Efficient 2nd and 4th harmonic generation of a single-frequency, continuous-wave fiber amplifier

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Abstract: We demonstrate efficient cavity-enhanced second and fourth harmonic generation of an air-cooled, continuous-wave (cw), single-frequency 1064 nm fiber-amplifier system. The second harmonic generator achieves up to 88% total external conversion efficiency, generating more than 20-W power at 532 nm wavelength in a diffraction-limited beam ($M^2 < 1.05$). The nonlinear medium is a critically phase-matched, 20-mm long, anti-reflection (AR) coated LBO crystal operated at 25°C. The fourth harmonic generator is based on an AR-coated, Czochralski-grown β-BaB_2O_4 (BBO) crystal optimized for low loss and high damage threshold. Up to 12.2 W of 266-nm deep-UV (DUV) output is obtained using a 6-mm long critically phase-matched BBO operated at 40°C. This power level is more than two times higher than previously reported for cw 266-nm generation. The total external conversion efficiency from the fundamental at 1064 nm to the fourth harmonic at 266 nm is >50%.

OCIS codes: (190.2620) Frequency conversion, (260.7190) Ultraviolet.

References and links

1. M. Takeda, M. Furuki, H. Yamatsu, T. Kashiwagi, Y. Aki, A. Suzuki, K. Kondo, M. Oka, and S. Kubota, "Deep UV Mastering Using an All-Solid-State 266 nm Laser for an over 20 GBytes/Layer Capacity Disk," Jpn. J. Appl. Phys. **38**, 1837 (1998).
2. N. Eguchi, M. Oka, Y. Imai, M. Saito, and S. Kubota, "A new deep-UV microscope," in Optical Engineering for Sensing and Nanotechnology (ICOSN '99), 3740 (SPIE Proceedings), 394, 1999.
3. M. Oka, L. Y. Liu, W. Wiechmann, N. Eguchi, and S. Kubota, "All solid-state continuous-wave frequency-quadrupled Nd:YAG laser," IEEE J. Sel. Top. in Quantum Electron. **1**, 859 (1995).
4. J. Sakuma, Y. Asakawa, and M. Obara, "Generation of 5-W deep-UV continuous-wave radiation at 266 nm by an external cavity with a $CsLiB_6O_{10}$ crystal," Opt. Lett. **29**, 92 (2004).
5. T. Okamoto, K. Tatsuki, and S. Kubota, Sony Corporation, US Patent No. 6,248,167 B1 (2001).
6. T. J. Kane, and R. L. Byer, "Monolithic, unidirectional single-mode Nd:YAG ring laser," Opt. Lett. **10**, 65 (1985).
7. I. Zawischa, K. Plamann, C. Fallnich, H. Welling, H. Zellmer, and A. Tünnermann, "All-solid-state neodymium-based single-frequency master-oscillator fiber power-amplifier system emitting 5.5 W of radiation at 1064 nm," Opt. Lett. **24**, 469 (1999).
8. A. Liem, J. Limpert, H. Zellmer, and A. Tünnermann, "100-W single-frequency master-oscillator fiber power amplifier," Opt. Lett. **28**, 1537 (2003).
9. Y. Jeong, J. Nilsson, J. K. Sahu, D. B. S. Soh, C. Alegria, P. Dupriez, C. A. Codemard, D. N. Payne, R. Horley, L. M. B. Hickey, L. Wanzcyk, C. E. Chryssou, J. A. Alvarez-Chavez, and P. W. Turner, "Single-

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frequency, single-mode, plane-polarized ytterbium-doped fiber master oscillator power amplifier source with 264 W of output power," Opt. Lett. **30**, 459 (2005).
10. W. J. Kozlovsky, C. D. Nabors, and R. L. Byer, "Efficient second harmonic generation of a diode-laser-pumped cw Nd:YAG laser using monlithic $MgO:LiNbO_3$ external resonant cavities," IEEE J. Quantum Electron. **24**, 913 (1988).
11. Z. Y. Ou, S. F. Pereira, E. S. Polzik, and H. J. Kimble, "85% efficiency for cw frequency doubling from 1.08 to 0.54 µm," Opt. Lett. **17**, 640 (1992).
12. R. Paschotta, P. Kürz, R. Henking, S. Schiller, and J. Mlynek, "82% Efficient continuous-wave frequency doubling of 1.06 µm with a monolithic $MgO:LiNbO_3$ resonator," Opt. Lett. **19**, 1325 (1994).
13. K. Schneider, S. Schiller, J. Mlynek, M. Bode, and I. Freitag, "1.1-W single-frequency 532-nm radiation by second-harmonic generation of a minature Nd:YAG ring laser," Opt. Lett. **21**, 1999 (1996).
14. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, "Laser phase and frequency stabilization using an optical resonator," Appl. Phys. B **31**, 97 (1983).

