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Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser [Phys. Rev. Lett. 73, 2192 (1994)]

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We have reported the first observation of large soft-x-ray amplification in a discharge-created plasma. A gain coefficient of 0.6 cm^{-1} at 46.9 nm was measured in a Ar-H_2 mixture, while higher laser intensities were reported in pure argon. It was later realized that the fraction of H_2 in the gas mixture experiments was, due to incomplete mixing of the gases, smaller than the 1:2 ratio reported, and amounted to less than 10%. Subsequent experiments have confirmed that larger amplification occurs in pure argon discharges, resulting in gain coefficients of up to 1.1 cm^{-1}.

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Metallic Screening and Correlation Effects in Superconducting Fullerenes [Phys. Rev. Lett. 74, 996 (1995)]

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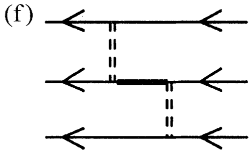
As originally printed, Fig. 2(f) was missing the lower electron line. The corrected figure appears below.



Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser

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We report the first observation of large soft-x-ray amplification ($gl = 7.2$) in a discharge-created plasma. A fast, ~40 kA, current pulse from a compact discharge was used to excite plasma columns up to 12 cm in length in 4-mm channels, producing population inversion in the $J = 0\text{-}1$ line of Ne-like Ar and resulting in a gain of 0.6 cm^{-1} at 46.9 nm. The beam divergence was measured to be <9 mrad.

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Since the first demonstrations of soft-x-ray lasers in plasmas generated by large laser facilities in 1984 [1,2], notable progress has been made in expanding the number of x-ray laser transitions, increasing their power [3], and in demonstrating their application in proof-of-principle experiments [4]. However, the widespread use of these laser sources in a number of important applications has been hampered by their large size, complexity, and cost. This has set the goal of demonstrating laser action in an often called *table-top* compact soft-x-ray laser that, due to its enhanced efficiency and simplicity, could be operated, for example, in the typical university laboratory. With this motivation, efforts have been recently devoted to the use of smaller laser drivers in the development of small-scale soft-x-ray lasers based on both collisional excitation [5] and recombination schemes [6], and gain-length products up to 4 have been reported.

It has been recognized that direct excitation of the plasma medium by a pulsed discharge could result in significantly increased laser efficiency. However, despite the early success in the development of discharge-pumped lasers at wavelengths as short as 116.1 nm [7], the problem of demonstrating lasing action at wavelengths below 100 nm had remained unsolved. The possibility of exciting collisional lasers using large pulsed power generators has been studied [8]. In these plasmas, the main obstacle has been connected with axial inhomogeneities produced by nonsymmetric compressions and instabilities, which can lead to severe distortions of the plasma column, thus destroying the amplification. This plasma uniformity problem has brought attention to laser schemes which are less sensitive to the symmetry of the plasma, such as photoexcitation and photoionization followed by recombination with separate plasmas as the excitation and active media. Recently, the former scheme resulted in population inversion in He-like Ne photopumped by a Na *Z*-pinch plasma generated by the largest pulsed power machine in the world [9].

We have proposed to overcome these limitations by the use of fast discharge excitation of capillary channels to pump plasma recombination [10] and collisionally excited soft-x-ray lasers [11,12]. These discharges provide the advantages of producing hot plasma columns of small diameters using only moderate radial compressions and highly homogeneous initial plasma conditions, which results in more stable plasma columns. Discharges through plastic capillaries have been previously studied as soft-x-ray sources for spectroscopy, microscopy, and lithography [13]. More recently, several experiments have been conducted to explore for amplification following plasma recombination into hydrogenic ions in capillary discharge plasmas [14–19] and in a gas liner pinch [20]. Gain [15,19] and anomalous line intensity ratios [21] have been reported, but only a limited scaling with length has been observed.

