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206 nm All-solid-state Deep-ultraviolet Laser for Addictive Manufacturing

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Solid-state ultrafast deep-ultraviolet (DUV) laser sources have improved the average power, peak power, and conversion efficiencies significantly in recent years. Compared with traditional excimer lasers, solid-state DUV lasers have higher peak power, shorter pulse duration, better beam quality and system reliability. These advantages benefit many important scientific and industrial applications such as ultrafast spectroscopy, seeding free-electron lasers, laser additive manufacturing and laser-produced plasma diagnostics. Especially, the fast advances in Yb:YAG laser technology provide much powerful pump sources for DUV laser and boost the related developments recently. However, the power scale-up of solid-state DUV laser is not trivial. Ultrafast solid-state DUV lasers are achieved through frequency up conversions from an infrared pump laser. At low intensity, the conversion efficiency of nonlinear frequency up conversion scales approximately linearly with respect to the incident intensity of the mixing beams. At high intensity, undesirable nonlinear effects such as two-photon absorption (TPA) and self-phase modulation (SPM) result in the eventual saturation of the generated upconverted signal power. In addition, damage to the nonlinear crystals also further limits the incident intensity of the driving laser. Here, we report an all-solid-state DUV laser delivering 0.8 W, 80 μJ, ~582 fs, 206 nm pulses with peak power of 129 MW from a 1030 nm Yb:YAG laser at a 10 kHz repetition rate.

NOMENCLATURE

τ = pulse duration of 206 nm laser
τ_1= pulse duration of 1 μm laser
τ_2= pulse duration of 258 nm laser

1. Introduction

Laser additive manufacturing (LAM) technology has benefited from the development of various lasers such as CO_2 laser, Yb:YAG laser, Yb-fiber laser, and excimer laser [1]. The strong absorption in deep-ultraviolet (DUV) wavelength for both the metals and polymeric materials enables the efficient energy transfer for versatile materials. Combined with the high-power output, DUV lasers would significantly improve the throughput and scanning speed of LAM. The DUV wavelength also shrinks the focused spot size and thus the manufacturing feature size by more than an order, enabling the sub-micron addictive manufacturing. Moreover, the ps pulse width concentrates the pulse energy in an ultrashort temporal window which cures or melts the materials instantaneously with minor thermal energy dissipation to surrounding material. This not only improves the throughput and process time, but also largely enhances the addictive manufacturing hardness and fineness with much smaller sintered grain size. Solid-state ultrafast DUV laser sources have improved the average power, peak power, and conversion efficiencies significantly in recent years [2-4]. Compared with traditional excimer lasers, solid-state DUV lasers have higher peak power, shorter pulse duration, better beam quality and system reliability. These advantages benefit many important scientific and industrial applications such as ultrafast spectroscopy, seeding free-electron lasers, laser additive manufacturing and laser-produced plasma diagnostics. Especially, the fast advances in Yb:YAG laser technology provide much powerful pump sources for DUV laser and boost the related developments recently. However, the power scale-up of solid-state DUV laser is not trivial. Ultrafast solid-state DUV lasers are achieved through frequency up conversions from an infrared pump laser such as Yb:YAG laser. At low intensity, the conversion efficiency of nonlinear frequency up conversion scales approximately linearly with respect to the incident intensity of the mixing beams. At high intensity, undesirable nonlinear effects such as two-photon absorption (TPA) and self-phase modulation (SPM) result in the eventual saturation of the generated upconverted signal power. In addition, damage to the nonlinear crystals also further limits the incident intensity of the driving laser. To date, the highest average and peak power for 5^{th}

harmonic generation (5HG) of Yb:YAG laser has been reported by [4], where up to 2.5 W average power and 12.5 MW peak power of 206 nm picosecond pulses were achieved at a repetition rate of 100 kHz via group velocity matching. Here, we report an all-solid-state DUV laser delivering 0.8 W, 80 µJ, ~582 fs, 206 nm pulses with peak power of 129 MW from a 1030 nm Yb:YAG laser at a 10 kHz repetition rate.

2. Experiment

We use a 1030 nm pump source in our experiment, which is a commercial Yb:YAG chirped-pulse amplification (CPA) system using the Innoslab amplification technology. It outputs 1.2 ps, 10 kHz pulses with maximum average power of 220 W. Fig. 1 depicts our experimental setup starting from the output of the 1030 nm Yb:YAG driving laser. The collimated pump beam is first sent through an energy tuner comprising of a half-wave plate (HWP) and thin-film polarizer (TFP) in order to control the pump laser power. The LBO (20 × 20 × 5 mm) has antireflection (AR) coatings for 1030 nm and 515 nm on both sides and is cut at θ = 90□ and φ = 0◦ for non-critically phase-matched 2[nd] harmonic generation (2HG) at ~190 ℃ to generate a 515 nm beam. A telescope (TS) is used prior to the LBO to control the diameter of the pump laser to avoid crystal damage (approximately 9 mm at $1/e^2$ diameter). Here, LBO is chosen due to its largest damage threshold amongst commercial nonlinear crystals for 2HG [2]. The LBO and its oven are mounted on a rotational stage which allows for precise adjustments of its yaw for optimizing phase-matching conditions. A dichroic mirror splits the 1030 nm and 515 nm beams.

