Powerful red-green-blue laser source pumped with a mode-locked thin disk laser

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Received March 29, 2004

We present a red-green-blue laser source with average powers of 8 W in the red, 23 W in the green, and 10.1 W in the blue. The entire pump power for the nonlinear conversion stages is provided by a single laser oscillator without any amplifier stages. Our system does not require any synchronized cavities, and all nonlinear crystals except one are critically phase matched at room temperature. © 2004 Optical Society of America

OCIS codes: 140.4050, 190.7110.

Laser projection systems have significant advantages over conventional lamp projectors. The superposition of three laser beams with a suitable combination of wavelengths in the red, green, and blue can provide access to a wide color gamut and allows excellent color saturation to be achieved. A laser projector permits fully digital data recording, handling, transmission, and storage, which brings additional advantages compared with analog film rolls. Moreover, the large focal depth of a laser beam allows for projection even on curved surfaces.

In this Letter we present a red-green-blue (RGB) laser source with greater than 8 W of average power per color in a setup that to our knowledge is unprecedented not only in terms of output power but also simplicity and practicability. Previous RGB laser sources with multiwatt output powers relied on complex oscillator–amplifier pump sources and nonlinear frequency conversion stages including optical parametric oscillators.[1,2] In our setup the entire pump power required for the nonlinear conversion stages is provided by a single laser oscillator without any amplifier stages. The system does not require any synchronized cavities, and all nonlinear crystals except one are operated at room temperature. Thus only one temperature-stabilized oven is required. Such a combination of attractive properties has been made possible by the recent enormous progress in the development of mode-locked lasers with very high average and peak output powers. In particular, passively mode-locked thin disk lasers[3–5] now deliver up to 80 W of average output power in subpicosecond pulses. The high peak powers of these lasers allow highly efficient wavelength conversion even in critically phase-matched nonlinear crystals. In this way they have allowed the development of novel simple and practical schemes for efficient nonlinear frequency conversion. Examples are optical parametric generators (OPGs) that are directly pumped by a mode-locked laser[6] or fiber-feedback optical parametric oscillators.[7]

We base our RGB system on an Yb:YAG thin disk laser, passively mode locked with a semiconductor saturable absorber mirror.[8,9] This laser is a modified version of the laser described in Ref. 5, with higher average output power and a higher pulse repetition rate. It delivers up to 80 W of average power in 705-fs pulses at a center wavelength of 1030 nm and a pulse repetition rate of 57 MHz. To our knowledge, this average power from a mode-locked laser is the highest reported to date.

To eliminate the need for synchronized cavities, we base our nonlinear frequency conversion scheme on an OPG. Such devices require a high parametric gain and thus high intensities in the nonlinear crystal. As a result, they tend to suffer from problems such as crystal damage and insufficient output beam quality,[10] although a device with 6.3 W of signal power in 3.6-ps pulses has been demonstrated.[11] Here, we solved

0146-9592/04/161921-03$15.00/0

both problems for a device with much shorter pulses and higher power by using a two-stage parametric generator. A first stage based on periodically poled stoichiometric $LiTaO_3$ (PPSLT) (Ref. 12) generates a seed beam at 1450 nm. A second stage based on LiB_3O_5 (LBO) employs optical parametric amplification to boost the power at this wavelength to the multiwatt level and to create an idler wave at 799 nm. The use of two different crystal materials and of optimized mode areas in the second stage results in reliable operation with nearly diffraction-limited beam quality. The first OPG stage uses a part of the residual 1030-nm light from a frequency doubler as a pump wave, whereas the second stage is pumped by the generated green light at 515 nm. The residual green pump light after the second OPG stage is the first output of the RGB system. The signal and idler beams are finally used to generate red and blue light at multiwatt power levels by sum-frequency mixing (SFM) of the output beams with the rest of the residual 1030-nm light from the frequency doubler.

The experimental setup is shown in Fig. 1. The laser output beam with 80 W of average power at 1030 nm in 705-fs pulses at a repetition rate of 57 MHz first enters a critically phase-matched frequency doubler based on a 5-mm-long antireflection-coated LBO crystal, operating at room temperature and generating up to 44 W at 515 nm. Around 8 W of the residual 1030-nm light is used for pumping the first OPG stage based on an uncoated PPSLT crystal. The PPSLT crystal is operated in a temperature-stabilized oven at 150 °C to avoid photorefractive damage. We use the 17.5-mm-long PPSLT crystal in a double-pass configuration to generate sufficient parametric gain without approaching the threshold for optical damage. The poling period is 29 μm, leading to a signal wavelength of 1450 nm. This first OPG stage generates 1-ps pulses at an average power level of 1.6 W, which can be maintained over hours without crystal damage.

