Continuous-wave single-frequency 532 nm laser source emitting 130 W into the fundamental transversal mode

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The nonlinear effect of second-harmonic generation is an efficient way to realize high-power green laser sources. But when scaling up the harmonic power, many setups reported in the literature have been limited by conversion efficiency degradation or the fundamental laser power. Here we report on the generation of 134 W of cw laser light at a wavelength of 532 nm from a fundamental power of 149 W by second-harmonic generation in an external optical resonator comprising a lithium triborate crystal. The external conversion efficiency was 90%. The harmonic light consisted of a single spectral line. At least 97% of it was emitted into the fundamental transversal mode. © 2010 Optical Society of America

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High-power cw green light is important in many applications. Examples are titanium–sapphire or dye laser pumping [1] and the generation of cw deep-UV radiation by second-harmonic generation (SHG), which are important for laser guide star adaptive optics systems [2], fiber Bragg grating production, or semiconductor mask inspection [3]. Further, cw welding in the green spectral region is advantageous when materials are processed that have higher reflectivities for IR than for green light [4]. A reduction of the power fractions inside higher-order transversal modes increases microwelding precision. Future ground-based gravitational-wave detectors, like the Einstein Telescope, and space-borne missions, like the Deci-hertz Interferometer Gravitational Wave Observatory or Big Bang Observer, might also benefit from a single-mode high-power laser source at 532 nm [5]. They will maintain their signal-to-quantum-noise ratio if both the optical wavelength and the circulating optical power are halved [6]. However, thermal effects would be strongly reduced. Compared to argon ion gas laser systems, neodymium-doped solid-state lasers emitting at 1064 nm are more efficient. Thus, it is a promising technique to generate light at 532 nm via the effect of SHG from such an IR laser.

In the past, several authors reported on single-pass SHG experiments with nonlinear materials that show very high effective nonlinearities d_{eff}, like (periodically poled) lithium niobate/tantalate or KTP. But the conversion efficiency of these materials (poled or not) was strongly degraded when exposed to incident fundamental powers of multiple tens of watts (e.g., [7–10]). In high-power experiments it is therefore beneficial to use nonlinear crystals with higher tolerances to optical power and place them inside an optical resonator (cavity) with sufficiently high finesse to compensate for their smaller d_{eff}. In some setups, the optical resonator was realized by the primary laser resonator itself. But such intracavity doubling schemes were limited by instabilities (e.g., [11,12]). Therefore, we decided to place the nonlinear crystal within an external optical resonator. As a nonlinear material, we chose lithium triborate (LBO) because it can be noncritically phase matched and is expected to be nonhygroscopic [13]. Noncritical phase matching is beneficial because it avoids a walk-off angle between the fundamental and harmonic waves, which tends to distort the harmonic beam shape [14] and limits the interaction length. Furthermore, several publications have reported that, at the employed intensity levels, LBO did not show the above-mentioned performance degradations (e.g., [15,16]). As we did not know if this holds for higher intensities, we intended to mitigate such problems in advance by use of a long crystal and by designing a considerably bigger waist inside the crystal than that which corresponded to maximum single-pass conversion efficiency (also known as Boyd–Kleinman focusing) [17]. Enlargement of the waist inside the crystal lowers the fundamental and harmonic intensity but not the external conversion efficiency (ECE) as long as the round-trip loss due to conversion dominates other losses and as long as the cavity is kept impedance matched. The intended setup was simulated in advance to find suitable values for waist size and reflectivity of the input coupler. The monochromatic simulation assumed a lossy optical resonator comprising an ideal LBO crystal without any thermal or nonlinear effects other than the conversion process itself.

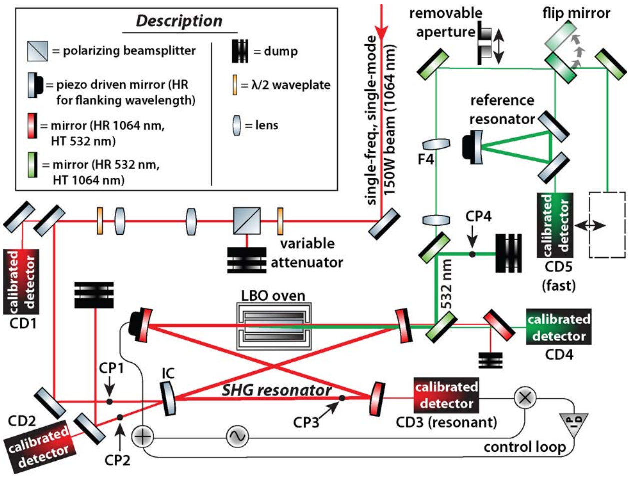

Fig. 1. (Color online) Schematic of experimental setup.

