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MEASUREMENT OF MULTILAYER MIRROR REFLECTIVITY
AND STIMULATED EMISSION IN THE XUV SPECTRAL REGION

By

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Measurement of Multilayer Mirror Reflectivity and Stimulated Emission
in the XUV Spectral Region

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ABSTRACT

We present measurements of multilayer mirror reflectivity and stimulated emission in the XUV spectral region. A molybdenum-silicon multilayer mirror with 12% measured reflectivity at 182 Å was found to produce a 120% enhancement of the C VI 182 Å line ($3 \rightarrow 2$ transition) in a strongly recombining plasma. No such enhancement of the CV 186.7 Å line was seen, demonstrating amplification of stimulated emission at 182 Å.

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I. Introduction

In recent years there has been a great deal of work aimed at generating soft x-ray lasing action in the laboratory, and a number of promising schemes to demonstrate this have been discussed at length.¹ Recently, there have been several encouraging experimental demonstrations of significant amplification of soft x-rays. The achieved gain length products have been as high as 6.0-6.5 in these experiments.^{2,3}

The demonstration of gain of this magnitude has quite naturally stimulated interest in constructing multiple pass amplifiers or cavities in the soft x-ray region using multilayer mirrors.⁴ The state of the art in fabrication of multilayer mirrors has advanced rapidly in the past few years and has recently been reviewed by Spiller.⁵ In this paper, we report on results obtained with a molybdenum-silicon multilayer mirror developed by T. Barbee⁶ and used in the Princeton University Soft X-Ray Laser Experiment. Section II of this paper will describe the experimental setup and results of reflectivity measurements for this mirror, while section III will discuss measurements of amplification of stimulated emission obtained at 182 Å with this multilayer mirror in use.

II. Experimental setup and reflectivity measurements

Figure 1 shows the experimental setup for the PPL soft x-ray laser experiment. A CO₂ laser operated in unstable resonator configuration is focussed onto a solid carbon target. The hot, dense carbon plasma which is created ($T_e \sim 200-300$ eV, $N_e \sim 10^{19}$ cm⁻³) is confined by a strong solenoidal magnetic field. This plasma then cools rapidly due to radiation losses, resulting in the generation of a strongly nonequilibrium regime characterized by strong recombination of fully stripped carbon to hydrogen-like carbon

(CVI). During this recombination process, a transient population inversion between levels three and two (wavelength = 182 Å) is generated which is large enough to provide significant single-pass gain. A number of theoretical and experimental studies of population inversions in CVI generated through this recombination scheme have been discussed in the literature.⁷⁻¹²

The plasma emission is monitored in the radial direction by an intensity-calibrated two-meter soft x-ray duochromator and in the axial direction by an intensity-calibrated one-meter monochromator/grazing incidence mirror combination. Both of these instruments are operated in photoelectric mode. Population inversions and gain, and the corresponding enhancement of the 182 Å line in the axial direction, have been measured by a number of methods involving comparison of the axial and radial emissions of the CVI ion (details of these measurements are described in Ref. 3). An enhancement of up to 100 of stimulated over spontaneous emission was measured for the CVI 182 Å transition, which corresponds to a gain-length product (averaged over the line profile) of 6.5.

Upon completion of this work the experimental setup was modified for installation of a spherical soft x-ray mirror used in normal incidence as shown in Fig. 1. This mirror, provided by T. Barbee,⁶ is composed of thirty alternating layers of molybdenum and silicon overlaid with a 5 Å carbon coating to deter oxidation of the outer molybdenum layer. The mirror was 2 cm in diameter with a 200-cm radius of curvature and was placed 200 cm from the plasma, which resulted in a magnification of one for the plasma image.

Prior to installation in the x-ray laser experiment, a series of preliminary measurements of the reflectivity of this mirror were carried out in the visible region on a separate test stand. The focal length of the mirror was measured and found to be within one percent of the nominal value.

A mirror similar to that used in the experiments described below was found to have roughly 30% reflectivity at both 3650 Å and 2536 Å, with a mercury lamp used as a light source. These measurements were repeated with this XUV mirror and target in place in the actual experimental chamber; a mercury lamp was placed near the target, and the reflectivity of the multilayer mirror measured again using the axial instrument. After optimization of the multilayer mirror alignment the results were very similar to those obtained on the test bench, indicating that the "optical efficiency" of the system was near unity.

