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Self-injection locked CW single-frequency tunable Ti:sapphire laser

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Abstract: A self-injection locked continuous-wave (CW) single-frequency tunable Ti:sapphire laser is demonstrated in this paper. Unidirectional operation of the presented Ti:sapphire laser is achieved by using a retro-reflecting device which can retro-reflect a seed laser beam from one direction back into the counter-propagating field. On the basis, the influence of the transmission of output coupler on the unidirectional operation is investigated and it is found that stable unidirectional and single-frequency operation of the Ti:sapphire laser is achieved when the loss difference between both output directions is larger than a certain value, which is easy to be realized by choosing the transmission of output coupler. When the output coupler with transmission of 6.5% is utilized, the maximal 5 W CW single-frequency Ti:sapphire laser with stable unidirectional operation is obtained with the pump power of 18 W. The measured power stability and M^2 are better than ±0.9% and 1.1, respectively. The maximal tuning range and continuous frequency-tuning ability are 120 nm and 40.75 GHz, respectively.

OCIS codes: (140.3590) Lasers, titanium; (140.3570) Lasers, single-mode; (140.3520) Lasers, injection-locked; (140.3600) Lasers, tunable.

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1. Introduction

All-solid-state continuous-wave (CW) single-frequency tunable Ti:sapphire lasers represent the highest level of the tunable lasers thanks to the 700-1000 nm broadband spectrum of Ti:sapphire crystal [1] and have had a profound impact on a variety of experiment researches and applications including atom trapping and cooling, quantum information storage, spectroscopic measurement, laser radar and so on. The first single-frequency CW Ti:sapphire laser with tuning range of 100 nm was realized by Schulz in 1988 [2]. However, the peak output power was restricted to 500 mW under the pump power of 10 W from an argon ion laser. The line-width of single-frequency Ti:sapphire laser was narrowed to 1 kHz by Vassen et al. [3] and Boyd et al. [4] in 1991, respectively. In 1996, Tsunekane and Taguchi reported an all-solid-state Ti:sapphire laser with output power of 1.4 W, where they pointed out the advantage of the all-solid-state green laser acting as the pump source of the Ti:sapphire laser compared to the argon ion laser [5]. Later, the influences of the longitudinal-mode structure of pump source on the intensity noise [6] as well as the phase-noise-amplitude-conversion [7] of Ti:sapphire laser were investigated, respectively. Further, the intensity noise of Ti:sapphire laser at low frequencies was effectively suppressed by optoelectronic negative feedback control [8]. Recently, depending on new physical mechanism including extra nonlinear loss [9] or intra-cavity locked electro-optic etalon (E) [10], several new kinds of single-frequency tunable Ti:sapphire lasers were developed. To date, several groups had already realized all-solid-state CW single-frequency tunable Ti:sapphire lasers and a series of corresponding products [11–14] could be supplied for researchers and engineers. For above mentioned Ti:sapphire lasers, a broadband optical diode (OD) was inserted into the ring resonator to eliminate the harmful spatial hole-burning effect and implement single-frequency and unidirectional oscillation of Ti:sapphire laser. Generally, the broadband OD usually comprised a Brewster-cut Faraday crystal, such as terbium gallium garnet (TGG) surrounded by external magnetic field, and a natural optical rotating crystal [15]. In order to enforce the laser unidirectional operation in its achievable wavelength-tuning range, however, it was especially important to precisely select the length of TGG crystal, the strength of magnetic field and the thickness of nature optical rotating crystal, which would enhance the difficulty of laser design and debugging. Even so, the complete compensation was not expected for whole wavelength covering range of the Ti:sapphire laser. In addition, the imperfect compensation would introduce additional intra-cavity loss and decrease the optical-optical conversion efficiency of Ti:sapphire laser. The simplest solution to this issue would be seed laser-injection locking technology, where the master seed laser determined the output wavelength and forced both single-frequency and unidirectional operation. In 2002, Cummings et al. demonstrated a 1-W injection-locked CW Ti:sapphire laser at 846 nm [16]. In 2008, Cha et al. developed a 5-W 756 nm injection-locked Ti:sapphire laser [17]. Due to the bandwidth limitation of the master seed laser, the tuning ranges of these obtained Ti:sapphire lasers were restricted to a small range. Moreover, the adoption of the extra injection-locking systems made the Ti:sapphire laser systems become relatively complex. Knowing from the seed laser-injection locked Ti:sapphire laser, Gorris-Neveux et al. demonstrated a two-wavelength, passively self-injection locked CW Ti:sapphire laser, which combined an interference wedge with a grazing incidence grating outside of the resonator [18]. Combining the advantages of aforementioned tunable Ti:sapphire lasers, in this paper, we demonstrated a novel self-injection locked single-frequency CW Ti:sapphire laser, where a retro-reflecting device outside of the ring resonator instead of the traditional broadband OD or extra seed laser injection-locking system was adopted to implement the unidirectional operation in the whole tuning range of Ti:sapphire laser. Though the adopted method had been reported by Frolich et al. as early as 1977 [19], their primary work was only focus on the optical-optical conversion efficiency by optimizing the output transmission. Subsequently, single-frequency self-injection locked $Nd:YVO_4$ and Nd:YAG lasers with output wavelengths of 1064 [20, 21] and 1342 nm [22] were developed. The goal of the work reported here was to attain a stable self-injection locked Ti:sapphire laser with broad tuning range over 100 nm, in which the retro-reflected beam itself could directly act as the seed laser for injection-locking. The realization of self-injection locked technology paved a way for the development of a high efficiency, high output power CW single-frequency tunable Ti:sapphire laser with broadband tuning range and simple structure. In the following, the schematic of designed single-frequency Ti:sapphire laser containing a retro-reflecting device with alterable reflection was firstly presented and then the unidirectional operation characteristic was investigated with different transmission of output coupler. Eventually, by choosing the transmission of output coupler, a stable CW single-frequency unidirectional tunable Ti:sapphire laser with tuning range up to 120 nm and output power over 5.0 W was achieved.

