Demonstration of a Collisionally Excited Optical-Field-Ionization XUV Laser Driven in a Plasma Waveguide

A. Butler, A. J. Gonsalves, C. M. McKenna, D. J. Spence, and S. M. Hooker*
Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom

S. Sebban,† T. Mocek, and I. Bettaibi
Laboratoire d'Optique Appliquée, ENSTA/Ecole Polytechnique, CNRS UMR 7639, F-91761 Palaiseau cedex, France

B. Cros‡
LPGP, UMR 8578, CNRS, Université Paris XI, Bâtiment 210, 91405 Orsay, France
(Received 29 May 2003; published 10 November 2003)

We describe the first demonstration of a collisionally excited optical-field-ionization laser driven within a waveguide. Lasing on the $4d^9 5d$-$4d^9 5p$ transition at 41.8 nm in Xe^{8+} was observed to be closely correlated to conditions under which the pump laser pulses were guided well by a gas-filled capillary discharge waveguide. Simulations of the propagation of the pump laser radiation show that gain was achieved over essentially the whole 30 mm length of the waveguide.

DOI: 10.1103/PhysRevLett.91.205001 PACS numbers: 52.38.Hb, 42.55.Vc

Ever since the first demonstrations [1,2] of lasing in the x-ray spectral region, considerable effort has been devoted to reducing the size and increasing the repetition rate of the pump lasers. Progress towards this goal has been achieved by using picosecond or femtosecond pump laser pulses [3–6]. For short pump laser pulses, traveling-wave excitation is usually necessary, which, in order to minimize the pump energy, is best realized by pumping longitudinally. However, with this configuration, diffraction and refraction of the pump beam limit the gain length to a few millimeters, and consequently lasing can be achieved only on transitions with high small-signal gain, and the energy extraction and transverse coherence of the short-wavelength beam will be poor. In order to overcome these limitations it is necessary to guide the pump laser pulse over long lengths.

Several techniques for guiding high-intensity laser radiation have been investigated, including guiding in hollow capillaries [7,8], relativistic channeling [9], and several types of plasma waveguide [10–12], although only a few of these have been used to increase the gain length of short-wavelength lasers. Recombination lasing has been demonstrated on the $n = 2 \rightarrow 1$ transition at 13.5 nm in Li^{2+}, driven within plasma channels up to 14 mm long formed by discharge or laser ablation of a LiF capillary [13]. Janulewicz *et al.* have investigated transient collisionally excited short-wavelength lasers driven within a plasma channel formed by a z-pinch discharge [14]. While these early results show the promise of driving short-wavelength lasers within a plasma channel, evidence for the generation of gain over the full length of the waveguide has not yet been presented in detail.

The present work utilizes a gas-filled capillary discharge waveguide. For H_2-filled capillaries this approach has been shown to form an approximately fully ionized, parabolic plasma channel [15]. A plasma channel of this form is able to guide a Gaussian beam with a constant spot radius, provided that the spot radius is correctly matched to the curvature of the plasma. In earlier work we demonstrated guiding of laser pulses with a peak input intensity of 1.2×10^{17} W cm^{-2} over lengths of up to 50 mm with low loss [16,17].

In this Letter we present the first demonstration of a short-wavelength laser driven within a gas-filled capillary discharge waveguide. This is also the first time that a collisionally excited optical-field-ionization (OFI) laser has been driven in any waveguide. We present spectra demonstrating short-wavelength lasing, measurements of the transmission of the pump laser pulse through the waveguide, and simulations that show that the lasant ion stage is generated over essentially the whole length of the plasma channel.

For this first demonstration it was decided to investigate lasing on the $4d^9 5d$-$4d^9 5p$ transition at 41.8 nm in Xe^{8+}. For this laser system, OFI of Xe gas with circularly polarized pump radiation generates Xe^{8+} ions and hot electrons that pump the laser transition by electron collisions. Lasing was first observed [5] on this transition by Lemoff *et al.* in a Xe gas cell, and recently saturation of this transition was reported [18] by Sebban *et al.* using a similar approach. In both of these experiments defocusing of the pump beam limited the gain length to less than 8.5 mm.

