Demonstration of a desk-top size high repetition rate soft x-ray laser

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Abstract: We have demonstrated a new type of high repetition rate 46.9 nm capillary discharge laser that fits on top of a small desk and that it does not require a Marx generator for its excitation. The relatively low voltage required for its operation allows a reduction of nearly one order of magnitude in the size of the pulsed power unit relative to previous capillary discharge lasers. Laser pulses with an energy of ~ 13 µJ are generated at repetition rates up to 12 Hz. About (2-3) x 10^4 laser shots can be generated with a single capillary. This new type of portable laser is an easily accessible source of intense short wavelength laser light for applications.

OCIS codes: (140.7240) UV, XUV, and X-ray lasers; (140.3460) Lasers; (140.3210) Ion lasers

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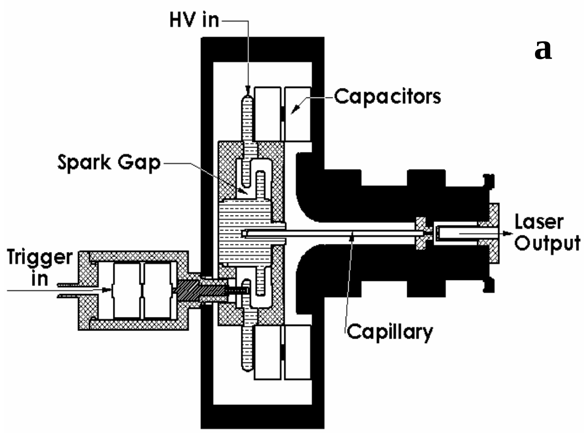
The development of compact high repetition rate short wavelength laser sources is of interest for numerous applications in science and technology. Significant efforts have been devoted to reducing the size of saturated soft x-ray lasers from laboratory size [1, 2] to table-top [3-7]. The demonstration of laser amplification in transitions of Ne-like ions in a capillary discharge plasma [3, 7] opened the possibility to develop very compact short wavelength lasers for applications. Table-top size Ne-like Ar lasers operating at a wavelength of 46.9 nm have been developed making use of water capacitors that are pulsed charged to high voltage (200-700 kV) by Marx generators [8-12]. These lasers have been used in numerous applications, including interferometry of dense plasmas [13], the measurement of optical constants [14], materials ablation [15], the characterization of soft x-ray optics [16], excitation of color centers in crystals [17], and nanopatterning [18].

We report a new type of capillary discharge laser that is significantly more compact and less costly than its predecessors. It is to our knowledge the first soft x-ray laser to fit onto a small desk and also the first to be easily transportable (Fig. 1(a)). It emits >10 μJ pulses of λ= 46.9 nm light at 12 Hz repetition rate. The laser occupies a table area of approximately $0.4 \times 0.4\ m^2$ ($0.4 X 0.8\ m^2$ including the vacuum pump), smaller than that occupied by many widely used ultraviolet gas lasers. The reduced size of this capillary discharge device is achieved making use of a very low inductance co-axial discharge configuration illustrated in Fig. 1(b) that decreases the voltage necessary to generate the peak current required for laser excitation. This allows the excitation of the capillary discharge channel utilizing ceramic capacitors, which are charged at moderate voltages (< 90 kV). The reduced voltage eliminates the need of a Marx generator. As a result the volume of the pulsed power unit is ~ 9 times smaller than that of previous capillary discharge lasers [9] and can be accommodated in a small rack under a regular optical table.

As in the case of the larger size Ne-like Ar 46.9 nm capillary discharge lasers previously demonstrated [3, 8-12], laser amplification is generated by fast discharge excitation of an Ar-filled capillary. The magnetic force of the current pulse and large thermal pressure gradients near the wall rapidly compress the plasma to form a dense and hot column with a large density of Ne-like ions, with a very high axial uniformity and a length to diameter ratio of the order of 1000:1. Collisional electron impact excitation of the ground state Ne-like ions produces a population inversion between the 3p $^1S_0$ and 3s $^1P_1$ levels resulting in amplification at 46.9 nm [7].

