Demonstration of an all-diode-pumped soft x-ray laser

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We have demonstrated an 18.9 nm Ni-like molybdenum soft x-ray laser, pumped by a compact all-diode-pumped Yb:YAG laser. The solid-state pump laser produces 8.5 ps pulses with up to 1 J energy at 10 Hz repetition rate. This diode-pumped laser has the potential to greatly increase the repetition rate and the average power of soft x-ray lasers on a significantly smaller footprint.

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There is a great interest in the generation of compact sources of coherent soft x-ray radiation for applications in high-resolution microscopy, metrology, nanopatterning, photochemistry, and other applications. Since the first demonstration of soft x-ray laser amplification [1,2] much progress has been made in both reducing the size and increasing the repetition rate of soft x-ray lasers. Desktop size 46.9 nm lasers [3] have been developed using fast capillary discharge excitation of Ne-like Ar ions [4]. Transient heating of plasmas with picosecond laser pulses [5,6] impinging at grazing incidence [7,8] has produced saturated tabletop lasers operating at wavelengths as short as 13.2 nm at repetition rates of 5–10 Hz [9,10]. However, these flashlamp-pumped soft x-ray lasers typically occupy several standard optical tables, and their repetition rate is limited by thermal loading of the pump laser gain media. The widespread use of soft x-ray lasers in applications requires more compact devices capable of operating at higher repetition rates with high average powers. Laser diode-pumped solid-state laser systems can be dramatically more compact than equivalent flashlamp-pumped systems. Moreover, the small quantum defect of Yb doped materials and the much higher pumping efficiency that results from pumping with a narrow bandwidth source of the optimum wavelength will allow for operation at significantly increased repetition rates. Several diode-pumped chirped pulse amplification (CPA) systems based on Yb:YAG (yttrium aluminum garnet) have been demonstrated [11–13]. A high-repetition-rate diode-pumped CPA for driving soft x-ray lasers is under development [13]. However, sub-10 ps lasers systems have not yet reached the energy necessary to efficiently pump soft x-ray lasers.

In this Letter, we report what we believe to be the first demonstration of an all-diode-pumped soft x-ray laser. Lasing was obtained in the 18.9 nm line of Ni-like Mo at a repetition rate of 10 Hz using a compact $\lambda = 1.03\ \mu m$ CPA Yb:YAG pump laser. The pump laser, with the exception of the pulse compressor, occupies a single 5 ft × 12 ft optical table. The results reported herein also constitute, to the best of our knowledge, the first demonstration of an all-diode-pumped CPA laser system capable of producing sub-10 ps laser pulses with 1 J energy. Figure 1 shows a block diagram of the soft x-ray laser system. The pump laser is based on a passively mode-locked Yb:KYW (potassium yttrium tungstate) oscillator, a cryogenically cooled Yb:YAG regenerative amplifier, and a cryogenically cooled Yb:YAG multipass amplifier, all pumped by laser diodes. Cryocooling of Yb:YAG significantly reduces the laser linewidth [14], consequently increasing the stimulated emission cross section and reducing the saturation fluence, allowing for more efficient energy extraction. Moreover, cryocooling greatly improves the thermal properties of YAG [15], making it attractive for the development of compact high repetition rate laser amplifiers.

The Yb:KYW oscillator generates 300 fs pulses at a repetition rate of 57 MHz with an average power of 1.2 W. Similar oscillators have been previously demonstrated [16,17]. The laser oscillator is pumped by a 30 W 980 nm fiber-coupled laser diode and is mode locked utilizing a semiconductor saturable absorber mirror with 2% unsaturated absorption loss. The output of the oscillator is divided to generate a sequence of three amplified 1.03 μm laser pulses that are used to generate the soft x-ray laser. The first and second pulses are sent through a negative group velocity dispersion (GVD) stretcher, while the third pulse is sent through a standard positive GVD stretcher. After amplification, the duration of the first two pulses is 160

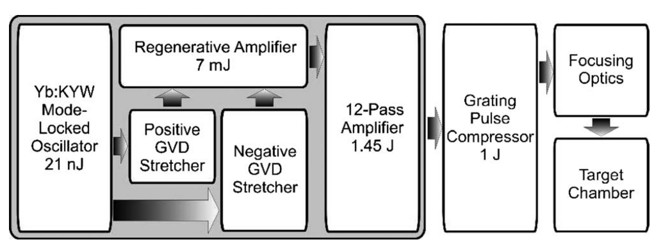

Fig. 1. Block diagram of the diode-pumped soft x-ray laser. The oscillator, stretchers, and amplifiers are shown to fit on a single 12 ft × 5 ft optical table.

