Scalable Approach for Continuous-Wave Deep-Ultraviolet Laser at 213nm

Yushi Kaneda[1,2], Tsuyoshi Tago[1], Toshiaki Sasa[1], Masahiro Sasaura[1], Hiroaki Nakao[1], Junji Hirohashi[1], and Yasunori Furukawa[1]
[1]Oxide Corporation, 1747-1 Mukawa, Hokuto, Yamanashi 408-0302, JAPAN
[2] University of Arizona, College of Optical Sciences, 1630 E University Blvd., Tucson, AZ 85721 USA
kaneda@opt-oxide.com

Abstract: We present a novel approach for generation at 213nm, corresponding to the fifth harmonic of common 1064nm laser, in pure continuous-wave mode. Starting from two infrared fiber laser sources, we demonstrated 0.45W output at 213nm.

OCIS codes: (140.3610) Lasers, ultraviolet; (140.3515) Lasers, frequency doubled; (190.2620) Harmonic generation and mixing;

Continuous-wave (CW) fourth-harmonic laser sources at 266nm, the fourth harmonic wavelength, being industrially deployed in a variety of applications. Now, CW laser sources at 213nm, a natural next step at the fifth harmonic wavelength, had long been sought for. Demand for shorter wavelengths and higher output powers seems persistent, for example, for higher throughput or for higher S/N ratio in the inspection of semiconductor which keeps shrinking in size. In order to generate 213nm, conventionally the forth harmonic of 1064nm is frequency mixed with the fundamental [1]. However, this approach requires the forth harmonic, which is already in the deep UV, to be tightly focused into the nonlinear crystal, hence limiting the operational lifetime of the crystal. Further, the output power will be limited by the availability of the fourth harmonic power.

For the objective of stably generating higher powers at 213nm, we decided to take a different approach [2]; 213nm is generated by the second harmonic generation (SHG) of 426nm, which can be obtained by the second harmonic of 852nm. To generate high-power at 852nm, we chose the sum-frequency mixing as the scalable approach; 1907nm from a thulium-doped fiber source and 1540nm from an erbium-doped fiber source are employed to efficiently generate 852nm by doubly-resonant sum-frequency mixing (DRSFM). Generated 852nm is subsequently converted to 213nm by cascaded external resonant doublers. The resulting output is purely continuous and in single frequency. Fig. 1 shows the schematic of our approach.

