Saturated high-repetition-rate 18.9-nm tabletop laser in nickellike molybdenum

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We report saturated operation of an 18.9-nm laser at 5-Hz repetition rate. An amplification with a gain–length product GL of 15.5 is obtained in the $4d\ ^1S_0-4p\ ^1P_1$ laser line of Ni-like Mo in plasmas heated at grazing incidence with ~1-J pulses of 8.1-ps duration from a tabletop laser system. Lasing is obtained over a broad range of time delays and pumping conditions. We also measure a GL of 13.5 in the 22.6-nm transition of the same ion. The results are of interest for numerous applications requiring high-repetition-rate lasers at wavelengths below 20 nm. © 2005 Optical Society of America

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There is great interest in the development of compact saturated high-repetition-rate lasers capable of producing significant average output powers at soft-x-ray wavelengths for applications. Ne-like Ar capillary-discharge-pumped lasers operating at repetition rates of up to 10 Hz have been demonstrated to produce milliwatt average powers at 46.9 nm.[1,2] More recently, saturated optical field ionization lasers operating in Pd-like Xe at 41.8 nm and in Ni-like Kr at 32.8 nm were obtained by use of 0.33- and 0.76-J pulses, respectively, from a femtosecond 10-Hz pump laser.[3,4] Longitudinal pumping of Mo plasma with short pulses from 10-Hz lasers produced nonsaturated amplification at 18.9 nm in Ni-like Mo,[5,6] a laser line first observed in a small-scale pump system using 80-ps pump pulses.[7] Transient collisional electron excitation of targets at normal incidence with 3–10 J of pump energy has produced several saturated lasers in the 12–33-nm range at repetition rates of one shot every several minutes.[8,9] Excitation of a Mo target with 150-fs, 300-mJ pulses impinging at 60° from normal incidence resulted in the appearance of the 18.9- and 22.6-nm laser lines of Ni-like Mo.[10] Recently, it was shown that the pumping energy necessary for lasing could be significantly reduced by directing the short pulse onto the target at grazing incidence.[11,12] This inherently traveling-wave 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. A gain–length product of ~15 was reported in the 18.9-nm line of Ni-like Mo with 150 mJ of total pumping energy from a 10-Hz laser.[13] A normal-incidence 200-ps prepulse was focused into a 15-μm-wide line focus and followed by a 1.5-ps short pulse impinging at a grazing-incidence angle of 14°. Lasing was observed to occur over only an extremely narrow ~50-ps range of prepulse-to-short-pulse time delays.

Herein, we report saturated laser operation in the 18.9-nm line of Ni-like Mo and strong amplification at 22.6 nm by use of a 5–10-Hz tabletop pump laser. Lasing was obtained over a very broad range of time delays. The gain medium was created by the combination of laser pulses generated by an 800-nm tabletop Ti:sapphire laser system with three stages of amplification. A beam splitter directed 20% of the third-stage output to the prepulse arm (120 ps FWHM, 350 mJ), and the remaining output was compressed (1.8–8.1 ps FWHM, 1 J) and sent to the short-pulse arm. Amplification of spurious light from the first-stage amplifier produced a pulse with a few percent of the total energy that preceded the main pulse by 6.7 ns. The laser can operate at a repetition rate of 10 Hz; however, for the present experiments the repetition rate was reduced to 5 Hz. An electromechanical shutter was placed on the pump beam of the first amplifier to allow for single-shot data acquisition.

The experimental setup is shown in Fig. 1. A 2-mm-thick polished Mo slab was used for the target. The target was irradiated at normal incidence with the prepulse focused into a line of 30 μm FWHM in width and 4.1 mm FWHM in length by use of a combination of an $f = 67.5$ cm spherical lens and an $f = 200$ cm cylindrical lens. The preplasma was then rapidly heated with the short pulse impinging at a grazing-incidence angle of 14° to generate a transient population inversion. The short pulse was focused into a line of 30-μm FWHM width by use of an $f = 76.2$ cm parabolic mirror placed at 7° from normal incidence. The off-axis placement of the paraboloid forms an astigmatic focus that results in a line that is further elongated when intercepted at grazing incidence by the target. A cylindrical lens pair before the compressor added minor adjustments to the astigmatism to yield a 4.1-mm FWHM length. The delay between the 120-ps duration prepulse and the short pulse was selected with a variable delay stage. The plasma emission was monitored with a flat field spectrograph composed of a variably spaced 1200-line/mm gold-coated spherical grating placed at a 3° grazing incidence and a backilluminated CCD detector. Spectral filtering was performed with combinations of Al and Zr filters. In some of the

