Advances in High Average Power, 100 Hz Repetition Rate Table-Top Soft X-Ray Lasers

Brendan A. Reagan, Cory Baumgarten, Mark Berrill, Keith A. Wernsing, Mark Woolston, Lukasz Urbanski, Wei Li, Mario C. Marconi, Vyacheslav N. Slyaptsev, Carmen S. Menoni and Jorge J. Rocca

Abstract We discuss new results of the demonstration of 100 Hz table-top soft x-ray lasers operating at wavelengths from 10.9 nm to 18.9 nm and report the highest soft x-ray laser average power to date at sub-20 nm wavelength. The results include the generation of average powers up to 0.2 mW at $\lambda = 18.9$ nm, 0.1 mW at $\lambda = 13.9$ nm, and 20 μW at $\lambda = 11.9$ nm. These lasers are driven by a compact chirped pulse amplification laser system featuring diode-pumped, cryogenically-cooled Yb:YAG power amplifiers that produces 1 J pulses of 5 ps FWHM duration at 100 Hz repetition rate. The driver laser pulse shape was tailored to more efficiently pump soft x-ray plasma amplifiers operating at sub-15 nm wavelengths leading to a threefold increase in the $\lambda = 13.9$ nm laser pulse energy and lasing down to 10.9 nm. The pump pulse profile consisting of a nanosecond ramp followed by two closely spaced peaks of picosecond duration, is shown to create a plasma with an increased density of Ni-like lasing ions at the time of peak temperature, resulting in a larger gain coefficient over a temporally and spatially enlarged space. The development of rotating solid targets with high shot capacity has allowed the uninterrupted operation of the $\lambda = 18.9$ nm soft x-ray laser for hundreds of thousands of consecutive shots making it suitable for applications in nanoscience and nanotechnology that require high photon flux at short wavelengths. As a proof-of-principle demonstration of the utility of this laser in such applications we have lithographically printed an array of nanometer-scale features through coherent Talbot self imaging. These results open the path to milliwatt average power table-top soft x-ray lasers.

B. A. Reagan (✉) · C. Baumgarten · M. Berrill · K. A. Wernsing · M. Woolston · L. Urbanski · W. Li · M. C. Marconi · C. S. Menoni · J. J. Rocca
NSF ERC for Extreme Ultraviolet Science and Technology, Fort Collins, CO, USA

B. A. Reagan · M. Berrill · K. A. Wernsing · M. Woolston · L. Urbanski · W. Li · M. C. Marconi · V. N. Slyaptsev · C. S. Menoni · J. J. Rocca
Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO, USA

C. Baumgarten · J. J. Rocca
Department of Physics, Colorado State University, Fort Collins, CO, USA

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1 Introduction

There is great interest in the development of bright, coherent soft x-ray sources for a large number of applications. Despite the significant progress recently made in plasma-based soft x-ray lasers (SXRLs) [1–11], their average power is at present much lower than that produced by soft x-ray FELs [12, 13]. In the case of SXRLs, their average power has been limited by the relatively low repetition rate of the high energy optical wavelength pump lasers used to drive them and by low pumping efficiency. Capillary discharge soft x-ray lasers can produce milliwatt average power [14, 15], but are presently limited to longer wavelengths [16]. Laser-pumped $\lambda = 10$–20 nm soft x-ray lasers have been limited repetition rates of 10 Hz or less, resulting in average powers ranging from 1 to 20 μW [4,6]. We previously reported the first table-top SXRL capable of 100 Hz repetition rate operation, generating 0.15 mW average power on the $\lambda = 18.9$ nm line of Ni-like Mo [17]. Recently the diffraction grating used to conduct the measurement was calibrated at a synchrotron facility showing that the average power we had reported was underestimated and was the corrected value is ~ 0.2 mW. This achievement was made possible by the development of a diode-pumped, picosecond Yb:YAG driver laser. Here, we report the demonstration of a 0.1 mW average power, gain-saturated, $\lambda = 13.9$ nm soft x-ray laser operating at 100 Hz repetition rate. The infrared driver laser pulse was temporally tailored to more efficiently pumps the plasma amplifier, resulting in a threefold enhancement of the $\lambda = 13.9$ nm laser energy [18]. Additionally, we demonstrated high repetition rate, gain saturated operation of a $\lambda = 11.9$ nm laser from a Sn plasma. We also report the continuous, hour-long operation of the $\lambda = 18.9$ nm Ni-like Mo laser at high repetition rates [19]. Finally, using this robust laser we have made a proof-of-principle demonstration of the printing of nano-scale features through coherent Talbot lithography.

