Watt-level 193 nm source generation based on compact collinear cascaded sum frequency mixing configuration

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Abstract: A compact, dual-stage, collinear-cascaded sum-frequency mixing configuration is presented for generating 193 nm sources. Due to the less-introduced, deep-ultraviolet optical components, the system is less prone to damage. In our proof-of-concept experiments, a 1030 nm laser and a 1553 nm laser synchronized to each other were used as drivers and an average power of ~0.7 W was obtained. For comparison, the noncollinear configuration gave an average power of 0.77 W. The difference of 0.07 W is attributed to the spatial walk-off inside the cesium lithium borate (CLBO) crystal, confirmed by indirect visualization. A possible way to overcome the small gap of 0.07 W is proposed for future work.

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1. Introduction

Generating radiation at the deep-ultraviolet (DUV) wavelength of 193 nm has attracted considerable attention for applications such as semiconductor metrology, photolithography, photoelectron spectroscopy, seeding argon fluoride (ArF) excimer lasers, and laser processing [1–5]. Presently, ArF excimer lasers are the only lasers that output directly at 193 nm, with average powers exceeding 100 watts. Unfortunately, the beam quality is usually poor. For example, typical M² values of a twin-chamber ArF laser beam are approximately 13 and 61 in the horizontal and vertical directions, respectively [6]. The use of a solid-state 193 nm seed laser has significantly improved this situation to M²<2 for both the horizontal and vertical directions [6]. Therefore, developing a compact and robust solid-state 193 nm seed source is critical to optimize the performance of ArF laser systems and obtain high beam quality and high coherence.

The average power of solid-state 193 nm sources is usually quite low because of the multistage nonlinear frequency conversion processes on which they are based. The two main nonlinear frequency conversion processes used are SHG and sum frequency mixing (SFM).

For second harmonic generation (SHG), the only available option is to use a potassium fluoro-beryllo-borate (KBBF) crystal pumped with a 387 nm laser, which can be obtained by frequency doubling the 774 nm output of a Ti:sapphire laser [7]. The highest average power of 1.05 W at 193 nm has been demonstrated with this type of configuration [7], but the cost of the entire system is expected to be quite high because green lasers are commonly used as pumping sources for Ti:sapphire lasers. In a much simpler scheme, a continuous wave (CW) 193 nm source was implemented by frequency quadrupling the output of amplified 772 nm diode lasers; however, the power scaling of such a system is limited [8]. Another disadvantage with KBBF crystals is that they remain commercially unavailable and the choice of thickness is restricted.

For SFM, barium borate (BBO), lithium triborate (LBO), and cesium lithium borate (CLBO) crystals are most frequently used, and CLBO crystals are known to lead to high average powers and high conversion efficiencies. SFM requires two pump beams: one in the DUV region and the other in the near infrared (NIR). To date, several different wavelength
combinations have been reported, these include: 213 nm + 2074 nm [9], 221 nm + 1547 nm [10], 221 nm + 1553 nm [11], 226 nm + 1342 nm [12], 234.1 nm + 1110 nm [13], 235.8 nm + 1064 nm [14], 258 nm + 774 nm [15], and 266 nm + 708.6 nm [16]. The highest average power obtained was 1.02 W, which was with the 221 nm + 1553 nm combination [17]. This result is also similar to that obtained through frequency doubling using a KBBF crystal.

Comparatively speaking, configurations based on SFM are more complex than those based on SHG, and the need for two pump lasers increases the assembly and material costs. A major advantage of SFM systems is that they can be directly pumped by laser diodes (LD). In the aforementioned wavelength combinations, all ultraviolet (UV) beams are generated from a one-stage SFM scheme, except for 258 nm and 266 nm, for which phase matching is impossible for generating a 193 nm wavelength in a CLBO crystal. Therefore, two stages of SFM are required altogether, and they are usually carried out stage by stage. Accordingly, the setup requires not only two different dichroic mirrors (DM) to combine beam sources for SFMs, but also half-wave plates (HWP) to adjust the polarization directions. Specifically, in our previous work on a 193 nm source [11,17], the CLBO crystals used to generate wavelengths of 221 nm and 193 nm were both type-I phase matched [1553 nm (o) + 258 nm (o) → 221 nm (e), 1553 nm (o) + 221 nm (o) → 193 nm (e)]. After the first-stage SFM, the 1553 nm and 221 nm sources were extracted, polarization adjusted, and then they were recombined by using another DM and serve as inputs to the second-stage SFM to generate the 193 nm source.

