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Compact narrow-linewidth nanosecond Ti:sapphire laser

© 2017 Hongling Cheng*,**; Zhimin Wang**; Fengfeng Zhang**; Wei Tu**; Nan Zong**; Baoshan Wang**; Mingqiang Wang**; Zhaoshuo Tian*; Qinjun Peng**; Dafu Cui**; Zuyan Xu**

*Information Optoelectronics Research Institute, Harbin Institute of Technology at Weihai, Weihai, Shandong Province 264209, China;
**Research center of laser physics and technology, Key lab of function crystal and laser technology, Technical institute of physics and chemistry, CAS, Beijing, 100190, China

E-mail: wangzmok@163.com; tianzhaoshuo@126.com

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A compact high peak power tunable narrow-linewidth nanosecond Ti:sapphire laser is presented in this paper. A maximum average output power of 1.4 W with a linewidth of 0.12 nm at 780.21 nm is achieved at a pulse width of 120 ns and a repetition rate of 3 kHz, leading to a peak power of 3.89 kW. Tunable emission wavelength range from 779.64 nm to 780.35 nm with a tuning resolution of 0.1 nm has also been demonstrated by the existing system.

Keywords: *Ti:sapphire laser, nanosecond, narrow linewidth, tunable, alkali laser.*

OCIS codes: *140.0140; 140.3538; 140.3580; 140.3590; 140.3600.*

Компактный наносекундный Ti-сапфировый лазер с узкой линией излучения

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Описан компактный Ti-сапфировый лазер с высокой пиковой мощностью и перестраиваемой узкой линией излучения. Максимальная выходная мощность излучения составила 1,4 Вт при ширине линии излучения 0,12 нм, длительности импульса 120 нс и частоте следования импульсов 3 кГц, что соответствует пиковой мощности 3,89 кВт. В реализованном устройстве продемонстрирована область перестройки от 779,64 нм до 780,35 нм с разрешение по длине волны 0,1 нм.

Ключевые слова: *Ti-сапфировый лазер, наносекундный диапазон, монохроматичность, перестройка длины волны, лазеры на парах щелочных металлов с оптической накачкой.*

Коды OCIS: *140.0140; 140.3538; 140.3580; 140.3590; 140.3600.*

1. INTRODUCTION

The high peak-power and narrow-linewidth nanosecond (ns) Ti:sapphire lasers are important for many applications such as laser spectroscopy, environmental monitoring, material processing, and nonlinear optics, etc. [1–3]. Especially, these lasers have been demonstrated to be suitable for the investigation of alkali lasers [4–6]. The Ti:sapphire lasers are widely studied due to their tunable emission wavelengths, high peak powers, and high beam qualities. However, most studies have been focused on the development of CW, picosecond and femtosecond modes operation Ti:sapphire lasers, with only a few works on the nanosecond operation mode.

Moreover, studies on the high peak-power and narrow linewidth ns Ti:sapphire lasers operating at room temperature are rarely reported. Based on master oscillator power amplifier (MOPA) approach, in 2002, Suganuma et al. demonstrated a 0.5 W Ti:sapphire oscillator laser at 768 nm with a linewidth of 28.3 MHz and a pulse width of 18.4 ns at a repetition rate of 1 kHz, leading to a peak power of 27.2 kW. The power was further amplified to the maximum average output power of 8.5 W [1]. In 2012, Wang et al. reported a 0.9 W nanosecond Ti:sapphire oscillator at 790 nm with a linewidth of 0.4 pm and a repetition rate of 1 kHz. After amplification, the MOPA system delivered a maximum power of 6.5 W with a pulse duration of 16 ns [2, 3]. However, these MOPA systems consisting of a seed oscillator and an amplifier are inherently complex and expensive, thus limiting their applications in the laboratory experiments. Therefore, a compact, robust, and user-friendly ns Ti:sapphire oscillator with a high power and a narrow-linewidth is highly desirable. To achieve that, Sulham et al. reported a ns Ti:sapphire laser with a peak power of 18.9 kW (10 kHz, 100 ns) and a linewidth of 0.07 nm [5]. Also, Zameroski et al. demonstrated a ns Ti:sapphire laser with a peak-power of around 12 kW (10 kHz, 100 ns) and a linewidth of 0.1 nm [6]. Unfortunately, their ns Ti:sapphire laser systems were operated in a cryo-cooled mode. A narrow-linewidth ns Ti:sapphire laser operating at room temperature was presented by Shi et al. [7], which produced an average output power of 1.6 W with a linewidth of 0.3 nm at 800 nm. However, no information on the exact pulse width and corresponding peak power was reported.

