Measurement of the Spatial Coherence Buildup in a Discharge Pumped Table-Top Soft X-Ray Laser

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We have measured the variation of the spatial coherence with plasma column length in a saturated table-top 46.9-nm Ne-like Ar capillary discharge soft x-ray amplifier for lengths up to 16.4 cm. The measurements, which are in good agreement with time dependent wave-optics model computations, provide the first experimental evidence of a monotonic increase of the coherence with length in a soft x-ray amplifier. The variation of the coherence across the beam profile was also studied. Off axis, the coherence is larger in the tangential than in the radial direction. [S0031-9007(97)04235-X]

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The rapid progress in the development of soft x-ray lasers opens the possibility of the widespread use of very intense table-top sources of soft x-ray coherent radiation in applications. Good spatial coherence will be essential in realizing the full potential of these lasers in nonlinear optics, holography, and interferometry. Present saturated soft x-ray lasers operate by amplifying incoherent spontaneous radiation in a single or a double pass through a plasma column [1]. They face the difficulty of achieving a highly coherent beam without the aid of an optical cavity, a limitation that is mainly due to the short duration of the gain. Research is under way to improve the spatial coherence of soft x-ray lasers. The approaches that have been investigated include the use of double pass amplification, and its combination with curved target geometries [2–4]. Of related interest is the recently measured spatial coherence of soft x-ray radiation produced by high order harmonic generation [5].

Several theoretical studies have been conducted to understand the spatial coherence of soft x-ray amplifiers [6–10]. In general they predict an improvement of the coherence with amplifier length. This is the result of the decreasing number of modes guided along the amplifier column due to gain guiding and refractive antiguiding [6]. Such buildup of the coherence with plasma column length is essential in achieving very good spatial coherence in cavityless soft x-ray amplifiers. Several measurements of the spatial coherence of laser pumped soft x-ray lasers have been reported [11–14]. However, most of them correspond to a single amplifier length of the particular x-ray laser studied [12,14]. The only measurements of the spatial coherence as a function of amplifier length, conducted in a Ne-like Se soft x-ray laser produced by irradiation of a Se foil target with a powerful laser pulse, failed to observe the predicted coherence increase [11]. It has been recently suggested that the absence of the expected increase of the spatial coherence might be due to "hose-type" random fluctuations in the plasma column that lead to mode coupling [15].

In this Letter we report the first observation of a monotonic increase of the spatial coherence as a function of length in a soft x-ray amplifier. The coherence in a capillary discharge soft x-ray laser was measured for different plasma column lengths up to 16.4 cm and was found to increase with plasma column length, in good agreement with wave-optics calculations. The observed continuous increase of the coherence also confirms the unprecedented high uniformity and stability of these discharge created plasma columns at the time of lasing. We also present measurements of the variation of the coherence across the beam.

The measurements were conducted in a table-top discharge pumped amplifier operating in the 46.9-nm line of Ne-like Ar. The laser has been previously described [16]. In this laser the gain medium is an elongated plasma column generated in a capillary channel by a fast discharge current pulse. The magnetic force of the current pulse rapidly compresses the plasma to form a dense and hot column with length-to-diameter ratios approaching 1000:1, in which amplification is obtained by collisional excitation of Ne-like ions [17,18]. We have previously reported saturated operation of this laser [18]. The longest plasma column length used in the experiments reported in this Letter, 16.4 cm, is sufficient to amplify the beam to the intensity necessary to produce gain saturation near the ends of the plasma column [18]. The measurements were conducted in polyacetal capillaries 4 mm in diameter filled with Ar gas at pressures ranging from 600 to 700 mTorr. The plasma was excited by current pulses of approximately 37 kA peak current, having a first half cycle duration of about 70 ns. For the measurement of the variation of the coherence as a function of plasma column length, the duration and the amplitude of the current pulse were maintained approximately constant by adjusting the discharge voltage and by equalizing the inductance for all cases.

The degree of coherence $|\mu(P_1, P_2)|$ of points P_1 and P_2 on the detector plane [19] was measured by recording the diffraction of the soft x-ray laser beam by a blade

