High repetition rate operation of saturated table-top soft x-ray lasers in transitions of neon-like ions near 30 nm

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Abstract: We report average powers exceeding 1 microwatt in laser transitions of Ne-like ions at wavelengths near 30 nm. Gain-saturated operation was obtained at a repetition rate of 5 Hz exciting solid targets with pump pulses of ~1 J energy and 8 ps duration impinging at grazing incidence of 20 degrees. Gain-length products of about 20 were obtained in the 30.4 nm and 32.6 nm transitions of Ne-like V and Ne-like Ti respectively. Strong lasing was also observed in Ne-like Cr at 28.6 nm and in the 30.1 nm line of Ne-like Ti.

OCIS codes: (140.7240) UV, XUV, and X-ray lasers; (340.7480) X-rays

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1. Introduction

There is much interest in the development of compact soft x-ray lasers capable of generating high average powers for applications. This requires operation of the soft x-ray amplifiers in the gain-saturated regime at high repetition rate. The first soft x-ray lasers to achieve high average powers used collisional electron impact excitation of Ne-like ions in a capillary discharge plasma [1,2]. Capillary discharge excitation has produced average powers of a few mW in the 46.9 nm line of Ne-like Ar. Collisional optical-field-ionization lasers operating at 10 Hz repetition rate in Pd-like Xe at 41.8 nm [3,4] and in Ni-like Kr at 32.8 nm [5] have also been reported to reach gain saturation. Saturated soft x-ray amplification in transitions of Ne-like and Ni-like ions excited by transient collisional electron excitation was also obtained but only at repetition rates of one shot every several minutes in plasmas heated by picosecond duration pulses of 3-7 J energy [6-8]. In recent work the energy necessary to pump transient collisional soft x-ray lasers has been significantly reduced using a grazing incidence pumping geometry that increases the absorption of the pump beam in the gain region [9-12]. This pumping geometry significantly increases the energy deposition efficiency of the pump beam into the gain region by taking advantage of refraction to increase the path length of the pump rays through this region of the plasma. Excitation of Mo plasmas at a grazing incidence angle has resulted in gain saturated operation in the 18.9 nm line of Ni-like Mo at 5-10 Hz repetition rate [9-11]. Most recently saturated laser operation at 5 Hz repetition rate was obtained in several transitions of Ni-like ions with wavelengths ranging from 16.4 nm to 13.9 nm by grazing incidence heating of plasmas with 8 picosecond pulses of 1 J energy [12]. It is of significant interest to extend these results to other isoelectronic sequences, as different applications require access to different wavelengths. For example, the characterization of extreme ultraviolet optics for solar coronal studies would significantly benefit from compact high repetition lasers with wavelengths between 30 and 37 nm that includes both the HeII 30.4 nm line and strong lines of FeXI-XVI [13].

Herein we report the extension of gain saturated high repetition rate laser-pumped transient soft x-ray lasers to transitions in Ne-like ions using grazing incidence pumping. High average power soft x-ray laser operation was obtained for the first time to our knowledge in the $2p^5 3p\,^1S_0 \rightarrow 2p^5 3s\,^1P_1$ transitions of Ne-like Ti and V at 32.6 nm and 30.4 nm respectively. We also observed strong lasing in the corresponding line in Ne-like Cr at 28.6 nm, and in the 30.1 nm $2p^5 3d\,^1P_1 \rightarrow 2p^5 3p\,^1P_1$ line of Ne-like Ti which inversion relies on strong re-absorption of the 2.335 nm resonant transition linking the $3d\,^1P_1$ laser upper level to the ion ground state [14].

