Powerful high-repetition-rate tabletop soft x-ray lasers

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A new, compact 100-shot-per-second soft x-ray laser produces record-breaking average power (0.15mW) at 18.9nm wavelength, potentially enabling numerous applications in nano-scale science and technology.

The generation of high-average-power, coherent, soft x-ray and extreme ultraviolet (EUV) radiation is of great interest for numerous applications, such as sequential single-shot imaging of dynamic nano-scale phenomena, inspection of next-generation EUV lithographic masks at their specific wavelength, and printing of nanostructures without defects. The development of tabletop sources of soft x-ray radiation with increased average power can greatly expand access to high flux, coherent beams of this type of radiation, which at present are only available at dedicated laser facilities. However, achieving the necessary performance has remained a challenge.

Plasma-based laser-pumped soft x-ray lasers, in which spontaneous emission is amplified in a highly ionized plasma column, typically have low repetition rates (of a few shots per day to one shot per minute in the first devices), which limits their average power. Several research groups made significant progress in this area, greatly reducing the size of this type of laser and extending the wavelength to below 10nm. However, the repetition rates of these devices are below ~10Hz, resulting in average powers that are insufficient for applications requiring high photon flux (such as printing nano-scale features by self-imaging coherently illuminated masks). This limitation originates in thermal effects within the flash-lamp-pumped solid-state lasers that drive plasma-based soft x-ray lasers. To address this issue, we developed a compact, ultrashort solid-state laser system driven entirely by laser diodes that produces picosecond duration, \( \lambda = 1.03 \mu m \) pulses of sufficient energy to efficiently drive \( \lambda = 10-20nm \) lasers at much higher repetition rates.

Our device is the first tabletop soft x-ray laser with a 100Hz repetition rate, and it produces an average power of 0.15mW at \( \lambda = 18.9nm \). In our experiments, laser diodes efficiently pumped a high energy (1J) chirped-pulse amplification ytterbium-doped yttrium-aluminum-garnet (Yb:YAG) laser, which we used to drive a soft x-ray plasma amplifier (see Figure 1). The amplification in a highly ionized molybdenum plasma—created and heated by picosecond duration pulses with tailored temporal profiles from the diode-pumped laser—produced gain-saturated, picosecond-duration soft x-ray laser pulses.

Our diode-pumped chirped-pulse amplification laser system consists of a mode-locked ytterbium-doped potassium-yttrium-tungstate (Yb:KYW) oscillator, a grating pulse stretcher, three amplifier stages, and a dielectric-grating-pair pulse compressor. In the first amplifier stage, a regenerative device employs Yb:YAG at room temperature, which produces millijoule-level pulses that are subsequently amplified by two cryogenic Yb:YAG multipass amplifiers. The combination of a relatively broad bandwidth room-temperature preamplifier with cryogenic power amplifiers allowed us to exploit the high gain and excellent thermal properties of Yb:YAG at very low temperatures while avoiding excessive bandwidth loss in the high-gain

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Figure 2. Soft x-ray laser source layout. Cylindrical optics focus the driving laser into a high-aspect-ratio line focus on a solid metal target. The insets show a diagram of the temporal pulse profile of the driver laser pulse (that creates and heats the plasma gain medium) and a photograph of the line-focus plasma.

We focused the $\lambda = 1.03$nm pulses into a narrow line on a flat molybdenum slab (see Figure 2). This produced a plasma with a large transient population inversion and gain in 14-times-ionized molybdenum ions, resulting in powerful lasing at $\lambda = 18.9$nm. Figure 3 shows 3000 consecutive shots of the soft x-ray laser operating at a 100Hz repetition rate along with a single-shot, on-axis spectrum of the plasma emission in the EUV spectral region. (We shifted the molybdenum target 2μm between successive shots.) The mean laser pulse energy of this series was 1.5μJ with a shot-to-shot standard deviation of 11.5%. We also obtained strong lasing at 100Hz at $\lambda = 13.9$nm from a silver plasma using this source.

In summary, we demonstrated 100Hz generation of soft x-ray laser pulses of microjoule energy at $\lambda = 18.9$nm, obtaining a record high average power from a coherent compact source. The approach increased the repetition rate of this type of laser by an order of magnitude, demonstrating the feasibility of multi-milliwatt average power soft x-ray beams on a table top. We anticipate this increase will enable new scientific research and advanced technology applications that require high soft x-ray photon flux. Future work includes the demonstration of these lasers at shorter wavelengths and their use in real-world applications.

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