Realization of a continuous frequency-tuning Ti:sapphire laser with an intracavity locked etalon

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A continuous-wave all-solid-state tunable Ti:sapphire laser with compact configuration is presented. The frequency-tuning range extends from 760 to 825 nm by rotating the birefringent filters. When the intracavity etalon is locked on the oscillating frequency of the laser and the length of the resonator is scanned by the piezoelectric ceramics transducer, a maximal continuous frequency-tuning range of 15.3 GHz is realized. The obtained Ti:sapphire laser is successfully applied to scan the saturation absorption spectroscopy of D_1 transitions of ^{87}Rb atoms around the wavelength of 794.97 nm.

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All-solid-state continuous-wave (cw) tunable Ti:sapphire lasers with single-frequency operation have been widely applied to spectroscopic measurements, quantum communication, laser radar, and so on owing to their characteristics of high conversion efficiency, broad tuning range, and good beam quality[1]. Since the first single-frequency Ti:sapphire laser was demonstrated in 1988[2], much attention[3–5] have been focused on its high output power[6], small frequency drift[7], and low-intensity noise[8]. Recently, many experiments require a Ti:sapphire laser with continuous frequency-tuning ability. For example, in an experiment of cooling atoms, it is important to be able to precisely control the frequency of the lasers corresponding to the absorption line of the atoms, which is applied in quantum information protocols to implement quantum storage[9]. Three commercial versions of continuous frequency-tuning Ti:sapphire lasers have been supplied by Coherent[10], Spectra-Physics[11], Tekhnoscan Joint-Stock[12] companies. In all these laser products, the length of the resonator is sufficiently long that they had to insert other tuning elements to realize continuous frequency-tuning, which will introduce extra loss and decrease the optical conversion efficiency. Another version of the Ti:sapphire laser supplied by M-square company[13] is compact, but the matched pump source with multi-longitudinal-mode operation increases its intensity noise[14], which limits the application of the Ti:sapphire laser. In 2014, we obtained a single-frequency Ti:sapphire laser with a continuous frequency-tuning range of 48 GHz by inserting a nonlinear crystal into the resonator which was composed of six mirrors[15]. On this basis, a compact Ti:sapphire laser with continuous frequency-tuning by means of an intracavity locked etalon is reported in this Letter. The adopted length of the resonator is sufficiently short that it is not necessary to insert other tuning elements into the cavity to tune the frequency of the laser and only scanning the piezoelectric transducer (PZT) adhered to the cavity mirror is enough to achieve a broad frequency-tuning range of the Ti:sapphire laser.

The experimental setup of the continuous frequency-tuning Ti:sapphire laser with intracavity locked etalon is shown in Fig. 1. The pump source is a homemade cw single-frequency and frequency-doubled Nd:YVO_4 laser with the output power of 11 W at the wavelength of 532 nm (F-VIII B, Yuguang Co., Ltd)[16]. The pump 532 nm laser is coupled into the Ti:sapphire ring cavity and focused onto the Ti:sapphire crystal by a coupling system including f_1 ($f = 200$ mm) and f_2 ($f = 120$ mm). A half-wave plate (HWP) in front of the resonator is used for the polarization alignment of the pump laser with respect to the optical axis of the Ti:sapphire crystal. The resonator of the Ti:sapphire laser, which has a ring-type configuration for the prevention of spatial hole burning, is composed of two curved mirrors with a 100 mm radius of curvature [M1 and M2, both coated with high-reflection

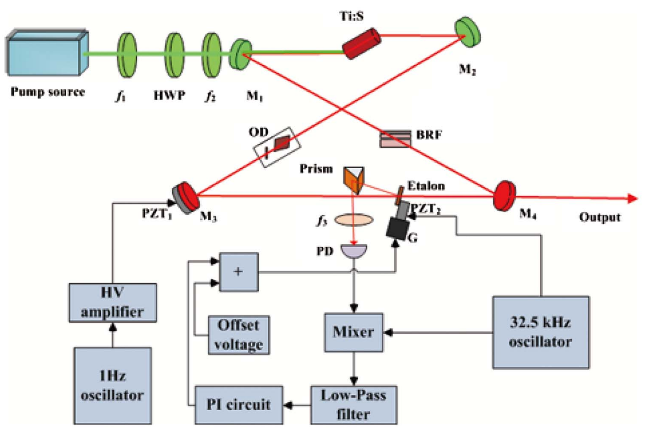

Fig. 1. Schematic diagram of the continuous frequency-tuning Ti:sapphire laser.

