

Saturated 13.2 nm high-repetition-rate laser in nickellike cadmium

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We report gain-saturated operation of a 13.2 nm tabletop laser in Ni-like Cd at a 5 Hz repetition rate. A gain-length product $G \times L = 17.6$ was obtained by heating a precreated plasma with 8 ps duration Ti:sapphire laser pulses with an energy of only 1 J impinging at a grazing angle of 23° . With an average power of $\sim 1 \mu\text{W}$, this laser is an attractive coherent source for at-wavelength metrology of extreme UV lithography optics and other applications. © 2005 Optical Society of America

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There is significant interest in the development of compact high-average-power soft-x-ray lasers for a variety of applications. In particular, there is a need for the development of compact coherent sources emitting at wavelengths within the bandwidth of the Mo-Si mirrors centered at 13.5 nm for at-wavelength metrology of extreme ultraviolet (EUV) projection lithography optics.¹ Laser amplification at this wavelength was demonstrated at a 2–3 Hz repetition rate in H-like Li ions following collisional recombination of completely ionized Li atoms in plasmas created by optical field ionization.^{2,3} However, the maximum amplification reported to date for this laser excitation scheme,⁴ a gain-length product of $G \times L \sim 6-7$, is still insufficient to produce the laser output pulse energies and average powers required for most applications. Saturated laser operation at a repetition rate of one shot every several minutes has been obtained at 13.9 and 13.2 nm by transient collisional electron excitation of Ag and Cd targets with a combination of a nanosecond and picosecond laser pump pulses impinging in the direction normal to the target surface. In those experiments^{5,6} the short-pulse pump energy was 3–7 J.

Approaches investigated to reduce the pump energy necessary to produce saturated collisional lasers at wavelengths below 20 nm have included the use of longitudinal pumping.⁷ In recent work^{8–11} it was shown that the short-pulse pump energy required can be significantly decreased by directing this pump beam onto the target at a grazing angle θ . This pumping geometry takes advantage of the refraction of the pump beam to increase the path length of the rays in the gain region of the plasma, thereby increasing the fraction of the pump energy absorbed in that region.¹⁰ It is inherently a traveling wave, with a traveling wave pump speed $v = c/\cos \theta$ (e.g., $v = 1.09c$ at $\theta = 23^\circ$). Excitation of Mo plasmas at grazing incidence angles has resulted in $G \times L \sim 14$ amplification at a 10 Hz repetition rate⁹ and gain saturation operation at 5 Hz (Ref. 10) in the 18.9 nm line of Ni-like Mo. Very recently,¹¹ saturated operation at a 5 Hz repetition rate has been obtained at 13.9 nm in a Ni-like Ag plasma heated with 1 J pulses of 8 ps duration impinging at a grazing incidence angle of

23° . However, at this laser wavelength the reflectivity of a single Mo-Si mirror centered at 13.5 nm is only about 10%.¹² This low reflectivity significantly limits the use of a Ni-like Ag laser in at-wavelength metrology of EUV optical systems composed of multiple mirrors.

In this Letter we report the demonstration of a saturated 5 Hz repetition rate laser emitting highly monochromatic light at 13.2 nm in the $4d^1S_0-4p^1P_1$ transition of Ni-like Cd ions. An amplification of $G \times L = 17.6$ was obtained by heating a precreated plasma with 8 ps pulses of only 1 J energy. This wavelength falls within the bandwidth of the Mo-Si multilayer coatings designed for EUV lithography, which at this wavelength have a reflectivity of about 50%. The laser was pumped by a tabletop Ti:sapphire chirped-pulse amplification laser system ($\lambda = 800 \text{ nm}$) consisting of a Kerr mode-locked oscillator and three stages of amplification. Pulses from the laser oscillator were stretched to about 120 ps and were subsequently amplified in a chain consisting of three Ti:sapphire amplifiers: an eight-pass first stage amplifier, a five-pass second stage amplifier, and a final three-pass amplifier. A multilayer coated beam splitter was placed at the output of the third-stage amplifier to direct 20% of the laser energy to a prepulse arm. The rest of the third-stage amplifier output was sent to a vacuum-grating compressor. This laser can operate at a repetition rate of 10 Hz, corresponding to the repetition frequency of the two Nd:YAG lasers used to pump the amplifiers, but in the present experiments the repetition rate of the third amplifier was reduced to 5 Hz with the purpose of improving the pump beam mode quality.