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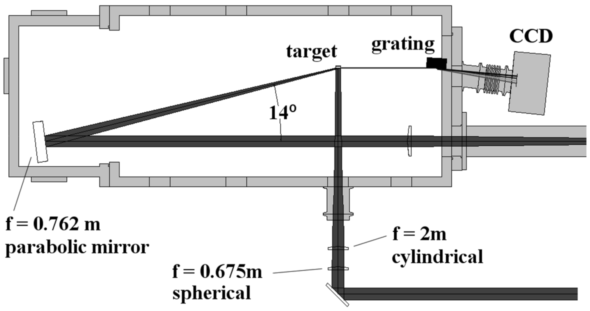

Fig. 1. Schematic diagram of the experimental setup for obtaining saturated lasing in Ni-like Mo showing the target chamber, pumping configuration, and detection system.

measurements the beam was further attenuated by placing meshes of known transmission in front of the diffraction grating.

Figure 2(a) shows an on-axis 10–19-nm spectrum from a 4-mm-long Mo plasma created by a 320-mJ laser prepulse. Several of the strongest lines correspond to Cu-like Mo,[12] indicating that the preplasma was likely to contain a significant concentration of Ni-like ions. Figure 2(b) shows a typical spectrum obtained when a 4-mm Mo plasma was irradiated with a 930-mJ, 8.1-ps FWHM short pulse 700 ps after the prepulse. Strong laser emission was observed in both the 18.9-nm $4d\ ^1S_0-4p\ ^1P_1$ and in the 22.6-nm $4f\ ^1P_1-4d\ ^1P_1$ lines of Ni-like Mo. Lasing was also observed in plasmas generated with both broader (50-μm FWHM) and narrower (18-μm FWHM) prepulse line focus widths and broader (50-μm FWHM) and narrower (15-μm FWHM) short-pulse linewidths. However, the best results in terms of output intensity and shot-to-shot reproducibility were obtained by use of 30-μm FWHM widths for both of the pulses. In contrast, the laser output obtained with the narrower line focus was significantly more erratic. Lasing was also observed for short-pulse durations of 1.8 and 6 ps. However, since the shorter pulses did not result in significant improvements of the laser output with respect to the 8.1-ps pulses, the characterization of the laser reported herein was conducted with longer pulses to reduce the possibility of damage to the optics. Lasing at 18.9 nm was observed with pumping energies as low as 140 mJ for the prepulse and 310 mJ for the short pulse.

Targets with steps ranging from 1.5 to 4 mm in length were used to measure gain. Figure 3 shows the results obtained with a 350-mJ prepulse and an ~1-J short pulse separated by 700 ps. The intensity of the 18.9-nm Ni-like Mo line increased by nearly 3 orders of magnitude when the target length was varied between 1.5 mm, the minimum length for which the line was observed, and 4 mm. The solid curves in Fig. 3 are fits of the data with the expression from Tallents *et al.*[15] for the variation of the line intensity with plasma length, taking into account gain saturation. The resulting small-signal gain coefficient for the 18.9-nm line is 58 cm^{-1}, and the gain–length product GL reaches 15.5, a value that corresponds to saturated operation in collisional laser systems. The laser beam divergence was measured to be ~10 mrad. The energy of the most-intense 18.9-nm laser pulses was estimated from the CCD counts to exceed 150 nJ. Assuming a laser pulse width equal to the duration of the gain divided by $(GL)^{1/2}$ (~2 ps) and a gain region of 35-μm diameter, the 18.9-nm laser beam intensity can be calculated to reach the computed gain saturation intensity of $2-6\times10^{10}\ \text{W/cm}^2$ (Ref. 16) when the pulse energy reaches 40–120 nJ. The 22.6-nm line was measured to amplify with a smaller gain coefficient of 41.1 cm^{-1} and to reach a gain–length product GL of 13.5.

Figure 4 shows the 18.9-nm laser output intensity as a function of delay between the 350-mJ prepulse and the ~1-J main pulse for a 4-mm target. Strong lasing is observed to take place for a broad range of time delays, ranging from approximately 500 to 1200 ps. Model computations show that at significantly shorter times the electron density profile is too steep, whereas at times longer than 1200–1400 ps the electron density drops substantially below the values for optimum amplification. This time window for lasing is significantly broader than that observed in the experiment by Keenan *et al.*[11] (~50 ps) and is indication that the Ni-like Mo lasers demonstrated in these two experiments operate in different regimes. The larger pump energy and broader prepulse line focus in the present experiment can be expected to

