Generation of deep ultraviolet narrow linewidth laser by mixing frequency Ti:sapphire laser at 5 kHz repetition rate

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We demonstrate a scheme to generate deep ultraviolet source by the single-stage high-power Ti:sapphire laser with linewidth of 0.05 nm cryogenically operating at repetition rate of 5 kHz. The fundamental laser was tuned by an intracavity birefringent filter and three etalons with an output power greater than 8 W, corresponding to about 17% optical efficiency. The pulse width was 112 ns and $M2 < 1.1$. By using the nonlinear crystals BiB_3O_6 and $KBe_2BO_3F_2$, the output power of 2.2 W at second harmonic and 8.5 mW at fourth harmonic laser of about 195 nm were produced. This compact high-repetition rate laser with narrow linewidth would be a promising tunable source for spectroscopy.

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1. Introduction

Coherent laser sources have wide applications in spectroscopy, lithography, and photochemical process [1–3]. In particular, such kind lasers with narrow linewidth and high power are more attractive in fine precision spectroscopy, optical pumping, and laser isotope separation [4–6]. Conventional dye lasers have been used as the primary sources in visible and near-IR range because of their excellent tunable ability, but the disadvantages such as poor beam quality, degradation with time, toxic chemicals, complex recycle system, and expensive cost restrict their further development. In recent years, all-solid-state lasers have performed with excellent properties as the tunable laser sources because of their compact size, high efficiency, long lifetime, low cost, and robust configuration. Combined with some nonlinear crystals, such as BiB_3O_6 (BIBO), Ba_2BO_4 (BBO), and $KBe_2BO_3F_2$ (KBBF), the wavelength can be even tuned to deep UV (DUV) range. Sakuma *et al.* obtained DUV radiation at 196 nm with an output power of 1.5 W operating at 5 kHz repetition rate, by using sum frequency mixing of third harmonic generation (THG) of a master oscillator power amplifier Nd:YLF laser system with an amplified Ti:sapphire laser system [7]. Kanai *et al.* reported a 200 nm laser with watt-level power at 5 kHz repetition rate, generated by two-step fourth harmonic generation of a picosecond Ti:sapphire laser system, using a 2.71 mm thick KBBF as frequency conversion crystal at DUV [8]. The pulse energy of up to 20 mJ at near-vacuum ultraviolet, achieved by Zhu *et al.* [9], was produced by a three-step fourth harmonic generation from a picosecond Ti:sapphire laser system with output energy of 360 mJ at 10 Hz repetition rate by using BBO as sum frequency crystal. The works mentioned thus far are approbatory for many applications from IR to UV. However, their fundamental laser systems are expensive and complex. What is more, the poor beam quality after multipass amplifier is not conducive to frequency conversion. To get an effective DUV source from a simple, compact high-power tunable laser with high repetition rate and good beam quality is significantly important

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and challenging work. As is well known, the optical damage of the gain medium is a severe problem for a high-power laser system and the repeated pulse can damage the laser gain medium with pulse energies considerably below that required for damage with a single pulse. Liquid-nitrogen-cooled lasers are attractive for high-power, high-repetition rate applications and simplifying the optical scheme remarkably. Schulz and Henion achieved a continuous wave (CW) Ti:sapphire laser with output power of up to 350 W by cryogenic cooling of the laser medium [10]. Ultrafast laser amplifiers with power of 11 and 40 W were obtained by Gaudiosi *et al.* and Matsushima *et al.* [11,12], respectively, which were both operating with a single-stage layout at kilohertz repetition rate by liquid-nitrogen-cooling. However, the compact high-power lasers with narrow linewidth and high repetition rate have not been reported to our knowledge. This might be due to the difficulties of linewidth compression for high-power pulse lasers with wide bandwidth emission spectrum. Seed injection method was developed and effectively used in many high-power laser systems [13], but in the meantime, the complexity of laser system was increased simultaneously. Optical intracavity elements, such as prisms and gratings, were finite for linewidth compression or vulnerable in high-power operation [14], whereas birefringent filters (BRFs) and etalons were mostly used in CW laser operations.

In this paper, we report a high-power single-stage Ti:sapphire laser with narrow linewidth, using a BRF together with three etalons as linewidth compression and wavelength tuning elements in the cavity. Average output power higher than 8 W was obtained at 5 kHz repetition rate. The typical laser output has a linewidth of less than 0.05 nm with a pulse width of about 112 ns and a beam profile M2 of less than 1.1. With nonlinear frequency conversion process, output powers of second harmonic generation (SHG) up to 2.2 W and 8.5 mW in the DUV range were realized. The experimental results proved that this new solid-state laser system could be tuned to around 780 nm with a narrow linewidth of less than 0.05 nm, corresponding to a UV laser wavelength down to 195 nm.

