High-power tunable narrow-linewidth Ti:sapphire laser at repetition rate of 1 kHz

Rui Wang,[1] Nan Wang,[1] Hao Teng,[1,2] and Zhiyi Wei[1,*]

[1]Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

[2]e-mail: hteng@iphy.ac.cn

*Corresponding author: zywei@iphy.ac.cn

Received 29 May 2012; accepted 22 June 2012; posted 2 July 2012 (Doc. ID 169411); published 30 July 2012

We report a high-power tunable narrow-bandwidth Ti:sapphire laser at a repetition rate of 1 kHz. The spectral linewidth of 0.4 pm with wavelength tuning range from 780 nm to 820 nm is obtained by a spectrum-compressing technique that consists of one grating and four fused silica prisms in the oscillator cavity. This narrow-bandwidth seed from the oscillator is further amplified to 6.5 W with pulse duration of 16 ns under the pumper power of 22 W. This high-power laser with narrow linewidth is candidate for isotope separation and accuracy spectrum analysis.

OCIS codes: 140.3600, 140.3538, 140.3280, 300.3700.

1. Introduction

With advanced progress of laser techniques, narrow-linewidth lasers have many applications in high-precision spectroscopy, nonlinear spectroscopy, atmospheric optics, laser spectroscopy, laser remote sensing, laser physics and laser chemistry, and so forth. Among these applications, laser isotope separation (LIS) has become a more attractive research topic for enriching isotopes (e.g., uranium 238) in nuclear fuels [1–3] due to the serious energy shortage in the world. The key of LIS is that the spectral linewidth of the laser must be narrow to selectively photoionize specific isotopes among other species in the atomic beam, and the wavelength can be tunable widely. The copper vapor laser is already employed for isotope separation by two-step photoionization, but there are some disadvantages for this two-step separation, for example, very low efficiency and difficulty of operatioin due to a vast laser system. So one-step photoionization separation based on a narrow-linewidth ultraviolet (UV) laser has been proposed recently, considering that it is highly efficient, compact, and easy to operate. The Ti:sapphire laser is one of the best candidates for one-step separation due to high saturation flux with wide gain spectrum. As we known, a Ti:sapphire laser can work for generation of femtosecond laser pulses by a Kerr-lens mode-locked mechanism and can work as a narrow-linewidth laser by the spectrum-compressing technique [4–7]. Furthermore, nonlinear crystal (i.e., BaB_2O_4, LiB_3O_5, $KBe_2BO_3F_2$) can be used for frequency conversion of the Ti:sapphire laser to get a UV or deep-UV laser, and the wavelength can be tunable. Some progress toward a narrow-linewidth Ti:sapphire laser has already been achieved. A single-frequency tunable pulsed Ti:sapphire laser at the repetition rate of 10 Hz was reported by Tiffany *et al.* in 1997, which used an etalon and a grating as frequency-selecting components [5]. Togashi *et al.* reported an all-solid-state tunable Ti:sapphire laser system, which consists of an oscillator and three-stage amplifier, to produce a laser with power of 32 W and linewidth of 0.7 GHz at a repetition rate of 5 kHz, and its frequency conversion to vacuum UV radiation in 2001 [8]. A single-mode Ti:sapphire oscillator-amplifier system pumped by three external synchronized sources was developed by Suganuma *et al.*, in which generation of a coherent

1559-128X/12/225527-04$15.00/0

light source at 157 nm is obtained, the linewidth of the output laser is compressed to 28.3 MHz by a dispersive component in the oscillator, and the output power is 8.5 W by following a four-pass amplifier [9]. In 2007, Hannemann *et al.* reported a narrow-bandwidth injection-seeded self-synchronized Ti:sapphire oscillator-amplifier system at 10 Hz, in which the maximum energy of pulses is 41 mJ with a linewidth of 45.5 MHz and a tunable wavelength range of 764 to 856 nm [10].

In this paper, we report a high-power tunable narrow-linewidth Ti:sapphire laser that consists of a narrow-linewidth oscillator and a two-pass amplifier pumped by a Q-switched green Nd:YLF laser (DM-527-40, Photonics Industries, Inc.). The laser works with a spectral linewidth of 0.4 pm in the wavelength tunable range of 780 to 820 nm, and the maximum output power of 6.5 W at 790 nm is obtained under the pump power of 26.5 W (4.5 W for oscillator and 22 W for amplifier). The output pulse with duration of 16 ns is obtained under the pump pulse duration of 200 ns due to the gain-switching characteristics of the pulse-pumped Ti:sapphire laser [11].