In this paper, a compact ns Ti:sapphire laser operating at room temperature with narrow linewidth and high peak power is presented. The reported laser system is specifically designed for future alkali lasers research. The combination of a prism and a birefringent filter (BF) is utilized to realize tunable wavelength and narrow-linewidth laser output. The Ti:sapphire laser delivers a maximum average output power of 1.4 W at 780.21 nm with a linewidth of 0.12 nm and a pulse width of 120 ns at a repetition rate 3 kHz, leading to a peak power as high as 3.89 kW.

2. EXPERIMENTAL SETUP

The 3D schematic diagram of Ti:sapphire laser is shown in Fig. 1. The 1064 nm fundamental laser is a homemade diode laser (LD) pumped Q-switched Nd:YAG laser with 48 W maximum output power. The LD repetition rate is 500 Hz, and the Q-switch works at 100 kHz repetition rate, which produces a laser pulse chain of 500 macro pulses per second, and each macro pulse is composed of 6 micro pulses as shown in Fig. 2, resulting in the 1064 nm Nd:YAG laser operating at a repetition rate of 3 kHz. The Nd:YAG fundamental laser is collimated by an antireflection-coated plano-convex lens L_1 with a focal length f of 300 mm. The fundamental laser is then frequency-doubled by a lithium triborate LiB_3O_5 (LBO) crystal, yielding an 18 W average power and a 60 ns pulse duration at 532 nm with a conversion efficiency of 37.5%. The residual fundamental laser and the second harmonic laser are separated by a flat-mirror M_1 with 45° high reflection at 1064 nm and high transmission at 532 nm.

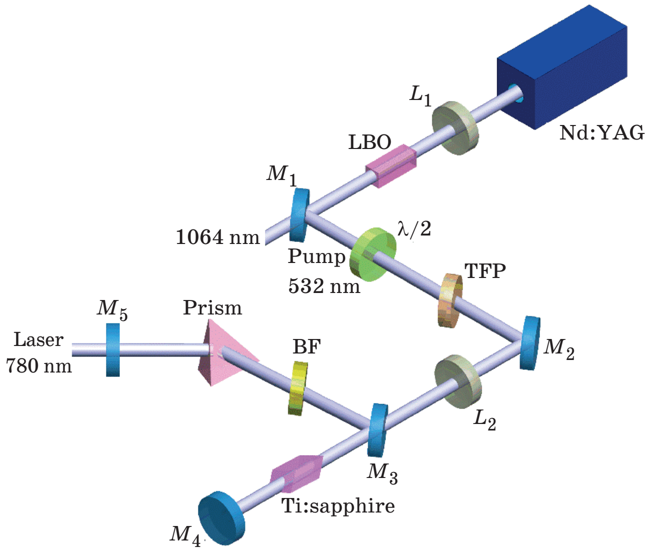

Fig. 1. 3D schematic diagram of the Ti:sapphire laser system.