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ps and the duration of the third pulse is 200 ps. The relative energies of the pulses and the delays between them are adjusted, the pulses are recombined, and then sent to the amplifiers and a vacuum compressor (negative GVD grating pair). This grating pair further stretches the first two pulses while compressing the final heating pulse. This allows us to generate a sequence of two long pulses for plasma creation, followed by a short plasma heating pulse. Furthermore, since the alignment of the three beams is determined by the cavity of the regenerative amplifier, the spatial overlap of the three pulses is ensured by design.

The regenerative amplifier boosts the combined pulse energy to 7 mJ using a 2-mm-thick 5 at. % Yb:YAG crystal that is cryocooled using a closed-cycle helium cryostat. The crystal temperature is tuned to about 100 K utilizing an electrical heater to increase the bandwidth of the amplified pulses. The regenerative amplifier is pumped by a 90 W fiber-coupled laser diode emitting at a wavelength of 940 nm. The diodes are modulated to produce 1.2 ms pulses that are focused into a ~700 μm diameter spot on the crystal. The repetition rate of the amplifier was varied between 10 and 100 Hz with practically no reduction in energy or beam quality.

The energy is increased to the joule level in a compact multipass amplification stage, schematically shown in Fig. 2. The gain medium is split into two 5.5-mm-thick 2 at. % Yb:YAG crystals in an active-mirror configuration. Off-axis spontaneous emission is absorbed by a Cr:YAG cladding eliminating parasitic lasing. The crystals are mounted on the opposite faces of a cold finger that is cooled by liquid nitrogen in an evacuated chamber. Each of the crystals is pumped by 3.5 kW pulses of 2 ms duration produced by a stack of 940 nm laser diodes. The pump beams are shaped to illuminate a circular region of 16 mm diameter on each of the Yb:YAG laser crystals. The beam exiting the regenerative amplifier makes 12 passes through the amplifier. The beam diameter is increased to ~8 mm to make the initial four passes through the amplifier (two on each crystal) passing through small holes in the large mirrors used to focus the pump beams onto the crystals. After these initial four passes the amplified pulses reach ~100 mJ. Subsequently, the beam is expanded to match the size of the pump beams and is sent eight additional times through the gain media (four times through each crystal) by means of changing the polarization. In Fig. 3(a) the energy of the pulses exiting the amplifier is plotted as a function of diode pump power. We measured a maximum energy of 1.45 J at 10 Hz repetition rate. The laser was operated at repetition rates of up to 50 Hz with only very slight thermal lensing but with significantly decreased output pulse energy owing to a reduction in the gain caused by localized heating of the gain medium that lowers the stimulated emission cross section. A reduction of the excessively long rise and fall times of the diode laser pulses used in the present setup combined with better thermal management can help to mitigate this limitation. Nonlinear effects were observed to have

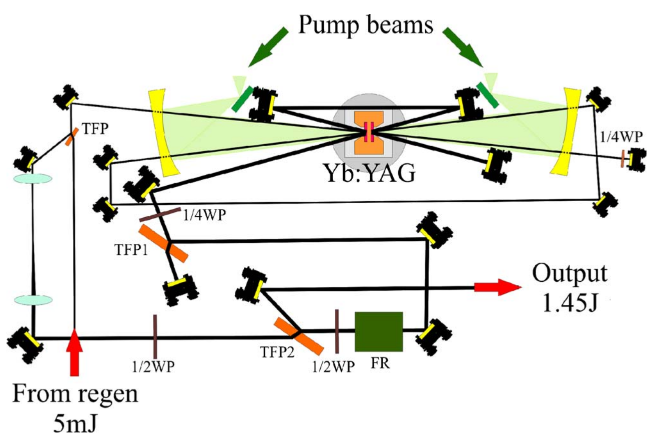

Fig. 2. (Color online) Schematic layout of multipass amplifier. The beam from the regenerative amplifier makes four passes through the gain medium changing the polarization from p to s after the second pass. Next the beam is expanded, sent through the Faraday rotator, and further amplified in additional four passes. Subsequently the polarization changes from s to p, the beam goes through TFP1, and is sent back on itself to make four more passes. Finally the beam switches polarization back to s, and is ejected by TFP2. FR, Faraday rotator; WP, wave plate; TFP, thin film polarizer.

