Soft X-Ray Lasing in Neonlike Germanium and Copper Plasmas

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(Received 27 March 1987; revised manuscript received 22 June 1987)

Soft x-ray $3p \rightarrow 3s$ lasing in neonlike germanium (Ge^{22+}) and copper (Cu^{19+}) in the wavelength interval of 195 to 285 Å is observed for the first time, with gain coefficients ranging from 1.7 to 4.1 cm^{-1}, the higher gain with germanium. The lasing plasmas are produced by the focusing of a driving laser beam ($\lambda = 1.05$ μm, 2-ns FWHM) into an 18-mm-long line onto thin films and slab targets. The measured $J=0$ to 1 gain coefficients are comparable to those of the $J=2$ to 1 transitions. The measured wavelengths of the six lasing lines compare favorably with recent calculations.

PACS numbers: 42.60.By, 32.30.Rj, 32.70.Fw, 52.50.Jm

Significant $3p \rightarrow 3s$ amplification of soft x rays in neonlike selenium with a gain coefficient of $\simeq 5$ cm^{-1} was recently demonstrated[1] in experiments at the Lawrence Livermore National Laboratory (LLNL) using laser-vaporized ultrathin foils.[2] As successful as these initial experiments were, certain puzzling aspects arose from the data analyses[1-3] that deserve further investigation. There was surprisingly low emission on the transition originating on the $2p^5_{1/2}3p_{1/2}$ $J=0$ level (for molybdenum as well as selenium). The gain for this transition is predicted to be $\simeq 1-2$ times larger than that for the $2p^5_{1/2}3p_{3/2}$ and $2p^5_{3/2}3p_{3/2}$ $J=2$ levels.[3,4] In fact, it was first undetected[1] and later found[3] to have a factor-of-5 lower gain coefficient (<1 cm^{-1}). An understanding of this anomaly could be important. It is also worth investigating target designs other than thin foils in order to understand more fully the hydrodynamic conditions[2,5] for optimum laser output. Finally, high-precision wavelength measurements for the lasing lines are needed for comparison with theoretical predictions and atomic physics models.

The present experimental investigation using time-integrated diagnostics addresses these issues, in elements of lower Z (Ge and Cu) than those used at LLNL. These elements are compatible[4] with our lower-power driving laser. To our knowledge, the successful results reported here represent the first measurements of gain in Ge and Cu in the extreme-ultraviolet spectral region, and, furthermore, the first demonstration of gain for neonlike ions with use of slab targets (rather than thin exploding films). In addition, we report here the first evidence of gain on a transition from a $J=0$ level being comparable to that from a $J=2$ level, in reasonable agreement with calculations.[3]

The experimental setup is described as follows, with further details given by Elton and co-workers.[6] A single beam of the Pharos III Nd-doped glass laser was operated at 1.05-μm wavelength over an energy range of 350–480 J in a 2-ns-FWHM pulse. A 200-μm-wide, 18-mm-long line focus was produced with use of a combination cylindrical-spherical lens system. This gave a target irradiance of about 6×10^{12} W/cm^2. The length of the target was always less than that of the line focus by at least 2 mm at the viewing end. The germanium targets were all slabs about 3 mm thick. Most Cu targets consisted of a Formvar ($C_{11}H_{18}O_5$) substrate of 1200 Å nominal thickness, with a copper overcoating of 1000 Å; the driving laser irradiated the copper side. Thicker (1.3 μm) copper foils as well as 3.2-mm-thick copper slab targets also were tested successfully.