This approach clearly has some drawbacks. First, additional optical elements (e.g., reflective mirrors, lenses, and DMs) must be introduced into the system for the second-stage SFM, which increases the system's complexity and instability. Second, the UV optical components are usually more expensive than those for NIR. Furthermore, the coating performance of the UV optics in terms of reflectance, transmission, and damage threshold is inferior to that for NIR optics. More so, extra efforts are required to perfectly overlap the two pump beams in the second-stage SFM temporally and spatially. Therefore, a more compact and simpler configuration is preferred, without introducing significant inefficiency into the system.

Inspired by the collinear cascaded frequency-tripling scheme [18], which is used for high-power extra-cavity 355 nm source generation, and collinear fifth-harmonic generation of 1 μm lasers in both “ω+4ω” and “2ω+3ω” configurations [19,20], we propose to extend this idea to a system to generate a 193 nm wavelength by constructing a collinear cascaded dual-stage SFG configuration. Concretely, the combination of type-II CLBO and type-I CLBO in tandem, or with a dual-wavelength wave plate (DWP) introduced in between, are both possible in a collinear cascaded dual-stage SFG configuration, which can address the aforementioned problems and lead to a compact and robust DUV-generation scheme.

In this manuscript, building on our previous system, we thus use a collinear cascaded two-stage SFM scheme to reduce size and cost. Two configurations were tested to verify this proposal. The first configuration involves inserting a DWP between the first and second SFM stages of our previous system. The second configuration uses a CLBO crystal cut at a different angle to enable type-II phase matching to generate a 221 nm source [1553 nm (e) + 258 nm (o) → 221 nm (e)]; a setup that avoids using a DWP. Both setups work well for generating the 193 nm sources; however, less average power is obtained compared with the more traditional setup (0.41 W and 0.7 W, versus 0.77 W). This is due to the imperfect spatial overlap, originating from their relative spatial walk-off in the first-stage SFM, of 1553 nm and 221 nm beams inside the second-stage SFM. Simple experiments were carried out to visualize the walk-off between the 1553 nm and 258 nm beams as an indirect proof for the walk-off between 1553 nm and 221 nm beams. These experiments show that, we obtain a much more compact and cost effective system by simply using CLBO crystals cut at a different angle (power at 193 nm is only ~9% less than that obtainable with the conventional system). Finally, we propose a dual-crystal system to compensate for the spatial walk-off but
do not verify this approach herein. This work thus demonstrates a collinear, dual-stage cascaded SFM configuration for generating coherent radiation at 193 nm.

2. Experimental setup

Figure 1 shows the schematic diagram of the dual-stage collinear cascaded SFM configuration for the generation of 193 nm sources, which comprises of four parts: Part-(a) is a pulsed 1030 nm fundamental laser. It starts from a narrow-linewidth pulsed distributed feedback laser diode (LD) with a pulse duration of 10 ns and a repetition rate of 160 kHz [17]. Next, a fiber-coupled acousto-optic modulator serves to lower the pulse repetition rate down to 10 kHz. A photonic crystal fiber with a core diameter of 40 μm is used as a pre-amplifier and two Yb:YAG ceramic rods as the main amplifiers. This setup differs slightly from that of our previous system [17], where a single-crystal fiber (SCF) was used as the final-stage main amplifier. Replacing the SCF with the ceramic amplifiers allows us to maintain the performance of the previous system while reducing costs. Part-(b) of the system is a pulsed 1553 nm fundamental laser with a repetition rate of 10 kHz, which is synchronized, by sharing a common pulse function generator, to the 1030 nm laser system of part-(a) and delivers an average power up to 1.5 W. Part-(c) is the SHG system at 515 nm, with a noncritically phase-matched LBO crystal (5 × 5 × 30 mm³) that operates at 186.5 °C, and a fourth-harmonic generation (FHG) system at 258 nm that uses a CLBO crystal (5 × 5 × 20 mm³), operated at 155°C, and is sealed inside a cell purged with Ar gas to avoid hydration. Finally, part-(d) is a dual-stage collinear cascaded SFM configuration for generating a 193 nm beam and uses two 5 × 5 × 20 mm³ CLBO crystals operated at 155°C and sealed inside a cell purged with Ar gas. A calcium fluoride (CaF₂) prism serves to separate the generated 193 nm beam from the other beams.

