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Characterization of germanium stripe x-ray lasers

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ABSTRACT

One method of improving the transverse spatial coherence of x-ray lasers (XRLs) is by adaptive spatial filtering of XRL apertures using geometric shaping in the form of bowtie or wedge XRLs. However, we must maintain the desired geometric shapes in exploding foil or slab configurations during the lasing period. As a first step toward understanding lasing in such geometries we study the behavior of simple stripe XRLs. Past experience with stripe XRLs deposited on thick plastic substrates resulted in significantly weaker laser intensities as compared to line-focused slab XRLs. Possible reasons for this intensity reduction of stripe XRLs could include mixing at the laser boundary, and changes in plasma, kinetics, and hydrodynamic properties which affect laser gains and propagation. We will present experimental and theoretical characterizations of germanium line-focused and stripe XRLs. Key experimental parameters we will study include images of emission profiles of the laser blow-off, angular divergences, XRL output intensities, and ionization balances as we vary XRL designs. We will compare the experimental results with two-dimensional (2-D) laser deposition and hydrodynamics simulations using LASNEX, and study the changes in ionization balances and level populations from post-processing LASNEX results.

1. INTRODUCTION

Since the first demonstration of a soft x-ray laser¹ (XRL) in the laboratory, XRLs have been considered for applications in the fields of microscopy, holographic imaging, material processing, microelectronics, and as probing tools for plasma, atomic, and molecular physics phenomena.² Typically, applications of XRLs in areas such as holography and non-linear optics require the laser to be both bright and spatially coherent. Although saturated XRLs have been demonstrated,^{3,4} XRLs are spatially incoherent with large Fresnel numbers of order 50 - 100.⁵ Improved coherence has been demonstrated by using multilayer mirrors and oscillator-amplifier configurations,^{2,4} but these multi-staged configurations are limited by uncertainties in refractive ray propagation and the multilayer damage threshold.⁶ The recent proposal of using adaptive spatial filtering⁷ by geometric shaping is an alternative technique that can produce saturated, single-staged, and diffraction-limited XRLs. This shaped laser can be either a stand-alone laser or used as an oscillator driving a larger aperture amplifier in an optical architecture.

In collisionally excited XRLs, high temperature and density plasmas are produced by optical laser heating of foil or slab targets. The upper laser levels are preferentially populated by monopole coupled collisional excitation processes but these levels are not radiatively coupled to the ground states. The fast depopulation of the lower laser levels by resonance emission produces the population inversion. The population inversion depends sensitively on collisional and radiative processes and is therefore a strong function of plasma conditions. A typical experimental configuration consists of a line-focused laser illuminating a uniformly coated solid or foil target. The laser-driven plasma expands in two dimensions, with electron density (n_e) gradients both parallel and perpendicular to the target surface. Laser photons propagate in a highly refractive medium and produce typical 2-D laser divergences of order 10 mrad in the blow-off direction (herein defined as the direction normal to the target surface) and by 16 - 20 mrad in the transverse direction (herein defined as the direction parallel to the target surface).⁵

Figure 1. (a) Incoming optical laser overfills a bowtie-shaped XRL (dark region) deposited on similar-Z substrate (light region) and produced a more one dimensional hydrodynamic expansion of the XRL plasma (b,c) which maintains the geometric shape of the bowtie laser during expansion.

The concept of adaptive spatial filtering of an XRL uses geometric shaping to control the laser aperture. This could be in a conical or bowtie shaped laser. Figure 1(a) shows an example of the bowtie XRL (dark region) on a substrate made of similar-Z element (light region). In the unsaturated regime, rays that traverse the longest gain regions have the possibility of attaining the most gain-lengths (GL) and highest output intensities. The neck of the bowtie laser acts as a narrow spatial filter where the high GL rays must pass through. These high GL rays have strong correlation between their angle of tilt and their transverse positions. Rays that travel outside of the bowtie neck achieve lower GLs and are also attenuated by surrounding materials. In a non-refractive and uniform-gain medium, the output of a unsaturated bowtie XRL would be weaker than a stripe XRL by the ratio of the neck area to the end area.