(HR) films at 760–825 nm and antireflection (AR) films at 532 nm], a flat mirror [M3, coated with HR films at 760–825 nm], and an output mirror with a 2.95% transmission at 795 nm (M4). The folding angles at the curved mirrors (M1 and M2) are set to 15.8° to compensate the astigmatism induced by the Brewster-cut intracavity elements including the Ti:sapphire gain crystal, three-plate birefringent filters (BRFs), and an optical diode (OD)[17]. The cavity mirror M3 is adhered to a PZT (PZT1, HPSt 150/14–10/12, Piezomechanik), which can continuously scan the length of the cavity. The Brewster-angle-cut (60.4°) Ti:sapphire crystal doped 0.05 wt.% with 20 mm length and a 4 mm diameter is mounted in a closed copper block oven cooled by circulated water and positioned between M1 and M2. To enforce unidirectional oscillation, an OD based on the Faraday effect is used. The OD comprises a Brewster-cut, 8 mm long, terbium gallium garnet (TGG) Faraday crystal placed inside a stack of permanent Sm–Co ring magnets and a thin quartz plate, which is used to compensate, via optical activity, the polarization rotation induced by the TGG crystal. The three-plate BRF with thickness of 0.5, 2, and 8 mm is inserted into the resonator with its Brewster incidence angle (57°) for coarsely frequency-tuning in a broad frequency-band. In order to achieve fine frequency-tuning and prevent mode-hopping during the frequency-tuning, a thin etalon with the thickness of 0.5 mm and finesse of 0.6 is inserted into the resonator and its transmission peak must be locked on the wavelength of the oscillating laser. Consequently, the etalon is adhered to PZT2 (HPSt 500/10-5/7, Piezomechanik) mounted on a high-precision galvanometer (G) scanner and positioned with a small angle in the vertical direction of the light, which can reflect some of the light. The reflected laser is focused onto a silicon photodetector (PD) (S3399) by a lens f_3 ($f = 50$ mm) through the reflection of a prism.

To maintain stable operation of the Ti:sapphire laser and to protect it from temperature fluctuation, the laser resonator is built in a firm and thoroughly closed whole cavity with a thick hard metal wall. All elements of the resonator are fixed on the inside of the metal wall and the two small windows on the cavity for the pump laser going in and the produced laser going out, respectively, are also closed by the transparent glass plates. A large thermal electronic cooler (TEC) connected to a temperature controller is attached on the outside wall of the whole cavity to maintain its temperature around 30°C for reducing the influence of the environmental temperature fluctuation. The scheme of the entire cavity temperature-control provides a good environment for the stable operation of the laser.

When the Ti:sapphire laser is working at the wavelength of 795 nm by rotating the BRF, the function curve of the output power versus the incident pump power is as in Fig. 2. The red dots are the experimental results and the blue solid line is the linear fitting by means of the equation given in Ref. [18]. The threshold pump power is 3.1 W, and the maximal output power is 844 mW at a pump level of 11 W with a slope efficiency of 11%. The lower slope efficiency than the commercial devices is ascribed to the high loss induced by the OD used in our work. By rotating the BRF, the frequency-tuning range of 65 nm (760–825 nm) can be obtained, which is shown in Fig. 3. The maximal tuning range is limited by the coated films of the aforementioned resonator mirrors. The tuning characteristic of the intracavity etalon with a finesse of 0.6 is measured as shown in Fig. 4. By adjusting the offset voltage of the G scanner, the tuning range of the intracavity etalon is 189 GHz which equals its free spectral range (FSR). The different control voltage corresponds to different output wavelength since the transmission peak of the etalon changes with the incidence angle, which is decided by the control voltage of the G scanner.

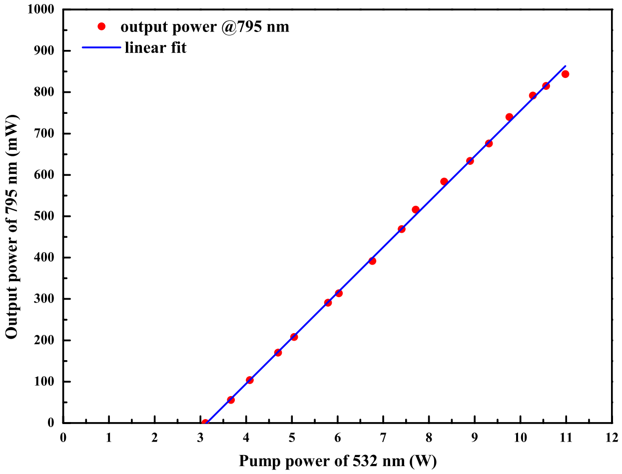

Fig. 2. Output power of Ti:sapphire laser at 795 nm versus pump power.