2. Experiment of Narrow Linewidth Ti:Sapphire Laser

The experimental scheme of our narrow linewidth laser is shown in Fig. 1. The Ti:sapphire oscillator was pumped by a *Q*-switched Nd:YLF laser (DM-30, Photonics Industries, Inc.), which is capable of 60 W output power with a pulse width of 300 ns operating at 5 kHz repetition rate. A fold cavity with three mirrors was adopted for the laser generation. The total laser cavity length was about 1.5 m. Both of the M2 mirrors are concave mirrors with a radius of curvature (ROC) of 1000 mm, and coated with a wide-bandwidth, high-reflectivity dielectric film centered at 780 nm. OC is the output coupler with 25% transmission at 780 nm. The pump laser beam was focused by a lens with 300 mm focal length to match the cavity beam waist of 380 μm. A Brewster-cut Ti:sapphire crystal, with a size of 3 mm × 3 mm × 20 mm (length), was wrapped with indium foil and mounted tightly in a copper heat sink, which was cooled by liquid nitrogen to 77 K to remove the deposited heat and settled in the vacuum chamber. To tune the wavelength and compress the linewidth of the laser, a commercial multiplate BRF and three etalons with thickness of 200 μm, 1 mm, and 2 mm were inserted into the cavity sequentially. Coarse tuning was achieved by rotating of the BRF. Fine-tuning was achieved by tilting the etalons that were mounted on the stepper motor and controlled with a personal computer.

Under the optimized alignment of the laser oscillator without tuning elements, the measured free-running output power was about 18 W under a pump power of 60 W, corresponding to an optical efficiency of 30%. The wavelength was centered at 780 nm with FWHM of 25 nm. After inserting the BRF into the cavity, the output power was reduced to 16 W. But the linewidth was sharpened to about 1 nm and could be tunable from 750 to 800 nm. We believed that the limited tunable range resulted from the 50 nm coating bandwidth of the mirrors. To further compress the linewidth, three uncoated etalons with different thickness were inserted into the laser cavity, leading to an even narrower linewidth and more accurate resolution of the tunable wavelength. The linewidth measured by spectrometer (AQ6315 A, Yokogawa Corp.) was to be 0.5 nm, 0.12 nm, and less than 0.05 nm as three etalons each were inserted into the cavity one by one. The measured spectrum after all of the elements were inserted is shown in Fig. 2. The minimum linewidth, 0.05 nm, has reached

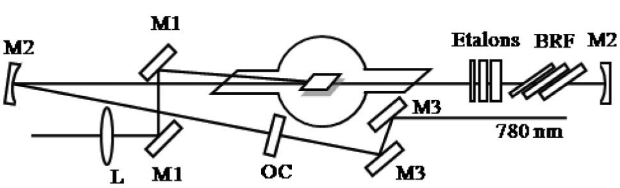

Fig. 1. Experiment setup of fundamental Ti:sapphire laser.

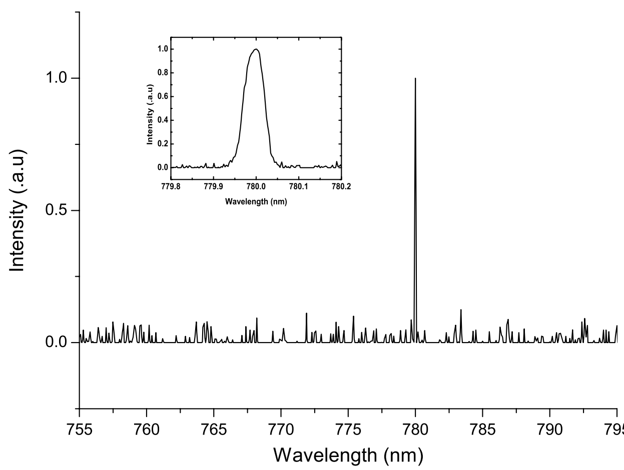

Fig. 2. Linewidth of Ti:sapphire laser with intracavity elements.