The soft-x-ray laser amplifier consisted of a line focus plasma up to 4 mm in length generated by exciting a 2 mm thick polished Cd slab target with a sequence of an early prepulse of 120 ps duration and 15 mJ energy, followed after about 5 ns by a main prepulse of the same duration and $\sim 350 \text{ mJ}$ energy, which in turn was followed after a variable delay (typically 100–200 ps) by an 8 ps duration, $\sim 1 \text{ J}$ energy heating pulse. The prepulse beam was focused into a 30 μm wide, 4.1 mm FWHM line focus by us-

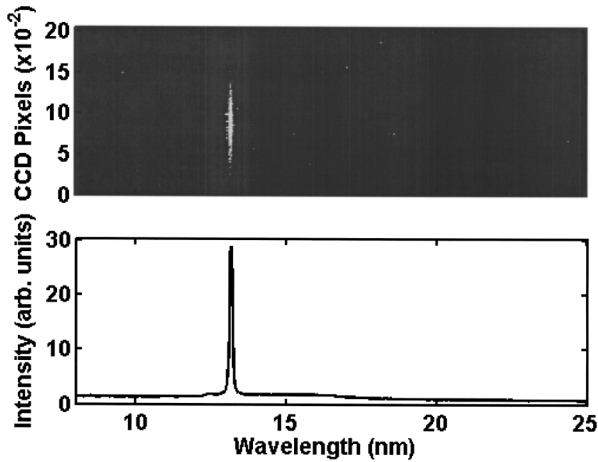


Fig. 1. Single-shot on-axis spectrum of a 4 mm long Cd plasma column. The short-pulse energy was 1 J. The 13.2 nm laser line of Ni-like Cd is observed to completely dominate the spectrum.

ing the combination of an $f=67.5$ cm focal length spherical lens and an $f=200$ cm focal length cylindrical lens. The short pulse was focused into a similar line focus by utilizing a parabolic mirror of $f=76.2$ cm positioned at 7° from normal incidence. The off-axis placement of the paraboloid formed an astigmatic focus that resulted in a line that was further elongated to 4.1 mm when intercepted at grazing incidence by the target. The target surface was tilted with respect to the axis of the prepulse beam to form grazing incidence angles of 17° , 20° , 23° , or 26° with respect to the axis of the short pulse beam. The overlap of the line foci on target was observed and adjusted by imaging the target into a CCD, utilizing digital zoom. The output of the x-ray laser was analyzed by using a flat field spectrograph composed of a variably spaced 1200 lines/mm Ag-coated spherical grating placed at 3° grazing incidence and a 2048×2048 channel, 1 in. square (1 in. = 2.54 cm), back-illuminated CCD detector placed 48 cm from the target. Spectral filtering and attenuation were performed by using Zr filters and meshes of known transmission between the target and the grating.

Figure 1 shows a typical on-axis spectrum corresponding to a 4 mm long Cd plasma heated by a 1 J pulse of 8 ps FWHM duration impinging onto the target at 23° grazing incidence angle. The $4d^1S_0-4p^1P_1$ laser line of Ni-like Cd completely dominates the spectrum. Lasing was observed with pumping energies as low as ~ 180 mJ for the main prepulse and ~ 460 mJ for the short pulse. The laser beam divergence was measured to be ~ 14 mrad in the direction parallel to the target and ~ 7 mrad in the perpendicular direction. Figure 2 shows the variation of the laser output intensity as a function of the grazing incidence angle of the pump beam. As the angle of incidence, θ , is incremented, the electron density of the plasma region in which refraction couples the pump beam increases as $n_e = \theta^2 \times n_{ec}$, where n_{ec} is the critical density. At the lower angles refraction couples the pump beam into a plasma region at which the density is lower than optimum for amplification by tran-

sient collisional excitation. The maximum laser output intensity is observed at an angle of 23° , for which the plasma density is $2.8 \times 10^{20} \text{ cm}^{-3}$.