1. Introduction

Laser sources generating continuous-wave DUV light at high average output power are essential for numerous commercial and scientific applications, including defect detection in semiconductor manufacturing, disc mastering, and fiber Bragg grating fabrication [1, 2]. Especially for industrial applications, the requirements are highly demanding, such as excellent reliability, long lifetime, high wall-plug efficiency, small footprint, and low noise operation. A major advancement in the development of such sources was the demonstration of frequency quadrupled diode-pumped Nd:YAG solid-state lasers operating at 266 nm. Typically, these sources rely on intracavity or resonator enhanced second harmonic generation (SHG) and resonator enhanced fourth harmonic generation (FHG), because the single-pass conversion efficiency through a practical nonlinear crystal is too low in continuous wave operation. In order to obtain high power levels at 266-nm wavelength, a frequency doubling crystal with low absorption and high damage threshold is required. For several years, the highest power levels in continuous-wave DUV generation were obtained using BaB_2O_4 (BBO) crystals in the FHG-stage, achieving up to 1.5 W at 266-nm in 1995 [3]. This result remained state-of-the-art until 2003, when Sakuma et al. reported 5 W power at 266-nm employing a $CsLiB_6O_{10}$ (CLBO) crystal in an external resonant frequency doubler [4]. The nonlinear crystal was Brewster-cut and operated at 140°C, and the fundamental laser source was an intracavity frequency-doubled $Nd:YVO_4$ laser with up to 10 W average power at 532 nm. This result, which represented a 3-fold power increase compared to the previous record, showed the potential of CLBO for high power continuous-wave 266-nm generation. However, BBO crystals are also capable of handling substantially higher DUV power levels than previously reported, if the growth conditions are optimized for low absorption losses [5]. Here we present a laser system generating 12.2 W of usable continuous-wave 266-nm DUV radiation from a 6-mm long BBO crystal. The system is illustrated in Fig. 1. It consists of three main sections: a 1064-nm single-frequency, master-oscillator fiber power amplifier (MOFPA), a 1064-nm resonator for cavity-enhanced second harmonic generation in LBO, and a 532-nm resonator for cavity-enhanced DUV generation in BBO.

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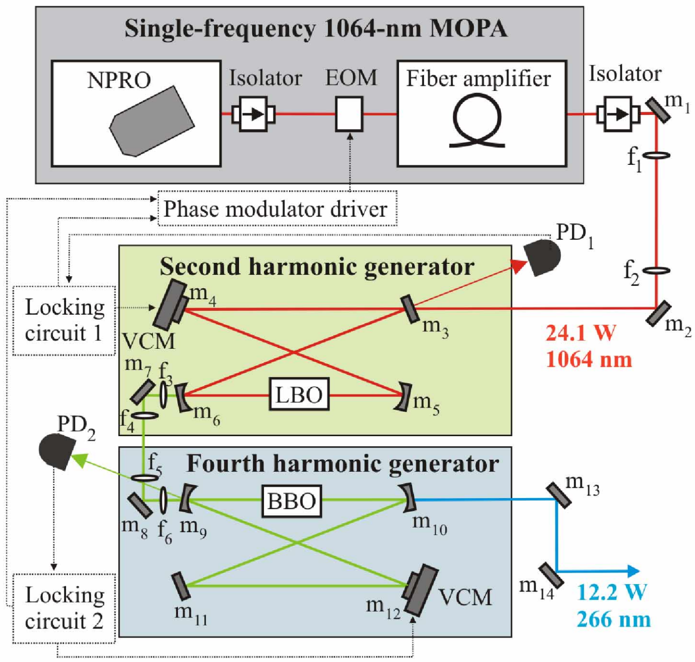

Fig. 1. Experimental setup of the DUV laser system.

2. Single-frequency 1064-nm master oscillator fiber power amplifier

Cladding-pumped, ytterbium-doped fiber amplifiers have many advantages, including high reliability, easy maintenance, compactness, high electrical to optical efficiency, and air-cooled operation even at very high output power levels. High power single-frequency laser systems can be realized with a master-oscillator fiber power amplifier. Already in 2003, the combination of a non-planar ring oscillator (NPRO) [6] as seed source for a double-clad large-mode area Yb-doped fiber amplifier resulted in up to 100 W of single frequency radiation at 1064-nm [7, 8]. In 2005, up to 264 W of single-frequency output power was obtained at 1060 nm from a DFB fiber laser master-oscillator, several Yb-doped fiber pre-amplifiers, and a large-core double-clad Yb-doped fiber power amplifier [9]. In our experiment, we used an NPRO master-oscillator and an air-cooled Yb-doped fiber amplifier of moderate power, resulting in linearly polarized single-frequency output at 1064 nm with 24 W power and good transverse mode-quality (M^2<1.1). An optical isolator protects the NPRO from back reflections of the amplifier. Between the seed NPRO laser and the fiber power amplifier, a KTP-based electro-optical modulator (EOM) is inserted for modulation of frequency side bands, which are used for frequency locking of the following two enhancement cavities [10]. The insertion of the modulator in front of the power amplifier is favorable, because the power at this position is below 100 mW, thus an inexpensive low power EOM can be used. Moreover, moderate losses at the EOM are not relevant for the overall efficiency because the fiber amplifier is strongly saturated. An optical isolator at the fiber output protects the fiber amplifier from back reflections of the following components.