The experiments described in this Letter were conducted at the Laboratoire d'Optique Appliquée-ENSTA (LOA), using the arrangement shown schematically in Fig. 1. Fundamental radiation from a Ti:sapphire laser, with a pulse duration of 37 fs FWHM, was circularly polarized by a quarter-wave plate and focused to the entrance of the waveguide by an off-axis parabolic mirror

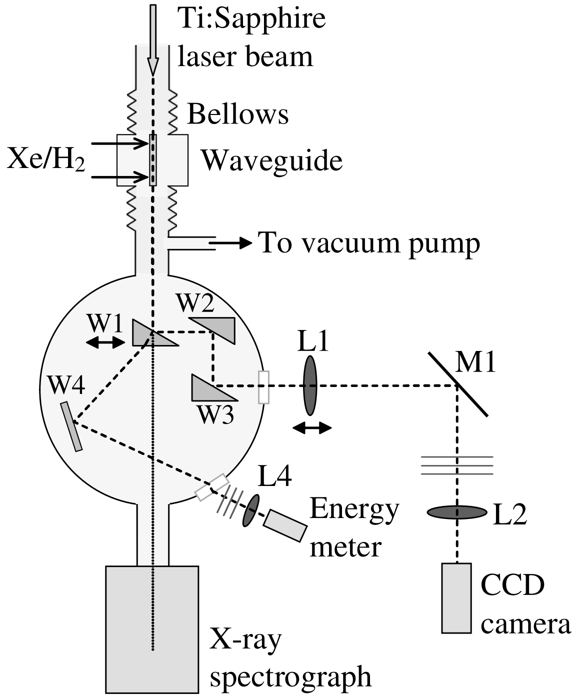

FIG. 1. Diagram of the experimental layout used in the present experiments.

(not shown) used at $f/25$. The radiation transmitted by the capillary was reduced in intensity by reflections from three wedged optical flats (W1–W3), rendered parallel by lens L1 and imaged onto a 12-bit CCD camera by L2 and a microscope objective. The limiting aperture of the imaging system was such that L1 was effectively $f/25$. Radiation transmitted by W1 was reduced in intensity by reflection from W4 and loosely focused by L4 onto an energy meter. The energy of the laser pulses entering the capillary was determined by a calibrated photodiode (not shown). The energy transmission of the waveguide was then determined by comparing the measured energy transmission with that recorded when the capillary was replaced by an evacuated pipe.

The mean energy of the laser pulses input to the capillary was (240 ± 20) mJ, and the beam focus was found to have a peak fluence of 9.8 $\mathrm{kJ\,cm^{-2}}$, corresponding to a peak input intensity of 2.5×10^{17} $\mathrm{W\,cm^{-2}}$. A fit to the measured intensity profile of the form $I(r) = I(0)\exp[-2(r/w)^2]$ yields a spot radius w of approximately 34 μm. This value may be compared to $w = 20$ μm expected for $f/25$ focusing, suggesting that the beam was 1.7 times diffraction limited with a Rayleigh range of 2.6 mm.

The extreme ultraviolet (XUV) spectrum of radiation leaving the capillary was recorded by moving W1 out of the beam path, the pump laser radiation being blocked by a 0.3 μm thick Al filter. The XUV spectrograph [18] utilized a transmission grating to disperse the spectrum from the zero order up to 70 nm onto a 16-bit x-ray CCD camera.

The gas-filled capillary discharge waveguide was similar to the "two-armed" design described in detail previously [17], but with a storage capacitance of 4.5 nF and an increased circuit inductance. The discharge current had a damped, approximately sinusoidal profile, with a quarter period of 500 ns and a peak of 105 A per arm.

Guiding in a capillary discharge waveguide filled with pure Xe is not possible since OFI of the Xe would destroy the plasma channel. Instead, Xe must be doped into the fully ionized plasma channel formed by a capillary discharge in hydrogen. This was achieved by flowing premade mixtures of Xe and H_2 gas into the capillary through slots machined near each end, the flow being measured by a gap flow meter. The capillaries were of length 30 mm and internal diameter 210 μm.

To allow comparison with the earlier work of Lemoff *et al.* and Sebban *et al.*, we also investigated XUV lasing in a Xe gas cell. In this configuration the pump laser radiation entered and exited the gas cell through two pinholes of 200–500 μm diameter, separated by 4 mm. The vacuum focus of the pump laser was located 2.5 mm after the entrance pinhole.