2. Experimental setup

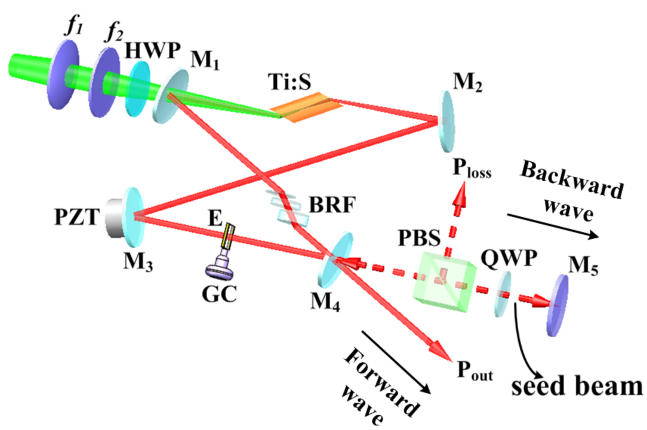

Fig. 1. Schematic diagram of the designed self-injection locked CW single-frequency tunable Ti:sapphire laser. HWP, half wave-plate; Ti:S, Ti:sapphire; BRF, birefringent filters; PZT, piezoelectric transducer; E, etalon; GC, galvanometer scanner; PBS, polarization beam splitter; QWP, quarter wave-plate.

The designed self-injection locked CW single-frequency tunable Ti:sapphire laser is schematized in Fig. 1. A homemade single-frequency and frequency-doubling $Nd:YVO_4$ laser (F-VIII B, Yuguang Co., Ltd) at the wavelength of 532 nm [23] is employed as the pump source, which delivers up to 18 W of single-frequency output in a linearly polarized laser. The power