2. Experiment of Narrow-Linewidth Ti:Sapphire Laser

In order to obtain a narrow-linewidth laser, there are two aspects which must be taken into consideration. First, the length of the oscillator cavity should be short to ensure that only few longitudinal modes be present in the cavity. Second, some dispersion components should be employed to compress the spectral bandwidth and select the spectrum in the cavity. Based on the principle above, a short, folded plano–plano cavity oscillator with a holographic grating (1200 lines/mm) and an expander for spectral bandwidth compression are adopted. The folded cavity can avoid the reflection of the Ti:sapphire laser back to the pump laser and also improve the coupling efficiency. As shown in Fig. 1, the length of the cavity is 250 mm, including a short arm of 90 mm in length with the output coupler and a long arm of 160 mm in length with a grating as the end mirror and four prisms for intracavity beam expansion. A classic achromatic prism beam expander (PBE), which is in a configuration of down-up-up-down with four identical fused-silica right-angle prisms, is used as a beam expander, and it is very suitable for the cavity due to high transmission of the p-polarized beam [12,13]. Each prism in the expander is uncoated on the incident plane at the Brewster angle of incidence and antireflection coated at 765 to 835 nm on the exit plane. The magnified beam from the PBE, which offers a magnification of 11.7 according to our design, is incident on the grating at the Littrow angle. The larger spot size on the grating results in higher spectral resolution, and thus much narrower spectral bandwidth can be obtained.

A 5 mm × 5 mm × 10 mm Ti:sapphire crystal with figure of merit of 200 is used in the cavity. The pump spot in the Ti:sapphire crystal is 350 μm, which is measured by knife-edge, and is well matched with the theoretical spot radius in the Ti:sapphire crystal (330 μm). The oscillator and the amplifier are pumped by the same 527 nm laser, which is divided by the beam splitter M1 (reflectivity of 18%) after beam expansion by the lens F1 ($f = -100$ mm) and F2 ($f = 200$ mm). The reflection of the pump laser is coupled into the oscillator by a lens with focal length of 200 mm. The Ti:sapphire crystal is cooled at 15 °C by thermoelectric (TE) cooling, which could reduce thermal lens effect and improve the efficiency and beam quality. The fold mirror M5 is highly reflective of 765 to 835 nm wavelengths at 45°; the output coupler M6 has transmittance of 30% for the wavelength range of 765 to 835 nm. With fine adjustment of output coupler and grating, the oscillator works with very good performance. The output power of this oscillator is limited to 1 W due to the low damage threshold of the gold-coated grating. The seed from the oscillator is further amplified by injection into a two-pass amplifier; because the oscillator and amplifier share the same pump laser, the repetition rate is also the same. It can be seen from Fig. 2 that the build-up time of the seed in the oscillator is 120 ns when the pump power is 4.5 W, which is much shorter than the lifetime (3.2 μs) of the upper state of the Ti:sapphire crystal, so self-synchronization can be realized between the oscillator and amplification, and the seed can be amplified to high energy.

The two-pass amplifier is a confocus asymmetrical configuration, which comprises 4 concave mirrors

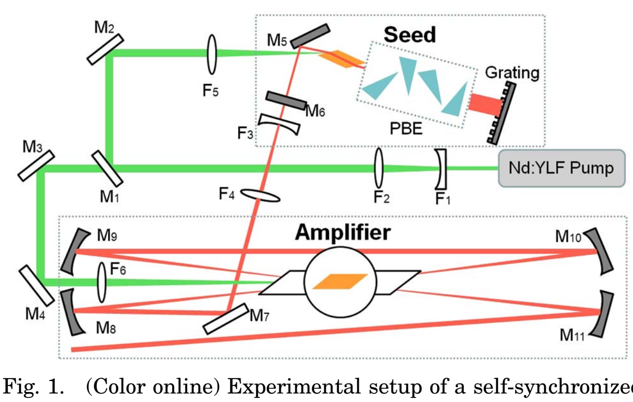

Fig. 1. (Color online) Experimental setup of a self-synchronized narrow-linewidth tunable Ti:sapphire laser system.