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A schematic of the overall experiment is shown in Fig. 1. The fundamental laser light was provided by a spatially filtered laser with higher-order mode content of less than 2% [18]. Its alignment, focusing, and polarization was optimized for maximum conversion efficiency. The SHG resonator consisted of two convex mirrors with a radius of curvature (ROC) of 1.0 m and two concave mirrors (ROC $= +0.2$ m) in a bow-tie configuration. Its parallel arms were 21.5 and 27 cm long and 7.5 cm apart. Convex mirrors eased the incorporation of the rather big LBO oven, because they allowed enlarging the resonator mirror distances without an increase of the eigenmode's astigmatism. The LBO crystal with dimensions 3 mm × 3 mm × 5 cm was cut for Type I noncritical phase matching around 149.5 °C, and the resonator was designed to form an astigmatically compensated waist of 65 μm at the crystal's center. The only mirror with intentional transmission was the input coupler (IC, $R = 74\%$), and its reflectivity R was chosen to match the round-trip losses for the fundamental light at maximum available IR power, which were by far dominated by the conversion process. This choice assured maximum circulating power, which optimizes the ECE. The low value of R caused a rather big resonator linewidth, which eased the stabilization of one of its resonances to the incident light via a control loop similar to a Pound–Drever–Hall scheme [19]. The photodetectors CD1 to CD4 utilized semiconductors as light-sensitive elements, and their output voltages were calibrated to represent the optical powers at calibration points CP1 to CP4. The maximum accuracy error of the detector calibration was determined to be ±7.3%. A triangular reference resonator (RR) with adjustable length and a measured finesse of 530 was used for transversal mode analysis and to determine the fraction of harmonic power η_{00} that was emitted into the TEM_{00} mode. Its design resulted in a circular eigenmode and avoided the degeneracy of resonances of transversal modes below a mode index sum of 30. A flip mirror was used to detect either its transmitted or its incident light. A removable circular black aperture with a radius of $R_{ap} = 0.85$ mm could be placed at a distance of 40.5 cm in front of the waist inside the reference resonator, which had a radius of 263 μm.

The conversion performance of the SHG resonator is shown in Fig. 2. Each data point is the mean of a 10-s-long continuous measurement. The measurement agreed within its error bars with the results of the same numerical simulation of the light propagation from CP1 to CP4, which was already mentioned above. This agreement shows that thermal and nonlinear effects other than the conversion itself are negligible in our LBO doubling cavity. A harmonic output power of 134 W was measured at an incident fundamental power of 149 W. To the best of our knowledge, this is the highest power of green single-frequency laser radiation and the highest power of cw green light generated by SHG in general reported so far. The harmonic linewidth was measured to consist of a single spectral line narrower than 700 kHz by transmission through the RR, and it is expected to resemble that of the primary laser, namely, an nonplanar ring oscillator with a spectral linewidth of the order of 100 Hz [20]. Both linewidths refer to a 25 ms long measurement interval. The relative peak-to-peak power fluctuations of the harmonic light amounted to 8% within 100 s at maximum power and to 12% within 48 h of continuous operation at harmonic power levels above 110 W. All in all, the system was operated for more than 100 h at such power levels. No obvious performance change could be measured during these long-term tests, as well as after periods without operation. The ECE from point CP1 to CP4 was deduced from the power measurements just stated and is also shown in Fig. 2. At maximum harmonic power, 90% efficiency was achieved. To the best of our knowledge, this is, again, the highest value published so far for SHG of any wavelength with harmonic output powers above 150 mW (for smaller harmonic powers, a slightly higher value of 92% was reported [21]). It is almost completely limited by imperfections of the overlap of the incident beam with the resonator eigenmode, which were measured to amount to 7.8%. This value was calculated as the ratio of reflected and incident fundamental power in the approximately impedance-matched case at maximum harmonic power. The round-trip losses of the resonator by absorption and outcoupling were measured to be 1.5%.

