

Demonstration of a 100 Hz repetition rate gain-saturated diode-pumped table-top soft x-ray laser

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We demonstrate the operation of a gain-saturated table-top soft x-ray laser at 100 Hz repetition rate. The laser generates an average power of 0.15 mW at $\lambda = 18.9$ nm, the highest laser power reported to date from a sub-20-nm wavelength compact source. Picosecond laser pulses of 1.5 μ J energy were produced at $\lambda = 18.9$ nm by amplification in a Mo plasma created by tailoring the temporal intensity profile of single pump pulses with 1 J energy produced by a diode-pumped chirped pulse amplification Yb:YAG laser. Lasing was also obtained in the 13.9 nm line of Ni-like Ag. These results increase by an order of magnitude the repetition rate of plasma-based soft x-ray lasers opening the path to milliwatt average power table-top lasers at sub-20 nm wavelengths. © 2012 Optical Society of America
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Soft x-ray lasers have the ability to generate pulses of ultrashort wavelength radiation with unsurpassed pulse energy, which makes it possible to diagnose hot dense plasmas, acquire single-shot soft x-ray images that freeze the motion of fast nanoscale phenomena, and extend laser-induced material modification to the nanoscale. However, the first soft x-ray lasers did not allow for applications demanding high average power because they operated at repetition rates that ranged from a shot per minute [1] to several shots per day [2]. In spite of significant subsequent progress in the development of plasma-based soft x-ray lasers, their operation has remained limited to repetition rates of up to 10 Hz and average power of a few tens of microwatts [3]. An exception are capillary discharge-driven soft x-ray lasers that generate milliwatt average power, but operate at wavelengths above 46 nm [4]. Soft x-ray lasers pumped by solid-state optical lasers are capable of shorter wavelength operation but are limited to relatively low repetition rate by detrimental thermal effects originating in the flash-lamp pumped gain medium of the laser driver. In turn, this limitation in repetition rate restricts their average power and consequently their range of applications. The increase in photon flux that will result from operating compact soft x-ray lasers at much higher repetition rates will open up new applications. For example, it will allow for high throughput nanoscale surface imaging and inspection, and will extend the use of lasers in material processing to the nanoscale [5,6].

Diode pumping can greatly reduce the heat load in the gain medium of the pump lasers used to pump soft x-ray lasers. The promise of increased repetition rate has motivated recent work in the development of diode-pumped high energy chirped pulse amplification (CPA) lasers capable of pumping plasma-based table-top soft x-ray lasers [7,8]. We previously reported results of a proof-of-principle experiment in which we demonstrated a compact all-diode-pumped soft x-ray laser producing

pulses of 50 nanojoule energy at 10 Hz repetition rate [7]. Here, we report the first demonstration of a plasma-based soft x-ray laser operating at 100 Hz repetition rate. Gain-saturated laser pulses of 1.5 μ J energy were obtained at 18.9 nm from a nickel-like molybdenum laser. This high repetition rate regime is made possible by the development of a new compact diode-pumped CPA Yb:YAG laser that produces picosecond pulses of 1 J energy at a record high repetition rate of 100 Hz. Moreover, in contrast to our previous 10 Hz demonstration that made use of a sequence of three excitation pulses, the generation of the plasma amplifier is simplified by a single tailored pulse impinging at grazing incidence.

A block diagram of the all-diode-pumped CPA laser used to pump the soft x-ray laser is shown in Fig. 1. The system combines a diode-pumped mode-locked Yb:KYW oscillator, a grating stretcher, three stages of amplification, and a dielectric grating pair to produce 1 J pulses with durations as short as 5 ps FWHM at 100 Hz repetition rate. The amplification chain consists of a Yb:YAG regenerative amplifier operated at room temperature for

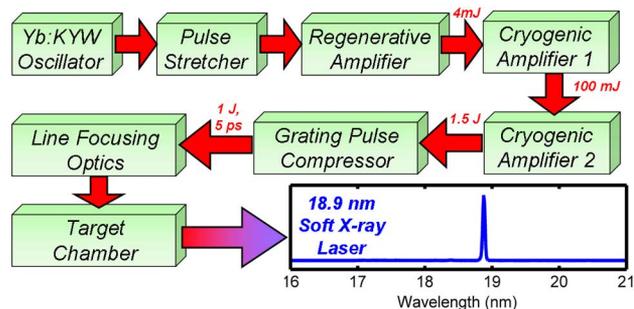


Fig. 1. (Color online) Block diagram of the diode-pumped high repetition rate soft x-ray laser system with diode-pumped Yb:YAG chirped pulse amplification pump laser. The entire pump laser with the exception of the grating compressor fits on a 12' \times 5' optical table. The inset shows an on-axis spectrum of the Mo plasma displaying the highly monochromatic laser output.

