of meshes is in good agreement with that computed from the product of individual meshes.

Figure 1 shows the average laser output pulse energy obtained by use of capillary plasma columns 16, 25, and 34.5 cm in length. The laser average output pulse energy was measured to increase from 0.075 mJ for a plasma column 16 cm in length to 0.88 mJ for a plasma column 34.5 cm in length. Estimates of the laser intensity based on these energies and on the pulse-width measurements discussed below indicate that the saturation intensity of 56–78 MW cm^{-2} (Ref. 14) is exceeded before the end of the 16-cm capillary and that the output of the longest capillary exceeds the saturation intensity by more than an order of magnitude, approaching 1 GW/cm^2. Figure 2(a) shows the shot-to-shot variations of the measured laser output pulse energy and the corresponding laser average power for the 34.5-cm-long discharge operated at a 4-Hz repetition frequency. The data correspond to 100 s of uninterrupted operation of the laser. The solid curve shows that the average laser power is ~3.5 mW, corresponding to $>8 \times 10^{14}$ photons/s. Figure 2(b) shows that the average laser output energy per pulse is 0.88 mJ and that the energy of the highest energy pulses exceeds 1 mJ. More than 5000 laser shots were obtained from a single capillary.

The temporal evolution of the laser pulse was measured with a fast vacuum photodiode and a 1-GHz-bandwidth analog oscilloscope. A typical laser output pulse that corresponds to the 34.5-cm-long amplifier is shown in Fig. 3. The full width at half-maximum of the laser pulse is determined to be 1.5 ± 0.05 ns by correction of the measured pulse for the limited bandwidth of the detection system. This laser pulse width is longer than the 1.2 ns that we measured for an 18.2-cm-long amplifier.[16] The increase of the laser pulse width is the result of the increased transit time of the radiation through the amplifier. With this pulse width taken into consideration, the average peak laser output power obtained with the longest plasma column is estimated to be ≈0.6 MW.

The far-field laser output intensity distributions that correspond to the three capillary plasma lengths of Fig. 1 were measured with a phosphor screen and a CCD array detector of 1024 × 1024 pixels. In all cases the beam profile had a ring shape that was the result of refraction of the rays by plasma density gradients in the plasma column.[18,19] Figure 4 shows cross sections of the output intensity patterns. The measurements are an average of five consecutive laser shots. The peak-to-peak divergence is ~4.6 mrad in all three cases. The beam profiles are similar for all amplifier lengths, with slightly more-pronounced peaks for the longer plasma column lengths. The similarity of the profiles is a consequence of the waveguide nature of the amplifier column. The combination of gain guiding and refraction antiguiding determines the intensity distribution,[19] which for the plasma column length of 16 cm is already converging to that of the eingenmode of the waveguide. From the measured

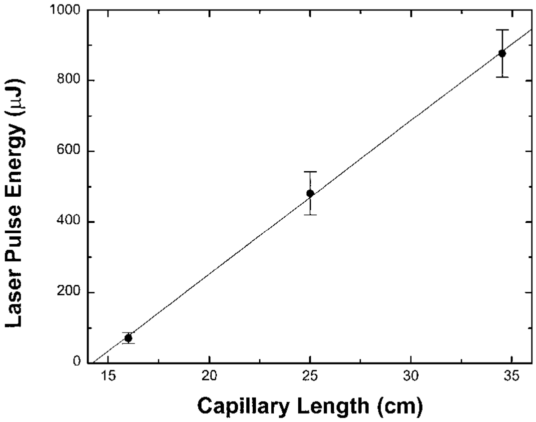

Fig. 1. Measured average laser output pulse energy as a function of capillary plasma column length. Error bars represent the standard deviations of the shot-to-shot pulse energy variations that correspond to 400 consecutive laser pulses obtained at a repetition rate of 4 Hz.