The evolution of η_{00} with increasing harmonic power is shown in Fig. 3. Setting lens F4 under an angle of 7° improved η_{00} slightly. For maximum power, an upper limit of $\eta_{00} \leq 98\%$ was obtained by summation of nine recognizable transversal modes in the transmitted light of a scan over the RR's free spectral range. This mode-scan technique (MT) is described in [22]. The weakest still recognizable mode in our experiments would have contained a power fraction of $\beta \geq 5 \times 10^{-4}$. As there could be weaker

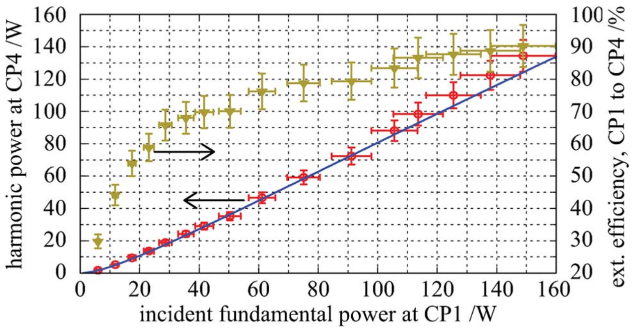

Fig. 2. (Color online) Harmonic power (red circles) and ECE (yellow triangles) of the SHG resonator compared to a numerical simulation (blue solid line).

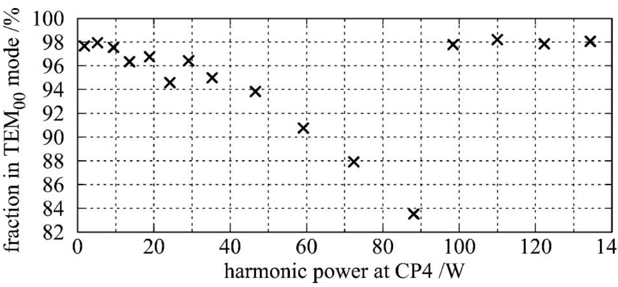

Fig. 3. Evolution of η_{00}. The alignment was optimized for each data point. The positions of the mode shaping lenses were optimized only once at a harmonic power of 90 W. The reduction of η_{00} prior to this was mainly due to increased power fractions within the $\mathrm{TEM}_{02}/\mathrm{TEM}_{20}$ modes hinting on thermal lensing effects in the crystal.

and, thus, not identified, higher-order modes in the beam, the MT could only set an upper limit for η_{00}.

A weak lower limit of $\eta_{00} \geq 91\%$ was derived from the fraction of incident light that was transmitted through the RR on the peak of its TEM_{00} resonance. But this limit is strongly influenced by the resonator's impedance mismatch and losses. To end up with a stronger lower limit, the fraction C_{ap} that was cut off from the entire harmonic power P_0 by transmission through the above-mentioned circular aperture was measured to be $C_{ap} \leq 0.4\%$. This fraction has contributions from modes already identified by MT and from not-identified modes:

$$C_{ap} = \sum_{(n,m)\in\{\text{ident. modes}\}} \alpha_{nm}(1 - T_{nm}) + \sum_{(w,v)\in\{\text{not ident. modes}\}}^{\mathcal{N}} \beta_{wv}(1 - T_{wv}). \qquad (1)$$

Here α_{nm} and β_{wv} denote the fraction of P_0 contained in a certain higher-order mode and T_{yx} is the power transmission of the aperture for the transversal mode with indices (y, x). While the first sum can be evaluated with the data from MT, the second cannot. $\mathcal{N}$ is the unknown number of not-identified higher-order modes present in the harmonic beam in front of the aperture. To derive a conservative estimation of the amount of power contained in not-identified modes, we assume that $\beta_{wv} \leq \beta$ and that the contributing pairs (w, v) are given by those not-identified modes with the biggest values of T_{wv}. With these estimations, Eq. (1) can be evaluated to get the value of $\mathcal{N}$. From that, one gets an upper limit for the maximum fraction of power in higher-order modes in general:

$$(1 - \eta_{00}) \leq (P_{\text{identified modes}} + \mathcal{N}\tilde{\beta}P_0)/P_0. \qquad (2)$$

In our case, Eq. (2) gave a much stronger lower limit of $\eta_{00} \geq 97\%$. Thus, the SHG resonator emitted a harmonic power of 130 W into the TEM_{00} mode.