The second stage is based on a 10-mm-long antireflection-coated LBO crystal that is critically phase-matched at room temperature. The crystal is pumped with 42 W of 515-nm light from the frequency doubler. It amplifies the 1450-nm beam from the first stage and also generates an idler wave at 799 nm. We obtained up to 7 W of signal power at 1450 nm and 11.9 W of idler power at 799 nm. The measured pulse durations for signal and idler are 1.2 and 0.7 ps, respectively. The beam quality of the idler is close to the diffraction limit with a measured M^2 factor of <1.2. The residual 23 W of green light is separated from the signal and idler wavelengths as a first output of the RGB system. The beam quality of the 515-nm output is still fairly good with an M^2 factor of 1.9 and could be further improved by spatial filtering, since the power level of the green light would tolerate the additional loss. The degradation of the spatial beam quality of the 515-nm light is caused by pump depletion in the second OPG stage, although the parametric gain in the second OPG stage is chosen in a way that pump depletion is small enough that it does not affect the beam quality of the signal and idler outputs substantially.

Subsequent SFM of the idler and signal beams with the residual 22.6 W of 1030-nm light from the frequency doubler then generates wavelengths in the

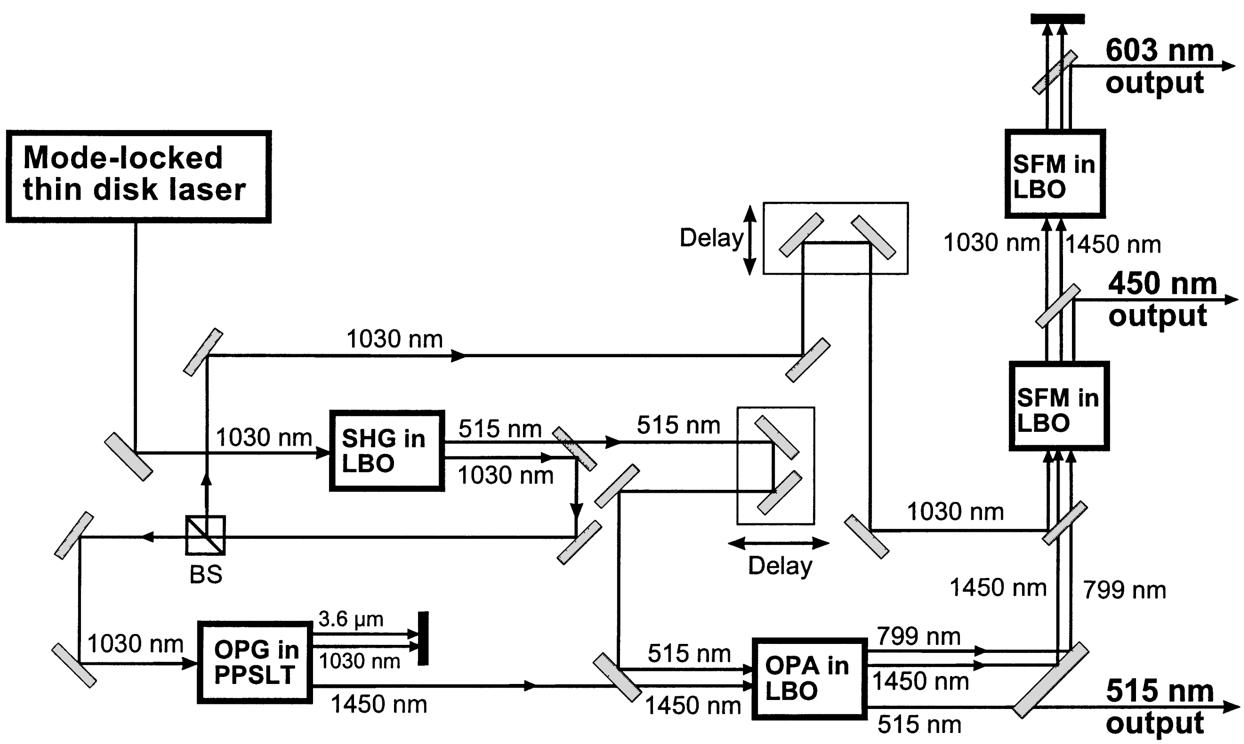

Fig. 1. Experimental setup of the RGB source. BS, beam splitter; SHG, second-harmonic generation; OPA, optical parametric amplification. All beams are collinear in the nonlinear crystals, although for clarity they are shown with some spatial separation.