As shown in Fig. 3, lasing is observed for a broad range of time delays between the prepulse and the heating pulse. Optimum amplification is observed to occur for a time delay of 100–200 ps. The optimum delay for lasing in this Ni-like Cd line is observed to be significantly shorter than the ~ 700 ps required for maximum laser output in the 18.9 nm line of Ni-like Mo.¹⁰ This is consistent with the fact that the higher degree of ionization necessary for lasing in Ni-like Cd is present only in the early stages of the prepulse plasma expansion.

The gain was measured by integrating the laser line intensity as a function of plasma length. For this purpose a Cd target with steps ranging from 1.5 to 4 mm in length was used. Figure 4 shows the results obtained at the optimized grazing incidence angle of 23° . The 13.2 nm laser line intensity increases exponentially until it rolls off into saturation for target lengths above 2 mm. The gain was evaluated by fitting the data with the expression by Tall-

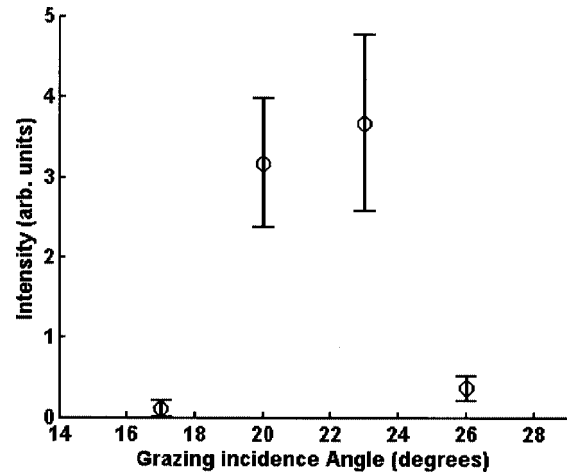


Fig. 2. Variation of the intensity of the 13.2 nm line of Ni-like Cd as a function of grazing incidence angle of the 8 ps beam onto the target.

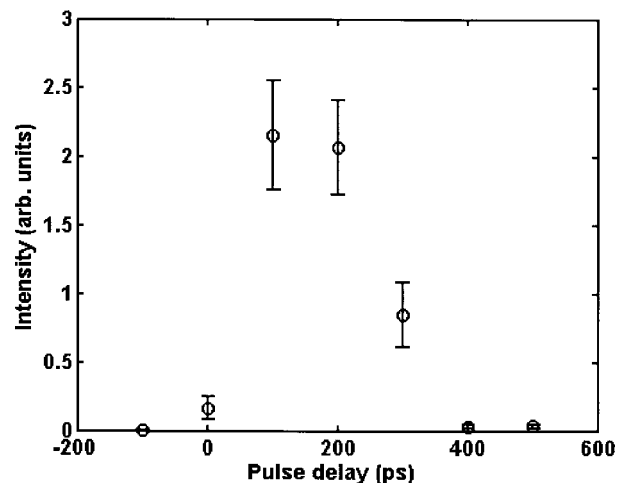


Fig. 3. Variation of the intensity of the 13.2 nm line of Ni-like Cd as a function of time delay between the 120 ps prepulse and the 8 ps heating pulse.