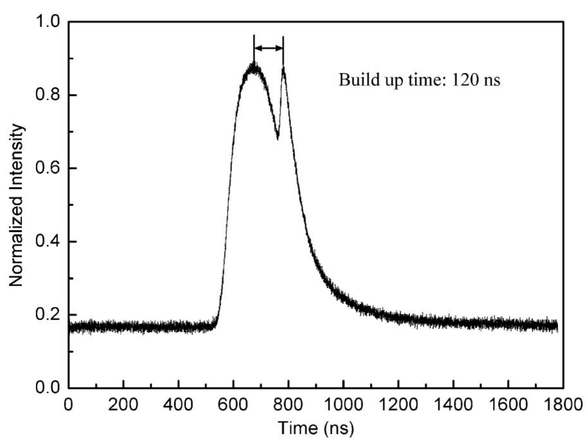

Fig. 2. Build-up time of pulses in oscillator.

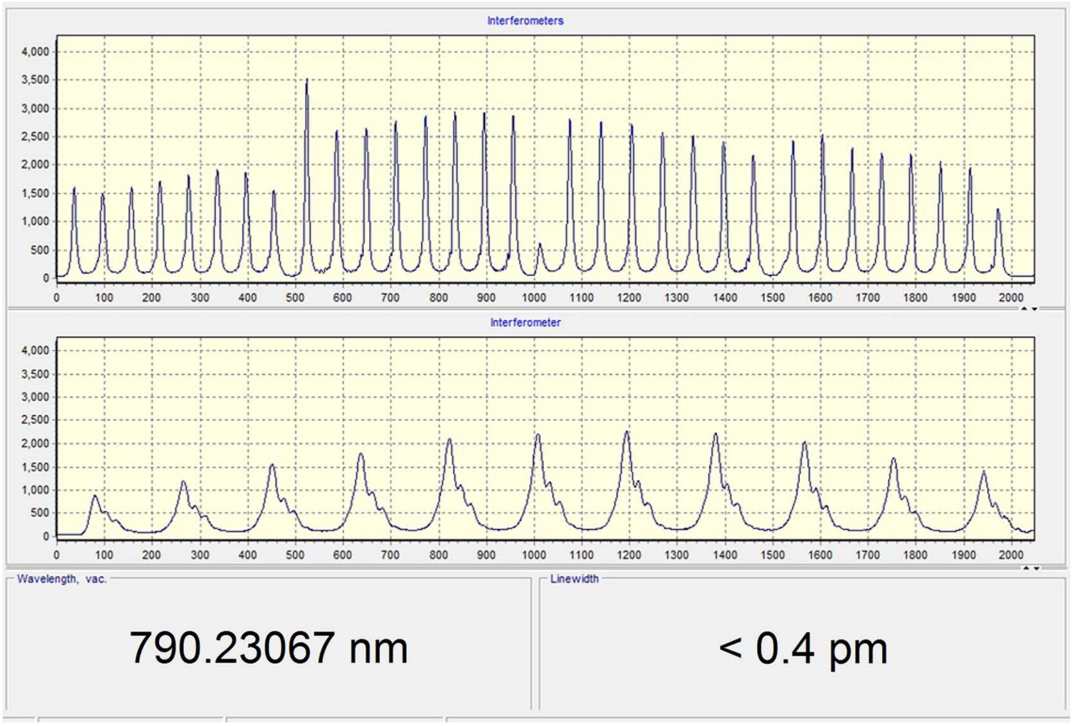

Fig. 3. (Color online) Linewidth of output pulse at 790 nm.

with curvature radius of 1000 or 800 mm respectively, and with high-reflection coating from 765 to 835 nm at normal incidence. A Ti:sapphire crystal with the size of $7 \times 7 \times 10\ \mathrm{mm}^3$ is located on the confocal position. In order to eliminate the thermal effect, a liquid nitrogen cooler for the Ti:sapphire crystal, which is in the vacuum chamber, is employed. The seed pulse from the oscillator is injected into the amplifier by collimation from a telescope consisting of F3 ($f = -200$ mm) and F4 ($f = 400$ mm); the remaining part of the pump laser from beam splitter M1 is focused into the Ti:sapphire crystal by lens F6 ($f = 400$ mm). The focal spot of the pump laser is 420 μm, which is a little bigger than the waist (380 μm) of the seed in the amplifier, so it is very easy to realize spatial overlap between pump and seed.