2. Setup

The pump beam geometry is similar to the one used in recent experiments with Ni-like ions [10-12]. The targets were 4 mm wide polished slabs with a thickness of 2 mm for Ti and V and 1mm for Cr. They were irradiated with pulses from a Ti:sapphire laser system operating at a center wavelength of 800 nm consisting of a mode-locked oscillator and three stages of chirped-pulse amplification. A beam splitter was placed at the exit of the third amplifier stage to direct a fraction of the energy of the uncompressed laser pulses (120 ps duration) into the pre-pulse arm. The rest of the laser energy was compressed to 8 ps to form the main heating pulse. Pre-pulses of 0.35 J for Ti and 0.5 J for V and Cr, were used to form a plasma by irradiating the target at normal incidence. This pre-pulse was preceded by a 10 mJ pre-pulse about 5 ns before. The pre-pulses were focused into a 4.1 mm long × 30 μm wide line using the combination of a spherical and a cylindrical lens. The plasma was allowed to expand to reduce the density gradient and it was subsequently rapidly heated by the 8 ps duration pulse with ~ 1 J of energy impinging at a selected grazing incidence angle onto the target. The short pulse was focused into a line of the same size utilizing an f = 76.2 cm parabolic mirror placed at 7 degrees from normal incidence. The normal to the target surface was tilted from the axis defined by the pre-pulse beam to form grazing incidence angles of 17, 20 or 23 degrees with respect to the axis of the short pulse beam. The plasma emission was attenuated with calibrated Al filters and a set of metallic meshes of measured transmissivity. The soft x-ray laser beam was monitored using a flat field spectrograph composed of a 1200 l/mm gold-coated variably spaced spherical grating and a 1 square inch back-illuminated CCD detector array placed in the image plane of the grating.

3. Results

Figure 1 shows on-axis spectra corresponding to 4 mm long plasmas of Ti, V and Cr irradiated at a grazing incidence angle of 20 degrees. In the Ti experiment the energy of the picosecond pulse was 1 J. In the V and Cr experiments the energy of the main pre-pulse was increased to 0.52 J at expense of the energy of the picosecond pulse, which in these cases was ~ 0.9 J. In all cases, the $3p^1S_0 \rightarrow 3s^1P_1$ line of the Ne-like ions is observed to clearly dominate the spectra. In the case of Ti, lasing was also observed in the 30.1 nm $3d^1P_1 \rightarrow 3p^1P_1$ line of the Ne-like ion, but its intensity of was weaker for the range of pump parameters investigated.

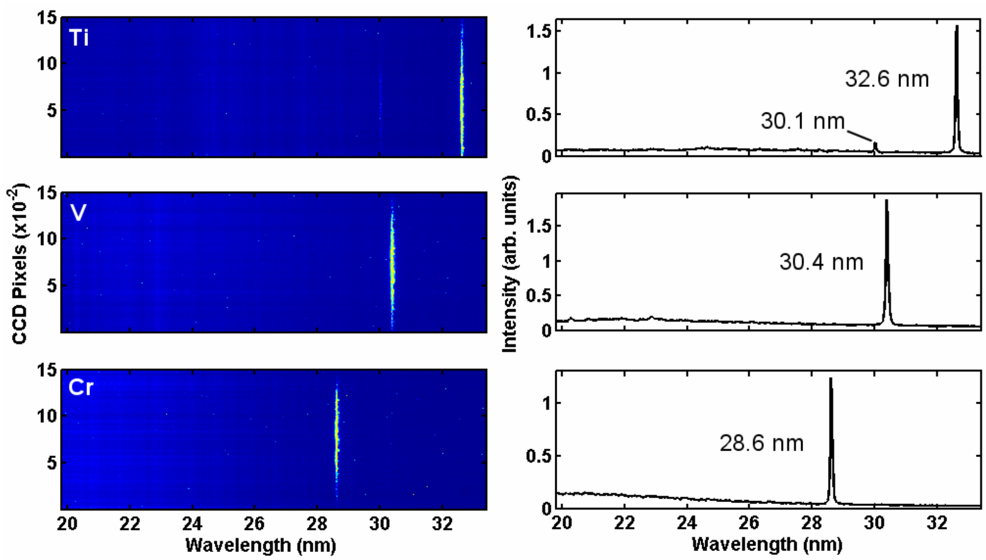

Fig. 1. Single shot on-axis spectra of 4 mm long line focus plasmas showing lasing in the $2p^53p^1S_0$-$2p^53s^1P_1$ transition of Ne-like Ti, V and Cr ions. In all three cases, this laser-line dominates the spectrum.

Figure 2 shows the variation of the soft x-ray laser output intensity as a function of the angle of incidence of the short pulse beam for all three lasers. At an incidence angle of 17 degrees lasing was observed for the $3p^1S_0$-$3s^1P_1$ lines of the Ne-like ions of all three species (see Fig. 2). However, at this angle the pump beam is deposited in a region where the electron density is lower than the optimum value for maximum soft x-ray laser output intensity.