3. Second harmonic generator based on resonator-enhanced conversion in LBO

A critical issue for efficient resonator enhanced second harmonic generation is the round trip loss of the enhancement cavity. If we assume that perfect impedance matching, frequency matching and spatial mode matching are provided, then the total efficiency is given by [11]

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$$\eta = \frac{\gamma_s\, P_c^2}{P_i} = \frac{\eta_s}{\delta_c + \eta_s}$$

In this equation, the coefficient η specifies the conversion efficiency of the resonator enhanced SHG conversion process, γ_s specifies the nonlinear conversion factor (for a single-pass through the crystal), P_c is the power circulating inside the cavity, P_i is the power incident on the cavity, $\eta_s = \gamma_s P_c$ is the single pass conversion efficiency with respect to P_c, and δ_c represent the other losses in the cavity. In order to exceed an efficiency of >80%, the single-pass conversion efficiency needs to be more than 4 times higher than the round-trip losses. The highest SHG conversion efficiency reported so far in an external enhancement cavity based on discrete bulk components was 85%, using a low loss resonator and high single-pass conversion in a KTP crystal cut for type II non-critical phase matching near 1.08 µm [12]. Another successful way to achieve extremely high conversion efficiency is to apply low-loss monolithic nonlinear resonators, which eliminate losses at interfaces. In this way, external conversion efficiencies of up to 82% [13] and internal conversion efficiencies (with respect to the mode-matched fundamental power) of up to 89% [14] were achieved.

In order to achieve high conversion efficiency, we optimized all cavity components of the 2nd harmonic generator for low loss at 1064-nm (estimated: <0.25% total loss) and high single-pass conversion efficiency (estimated: 4.4%). We employed a critically phase-matched low-loss, 20-mm-long, AR-coated LBO crystal operated at 25°C. The input coupler had 4.5% transmission at 1064 nm, which was close to the optimum impedance matching condition. The dichroic output coupler (m_6) was highly transmissive for 532-nm (estimated: 99.7%). The output of the fiber amplifier was transversally mode-matched with lenses f_1 and f_2 to an external 1064-nm bow-tie ring resonator, which consisted of mirrors m_3-m_6. The beam radius inside the LBO crystal was ~50 µm, the AR coating had a reflectivity of <0.05%. The estimated absorption of the 20 mm long crystal was <0.05%. The ring resonator was frequency-locked to the 1064-nm single-frequency output using the Pound-Drever-Hall method [14]. We used Voice-Coil-Motors (VCMs, Fig. 2) as actuators for the Pound-Drever-Hall frequency locking, resulting in excellent locking stability [3].

The frequency doubler generated more than 20-W power at 532 nm (Fig. 3) in a diffraction-limited beam ($M_x^2 = 1.00$, $M_y^2 = 1.03$). The estimated conversion with respect to the mode-matched input power was >94%, and the total external conversion efficiency was 88%, which is to our knowledge higher than previously reported values [11, 12].

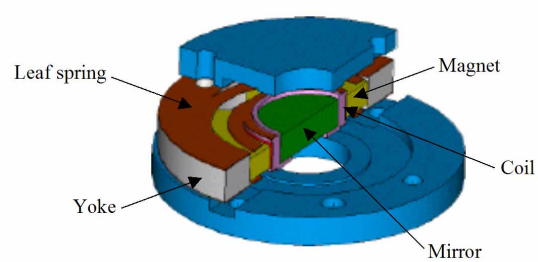

Fig. 2. Schematic of the voice-coil-motor (VCM) actuator used for frequency locking of the enhancement cavities.

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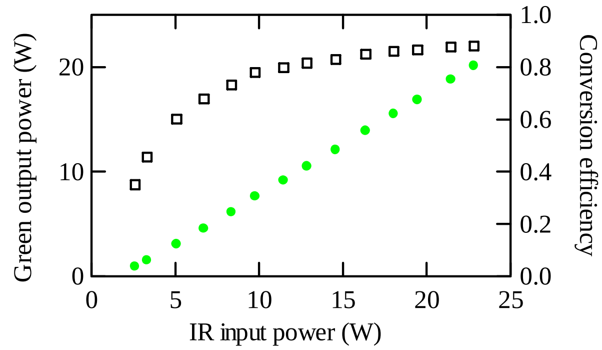

Fig. 3. Measured second-harmonic output power (left axis, circles) and total external conversion efficiency (right axis, open rectangles) as a function of the IR input power.