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edge. This technique has been recently utilized to observe an improvement in the coherence of a laser pumped Ne-like Zn laser when a reflecting multilayer mirror was used [13]. It has the advantage of determining in a single shot the degree of coherence for points P_1 and P_2 on a line perpendicular to the blade edge, with P_1 on the geometrical shadow of the edge. To generate the diffraction patterns, we placed a blade in the beam path at a distance of 56 cm from the exit of the amplifier. The interference fringes were recorded using a gated detector with an active area 2.3 cm in diameter placed at 533 cm from the blade. The detector consisted of the combination of a microchannel plate, a phosphor screen, an image intensifier, and a 1024 × 1024 pixels CCD array. A compromise between acceptable spatial resolution and reduced noise was obtained by averaging 50 pixels along the fringes. The microchannel plate was gated for about 5 ns to discriminate the laser radiation from the long lasting (>100 ns) soft x-ray spontaneous emission generated by the plasma. The voltage of the gate pulse was maintained low (<150 V) to avoid saturating the microchannel plate response. The linearity of the entire detector system was experimentally verified, and the dynamic range, which limits the detection of small amplitude fringes, was sufficiently large ($\approx 100{:}1$) to allow for the measurement of coherence lengths up to at least 7 mm in the detector plane. A thin Al coating was deposited on the phosphor screen to filter longer wavelength radiation emitted by the plasma. The spatial resolution of the entire detector system was measured by irradiating with the soft x-ray laser beam a test pattern containing 100 μm wide features placed in close proximity (4 cm) to the detector. The measured resolution would broaden a delta function to 128 μm FWHM.

Figure 1(a) shows the measured diffraction patterns for capillary plasmas with lengths between 8 and 16.4 cm. The data were obtained at an Ar pressure of 600 mTorr. At this pressure the laser emitted the maximum intensity with a profile that had an intensity depression in the center and a beam divergence of about 5 mrad, caused by refraction. To conduct the measurements of the spatial coherence as a function of plasma column length, the edge of the blade was placed along a diameter of the beam as shown in Fig. 2 (left). For points P_1 off axis, where the intensity is maximum, this measurement gives the coherence in the direction tangential to the beam. In this Letter we use the term tangential (radial) direction when the points P_1 and P_2 lie perpendicular to (along) a radius of the beam as illustrated in Fig. 2. The continuous improvement of the coherence with amplifier length is evident in the increased fringe visibility observed in the diffraction patterns corresponding to the longer plasma columns. Figures 1(b) and 1(c) compare the observed diffraction patterns with those obtained numerically using the results of a wave-optics model for the generation and propagation of the radiation in the capillary plasma column. The computed diffraction patterns were produced by numerical 1D propagation of the simulated soft x-ray output of the amplifier from the exit of the discharge to the detector plane. The measured diffraction profiles compare well with the simulated profiles, except for the 8-cm-long plasma column, a short amplifier length for which the contribution of the background emission from hundreds of plasma lines to the measured signal (not considered in the model) becomes important.

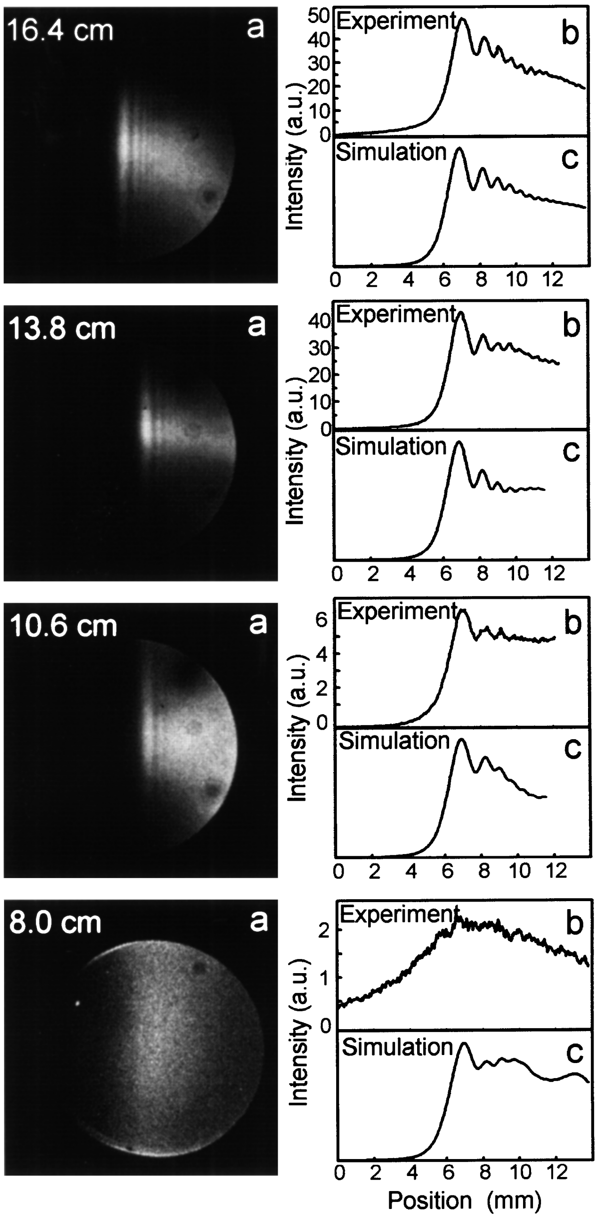

FIG. 1. (a) Measured diffraction patterns corresponding to capillaries with lengths between 8 and 16.4 cm. (b) Cross sections of the diffraction patterns of (a) obtained by vertically integrating 50 pixels of the CCD in the region of maximum fringe visibility. (c) Corresponding diffraction patterns computed using the results of the wave-optics model.

