Demonstration of a 10-μJ tabletop laser at 52.9 nm in neonlike chlorine

M. Frati, M. Seminario, and J. J. Rocca

Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado 80523

Received March 30, 2000

We report the demonstration of laser amplification at 52.9 nm in Ne-like Cl with a compact capillary discharge. Laser output pulses with energies of as much as 10 μJ have been obtained. The beam divergence was approximately 4 mrad. This new 23.4-eV tabletop laser is of particular interest for applications that require high peak fluxes of photons with energy slightly below the He photoionization threshold. © 2000 Optical Society of America

OCIS codes: 140.7240, 140.3210.

There is much interest in the demonstration of practical extreme-ultraviolet and soft-x-ray lasers for applications. Several schemes for the excitation of tabletop short-wavelength lasers, based on excitation by optical lasers or fast capillary discharges, are currently under investigation.[1–12] Whereas gain has been demonstrated in a large number of transitions, to date only a few compact short-wavelength lasers have been reported to produce laser pulse energies greater than 1 μJ. These lasers include a capillary discharge–pumped 46.9-nm Ne-like Ar laser that has produced average output pulse energies of 0.88 mJ at a 4-Hz repetition rate[11] and laser-pumped transient inversion lasers in Ni-like Pd at 14.7 nm and Ni-like Mo at 18.9 nm, which have produced output pulse energies of approximately 10 μJ and 2–5 μJ, respectively, at repetition rates of one shot every 4 min.[8] There is significant interest in extending the availability of practical tabletop short-wavelength lasers to other wavelengths. In particular, applications in photochemistry and photophysics can significantly benefit from laser sources of high-energy photons that are capable of single-photon ionization of any neutral species but fall short of the 24.6 eV that corresponds to the He photoionization threshold. These applications include the study of nanoclusters created by optical laser ablation, a technique that uses He as a carrier gas.[13]

In this Letter we report the generation of laser pulses at 52.9 nm (23.4 eV) in the $3p\,^1S_0$–$3s\,^1P_1$ transition of Ne-like Cl with a compact tabletop capillary discharge. Laser amplification of this line was previously observed by Li *et al.* in a plasma generated by excitation of a solid KCl target with 450 ± 20 J laser pulses of 0.45-ns duration produced by the powerful Asterix iodine laser facility at a rate of several shots per hour.[14] In that experiment the amplification obtained in a 3-cm-long plasma (gain × length ~ 7.5) was far below that required for gain saturation, limiting the laser pulse output energy to relatively low values. In the 18.2-cm-long discharge-pumped plasma column used in the experiments reported herein the amplified spontaneous emission intensity reached values of the order of the saturation intensity, allowing for the generation of a significantly greater laser output pulse energy. Laser pulses with energies of as much as 10 μJ were measured with the discharge operating at rates of 0.5–1 Hz. Moreover, the results were obtained with a compact tabletop device of a size comparable with those of some of the most widely used visible and ultraviolet gas lasers.

We generated the gain medium, consisting of an 18.2-cm-long plasma column, by rapidly exciting a 3.2-mm inside-diameter aluminum oxide capillary channel filled with preionized Cl gas with a fast current pulse. Amplification was observed at Cl_2 pressures ranging from 180 to 300 mTorr. The plasma columns were excited by current pulses of approximately 23-kA peak amplitude with 10–90% rise times of approximately 25 ns and first half-cycle duration of 110 ns. In this discharge, the fast current pulse rapidly compresses the plasma, creating a small-diameter column[1,5] in which monopole collisional electron excitation of Ne-like Cl ions creates a large population inversion between the $3p\,^1S_0$ and $3s\,^1P_1$ levels, resulting in strong amplification at 52.9 nm. The capillary discharge setup utilized in the experiment is similar to that previously used to generate lasing in Ne-like Ar at high repetition rates.[10] The current pulse was produced by discharge of a water dielectric capacitor through a spark-gap switch pressurized with SF_6. The water capacitor was pulse charged by a compact four-stage Marx generator. Cl_2 was continuously admitted into the capillary channel through chemically compatible Teflon tubing and stainless-steel fittings. The gas was pumped with a rotary vane pump containing perfluoropolyether oil and turbomolecular pumps purged with N_2.

A spectral diagnostic was implemented with a 1-m focal-length normal-incidence spectrograph containing a 600-lines/mm diffraction grating. The detector consisted of two microchannel plates (MCP's) in a chevron configuration, a phosphorus screen, and a CCD detector array. The front MCP was coated with magnesium oxide to enhance the photoelectron response. Because of the corrosive nature of Cl, which can rapidly deteriorate the MCP's, special care was taken to avoid diffusion of this gas into the spectrometer. For this

0146-9592/00/141022-03$15.00/0

purpose a 140-nm-thick Al–Si filter was used to separate the laser from the detection system. Figure 1 shows spectra of the axial emission of the discharge, covering a 40-nm region in the vicinity of the $J = 0–1$ laser line of Ne-like Cl. The spectrum obtained at a pressure of 120 mTorr [Fig. 1(a)] shows line emission at the 52.9-nm wavelength of the laser transition. However, at this pressure the intensity of this line is weak, smaller than that of several neighboring transitions of Cl VI and Cl VII, which cannot be inverted. A dramatic change in the spectrum is observed when the pressure is adjusted to 224 mTorr, the optimum pressure for lasing [Fig. 1(b)]. At this pressure the laser line is more than 2 orders of magnitude more intense and completely dominates the entire 40-nm wide spectrum. This is clear evidence of large amplification in the 52.9-nm line.