the resolution limit of the spectrometer. By using a wavelength meter (WS-7, HighFinesse GmbH) with higher resolution, the measured linewidth was about 20 GHz. Tuning accuracy of less than 0.01 nm for laser wavelength was achieved by fine controlling the motor of the etalons. Via tuning the BRF, output power of more than 8 W was obtained under a pump power of 47 W, as shown in Fig. 3. When the wavelength was tuned out of the range given in Fig. 3, or the laser was operated at a higher pump power scheme, the laser operation was in dual-wavelength mode, indicating that the laser emission at side peaks of BRF's transmission curve appeared. Thus, the BRF should be designed for a high-contrast ratio to suppress the side peak oscillation and limit the pump power at a high power, if needed. The pulse width at maximum power was about 112 ns measured by a fast photodiode. This long pulse width, resulted from low-peak pump-power density at a high repetition rate for laser pulse generation, allowed 22 round trips to pass intracavity elements to obtain the narrower linewidth required. However, the lower fundamental power density is a limit factor for the harmonic generation process. The bargain between conversion efficiency and beam quality with a focal parameter is needed in the next step. We measured the beam profile by a commercial M2 analyzer (M2-200 s, Spiricon Inc.), and the beam quality of $M_x^2 = 1.03$ and $M_y^2 = 1.05$ was remarkable for the following frequency conversion.

3. Harmonics Generation

Many kinds of nonlinear optical crystals can be used for harmonic generation in the visible wavelength range to UV. But only KBBF and $RbBe_2(BO_3)F_2$ crystal can be used to generate DUV down to 205 nm from two-step direct SHG method because of the phase matching limit [15,16]. By means of three-step sum frequency generation (SFG) process, DUV laser down to 187.9, 172.7, and 157.6 nm could be achieved with BBO, LiB_3O_5 (LBO), and KBBF crystal, respectively [17–19]. This was an effective complementary method to obtain DUV laser sources. We used two methods above for harmonics generation to obtain DUV for comparison, as shown in Fig. 4. Figure 4(a) was a three-step DUV generation scheme, consisting of an SHG process and two SFG process. First, the fundamental laser was divided into two parts by a beam splitter with partly reflected coating at 780 nm. The reflected beam, with about 20% of fundamental power, was used for the second sum frequency process, while the transmitted beam was used for SHG and was focused in a BIBO crystal by a plane-concave lens with a focal length of 315 mm. The BIBO crystal with a size of 5 mm × 5 mm × 10 mm (length) was cut at $\theta = 151.1°$, $\varphi = 90°$ for phase matching type in the YZ plane. It had an effective nonlinear coefficient $d_{\text{eff}} = 3.7$ pm/V [20,21], which is about two times that of BBO with $o + o- > e$ type and five times that of LBO with $o + o- > e$ type in the XY plane. However, the damage threshold of BIBO crystal is about 0.1 GW/cm^2, which was much lower than the other two. We also used a BBO crystal cut at $\theta = 25.7°$, $\varphi = 0°$ with a size of 8 mm × 8 mm × 14 mm (length), and an LBO crystal cut at $\theta = 90°$, $\varphi = 31.7°$ with a size of 6 mm × 6 mm × 8 mm (length) to compare with formal BIBO at SHG process. The results are shown in Fig. 5. The highest power of 2.2 W at an SHG of 390 nm was obtained from the BIBO with a conversion efficiency of 45% under a fundamental power of 4.9 W. To protect the BIBO from optical damage, the fundamental power was limited to about 5 W. We believe that the higher effective nonlinear coefficient and lower walk-off angle make BIBO quite suitable for frequency conversion under lower peak power density. And the LBO crystal would be preferred for higher peak power density conversion process because of its small walk-off angle and high damage threshold, although the effective nonlinear coefficient is not very high at short wavelength phase-matching conditions.

The beam quality of the second harmonic (SH) laser was good enough for THG process with long focal length of SHG. After the SHG process, the produced SH laser was reflected by a dichroic mirror (M4) and

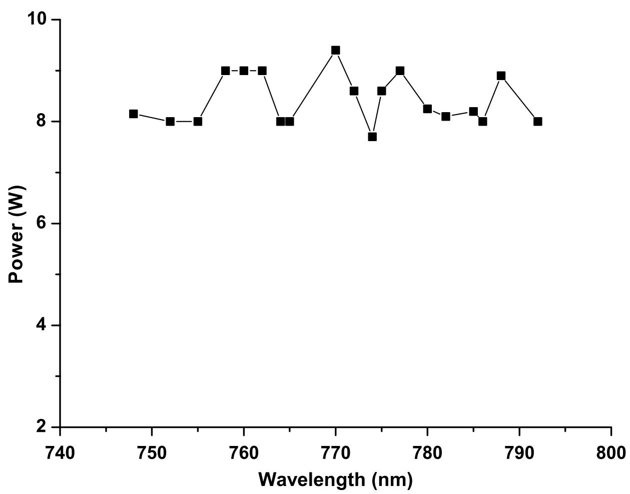

Fig. 3. Output power versus the tuning wavelength.