4. Fourth harmonic generator

The 4th harmonic generator was based on a critically phase-matched, 6-mm long BBO crystal operated at 40°C. The crystal was Czochralski-grown with high crystallinity and high uniformity at Sony Corporation. It was optimized for high damage threshold and low absorption [5], which was <0.1% / cm at 532 nm wavelength. The crystal was AR-coated with <0.05% reflection at 532 nm. The estimated total intracavity loss was <0.2%, and an input coupler m_9 with a transmission of 2.5% at 532 nm was employed. The cavity was also locked using the Pound-Drever-Hall method and a VCM actuator. The beam radius inside the crystal was ~40 µm. Up to 12.2 W of 266-nm DUV output was obtained for 24.1 W of 1064-nm input. On the left axis in Fig. 4, the 266-nm DUV output power measured behind mirror m_{14} is shown as function of the 1064-nm input power incident onto mirror m_3. Their ratio is defined as external conversion efficiency from 1064 nm to 266 nm, which is shown on the right axis.

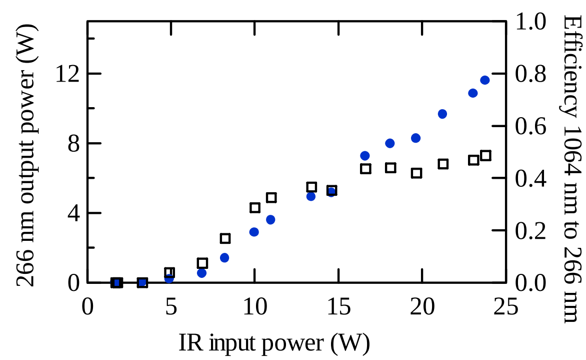

Fig. 4. Measured 266-nm UV output power (left axis, circles) and external conversion efficiency (right axis, open rectangles) from the 1064-nm IR to the 266-nm UV (right axis, open rectangles) as a function of the IR input power.

In Fig. 5, preliminary long-term evaluation results are shown, which were taken from a non-optimized system. Standard commercially available mirror mounts were employed, which contained oil contaminations in the actuator screws. All components were operated in normal laboratory atmosphere; only the area around the BBO was purged with clean dry air. Nevertheless, a 266-nm power of 7 W was generated stably for 10 hours; after 40 hours, still >4.5 W were achieved. No change of the incident green power was observed. After this experiment, mirror m_{10} showed degradation due to coating damage and/or contamination. At

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8 W power, the transverse beam quality of the 266-nm DUV in sagittal direction was nearly diffraction-limited with M_y^2 =1.2. The tangential direction corresponds to the walk-off direction in the BBO crystal, resulting in a slightly reduced transverse beam quality with M_x^2 = 1.5.

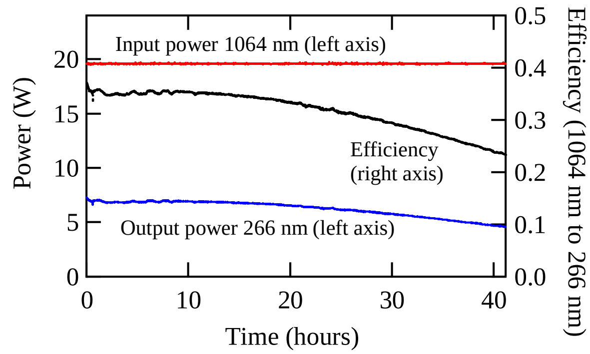

Fig. 5. Preliminary long term evaluation of the DUV system (taken from a non-optimized system containing oil contaminations)

5. Conclusion

In summary, we present a high-power DUV laser system based on an air-cooled Yb-doped fiber amplifier and highly efficient resonator-enhanced 2nd and 4th harmonic converters. Stable and reliable locking of the enhancement cavities was achieved with VCM actuators, which were controlled in a Pound-Drever-Hall scheme.

The green generator was based on a critically phase matched LBO crystal. It generated >20 W continuous-wave 532-nm radiation with an M^2<1.05 at a record-high external conversion efficiency of 88%. Compared to standard commercially available intracavity frequency doubled Nd:YVO_4 lasers with similar power levels, substantially higher electro-optical efficiency was obtained, and no water cooling was required. All components including the nonlinear crystal were operated near room temperature, resulting in very short warm-up time.

The DUV generator was based on a low-loss BBO crystal, which was produced at Sony Corporation. The AR-coated crystal was also critically phase-matched and operated near room temperature. It generated record-high 12 W continuous-wave DUV power at 266 nm, which is more than twice higher than previously reported for any nonlinear crystal [4], and more than 8 times higher than previously reported for BBO [3].

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