The most common way to characterize the performance of extreme-ultraviolet and soft-x-ray lasers is the measurement of the gain of the integrated laser line intensity as a function of plasma column length. However, because in our case the laser output intensity was observed to be high, we could afford to measure the laser output energy directly, which is of greater practical interest for applications. The energy and temporal evolution of the laser output pulse were monitored with a vacuum photodiode placed at a distance of 90 cm from the exit of the laser. The data were recorded and stored by a 2-gigasample/s digitizing oscilloscope with 500-MHz analog bandwidth. The efficiency of the Al photocathode had previously been calibrated with respect to a Si photodiode of know quantum efficiency.[5] To avoid saturation of the photodiode, we attenuated the laser output with a stainless-steel mesh of measured tranmissivity. Figure 2 shows a laser pulse with an energy of 10 μJ operating the system at a repetition frequency of 0.5 Hz. For an accurate measurement of the laser pulse width we used a fast vacuum photodiode and a 1-GHz-bandwidth analog oscilloscope. We obtained the laser pulse width by correcting the measured signal for the response of the detection system. The measurement of multiple shots yielded an average laser FWHM pulse of 1.46 ± 0.25 ns. The corresponding peak power was $\sim$7 kW. However, the shot-to-shot variation in the laser pulse energy was significantly larger than those measured when the laser was operated at 46.9 nm with Ar.[10,11] The laser output pulse energy was observed to be significantly deteriorated at repetition rates greater than 1 Hz, probably because of insufficient gas renewal in the capillary channel, in which the reactive nature of excited Cl_2 gas leads to the buildup of contaminants.

We also obtained a direct measurement of the beam divergence by recording the far-field pattern of the laser beam. The laser beam profiles were recorded by a detector composed of a MCP, a phosphorous screen, and a CCD, placed at 97 cm from the end of the capillary. The MCP was gated for $\sim$5 ns to minimize the background signal that resulted from the long-lasting spontaneous emission radiated by hundreds of spectral lines excited by the discharge. The laser beam was attenuated by the Al–Si filter that was again used to protect the MCP from Cl_2 gas. Figure 3 illustrates the far-field beam profile measured at optimum discharge conditions. The beam was observed to exhibit maximum intensity on axis and had a FWHM divergence of approximately 4 mrad.

In summary, we have demonstrated and characterized the generation of 10-μJ laser pulses at 52.9 nm by using a compact capillary discharge that can be operated repetitively, extending the range of tabletop extreme-ultraviolet lasers. This new 23.4-eV tabletop

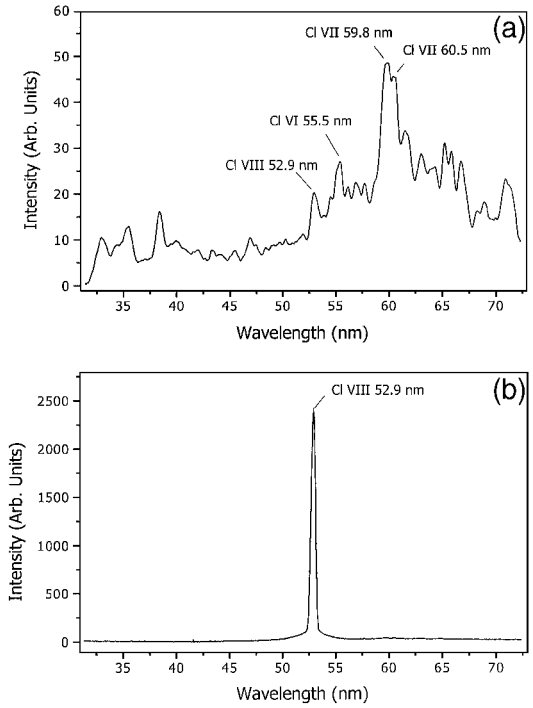

Fig. 1. On-axis emission spectra of the Cl capillary discharge plasma in the region from 30 to 70 nm: spectra corresponding to (a) a 120-mTorr discharge and (b) a 224-mTorr discharge. In (b) the dominance of the 59.2-nm Ne-like Cl transition is a clear indication of strong amplification.