Laser amplification is obtained in a Ne-like Ar plasma column generated in an aluminum-oxide capillary 3.2 mm inside diameter and 21 cm in length filled with pre-ionized Ar gas at



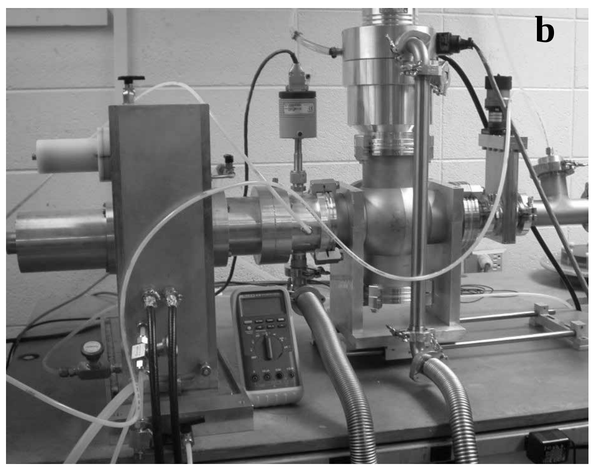


Fig. 1. (a) Schematic representation of the 46.9nm capillary discharge laser. (b) Photograph of the laser device. A handheld multimeter is shown to provide a reference of scale.

an optimized pressure of 700 mTorr. The plasma column is excited by current pulses of ≈22 kA peak amplitude that are monitored with a Rogowski coil. The excitation current pulse is produced by discharging a set of ceramic capacitors with a combined capacitance of 27 nF through a pressurized air high voltage spark-gap switch that is connected in series with the capillary load. The capacitors, which are placed in a ring configuration surrounding the spark-gap, are pulse-charged to 80-90 kV by a single-stage pulsed power unit that is enclosed in a separate box and which is connected to the laser head with a coaxial cable. The main current pulse through the capillary is initiated by triggering the spark-gap with a ~ 50 kV pulse of opposite polarity to that used to charge the capacitors. This allows the synchronization of the laser output with external events with a jitter of several ns, as required in some of the applications. Sub-nanosecond jitter can also be obtained using laser triggering of the spark-gap [19]. A typical current pulse is shown in Fig. 2. The pulse has 10% to 90% rise time of approximately 60 ns, and first half cycle duration of 165 ns. A pronounced kink in the current is observed to occur about 40 ns after the beginning of the current pulse. This local minima of the current occurs at the time the plasma column reaches its minimum diameter of 200-300 μm, and is caused by the significant increase in the plasma column inductance that accompanies the reduction of the plasma column diameter. The laser pulse of 1.5 ns FWHM duration occurs shortly before the time of maximum plasma compression, which takes place

#7073 - $15.00 US Received 5 April 2005; revised 2 May 2005; accepted 17 May 2005

about 35 ns after the initiation of the current pulse. The capillary discharge tube, the ceramic capacitors, and spark-gap are all contained in an Al enclosure that helps to shield the electromagnetic noise produced by the fast discharge. Biodegradable transformer oil is circulated for electrical insulation and also for cooling using a commercially available chiller unit. The laser light exits the cathode electrode that has a hole on axis and that is maintained at ground potential. Argon is continuously flown at the cathode end of the discharge, and is differentially pumped using the combination of a scroll pump and a 360 l/s turbomolecular pump to avoid significant attenuation of the laser beam by photoionization of Ar atoms.

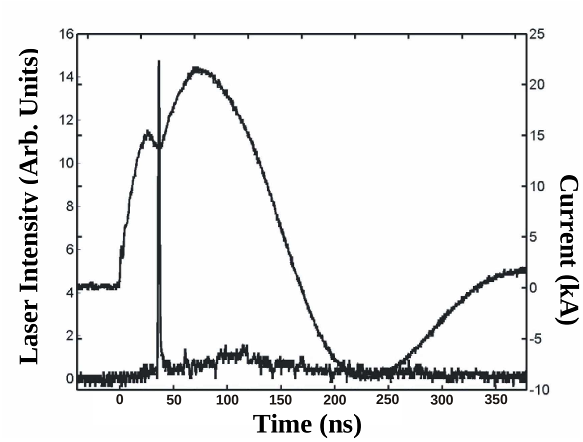


Fig. 2. Discharge current pulse (upper trace) and laser output pulse (lower trace). The kink in the current trace is caused by the abrupt increase of the plasma column inductance at the time of the pinch.