2 Demonstration of 50–100 Hz Operation of Sub-15 nm Wavelength Lasers

The plasma amplifiers were excited by a single shaped pump pulse. Although the use of a single pulse has been used to drive table-top soft x-ray lasers before [5,9,17,20], the pulse employed here has different characteristics. The advantage of shaping the temporal sequence of pulses used to efficiently create and heat soft x-ray plasma amplifiers has been recognized [3, 9]. In particular, it was recently shown that the addition of a short duration (2 ps FWHM) pre-pulse with a fraction of the intensity of the main pulse can significantly increase the soft x-ray laser pulse energy produced by a $\lambda = 13.9$ nm Ni-like Ag laser when pumping with relatively low driving laser pulse energies [3]. In another recent paper, this scheme was expanded upon to allow the generation of 4.7 μJ pulses at $\lambda = 13.9$ nm using less than 2 J of total pump laser energy [21]. In recent previous work, we have used a single shaped pump laser pulse of < 1 J energy to drive lasing on the $\lambda = 18.9$ nm transition of Ni-like Mo at 100 Hz repetition. rate that resulted in an average power of 0.15 mW [17] (which we subsequently realized was ~ 0.2 mW after calibration of the spectrometer diffraction grating). Here, in order to more efficiently pump the soft x-ray amplifier plasma and allow generation at shorter wavelengths, we made use of a tailored temporal pulse profile that consists of a ~ 2 ns long, low amplitude ramp that creates and ionizes the plasma and a short duration intense pulse that precedes the main peak of the pulse. Hydrodynamic/atomic physics plasma simulations show that the pump pulse profile, consisting of a nanosecond ramp followed by two peaks of picosecond duration, creates a plasma with an increased density of Ni-like ions at the time of maximum temperature that results in a larger gain coefficient over a temporally and spatially enlarged region leading to a three-fold increase in the soft x-ray laser output pulse energy. These simulations are presented in detail in [18]. This increase in pumping efficiency combined with the increased repetition rate results in record-high average power at these wavelengths from a table-top device. Using this approach, bright lasing was also demonstrated at a number of wavelengths between 10.9 nm and 14.7 nm, including the high repetition rate, gain-saturated operation of a $\lambda = 11.9$ nm laser from Ni-like Sn. These results will enable new technologic applications and basic research experiments requiring high average photon flux, and opens a path to further scale compact SXRLs to milliwatt average power in this wavelength range and possibly at shorter wavelengths.

The high repetition rate diode pumped $\lambda = 1.03$ μm CPA laser system based on cryogenic Yb:YAG amplifiers was used to obtain the results reported here is described in references [17, 22, 23]. This laser produces 1 J pulses with durations as short as 5 ps FWHM at 100 Hz repetition rates. The laser pulses are focused using cylindrical optics onto a solid target at a grazing incidence [11, 24] angle of 32° to form a 30 μm FWHM wide by 5 mm long line focus as shown in Fig. 1a. For prolonged high repetition rate operation we made use of a circular target consisting of a 100 mm diameter copper disk (Fig. 1a) with a foil of the desired lasing material (in this case Mo, Ag, and Sn) bonded to its face. The target material is mechanically polished to a smooth flat face suitable to produce an axially uniform plasma column when irradiated with the driving laser. The target is rotated using a motorized stage to present a fresh surface for each consecutive laser shot allowing for prolonged laser operation. Single shot, on-axis EUV plasma emission spectra were obtained using a 1200 lines/mm, flat-field, gold-coated diffraction grating positioned at grazing incidence and an x-ray sensitive CCD. For the high repetition rate soft x-ray laser measurements, an EUV-sensitive 10×1 mm silicon photodiode was placed in the imaging plane of the spectrometer at the location corresponding to the laser wavelength. Thin foil filters were used to reject visible plasma emission and also to prevent detector saturation. Absolute energy measurements were estimated using the efficiency of the diffraction grating, the reported responsivities of the Si photodiode and CCD, and the transmission efficiency of the thin filters measured *in situ*.

