Highly coherent injection-seeded 13.2 nm tabletop soft x-ray laser

F. Pedaci, Y. Wang, M. Berrill, B. Luther, E. Granados, and J. J. Rocca*

National Science Foundation Engineering Research Center for Extreme Ultraviolet Science and Technology, Colorado State University, Fort Collins, Colorado 80523, USA

**Corresponding author: rocca@engr.colostate.edu*

Received November 26, 2007; accepted December 12, 2007;
posted January 28, 2008 (Doc. ID 90055); published February 27, 2008

We report a dramatic improvement of the spatial coherence and beam divergence (0.66 mrad) of a 13.2 nm wavelength Ni-like Cd tabletop laser by injection seeding the soft x-ray laser amplifier with high-harmonics pulses generated in a Ne gas jet. This phase coherent laser is an attractive light source for at-wavelength interferometry of extreme ultraviolet lithography optics and other applications. © 2008 Optical Society of America

OCIS codes: 140.7240, 340.7480.

There is significant interest in the development of compact coherent sources emitting at wavelengths within the bandwidth of 13.5 nm Mo–Si mirrors for at-wavelength metrology of extreme ultraviolet (EUV) projection lithography optics and other applications [1]. Currently, all the interferometry measurements of EUV lithography optics are conducted at third-generation synchrotron facilities. Very recently, a free electron laser based on a 1 GeV accelerator was demonstrated to operate near this wavelength [2]. Significant efforts are also underway to develop more compact coherent sources within this bandwidth based on high-order harmonics (HH) [3,4] or soft x-ray laser (SXRL) amplifiers [5–8].

Saturated SXRL 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 plasmas heated by a short laser pulse with 3–7 J energy impinging at normal incidence [5,9]. Recently, it was shown that the required short-pulse pump energy can be significantly decreased by directing this pump beam onto the target at a grazing angle [7–10], by taking advantage of refraction to increase the fraction of the pump energy absorbed in the gain region. Saturated operation at 5 Hz repetition rate has been obtained at 13.9 nm in Ni-like Ag and at 13.2 nm in Ni-like Cd by collisional excitation of the transition of these ions in plasmas heated with 1 J pulses of 8 ps duration impinging at a grazing incidence angle of 23° [7,8,11]. However, both these lasers have a relatively large beam divergence of ~10 mrad, and low spatial coherence that limits their potential in applications such as interferometry and coherent imaging. Moreover, the temporal coherence of the plasma- and accelerator-based SXRLs mentioned above is limited by the fact that the amplification starts from spontaneous emission noise.

Injection seeding of soft x-ray plasma amplifiers with HH pulses can produce laser beams of dramatically increased coherence and reduced divergence [12–16]. An early experiment demonstrated the amplification of HH pulses in a Ne-like Ga plasma amplifier pumped by 600 J optical laser pulses, but only by a factor of 3 [12]. More recently, an optical field ionization SXRL amplifier produced by femtosecond optical laser excitation of a Kr gas cell was injection seeded with HH pulses to generate saturated amplification in the 32.8 nm laser line of Ni-like Kr [13]. Our group demonstrated the saturated amplification of HH seed pulses in the 32.6 nm line of Ne-like Ti in a significantly denser transient collisional SXRL plasma amplifier created by heating a Ti target [14]. Seeding of solid target SXRL amplifiers, which due to their significantly larger electron density have an increased saturation intensity and broader laser linewidth, can lead to phase coherent lasers with higher intensities and shorter pulsewidths. We have recently extended these results to shorter wavelengths using Ni-like ions [15]. Injection seeding of the 13.9 nm laser transition of Ni-like Ag with HH pulsed produced in a Ne gas cell produced a highly coherent laser beam.

In this Letter we report the demonstration of a highly coherent 13.2 nm Ni-like Cd laser by saturated amplification of injected HH seed pulses from a Ti:sapphire laser. This transition falls within the bandwidth of the Mo–Si multilayer coatings designed for EUV lithography, which at this wavelength have a reflectivity of ~50%. The experiments were conducted generating the 59th harmonic of Ti:sapphire in a Ne gas jet and injecting the HH pulses into a grazing incidence pumped Ni-like Cd SXRL plasma amplifier. The gas jet was observed to produce a significantly stronger HH output than Ne gas cells of various lengths tested under optimized pressure conditions. A single chirped-pulse-amplification Ti:sapphire laser system operating at a center wavelength of 780 nm was used for both generating the HH seed pulses and pumping the SXRL amplifier. Separate grating pulse compressors were used to produce the ~50 fs and 6.8 ps duration laser pulses used to drive the HH and SXRL amplifiers, respectively. The SXRL amplifier consisted of a polished Cd slab target up to 3.5 mm in length irradiated with a sequence of Ti:sapphire laser pulses, as described in [8]. A transient population inversion was created by a 0.85 J pulse impinging at a grazing inci-