In order to realize a continuous frequency-tuning of the Ti:sapphire laser, we must lock the peak of the etalon transmission curve to the oscillating frequency of the laser. Consequently, a sinusoidal modulating signal with a frequency of 32.5 kHz and an amplitude of 4 V peak-to-peak voltage generated by the function generation [shown in

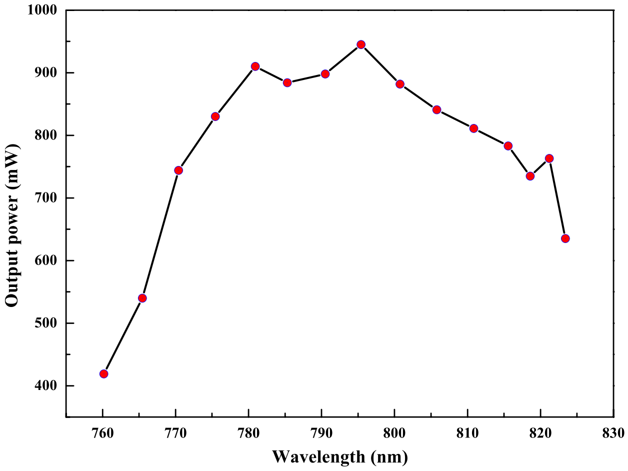

Fig. 3. Tuning curve of the BRF.

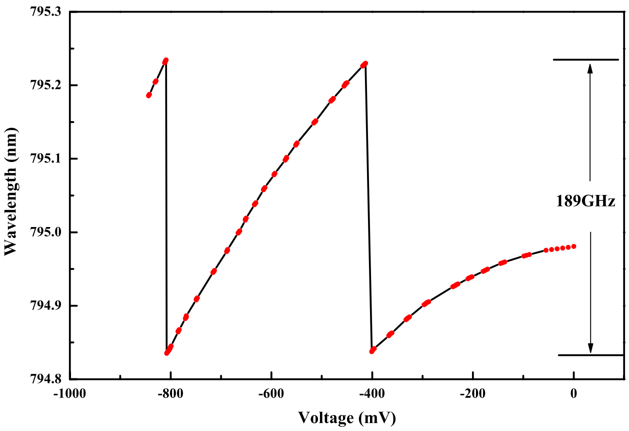

Fig. 4. Tuning curve of the intracavity etalon.

Fig. 5(a)] is first added to PZT2. Meanwhile, the signal is mixed with the detected signal reflected from the etalon. The mixed signal goes through a low-pass filter circuit and a proportion–integration (PI) circuit then become a feedback signal. The feedback signal is also added to the G scanner together with the offset voltage for locking the etalon to the oscillating frequency of the laser. When the intracavity etalon is locked on the oscillating frequency of the laser, the frequency of the detected signal (65 kHz) is twice that of the modulation signal [shown in Fig. 5(b)]. In the process of etalon-locking, the average optical path in the etalon is an integer multiple of the oscillating wavelength, where the detected signal is the peak value. Whenever the optical path in the etalon derives from the average value, the detected value should decrease. There are two zero-error points in a modulation period, which indicates that the detected signal has two peaks in a modulation period. Consequently, the detected frequency is twice that of the modulation signal[19].

After the transmission peak of the intracavity etalon is locked on the oscillating frequency of the laser, an electric triangle scanning signal with a frequency of 1 Hz is added to PZT1 for scanning the length of the resonator to continuously tune the frequency of the laser. In a cw, all-solid-state laser with a traveling-wave resonator, the oscillating frequency of the longitudinal-mode is given by

$$\nu = m\frac{\mathrm{c}}{L}, \tag{1}$$

where ν is the oscillating frequency of the laser, L is the length of the cavity, c is the speed of the light, and m is an integer. In the process of continuous frequency-tuning of the single-frequency Ti:sapphire laser, m must be kept a fixed value. The continuous frequency-tuning range can be expressed as

$$\Delta\nu = -\frac{\nu}{L}\Delta L. \tag{2}$$

It is clear that the maximal continuous frequency-tuning range can be evaluated by Eq. (2) when the length of the resonator, the maximal mirror travel, and the working wavelength of the laser are ensured. For our Ti:sapphire laser, the length of the resonator is 618 mm, the maximal travel of the PZT1 is 12 μm, and the wavelength of the Ti:sapphire laser is 795 nm, a maximal frequency-tuning range of 14.1 GHz is expected. In our work, PZT1 is actuated by a home-made high-voltage (HV) direct current (DC) amplifier (YG-2003, Yuguang Co., Ltd) with low noise and the output wavelength of the Ti:sapphire laser is recorded by a wavelength meter with a measurement resolution of 100 MHz (WS6/765, High Finesse Laser and Electronic System). The used wavelength meter can not only read the wavelength of the laser but can also record the wavelength of the laser in real time. Before the intracavity etalon is not locked, a mode-phenomenon will occur when the cavity length is scanned over a FSR of the laser. After the intracavity etalon is locked on the oscillating frequency of the Ti:sapphire laser, a maximal continuous frequency-tuning range of 15.3 GHz is achieved, which is shown in Fig. 6. The experimental result is in good agreement with the theoretical