extended bandwidth [9,10], followed by two multipass cryogenic power amplifiers that take advantage of the improved thermal properties and high gain of Yb:YAG at cryogenic temperatures. The front end of the laser system was described in detail in recent publications [9,10]. The first amplification stage is a regenerative amplifier that amplifies stretched pulses from the oscillator to the millijoule level. The pulses are subsequently amplified to ~ 100 mJ by a four-pass amplifier consisting of a 5 mm thick, liquid nitrogen-cooled Yb:YAG active mirror pumped by a fiber-coupled 500 W laser diode array. The final stage of amplification is a five-pass amplifier consisting of two cryogenically cooled active-mirror Yb:YAG crystals mounted on a single evacuated cooling head. Each crystal is pumped with 4 kW peak power, 1.5 ms duration pulses from a laser diode array. A pulse energy of 1.5 J was obtained prior to compression with good beam quality, no observable thermal depolarization, and only slight thermal lensing. The pulses were compressed in a grating compressor that uses dielectric gratings to generate 1 J pulses as short as 5 ps duration at repetition rates up to 100 Hz.

To obtain lasing in the $4d^1S_0 - 4p^1P_1$ line of Ni-like Mo at $\lambda = 18.9$ nm, pulses from the diode-pumped CPA laser were directed onto a Mo target at a grazing incidence angle of 29° as illustrated in Fig. 2, which preferentially heats the plasma region where the electron density is $\approx 2.5 \times 10^{20} \text{ cm}^{-3}$. The pump pulses were focused to form a high-quality line focus of ~ 5.5 mm FWHM length and $\sim 30 \mu\text{m}$ FWHM width on the target surface [Figs. 2(c) and 2(d)]. This inherently quasi-traveling wave geometry takes advantage of the refraction of the pump beam in

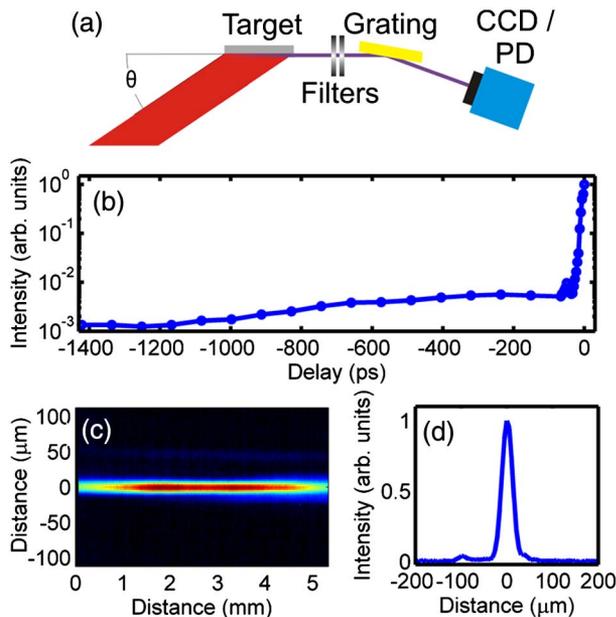


Fig. 2. (Color online) (a) Schematic diagram of the soft x-ray laser pumping configuration and detection spectrometer with either a CCD or Si photodiode. For the Mo laser the grazing incidence angle is 29° . (b) Second order autocorrelation resulting from the tailored single laser pulse used to drive the soft x-ray laser. An adjustable nanosecond amplified spontaneous emission (ASE) pedestal is followed by a 6 ps FWHM laser pulse. (c), (d) Image and lineout of the line focus used to generate the plasma amplifier.

the electron density gradient of the plasma to efficiently deposit the energy in the plasma region with optimum density for amplification [11,12]. The plasma was created and heated by a single tailored laser pulse, which is a significant simplification over the typical multiple pulse excitation schemes. Lasing at soft x-ray wavelengths in transient plasmas created by a single grazing incidence laser pulse has been previously demonstrated [13]. The single pulse used here has different characteristics. A second-order autocorrelation trace of the pump pulse is shown in Fig. 2(b). From this trace we infer that the pulse consists of a pedestal that reaches an intensity $\sim 2.5 \times 10^{-3}$ of the peak value at the onset of the short pulse, steadily decreasing in intensity at earlier times to a relative intensity of $\sim 1 \times 10^{-3}$ in 1.5 ns. The pedestal, which creates and preheats the plasma, is followed by a short high-intensity pulse ($\sim 5 \times 10^{13} \text{ W cm}^{-2}$) 6 ps FWHM duration that rapidly heats the plasma to generate a transient population inversion. The pedestal was generated by controlling the amplified spontaneous emission produced by the regenerative amplifier. Both its intensity and duration were tailored to maximize the 18.9 nm laser energy. Under the optimal conditions, the pedestal contains approximately 25% of the total pulse energy. The fast increase in intensity that follows rapidly heats the plasma to create a transient population inversion and gain. On-axis spectra were recorded using a flat-field grazing incidence diffraction grating and an x-ray CCD camera. High repetition rate soft x-ray laser operation was monitored using a soft x-ray sensitive silicon photodiode placed in the image plane of the spectrometer. Thin aluminum and zirconium foil filters were used to reject visible plasma emission and stray laser light.