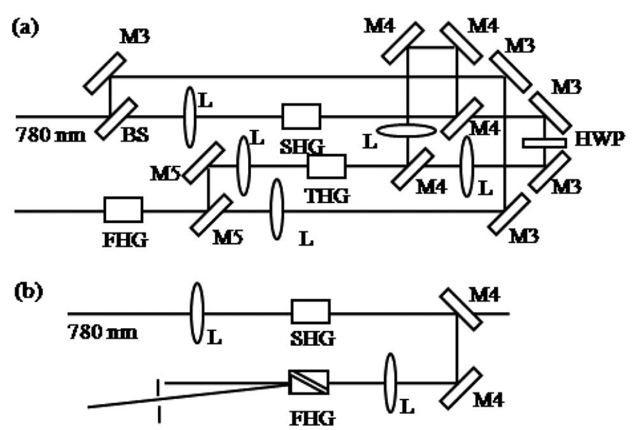

Fig. 4. Optical harmonic generation with (a) three-step method, and (b) two-step method.

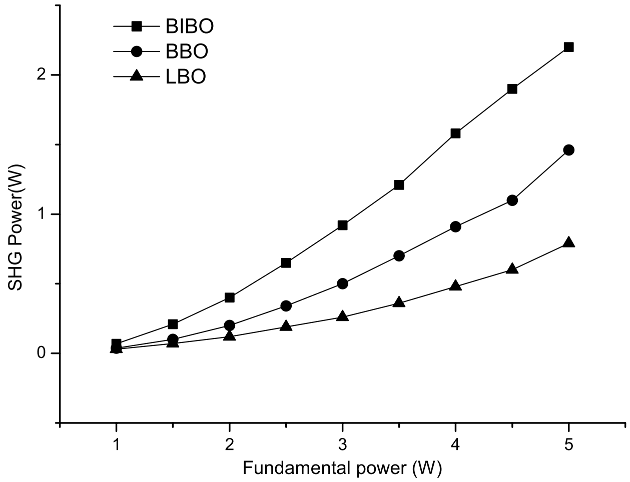

Fig. 5. Comparison of output powers of SHG with BIBO (square), BBO (circle), and LBO (triangle).

focused with a focal length of 150 mm into the THG crystal, which was combined with residual transmitted fundamental laser, polarization-rotated by a broadband half-wave-plate (HWP), and focused with a focal length of 125 mm. Many groups of focal length combinations were tested for beam waist match. The BBO crystal was chosen for THG, which had the size of 8 mm × 4 mm × 12 mm (length) and cut at $\theta = 44.3°$, $\varphi = 0°$. The power of more than 0.7 W at third harmonic (TH) of 260 nm was obtained. The conversion efficiency for THG was 28%. Another BBO crystal with a size of 10 mm × 10 mm × 9 mm (length) and cut at $\theta = 55.5°$, $\varphi = 30°$ was also tested for a Type II phase match to achieve THG, but the power of only about 30 mW was obtained. We believed this resulted from the low effective nonlinear coefficient and short crystal length.

We tried to produce fourth harmonic by using a BBO crystal, which had a size of 10 mm × 10 mm × 9 mm (length) and was cut at $\theta = 64.8°$, $\varphi = 0°$, but it did not obtain radiation at DUV. We checked the transmitted TH, and found that most of the TH power was attenuated at the focal lens and mirrors. So the absorption of the plate and coating problem for lens and mirrors in the UV should be considered seriously, and even reflected mirrors in an optical scheme would be preferred. To further obtain the tunable DUV laser and simplify the FHG process, we used a prism-coupled KBBF crystal with a size of 16 mm × 6 mm × 0.76 mm (length), to generate DUV laser by direct harmonic generation from the SHG, as is shown in Fig. 4(b). The angle of coupled fused silica prism was cut at 58.4°. Average power of 8.5 mW at 195 nm was generated with focal length of 50 mm with UV power of 2 W at 390 nm, corresponding to efficiency of 0.4%, which was a little higher than that of 0.13% reported in Zhang *et al.* [14]. The low power mainly resulted from the low peak power density of the nanosecond laser and the thin nonlinear crystal, for which it was rather difficult to grow thick KBBF because of its platelike nature.

4. Conclusion

In summary, we developed a 5 kHz nanosecond all-solid-state tunable laser with narrow linewidth. The beam power up to 8 W was obtained with linewidth of less than 0.05 nm and a tunable range from 750 to 800 nm. By means of harmonic generation in nonlinear crystals with BIBO, BBO, and KBBF, laser wavelength tuning in UV and DUV was achieved. High power at DUV could be obtained by optimizing the mirror coating and using thick-frequency conversion crystals. This work demonstrated a new way of generating tunable narrow linewidth laser toward high repetition rate, high power, and DUV wavelength with compact size, high efficiency, lost cost, long lifetime, and robust configuration, which is an ideal laser source for many applications.

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