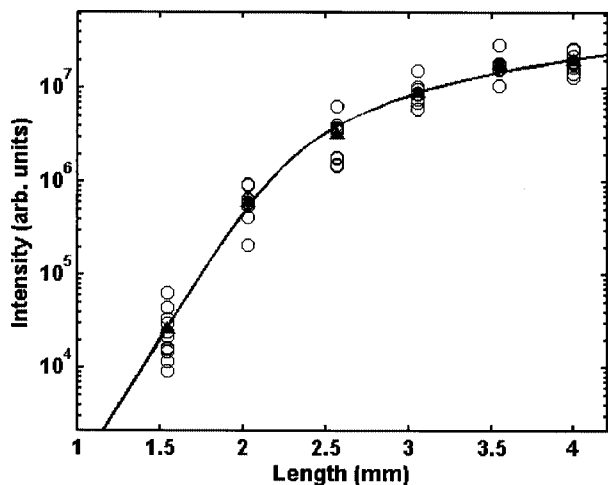


Fig. 4. Variation of the intensity of the 13.2 nm line of Ni-like Cd as a function of plasma column length. The fit of the data corresponds to a small signal gain of 69 cm^{-1} and a gain-length product of 17.6. The filled triangles are the average of about 10 laser shots.

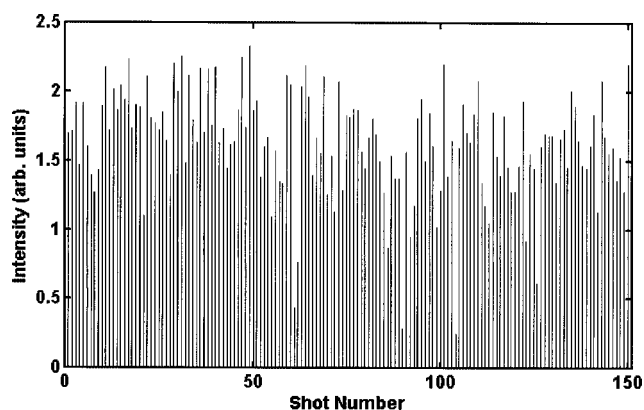


Fig. 5. Sequence of 150 contiguous laser pulses of the 13.2 nm Ni-like Cd laser acquired at a 5 Hz repetition rate. The grazing angle of incidence of the short pulse was 20° .

ents *et al.* for the variation of the line intensity with plasma length, taking into account gain saturation.¹³ The resulting small signal gain coefficient is 69 cm^{-1} , and the gain-length product reaches $G \times L = 17.6$, a value at which collisionally excited soft-x-ray laser systems are normally in the gain-saturated regime. The energy of the most intense laser pulses was estimated from the CCD counts to exceed 430 nJ, taking into account the attenuation losses of the filters and meshes, the grating efficiency, and the quantum efficiency of the detector. Assuming the laser pulse width is that predicted by model computations, ~ 5 ps, and an exit beam diameter corresponding to the width of the pump beam, $30 \mu\text{m}$, the 13.2 nm laser beam is estimated to reach an intensity of $\sim 1.2 \times 10^{10} \text{ W cm}^{-2}$, which exceeds the computed saturation intensity of this line $(0.5\text{--}0.8) \times 10^{10} \text{ W cm}^{-2}$ for the plasma conditions corresponding to a grazing incidence angle of 23° .

Figure 5 illustrates a sequence of 150 contiguous shots obtained at a 5 Hz repetition rate. The data were obtained while the target was moved at a veloc-

ity of 0.2 mm/s to avoid the soft-x-ray laser pulse output energy degradation that occurs when more than two shots are fired onto the same target location. Lasing is observed for all shots with an intensity variation characterized by a standard deviation equal to 23% of the mean. The average output power is of the order of $1 \mu\text{W}$. Optimization of the pump laser should allow operation at a 10 Hz repetition rate and a corresponding increase in the average power.

In summary, we have demonstrated saturated lasing at 13.2 nm at a repetition rate of 5 Hz with a tabletop pump laser. This high-repetition-rate laser is of interest for numerous applications, in particular the metrology of EUV lithography optics.

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