We report the demonstration of a diode-pumped chirped pulse amplification Yb:YAG laser that produces $\lambda = 1.03 \mu m$ pulses of up to 1.5 J energy compressible to sub-5 ps duration at a repetition rate of 500 Hz (750 W average power). Amplification to high energy takes place in cryogenically cooled Yb:YAG active mirrors designed for kilowatt average power operation. This compact laser system will enable new advances in high-average-power ultrashort-pulse lasers and high-repetition-rate tabletop soft X-ray lasers. As a first application, the laser was used to pump a 400 Hz $\lambda = 18.9 \text{ nm}$ laser.

The development of picosecond lasers with simultaneously high energy and high average power is of great interest for applications in basic research and technology. These applications include the development of compact sources of coherent extreme ultraviolet and soft X-ray radiation [1–3] as well as driving the next generation of high-average-power ultrashort-pulse lasers with wavelengths ranging from the ultraviolet to the mid-infrared through parametric amplification schemes such as optical parametric chirped pulse amplification (OPCPA) [4] and frequency-resolved optical parametric amplification (FOPA) [5].

A number of chirped pulse amplification (CPA) [6], picosecond lasers with increased average power have recently been developed [7–17]. This includes the demonstration of a 100 W thin disk Yb:YAG laser which produced 1 ps pulses of 20 mJ [7], as well as a 250 W cryogenic Yb:YAG amplifier that produced 2.5 mJ pulses at 100 kHz [14]. However, the development of picosecond lasers with simultaneous high energy and high average power has been slower. We have previously reported a laser system that produced 1 J, 5 ps pulses at 100 Hz repetition rate [8,9]. In this earlier demonstration, we exploited the improved thermal [18,19] and spectral [20,21] characteristics of Yb:YAG at cryogenic temperatures. Other groups have also taken advantage of cryogenic Yb:YAG [10,12–14,16,17], obtaining results that include the recent demonstration of 70 mJ picosecond pulses at 1 kHz repetition rate [16]. Our 100 Hz laser system was employed to drive plasma-based soft X-ray lasers at 100 Hz repetition rate operating at a number of wavelengths between $\lambda = 10.9$ and 18.9 nm, including the demonstration of a $\lambda = 13.9 \text{ nm}$ laser with 0.1 mW average power [1]. The laser was also used to study the conversion efficiency and plasma characteristics of a $\lambda = 6.7 \text{ nm}$ laser-produced plasma source for future lithography [22] and to pump an OPCPA that produced 5 mJ pulses at $\lambda = 1.6 \mu m$ [23]. In this Letter, we report a compact all-diode-pumped $\lambda = 1.03 \mu m$ CPA laser based on cryogenically cooled active mirror Yb:YAG power amplifiers that produces pulses with energy of up to 1.5 J at a repetition rate of 0.5 kHz, resulting in an uncompressed average power of 0.75 kW. The output is demonstrated to have good beam quality and good shot-to-shot stability. The laser pulses are compressed in vacuum to durations of about 5 ps FWHM by a pair of dielectric diffraction gratings. Finally, we demonstrate the use of this new laser in driving a $\lambda = 18.9 \text{ nm}$, plasma-based soft X-ray laser at the high repetition rate of 400 Hz.

A schematic of the kilowatt-class CPA laser system is shown in Fig. 1. The power amplifiers are seeded by pulses produced by a diode-pumped, SESAM-mode-locked, prismless, Yb:KYW oscillator and are stretched by a grating pulse stretcher. The seed pulses are first amplified by a room-temperature active mirror regenerative preamplifier and are subsequently further amplified in two cryogenically cooled Yb:YAG active mirror amplifiers, to be finally compressed by a vacuum grating pulse compressor. Amplification in the water-cooled Yb:YAG regenerative amplifier results in the production of $\sim$1 mJ pulses at 500 Hz repetition rate. This amplifier uses a 0.5 mm thick, 10%-at Yb:YAG active mirror, which constitutes a compromise between the thermally efficient thin-disk geometry and simplified pump absorption. The Yb:YAG disk is pumped by $\sim$200 W pulses of 200 µs duration from a fiber-coupled $\lambda = 940 \text{ nm}$ semiconductor laser diode module. The stretched pulses suffer gain narrowing during amplification, and their pulse duration becomes 270 ps. We have compressed these pulses to $\sim$2 ps pulse durations. However, the bandwidth is...
reduced when the wavelength is tuned to match the peak gain of the subsequent cryogenic amplifiers. A Pockels cell and a pair of crossed polarizers are used to improve the pulse contrast prior to further amplification.