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stability and beam quality M^2 factor are better than ±0.5% (8 hours) and 1.1, respectively. The pump green laser beam is collimated using an aspherical lens (f_1) with a focal length of 200 mm and focused onto the Ti:sapphire crystal by a second aspherical lens (f_2) with a focal length of 120 mm. The half wave-plate (HWP) in front of resonator can efficiently align the polarization of pump green laser with respect to the optical axis of Ti:sapphire crystal, which ensures that the pump energy can be effectively absorbed by the gain Ti:sapphire crystal. The laser resonator with eight-ring-shaped structure is constructed by one concave-convex mirror with radius of curvature of 100 mm (M_1), one plano-concave mirror with radius of curvature of 100 mm (M_2) and two flat mirrors (M_3 and M_4). The input mirror M_1 is coated with antireflection (AR) film at the wavelength of 532 nm and high reflection (HR) film at the wavelength of 740-890 nm to avoid introducing extra divergence of the pump laser. M_2 and M_3 are both coated with HR films at the wavelength of 740-890 nm. The output mirror M_4 is coated with partial transmission film at the wavelength of 740-890 nm (T_1). The incident angles of cavity mirror M_1 and M_2 are both set 15.8 °, which could be enough to compensate the astigmatism caused by the Brewster-cut intra-cavity elements including Ti:sapphire crystal and birefringent filters (BRF) [24]. After astigmatism-compensation, the generated laser beam waists between M_1 and M_2 are 38 μm in the sagittal plane and 36 μm in the tangential plane, respectively. The Brewster-angle-cut (60.4°) Ti:sapphire crystal with doped concentration of 0.05 wt.% and the size of $\Phi 4mm \times 20mm$ is mounted in a closed copper block oven cooled by circulated water and positioned between M_1 and M_2. A set of three-plate BRF with thickness of 0.5 mm, 2 mm, and 8 mm is inserted into the resonator with its Brewster incidence angle (57°) and serves as tuning element for roughly frequency-tuning in a broad frequency-band. An electro-optic E made of lithium niobate ($LiNbO_3$) crystal adhered to the rotation axis of the galvanometer scanner (GC) is used to finely tune the frequency and suppress the mode-hopping phenomenon of the Ti:sapphire laser. The continuous frequency-tuning of the Ti:sapphire laser is implemented by scanning the voltage loaded on a piezoelectric transducer (PZT) which is adhered to M_3 after the electro-optic E is locked to the oscillating mode of the Ti:sapphire laser [10]. In order to achieve the unidirectional operation of the Ti:sapphire laser, a retro-reflecting device [21] with alterable reflection composed of a polarization beam splitter (PBS), a quarter wave-plate (QWP) and a seed mirror (M_5) coated with HR film at the wavelength of 740-890 nm is placed in one arm of the output laser beam.

3. Experimental results

In the experiment, the Ti:sapphire laser was firstly characterized without the retro-reflecting device. When the transmission of output coupler M_4 was 6.5% and the laser worked at the wavelength of 795 nm by rotating the angle of the optical axis of BRF, two power meters (LabMax-Top, Coherent) were utilized to simultaneously monitor powers of both output directions and corresponding results were depicted in Fig. 2. The results depicted that the laser could not oscillate in both two oscillating directions simultaneously and the noticeable power switch between both directions of the laser was easily observed, which was owing to the insertion of electro-optic E. In this case, the net gain of the lasing mode was so dominant that the single-longitudinal-mode operation of the laser was established and the intra-cavity light fields in two oscillating directions were degenerate with respect to the laser frequency owing to the symmetry of the resonator. However, the ambient perturbation would ruin this symmetry. The laser started oscillation in one direction rapidly and that in another direction was automatically suppressed due to the fiercely gain competition between them. Similarly, the ambient perturbation would make the laser oscillate in another direction. As a result, the laser oscillation switched randomly between two circulation directions. The irregular power switch also exposed the fragility of Ti:sapphire laser for adaption to environment. To attain stable unidirectional operation of the Ti:sapphire laser, a retro-reflecting device was mounted after