The output intensity of all three lasers was observed to increase significantly for an angle of 20 degrees, for which refraction helps to couple the pump beam into a region of higher electron density ($2x10^{20}$ cm^{-3}). At the steeper angle of incidence of 23 degrees a significant fraction of the beam energy is absorbed in a higher density region where the electron density gradients are too steep for optimum amplification. Also contributing to a lower laser output at this angle is the shorter duration of the gain and the increased mismatch between the velocity of the traveling wave of the pump and the speed of light in the plasma.

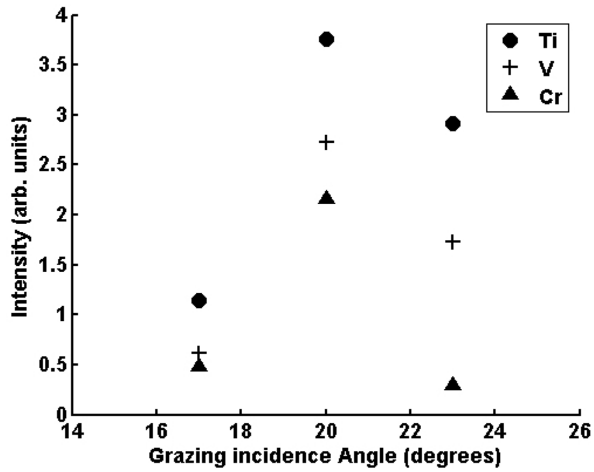

Fig. 2. Variation of output laser intensity as a function of grazing incidence angle for Ne-like Ti, V and Cr. Each point represents the mean of 15 or more consecutive laser shots. In all three cases the laser operates best at 20 degrees. At this angle the standard deviation of each data set ranges from 14% to 38% of the mean.

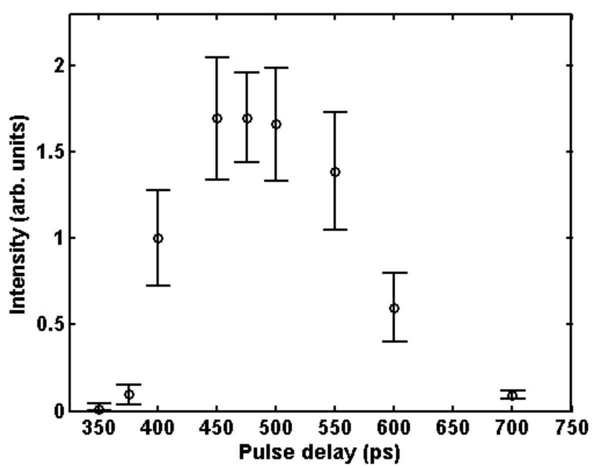

Fig. 3. Laser output intensity of the 30.4 nm line of Ne-like V as a function of time delay between the main pre-pulse and the short pulse. Lasing is strong for delays ranging from 400 ps to 600 ps. Each point is the average of 10 or more laser shots; the error bars correspond to ± the standard deviation of the set.

Figure 3 shows the output intensity of the 30.4 nm line of Ne-like V as a function of time delay between the main pre-pulse and the short pulse for a grazing incidence angle of 20 degrees. Strong lasing was observed to occur over a wide range of time delays. The optimum delays were observed to be approximately 600 ps for Ne-like Ti and 450 ps for Ne-like V and Cr. This result, which follows the same trend observed for lasing in Ni-like ion transitions [12], is related to the fact that a more highly ionized pre-plasma is required for lasing at higher

Z, allowing less time for plasma cooling during expansion and recombination. The maximum intensity of the 30.1 nm line of Ne-like Ti occurs at a delay of 520 ps, an earlier time than the optimum for the 32.6 nm line. At this delay the intensity of the 30.1 nm line is typically half that of the 32.6 nm line.

Figure 4 shows the variation of the laser intensity of the 30.4 nm line of the Ne-like V as a function of plasma length. The solid line represents a fit of the data with the expression derived by Tallents *et al.* for the variation of the laser intensity with plasma length taking into account gain saturation [15].