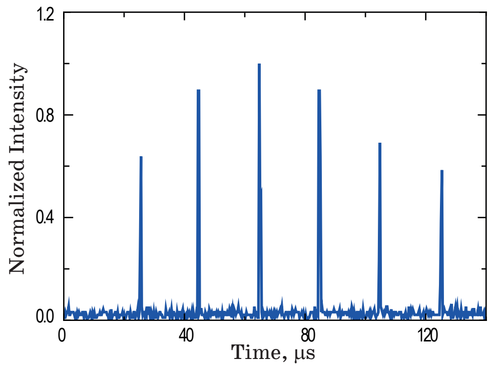

Fig. 2. Micro pulse chain of 1064 nm Nd: YAG laser.

The laser power of 532 nm is tuned by a combination of a thin film and a half-wave plate and then is focused onto the Ti:sapphire rod by a 532 nm antireflection-coated plano-convex lens L_2 with a focal length f of 150 mm and a 1 mm pumping beam diameter in the Ti:sapphire. A flat-mirror M_3 with 45° high reflection at 780 nm and high transmission at 532 nm is placed between the Ti:sapphire rod and the lens L_2 as the output coupler. The crystal optical axis of the Ti:sapphire rod with both end facets cut at Brewster's angles is perpendicular to the geometric central axis of the rod. The rod is mounted in a water-cooled brass block maintaining at 23°C during the laser operation. The "L-shaped" Ti:sapphire laser cavity is consisted of a 45° flat-mirror M_3, a flat high reflection mirror M_4 at 780 nm, and a 20% flat output coupler M_5. The length of formed resonance cavity is 195 mm. The rod is positioned symmetrically between mirrors M_4 and M_5. A dense flint-glass Brewster prism and a BF are inserted into the cavity to obtain a narrow linewidth and tunable Ti:sapphire laser.

3. EXPERIMENTAL RESULTS

3.1. Ti:sapphire laser system under free operation

First, the Ti:sapphire laser system is characterized under free operation condition without Brewster prism and BF in the cavity. The measured output power of the laser versus 532 nm pump power is shown in Fig. 3. It can be seen from Fig. 3 that the threshold pump power is 6 W, and the maximum average output power of 4.6 W is obtained under the pump power of 18 W, corresponding to a "light-to-light" conversion efficiency of 25.6%. The spectrum of the laser monitored with an optical spectrum analyzer (AvaSpec-2048FT-SPU) is plotted in the inset of Fig. 3. The central wavelength is located at 788 nm with a laser linewidth of 18 nm.

3.2. Wavelength tuning and linewidth compressing of the Ti: sapphire laser system

A combination of a dense flint-glass Brewster prism and a BF was utilized to compress the linewidth and tune the wavelength of the Ti:sapphire laser.

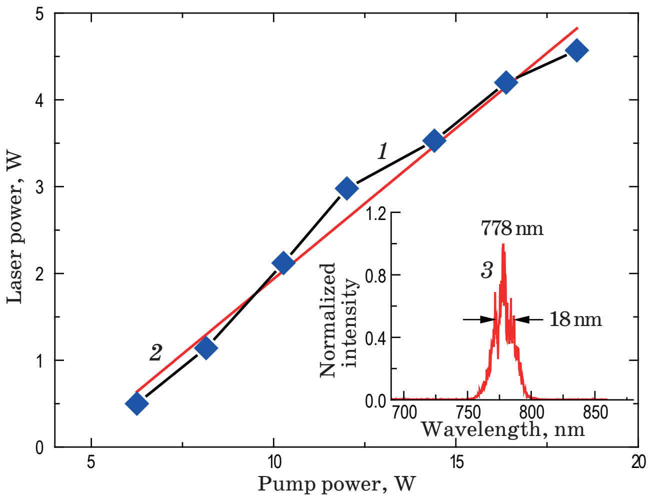

Fig. 3. Output power versus pump power of the Ti:sapphire laser under free operation (*1*). The red line is the linear fitting of the laser power (*2*).The inset shows the linewidth of output (*3*).