The laser output pulse energy was measured using a vacuum photodiode placed at 80 cm from the exit of the laser and the data were recorded and stored by a 5Gs/s digitizing oscilloscope. The quantum efficiency of the Al photocathode used was previously calibrated with respect to a silicon photodiode of known quantum yield [8]. The laser output was attenuated with several stainless steel meshes of measured transmissivity to avoid saturation of the photodiode. The laser was successfully operated at repetition rates up to 12 Hz. Figure 3a shows the shot to shot variation of the peak of the excitation current pulse for 1500 consecutive shots at 12 Hz repetition rate. Figure 3(b) and Fig. 3(c) illustrate the corresponding shot to shot variation of the laser output pulse energy as a function of the shot number and its statistical distribution respectively. The average pulse energy is 13 uJ and the standard deviation is +- 1.3 uJ, corresponding to an average power of about 0.15 mW. The use of external triggering of the spark-gap in Fig. 1(b) allowed to obtain relatively low jitter operation. Figure 3(d) illustrates the statistical distribution of the time delay between the TTL trigger signal into the high voltage trigger unit that fires the spark-gap and the laser output pulse for the 1500 laser shots of Fig 3a. The standard deviation of the jitter is + - 5 ns.

Ablation of the capillary walls by the powerful discharge over a large number of shots increases their surface roughness, ultimately leading to the deterioration of the uniformity of the plasma column and to a consequent decrease of the laser output energy. Capillary lifetime tests were conducted at 12 Hz repetition rate recording the laser output energy for a large number of shots. The laser output energy was measured to decay by 2 times after about (2-3) x 10^4 shots (Fig. 4). This is to our knowledge the longest series of soft x-ray laser shot achieved to date. The full output pulse energy can be recovered by replacing the used

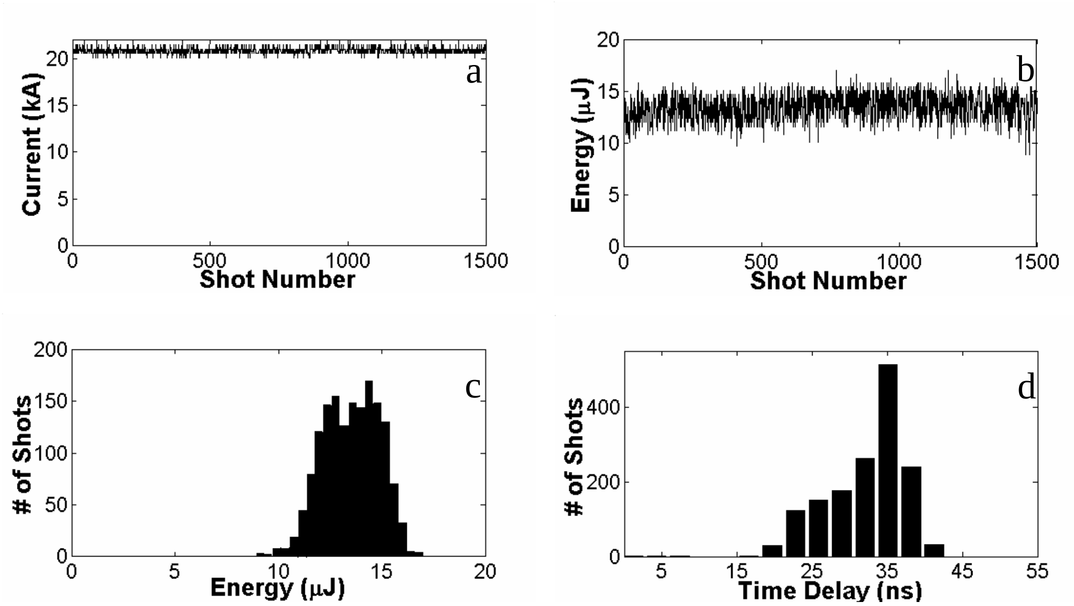


Fig. 3. Data corresponding to 12 Hz repetition rate laser operation. The data is for 1500 shots of continuous operation. (a) Peak current; (b) Measured laser output pulse energy. The average pulse energy is 13 uJ ± 1.3 uJ; (c) distribution of the laser output pulse energy, (d) time delay statistics of the laser pulse respect to TTL signal into the high voltage trigger unit.

capillary discharge tube by a new one, an operation that demands 30-40 minutes including the pumping time required to evacuate the system to a pressure of $\sim 1\times10^{-5}$ Torr.