We optimized the XUV laser signal obtained from the waveguide by varying the gas mixture, the gas pressure, and the delay t between the onset of the discharge pulse and the arrival of the pump laser. Figure 2(a) shows the spectrum recorded with the gas cell containing pure Xe at the optimum pressure of 20 mbar. Figure 2(b) shows the spectrum recorded with a 30 mm long gas-filled capillary discharge waveguide for the optimum conditions: 1:3 Xe:H atom gas mixture at an initial pressure of 120 mbar, and $t = 1000$ ns. Both spectra were integrated over ten pump pulses, under nominally identical conditions. It is seen that for both the gas cell and the

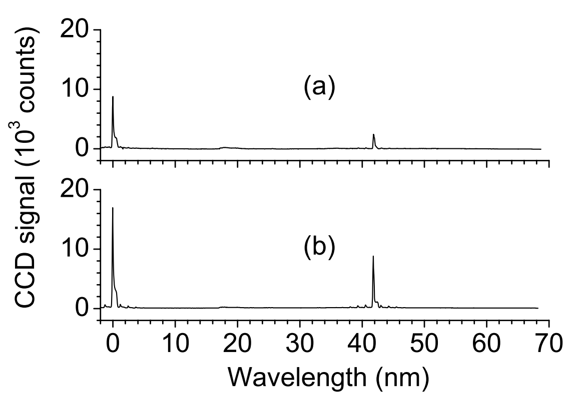

FIG. 2. The measured XUV spectrum integrated over ten pump laser shots for (a) a 4 mm long gas cell containing 20 mbar of pure Xe and (b) a 30 mm long Xe/H-filled capillary discharge waveguide filled with 120 mbar of a 1:3 Xe:H atom gas mixture.

waveguide strong lasing occurred at 41.8 nm, the XUV laser signal dominating the 70 nm bandwidth of the recorded spectra to the extent that no other spectral lines are visible. The signal recorded with the waveguide was approximately 4 times larger than achieved with the gas cell. We note that the sharp lines on either side of the zero order and XUV laser peaks arise from diffraction by a mesh supporting the grating.

Figure 3 shows, for the gas mixture of Fig. 2(b), the peak fluence transmission T_F of the pump laser pulses through the capillary and the normalized Xe^{8+} laser signal as a function of t. It is seen that T_F increases slowly to approximately 2% for t up to 900 ns. Thereafter T_F increases rapidly by a factor of ~6, owing to an increased energy and decreased spot radius of the transmitted pulse, reaching a peak of approximately 13% for t close to 1000 ns. At later times T_F falls slowly. The pulse energy transmission T_E behaved similarly, reaching a peak of ~55% for t close to 1000 ns. Note that for all data points T_F is smaller than T_E since the spot radius of the transmitted beam is larger than that of the input beam. As shown by the data presented in Fig. 3, the XUV laser signal was very sensitive to the delay t. For all the experiments performed, lasing was observed only for a range of delays approximately 200 ns wide, centered at $t \approx 1000$ ns.

We now discuss the experimental results and their implications. The measured fluence and energy transmission were observed initially to increase relatively slowly with the delay t followed by a much more rapid rise between $t = 900$ ns and $t = 1000$ ns. For capillaries filled with pure H_2, however, the energy transmission was found to rise much earlier, reaching 75% for delays of only 250–300 ns, consistent with our earlier work [17]. The reason for this difference in behavior is that OFI of Xe ions to Xe^{8+} produces extra electrons on the axis of the plasma channel and defocuses the pump laser beam.

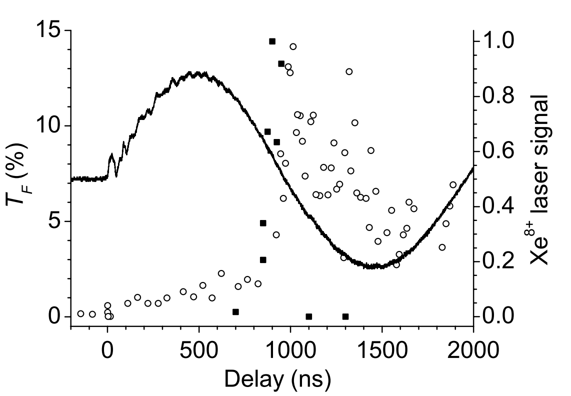

FIG. 3. The measured fluence transmission, T_F (circles) as a function of delay t for a 30 mm long capillary and the experimental conditions of Fig. 2(b). The Xe^{8+} laser signal (squares) is shown for the same conditions, together with the measured temporal profile of the discharge current (solid line).