The use of a prism as a dispersion element in a laser resonator benefits from low loss, broad wavelength tunability and narrow output linewidth. The latter two properties can be expressed mathematically by Eqs. (1) and (2) [8], respectively,

$$\frac{d\alpha}{d\lambda} \approx \frac{2}{n}\tan\alpha\frac{dn}{d\lambda}, \quad (1)$$

$$\delta\lambda = \frac{\theta}{\frac{d\alpha}{d\lambda}}, \quad (2)$$

where α is the incident angle, λ is the wavelength, n is the refractive index of the prism, and θ is half of the laser beam divergence angle. The chromatic dispersion angles at different wavelengths depend on prism refractive indices n and α of the laser beam. The wavelength at 780 nm that we want to achieve corresponds to a specific value of α. The output laser spectrum consists of several longitudinal modes close to the designed wavelength and those modes far from that wavelength are suppressed due to the gain competition effect after laying the Brewster prism in the cavity [9], thus leading to a compressed the linewidth of output laser spectrum.

To further compress the laser linewidth and tune wavelength precisely, a BF was inserted in the cavity at Brewster's angle. The BF with this special orientation is equivalent to a wave plate sandwiched by two parallel polarizers. The wavelength filtering effect of the BF can be described as,

$$\lambda_m = \frac{(n_e(\theta) - n_o)L_e}{m}, \quad (3)$$

where n_o and $n_e(\theta)$ are refractive indices for ordinary and extraordinary rays, respectively, m is the order of the selected wavelength, λ_m is the m-order transmission wavelength, and L_e is the plate thickness along the beam direction within the plate. When m is an integer, the transmission of the BF is equal to unity, and the laser beam at the wavelength λ_m in the cavity experiences no losses when passing through the plate. Rotating the BF about its surface normal changes n_e, and thus the wavelength is tuned to the maximum transmission of the filter. The tuned lasing spectra achieved with a BF are far more uniform and narrow than those achieved without a BF present in the cavity. This is due to the longitudinal mode discrimination provided by the BF, and the lack of a competing spectral filtering due to the microcavity resonance [10]. It has been shown that the narrower linewidth can be achieved by increasing the thickness of the BF [11–15]. However, this will lead to a reduced output power due to the additional loss. Thus, the number of the BF is a trade-off between the laser linewidth and the output power. Figure 4 shows the laser output power versus incident 532 nm pump power after a prism and a BF were inserted in the la-

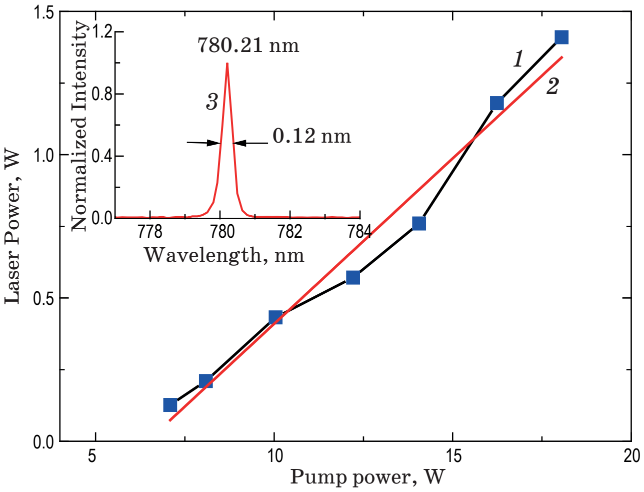

Fig. 4. Output power at 780.21 nm versus pump power with a prism and a BF in the cavity (*1*).The red line is the linear fitting of the laser power (*2*).The inset shows the corresponding laser linewidth (*3*).

