Recently, we described a cryogenic Yb:YAG laser system that has produced record amounts of sustained CW (963 W) and picosecond ultrafast average power (758 W) [1]. A mode-locked Yb fiber laser driven Yb:YAG cryogenic laser system was demonstrated operating at a 50 MHz repetition rate, with 12.4 ps FWHM pulsewidth, >15 μJ/pulse, and peak powers of >1.2 MW. The beam-quality $M^2$ was measured to be <1.3. This laser, with high brightness and high peak and average power, has been used to drive the high-average-power (HAP) frequency-doubling experiments described in this Letter. The system described here uses direct pulse amplification without pulse stretching or compression. A similar but somewhat more complex HAP green Yb:YAG cryogenic laser system has been described [2] that employed chirped-pulse-amplification (CPA) and produced 130 W of average power. HAP green sources have traditionally been produced using intracavity doubled acousto-optic Q-switched Nd:YAG and Nd:YLF lasers. Such lasers, while capable of hundreds of watts of output power, typically have multimode beam-quality with $M^2$ values in the range of 10–30, and low peak power due to the long pulse widths associated with acousto-optic Q-switching. While such sources are useful for some materials processing applications such as diamond processing, marking, and welding, and in pumping femtosecond low average power Ti:Sapphire lasers, advanced applications such as higher harmonic generation, optical parametric chirped pulse amplification, and producing ultrafast lasers that operate with concomitant high-peak-power (HPP) and HAP require new sources that are capable of high brightness near-diffraction-limited operation with both HPP and HAP. Cryogenic Yb based cryogenic lasers seem very promising in that regard. The favorable scaling of the thermal conductivity to higher values, as well as the significant decrease in the thermo-optic coefficient ($dn/dT$) and thermal expansion coefficients as temperature is lowered, has resulted in a number of recent demonstrations where the capability to be scaled to high average power with excellent beam-quality was achieved using CW, Q-switched, and mode-locked driven configurations [1–6]. The system used to produce the fundamental 1029 nm output is identical to that described in [1]. A mode-locked Fianium Yb fiber laser operating at 50 MHz and ~2 nJ/pulse was amplified, after a 40 db Faraday isolation stage, using a seven disk Yb:YAG cryogenic pre-amplifier, with each disk CW pumped by two fiber-coupled 30 W 940 nm diodes. The pre-amplifier was double-passed using polarization multiplexing. The beam exiting the pre-amplifier was then further amplified using a second single-passed amplifier with eight Yb:YAG disks. Each disk was CW pumped with two 100 W 940 nm fiber-coupled diodes. Lenses were used to image the Fianium laser into the first amplifier, and the beam exiting the first amplifier into the second. Various beam-diagnostics were used to characterize the laser, including a fast photodiode, an optical spectrum analyzer, an autocorrelator for pulsewidth measurements, a beam-quality measurement system, and a HAP calorimeter. This laser is capable of providing >750 W of average power at 1029 nm.

In Fig. 1, we show the experimental setup for the HAP second-harmonic generation (SHG) experiment. A half-waveplate was used to optimize the polarization for maximum SHG efficiency. A SiO$_2$ or BK-7 lens was used to focus the 1029 nm beam into the lithium triborate (LiB$_3$O$_5$) (LBO) crystal, mounted in an oven for noncritical phase-matching (NCPM) at ~195.563 K. A harmonic separator was used to reject the unconverted 1029 nm light, and to pass 514.5 nm.

Type I ooe NCPM in the nonlinear crystal LBO was used ($\theta = 90^\circ$, \(\varphi = 0\)); the calculated phase-matching temperature using the Sandia nonlinear optics program SNLO [2] is 195.563 C (468.563 K). The measured
phase-matching temperature as indicated by the crystal oven monitor was about 187°C; the temperature is monitored at a location away from the LBO crystal, and results in about an 8.5°C temperature differential. The $d_{31}$ of LBO is about 0.854 pm/V [7], or about 1/4 that of potassium titanyl phosphate (KTiOPO4) (KTP). The calculated LBO spectral FWHM bandwidth (using SNLO [8]) for our 20 mm long LBO crystal is 3.035 nm, or greater than 19 times that of the measured spectral bandwidth (0.155 nm) of the Yb:YAG laser operating at 500 W output power [1]. LBO has a rather high damage threshold (≈19 GW/cm²) [7] for antireflection (AR)-coated crystals, and no damage was observed in our experiments. The calculated (FWHM) temperature acceptance bandwidth for the 20 mm long crystal is 2.14 K, while the 90% bandwidth is 0.86 K. For 83 W of 1029 nm light incident on the LBO crystal, whose temperature was varied using the oven controller, our measured FWHM temperature bandwidth was 1.8 K.