The strength of this refractive defocusing will be reduced as the initial Xe ion stage generated by the discharge is increased. For capillaries filled with pure hydrogen, the hydrogen is fully ionized early in the discharge pulse. However, for Xe/H-filled capillaries it is later in the discharge pulse before the Xe is sufficiently preionized for good guiding.

XUV lasing was observed only for a narrow range of delays close to the observed rapid rise in pulse transmission, indicating that the conditions of the plasma channel were crucial for lasing to occur. However, the lasing did not follow the fluence transmission in detail since the Xe laser signal fell rapidly after $t = 1000$ ns even though T_F remained high. This behavior may be due to the discharge overionizing the Xe to the extent that the OFI pumping is substantially reduced, as discussed below, or reduction of plasma density owing to the ejection of plasma from the capillary. We also note that the rapid rise in pulse transmission and XUV lasing both occurred very close to the zero in discharge current. These points of detail will be investigated further in future work.

We now consider the propagation of the driving laser pulses within the waveguide. A simple model [15] of the capillary discharge under quasi-steady-state conditions predicts that for the conditions of this experiment capillaries filled with pure hydrogen would reach a plasma temperature of ~6 eV. For Xe/H mixtures the higher mean ion charge will reduce the thermal conductivity and hence increase the plasma temperature. We estimate that the plasma temperature would have been between 6 and 12 eV, corresponding to full ionization of the hydrogen and ionization of Xe to between Xe^{3+} and Xe^{7+}. Figure 4 shows, for the conditions of Fig. 2, the calculated [19] Xe ion stage following the passage of the driving laser pulse through (a) a gas cell and (b) a plasma channel. The plasma channel was assumed to be preionized by the discharge to Xe^{5+}, and parabolic with a matched spot radius of 25 μm, as deduced from a scaling relation for the channel curvature [15]. The simulations show that for both the gas cell and the waveguide Xe is ionized above Xe^{8+} in several places close to the axis, such that the longest lengths of Xe^{8+} are formed in an annular region. For the waveguide the gain region is calculated to extend over almost the entire 30 mm length, compared to the 4 mm achieved in the gas cell. Additional simulations show that the gain length achieved in the waveguide increases with the degree of initial preionization, reflecting the improved propagation of the driving laser pulse.

The simulations presented in Fig. 4 show that use of a gas-filled capillary discharge waveguide allows the lasant ion stage to be generated over much longer lengths than in a gas cell. However, it should also be acknowledged that the conditions within a plasma waveguide are significantly different than in a gas cell: for the waveguide the discharge partially preionizes and heats the Xe as well

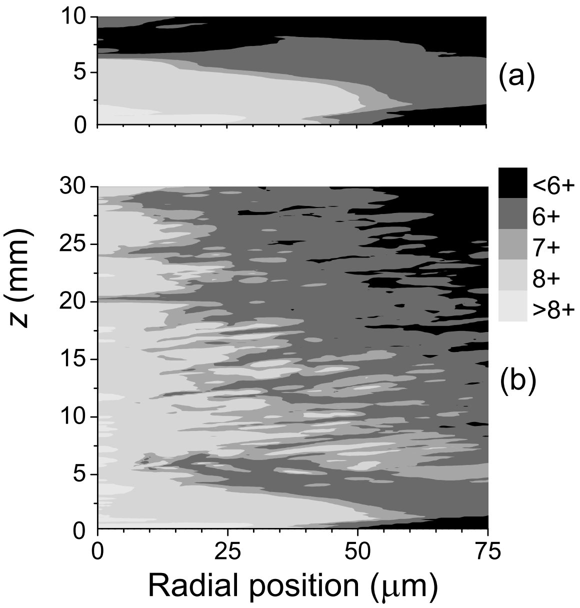

FIG. 4. The calculated Xe ion stage as a function of propagation distance z for the experimental conditions of Fig. 2 for (a) a gas cell filled with 20 mbar of Xe and (b) a 30 mm long plasma channel preionized to Xe^{5+} with a matched spot radius of 25 μm.