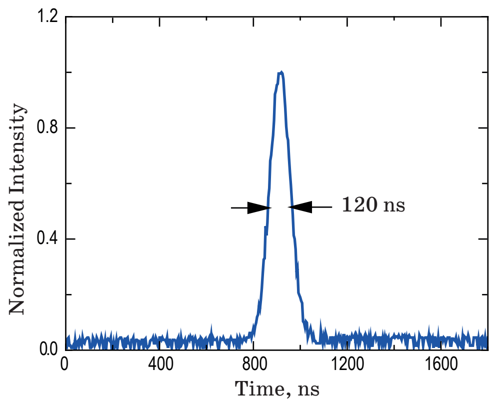

Fig. 5. Output pulse width of at 780.21 nm with 0.12 nm linewidth and 1.4 W output power.

ser cavity. The average output power was 1.4 W with pump power of 18 W, resulting in a maximum "light-to-light" conversion efficiency of 7.8%. The relatively low conversion efficiency is due to the large pumping beam size in the Ti:sapphire which makes the laser threshold higher, thus a higher input power and a reduced conversion efficiency. The final linewidth of Ti:sapphire laser is 0.12 nm at 780.21 nm measured by a spectrum analyzer (Anritsu MS9710B) with a resolution of 0.07 nm, as shown in Fig. 4. The pulse width of Ti:sapphire laser is measured by a fast photodiode (THORLABSDET10A/M, rise time 1 ns) connected a 500-MHz digital oscilloscope (Tektronix, TDS3052). Figure 5 illustrates that the laser pulse width is 120 ns which is mainly affected by the pump laser power

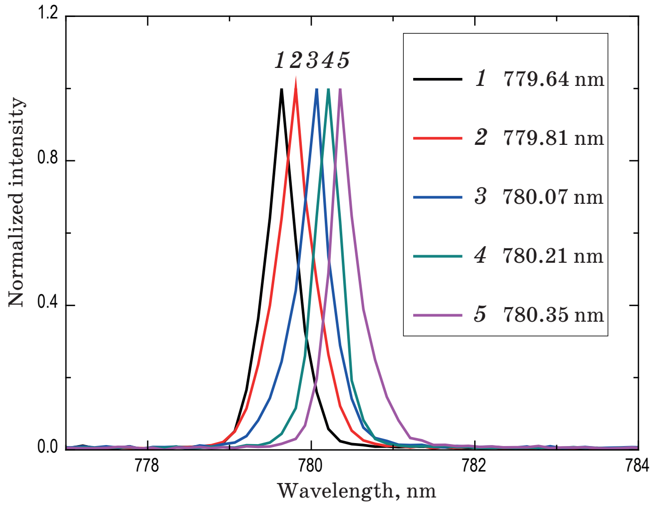

Fig. 6. Tunable spectra of the Ti:sapphire laser with linewidth of 0.12 nm.

and the cavity length [16]. The corresponding output power is 1.4 W.

In order to achieve efficient pumping of the alkali laser, the pump spectrum should have a good overlap with alkali atoms transition lines. Apparently, a tunable pumping source for alkali lasers would be beneficial for efficient pumping and experimental convenience. For the prototype system, the wavelength with narrow linewidth is tuned from 779.64 nm to 780.35 nm by adjusting the BF with a wavelength tuning resolution of 0.1 nm, as shown in Fig. 6.

4. CONCLUSIONS

In conclusion, a compact tunable ns Ti:sapphire laser with narrow linewidth has been demonstrated. Our system provides a 1.4 W maximum average output power at 780.21 nm with a linewidth of 0.12 nm and a 120 ns pulse duration at 3 kHz, leading to a peak power as high as 3.89 kW. Furthermore, the laser wavelength can be tuned from 779.64 nm to 780.35 nm with a tuning resolution of 0.1 nm. Such a narrow-linewidth high peak power laser is promising for the nonlinear frequency conversion research as a powerful pumping source. More importantly, it may serve as a good pumping source for the alkali lasers research.

This work was carried out at the Research Center for Laser Physics and Technology, Key Lab of Functional Crystal and Laser Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences.

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