Figure 3 shows the measured soft x-ray laser pulse energy as a function of plasma length. The laser pulse energy is seen to increase exponentially with a gain coefficient of 43 cm^{-1} until it saturates at a plasma column length of about 3.5 mm. A fit of the data with the Linford formula corrected for gain saturation [14] results in a gain-length product of 16.8, suggesting the rollover is due to gain saturation. Gain-saturated operation was

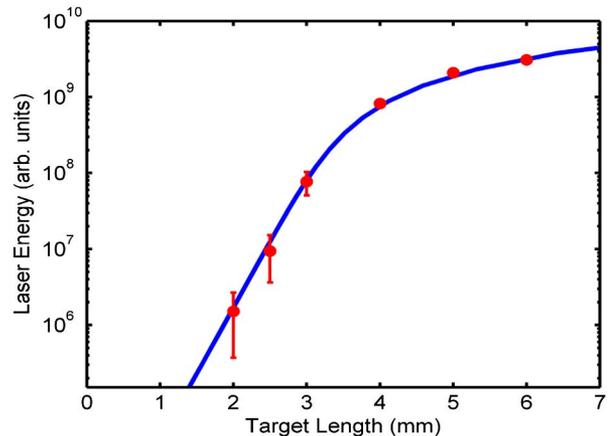


Fig. 3. (Color online) Energy of the 18.9 nm laser pulses as a function of plasma length. Each point represents the mean of 10 shots. The line is a fit of the data with the Linford formula corrected for gain saturation [14] that yields a small signal gain coefficient of 43 cm^{-1} .

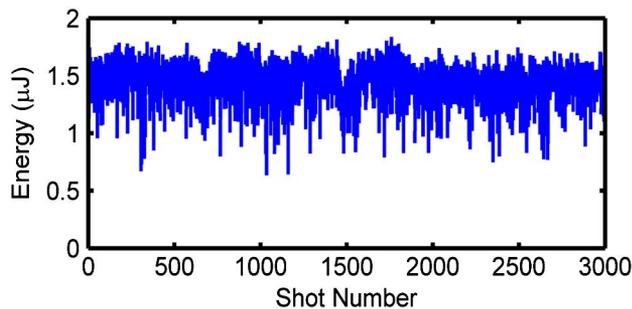


Fig. 4. (Color online) Sequence of 3000 successive $\lambda = 18.9$ nm soft x-ray laser pulses at 100 Hz repetition rate.

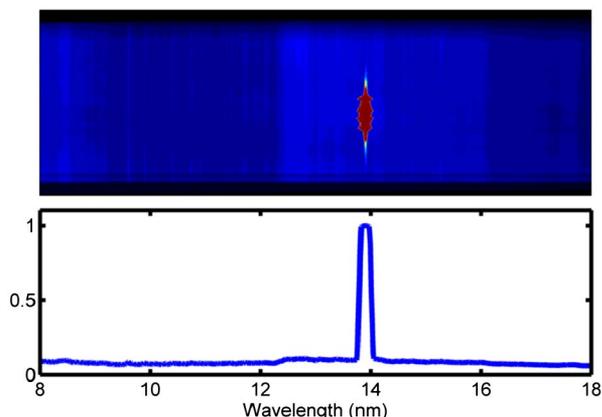


Fig. 5. (Color online) On-axis spectrum of the plasma generated by focusing pulses from the diode-pumped CPA laser onto an Ag target. Strong lasing is observed on the 13.9 nm line of Ni-like Ag.

verified by the measurement of a soft x-ray laser output pulse energy of $\sim 1.5 \mu\text{J}$ that, for a pulse duration of ~ 5 ps and near-field beam spot size of a few tens of micrometers typical of these plasma amplifiers [15], corresponds to an intensity that comfortably exceeds the computed gain-saturation intensity [12]. Figure 4 shows 3000 consecutive $\lambda = 18.9$ nm laser pulses obtained operating the laser at 100 Hz repetition rate. For this series a 1 cm wide Mo slab target was translated at a constant velocity of $200 \mu\text{m/s}$ ($2 \mu\text{m}$ per shot). Prolonged laser operation at this high repetition rate will require the use of a renewable target with a larger useful surface area, such as that demonstrated in [16]. The mean laser pulse energy in this series was $1.5 \mu\text{J}$ with a shot-to-shot stability defined by a standard deviation of 11.5%. The corresponding laser average power amounts to 0.15 mW, the highest value reported to date for a sub-20 nm coherent table-top source. Strong lasing was also obtained on the 13.9 nm line of Ni-like Ag. This is illustrated in Fig. 5, which shows a single-shot end-on spectrum of the Ag plasma created by irradiating a 10 mm wide Ag target with a similar laser pump pulse, but impinging on target at a grazing incidence angle of 33° .

In summary, we have demonstrated 100 Hz generation of soft x-ray laser pulses of microjoule energy at $\lambda = 18.9$ nm, obtaining a record high average power of 0.15 mW on a table-top. The increase in photon flux that results from operating compact soft x-ray lasers at high repetition rates will open up new applications.

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