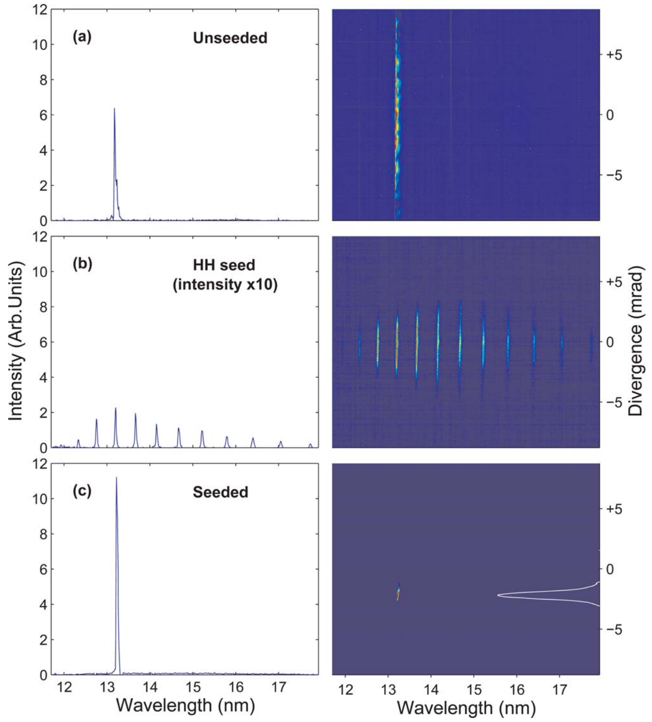

Fig. 1. (Color online) Spectra of (a) unseeded 13.2 nm Ni-like Cd laser, (b) HH seed pulse, and (c) seeded laser. The Cd plasma amplifier was pumped by a 0.85 J short pulse configured into a 3.5 mm FWHM long line focus.

dence angle of 23° that was selected to couple the pump beam into the region where the plasma density is 2.8×10^{20} cm^{-3}. The prepulses were focused into a 30 μm wide, 3.5 mm FWHM line. The HH pulses were generated focusing 20 mJ, ~50 fs duration, Ti:sapphire laser pulses into a Ne gas jet using a $f = 1.5$ m lens. The gas jet was produced using a stainless steel nozzle 7.6 mm in length and 0.6 mm in width, backed with 2×10^5 Pa of Ne. The HH beam was relay imaged onto the input of the Ni-like Cd amplifier using a Au-coated toroidal mirror placed at a grazing incidence angle of 10°. The 59th harmonic was made to overlap with the 13.2 nm Ni-like Cd laser line by tuning a thin etalon introduced in the first of the three multipass amplifiers of the Ti:sapphire laser system. Two BK7 windows positioned at 9° grazing incidence were used to protect the filters and detector from the Ti:sapphire laser beam. Two Zr filters 0.2 and 0.3 μm thick were used to attenuate both the remaining 780 nm HH driver beam and the plasma light. The output of the soft x-ray amplifier was dispersed with a 1200 lines/mm variable space diffraction grating and recorded by a back-illuminated CCD detector.

The spectra in Fig. 1 illustrate the dramatic decrease in the beam divergence achieved by seeding a 3.5 mm long Ni-like Cd amplifier. The top spectra [Fig. 1(a)] show the output of the unseeded Cd SXRL amplifier, which has a divergence of ~10 mrad in the direction parallel to the target. Figure 1(b) shows the HH spectra, in which the 59th harmonic has a divergence of ~3 mrad. Figure 1(c) shows that the intense amplified output of the seeded 13.2 nm amplifier has a FWHM beam divergence of 0.66 ± 0.10 mrad, considerably smaller than both the unseeded laser and the HH seed. The result demonstrates that the solid target laser amplifier column acts as a spatial filter that significantly improves the divergence of the seed pulse [16], showing that to produce a very narrow divergence-seeded SXRL beam it is not necessary to use a very-well-collimated HH seed.