Soft-x-ray lasing in the Ne-like sequence, originally demonstrated in Se XXIV [1], has been obtained in numerous elements between $Z = 22$ (Ti) and $Z = 47$ (Ag) but always using plasmas created by high power lasers as the gain medium. In this Letter we report the extension of the range of Ne-like soft-x-ray lasers to Ar ($Z = 18$), in what is the first clear demonstration of large soft-x-ray amplification in a discharge-created plasma. A gain of 0.6 cm^{-1} was obtained in the 46.9 nm line of Ne-like Ar in plasma columns up to 12 cm in length ($gl = 7.2$) generated by a compact capillary discharge.

In our experiments a fast capillary discharge, having a 10% to 90% current rise time of 20 ns, was used to generate plasmas up to 12 cm long in 4-mm-diam channels filled with either pure Ar, or with a mixture of Ar and H_2. The pulse generator and capillary discharge setup have been described in recent publications [11]. The pulse generator consists of a 3 nF liquid dielectric capacitor which is pulse charged by a Marx generator and rapidly discharged through the capillary channel by closing a spark gap pressurized with SF_6. By using this fast capillary discharge, we previously demonstrated that Ar can be easily ionized to the Ne-like and F-like states utilizing only modest currents [11]. Measurements conducted with a gated pinhole x-ray camera indicate that the rapidly rising current pulse detaches the plasma from the walls to generate a compressed plasma column with a high degree of ionization [11,22], in agreement with hydrodynamic calculations [22]. The current pulses used in the experiments described herein had an amplitude of ~40 kA and a half period of 60 ns and were preceded by a current pulse of about 10 A and several microseconds duration to produce a uniform preionization.

Soft-x-ray emission in the axial direction was measured with a 2.2-m grazing-incidence spectrograph having a 1200-lines/mm gold coated grating placed at 85.8°. The radiation from the capillary was imaged onto the spectrometer slit by a toroidal copper mirror positioned at grazing incidence. A microchannel plate (MCP) intensified charge coupled device array detector was used for detecting the soft-x-ray radiation. The spectral resolution of the system in the vicinity of 47 nm, 0.03 nm (for a 130 μm entrance slit), is limited by the detector. The entire system was characterized using a ray-tracing code to determine the angles of acceptance of the radiation by the spectrometer and to correlate the source divergence to the image size in the focal plane of the instrument. The calculated results were verified by measurements yielding an acceptance angle of approximately 15 mrad in the direction perpendicular to the slit, and of 1.5 mrad/mm in the detector, in the direction of the slit. Gating of the MCP allowed for the acquisition of time-resolved spectra with a resolution of ~5 ns.

The Ne-like Ar lines with potential for amplification were identified in spectra corresponding to pure Ar discharges at currents in the range of 30 to 40 kA and Ar pressures between 0.2 and 0.32 Torr. A typical spectrum from these discharges, corresponding to the spectral region around 47 nm, is shown in Fig. 1(a). Note the presence of three of the strongest transitions of Mg-like Ar, as well as the $J = 0$-1 line and one $3d$-$3p$ transition of Ne-like Ar. Our measured wavelengths for these Ne-like Ar lines, 46.875 ± 0.015 and 48.50 ± 0.015 nm, respectively, agree well with previously calculated and measured values in Θ-pinch plasmas [23,24]. Spectra in other wavelength regions also identified the $J = 2$-1 line of Ne-like Ar at 69.77 nm, but no gain experiments were conducted for the $J = 2$-1 transitions. The intensity ratio of the $J = 0$-1 laser line and the closely spaced 48.5 nm $3d$-$3p$ line, which cannot have amplification, provides a convenient reference in the search for amplification. At low plasma densities (1×10^{16} cm^{-3}), and in an optically thin plasma, this intensity ratio has been measured to have a value of about 6 [23], and decreases in value to ~1 at higher (10^{19} cm^{-3}) plasma densities. We have performed line intensity calculations utilizing two independent sets of atomic data [25], with up to 157 levels to model the population distributions in Ne-like Ar as a function of the plasma conditions. These yielded intensity ratios between 1.5 and 3 in the absence of amplification for electron densities in the range of interest for this experiment (1×10^{18} to 1×10^{19} cm^{-3}). The best results obtained at these discharge conditions showed the intensity of the $J = 0$-1 line to reach up to 5 times the value of that of the 48.5 nm line in 12-cm-long plasmas columns. Calculations performed utilizing a ray tracing code as a postprocessor of hydrodynamic or atomic computations to synthesize axial spectra, suggest these line ratios are the result of small amplification of the order of 0.1–0.2 cm^{-1}. Model calculations suggest that, at these discharge conditions, the maximum gain is usually obtained in a narrow annular region with small ion temperature (~50 eV) before the collapsing plasma column reaches the axis. At later times, the plasma compression is calculated to rapidly overionize the plasma and overheat the ions (to $T_i > 1$ keV), thus quenching the gain.