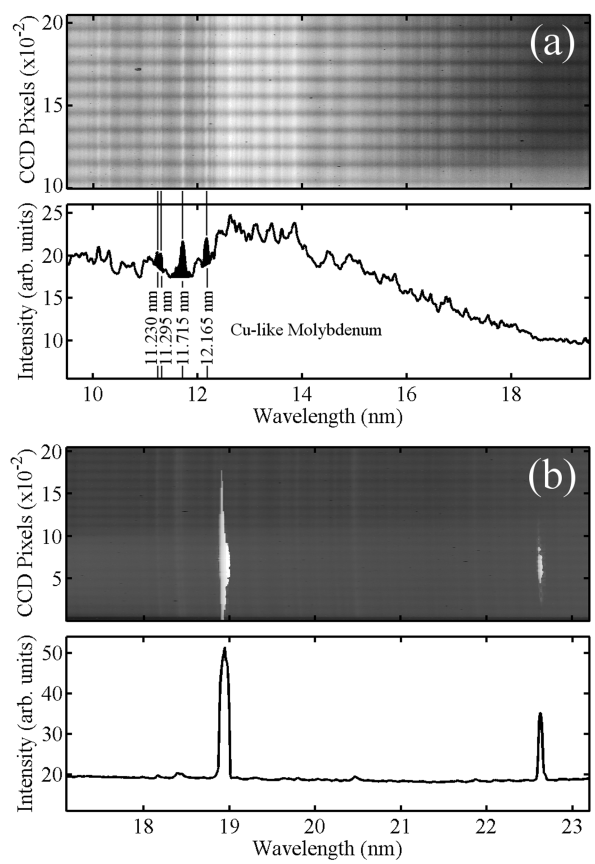

Fig. 2. (a) Axial spectra of a 4-mm-long Mo target excited by a 320-mJ, 120-ps duration pulse. Cu-like Mo lines are observed to be dominant. (b) Spectra obtained with an ~960-mJ, 8.1-ps short pulse 700 ps after the prepulse. Strong lasing is observed in the 18.9-nm $4d\ ^1S_0-4p\ ^1P_1$ and 22.6-nm $4f\ ^1P_1-4p\ ^1P_1$ lines of Ni-like Mo.

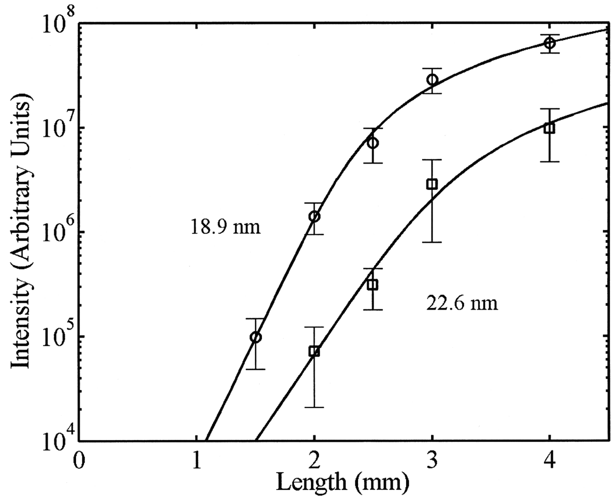

Fig. 3. Intensity of the 18.9-nm and 22.6-nm laser lines of Ni-like Mo as a function of plasma length. Each of the points is an average of ten or more laser shots.

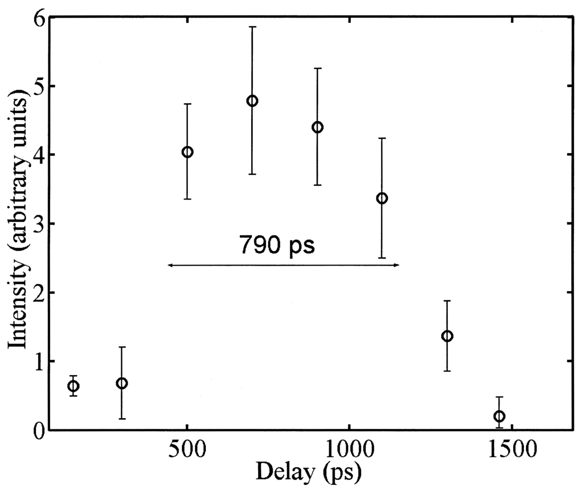

Fig. 4. Variation of the intensity of the 18.9-nm line as a function of time delay between the 120-ps prepulse and the 8.1-ps grazing-incidence short pulse.

give rise to an enlarged gain region that contributes to generating the increased laser output pulse energy we observed. Approximately 20–30 high-intensity laser shots were obtained for a given target location. Operation at a 5-Hz repetition rate was achieved for 200 continuous shots by moving the target at a velocity of 0.2 mm/s.

In summary, we have demonstrated saturated lasing at 18.9 nm and strong lasing at 22.6 nm using a high-repetition-rate table-top laser pump and grazing-incidence pumping. Lasing was achieved over a broad range of time delays with good reproducibility. The results are significant for the development and application of practical high-average-power lasers at this and other wavelengths below 20 nm.

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