Experimental study on injection-locked Ti:sapphire lasers

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An injection-locked Ti:sapphire laser is developed, with injection locking achieved using the Pound-Drever-Hall technique. By measuring the dependence of output power on the pump power with various Ti:sapphire laser parameters, we experimentally studied the influences of the ring cavity length, the focal length of the pump-laser mode-matching lens, and the output–coupler transmission on the threshold and slope efficiency. The dependence of the output power on the master laser power is also investigated. The present study provides a guideline for developing a Ti:sapphire laser with high slope efficiency and low threshold.

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A continuous-wave (CW) laser with high power, narrow linewidth, and low noise is important for atomic frequency standards, especially for optical lattice clocks[1]. In lattice-clock experiments, the laser with output power of a few watts is necessary to be the light source for the optical lattice. A CW Ti:sapphire laser[2,3] is one of the best candidates for such applications because of its good beam quality, high output power, and broad continuous tuning range compared with other lasers like diode lasers[4]. To achieve single-mode output from a traditional CW Ti:sapphire laser, the mode-selection components are usually installed into the ring cavity, such as a birefringent filter and etalons, so that the lasing efficiency is low and the additional noise is induced[5,6]. Since there are no mode-selection components inside of the cavity, the injection-locked Ti:sapphire laser can achieve single frequency operation with high power output and low noise[7]. It is typically implemented by locking the Ti:sapphire laser on an external cavity diode laser (ECDL). Several experiments[8−11] have demonstrated that injection locking can efficiently obtain a high-power CW Ti:sapphire laser. For instance, in Ref. [10], 5-W output power was generated using this technique.

Recently, we theoretically analyzed the dependence of output power on various Ti:sapphire laser parameters and found that there are optimal parameters for achieving high output power with low threshold[12]. Unfortunately, to date, no experiments have reported in detail Ti:sapphire laser optimization. Therefore, the dependence of the threshold and slope efficiency on several Ti:sapphire laser parameters are experimentally investigated, with the aim to provide a guideline for developing a Ti:sapphire laser with high slope efficiency and low threshold. The experiments on developing and optimizing an injection-locking Ti:sapphire laser are reported in this letter. By using the Pound-Drever-Hall (PDH) method[13], the Ti:sapphire laser is injection-locked for a few hours. Figure 1 shows the schematic of the experimental setup.

In our experiment, the ring cavity consists of four 0.5-inch mirrors (HR coating at 759 nm): curved mirrors M_5 (reflectivity $> 99.8\%$) and M_6 (reflectivity $> 99.5\%$, transmission at 532 nm $> 95\%$); plat mirror M_7 (reflectivity $> 99.8\%$); output coupler M_4. There is a Brewster-cut Ti:sapphire crystal ($5 \times 5 \times 10$ (mm)) held by a water-cooled copper heat sink mounted on a two-dimensional (2D) translation stage. M_5(M_6) is set to an angle of 22° for the astigmatism compensation with the crystal. According to the numerical analysis[12], the curvature radius of the curved mirror is chosen to be 10 cm, the distance between one end face of the crystal and the closed curved mirror (denoted by d) is set at about 4.9 cm, and the long distance between the two curved mirrors (denoted by D) is arranged at about 57.5 cm to achieve low threshold and high slope efficiency. The 1-cm-long crystal and 3.2 cm^{-1} absorption coefficient are

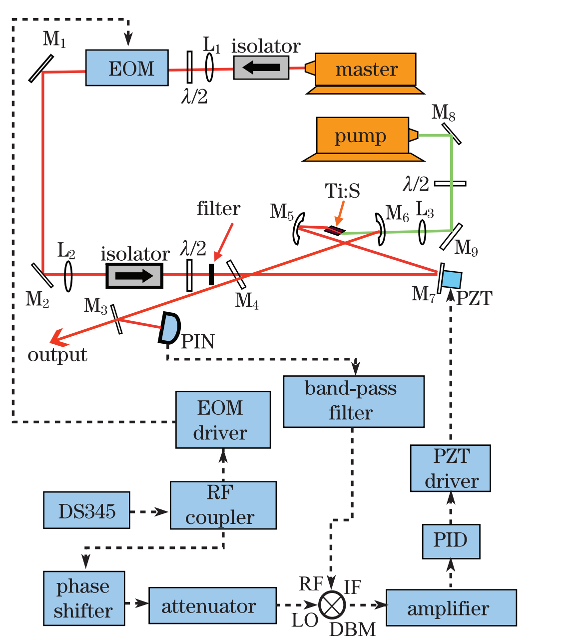

Fig. 1. Schematic of the PDH experiment in our injection-locked Ti:sapphire laser. L: lens; M: mirror; Ti:S: Ti:sapphire crystal; PZT: piezoelectric transducer; EOM: electro-optic modulator; PIN: photodiode; $\lambda/2$: half-wave plate; DBM: double balanced mixer; PID: proportional-integral-derivative controller; DS345: function generator; Master: master laser; and Pump: pump laser.