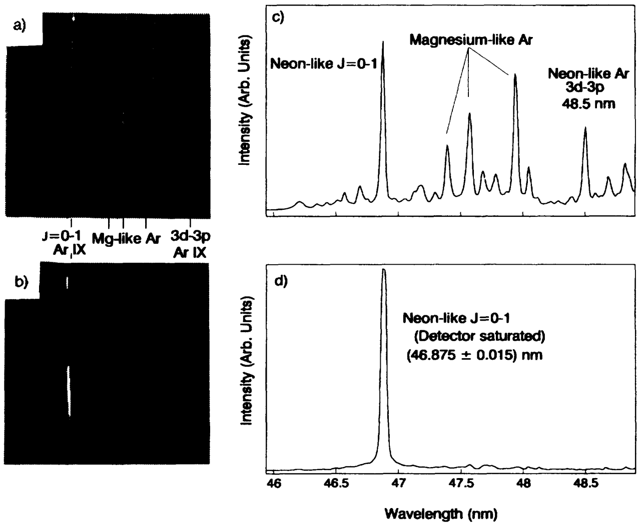

FIG. 1. (a) Time-resolved spectrum from a 40 kA discharge through a 4-mm-diam, 12-cm-long capillary channel filled with 0.25 Torr of Ar obtained about 29 ns after the beginning of the current pulse, corresponding to approximately the time of maximum emission from the $J = 0$-1 line. (b) Spectrum corresponding to a 39 kA discharge through the same capillary filled with 0.64 Torr of a 1:2 mixture of Ar to H_2 obtained near the time of maximum intensity of the $J = 0$-1 line at 38 ns from the beginning of the current pulse. The detector sensitivity was reduced in respect to that of (a). (c) and (d) are cross sections of the spectra shown in (a) and (b). The upper peak in the intensity distribution of the $J = 0$-1 line in (b) was observed only in one of several series of spectra, and while it is most likely the result of a spurious reflection, it could also be due to the spatiotemporal characteristics of the gain region, or refractive effects.

A more favorable regime for amplification, with a nearly optimum electron density and temperature for amplification at the axis, is achieved at higher pressures. A large increase in the intensity of the $J = 0$-1 line of Ne-like Ar was initially detected when H_2 was added to the Ar in the capillary channel. Ar was diluted in H_2 with the goals of achieving maximum gain at the axis with a lower ion temperature and reducing trapping of the lower laser level radiation. Subsequent experiments showed that large amplification can also be obtained in pure Ar discharges at pressures near 700 mTorr. Comparison of the spectrum of Fig. 1(b), corresponding to a 39 kA current pulse through a 12-cm-long capillary filled with 0.64 Torr of a 1:2 mixture of Ar to H_2, with that of Fig. 1(a), shows a dramatic increase in the intensity of the

$J = 0$-1 line. The intensity of this line, which saturates the detector, was measured to be more than 300 times that of the 48.5 nm Ne-like Ar line. These large ratios are a clear indication of amplification. Emission from the lasing line is observed for a short period of time in the vicinity of the current peak, while radiation of the adjacent Mg-like and Al-like Ar lasts beyond the end of the first cycle of the current pulse.

The value of the gain was determined by measuring the increase of the line intensity as a function of capillary length, using plasma columns 3, 6, and 12 cm long. Special care was observed in maintaining the amplitude and width of the current pulse constant. The current half period was measured to be between 59.5 and 62 ns for all the capillary lengths, and the peak amplitude of the current pulse was set to 38 ± 1 kA in all the shots by adjusting the charging voltage.