Figure 2 illustrates the amplification of the seed pulse as a function of the Cd plasma amplifier length. The data were obtained by irradiating target segments of the different lengths shown. Each point is an average of about ten shots. The observed slow initial increase of the intensity is dominantly determined by the initial mismatch between the bandwidth of the seed pulse (~0.03 nm) and that of the much narrower laser line ($\Delta\lambda/\lambda < 10^{-4}$, not resolved by the spectrograph) that results in the amplification of only a small fraction of the seed pulse energy. After ~1.5 mm through the amplifier, the linewidth of the amplified seed has narrowed to nearly match that of the laser light, which determines the onset of a quasi-exponential amplification phase. This phase lasts until the fluence of the amplified seed pulse exceeds the saturation fluence of the 13.2 nm Ni-like Cd line, computed to be ~2.5 mJ cm^{-2}, slightly above 2.5 mm within the amplifier. The energy of the amplified seed pulses reaches ~20 nJ, corresponding to an amplification of the HH seed energy within 0.66 mrad of ~200 times. This energy output could be increased by increasing the laser pump energy, which would increase the amplifier gain or volume, or the use of a stronger HH seed pulse that would more rapidly saturate the amplifier. Due to the short duration of the gain, saturated amplification of the seed pulses requires precise synchronization between the SXRL amplifier pump pulse and the HH seed pulse. Figure 3 shows that strong amplification takes place in a ~1.5 ps interval, centered at a delay of ~1.5 ps between the peak of the short pump pulse and the seed pulse.

Injection seeding is observed to also dramatically improve the spatial coherence of the laser beam. A Young's interference experiment was conducted placing pairs of 5 μm wide slits with separations ranging

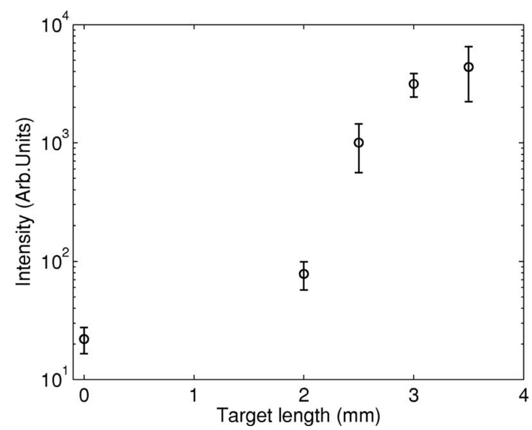

Fig. 2. Variation of the intensity of the 13.2 nm amplified seed pulse as a function of the Ni-like Cd amplifier plasma column length.

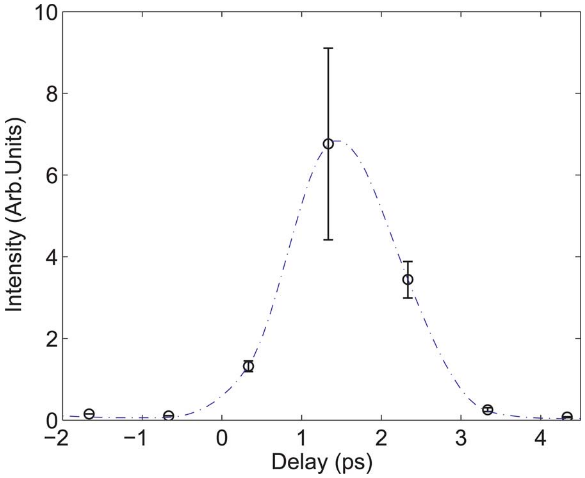

Fig. 3. Intensity of the amplified seed pulse as a function of time delay between the peaks of the short pump pulse and the seed pulse at the target position.

from 30 to 100 μm on the beam axis at a distance of 10 cm from the exit of the amplifier. The resulting interferograms were spectrally filtered by a diffraction grating and were recorded in a CCD. The fringe visibility is proportional to the modulus of the normalized complex degree of coherence, $|\boldsymbol{\mu}_{12}|$. The unseeded SXRL has very limited coherence: At 10 cm from the amplifier, where the unseeded beam is ~1 mm diameter, the 50 μm slits pair produces interferograms that do not reach the 61% visibility used here to characterize the spatial coherence length. This indicates that less than 1% of the unseeded beam energy is fully spatially coherent. In contrast, Fig. 4 shows that the coherence length of the seeded beam is ~70 μm, a value that approaches the beam diameter of 80–90 μm at that location. This, in combination with the very high temporal coherence that originates from the amplification of HH seed pulses in the very narrow bandwidth of the soft x-ray plasma amplifier, results in a beam with a uniquely high degree of phase coherence.

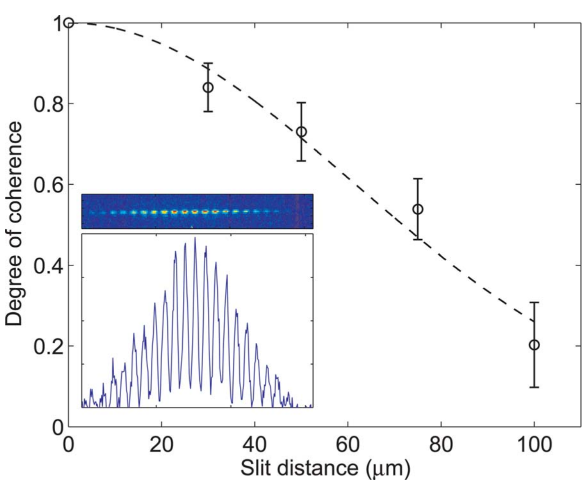

Fig. 4. (Color online) Degree of coherence $|\boldsymbol{\mu}_{12}|$ of the seeded laser beam as a function of slit separation. The slits were placed at 10 cm from the exit of the amplifier. The inset shows a single shot interferogram and corresponding lineout for the 30 μm slit pair.