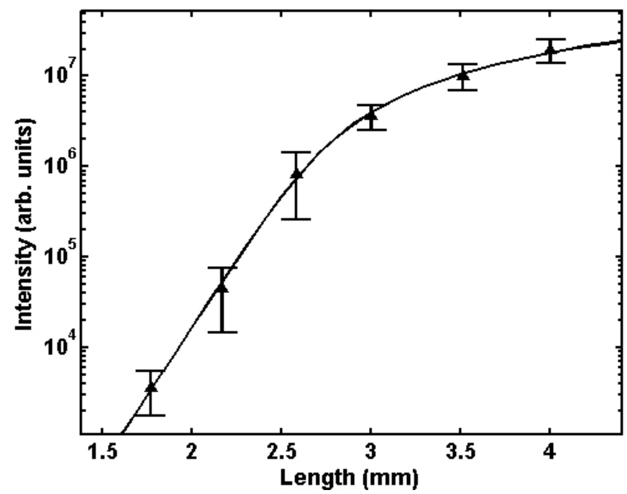

Fig. 4. Intensity of the 30.4 nm line of Ne-like V as a function of plasma length. Each point is the average of 10 or more shots. A fit of the data results in a gain coefficient of 72 cm^{-1} and a gain-length product of 21.7. Each point is the average of 10 or more laser shots; the error bars correspond to ± the standard deviation of the set.

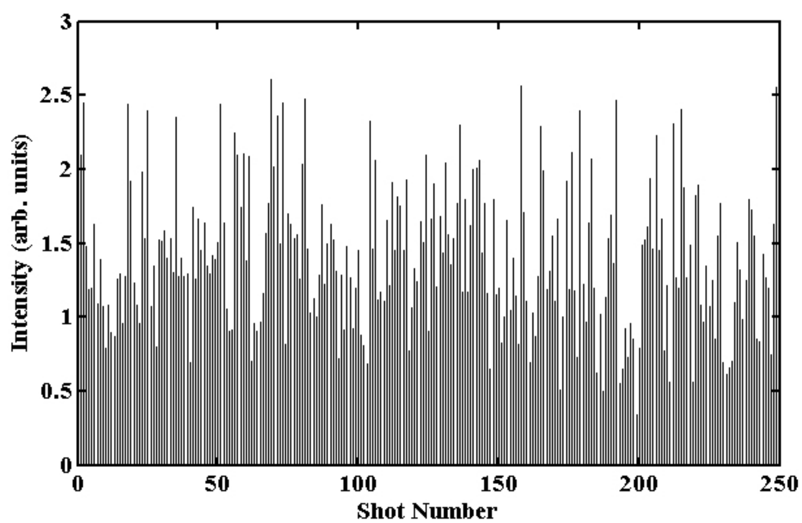

Fig. 5. Shot-to-shot variation of the intensity of the 30.4 nm Ne-like V laser line at 5 Hz repetition rate. The 250 consecutive shots have a distribution characterized by a standard deviation which is 35% of the mean.

For short plasma lengths the laser output intensity is observed to increase exponentially with a small signal gain coefficient of $g = 72\ cm^{-1}$, until saturation is reached. The gain-length product reaches 21.7 for a 4 mm target, which exceeds the gain-length product value of ~ 15 at which most collisionally excited soft x-ray lasers have been observed to reach gain saturation. A similar measurement for the 32.6 nm line of Ne-like Ti yielded a comparable gain-length product, gxl= 18.4. The gain-length product for the 28.6 nm line of Ne-like Cr was not measured, but the laser output intensity was lower than for the other two elements.

Operation at 5 Hz repetition rate was demonstrated for both Ne-like Ti and V moving the targets at a constant velocity of 40 µm per shot. Figure 5 illustrates a series of 250 contiguous laser shots at this repetition rate for the 30.4 nm line of Ne-like V. The 250 consecutive shots have a distribution characterized by a standard deviation which is 35% of the mean. Operation at 5 Hz repetition rate yielded laser pulses with an energy of up to 540 nJ, estimated from the counts on the CCD taking into account the quantum efficiency of the detector and the losses. The average pulse energy was 300 nJ corresponding to an average output power of about 1.5 µW. For the 32.6 nm line of Ne-like Ti the maximum soft x-ray laser pulse energy observed was estimated to be 780 nJ. The average energy for this line was 530 nJ, corresponding to an average output power of about 2.6 µW. This is to our knowledge the first report of laser average powers in excess of 1 microwatt in this region of the spectrum.

4. Conclusions

In summary, microwatt average power laser-pumped Ne-like ion lasers were demonstrated for the first time to our knowledge. This demonstration of saturated high repetition rate table-top lasers in Ne-like Ti and Ne-like V and its possible extension to other isoelectronic lines will significantly increase the diversity of soft x-ray laser wavelengths available for applications requiring high average powers.

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