The measured SHG power, as a function of the incident 1029 nm power, is shown in Fig. 2 for focusing lens focal lengths of 40, 50, and 75 cm. Using the 50 cm focal length lens, it can be seen that the average power was 201 W for 419 W of 1029 nm input power; the corresponding SHG efficiency was about 48%. The energy/pulse was 8.4 μJ, and the FWHM pulsewidth 12.4 ps, resulting in a peak power of 677 kW. We estimate that the peak intensity is about 2.6 GW/cm²; the 1/e² beam diameter incident on the focusing lens was about 4 mm. Partial results were obtained with the 40 and 75 cm focal lengths. A higher efficiency was obtained with the 40 cm lens, about 58% for 238 W input power. Data obtained with the 40 and 75 cm lenses could not be extended to higher average powers due to the misalignment of the fundamental beam in the vertical direction in the final power amplifier as average power was increased, resulting in optical damage of a disk, which necessitated system realignment. Nevertheless, it is apparent from Fig. 2 that conversion efficiencies of >60% can be achieved with a more optimized setup; to achieve that we would use an LBO crystal with the lowest possible fundamental and second-harmonic absorption, shorten the crystal, and further optimize the fundamental focusing conditions.

We believe this result to be the highest green average power obtained to date from a picosecond laser system. Recent similar work using a CPA system produced 130 W of green average power [2]. In agreement with that previous work, we determined that the highest average power was obtained with the lens focus located at or just beyond the exit face of the LBO crystal; in addition the LBO oven temperature had to be optimized for each input power.

Measurements of the green output beam-quality were obtained using a Spiricon measurement system for the range 0–100 W. Program end prevented extending the results to 200 W. Figure 3 shows the obtained results; above 25 W it can seen that beam-quality is nearly independent of average power. The average X value is 1.39 and the Y value 1.19. The fundamental beam has an $M^2$ value of 1.28 at 500 W. Based on these considerations and the high conversion efficiency obtained, it is likely that the second-harmonic beam-quality does not increase significantly from 100 to 200 W. A beam image is shown in Fig. 4 for an average power of 75 W.

The FWHM pulsewidth of the 514.5 nm pulses could not be obtained due to the falloff of our autocorrelator sensitivity in that spectral region. It is likely however that the green pulses have a somewhat shorter duration due to the conversion efficiency changing in response to the Gaussian temporal profile. The maximum green pulse energy obtained was 4 μJ; if we assume the same 12.4 ps pulsewidth as the 1029 nm pulses, then the minimum peak power obtained is about 324 kW. Spectral measurements of the pulses yielded a FWHM bandwidth...
of 0.18 nm, commensurate with a transform-limited pulse-width of 1.94 ps.

It is apparent from Fig. 2 that thermal effects begin to play an important role for more than about 100–150 W of fundamental incident power. We have built a coupled-wave computer code to solve the SHG equations for both flat-topped and Gaussian spatial and temporal pulses. For perfect phase-matching and a spatially and temporally Gaussian pulse, and assuming the same input parameters that were measured experimentally, the predicted SHG conversion efficiency of about 75% is about 15%–30% higher than what we demonstrated experimentally, indicating that thermal heating is becoming a significant issue at high average power, resulting in phase-mismatching that reduces conversion efficiency. We have built a separate three dimensional thermal model for LBO using a completely anisotropic description. We have found that for perfect phase-matching, the longitudinal gradient in the LBO crystal, the difference between the 0.77 K maximum temperature rise at the input face and that at the output face is about 2.67 K, and due almost entirely to the second-harmonic wave. This is comparable to the FWHM bandwidth of 2.14 K, and indicates that significant phase-mismatch is taking place. At the LBO exit face, the radial temperature gradient is about 0.7 K between the beam center and the radial coordinate \( r = \omega_0 \), and nearly equal for both transverse coordinates. The longitudinal and radial gradients are larger than those reported in [4], due to the larger fundamental pump power. The near-constancy of the fundamental beam-quality as average power increases, combined with these results, indicates that thermal effects are presently the limiting factor to producing higher average power. We are currently working to merge the SHG and thermal codes to provide a more detailed view of SHG generation at HAP, and expect to report those results in a separate publication.

References