After a preliminary series of experiments the effective reflectivity of the multilayer mirror in the soft x-ray region was measured in situ using a high voltage vacuum spark assembly inserted in the bore of the magnet. The mirror was aligned using a series of helium-neon lasers; the mirror position was adjusted until a good image of the helium-neon laser reflection was present on the entrance slit of the axial instrument. The low inductance vacuum spark¹³ consisted of a 2.2 μ F capacitor charged to 15 kV which was fired by an ignitron triggering circuit. Peak currents of 20 kA were obtained. Carbon and stainless steel electrodes were commonly used for these experiments; the electrode gap was set to 0.8 mm. For the reflectivity measurements described here, continuum radiation was employed.

The results of this reflectivity measurement are shown in Fig. 2. The measured reflectivity at 182 Å was 12%; the spark reproducibility was better than 4%. The total measured bandpass was 20 Å. Figure 2 also shows sample signals from the vacuum spark plasma at 182 Å with the multilayer mirror shutter in the open and closed position. Very recently, reflectivities as high as 40% at 182 Å (with a bandpass of 20 Å) have been achieved for XUV multilayer mirrors used in normal incidence.¹⁴ In the near future we plan to measure the effective reflectivity of a number of these mirrors in situ as

described above and utilize them in measurements of amplified stimulated emission at 182 Å.

III. Measurements of stimulated emission at 182 Å

With the XUV mirror situated in the experimental system as in Fig. 1, a series of preliminary measurements of the amplification of stimulated emission at 182 Å were performed. Figure 3 shows the results of this work; a factor of 2.2 increase in intensity of the 182 Å line was observed in a series of five shots with the multilayer mirror shutter being alternately opened and closed. As a check of this result the axial instrument was set to look at the 186.7 Å line in helium-like carbon (CV); no significant difference between shutter open and shutter closed shots was observed at this wavelength on the axial instrument. During this entire sequence of shots the transverse 182 Å emission was monitored and remained quite constant, as shown in Fig. 3.

Since the effective reflectivity of the XUV mirror at 182 Å is 12%, the measured enhancement of 120% with the mirror open represents amplification of stimulated emission. Experimental measurements³ indicate that the region of maximum gain in this configuration should occur near 1.3-1.5 mm off axis from the incident laser, where the electron temperature is low and the electron density relatively high. Furthermore, measurements indicate that the high gain region is expected to be on the order of 100-200 μ in radial extent. In the future we intend to improve the alignment of the XUV mirror with this relatively narrow gain region. In addition, we plan to use higher reflectivity XUV mirrors with a smaller radius of curvature placed closer to the plasma in order to minimize alignment difficulties. With these improvements, we hope to increase considerably the amplification of stimulated emission at 182 Å.

IV. Conclusions

The attainment of high single-pass gain in the strongly recombining plasmas described here stimulated interest in utilizing multilayer x-ray mirrors to increase the measured enhancement of the 182 Å line. A molybdenum-silicon multilayer mirror of 200 cm radius of curvature and 2 cm diameter was employed for this purpose. The effective reflectivity of this mirror was measured to be 12% at 182 Å, and the bandpass was found to be 20 Å. With this multilayer mirror in use, a 120% enhancement of the 182 Å line intensity in the axial direction was measured. At the nearby wavelength of 186.7 Å no such effect was noted; these data thus demonstrate amplification of stimulated emission at 182 Å. In the future, we plan to optimize the mirror alignment and plasma gain conditions in order to increase this observed enhancement.

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Figure Captions

Fig. 1 Experimental setup for measurement of a) stimulated emission at 182 Å and b) XUV mirror reflectivity.

Fig. 2 Measured reflectivity versus wavelength for a thirty layer silicon-molybdenum multilayer mirror. Sample vacuum spark signals at 182 Å are also shown.

Fig. 3 Axial and transverse 182 Å signals obtained with XUV mirror shutter open and closed.

EXPERIMENTAL ARRANGEMENTS:

A) GAIN MEASUREMENTS

B) BARBEE'S MIRROR REFLECTIVITY MEASUREMENTS IN XUV

Fig. 1

Fig. 2

#86x0023

C-Disc + 4 C-Blades ; B=90 kG ; $P_{CO_2} \approx 300$ JXUV Mirror: ClosedXUV Mirror: Open $k \times \ell \approx 4.3$ (Enh. ≈ 17)

$$\frac{I_{182}^{AXIAL}(\text{Open})}{I_{182}^{AXIAL}(\text{Closed})} \approx 2.2$$

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Fig. 3

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