In the saturated regime, bowtie XRLs actually increase the coherent power by causing significant power extraction into only a few modes and by eliminating parasitic modes. In saturation the effective (or loaded) gain depends on the overall intensity pattern in a non-linear and self-consistent way. The maximum gain of a saturated bowtie XRL is located at the neck region where the adaptive spatial filtering occurs. This effective spatial gain distribution maintains the correlation between ray tilt and transverse position at the laser output end that is needed to achieve high coherent power. Thus the energy content of a saturated XRL preferentially flows through the few Fresnel zones defined by the neck of the bowtie. In a non-refractive and uniform-gain medium, with all the energy extracted, the output intensity of a bowtie XRL would be weaker than a stripe XRL by the ratio of active gain volumes between the two geometries. But the coherent power of a bowtie XRL would be much stronger than a stripe XRL.

A key issue in the performance of bowtie XRLs is our ability to maintain the bowtie shape during the plasma expansion. We have several design options for a more hydrodynamically stable XRL. One way to fabricate a bowtie XRL is to deposit a bowtie-shaped thin film coating on a thick substrate. The substrate is made of similar-Z material such that the substrate plasma provides a hydrodynamic tamper to the XRL plasma and maintains the bowtie shape during the lasing period. Figure 1(a) shows the incoming optical laser overfilling the bowtie XRL and producing a one-dimensional (1-D) blow-off near the XRL plasma as shown in Figs 1(b) and 1(c). Such one-dimensionally expanding plasmas should also provide a flatter transverse n_e profile in the lasing region and reduce the transverse laser divergence. Since it is difficult to characterize the hydrodynamic stability of a complicated geometry like a bowtie laser, the first step of our plan is to characterize a simpler stripe XRL.

This paper presents our recent theoretical and experimental characterization of a Ge stripe x-ray laser coated on thick Cu substrates. The experiments were carried out at the Nova 2-Beam Facility at Lawrence Livermore National Laboratory. We will contrast the results of the stripe lasers with XRLs produced in the conventional line-focused geometry. Section 2 of this paper shows our experimental setup and section 3 presents the experimental results. In section 4 we present our computational modeling of these experiments. We will summarize our findings in section 5 and outline our future research directions.

2. EXPERIMENTAL SETUP

The stripe XRL is a 120 μm -wide, 1000 - 2000 $\text{\AA}$ -thick Ge stripe deposited on a thick (3 mm) Cu substrate. The width of the stripe corresponds to the best line-focused configuration on Nova. We overfill the stripe XRL by defocusing the beam to $\sim 240 \mu\text{m}$ in order to produce more one-dimensional XRL plasma expansion at the center. In this set of experiments we contrasted the properties of stripe lasers with 120 μm best-focused beam illuminating solid Ge slab (1000 - 2000 $\text{\AA}$ Ge uniformly coated on a thick Cu substrate) and Ge foil (1000 $\text{\AA}$ -thick uniformly coated on thin plastic LEXAN substrate) targets. We used a 600 ps square-pulse while maintaining typical intensities of $2 \times 10^{13} \text{ W/cm}^2$ at 2ω ($\lambda = 0.53 \mu\text{m}$) for both the stripe and solid targets. The intensity for the foil target was set at $5 \times 10^{13} \text{ W/cm}^2$.

Diagnostics used for the ongoing characterization of the stripe XRL includes on- and off-axis spectrometers, a pin-hole camera, and a coherence camera. A microchannel plate intensified grazing-incident spectrograph (MCPIGS) is located at the north on-axis port and measures the time-integrated, spectrally-resolved laser footprint. The MCPIGS has a 10 mrad angular coverage. With a 600 lines/mm grating, MCPIGS has spectral coverage from $\sim 150 - 680 \text{ \AA}$. We have fielded the MCPIGS in two configurations. Typically the MCPIGS slit is oriented perpendicular (normal direction) to the blow-off direction, which measured laser footprints with peaked intensities at ~ 10 mrad off-axis for both slab and foil targets. Since we are characterizing the change of transverse coherence, we have also rotated the MCPIGS 90° to measure the transverse laser footprint at 10 mrad off-axis.