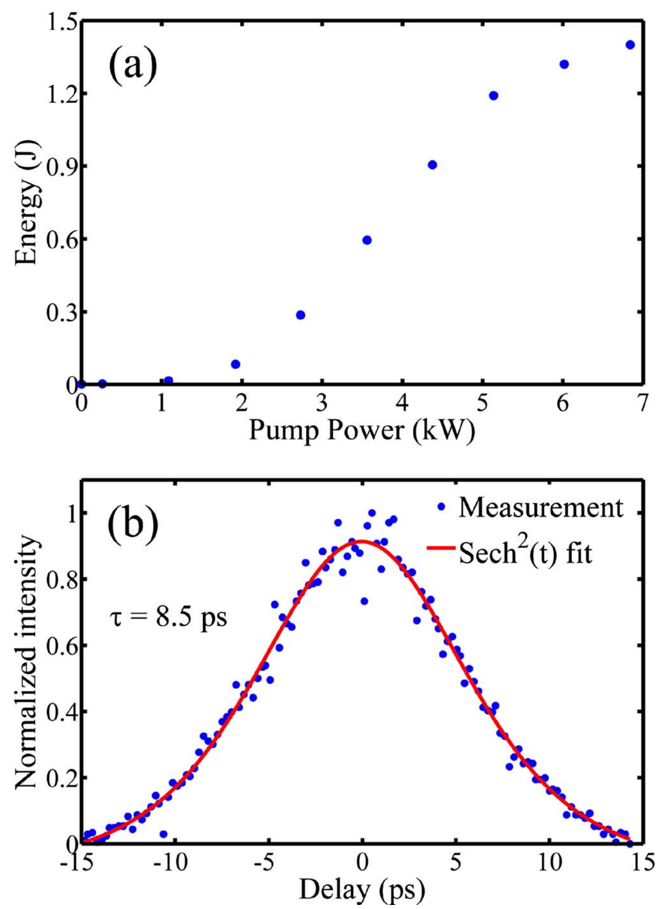

Fig. 3. (Color online) (a) Uncompressed Yb:YAG laser output pulse energy as a function of pump peak power from 2 ms pump pulses. A maximum energy of 1.45 J was obtained with a peak pump power of 7 kW. (b) Hyperbolic secant square fit of the autocorrelation data corresponding to 8.5 ps FWHM pulses.

an onset at about 1 J, but the B integral can be reduced by further stretching the input pulse.

The amplified pulses are sent to a 70% efficient vacuum compressor based on dielectric multilayer gratings. The short pulse is compressed to 8.5 ps FWHM ($sech^2$ pulses) as shown in the autocorrelation trace in Fig. 3(b), while the prepulses are further stretched to 350 ps FWHM. This set of collinear pulses is focused at a grazing incidence angle of 29° into a 4-mm-wide polished Mo target to form a 3.5 mm FWHM long line with a width of ~35 μm FWHM. The axial soft x-ray plasma emission is analyzed using a 1200 lines/mm variable space grating and a back-thinned CCD. Two 0.3-μm-thick aluminum filters were used to block the visible light emitted by the plasma. Figure 4(a) shows a single shot on-axis spectrum taken with 700 mJ of total pump energy incident on the target. The intensity of the 18.9 nm spectral line is similar to that of other plasma lines. Increase in the pump energy results in lasing in the 18.9 nm line of Ni-like Mo, as evidenced by its dramatic growth as seen in Fig. 4(b). This particular spectrum was obtained with a total pump energy on target of 940 mJ (10 and 310 mJ prepulses separated by ~4 ns, followed by a 620 mJ short pulse after 800 ps). The nonoptimized soft x-ray laser output energy was estimated to be 50 nJ. Improvement of the line focus quality can be expected to significantly increase the output energy.

In summary, we have demonstrated the first soft x-ray laser, driven by a solid-state laser system entirely pumped by laser diodes. Lasing in the 18.9 nm line of Ni-like Mo was observed using a compact Yb:YAG system that generates compressed pulses of 8.5 ps duration with up to 1 J energy, the highest energy pulses reported for an all-diode-pumped CPA laser system. Future work can be expected to lead to the development of very compact soft x-ray lasers that will operate at unsurpassed repetition rates.

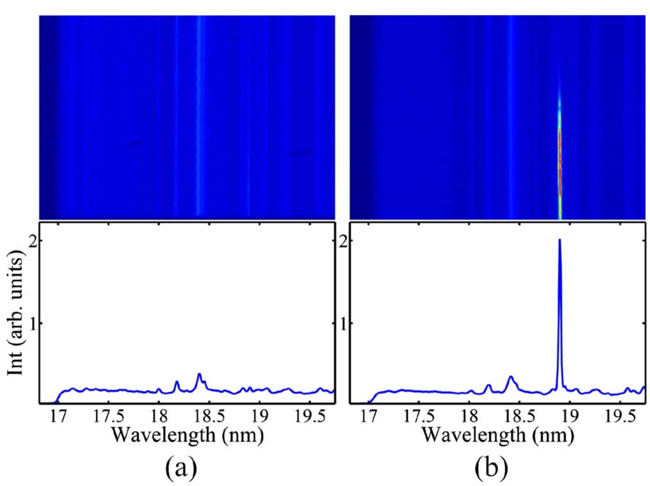

Fig. 4. (Color online) (a) On-axis soft x-ray spectrum taken with a total pump energy on target of 0.7 J. (b) The same spectrum taken with 0.94 J of pump energy, showing lasing in the 18.9 nm laser line of Ni-like Mo.

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