The pump pulse profile was measured via second harmonic generation (SHG) cross-correlation of the driving laser pulse with 100 μJ, 700 fs FWHM pulses produced by a Yb:KYW regenerative amplifier. The presence of any non-negligible

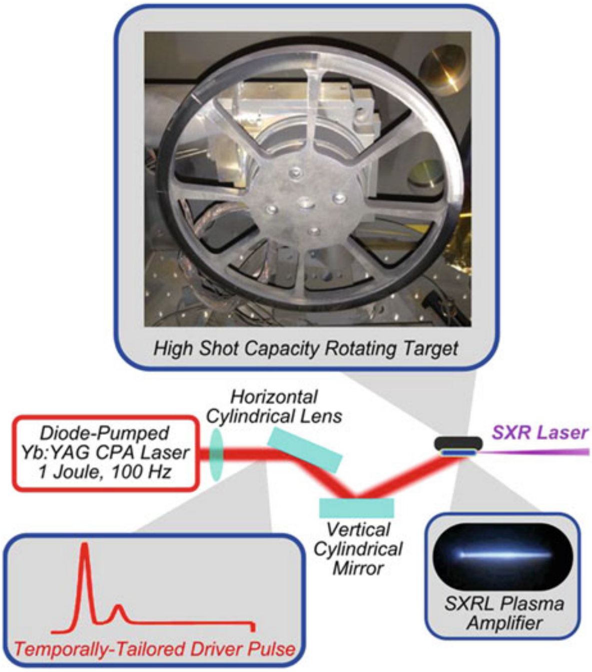

Fig. 1 Set up and target configuration for high repetition rate SXR laser operation. A high shot capacity, rotating target is irradiated by ~ 1 J pulses produced by diode-pumped CPA laser focused into a high aspect ratio *line* focus by cylindrical optics. The pump pulse temporal profile consists of a long ns ramp ending in a sequence of *two* closely spaced picosecond duration peaks

pulses before the 3.5 ns temporal window shown was ruled out by measurement with a fast photodiode. The main peak of the driving laser is preceded by an intentionally added pedestal that ramps from an intensity of 10^{-4} relative to the main peak at 2.7 ns before the peak, to about 10^{-3} before its onset. Additionally, a short picosecond peak preceding the main peak is generated by splitting the seed pulse beam from the pulse stretcher using a polarizing beamsplitter and a $\lambda/2$ waveplate, and subsequently recombining the beams into a single beam with an adjustable delay before seeding the regenerative amplifier. This feature precedes the main peak by 15 ps with a relative intensity of 12 %. Because all of the temporal features originate from within the regenerative amplifier cavity, they are collinear and share the same spatial mode profile making this truly a single pulse and avoiding the temporal and spatial overlapping that is otherwise required when using multiple pulses to drive soft x-ray lasers. Delays of 10–70 ps, and relative intensities within 10–25 % of the main pump peak were experimentally observed to produce similar $\lambda = 13.9$ nm laser pulse energies, which makes this a robust system.

Figure 2 shows the measured laser pulse energy of 2000 consecutive pulses of the $\lambda = 13.9$ nm laser operating at 100 Hz repetition rate on the $4d^1S_0 \rightarrow 4p^1p_1$ transition of Ni-like Ag obtained using the tailored pump pulse profile with the

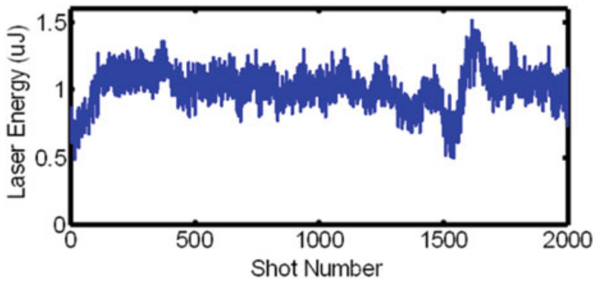

Fig. 2 Sequence of pulses from a 13.9 nm Ni-like Ag laser operating at 100 Hz repetition rate. The average pulse energy corresponds to an average power of 0.1 mW. The variation of the output pulse energy around shot 1500 is the result of shooting over a target region that was already irradiated

dual peak shown in Fig. 1b. The total pump pulse energy on target was 900 mJ. The circular target described earlier, which has a width of 1 cm in the direction of the line focus axis and an outer diameter of 100 mm, was rotated at 10 deg/s resulting in a distance between successive shots of ~90 μm at 100 Hz repetition rate. The mean SXRL pulse energy was measured to be 1.0 μJ with a shot-to-shot standard deviation of 14 %, resulting in an average power of 0.1 mW. This is to our knowledge the highest average power reported for a compact, coherent source at this wavelength.