The extreme-ultraviolet data (time integrated) in the 40–580-Å region were recorded on Kodak type-101 film with a 1-m grazing-incidence spectrograph, which was positioned to view the plasma axially. With a 5-μm entrance slit, the instrumental spectral resolution was $\simeq 0.04$ Å, which is comparable to the expected Doppler width of optically thin lines. A 1200-Å-thick aluminum filter was used to reject most higher-order radiation with wavelengths extending from approximately 70 Å to the 170-Å L edge. The spectrograph entrance slit was positioned close (4 cm from the center of the line focus) to the plasma and was oriented parallel to the driving laser beam, in order to collect refracted radiation[3,7] in the corresponding plane. The spectrograph thus accepted radiation refracted through an angle as large as ±9 mrad, and also viewed plasma extending as far as 3 mm from the target in the direction of the incoming driver laser beam. In addition, a bent-mica-crystal x-ray spectrograph set to view the plasma transversely was used to monitor resonance lines in the 6–17-Å spectral region from various ions. An x-ray pinhole camera, filtered to detect x rays of energy 1 keV, photographed the hot plasma in both the axial and the transverse directions. According to the x-ray pinhole photographs[6] taken in the transverse direction, the plasmas created were of good uniformity.

Amplified spontaneous emission was recorded for the three $3p \rightarrow 3s$ Ge XXIII lines (from neonlike Ge^{22+} ions) as indicated in Fig. 1, where the spectra for 4- and 15-mm target lengths are shown. A rapid increase in intensity with length is very apparent. Two of these originate on transitions from the $J=2$ levels and one from the

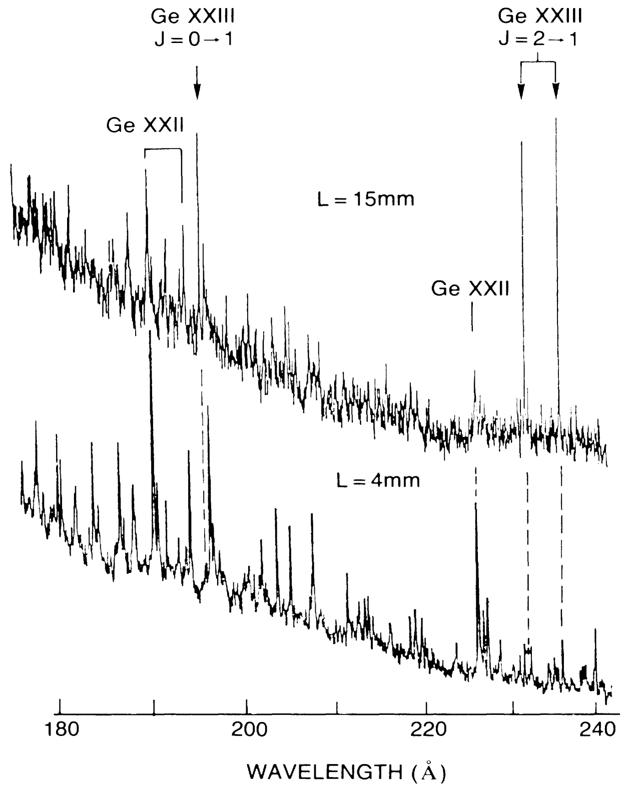

FIG. 1. Microdensitometer traces of second-order spectra obtained for plasma lengths of 4 and 15 mm, showing the neonlike Ge XXIII (Ge^{22+} ion) lasing lines at 236.26 and 232.24 Å ($J=2$ to 1) and 196.06 Å ($J=0$ to 1) increasing with length. Sodiumlike Ge XXII lines shown arise from 3 → 3 transitions.

$J=0$ level with line emissions at 236.26, 232.24, and 196.06 Å (±0.04 Å), respectively (see Table I). Unfortunately, the line at 236.26 Å is a blend with another spectral line and we did not determine the gain for this line. The other two lines are relatively free of overlapping lines.

Relative line intensities were derived from photographic densities with a density versus exposure curve, obtained with multiple exposures, and similar to that of Henke *et al.*[11] Exponentiation of the resulting intensities of the Ge lines with increasing target length is shown in Fig. 2(a) for the $J=2$ to 1 line. The solid line in this figure represents a best fit of the gain scaling relation[12] $[\exp(\alpha L)-1]^{3/2}/[\alpha L\exp(\alpha L)]^{1/2}$ for amplified spontaneous emission through a plasma of length L, with a gain coefficient at line center of $\alpha=4.1\pm0.3$ cm^{-1}. Similar data for the Ge XXIII $J=0$ to 1 line are plotted in Fig. 2(b), where a best fit is obtained with a gain coefficient at line center of $\alpha=3.1\pm0.3$ cm^{-1}. For the multiple-shot data obtained at each length, the shot-to-shot variations shown are more significant than relative-intensity uncertainties (approximately ±10%).