We have fielded two different instruments at south the on-axis port. The streaked flat-field spectrograph (SFFS) provides time and spectrally resolved data with integrated angular coverage in the blow-off direction from 5 - 15 mrad with ~ 1 mrad acceptance angle in the transverse direction. We use a 1200 lines/mm grating to obtain spectral coverage from $\sim 150 - 350 \text{ \AA}$. In some experiments the SFFS spectrograph is replaced with the coherence camera⁵ which uses a uniformly redundant array of slits to measure the diffraction pattern of the XRL in the transverse direction. A calibrated multilayer x-ray mirror, optimized at $\sim 230 \text{ \AA}$ and operating at a grazing angle of 67° , is used as a bandpass filter. The diffraction pattern is used to construct the complex coherence factor. The coherence camera has a 1 mrad acceptance solid angle, and is also positioned at 10 mrad off-axis.

Keanetech is an off-axis streaked x-ray crystal spectrograph viewing 72° down at the laser plasma. We use a KAP crystal which measured the emission spectrum from 8 - 11 $\text{\AA}$. This spectral range includes the main Ne-like Ge $n = 3$ to $n = 2$ lines, some O- and F-like Ge lines, some Ne-like Cu $n = 4$ to $n = 2$ lines, and a host of N-, O-, F-like Cu lines. We also have two off-axis reentrant pin-hole cameras, GAX views from $\sim 45^\circ$, and GSIX views from normal incident. By choosing proper filters we can selectively view x-ray emissions from Cu or Ge plasmas and estimate the hydrodynamic stability of the stripe XRL during the laser blow-off by the spatial images of plasma emission profiles.

3. EXPERIMENTAL RESULTS

The first phase of our experiments was to characterize Ge slab, stripe, and bowtie XRLs and maximize the coherent power of the stripe and bowtie lasers. Figure 2 plots the Keanetech-measured x-ray emission spectra of foil, slab, and stripe XRLs from 8 - 11 $\text{\AA}$. The foil target shows a typical Ne-like spectra with some F-like lines at shorter wavelengths (8.5 - 9 $\text{\AA}$). The Ne-like 3d and 3s $\rightarrow$ 2p lines at 8.92, 9.11, 9.76, and 10.01 $\text{\AA}$ are labeled 3C, 3D, 3F, and 3G respectively.⁸ Both the slab and stripe spectra show larger Cu emission mixed in with the Ge lines. The Cu emissions include contributions ranging from N- to Ne-likes. With more Cu exposed to direct-incident Nova beams, the stripe target has stronger Cu contributions and weaker Ge contributions than the slab target.

Looking from 45° down into the expanding plasma and with no spectral resolving power, the GAX pin-hole camera results can only provide a qualitative view of plasma expansion. We typically use a 50 - 100 μm Be filter which preferentially filter the longer wavelength emission from Cu near 12 $\text{\AA}$. However,

Figure 2. Keanetech-measured x-ray spectra comparing emission profiles of a foil, a slab, and a stripe XRL target, at 400 ps into the Nova pulse. The slab signal level is shifted by 0.002 and the stripe signal level is shifted by 0.006. The Ne-like 3d and 3s $\rightarrow$ 2p lines are labeled 3C, 3D, 3F, and 3G respectively.

as shown in Fig. 2, the 8 - 11 Å region for the stripe is still dominated by strong Cu emission with some strong Ne-like Ge lines. With GAX we observe double-hump spatial emission profile from the overfilled stripe configuration while the line-focused configuration showed a peaked single-hump emission profile. The double-hump feature of the stripe XRL suggests strong Cu emission flanking the weaker Ge emission at the center. In the near future we plan to use a reconfigured GAX camera which adds some spectral resolving capability. We are also planning to use the GSIX camera to view the plasma expansion at normal incidence so we can eliminate the uncertainty of the viewing angle.

The SFFS is used to measure on-axis spatially-integrated, time-resolved x-ray laser spectrum. The 1

Figure 3. Temporal histories of the J=2-1 (236Å) line for the 3.75 cm slab, stripe, and bowtie XRLs.

4. NUMERICAL SIMULATIONS AND ANALYSIS

The modeling of XRL plasmas is performed in stages. For collisionally dominated plasmas we can decouple the detailed level populations and line transfer physics from the rest of the problem.⁹ We use LASNEX¹⁰ to carry out the laser-deposition and hydrodynamics simulations. From LASNEX we obtain plasma characteristics, such as T_e , n_e , and variables such as mesh positions and velocities. Using atomic kinetic post-processing codes such as XRASER¹¹ and GLF^{9,12} we calculate the level populations and line transfer.