We also used the combination of the compact diode-pumped driver laser and the specially tailored driving laser pulse profile technique to demonstrate bright SXRLs at shorter wavelengths down to $\lambda = 10.9$ nm, as summarized by the single-shot on-axis spectra of Fig. 3. The same pumping geometry and detection configuration described above was employed. Rectangular slab targets were used for the case of Te, In, Cd, and Pd, and a circular target of the form described above was used for Sn. The $\lambda = 11.9$ nm Sn laser was operated at 50 Hz repetition rate and produced an average power of 20 μW [18]. For the shortest wavelength investigated, $\lambda = 10.9$ nm from Ni-like Te, the total driver laser pump energy of 0.9 J used to obtain lasing is significantly lower than that reported in previous experiments [6]. No lasing was observed when the single peak temporal pumping profile was used with Te or Sn targets, and lower laser energy was observed for Pd, Ag, Cd and In targets.

3 Hour-long Operation of a High Repetition Rate $\lambda = 18.9$ nm Soft X-Ray Laser and Demonstration of Defect-Free Nanoprinting Through Talbot Lithography Using a $\lambda = 18.9$ nm Soft X-Ray Laser

Figure 4 shows data corresponding to 1 h of continuous operation of the Ni-like Mo $\lambda = 18.9$ nm SXRL at 50 Hz repetition rate. The laser output pulse energy is quite stable with very few low intensity shots. This continuous sequence of 1.8×10^5

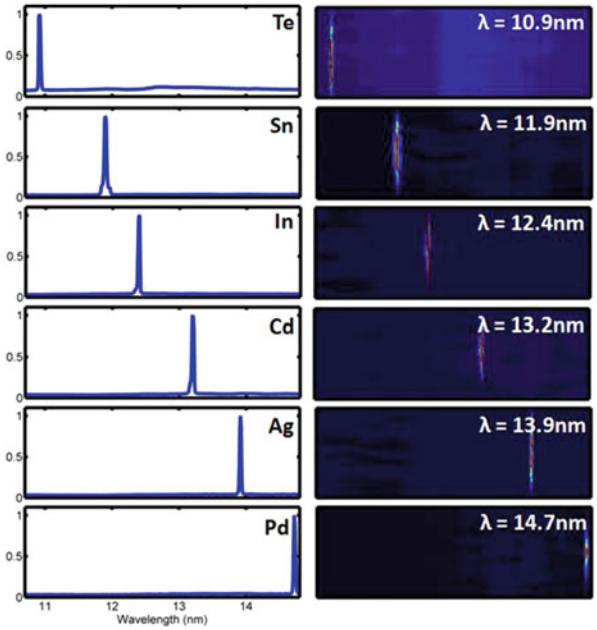

Fig. 3 Single shot, on-axis plasma emission spectra of $4d^1S_0 \rightarrow 4p^1p_1$ Ni-like ion soft x-ray lasers produced by irradiating solid targets of Te, Sn, In, Cd, Ag, and Pd with a single tailored pulse of 0.9 J energy produced by a diode-pumped Yb:YAG laser. The *right* column shows the raw CCD image of each spectrograph. All lasers down to 11.9 nm were operated in gain saturation