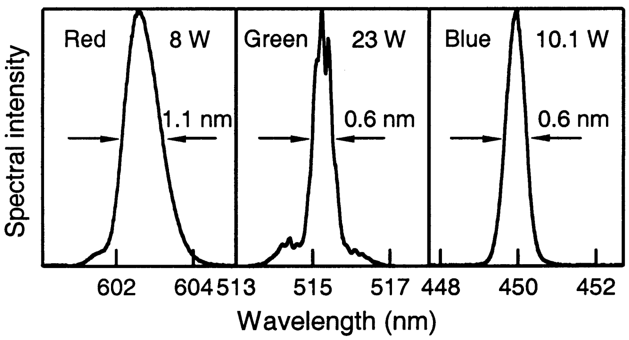

Fig. 2. Measured optical spectra of the 603-nm red, 515-nm green, and 450-nm blue outputs of the RGB system.

blue and red. The two SFM stages are based on two antireflection-coated LBO crystals, both critically phase matched at room temperature. The first SFM crystal is 10 mm long and mixes the 799-nm wave with the 1030-nm beam to generate the blue color at a wavelength of 450 nm (Fig. 2). The average power at 450 nm is 10.1 W, and the beam quality is close to the diffraction limit, with $M^2 = 1.1$. The second SFM crystal is 15 mm long and generates the red color at 603 nm (Fig. 2) by mixing the 1450-nm wave with the remaining 1030-nm light. The average power at 603 nm is 8 W, again in a nearly diffraction-limited beam with $M^2 = 1.1$. Note that the wavelengths of the red and blue outputs can be selected by the choice of poling period of the PPSLT crystal in the first OPG stage. Our system imposes only the boundary condition that the difference in photon energy between the blue and green colors equals that between the green and red. For example, one could choose a red wavelength of 620 nm in combination with a blue wavelength of 440 nm by choosing the poling period of the OPG for a signal wave of 1563 nm instead of 1450 nm.

The total infrared (1030 nm) to visible conversion efficiency of our RGB source is 51%. For generation of D65 white (ISO10526/CIES005/E standard, corresponding to a color temperature of $\approx$6500 K), the red color limits the total output power. The color-balanced output would be 24.9-W white light (8-W red, 6.4-W blue, and 10.5-W green), corresponding to 7840 lm.

In conclusion, we have demonstrated a RGB laser source with unprecedented output powers of 8 W in the red, 23 W in the green, and 10.1 W in the blue. Moreover, our setup features a combination of attractive properties. The entire pump power needed for the nonlinear conversion stages is provided by a single laser oscillator without any amplifier stages. Furthermore, our system does not require any synchronized cavities. Finally, it is based on critically phase-matched crystals operated at room temperature, except for the first OPG stage, which currently must be operated at elevated temperatures to avoid photorefractive damage. We expect that room-temperature operation even of the first OPG stage will become possible with improved materials such as magnesium-doped PPSLT.[13]

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References

1. R. Wallenstein, in *Conference on Lasers and Electro-Optics (CLEO)*, Postconference Digest, Vol. 56 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2001), paper CThC3.
2. D. Lee and P. F. Moulton, in *Conference on Lasers and Electro-Optics (CLEO)*, Postconference Digest, Vol. 56 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2001), paper CThJ2.
3. A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower, Appl. Phys. B **58,** 363 (1994).
4. J. Aus der Au, G. J. Spühler, T. Südmeyer, R. Paschotta, R. Hövel, M. Moser, S. Erhard, M. Karszewski, A. Giesen, and U. Keller, Opt. Lett. **25,** 859 (2000).
5. E. Innerhofer, T. Südmeyer, F. Brunner, R. Häring, A. Aschwanden, R. Paschotta, U. Keller, C. Hönninger, and M. Kumkar, Opt. Lett. **28,** 367 (2003).
6. T. Südmeyer, J. Aus der Au, R. Paschotta, U. Keller, P. G. R. Smith, G. W. Ross, and D. C. Hanna, J. Phys. D **34,** 2433 (2001).
7. T. Südmeyer, J. Aus der Au, R. Paschotta, U. Keller, P. G. R. Smith, G. W. Ross, and D. C. Hanna, Opt. Lett. **26,** 304 (2001).
8. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
9. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE J. Sel. Top. Quantum Electron. **2,** 435 (1996).
10. G. Arisholm, T. Südmeyer, and R. Paschotta, J. Opt. Soc. Am. B **21,** 578 (2004).
11. B. Köhler, U. Bäder, A. Nebel, J.-P. Meyn, and R. Wallenstein, Appl. Phys. B **75,** 31 (2002).
12. K. Kitamura, Y. Furukawa, K. Niwa, V. Gopalan, and T. E. Mitchell, Appl. Phys. Lett. **73,** 3073 (1998).
13. K. Kitamura, N. A. Yu, M. Nakamura, and S. Kurimura, in *Advanced Solid-State Photonics*, G. J. Quarles, ed., Vol. 94 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2004), paper PD10.