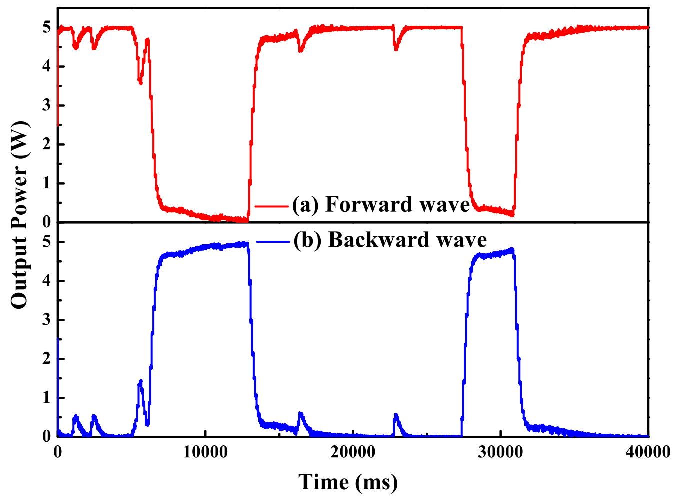

Fig. 2. Power fluctuation of two output directions without retro-reflecting device. (a) Forward wave. (b) Backward wave.

one light propagating direction to retro-reflect a laser beam back into the counter-propagating field, which could break the symmetry of the resonator. The loss introduced by the retro-reflecting device was marked before it was inserted into the Ti:sapphire laser system using the experimental setup illustrated in inset of Fig. 3. P_{in} and P_{loss} were the power of the signal laser and reflected power by PBS, respectively. The power ratio P_{loss}/P_{in} was the loss introduced by the retro-reflecting device, which was named transmission of retro-reflecting device (T_2). The marked results were shown in Fig. 3. The abscissa and ordinate axises were on behalf of the angle between the polarization direction and the long axis of the QWP and power ratio P_{loss}/P_{in}, respectively. Curve (a) of Fig. 3 was the variational trend of power ratio P_{loss}/P_{in} along with the rotation of QWP.

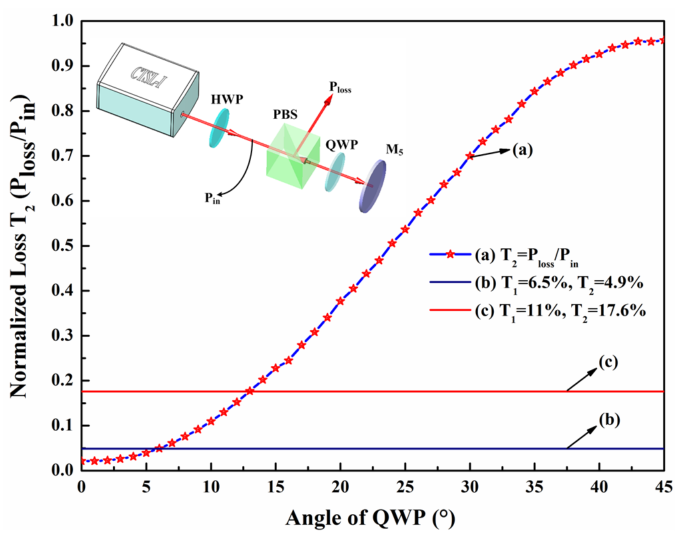

Fig. 3. Normalized loss of retro-reflecting device. (The inset is the experimental setup utilized to measure the introduced loss of retro-reflecting device.)

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After mounting the retro-reflecting device into one arm of the output directions of Ti:sapphire laser system, we compared the unidirectional characteristics of Ti:sapphire laser with the output coupler transmission of 3.5%, 5.5%, 6.5%, and 11%, respectively. When the transmission of the output coupler was 3.5%, the frequent reversal of the output power at two directions still occurred even though the loss introduced by the retro-reflecting device was neglected. The power fluctuation was same as that shown in Fig. 2. When the transmission of the output coupler was increased to 5.5%, the situation could be changed greatly and unidirectional operation was achieved. However, the instability of the output power was very easy to be observed. After about 20 minutes, the laser beam could flash in other direction and the laser power in original emergent direction reduced. When the output coupler with the transmission of 6.5% and 11% was utilized, a Ti:sapphire laser with stable unidirectional operation was attained. Further, by rotating the angle of QWP to change the loss of retro-reflecting device, it was found that the stable unidirectional operation could be well kept when the corresponding loss value smaller than 4.9% and 17.6% as shown in curves (b) and (c) in Fig. 3, respectively. The experimental results illustrated that the decisive factor for achieving the stable unidirectional operation using the retro-reflecting device instead of OD was transmission of output coupler. Moreover, the allowed loss introduced by retro-reflecting device increased with the increase of the transmission of output coupler. If the generated intra-cavity laser intensities in both directions were equal, i.e. $I_+ = I_-$ [19], and I_1 and I_2 were the output laser intensities from both directions with and without retro-reflecting device, respectively, there were that,