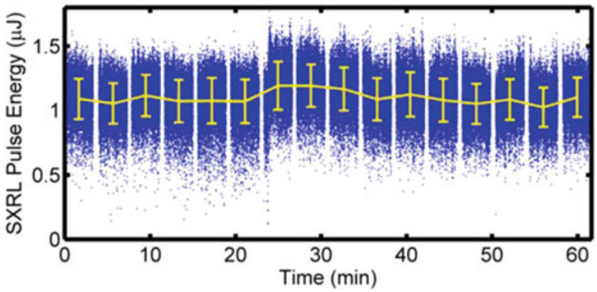

Fig. 4 Measured SXRL pulse energy at 50 Hz repetition rate for just over 1 h of operation. 180,000 consecutive shots were recorded. The *line* shows the running average of the pulse energy with the error bars representing the shot to shot standard deviation of each section of pulse sequence. The periodic gaps in the data correspond to transfers of the data from a digitizing oscilloscope during which the laser continued to operate

shots was acquired with one rotation of the target of Fig. 1a. We have also continuously operated this laser with similar performance at 100 Hz repetition rate for 30 min [19].

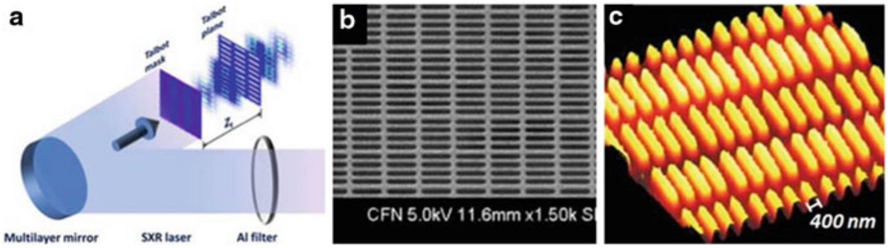

Fig. 5 **a** Talbot lithography experimental setup. A *two* dimensional periodic mask generates a Talbot image at the sample plane that is registered in photoresist. **b** Scanning electron microscope image of the Talbot mask. **c** Atomic force microscope image of the nanometer-scale features printed using the 18.9 nm laser

As a first demonstration of these high average power power soft x-ray lasers in applications requiring high photon flux we printed an array of nanometer-scale features using coherent Talbot lithography. The photo-lithographic approach used in this experiment is based on the self-imaging produced when a periodic transmission mask is illuminated with a coherent light beam. A semitransparent mask composed of an array of tiles each having an arbitrary design produces self images that replicate the mask on the surface of a photoresist [25]. When illuminated with coherent light, the tiled diffractive mask produces images which are 1 $\times$ replicas at certain locations (Talbot planes). Because the Talbot images are generated by the diffraction of the thousands of cells in the mask, a defect in any of the unitary cells is averaged over a very large numbers of tiles consequently rendering a virtually defect-free image [25]. Figure 5a shows the scheme of the experimental setup used to demonstrate Talbot printing. A scanning electron microscope (SEM) image of the mask is shown in Fig. 5b. The overall size of the mask is 0.5 $\times$ 0.5 mm^2, with a calculated first Talbot distance $Z_T = 2.65$ mm. However, the print was made at half this distance where a phase-shifted Talbot image is produced, yielding a numerical aperture (NA) of 0.186. Figure 5c is an atomic force microscope image of the print in the photoresist showing reproduced lines is $\sim$400 nm FWHM width in this initial proof-of-principle demonstration. The high flux of the soft x-ray laser allowed for efficient printing with an exposure of 30 s operating the laser at 50 Hz repetition rate. Ultimately, the short wavelength of this laser in combination with masks of larger NA will lead to defect-free printing of patterns with sub-20 nm resolutions.

4 Summary

In summary, we have demonstrated the high repetition rate, high average power, operation of soft x-ray lasers at wavelengths between 11.9 and 18.9 nm. Results include the continuous operation of a compact $\lambda = 18.9$ nm SXRL at 100 Hz repetition rate for extended periods of time with average powers up to 0.2 mW. Combining a soft x-ray plasma amplifier heated by a diode-pumped Yb:YAG laser with a tailored pulse shape and a high shot capacity rotating target we demonstrated 100 Hz repetition rate operation of $\lambda = 13.9$ nm laser with 0.1 mW average power. These results can be scaled to several hours of continuous operation and to shorter wavelengths. As a demonstration of the utility of these lasers for applications requiring a high average photon flux we printed an array of nanometer-scale features through coherent lithography. These compact high average power soft x-ray lasers can be expected to open the door to numerous photon flux intensive applications on a table-top. The results also open the path to milliwatt average power table-top soft x-ray lasers.

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