The far field laser output intensity distribution was measured using a microchannelplate/ phosphor screen read by a CCD array detector of 1024 X 1024 pixels placed at 157.5 cm from the exit of the laser. The microchannelplate was gated with a ~ 5 ns voltage pulse to be able to discriminate the laser light from the spontaneous light emitted by the plasma in hundreds of extreme ultraviolet transitions that while several orders of magnitude less intense than the

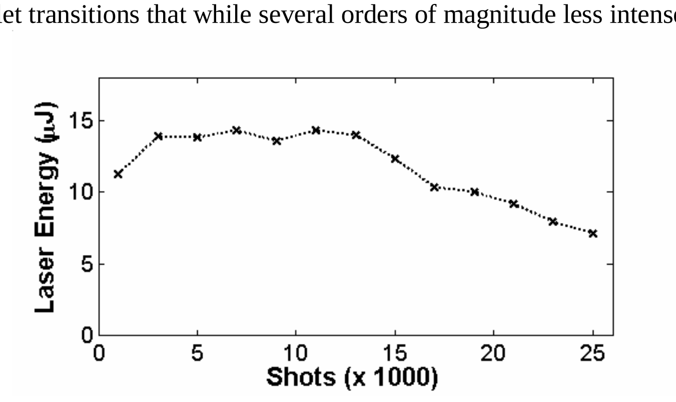


Fig. 4. Variation of the laser output pulse energy as a function of the number of shots. The data was obtained operating the laser at 12 Hz repetition rate. The output energy is observed to degrade to half of the maximum value in about 2-3 10^{4} discharge shots

laser line, produce a significant background when temporally integrated over the duration of the discharge. The beam profile was observed to have an annular shape that is the result of refraction of the amplified rays by radial electron density gradients in the plasma column [20, 21]. Figure 5 shows a cross section of an output intensity pattern acquired in a single shot. The

#7073 - $15.00 US Received 5 April 2005; revised 2 May 2005; accepted 17 May 2005

peak-to-peak divergence is about 5.2 mrad. While we have not yet characterized the wavefront, previous measurements of similar annular capillary discharge laser beams have shown good focusing properties [22].

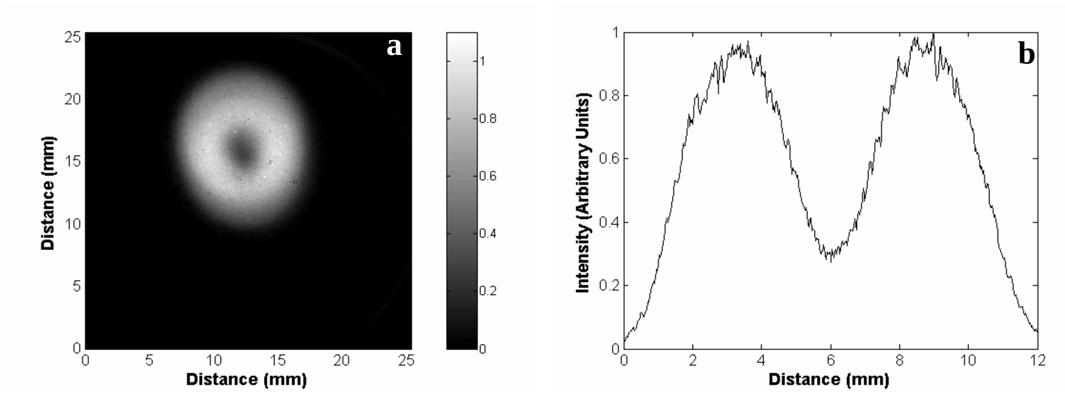


Fig. 5. (a) Far field image of the laser beam measured at 157.5 cm from the capillary exit. (b) corresponding intensity lineout.

Conclusions

In conclusion we have demonstrated high repetition rate (12 Hz) operation of a desk-top size 46.9 nm lasers that is easily transportable. This is to our knowledge the most compact soft x-ray laser demonstrated to date. This new type of portable short wavelength laser is of interest for numerous application including experiments in photochemistry, materials characterization and patterning and high-resolution imaging.

Acknowledgments

This work was supported by the NSF Center for Extreme Ultraviolet Science and Technology under NSF Award Number EEC-0310717 and the U.S. Department of Energy, Chemical Sciences, Geosciences and Biosciences Division of the Office of Basic Energy Science. We also gratefully acknowledge the support of the W.M. Keck Foundation and the valuable assistance of Paul Johnson and encouraging discussions with Elliot Bernstein.