$$I_1 = I_+ T_1 T_2, I_2 = I_- T_1 \tag{1}$$

where T_1 and T_2 were transmission of output coupler and loss introduced by the retro-reflecting device, respectively. The losses (L_1 and L_2) of two output directions due to the transmission of output elements could be expressed as,

$$L_1 = I_1/I_+ = T_1 T_2, L_2 = I_2/I_- = T_1 \tag{2}$$

As a result, the loss difference ΔL was,

$$\Delta L = L_2 - L_1 = T_1(1 - T_2) \tag{3}$$

Substituting the experimental results into Eq.(3), the corresponding loss difference of 3.5%, 5.5%, 6.18% and 9.06% were obtained, which illustrated that the stable unidirectional operation of Ti:sapphire laser could be reached in the case that the loss difference must be larger than 6.18%. The results confirmed that the transmission of the output coupler (T_1) may in fact play a major role in realization of stable unidirectional operation of Ti:sapphire laser with retro-reflecting device.

The output powers of the Ti:sapphire laser were measured with the transmissions of output coupler of 5.5%, 6.5%, and 11%, which were depicted in Fig. 4. The output powers were 4.8 W, 5.0 W and 4.62 W with corresponding threshold powers of 2.65 W, 2.89 W, and 3.61 W, respectively. The slope efficiencies were 31%, 34.8%, and 33%, respectively. The experimental results showed that the single-frequency Ti:sapphire laser with stable unidirectional operation and highest output power of 5.0 W could be achieved when the optimal transmission of the output coupler of 6.5% was utilized. In contrast to our previous results [10], the output power of Ti:sapphire laser was improved from 2.88 W to 5.0 W, and corresponding slope efficiency was improved from 22% to 34.8%. The high output power and slope efficiency were both attributed to the low intra-cavity loss. In this case, the measured long term power stability was better than ±0.9% in 5 hours, which was shown in Fig. 5. Compared to the power fluctuation shown in Fig. 2, a CW Ti:sapphire laser with stable unidirectional operation was attained under the action of the retro-reflecting device. The longitudinal-mode structure of the obtained Ti:sapphire laser

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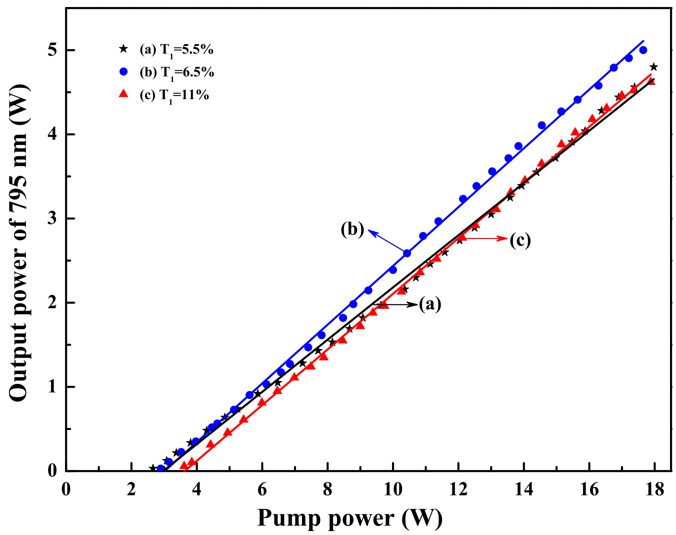

Fig. 4. Output power of the Ti:sapphire laser at 795 nm versus the pump power with different tramission T_1. (a) T_1=5.5%. (b) T_1=6.5%. (c) T_1=11%.

