20-W ultraviolet-beam generation by fourth-harmonic generation of an all-solid-state laser

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Received July 21, 1999

We have obtained UV power of 20.5 W with a repetition rate of 10 kHz by the use of a high-brightness high-power all-solid-state green laser and a high-quality $CsLiB_6O_{10}$ crystal. This power is, to our knowledge, the highest UV power achieved so far in all-solid-state lasers. © 2000 Optical Society of America

OCIS codes: 140.3480, 140.3610, 140.3540, 190.2620.

High-power all-solid-state UV lasers based on harmonic generation are promising for use in precise material processing applications in industrial fields with potential advantages in maintenance cost, system size, and efficiency compared with other UV lasers. Industrial precise processing applications such as drilling on printed circuit boards and cutting printed circuits require at least 20 W of UV power at kilohertz repetition rates. However, the UV power of all-solid-state lasers has been limited to less than the entry power level of 20 W, as shown in Fig. 1. Achievement of UV power by the fourth-harmonic generation of various types of solid-state laser is detailed in Fig. 1. In 1995, UV power of 1.5 W was reported with a β-BaB_2O_4 (BBO) crystal in cw mode.[1] Subsequently, higher UV powers were achieved with $CsLiB_6O_{10}$ (CLBO) crystal.[2–4] In 1996, 266-nm UV power of 5 W was reported with a CLBO crystal at a repetition rate of 10 Hz.[2] In 1997, 266-nm UV power of 9.7 W was reported with a CLBO crystal at a repetition rate of 100 Hz,[3] and 10.6 W was reported in 1998 with a CLBO crystal with a repetition rate of 100 Hz.[4] However, reports of saturation of UV power in conventional fourth-harmonic generation of all-solid-state lasers seemed to appear in 1997.

For fourth-harmonic generation at a repetition rate greater than in the kilohertz range, 266-nm UV power of 2.5 W was reported at the repetition rate of 1 kHz in 1997,[5] and 6.6 W was reported at a repetition rate of 5 kHz in 1998.[6] At high repetition rates, UV power was less than at a low repetition rate of less than 100 Hz. In fact, the thermal effect that is due to UV absorption in the crystal and the damage to the crystal caused by the absorbed UV power have been problems for high-power UV generation at high repetition rates.[5,6]

The UV power and the repetition rate have been limited by the lack of a high-repetition high-brightness all-solid-state green laser and also by the lack of high-quality CLBO crystals that can withstand high-power operations and thus thermal dephasing of the crystal. We have improved the quality of CLBO crystals, have found the optimum input conditions for high-repetition-rate high-power green laser beams in CLBO crystals, and have proved that generation of a higher-power UV beam is possible without damaging the crystal even at a high repetition rate. Here we report on generation of a higher-power UV beam by the use of a high-brightness high-power all-solid-state green laser and a high-quality CLBO crystal.

The CLBO crystal was grown at Osaka University from a solution by the top-seeded Kyropoulos method. High-quality CLBO crystals with higher damage thresholds were obtained by optimization of the growth speed. The CLBO crystal surfaces were polished by KogakuGiken Co., Ltd., for maximum hygroscopicity and minimum hardness. The surface roughness was measured by an optical surface-roughness meter to be 0.59 nm rms. This value is approximately equal to that of commercial BBO crystals.

The all-solid-state UV laser system is shown in Fig. 2. To generate a higher-power UV laser beam, we used a high-brightness high-power high-repetition-rate Q-switched diode-pumped Nd:YAG green laser as the light source and a high-quality CLBO crystal. The green laser generates an ~100-W green laser beam with a beam quality M^2 of 10.[7] We operated the green laser at a repetition rate of 10 kHz; the pulse width of the green beam was 80 ns. A 15-mm-long CLBO crystal, cut at a type I fourth-harmonic-generation angle θ of 62° without antireflection coating, was used at 140 °C to prevent hygroscopic deterioration. A plano–convex lens was used to focus the input green beam into the CLBO crystal. The input green beam's radius was 0.3 mm, as was found to be essential for avoiding damage. Two harmonic mirrors with high reflectance at 266 nm and high transmittance at 532 nm were used to separate the UV beam with a separation ratio of more than 99%. The average UV power is shown in Fig. 3 as a function of the input average green power. The UV power increased in proportion to the square of the green power. The average UV power of 20.5 W was obtained at an input average green power of 105.8 W. This value is, to our knowledge, the highest UV power in all-solid-state lasers, and for the first time the UV power exceeded the 20 W that is required for commercial applications. The conversion efficiency from a green beam to an UV beam was 19.4%.

The UV beam quality estimated from the output beam pattern was approximately the same as the input green beam quality M^2 of 10. Because no saturation of UV power was observed against the green power, we believe that increasing the green power should produce a higher UV power. No damage to the CLBO crystal and no UV power degradation were observed in 10-min operation at 20.5 W of UV power. Longer-time stability of the UV power and reliability of the CLBO crystal at this power level are under investigation. The pulse shape of the UV beam is shown in Fig. 4. The pulse shape width was 46 ns FWHM at the UV power of 20.5 W. The obtained UV power is plotted against the year in which it was first reported, together with other reported UV powers achieved by fourth-harmonic generation of solid-state lasers, in Fig. 5.