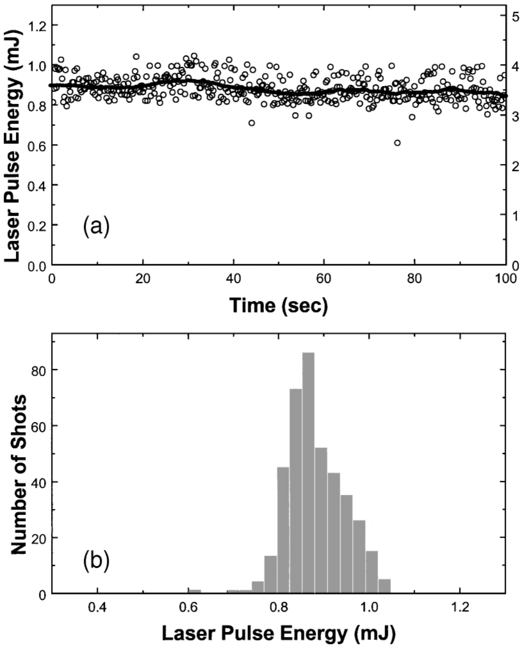

Fig. 2. Measured laser output pulse energy and average output power that correspond to the 34.5-cm-long amplifier operating at a repetition rate of 4 Hz. The data are for 100 s of continuous operation of the laser. (a) Shot-to-shot laser output pulse energy. Solid curve, the average output power computed as a walking average of 60 contiguous laser pulses. (b) Distribution of the output pulse energy. The average pulse energy is 0.88 mJ, and the standard deviation is ±0.06 mJ.

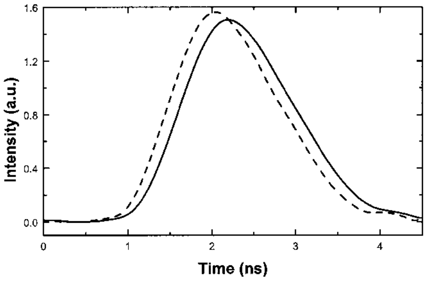

Fig. 3. Temporal characteristics of the laser pulse that corresponds to the 34.5-cm-long amplifier. Solid curve, the measured profile; dashed curve, result of correcting the data for the limited bandwidth of the detection system.

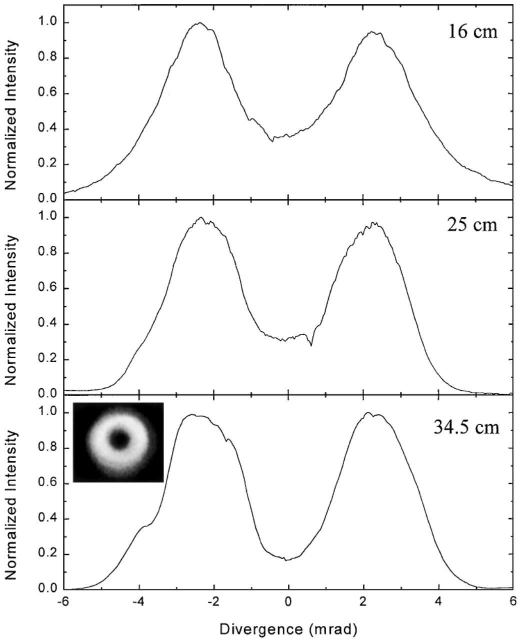

Fig. 4. Cross sections of the far-field laser intensity distribution patterns that correspond to the capillary plasma column lengths indicated. The two-dimensional far-field laser intensity distribution pattern for the 34.5-cm-long amplifier is shown as an inset.

laser beam parameters reported above for the 34.5-cm-long amplifier, and assuming a beam diameter of 300 μm at the exit of the laser,[18] the peak spectral brightness of this laser can be estimated to be ≈1 × 10^{23} photons/(s mm^2 $mrad^2$ 0.01% bandwidth). This value makes this tabletop laser one of the brightest soft-x-ray sources to date.[20]

In summary, we have demonstrated the generation of millijoule-level laser pulses from a tabletop soft-x-ray amplifier. The results obtained at a repetition frequency of 4 Hz include the generation of what we believe are the highest average output pulse energy (0.88 mJ) and average power (3.5 mW) obtained to date from a tabletop source of coherent soft-x-ray radiation.

We thank J. L. A. Chilla, V. N. Shlyaptsev, and E. Bernstein for useful discussions. This research was supported by the National Science Foundation under grant DMR-9512282. J. J. Rocca's e-mail address is rocca@engr.colostate.edu.

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