Amplification was also recorded for the three $3p\rightarrow3s$ Cu XX lines (from neonlike Cu^{19+} ions), as indicated in Fig. 3, with wavelengths (±0.04 Å) for $J=2$ to 1 transitions of 284.67 and 279.31 Å, and for $J=0$ to 1 transitions of 221.11 Å (see Table I). The 284.67-Å lasing line nearly coincides with the longer-wavelength component of the sixth order of the $4f\rightarrow3d$ Cu XIX doublet in sodiumlike Cu^{18+} ions at 47.442 Å.[13] The net contribution due to the lasing line can be determined by our subtracting the intensity of the nonoverlapping doublet component, because both lines of the doublet are about equal in intensity when there is negligible amplification of the neonlike Cu^{19+} ion lines (see the $L=6$-mm trace of Fig. 3). The resulting intensities of the two $J=2$ to 1 Cu XX lines were found to be approximately equal at all plasma lengths (as for Ge XXIII in Fig. 1). Likewise, the overall intensity of the $J=0$ to 1 Cu XX line was found to be comparable to that of the $J=2$ to 1 lines, as shown in Fig. 3. Exponentiations of the Cu XX line intensities are shown in Fig. 4, where a best-fit theoretical curve indicates gain coefficients of 1.7 ± 0.2 cm^{-1} for the two $J=2$ to 1 lines [Fig. 4(a)] and 2.0 ± 0.2 cm^{-1} for the $J=0$ to 1 line [Fig. 4(b)].

It is intriguing that comparable gain was obtained by

TABLE I. Predicted (Refs. 8–10) and measured wavelengths.

Transitions	Predicted values (Å) Ref. 8	Ref. 9	Ref. 10	Measured values (±0.04 Å) (Å)
		Cu XX		
$(2p^5_{1/2}3p_{1/2})_0\rightarrow(2p^5_{1/2}3s_{1/2})_1$	221.38	220.68		221.11
$(2p^5_{3/2}3p_{3/2})_2\rightarrow(2p^5_{3/2}3s_{1/2})_1$	279.22	279.37		279.31
$(2p^5_{1/2}3p_{3/2})_2\rightarrow(2p^5_{1/2}3s_{1/2})_1$	284.59	284.70	284.97	284.67
		Ge XXIII		
$(2p^5_{1/2}3p_{1/2})_0\rightarrow(2p^5_{1/2}3s_{1/2})_1$	196.38	195.44		196.06
$(2p^5_{3/2}3p_{3/2})_2\rightarrow(2p^5_{3/2}3s_{1/2})_1$	232.24	232.28		232.24
$(2p^5_{1/2}3p_{3/2})_2\rightarrow(2p^5_{1/2}3s_{1/2})_1$	236.27	236.27		236.26