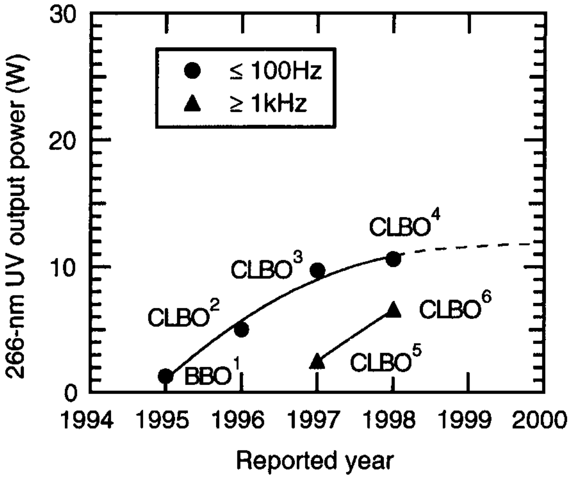

Fig. 1. History of UV power from fourth-harmonic generation of solid-state lasers. The crystals that were used to produce the plotted powers are identified. Superscripts 1–6 are reference numbers.

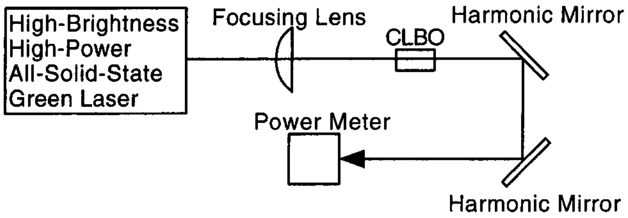

Fig. 2. All-solid-state UV laser system.

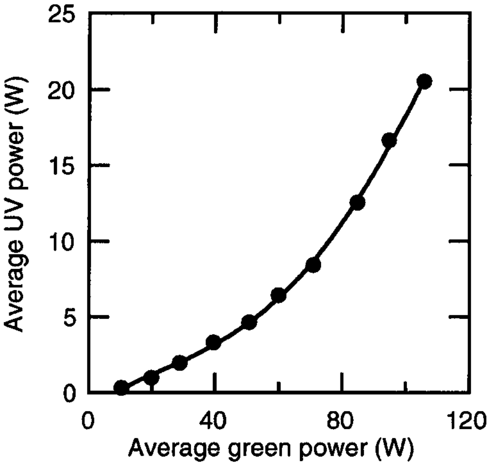

Fig. 3. Average UV output power as a function of average green input power.

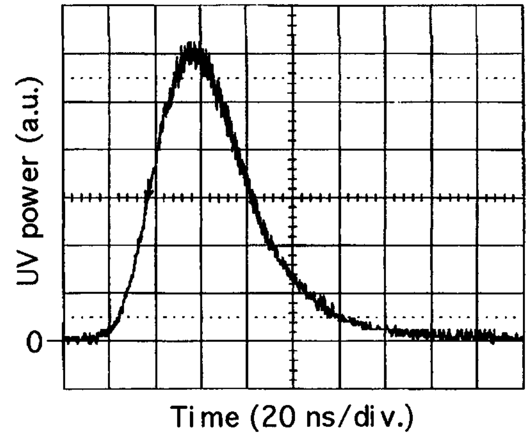

Fig. 4. Pulse shape of UV output beam at a power of 20.5 W.

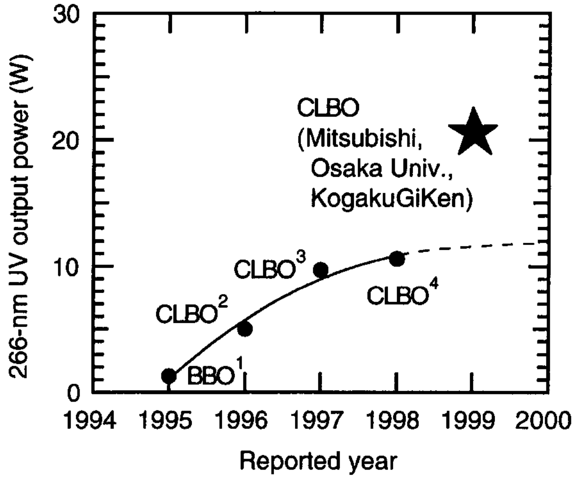

Fig. 5. New history of UV power from fourth-harmonic generation of solid-state lasers. Superscripts 1–4 are reference numbers.

In conclusion, we obtained an UV power of 20.5 W at a repetition rate of 10 kHz by the use of a high-brightness high-power all-solid-state green laser and a high-quality CLBO crystal. This power is, to our knowledge, the highest UV power achieved in all-solid-state lasers. The conversion efficiency was 19.4%, and pulse shortening by the conversion was observed.

Parts of this research were performed at Mitsubishi Electric Corporation, Osaka University, and KogakuGiken Co., Ltd., under the management of the Manufacturing Science and Technology Center as the Industrial Science and Technology Frontier Program, “Advanced Photon Processing and Measurement Technologies,” of the Ministry of International Trade and Industry, supported by New Energy and Industrial

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