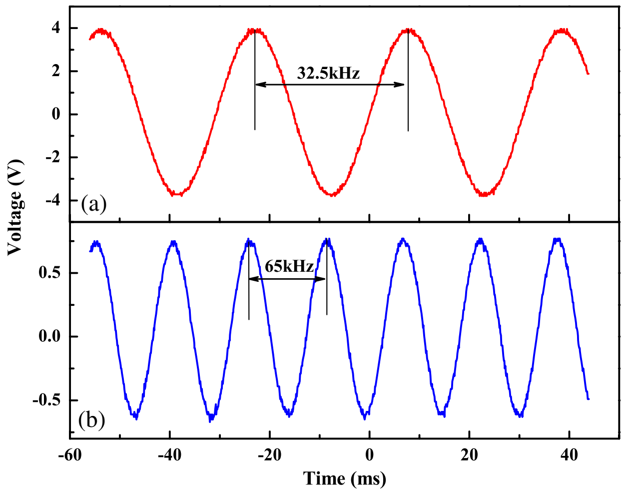

Fig. 5. Signals for locking the intracavity etalon: (a) modulating signal; (b) detected signal.

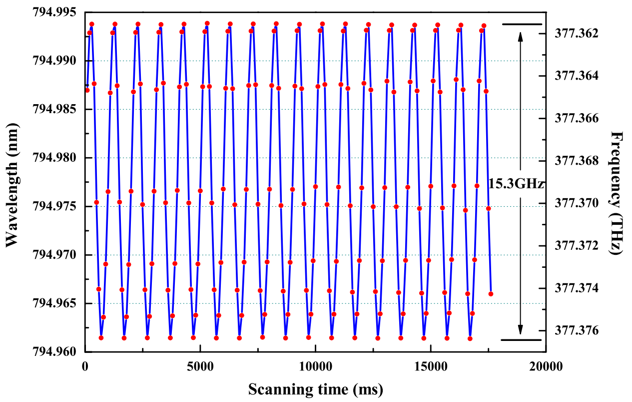

Fig. 6. Automatic smooth scanning frequency of the Ti:sapphire laser by scanning the voltage of PZT1.

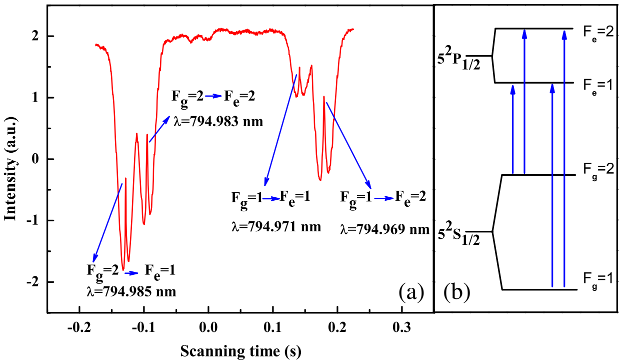

Fig. 7. Experimental result of the absorption line of ^{87}Rb atoms.

prediction. In the process of the frequency-tuning of the laser, the power fluctuation is less than ±0.12%. Last, a small part of the output laser is separated and leaded to a ^{87}Rb atom cell to scan the saturation absorption spectroscopy of D_1 transitions of ^{87}Rb atoms. The transmission curve of the cell is shown in Fig. 7(a), and Fig. 7(b) is the corresponding energy structure of the ^{87}Rb atoms, which shows that the obtained Ti:sapphire laser with continuous frequency-tuning is enough to satisfy the requirement of the atom-cooling physics.

In conclusion, a compact, stable Ti:sapphire laser with continuous frequency-tuning by means of an intracavity locked etalon is obtained in our work. A tuning range extends from 760 to 825 nm by rotating the BRF. When the output wavelength of the Ti:sapphire laser is 795 nm, the measured power is 844 mW with the threshold pump power of 3.1 W and optical slope efficiency of 11%. The maximal continuous frequency-tuning range of 15.3 GHz near 795 nm is realized by locking the etalon on the oscillating frequency. Last, the obtained Ti:sapphire laser is successfully applied to scan the saturation absorption spectroscopy of D_1 transitions of ^{87}Rb atoms around the wavelength of 794.97 nm.

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