Figure 2 shows typical spectra for each of the three plasma column lengths. In the spectrum from the 3-cm capillary, the intensity of the $J = 0$-1 line of Ne-like Ar at 46.9 nm is observed to be smaller than the intensity of the surrounding resonant lines of Mg-like Ar ions and to be only about twice the intensity of the neighboring 48.5 nm $3d$-$3p$ Ne-like Ar line. In the 12-cm capillary the laser line totally dominates the spectrum, resembling the spectra of the emission from soft-x-ray lasers pumped by large laser facilities [1]. Figure 3 is a plot of the integrated intensity of the $J = 0$-1 line of Ne-like Ar as a function of capillary length. A least squares fit of the data to the Linford formula [26] results in a gain coefficient of $0.6 \pm 0.04\ \mathrm{cm}^{-1}$, corresponding to a gain-length product $gl = 7.2$. This is to our knowledge the largest amplification obtained in a table-top soft-x-ray laser device.

Another conclusive evidence of lasing results from the measurement of the divergence of the radiation of the $J = 0$-1 Ne-like Ar line relative to all other transitions, and in particular to the neighboring 48.5 nm Ne-like line which originates in the same region of the plasma. The magnitude of the divergence was determined from the image size in the direction of the slit, which is correlated to the divergence and the size of the source. Figure 4(a)

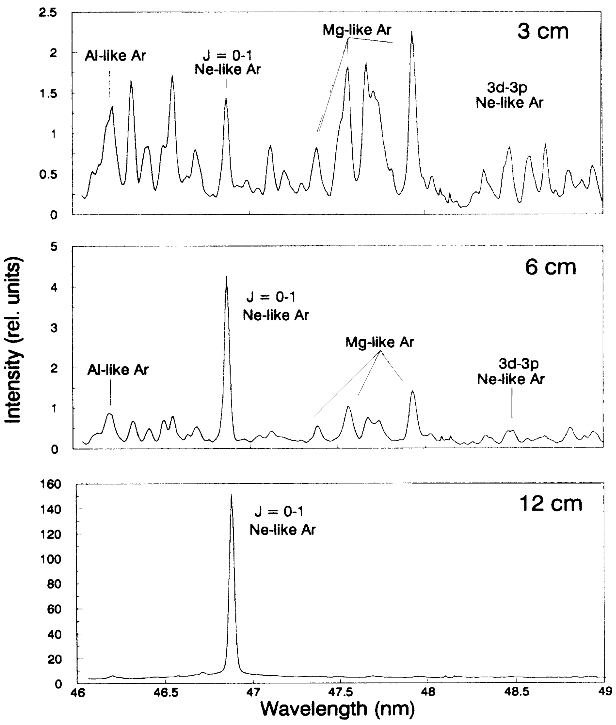

FIG. 2. Variation of the intensity of the spectral lines in the neighborhood of 48 nm as a function of capillary length.

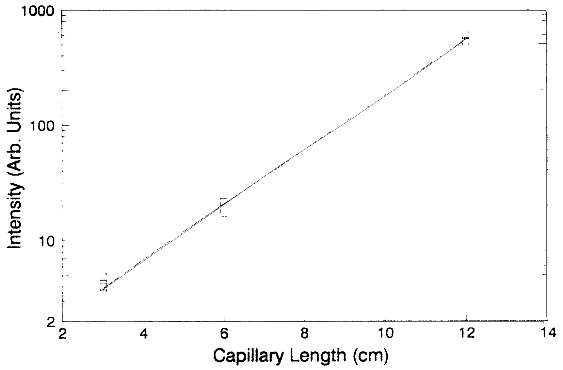

FIG. 3. Integrated line intensity of the $J = 0$-1 line of Ar IX as a function of the plasma column length. A fit to the Linford formula [26] yields a gain coefficient of $0.6 \pm 0.04\ \mathrm{cm}^{-1}$, corresponding to $gl = 7.2$.