In summary, we have demonstrated for the first time to our knowledge a phase coherent tabletop laser operating within the bandwidth of lithography Mo–Si multilayer mirrors by injection seeding of the soft x-ray amplifier with HH pulses. This highly coherent, low divergence, tabletop laser is of interest for numerous applications.

We gratefully acknowledge the contribution of Miguel Larotonda and David Alessi. This work was supported by the National Science Foundation Engineering Center for Extreme Ultraviolet Science and Technology.

References

1. D. T. Attwood, *Soft X-Rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge U. Press, 1999).
2. W. Ackermann *et al.*, Nat. Photonics **1**, 336 (2007).
3. X. Zhang, A. R. Libertun, A. Paul, E. Gagnon, S. Backus, I. P. Christov, M. M. Murnane, H. C. Kapteyn, R. A. Bartels, Y. Liu, and D. T. Attwood, Opt. Lett. **29**, 1357 (2004).
4. Y. Nagata, K. Furusawa, Y. Nabekawa, and K. Midorikawa, Opt. Lett. **32**, 722 (2007).
5. J. Dunn, Y. Li, A. L. Osterheld, J. Nilsen, J. R. Hunter, and V. N. Shlyaptsev, Phys. Rev. Lett. **84**, 4834 (2000).
6. A. Goltsov, A. Morozov, S. Suckewer, R. Elton, U. Feldman, K. Krushelnick, T. Jones, C. Moore, J. Seely, P. Sprangle, A. Ting, and A. Zigler, IEEE J. Sel. Top. Quantum Electron. **5**, 1453 (1999).
7. Y. Wang, M. A. Larotonda, B. M. Luther, D. Alessi, M. Berrill, V. N. Shlyaptsev, and J. J. Rocca, Phys. Rev. A **72**, 053807 (2005).
8. J. J. Rocca, Y. Wang, M. A. Larotonda, B. M. Luther, M. Berrill, and D. Alessi, Opt. Lett. **30**, 2581 (2005).
9. K. A. Janulewicz, A. Lucianetti, G. Priebe, W. Sandner, and P. V. Nickles, Phys. Rev. A **68**, 051802 (2003).
10. R. Keenan, J. Dunn, P. K. Patel, D. F. Price, R. F. Smith, and V. N. Shlyaptsev, Phys. Rev. Lett. **94**, 103901 (2005).
11. B. M. Luther, Y. Wang, M. A. Larotonda, D. Alessi, M. Berrill, M. C. Marconi, J. J. Rocca, and V. Shlyaptsev, Opt. Lett. **30**, 165 (2005).
12. T. Ditmire, M. H. R. Hutchinson, M. H. Key, C. L. S. Lewis, A. MacPhee, I. Mercer, D. Neely, M. D. Perry, R. A. Smith, J. S. Wark, and M. Zepf, Phys. Rev. A **51**, R4337 (1995).
13. Ph. Zeitoun, G. Faivre, S. Sebban, T. Mocek, A. Hallou, M. Fajardo, D. Aubert, Ph. Balcou, F. Burgy, D. Douillet, S. Kazamias, G. de Lachèze-Murel, T. Lefrou, S. le Pape, P. Mercère, H. Merdji, A. S. Morlens, J. P. Rousseau, and C. Valentin, Nature **431**, 426 (2004).
14. Y. Wang, E. Granados, M. A. Larotonda, M. Berrill, B. M. Luther, D. Patel, C. S. Menoni, and J. J. Rocca, Phys. Rev. Lett. **97**, 123901 (2006).
15. Y. Wang, E. Granados, F. Pedaci, D. Alessi, B. Luther, M. Berrill, and J. J. Rocca, Nat. Photonics **2**, 94 (2008).
16. J. Ph. Goddet, S. Sebban, A. S. Morlens, J. Montiers, J. Ph. Rousseau, F. Burgy, Ph. Zeitoun, C. Valentine, C. Hauri, G. Maynard, A. Boudaa, J. P. Caumes, H. Merdji, T. Mocek, M. Kozlova, and J. Jakubczak, Opt. Lett. **32**, 1498 (2007).
17. P. B. Mirkarimi, S. Bajt, and M. A. Wall, Appl. Opt. **39**, 1617 (2000).