Figure 2 highlights the differences between the previous and current setups. Indeed, Fig. 2(d)-1 represents the previous setup as reported in [17], where twice combinations of beams and more optical components were required to enable SFM. Figures 2(d)-2 and 2(d)-3 show the current setups for compact collinear cascaded SFM. As represented in Fig. 2(d)-2, we used a CLBO-2 type-I phase-matched crystal, where the 1553 nm and 221 nm beams were perpendicularly polarized with respect to each other. A DWP was used to adjust the
polarization direction of the 1553 nm beam, whereas the polarization of the 221 nm beam was unchanged. Note that the wavelength of the 1553 nm beam is seven times 221 nm, which enables the use of the DWP. The setup represented in Fig. 2(d)-3 uses a type-II phase-matched CLBO crystal, where the 1553 nm and 221 nm beams have the same polarization direction [1553 nm (e) + 258 nm (o) → 221 nm (e)]. This setup requires no DWP, making the system more compact and less lossy.

![Fig. 2](image_url)

Fig. 2. Different setups for a 193 nm beam generation, especially for part-(d) from Fig. 1. Setup (d)-1 is the previous setup used in Ref [17]. Setups (d)-2 and (d)-3 are two types of collinear cascaded SMF configurations. HWP: half-wave plate. DM: dichroic mirror.

### 3. Experimental results and discussion

#### 3.1 All-ceramic 1030 nm Yb:YAG amplifier and its performance for second- and fourth-harmonic generation

After replacing the SCF used in the previous system, as described in Ref [17], with a Yb:YAG ceramic thin rod as the main means of amplification for the 1030 nm laser, the overall performance was characterized using the performance of the SCF (doping concentration = 1%, diameter = 1 mm, length = 40 mm) as a benchmark. The Yb:YAG ceramic thin rods (from Konoshima Chemical Co., Ltd.) with different doping concentrations (1% and 2%), lengths (30 mm and 40 mm), and diameters (1 mm and 2 mm) were tested. The results are shown in Fig. 3 and are for a same seed laser. A fiber-coupled 940 nm LD from nLIGHT Photonics was used as pump, where the fiber core diameter was 105 μm and the NA was 0.22. Both ceramic rods (one with 1% doping, 1 mm diameter, and 40 mm long, and a second with 2% doping, 1 mm diameter, and 30 mm long) gave outputs similar to that of the SCF Taranis module. The use of the 2-mm-diameter, 30-mm-long Yb:YAG ceramic rod with 2% doping significantly improves the output power. At present, we cannot explain this result, but we note that another group has reported similar observations in SCF amplifiers [21].

Because of its noticeably improved performance, we used the 2-mm-diameter, 30-mm-long Yb:YAG ceramic rod with 2% doping for subsequent experiments. For SHG, over 22 W was obtained by using a LBO crystal, as shown in Fig. 4(a). The 1030 nm laser was not used at the maximum power. For FHG, nearly 7 W was obtained by using a CLBO crystal, as shown in Fig. 4(b). For both SHG and FHG, the conversion efficiency was not optimized to keep the system safer. Indeed, a maximum average power of 8.5 W at 258 nm beam was obtained with an average power of 22 W at 515 nm beam, which corresponds to a conversion efficiency of 38.6%. Experimentally, we observed that, when the conversion efficiency approached 40%, the CLBO crystal was more prone to damage. We deemed an average power of 7 W at 258 nm beam sufficient for subsequent measurements. During the whole
experimental period, we did not find any obvious performance decay, although we did not intentionally test the lifetime of CLBO crystals.

![Graph showing output power vs. pumping power for different SCF and ceramic Yb:YAG thin rod amplifiers. The inset shows a typical three-dimensional beam profile of the amplified laser at the highest output power for a 2-mm-diameter, 30-mm long Yb:YAG ceramic rod with 2% doping.]

**Fig. 3.** Output powers as function of pumping power for different SCF and ceramic Yb:YAG thin rod amplifiers. The inset shows a typical three-dimensional beam profile of the amplified laser at the highest output power for a 2-mm-diameter, 30-mm long Yb:YAG ceramic rod with 2% doping.

![Graphs showing average powers at 515 nm and 258 nm beams as a function of average power at 1030 and 515 nm beams, respectively.](image)

**Fig. 4.** Average powers at (a) 515 nm, and (b) 258 nm beams as a function of average power at 1030 and 515 nm beams, respectively.

### 3.2 Sum frequency mixing in CLBO: generation of 221 nm and 193 nm beams

This section presents the results for the generation of the 193 nm beam using the collinear cascaded SFM scheme, as represented in Fig. 2(d)-2 and 2(d)-3. As shown in Fig. 1, two concave mirrors were used to adjust the size of the 258 nm beam, and two spherical lenses were used to adjust the size of the 1553 nm beam for efficient nonlinear mixing at the center of the CLBO crystals.