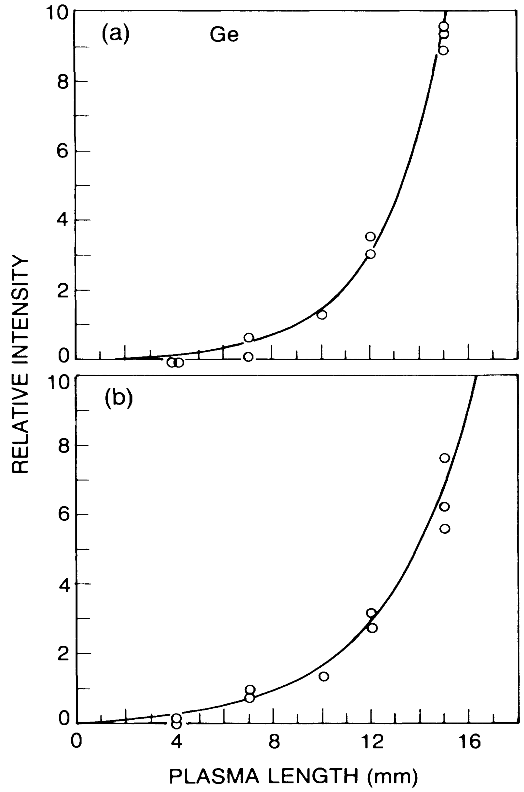

FIG. 2. Relative intensities vs plasma length for (a) 232.24 Å ($J=2$ to 1) and (b) 196.06 Å ($J=0$ to 1) lasing lines, along with calculated gain curves for gain coefficients of 4.1 and 3.1 cm^{-1}, respectively. Estimated uncertainties of ± 10% in relative intensities are within the shot-to-shot spread.

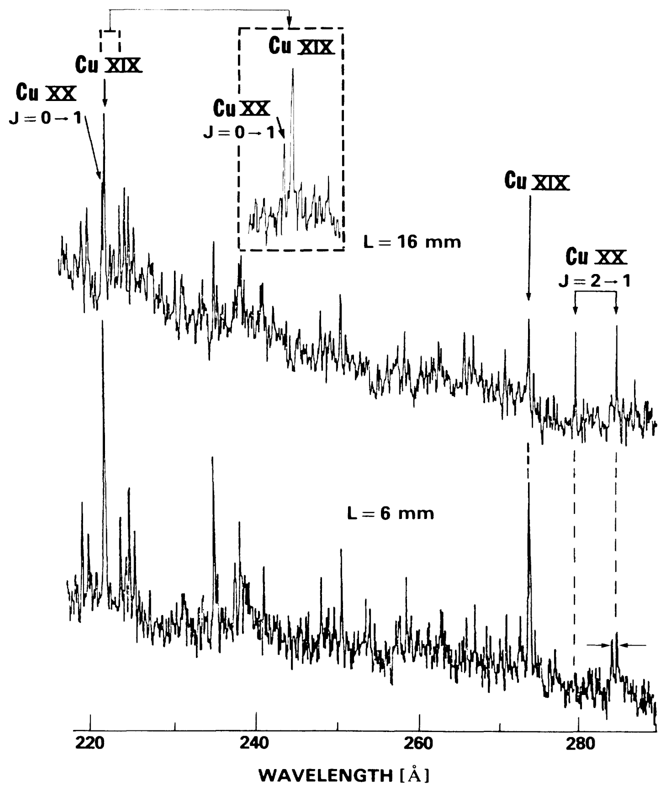

FIG. 3. Microdensitometer traces of first-order spectra obtained for plasma lengths of 6 and 16 mm, showing the neonlike Cu XX (Cu^{19+} ion) lasing lines at 279.31 and 284.67 Å ($J=2$ to 1) and 221.11 Å ($J=0$ to 1) increasing with length. The second order of the 221.11 Å ($J=0$ to 1) and the sodiumlike Cu XIX 221.37-Å lines are inserted on the expanded scale. Thin-film Cu-Formvar targets are used. The lines labeled as Cu XIX arise from 3 → 3 transitions. The doublet (marked by two horizontal arrows) which appears near 284 Å for the $L=6$-mm case arises from the sixth-order $4f \to 3d$ line of Cu XIX.

the irradiation of thin and thick (1.3 μm) copper foils of various lengths, and that thick-slab germanium targets gave such a high gain. Also, 3.2-mm-thick solid copper slab targets produced the three gain lines. Such thick targets have been avoided previously because it was thought that nonuniformities and radial gradients in density and temperature could inhibit lasing.