Series of measurements like those of Fig. 1 were analyzed to quantify the degree of coherence and its dependence on amplifier length. The spatial variation of the degree of coherence was obtained by normalizing

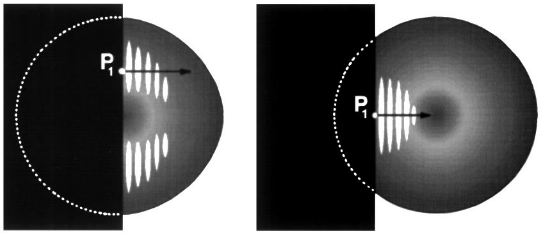

FIG. 2. Sketch showing the tangential (left) and radial (right) directions defined for the coherence measurement. The position of the shadows of the blade and the fringes relative to the laser beam are shown. The dots mark the position of points P_1. The points P_2 lie along the arrows.

the measured diffraction patterns point by point to the pattern computed using the Huygens-Fresnel integral for a perfectly coherent source having an intensity profile equal to that measured for the soft x-ray laser beam. The finite resolution of the detection system was taken into account. The resulting spatial distributions of the degree of coherence for capillaries 16.4 and 10.6 cm in length are shown in Fig. 3(a). The coherence length corresponding to these profiles, defined here as the distance in which the degree of coherence decays to 50%, is about 4.5 to 2.8 mm, respectively, in the detector plane located at 589 cm from the output of the laser. The former value corresponds to a coherence angle of 0.8 mrad, equivalent to that of an incoherent source of 26 μm in size. The laser beam is approximately 6 times diffraction limited in the tangential direction. The dependence of the coherence length on the plasma column length is shown in Fig. 4. The results of three series of measurements conducted in different capillaries are shown. The coherence is observed to increase monotonically with capillary length. This is to our knowledge the first observation of a monotonic increase of the spatial coherence with amplifier length in a soft x-ray laser.

The measurements were compared with the results of wave-model calculations. The model used for these calculations and to synthesize the interference profiles of Fig. 1 is similar to that developed by Feit and Fleck [10]. It differs from that previous model in that it considers the temporal variation of both the gain coefficient and the electron density, and in that it is extended to two transverse dimensions. The rapid change of the electron density causes the curvature of the wave front of the eigenmode of the amplifier to change appreciably during the laser pulse. This effect, not considered in previous calculations, can smear out the interference fringes and consequently limit the attainable spatial coherence. The time evolution of the optical field in the entire volume of the plasma column was computed taking into account the amplification of spontaneous emission in both axial directions. The spontaneous emission was simulated as a field of random phase, and amplitude determined by the upper laser level population. The propagation of radiation was computed including amplification, diffraction, and refraction effects as well as saturation of the gain. Based on our previous measurements, we assumed an effective gain coefficient of 1.16 cm^{-1} and a FWHM gain duration of 2.3 ns [18]. The small signal gain and electron density profiles were assumed parabolic with a FWHM diameter of 300 μm [18]. The evolution of the electron density used in the calculations is the result of magneto hydrodynamic computations reported in [18]. They give an electron density at the time of maximum gain of $\approx 5.6 \times 10^{18}\ \mathrm{cm}^{-3}$, increasing at about $5 \times 10^{18}\ \mathrm{cm}^{-3}/\mathrm{ns}$ due to the rapid plasma compression. Good agreement is observed in Fig. 4 between the measurements and the numerical results, represented by a line in that figure. While the precise value of the computed coherence length and its rate of increase with capillary length depends on the characteristics of the assumed electron density and gain profiles, the monotonic increase of the coherence is the main result.