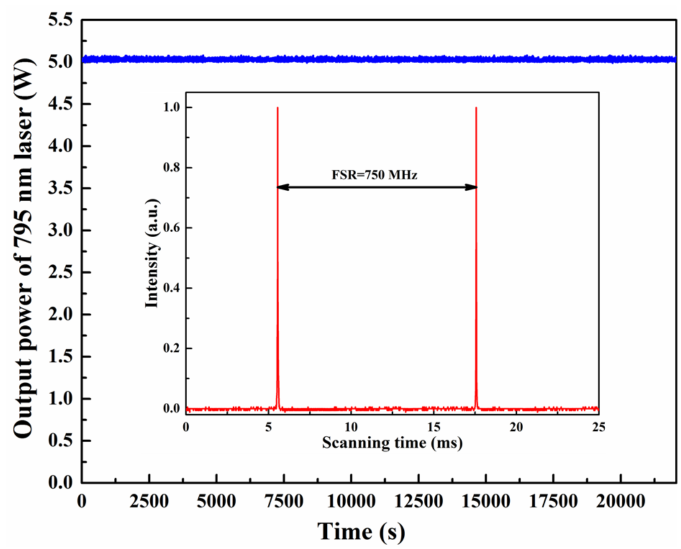

Fig. 5. Long term power stability. (The inset is the measured longitudinal-mode structure of the Ti:sapphire laser.)

was measured by a confocal Fabry-Perot (F-P) interferometer with finesse higher than 100 (F-P-100, Yuguang Co., Ltd.) and illustrated in inset of Fig. 5. The realization of the stable single-longitudinal-mode operation was relying on not only the retro-reflecting device but also the sets of BRF and intra-cavity electro-optic E, which could effectively narrow the gain linewidth of the laser. The transverse-mode characteristics of the obtained Ti:sapphire laser was measured by a M^2 beam quality analyzer (M2SETVIS, Thorlabs), and the result was depicted in Fig. 6. The measured beam quality were M_x^2=1.04 and M_y^2=1.03, respectively. The linewidth of the achieved Ti:sapphire laser was measured by beating frequency technology, which was implemented by detecting the interference signals between the achieved self-injection locked

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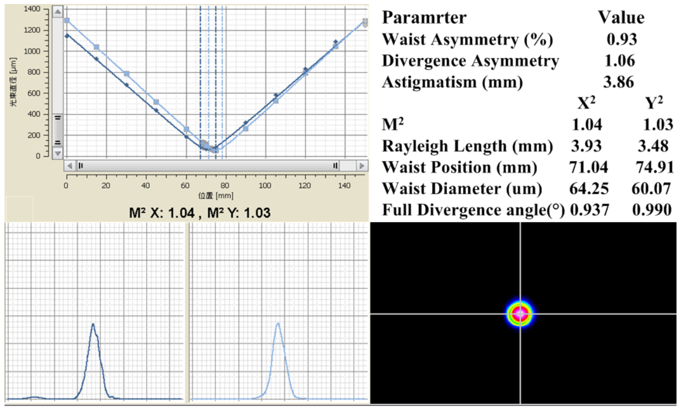


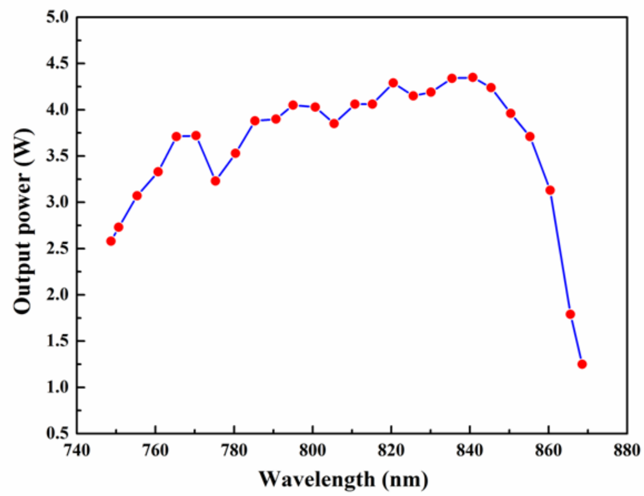
Fig. 6. Measured beam quality of the output laser.