In conclusion, we generated 134 W of cw single-frequency laser light at 532 nm. At least 97% of it was emitted into the TEM_{00} mode, and the ECE was 90%. Without significantly compromising the ECE, our design allowed us to reduce the intensities in the crystal by increasing the waist size compared to the one for optimal single-pass conversion. Comparison of measurement and simulation showed that thermal and nonlinear effects other than the SHG process itself did not significantly influence the ECE. The obtainable harmonic power appeared to be limited mainly by the available fundamental power. Thus our setup should be able to produce even more green light if equipped with a stronger IR laser.

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References

1. H. J. Baving, H. Muuss, and W. Skolaut, Appl. Phys. B **29**, 19 (1982).
2. S. Rabien, R. I. Davies, T. Ott, S. Hippler, and U. Neumann, Proc. SPIE **4494**, 325 (2002).
3. J. Sakuma, Y. Asakawa, and M. Obara, Opt. Lett. **29**, 92 (2004).
4. G. Hummelt, Laser Focus World **42**, 77 (2006).
5. J. R. Gair, I. Mandel, A. Sesana, and A. Vecchio, Class. Quantum Grav. **26**, 204009 (2009).
6. D. G. Blair, *The Detection of Gravitational Waves* (Cambridge U. Press, 1991).
7. S. Spiekermann, F. Laurell, V. Pasiskevicius, H. Karlsson, and I. Freitag, Appl. Phys. B **79**, 211 (2004).
8. Z. M. Liao, S. A. Payne, J. Dawson, A. Drobshoff, C. Ebbers, and D. Pennington, J. Opt. Soc. Am. B **21**, 2191 (2004).
9. O. A. Louchev, N. E. Yu, S. Kurimura, and K. Kitamura, Appl. Phys. Lett. **87**, 131101 (2005).
10. S. Sinha, D. S. Hum, K. E. Urbanek, Y.-W. Lee, M. J. F. Digonnet, M. M. Fejer, and R. L. Byer, J. Lightwave Technol. **26**, 3866 (2008).
11. L. McDonagh and R. Wallenstein, Opt. Lett. **32**, 802 (2007).
12. Y. Zheng, F. Li, Y. Wang, K. Zhang, and K. Peng, Opt. Commun. **283**, 309 (2010).
13. Z. Lin, L. F. Xu, R. K. Li, Z. Wang, C. Chen, M. Lee, E. Wang, and D. Wang, Phys. Rev. B **70**, 233104 (2004).
14. T. Umeki, O. Tadanaga, and M. Asobe, IEEE J. Quantum Electron. **46**, 1206 (2010).
15. T. Südmeyer, Y. Imai, H. Masuda, N. Eguchi, M. Saito, and S. Kubota, Opt. Express **16**, 1546 (2008).
16. L. R. Taylor, Y. Feng, and D. B. Calia, Opt. Express **18**, 8540 (2010).
17. T. Meier, in *AIP Conference Proceedings* (2010), Vol. 1274, pp. 156–162.
18. B. Willke, K. Danzmann, M. Frede, P. King, D. Kracht, P. Kwee, O. Puncken, R. L. Savage, B. Schulz, F. Seifert, C. Veltkamp, S. Wagner, P. Wessels, and L. Winkelmann, Class. Quantum Grav. **25**, 114040 (2008).
19. E. D. Black, Am. J. Phys. **69**, 79 (2001).
20. J. W. Czarske, R. Phillips, and I. Freitag, Appl. Phys. B **61**, 243 (1995).
21. T. Umeki, M. Asobe, Y. Nishida, O. Tadanaga, K. Magari, T. Yanagawa, and H. Suzuki, IEEE Photonics Technol. Lett. **20**, 15 (2008).
22. P. Kwee, F. Seifert, B. Willke, and K. Danzmann, Rev. Sci. Instrum. **78**, 073103 (2007).