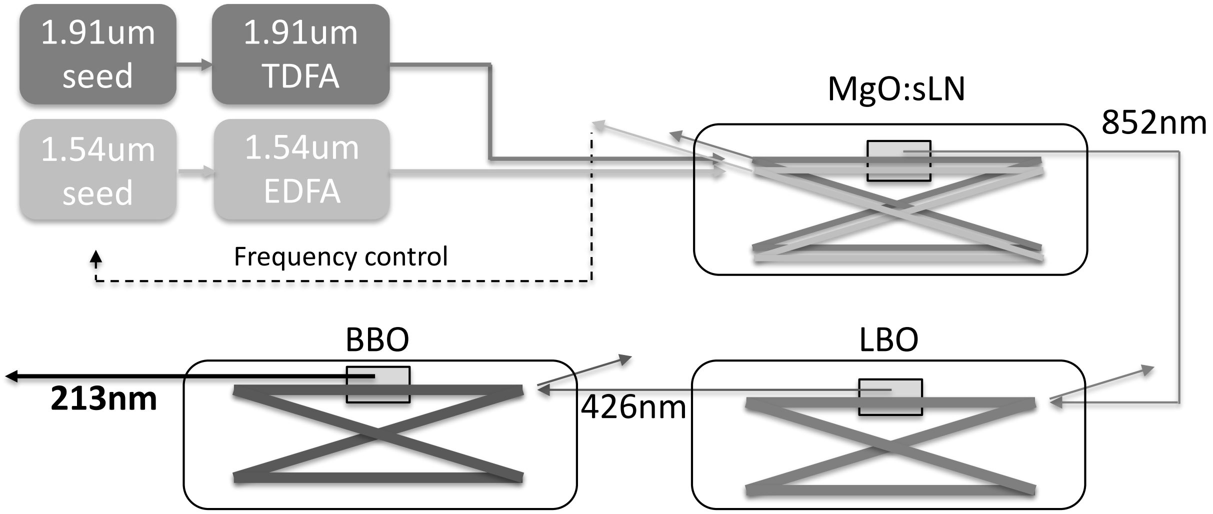

Fig. 1. Schematic of the continuous-wave 213nm laser

The thulium-doped fiber amplifier (TDFA) is an in-house, single-stage clad-pumped amplifier, and is seeded by an in-house, single-frequency fiber laser oscillator at 1907nm with an output power of 40mW. Pumped with two 9-W multimode diode lasers at 793nm, it gives an output power of approximately 5W. The seed laser at 1907nm is free running and does not have the frequency control capability. A commercial erbium-doped fiber amplifier (IPG Photonics) has the maximum output power of 10W and is seeded by a commercial single-frequency fiber laser with frequency control capability (NKT Photonics). The DRSFM cavity is locked to the free-running 1907nm, and the frequency of the 1540nm is locked to the cavity, hence realizing simultaneous resonance of two wavelengths [3]. A Brewster-cut MgO-doped periodically-poled stoichiometric lithium tantalate poled at 25.37μm for the first order quasi-phasematching for SFM is placed at the waist of the cavity. With the maximum available input from two fiber sources, a maximum output power of 5.2W of 852nm was observed. Since all 3 interacting beams are all in the same polarization, the Brewster-cut end facets are effective for low loss resonator as well as for low-loss outcoupling of the generated 852nm. With up to 4.02W of 852nm available for the harmonic generation, 2.41W of 426nm was obtained from the first external resonant doubler containing 20mm long type-I LBO cut at φ=90°, θ=27.4° for the type-I critical phasematching at room temperature.

For the harmonic generation at 213nm, BBO is practically the only choice as the nonlinear material. We used a Brewster-cut, 10mm long, Czochralski-grown BBO crystal cut at θ=72.9° for the type-I phasematched SHG at 213nm [4]. The second resonant doubler has the waist of 44 μm (non-walkoff direction) and 35 μm (walkoff direction) in radius. We estimate the normalized conversion efficiency to be approximately $0.5 \times 10^{-4}\ W^{-1}$. The generated 213nm light is outcoupled by a dichroic Brewster beamsplitter; a fused silica plate with the angle of incidence of 56° with the first surface coated for high reflection at 213nm in s-polarization and high transmission at 426nm in p-polarization. With 2.41W at 426nm incident onto the second doubler, more than 0.45W of 213nm was observed. The input-output characteristics of 213nm generation is shown in Fig. 2.

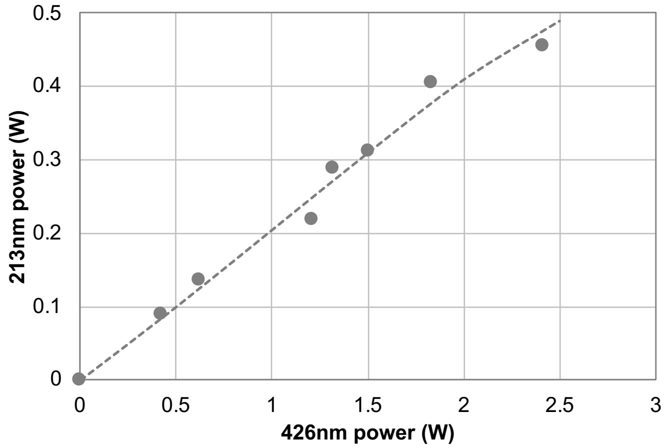

Fig. 2. Input-Output characteristics of 213nm generation

We believe this is the highest output power of CW 213nm reported so far to the best of our knowledge. The output powers from the fiber sources at both 1540nm and 1907nm are readily scalable. With higher output powers at 852nm, we believe the CW 213nm output is also scalable.

We gratefully acknowledge the support from New Energy and Industrial Technology Development Organization (NEDO) of Japan.

References

[1] J. Sakuma, Y. Asakawa, T. Imahoko, and M. Obara, "Generation of all-solid-state, high-power continuous-wave 213-nm light based on sum-frequency mixing in $CsLiB_6O_{10}$," Opt. Lett. **29**, 1096-1098 (2004).

[2] Y. Kaneda, U.S. Patent 9,429,813 "Deep ultraviolet laser generation device and light source device," (2016).

[3] Y. Kaneda, and S. Kubota, "Theoretical treatment, simulation, and experiments of doubly resonant sum-frequency mixing in an external resonator," Appl. Opt. **36**, 7766-7775 (1997).

[4] K. Kato, N. Umemura, and T. Mikami, "Sellmeier and thermo-optic dispersion formulas for β-BaB2O4 (revisited)," Proc. SPIE **7582**, 75821L (2010).