The millijoule-level pulses exiting the laser frontend are amplified to 100 mJ by a four-pass (where one pass is defined as the laser pulse traversing the gain medium, reflecting from the HR coating, and traversing the gain medium again) cryogenically cooled Yb:YAG preamplifier. Here, the active mirror geometry is again used, in the form of a 5 mm thick, 2% at Yb:YAG slab mounted onto a cryogenically cooled head inside an evacuated chamber. The back face of the indium wire sealed active mirror is cooled by forced convection with flowing liquid oxygen cooled to 77 K by a nitrogen cryogenic heat exchanger. This results in thermal gradients which are mainly longitudinal to the beam path within the slab and allows us to surpass the heat flux which can be removed via boiling heat transfer without the use of a heat spreader. This preamplifier is pumped by the combination of two 400 W fiber-coupled laser diode modules which are imaged into a \( \sim 4 \) mm spot on the Yb:YAG active mirror by achromatic lenses. The pulses make four passes through the active region where they are amplified to a maximum energy of 100 mJ at 500 Hz repetition rate, as shown in Fig. 2(a). The amplified pulses have a bandwidth of nearly 0.4 nm FWHM centered near \( \lambda / 0.136 \) \( \mu m \) [Fig. 2(b)], which supports compression to sub-5 ps duration.

The pulses from this preamplifier are subsequently injected into the final stage of amplification, consisting of an eight-pass amplifier comprising two custom-designed active mirror amplifier slabs mounted on a single cryogenic cooling head, which is sealed with indium wire, in an evacuated enclosure. The two amplifier slabs were designed to have a large lateral size to thickness ratio that allows for efficient cooling and large pump area, thereby reducing the deleterious thermal effects of thermal lensing, stress, and depolarization. The slabs are composed of a 2 mm thick by 30 mm \( \times \) 30 mm square, 3% at Yb:YAG slab that is surrounded by a 10 mm wide Cr:YAG cladding optically bonded along the perimeter for mitigating amplified spontaneous emission (ASE) and parasitic lasing. As in the previous amplification stage, the entire back faces of the slabs are cooled by direct contact with a flowing, subcooled liquid at 77 K.

The front face of the Yb/Cr:YAG assembly is optically bonded to a 3 mm thick undoped YAG cap that provides structural integrity and further reduces ASE. Each amplifier slab is pumped by a \( \lambda / 0.136 \) 940 nm, 6 kW, 60 bar laser diode array. These pump lasers were pulsed to produce 500 \( \mu \)s duration pulses, and the output was reshaped and homogenized to form a 16 mm diameter, nearly flat-top pump spot on each slab. The unabsorbed pump light is relay imaged back onto the active region by a spherical mirror. This allows for absorption of greater than 90% of the pump radiation, while avoiding an increased doping concentration that has been measured to reduce the thermal conductivity of Yb:YAG at cryogenic temperatures [19]. The pulses are injected into the amplifier through a thin film polarizer (TFP) at the input of the amplifier. The seed pulses make one bounce of each slab before the beam height is changed via a periscope and then proceeds to make one more
bounce of each slab. After these bounces, a $\lambda/4$ wave plate placed before a $0^\circ$ send-back mirror rotates the polarization 90 deg, allowing for the beam to retrace the same path and reflect from the TFP to exit the amplifier. Figure 3(a) shows the measured laser pulse energy at 500 Hz repetition rate as a function of the total pump energy. A maximum laser pulse energy of 1.5 J (750 W average power) was obtained with a total pump energy incident on the Yb:YAG slabs of 4 J. This results in an optical-to-optical efficiency of $\sim$37%. Our simulations of the amplifiers predict an accumulated B-integral at 1.5 J of about 0.7. As can be seen from the $M^2$ measurement of Fig. 3(b), the laser displayed good beam quality with values of $M^2 \approx 1.3$. Very slight thermal lensing was observed that we compensated with the addition of a telescope between the main amplifier and grating pulse compressor. The effective focal length of the thermal lens was determined to be longer than 200 m for a single pass of the amplifier. No observable depolarization occurred. Figure 3(c) shows the measured pulse-to-pulse energy variations over 30 min of continuous operation. During this period, the laser fired nearly 1 million consecutive shots with a standard deviation of 0.75% over the entire run. This variation is close to the specified 0.5% shot-to-shot repeatability of the energy meter used for this measurement. We have typically operated the laser for several hours at a pulse energy of 1.4 J at 500 Hz repetition rate. As can be seen in Fig. 2(b), the fully amplified pulses have a bandwidth of about 0.36 nm FWHM, which supports compression to sub-5 ps pulse durations. Following amplification, the beam is magnified and collimated by a Galilean telescope to a diameter of 40 mm, creating a footprint of 22.5 cm$^2$ on the first grating. This is compressed in vacuum by a pair of 1740 mm$^{-1}$ dielectric gratings with a total path length of about 5300 mm between the gratings. The compressor has an overall efficiency of 72%. Figure 4 shows a second-harmonic generation (SHG) autocorrelation of the compressed pulses. This measurement was made with the pulses traversing the full system and with the cryogenic preamplifier stage operating at full power (100 mJ), where the vast majority of the gain narrowing occurs. The SHG autocorrelation shows a nearly sech$^2$ pulse shape and corresponds to a pulse duration of 3.8 ps FWHM. We routinely operate the system at 5 ps pulse duration. Furthermore, no beam degradation has been observed after compression, and the compressed beam’s quality is evidenced by our ability to form a high-aspect-ratio line focus and generate a soft x-ray laser (SXRL) at 400 Hz.