The energy emitted in the Ge and Cu lasing lines was derived from the spectrographic data with use of a film calibration by Henke *et al.*[11] The magnitudes of the output from both ends of the 15-mm Ge and 16-mm Cu lasing plasmas were estimated to be ≃3 and 1 μJ, respectively. This is assumed to be emitted over a solid angle of $\simeq 10^{-4}$ sr, as defined by the source geometry. These energies correspond to a LLNL value for similar target lengths.[1] The data plotted in Figs. 2 and 4 represent 90% of the shots taken, indicating good reproducibility. It is important to note that no lines in the covered spectral region other than those from neonlike ions increase nonlinearly with length.

In addition to the three lasing lines, the end-on extreme-ultraviolet spectra showed resonance lines from the sodiumlike Cu^{18+} and Ge^{21+} ions (see Figs. 1 and 3), including the 3 → 3 transition lines in the 220–304-Å region for Cu and 190–240-Å region for Ge, which served as reference wavelengths.[13] All of these lines were predicted to be highly optically thick, as evidenced by measured widths much greater than the Doppler width. Surprisingly, their intensities were found to be particularly weak for longer target lengths (see Figs. 1 and 3). This remains a problem for further investigation. According to the x-ray crystal-spectrograph data, plasma conditions are the same on most shots. On all shots, such time-integrated data showed relatively strong resonance-line emission from fluorinelike Cu^{20+} and somewhat weaker oxygenlike Cu^{21+} ions, in addition to the intense emission from the neonlike Cu^{19+} lasing ions. Essentially, similar spectral features are observed for germanium, except for somewhat fluorinelike Ge^{23+} and very weak oxygenlike Ge^{24+} ion lines for similar irradiances, as expected. These data indicate a peak electron

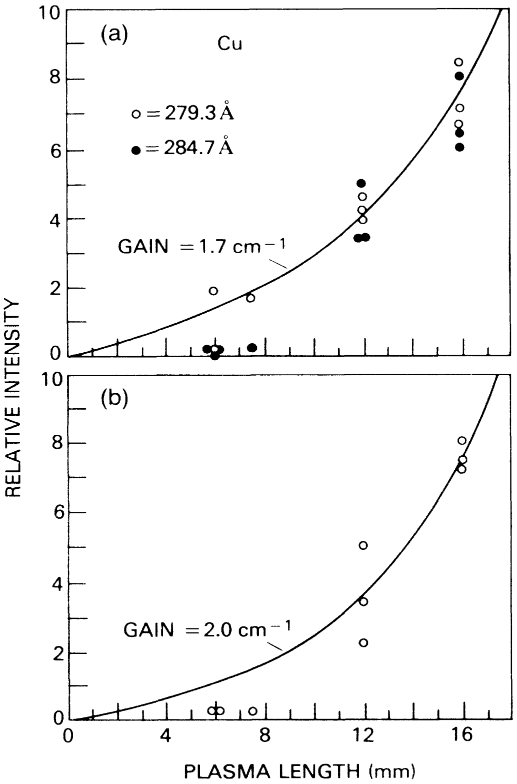

FIG. 4. Relative intensities vs plasma length for (a) the 279.31 and 284.67 Å ($J=2$ to 1) and (b) the 221.11 Å ($J=0$ to 1) lasing lines, along with calculated gain curves for gain coefficients of 1.7 and 2 cm^{-1}, respectively. Estimated uncertainties of ± 10% in relative intensities are within the shot-to-shot spread. Data from thin-film Cu-Formvar targets were used.

temperature in the range of 400–700 eV.

End-on x-ray pinhole photographs obtained with thin-film targets indicate that the foil-plasma boundary remained intact as the plasma expanded towards the incoming laser beam, except for an occasional narrow jetting towards the rear. This suggests that the thin-film targets mainly ablated, rather than exploding symmetrically. This is consistent with the lasing from thicker Ge and Cu targets.