First, we tested the setup of Fig. 2(d)-2. The crystals CLBO-2 and CLBO-3 were cut at 51.8° and 61.5°, respectively, and both were operated under type-I phase matching. Two DMs (high reflective at a 221 nm, antireflective at 1553 nm and 258 nm), not shown in Fig. 2, were used to measure the average power of the 221 nm beam. The average power of the 221 nm output beam as a function of the average incident power at the 258 nm is shown in Fig. 5(a) by red circles. The maximum average power was 1.6 W. After this measurement, the DMs were removed and a 0.1-mm-thick DWP was inserted between the two CLBO crystals. The average power of the 193 nm beam thus generated was measured after dispersing the beams by a CaF₂ prism, and the results are shown by the red circles in Fig. 5(b). The maximum average power was 0.41 W.
Second, we tested the setup of Fig. 2(d)-3. In this case, the crystals CLBO-2′ (5 × 5 × 20 mm³) and CLBO-3 were cut at 56.2° and 61.5°, respectively, and operated under type-II and -I phase matching, respectively. In the same way as described above, the average power of the 221 nm beam was measured, and the results are shown in Fig. 5(a) by the red triangles. The maximum average power was 2.2 W. In this case, no DWP is necessary so the setup is simpler. With CLBO-3 in place, we measured the average power of the 193 nm beam thus generated, and the results are shown in Fig. 5(b) by red triangles. The maximum average power was 0.7 W.

![Fig. 5](image-url)

Fig. 5. Average power and conversion efficiency for (a) 221 nm and (b) 193 nm beams. Type-I and -II are the phase-matching type of CLBO-2 and CLBO-2′, respectively, shown in Fig. 2. CE: conversion efficiency.

Although the effective nonlinear coefficients $d_{eff}$ of CLBO-2 and CLBO-2′ are almost the same (0.797 versus 0.800 pm/V, respectively), the setup of Fig. 2(d)-3 yields significantly higher average power. Three reasons may explain this result: To a minor extent, the losses introduced upon inserting the DWP, which has a transmission coefficient measured to be ~96.1% for both 221 nm and 1553 nm beams, contribute to this result. The second reason is that the CLBO-2 crystal has an acceptance angle of 2.56 mrad·cm for 1553 nm beam, which is only about 25% that of CLBO-2′, which is 11.10 mrad·cm. Therefore, under the same focusing conditions, the effective beam overlap between the 258 nm and 1553 nm beams within CLBO-2′ should be better than that in CLBO-2, which allows for the generation of higher average power of the 221 nm beam. Experimentally, we kept the same loose focusing condition for both Fig. 2(d)-3 and Fig. 2(d)-2 configurations. The third reason is that the relative spatial walk-off angle between the 221 nm and 1553 nm beams is 41.08 mrad in CLBO-2, and 9.69 mrad in CLBO-2′, which means that the spatial overlap of the beams is much better between the 221 nm and 1553 nm beams in the following CLBO-3 crystal for the setup of Fig. 2(d)-3.

To have an intuitive feeling on the spatial walk-off, we visualized it experimentally. It is quite challenging to directly observe the spatial separation between 221 nm and 1553 nm beams after CLBO-2′, because all the three beams (258 nm, 1553 nm, 221 nm) would have high average power. In CLBO-2′ [1553 nm (c) + 258 nm (o) → 221 nm (e)], the ordinary beam is 258 nm, and the 1553 and 221 nm beams are extraordinary, so there is no spatial walk-off for the 258 nm beam, and we can use it as a reference. The SNLO software, gives the walk-off angles for 1553 nm and 221 nm beams as 29.18 mrad and 38.87 mrad, respectively, which means a relative walk-off of 9.69 mrad between the two beams. Thus, it should be easier to observe the separation between the 1553 nm and 258 nm beams (29.18 mrad) instead of that between the 1553 nm and 221 nm beams (9.69 mrad), which means a 3 times difference.