As the first application of this high-repetition-rate CPA laser, we used it to drive a plasma-based high-repetition-rate, $\lambda = 18.9$ nm soft x-ray laser operating on the $4d^1S_0 \rightarrow 4p^1P_1$ transition of Ni-like Mo. Using a setup similar to that presented in [1], we focused $\sim$1 J temporally shaped pulses into

![Fig. 3.](image)

Fig. 3. (a) Measured pulse energy exiting the final amplifier as a function of total pump energy at 500 Hz repetition rate. A maximum energy of 1.5 J was obtained with a total pump energy incident on the Yb:YAG slabs of 4 J. (b) $M^2$ measurement of the amplified pulses measured with an output pulse energy of 1.4 J at 500 Hz repetition rate. The inset image shows the beam profile at focus. (c) Measured pulse energy over 30 min of continuous operation. The mean energy is 1.41 J with a standard deviation of 0.75% over the entire run.

![Fig. 4.](image)

Fig. 4. Second-harmonic autocorrelation after pulse compression. The solid trace is sech$^2$ fit with a width corresponding to a pulse duration of 3.8 ps FWHM.
a \sim 30 \, \mu m \text{ wide} \times 4 \, mm \text{ FWHM line focus} \text{ onto the surface of a solid molybdenum target. The laser \text{ pulses impinging} \text{ onto the target at a grazing incidence angle of 29 deg to make use of refraction within the plasma to efficiently deposit the pump laser energy into a region of reduced density gradients and optimum density for amplification} [24,25]. \text{ The shaped} \text{ pump pulses} \text{ consisted of a few nanoseconds long ramp that has the purpose of forming plasma ionized to the Ni-like ionization stage, followed by a main plasma heating pulse of about 6 ps FWHM duration.} \text{ The short plasma heating pulse creates a transient population inversion and a sufficiently large gain for the ASE to reach gain saturation in a single pass through the plasma amplifier. On-axis spectra of the plasma emission were recorded using a grazing incidence flat-field diffraction grating and an x-ray-sensitive CCD with thin Al filters to reject visible/ultraviolet plasma spontaneous emission and scattered pump laser light. Figure 5 shows a single-shot spectrum with the driver laser operating at 400 Hz repetition rate in which strong lasing at \lambda = 18.9 \, \text{nm} \text{ is observed. We also made runs of several thousand shots of the} \lambda = 18.9 \, \text{nm} \text{ laser operating at 400 Hz to demonstrate the viability of this method for creating a tabletop high-power SXRL.}\n
In summary, we have developed an entirely diode-pumped CPA laser based on cryogenically cooled Yb:YAG active mirror amplifiers that produces pulses of up to 1.5 J at 500 Hz repetition rate. The amplified laser output can be compressed to yield Joule-level laser pulses of sub-5 ps duration. To the best of our knowledge, these results constitute the highest average power Joule-level laser pulses of sub-5 ps duration. To the best of our knowledge, these results constitute the highest average power reported to date for a Joule-level, ultrashort-pulse laser. The cryogenic cooling technique employed is scalable and is envisioned to enable kilowatt average power short pulse lasers. This laser will enable compact sources of coherent short wavelength radiation with unprecedented average power, as well as make possible a plethora of other applications.

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