The specification of spectral linewidth was investigated first. Because a grating together with PBE was linewidth compressed and central-wavelength-selected components were employed in the oscillator, the linewidth of the output laser was compressed to picometer scale across the tunable wavelength range. As shown in Fig. 3, the linewidth at 790 nm was less than 0.4 pm, which was measured by a commercial wavelength meter (WS7, Highfinenss) with high accuracy illustrated from the high distinguishability of interferometric fringes. The linewidth was kept almost the same across the tunable range from 780 to 820 nm, and it was also kept the same after the amplifier.

The grating was mounted on a motorized rotation stage, and the angle of the grating could be finely adjusted with high accuracy. By rotation of the grating angle, the central wavelength of the output laser can be tuned from 765 to 835 nm, as shown in Fig. 4.

The threshold of the oscillator was 1.5 W, and it normally worked at an output of 0.9 W at 790 nm with linewidth of 0.4 pm under the pump power of 4.5 W. The output narrow-linewidth laser from the oscillator was injected into the two-pass amplifier as a seed. The output power of the amplified narrow-linewidth laser with pump power is shown in Fig. 5. The output power of the amplified laser linearly increases with pump power when pump power is less than 15 W, and increases to saturation when pump power is up to 22 W, which matches well with the theoretical simulation. The maximum of the amplified laser with power of 6.5 W can be obtained under the pump power of 22 W, which corresponds to an efficiency of 29.5%. The bandwidth of the narrow-line laser after the amplifier is kept the same.

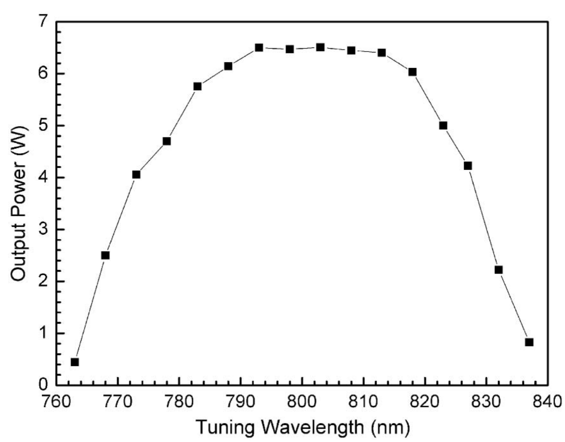

Fig. 4. Output power of amplifier with tunable wavelength.

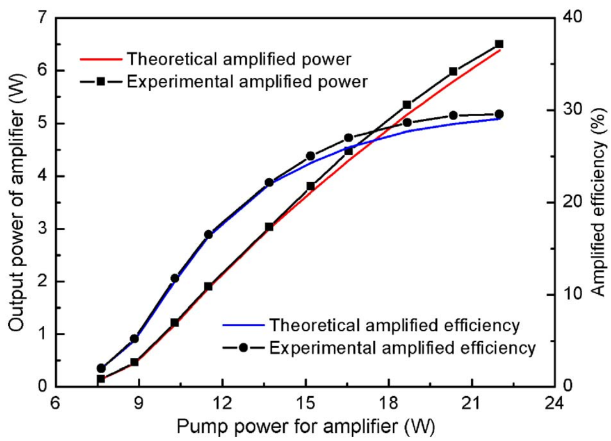

Fig. 5. (Color online) Output power of amplifier at 790 nm and corresponding conversion efficiency with pump power.

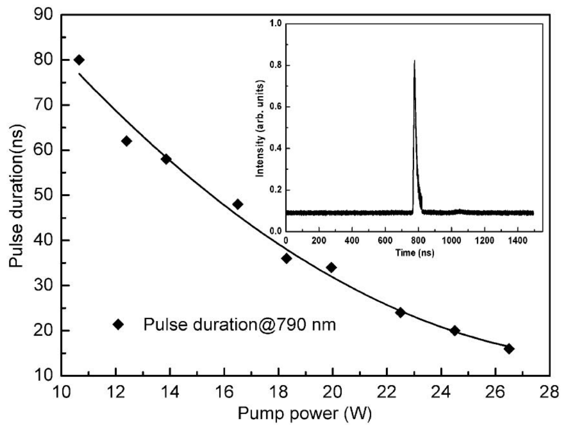

Fig. 6. Pulse duration of output pulses at 790 nm with pump power.