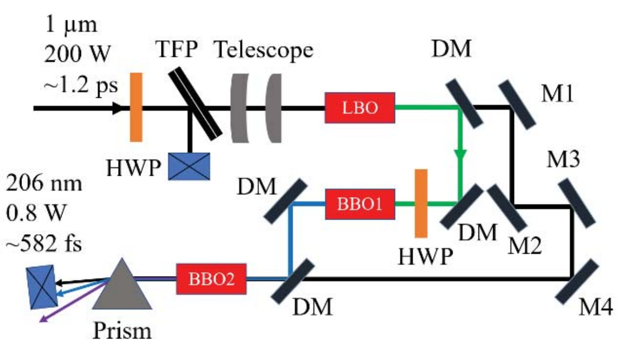

Fig. 1 The schematic of the high power, sub-ps, all-solid-state DUV laser. HWP: half-wave plate. TFP: thin-film polarizer. DM: dichroic mirror. M1-M4: 1 µm mirrors.

For 4[th] harmonic generation (4HG), the 515 nm beam is directed into BBO1, which has high nonlinear coefficient (~2.6 pm/V) [5] allowing for a shorter crystal length to minimize undesired nonlinear effects such as TPA and SPM. BBO1 (20 × 20 × 0.2 mm) is cut at θ = 50◦ and φ = 0◦ for Type-I phase-matching and has AR coating on both sides for 515 nm and 258 nm. The crystal is fixed in a kinematic mount with fine-tuning capabilities to adjust its pitch and yaw for phase-matching. Another HWP is placed before BBO1 to optimize the polarization of the input 515 nm beam. The generated 258 nm beam after BBO1 is combined with the 1 µm beam at BBO2 for 5HG. A delay line is built by mirrors M3 and M4 to ensure temporal overlap of 258 nm and 1 µm beams. The 206 nm beam is filtered out by a DUV prism. The 206 nm laser power is measured with respect to the input 1 µm laser power as shown in Fig. 2 and the inset is its beam profile. The 206 nm laser power increases to around 0.55 W when the 1030 nm pump laser power is slightly above 200 W. The DUV laser spectrum measured is centered at 206 nm with a full width at half maximum (FWHM) of 1.09 nm as shown in Fig. 3, which supports 57.3 fs Fourier transform limited pulse duration.

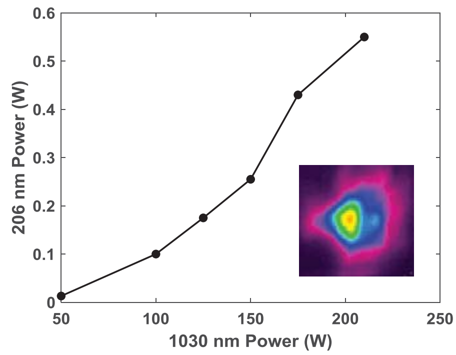

Fig. 2 The 206 nm DUV laser power versus the 1 µm driving laser power. The inset is the beam profile of the DUV beam.

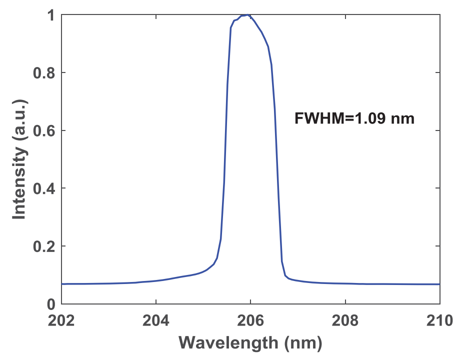

Fig. 3 The 206 nm DUV laser spectrum measured which has a FWHM bandwidth of 1.09 nm.

By increasing the telescope distance which slightly focuses the input 1 µm beam, we optimize the 206 nm laser power to 0.8 W as shown in Fig. 4. The relative telescope distance is defined as the increasing amount with respect to the initial distance for collimation beam. The 1 µm pump laser power is fixed at 200 W. The 206 nm laser power increases from 0.45 W to 0.8 W when the relative telescope distance is increased from 0 to 4 mm. The 206 nm pulse duration is estimated to be ~582 fs by sum frequency formula $\tau = \tau_1\tau_2/\sqrt{\tau_1^2 + \tau_2^2}$ where $\tau_1 = 1.2\ ps$ is the 1 µm pulse duration and $\tau_2 = 665\ fs$ is the 258 nm pulse duration. The 1 µm and 258 nm pulse durations were both measured in our previous paper [3]. Knowing that the repetition rate is 10 kHz, we can calculate that the optimized pulse energy of 206 nm laser is 80 µJ with a peak power of 129 MW, which is the highest peak power for a kHz-rate, all-solid-state DUV source at 206 nm driven by a 1 µm pump laser at the time of writing.

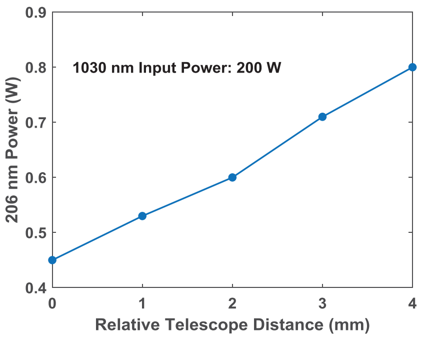

Fig. 4 The 206 nm DUV laser power versus the relative telescope distance when the input 1 μm laser power is at 200 W.

3. Conclusions

We have demonstrated the generation of a 206 nm DUV laser via 5HG of a 1030 nm, 1.2 ps, 10 kHz, Yb:YAG Innoslab solid-state laser using LBO, BBO, and BBO as 2HG, 4HG, and 5HG crystals respectively. We obtain a 0.8 W, 80 μJ, 206 nm DUV laser with a pulse duration of ~582 fs, which corresponds to a peak power of 129 MW-the highest peak power for a kHz-rate, all-solid-state DUV source at 206 nm driven by a 1 μm pump laser at the time of writing. Future improvements of average power and peak power can be explored by further reducing the input beam diameters before each crystal, up to before the point of crystal damage. This ultrafast DUV laser developed will benefit additive manufacturing of various materials such as metals and semiconductors.

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