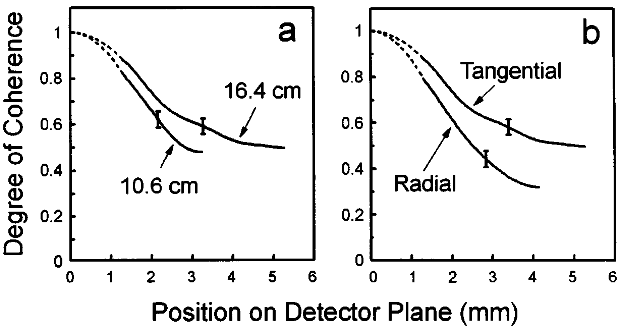

FIG. 3. Measured spatial variation of the degree of coherence in the (a) tangential direction for capillary plasma columns with lengths of 10.6 and 16.4 cm (b) Tangential and radial directions for the laser beam produced by a 16.4-cm-long Ar capillary discharge.

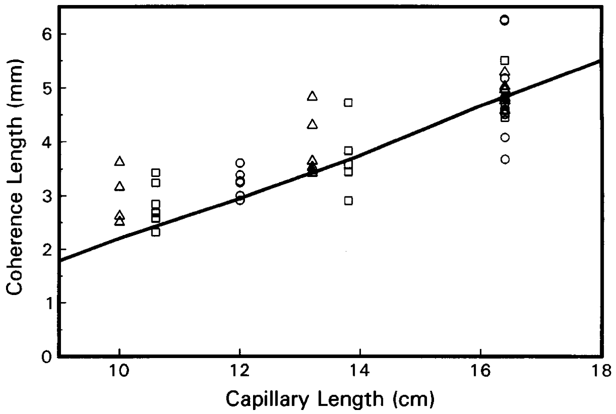

FIG. 4. Variation of the coherence length in the tangential direction as a function of plasma column length. The coherence lengths are at the detector plane, at 589 cm from the exit of the laser. Different symbols correspond to series of measurements conducted in several identical capillaries. The line is the result of the wave-model calculations.

Recent measurements of the coherence in a laser pumped soft x-ray laser found the coherence to be lower in the periphery of the beam [13]. To study the uniformity of the coherence across the beam profile in the discharge pumped amplifier, we performed measurements placing the blade in different positions relative to the laser beam. Measurements conducted for P_1 on axis showed that the coherence is the same in all directions. In contrast, as illustrated in Fig. 3(b), off-axis measurements for a 16.4-cm-long capillary show that the coherence length is 30% to 50% lower for the radial direction than for the tangential direction. The coherence in the tangential direction was observed to be roughly independent of the radial position of P_1. This anisotropy is consistent with the model prediction of a monotonic decrease of the radial coherence with distance from the axis. The wave-model computations suggest that a likely cause of the observed anisotropy of the spatial coherence is the change of electron density during the laser pulse. As the curves of the constant phase are circles concentric with the beam, the dephasing due to a change in the curvature of the wave front is more significant off axis and in the radial direction. This effect is clearly shown by our simulations that use parabolic profiles and a time varying electron density. It is nevertheless possible that the anisotropy could be caused by a nonparabolic density profile in which the curvature is radially dependent.

The model computations conducted assuming the above mentioned plasma parameters predict the coherence should continue to improve for longer capillaries. The computations show that even in the absence of refraction antiguiding, the coherence continues to increase for plasma columns of lengths longer than the unidirectional saturation length ($\approx$15 cm), in agreement with previous calculations [9]. This is a consequence of the gain saturation caused by counterpropagating beams that result in an active medium with lower gain but a larger length-to-diameter ratio. However, our time dependent computations show that the previously mentioned change in wave front curvature induced by the rapid variation of the plasma density can impose a limitation to the maximum spatial coherence that can be obtained by extending the plasma column length. For the parameters used to calculate the curve in Fig. 4, this dynamic effect is found to limit the increasing trend of the coherence for plasma column lengths above $\approx$25 cm. A reduction of the rate of change of the electron density during the laser pulse should lead to a continuous increase of the coherence for longer plasma columns and to diffraction limited beams. Improved coherence could also be obtained in a shorter plasma column by double pass amplification using a mirror [13]. This has the advantage of not requiring a long amplifier column, but its drawback is the rapid deterioration of the mirrors that is a limitation for repetitive laser operation [18].

In conclusion, we have studied the spatial coherence of a capillary discharge pumped 46.9-nm table-top amplifier for plasma columns up to 16.4 cm in length. We have observed for the first time a monotonic increase of the spatial coherence with amplifier length in a soft x-ray laser, in agreement with the results of a wave-optics model computation. Measurements in the tangential direction yield a coherence angle of 0.8 mrad and an effective source size of 26 μm for a capillary length of 16.4 cm. Model computations suggest that the variation of electron density during the laser pulse has a significant influence in determining the coherence of the amplifier. The above results are of significance for the development of near diffraction limited table-top soft x-ray lasers.

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