In our LASNEX simulation the incident laser (from the z-direction) is defined by a Gaussian spatial profile with FWHM set at the experimentally defined line width, with a symmetry plane ($r = 0$) defined at the center of the line focus geometry. Figures 4 and 5 compare the 2-D plasma expansions, at 500 ps into the laser pulse, between the best focused (120 μm) slab XRL and the defocused stripe XRL (240 μm) configurations. The dark line marked the edge of the Ge XRL plasma. For the 120 μm line-focus case the plasma has large transverse-direction velocities which result in larger transverse n_e gradients. By overfilling the stripe, the Ge laser plasma is hydrodynamically tamped by the Cu plasma and the laser plasma expansion is more one-dimensional, confirming our previous assumptions.

Figure 6. 1-D snapshots comparing spatial T_e , n_e , and the Ge 236 Å line gain profiles, at the $r = 0$ symmetry plane, between the slab (solid line) and stripe (dotted line) XRL simulations shown in Figs. 4 and 5, at 500 ps into the Nova pulse.

Figure 6 plots snap shots, at 500 ps into the shot, of spatial T_e and n_e profiles, and gain profile of the 236 Å Ge line of the two simulations shown in Figs. 4 and 5. The 1D cuts are taken along the $r = 0$ symmetry plane, in the z -direction or the direction of plasma blow-off. With better transverse confinement the stripe plasma, shown with the dotted line, is both hotter and denser, and with flatter n_e profiles in both r - and z -directions. The gain values are obtained by post-processing the LASNEX-calculated plasma parameters using GLF from which we obtained level populations of excited Ne-like Ge states. Although the peak gain values are similar we observe a larger gain region (in the z -direction) for the hotter and denser stripe plasma. For this set of GLF calculations we did not include the effect of trapping. With trapping the peak gain values would be reduced significantly.⁸

With the spatial gain and n_e profiles, we can perform ray propagation calculations to match the simulations with actual observable quantities such as laser output intensities. We are currently working on a three-dimensional Monte-Carlo ray propagation code¹² to study the effect of refraction and gain saturation.

5. SUMMARY

Shaped x-ray lasers in the form of a bowtie has been proposed as a spatially adaptive filter technique to achieve saturated output with diffraction-limited transverse coherence. We have performed numerical simulations and a series of Nova experiments to characterize the stripe XRL as the first step in demonstrating our ability to control the designed XRL shaped during plasma expansion. We performed a series of 2-D LASNEX calculations simulating the line-focused slab and stripe XRL geometries. We found a similar-Z hydrodynamic tamper, such as Cu on Ge, can effectively control the XRL plasma expansion and control the expansion to 1-D. Pin-hole camera images contrasting the stripe and slab emission features qualitatively confirmed our LASNEX results. At or near saturation the stripe XRL intensities are comparable to a line-focused slab XRL. The comparable laser intensities indicate no significant differences in gains and refractive ray propagation between the two lasers. The bowtie XRL intensities were factor of 10 - 15 lower than the saturated stripe and slab XRLs. This intensity difference is likely due to less gain medium of the bowtie configuration. But the coherent power of a saturated bowtie should be stronger than the other laser configurations. X-ray emission spectra in the 8 - 11 Å range of the foil, slab, stripe, and bowtie targets found contributions dominated by Ne-like Ge lines, and a forest of Cu lines ranging from N- to Ne-like. Intensities of Cu and Ge emissions are in agreement with the types of XRLs fielded. A clean Ge spectrum is observed from the foil target while the Cu dominated spectra of stripe and bowtie targets.

We are planning further characterization of stripe and bowtie XRLs, such as measurements of small signal gains, plasma expansion characteristics, and coherence. We also have plans to further enhance the bowtie output by varying Nova pulse shapes, using new XRL target designs, and using multiple-staged oscillator-amplifier configurations. A bright, coherent XRL source has potential applications in imaging rapidly evolving high density plasmas, and a short wavelength bowtie XRL, such as a Ni-like Ta XRL with laser wavelength of 44.8 Å, has significant potential in biological imaging and holography applications.

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