Experimentally, we first ensured that the 1553 nm and 258 nm beams overlapped in both the near and far fields, by the aid of two irises, with no crystal in the beam path, as shown in
Fig. 6(a). The two beams were then guided onto a laser viewing card (Thorlabs VRC4), and a Nikon CCD camera was used to record the beam profiles on the card. Figures 6(e) shows the overlapped beam profiles of the 258 nm and 1553 nm beams. A HWP in the beam path of the 1553 nm beam serves to adjust the polarization direction for the different phase-matching requirements of the various setups [see Figs. 2(d)-1, 2(d)-2 and 2(d)-3]. Figure 6(f) shows the beam profiles of the 1553 nm (extraordinary light, with HWP at 220°) and 258 nm (ordinary light) lasers with the CLBO-2’ crystal in the beam path, as shown in Fig. 6(b); the beams clearly separate. To confirm this spatial separation, the CLBO-2’ crystal was replaced with the CLBO-2 crystal, shown in Fig. 6(c), for which no walk-off between the beams is expected if the beam polarizations are well configured (type-I phase-matching condition). Figure 6(g) shows the beam profiles after CLBO-2 with the HWP angle unchanged. This separation was expected, because 1553 nm was still extraordinary light at that moment. When the HWP was rotated by 45°, shown in Fig. 6(d), the two beams overlapped [see Fig. 6(h)] because both 258 nm and 1553 nm beams were ordinary light, as expected. Accordingly, we conclude that the relative spatial walk-off between the 1553 nm and 221 nm beams limits the conversion efficiency in CLBO-3 for generating the 193 nm source. The setup of Fig. 2(d)-3 is better than that of Fig. 2(d)-2 in terms of spatial walk-off. Thus, we expect better results from the setup of Fig. 2(d)-3 than from the setup of Fig. 2(d)-2.

Fig. 6. Experimental setup for direct observation of spatial walk-off between the 1553 nm and 258 nm beams, a-d; and the results, e-h. HWP: half wave plate. In e-h, the yellow spot is for 1553 nm, the blue color for 258 nm.
With collinear-cascaded SFM configurations, the walk-off incurred in the first crystal cannot be avoided in the second crystal because no degrees of freedom remain to be adjusted. Alternatively, the two beams could be separated and recombined by using suitable dielectric mirrors, as shown in Fig. 2(d)-1 (as was done in our previous work [17] with CLBO-2). To evaluate the power loss due to the setup of Fig. 2(d)-3 relative to the setup of Fig. 2(d)-1, we experimented with the latter. The results are shown by the black squares in Fig. 7. For comparison, the results obtained with the other two setups are also shown in Fig. 7. The maximum average powers were 0.77, 0.7, and 0.41 W at 193 nm beam for setup of Fig. 2(d)-1, 2(d)-3, and 2(d)-2, respectively. We conclude that cascaded collinear SFM setup does not introduce much loss (~9%), but it does render the system more compact and cost effective. Figure 8 shows typical two- and three-dimensional beam profiles of the resulting 193 nm beam recorded by using a NanoScan camera from Ophir Photonics.

Note that another phase-matching condition is also available for generating the 193 nm radiation with a CLBO crystal; namely, type-II phase matching [1553 nm (e) + 221 nm (o) → 193 nm (e)] with the crystal cut at θ = 66.6°. However, the effective nonlinear coefficient is 30% less than that used in the experiment (0.692 versus 0.997 pm/V), so this scheme was not tested.

![Graph](image1.png)

**Fig. 7.** Average power of 193 nm beam as a function of average power of 258 nm beam obtained by using the three kinds of configurations shown in Fig. 2.

![Graph](image2.png)

**Fig. 8.** Typical two- and three-dimensional beam profiles of the 193 nm beams.
3.3 Further possible improvements?

As shown herein, the efficiency of the collinear-cascaded SFM configuration is limited by the spatial walk-off between 1553 nm and 221 nm beams in the first CLBO crystal. If this could be compensated, better performance could be expected. Figure 9(a) shows a schematic diagram of the beams propagating inside the CLBO-2 crystal. Here, we propose a scheme inspired by Ref [22] and shown in Fig. 9(b). Two shorter crystals with the optical axes arranged as mirror images of each other are placed together or bonded to correct for the direction of the Poynting vector so that the 1553 nm and 221 nm beams overlap, thereby allowing a perfect spatial overlap in the following CLBO crystal for the 193 nm beam generation. In the future, we hope to improve the performance by using such a scheme.

4. Summary

In conclusion, we have developed and experimentally demonstrated a cascaded collinear SFM configuration to generate coherent radiation at the wavelength of 193 nm. The configuration is more compact and cost effective than traditional configurations, albeit at the expense of a slightly lowered conversion efficiency (~9% lower). We have also developed a 1030 nm laser amplifier based on all-ceramic Yb:YAG thin rods. Finally, we propose possible solutions to compensate for the spatial walk-off as an avenue for further improvements.

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