chosen according to our calculations. The analysis indicates that the optimal coupler transmission is about 12%; thus, three different couplers with transmissions (T) of 5%, 10%, and 15% were used in the experiment. The master oscillator is a diode laser (Sacher, LYNX) with maximum output power of about 80 mW and vertical polarization, which is protected by a first isolator (60 dB). With a 40-cm focal length lens, the master laser beam passes through an EOM (modulation frequency of 15 MHz). Before passing through the lens, there is a first half-wave plate that rotates the polarization of the master laser to optimize the EOM. After the EOM optimization, there is a lens (L_2) with 15-cm focal length for the master beam mode matching with the ring cavity and a second isolator, which is used to protect the EOM from the optical feedback. The second half-wave plate is used to adjust the polarization of the mater laser beam out of the second isolator to match the Brewster-cut Ti:sapphire crystal. Since there is an intense influence on the EOM from the residual pump laser out of the ring cavity, which is filtered off by a high-pass spectral filter. On the other side, the pump laser is provided by a diode-pumped solid-state laser (Coherent, Verdi-V5). A lens and a half-wave plate were also used for the pump beam mode matching and polarization adjustment.

Following are descriptions of the electric feedback system for the PDH method. The 15-MHz radio frequency (RF) output with 24 dBm is generated by the signal generator (SRS, DS345) and divided into two parts by a lumped directional coupler: one (about 23 dBm) drives the EOM and the other (14 dBm) is sent as the local signal to the double balanced mixer (DBM, Mini-circuits, ZAD-1-1). A lumped Pi attenuator is used to ensure that the power of the local signal does not exceed 7 dBm. On the other hand, the output signal from a photo detector (PIN, EOT, ET-2030A, bandwidth from 30 kHz to 1.2 GHz) is sent into a lumped band-pass filter (3-dB pass band of 10–19 MHz) to extract the required part (15 MHz) from the two frequency components (15 and 30 MHz) and then used it as the RF signal of the DBM. To achieve injection locking, the error signal (out of the DBM IF port) is sent successively into a PID circuit (parallel type, composed of OP177) and a PZT driver (two-stage amplification with OP07 and PA241DW) for the feedback control of the piezoelectric transducer on the cavity mirror M_7.

In the experiment, the transmission signal output from one of the curved mirrors was obtained by scanning the PZT, as shown in Fig. 2(a). Figure 2(b) shows the dispersive error signal, with signal-to-noise ratio of about 15. Figure 2(c) presents the error signal when the laser had been locked. Meanwhile, we monitored the transmission signal output from one curved mirror (Fig. 2(d)) and the beam profile output from the other curved mirror (Fig. 2(f)). The transmission signal was at the peak of Fig. 2(a), and the beam profile is pure Gaussian after injection locking. For comparison, Fig. 2(e) shows a beam profile when the laser is not locked. In our experiment, the laser can be locked for several hours.

We investigated the influence of the ring cavity length, the focal length of the mode-matching lens for the pump laser, and the output–coupler transmissions on the threshold and slope efficiency. The dependence of the output power on the pump power with various parameters was measured. First, we used three couplers with transmissions of 5%, 10%, and 15%. The results are shown in Fig. 3(a), which indicates that the higher the transmission of the coupler is, the higher will be the threshold and slope efficiency. The results show that output coupler transmission can be considered as both intracavity loss and output gain so that optimization can be achieved through a compromi se. Second, we measured