In summary, time-integrated gain coefficients for neonlike Cu^{19+} and Ge^{22+} ions have been measured for the first time. It is particularly interesting to notice that the $J=2$ to 1 gain coefficient of 4.1 cm^{-1} observed with a thick, plain slab of germanium under single-sided illumination is comparable to that obtained by the LLNL group with a selenium-film target which was illuminated from both sides. Also, for the first time, the copper $J=0$ to 1 line showed a gain coefficient comparable to that for the $J=2$ to 1 lines, in approximate agreement with recent calculations.[3,4] These results support electron-collisional excitation, where the cross section is known to favor the $J=0$ level. Because of the high spectral resolution possible with photographic detection and a very narrow (5 μm) entrance slit, we are able to make detailed comparisons of the measured wavelengths with theoretical calculations and extrapolations,[8-10] as shown in Table I. Our results should provide valuable input for future target designs and experiments with modest laser facilities.

The authors gratefully acknowledge the unwavering support of S. E. Bodner and B. H. Ripin and the many valuable contributions of H. R. Griem. We recall with appreciation numerous useful discussions with members of the LLNL group. Generous contributions at the U.S. Naval Research Laboratory were made by U. Feldman, J. F. Seely, C. M. Brown, J. O. Ekberg, J. E. Dahlburg, J. H. Gardner, J. A. Stamper, S. P. Obenschain, R. H. Lehmberg, A. Mostovych, J. Grun, C. K. Manka, K. Kearney, D. J. Michels, and W. A. Molander. Valuable technical support was provided by J. L. Ford, L. M. Shirey, and N. E. Nocerino. This research was supported by the U.S. Office of Naval Research, the Strategic Defense Initiative Office, and the U.S. Department of Energy.

Note added.—Since the submission of this paper, two more lasing lines in the neonlike Ge^{22+} ion have been identified. They are the $(2p^5_{3/2}3p_{3/2})_1$-$(2p^5_{3/2}3s_{1/2})_1$ and $(2p^5_{3/2}3p_{1/2})_2$-$(2p^5_{3/2}3s_{1/2})_1$ lines at 247.32 and 286.46 Å, respectively.

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[1] D. L. Matthews *et al.*, Phys. Rev. Lett. **54**, 110 (1985).

[2] M. D. Rosen *et al.*, Phys. Rev. Lett. **54**, 106 (1985).

[3] D. L. Matthews *et al.*, J. Phys. (Paris) **47**, 1 (1986).

[4] U. Feldman, J. F. Seely, and G. A. Doschek, J. Phys. (Paris) **47**, 187 (1986).

[5] R. A. London and M. D. Rosen, Phys. Fluids **29**, 3813 (1986).

[6] R. C. Elton, T. N. Lee, and W. A. Molander, J. Opt. Soc. Am. B **4**, 539 (1987); T. N. Lee, W. A. Molander, J. L. Ford, and R. C. Elton, Rev. Sci. Instrum. **57**, 2052 (1986).

[7] V. A. Chirkov, Kvantovaya Elektron. (Moscow) **11**, 2253 (1984) [Sov. J. Quantum Electron. **14**, 1497 (1984)].

[8] J. H. Scofield (LLNL), private communication.

[9] J. A. Cogordan and S. Lunell, Phys. Scr. **33**, 406 (1986).

[10] R. R. Harr, L. J. Curtis, N. Reistad, C. Jupen, I. Martinson, B. M. Johnson, K. W. Jones, and M. Meron, Phys. Scr. **35**, 296 (1987).

[11] B. L. Henke, F. G. Fujiwara, M. A. Tester, C. H. Dittmore, and M. A. Palmer, J. Opt. Soc. Am. B **1**, 828 (1984).

[12] G. J. Linford, E. R. Peressini, W. R. Sooy, and M. L. Spaeth, Appl. Opt. **13**, 379 (1974); R. A. London, M. D. Rosen, and C. Cerjan (LLNL), private communication.

[13] J. Reader, V. Kaufman, J. Sugar, J. O. Ekberg, U. Feldman, C. M. Brown, J. F. Seely, and W. L. Rowan, J. Opt. Soc. Am. B (to be published).