as forming a high density of relatively cold electrons. This difference in plasma conditions could lead to a decrease in the small-signal gain coefficient of the Xe laser transition, as discussed previously [20]. In particular, partial preionization of the Xe by the discharge will reduce the number of electrons able to pump the upper laser level, and reduce the gain cross section by increasing the transition linewidth. The higher electron density may also reduce the population inversion density through increased deexcitation of the laser levels. A full understanding of the differences in the Xe^{8+} laser kinetics when pumped in a gas cell and a capillary discharge waveguide requires detailed numerical modeling and is beyond the scope of the present paper. However, it is clear from the spectra presented in Fig. 2 that the single-pass gain achieved with the waveguide was more than sufficient for lasing to occur, and that the output was greater than that obtained with a gas cell. Further, the increase in gain length achieved with the waveguide is expected to decrease the divergence of the short-wavelength laser significantly, corresponding to a large increase in brightness.

In summary we have demonstrated lasing on the $4d^9 5d$ $4d^9 5p$ transition in Xe^{8+} using a gas-filled capillary discharge waveguide, this being the first time that a collisionally excited OFI laser has been driven within a waveguide. The success of this proof-of-principle experiment suggests that many other short-wavelength lasers could be driven within gas-filled capillary discharge waveguides, with increased energy extraction and reduced beam divergence.

The authors acknowledge invaluable technical assistance from the laser support staff at LOA. A. B., A. J. G., and C. M. M. are grateful to the EPSRC for research aid. T. M. is supported by a Marie Curie Individual Fellowship of the European Commission and S. M. H. by a Royal Society University Research Fellowship. This work was supported by the European Union via the Access to Large Scale Facilities Program, Contract No. HPRI-1999-CT-00086.

*Email address: simon.hooker@physics.ox.ac.uk
†Email address: sebban@ensta.fr
‡Email address: brigitte.cros@lpgp.u-psud.fr

[1] D. L. Matthews *et al.*, Phys. Rev. Lett. **54**, 110 (1985).
[2] S. Suckewer *et al.*, Phys. Rev. Lett. **57**, 1004 (1986).
[3] V. N. Shlyaptsev *et al.*, SPIE Ultrashort Wavelength Lasers II **2012**, 111 (1993).
[4] J. Nilsen *et al.*, Phys. Rev. A **48**, 4682 (1993).
[5] B. E. Lemoff *et al.*, Phys. Rev. Lett. **74**, 1574 (1995).
[6] T. Ozaki *et al.*, Phys. Rev. Lett. **89**, 253902 (2002).
[7] S. Jackel *et al.*, Opt. Lett. **20**, 1086 (1995).
[8] F. Dorchies *et al.*, Phys. Rev. Lett. **82**, 4655 (1999).
[9] P. Monot *et al.*, Phys. Rev. Lett. **74**, 2953 (1995).
[10] C. G. Durfee and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993).
[11] Y. Ehrlich *et al.*, Phys. Rev. Lett. **77**, 4186 (1996).
[12] T. Hosokai *et al.*, Opt. Lett. **25**, 10 (2000).
[13] D. V. Korobkin *et al.*, Phys. Rev. Lett. **77**, 5206 (1996).
[14] K. A. Janulewicz *et al.*, Phys. Rev. A **63**, 033803 (2001).
[15] N. A. Bobrova *et al.*, Phys. Rev. E **65**, 016407 (2002).
[16] D. J. Spence, A. Butler, and S. M. Hooker, J. Phys. B **34**, 4103 (2001).
[17] A. Butler, D. J. Spence, and S. M. Hooker, Phys. Rev. Lett. **89**, 185003 (2002).
[18] S. Sebban *et al.*, Phys. Rev. Lett. **86**, 3004 (2001).
[19] D. J. Spence and S. M. Hooker, J. Opt. Soc. Am. B **17**, 1565 (2000).
[20] D. J. Spence, A. Butler, and S. M. Hooker, J. Opt. Soc. Am. B **20**, 138 (2003).