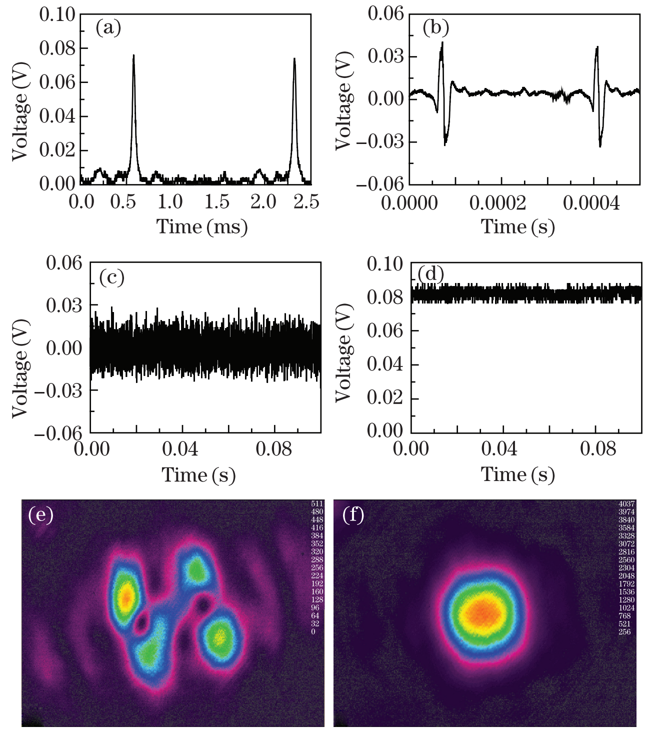

Fig. 2. (a) Transmission signal and (b) dispersive error signal during scanning; (c) error signal and (d) transmission signal after locking; laser output beam profiles when (e) unlocked and (f) locked.

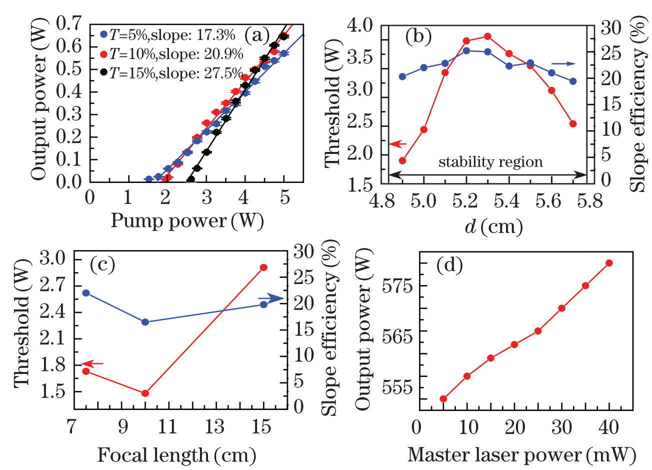

Fig. 3. (a) Influence of the different coupler transmissions on the threshold and slope efficiency; (b) threshold and slope efficiency change in the stability region; (c) influence of the focal length of the mode-matching lens for pump laser on the threshold and slope efficiency; (d) influence of the master laser power on the output power.

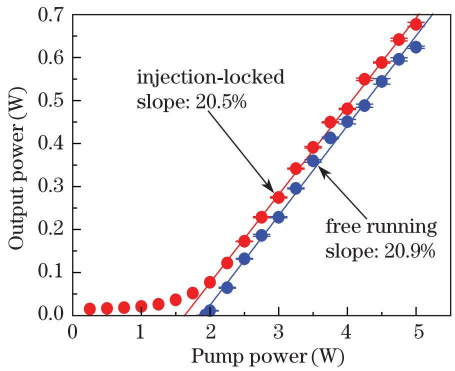

Fig. 4. Output power versus pump power during injection locking and free running.

the dependence of the threshold and slope efficiency on the length of the ring cavity, fixing D at about 57.5 cm and changing d from 4.9 to 5.7 cm in the stability region. Figure 3(b) shows that both the threshold and slope efficiency are low near the edge of the stability region. These results are roughly in agreement with our theoretical predictions[12]. Third, we chose pump-laser mode-matching lenses with different focal lengths f of 7.5, 10, and 15 cm to change the mode-matching efficiency between the pump and the lasers. Figure 3(c) shows that the 7.5-cm lens is the best choice. Finally, we measured the output power by varying the injected master laser power, and the results are shown in Fig. 3(d). This clearly suggests that the master laser power should be at a maximum to obtain high output power. We also found that injection locking can still be realized even with a low master laser power.

Based on the abovementioned measurements, we chose D= 57.5 cm, d= 4.9 cm, T= 10%, f= 7.5 cm, and master laser power of 30 mW as the good conditions for achieving an injection-locked Ti:sapphire laser. Figure 4 shows the results of output power versus pump power during the injection locking (the experiment data are denoted by the red points) and free running (the experiment data are denoted by the blue points). A similar slope efficiency for the two cases was observed. The output power was about 700 mW with 5-W pump power during locking. Surprisingly, we observed that the threshold was about 0.2 W after injection locking.

In conclusion, we develope an injection-locked Ti:sapphire laser and achieve injection locking using the PDH technique. We experimentally study the dependence of the threshold and slope efficiency on the ring cavity length in the stability region and the output–coupler transmission. In addition, the influences of the focal length of the pump-laser mode-matching lens and the master laser power on the output power are determined. Using the optimal parameters, we observe the 759-nm laser output with power of about 700 mW from the Ti:sapphire laser. In the future, further optimization for this laser system will be implemented, including fine adjustments of the ring cavity and the pump mode matching system, isolation of the vibration, heat, and sound, as well as a new electro-optic modulator with higher modulation frequency. This injection-locked Ti:sapphire laser is expected to be utilized in experiments on Ytterbium optical lattice clocks.

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