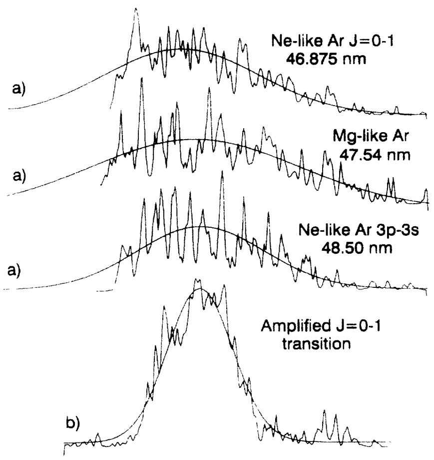

FIG. 4. (a) Spatial distribution of the line intensity in the detector in the direction parallel to the spectrometer slit for three of the lines in Fig. 1(a), corresponding to a condition of negligible amplification. (b) Similar data for the $J = 0$-1 line of Ne-like Ar under discharge conditions corresponding to large amplification. The profile of this line is observed to be significantly narrower, with a maximum divergence of 8.7 mrad assuming a point source. The smooth line corresponds to a fit of the experimental data. In (b) the detector sensitivity was reduced to avoid saturation by the 46.9 nm line.

shows the intensity distribution of Ne-like and Mg-like Ar lines, corresponding to a condition of negligible amplification. In this case all the lines, including the $J = 0\text{-}1$ line, are observed to have similar intensity distributions, stretching over the majority of the detector. A sharp decrease in the divergence of the $J = 0\text{-}1$ line with respect to all other lines was measured for the discharge conditions in which large amplification is obtained. Figure 4(b) shows the intensity distribution of the amplified 46.9 nm line (obtained by decreasing the sensitivity of the detector to avoid saturation), corresponding to a divergence of less than 8.7 mrad. This maximum divergence value results from assuming a point source. A slightly smaller divergence would result from a finite source size.

Preliminary discharges conducted in 12-cm-long capillaries filled with pure Ar at pressures near 700 mTorr yielded $J = 0\text{-}1$ line intensities about two times larger than obtained for the Ar-H_2 mixtures, showing that large amplification can also be obtained with a single component gas fill. While the results reported herein were obtained in single-shot experiments, multi-Hertz operation should be possible.

In conclusion, we have realized the first demonstration of large soft-x-ray amplification using a discharge created plasma. The observed amplification ($gl = 7.2$) is the largest obtained to date from a table-top soft-x-ray laser. This is also the first time that lasing is observed in Ne-like Ar and that a gas target is utilized to obtain amplification in this sequence. The capillary discharge excitation scheme demonstrated herein is likely to also result in the successful excitation of soft-x-ray laser transitions in other ions and has the potential for increasing the wall-plug efficiency of ultrashort wavelength lasers by two orders of magnitude.

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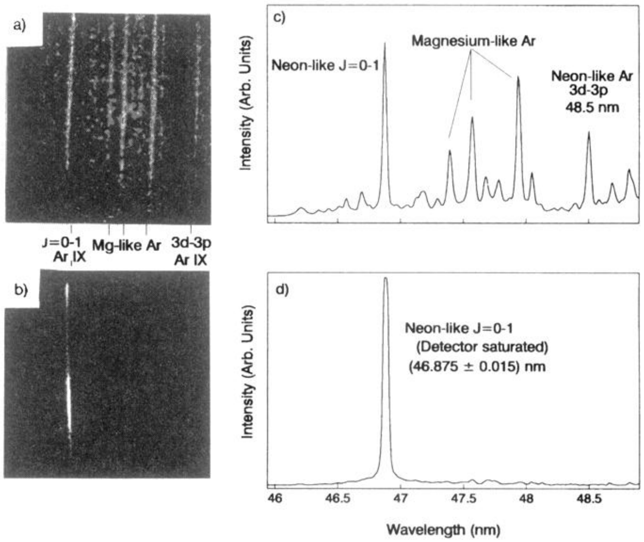

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