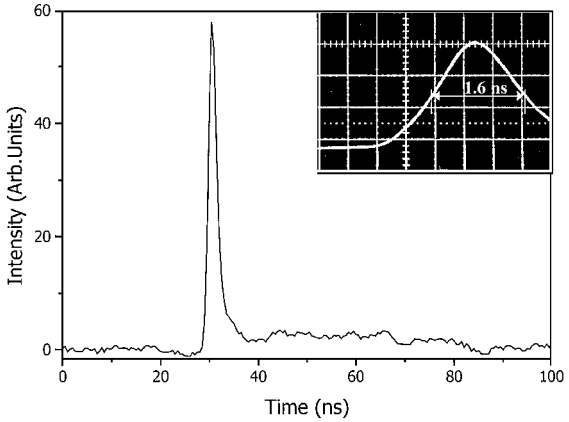

Fig. 2. Temporal evolution of the laser output pulse. Inset, the signal recorded with a fast vacuum photodiode and a 1-GHz-bandwidth analog oscilloscope. The signal corrected for the limited bandwidth of the detection system yields a laser FWHM pulse width of 1.46 ns.

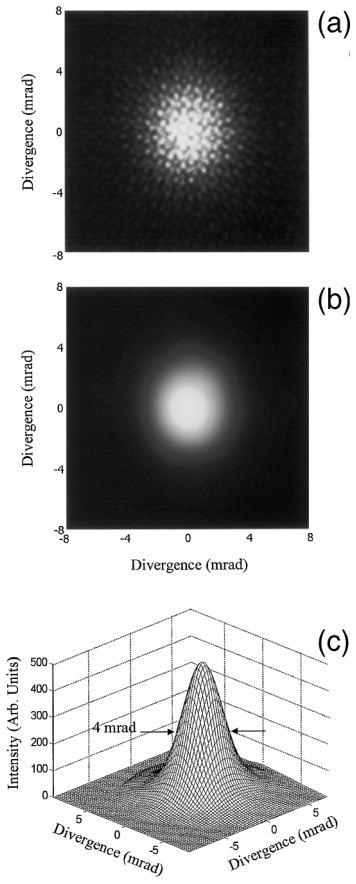

Fig. 3. Image of the laser beam recorded at a distance of 97 cm from the end of the capillary. (a) Recorded image. The structure observed in the picture is due to the mesh that was used to sustain the Al–Si filter. (b) The same image after digital filtering. (c) Intensity distribution of the filtered image.

laser is of particular interest as a high-energy photon source for photochemistry and photophysics studies in which He is used as a carrier or buffer gas.

This research was supported by the National Science Foundation. We thank Elliot Bernstein for numerous discussions of the potential contributions of repetitive ultrashort-wavelength lasers to the study of nanoclusters. We also acknowledge the experimental contribution of Brady Benware and discussions with V. N. Shlyaptsev. J. J. Rocca's e-mail address is rocca@engr.colostate.edu.

References

1. J. J. Rocca, V. N. Shlyaptsev, F. G. Tomasel, O. D. Cortazar, D. Hartshorn, and J. L. A. Chilla, Phys. Rev. Lett. **73,** 2192 (1994).
2. B. E. Lemoff, G. Y. Yin, C. L. Gordon III, C. P. J. Barty, and S. E. Harris, Phys. Rev. Lett. **74,** 1576 (1995).
3. D. Korobkin, C. H. Nam, S. Suckewer, and A. Golstov, Phys. Rev. Lett. **77,** 5206 (1996).
4. F. G. Tomasel, J. J. Rocca, V. N. Shlyaptsev, and C. D. Macchietto, Phys. Rev. E **55,** 1437 (1996).
5. J. J. Rocca, D. P. Clark, J. L. A. Chilla, and V. N. Shlyaptsev, Phys. Rev. Lett. **77,** 1476 (1996).
6. P. V. Nickles, V. N. Shlyaptsev, M. Kalashnikov, M. Schnurer, I. Will, and W. Sandner, Phys. Rev. Lett. **78,** 2748 (1997).
7. J. Dunn, A. L. Osterheld, S. Sheperd, W. E. White, V. N. Shlyaptsev, and R. E. Stewards, Phys. Rev. Lett. **80,** 2825 (1998).
8. J. Dunn, Y. Li, A. L. Osterheld, J. Nilsen, S. J. Moon, K. B. Fournier, J. R. Hunter, A. Ya. Faenov, T. A. Pikuz, and V. N. Shlyaptsev, Proc. SPIE **3776,** 2 (1999).
9. D. Korobkin, A. Goltsov, A. Morozov, and S. Suckewer, Phys. Rev. Lett. **77,** 1476 (1998).
10. B. R. Benware, C. D. Macchietto, C. H. Moreno, and J. J. Rocca, Phys. Rev. Lett. **81,** 5804 (1998).
11. C. D. Macchietto, B. R. Benware, and J. J. Rocca, Opt. Lett. **24,** 1115 (1999).
12. R. Tommasini, F. Lowenthal, and F. E. Balmer, Phys. Rev. A **59,** 1577 (1999).
13. M. Foltin, J. G. Stuber, and E. R. Bernstein, J. Chem. Phys. III, 9577 (1999).
14. Y. Li, G. Pretzler, and E. E. Fill, Phys. Rev. A **52,** R3433 (1995).