The temporal characteristic of the amplified pulses at 790 nm was measured by a high-speed photodiode. Due to the gain-switching characteristics of the pulse-pumped Ti:spphire oscillator, the output pulse duration gets shorter with increasing pump power, and the minimum value of 16 ns is achieved when the total pump power increases to 26.5 W, as shown in Fig. 6. The evolution of the pulse duration with the output wavelength was also investigated when the pump power was 26.5 W, and it basically remains the same value in the range from 780 to 820 nm.

3. Conclusion

In summary, a high-power tunable narrow-linewidth Ti:sapphire laser at 1 kHz is demonstrated. The narrow-linewidth laser is obtained from a Ti:sapphire oscillator in which a holographic grating and PBE are employed in the cavity for compressing spectral bandwidth and tuning wavelength. The bandwidth of this laser is 0.4 pm in the wavelength tunable range from 780 to 820 nm. The narrow-linewidth laser from the oscillator is further amplified to 6.5 W under the pump power of 22 W in a two-pass confocus amplifier, which corresponds to an efficiency of 29.5%. The narrow-linewidth laser can be used for LIS, laser spectroscopy, laser remote sensing, laser physics, and laser chemistry.

This work was supported by the National Key Technology R&D Program of the Ministry of Science and Technology under Grant No. 2012BAC23B00, the National Natural Science Foundation of China under Grants No. 91126008 and No. 11074298, and the Knowledge Innovation Program by the Chinese Academy of Sciences (CAS) under Grant KJCX2-YW-N48.

References

1. V. S. Letokhov and C. B. Moore, "Laser isotope separation (review)," Sov. J. Quantum Electron. **6**, 129–150 (1976).
2. V. S. Letokhov and C. B. Moore, "Laser isotope separation (review)," Sov. J. Quantum Electron. **6**, 259–276 (1976).
3. P. Parvin, B. Sajad, K. Silakhori, M. Hooshvar, and Z. Zamanipour, "Molecular laser isotope separation versus atomic vapor laser isotope separation," Prog. Nucl. Energy **44**, 331–345 (2004).
4. B. Pati and J. Borysow, "Single-mode tunable Ti:sapphire laser over a wide frequency range," Appl. Opt. **36**, 9337–9341 (1997).
5. A. J. Tiffany, L. T. Mckinnie, and D. M. Warrington, "Low-threshold, single-frequency, coupled cavity Ti:sapphire laser," Appl. Opt. **36**, 4989–4992 (1997).
6. K. Tamura, "Self-seeding of a pulsed double-grating Ti:sapphire laser oscillator," Appl. Opt. **47**, 1517–1521 (2008).
7. X. Ding, X. Li, Q. Sheng, C. P. Shi, S. J. Yin, B. Li, X. Y. Yu, W. Q. Wen, and J. Q. Yao, "High power widely tunable narrow linewidth all-solid-state pulsed titanium-doped sapphire laser," Chin. Phys. Lett. **28**, 0942051 (2011).
8. T. Togashi, N. Nabekawa, T. Sekikawa, and S. Watanabe, "Generation of milliwatt narrow-bandwidth vacuum ultraviolet radiation by an all-solid-state tunable high-average-power laser system," Opt. Lett. **26**, 831–833 (2001).
9. T. Suganuma, H. Kubo, O. Wakabayashi, H. Mizoguchi, and K. Nakao, "157 nm coherent light source as an inspection tool for F2 laser lithography," Opt. Lett. **27**, 46–48 (2002).
10. S. Hannemann, E.-J. van Duijn, and W. Ubachs, "A narrow-band injection-seeded pulsed titanium:sapphire oscillator-amplifier system with on-line chirp analysis for high-resolution spectroscopy," Rev. Sci. Instrum. **78**, 103102 (2007).
11. X. Ding, H. Zhang, R. Wang, X. Y. Yu, W. Q. Wen, B. G. Zhang, P. Wang, and J. Q. Yao, "Performance of gain-switched all-solid-state quasi-continuous-wave tunable Ti:sapphire laser system," Chin. Phys. B **17**, 3759–3764 (2008).
12. R. Trebino, "Achromatic N-prism beam expanders: optimal configurations," Appl. Opt. **24**, 1130–1138 (1985).
13. F. J. Duarte, "Multiple-prism array in laser optics," Am. J. Phys. **68**, 162–166 (2000).