Ti:sapphire laser and another home-made Ti:sapphire laser, where the working wavelengths of both Ti:sapphire laser could be tuned as close as possible by rotating the angles of BRF and intra-cavity electro-optic E. The measured linewidth was about 380 kHz.

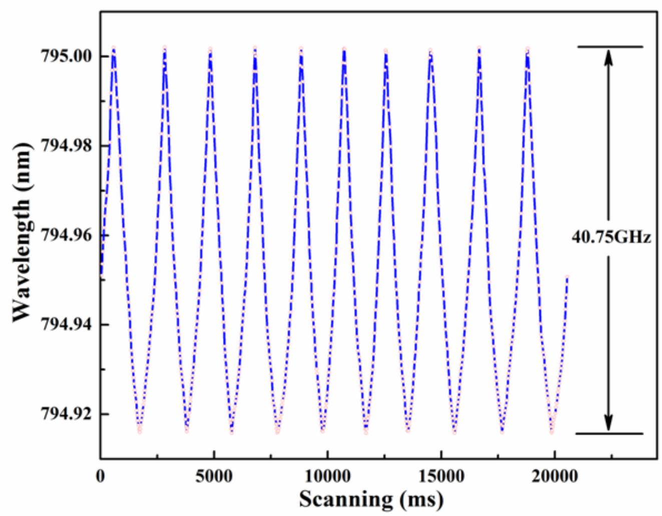
Lastly, the tuning characteristics of Ti:sapphire laser were also investigated. A small part of the Ti:sapphire laser was injected into a wavelength meter (WS6/765, High Finesse Laser and Electronic Systems) which could read the wavelengths of injected lasers as well as record the wavelength variations. The output powers of the Ti:sapphire laser at different output wavelengths were illustrated in Fig. 7(a). Because there were a part of generated laser were used to implement aforementioned measurements including longitudinal-mode structure, beam quality and linewidth, the recorded power values depicted in Fig. 7(a) were a little lower than the real output power. It was clear that the wavelength of output laser was tuned from 748 nm to 868 nm with the rotation of the BRF, and the maximal tuning range of 120 nm was achieved. Because the attained CW single-frequency tunable Ti:sapphire laser was immune to the restriction of the bandwidth of OD or additional seed laser, it was expected that the tuning range could cover the whole fluorescence spectrum 700-1000 nm of the Ti:sapphire crystal only if the cavity mirrors were coated with films covering the whole wavelength range of 700-1000 nm and the BRF with broader tuning range was designed. Further, the continuous frequency-tuning ability of the Ti:sapphire laser was also tested after the intra-cavity electro-optic E was locked to the oscillating longitudinal-mode of the laser near the wavelength of 795 nm according to Ref. [10]. When the cavity-length of Ti:sapphire laser was scanned by changing the voltage loaded on the PZT adhered to M_3, the continuous frequency-tuning range over 40.75 GHz was attained, which were depicted in Fig. 7(b).

4. Conclusions

In conclusion, we presented an all-solid-state CW single-frequency tunable Ti:sapphire laser with simple structure, where the unidirectional operation of laser was achieved by using a retro-reflecting device. After the retro-reflecting device was used to retro-reflect the seed laser beam of one arm back into the counter-propagating field, the stable unidirectional operation of Ti:sapphire laser was realized by optimizing the transmission of output coupler. When the output coupler with transmission of 6.5% was used, a CW self-injection locked single-frequency Ti:sapphire laser with stable unidirectional operation and maximal output power of 5 W was obtained. The power stability and M^2 factor were better than ±0.9% and 1.1, respectively. On the help of BRF and intra-cavity locked electro-optic E, the attained maximal tuning range and continuous frequency-tuning were 120 nm and 40.75 GHz, respectively. Because



(a)



(b)

Fig. 7. Tuning characteristics of the Ti:sapphire laser. (a) Maximal tuning range. (b) Continuous frequency-tuning ability.

the wavelength of the obtained Ti:sapphire laser covered the transition lines of kalium (K), Rubidium (Rb), cesium (Cs) atoms, it can be utilized in applications of atoms-cooling and trapping as well as quantum information storages.

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