We developed an injection-locked Ti:sapphire laser at a wavelength of 671 nm where the fluorescence gain of the Ti:sapphire crystal is quite low. We obtained an output of more than 500 mW at a pump power of 10 W. The injection-locked lasing operates at a single-frequency and unidirectionally lasing with no intracavity optical components. The spectral property and the stability condition for the unidirectional lasing of the injection-locked Ti:sapphire laser are reported. The developed laser will produce the powerful light source required for the laser cooling of lithium atoms.

1. INTRODUCTION

A system of ultracold atoms provides us with high controllability in experimental degrees of freedom, making the system an ideal platform for studying quantum many-body systems. Especially lithium (Li) atoms are widely used because the interatomic interactions can be controlled using Feshbach resonances [1–5]. A single-frequency, high-power laser at 671 nm is required to efficiently cool Li atoms. Diode-based lasers have been widely used [6–8], but the effective laser intensity available for the experiment is limited because of a poor beam profile. A dye laser can be an alternative choice [9–11], but the degradation of the dye requires a frequent realignment of the laser. Solid-state lasers have been developed to provide 1342 nm, and the second harmonic generation of the light has been successfully used for the laser cooling experiment of Li atoms [12–14]. A Ti:sapphire laser, which is known to be one of the most powerful lasers both in continuous and pulsed oscillation in the near-infrared region at 700 to 1000 nm, has the potential to provide the laser at 671 nm but is yet to be utilized because of the low fluorescence gain at 671 nm [15].

In previous research pursuing a short-wavelength oscillation with the Ti:sapphire laser, Liu et al. used a specially designed mirror in the laser cavity to realize a strong 725 nm oscillation by suppressing the laser at the wavelength with a higher gain [16]. However, it is not obvious whether the same scheme can be applied to obtain the resonant laser for Li atoms at 671 nm because the reflectivity edge of the mirror cannot be precisely designed to achieve the laser oscillation at the Li atomic resonance.

In this study, we demonstrate the development of a Ti:sapphire laser with a single-mode oscillation in longitudinal and transversal modes at a wavelength of 671 nm. To realize the unidirectional lasing and the narrow spectral width usable for atomic spectroscopy, we injected the seed laser into the Ti:sapphire laser cavity [16–19], instead of placing the optical components to realize the unidirectional lasing and spectral narrowing [20–23]. To realize a stable injection-locked condition, the free-running oscillation wavelength of the Ti:sapphire laser needs to be close to the wavelength of the seed laser, and the power of the seed laser is required to be high enough to suppress the mode competition among multiple longitudinal modes. Here we used a specially designed mirror with a reflectivity edge at around 671 nm to support the free-running oscillation near 671 nm. The fine-tuning of the laser frequency has been done by precisely selecting the angle of incidence on the specially designed mirror. Furthermore, the laser for laser cooling of atoms requires a narrow spectral width on the order of 1 MHz. Injection locking is also useful because the spectral quality of the seed laser is transferred to the output of the Ti:sapphire laser. In this study, we have achieved more than 500 mW of output with single longitudinal and transversal modes at around 671 nm, which is useful for the laser cooling of Li atoms.

2. LASER CONFIGURATION

Figure 1(a) depicts the structure of our Ti:sapphire laser. The Ti:sapphire laser with a bow-tie cavity configuration was composed of Ti:sapphire crystal, two concave mirrors with a 100 mm radius of curvature (M1 and M2), a flat mirror (M3), and an output coupler (M4) with 95% reflectivity. A cut-off wavelength of the M3 mirror is chosen to be close to the target wavelength of the lasing, and the slight angle dependence of the reflectivity is used to fine-tune the lasing wavelength. The round-trip length of the laser was about 280 mm, yielding a longitudinal-mode spacing of 1070 MHz. The Ti:sapphire crystal was 15 mm long, 6 mm in diameter, Brewster-cut, and 0.20 wt.% doped. The crystal was held in copper holders with a water-cooled heat sink at 20.5 °C. The Ti:sapphire laser was pumped by 532 nm DPSS laser (Laser Quantum, Axiom532).
with a maximum output power of 12 W. The pump beam with a single transverse mode was focused into the Ti:sapphire crystal by a lens (L1). The lens L1 was slightly tilted to compensate astigmatism caused by the mirror M1 [24].

In this study, we have two different configurations to realize the lasing. One configuration was to place the mirror MR at one of the output ports to retro-reflect the beam back into the cavity. In this way, we realized multi-mode lasing at the wavelength determined by the mirror M3. The other configuration was to remove the mirror MR and inject the laser at 671 nm to achieve single-frequency and unidirectional lasing instead of placing the intra-cavity optics. The seed laser consisted of an external cavity diode laser (ECDL) with an appropriate linewidth for 7Li atoms’ $S_{1/2} - P_{3/2}$ transition. The light from the ECDL was phase-modulated at 47.2 MHz using an electro-optic-modulator (EOM), amplified with a tapered amplifier (TA), and then sent through a polarization-maintaining single-mode fiber. A part of the output was sent to a photodetector (PD) to generate the Pound-Drever-Hall error signal and then fed back to the PZT attached to the mirror M3 [25].

Figure 1(b) shows the output power of the Ti:sapphire laser in a free-running oscillation as a function of the pump power in the retro-reflecting configuration using the mirror MR. In this configuration, the lasing wavelength was determined by the reflection characteristics of the cavity mirrors (M1-M4).

Using the high reflectivity mirrors for M1-M3 and 95% reflectivity for M4 at the wavelength of 760 to 800 nm, we observed a free-running oscillation at 770 nm (black squares in Fig. 1(b)). When we used mirrors with the same reflectivity designed at 729 nm, we observed a free-running oscillation at 729 nm as expected (blue triangles in Fig. 1(b)). In both cases, we obtained more than 2 W of the output with 12 W of pump power. However, even when using mirrors with a peak reflectance at 671 nm for M1-M4 mirrors, the free-running oscillation wavelength was still observed at 710 nm. This is because the Ti:sapphire crystal has a lower fluorescence gain and greater absorption at 671 nm compared to the longer wavelength range. [15].

Previous work realized the fine control of the lasing wavelength using a long-pass filter for one of the cavity mirrors to obtain the lasing wavelength at 725 nm [16]. Another work used a short-pass filter to obtain the regenerative amplification of the Ti:sapphire laser at 940 nm where the crystal gain is low in the long wavelength side [26]. Here, we used a similar scheme to obtain the free-run lasing at 671 nm. In the present work, the mirror with the sharp cut-off wavelength at around 671 nm was used for the mirror M3 ($R = 98\%$ around 671 nm and $R = 10\%$ above 685 nm at the incidence angle of $10^\circ$).

For the purpose of the laser for the laser cooling of Li atoms, we need to be able to fine-tune the lasing wavelength to the Li atomic line. In order to achieve that, the free-running oscillation wavelength must be within the range of 1 nm from the atomic line. We utilize the slight angle dependence of the cut-off wavelength of the mirror M3 to control the lasing wavelength. Figure 1(c) shows the experimentally observed reflectivity of M3 as a function of the angle of incidence measured with the laser at various wavelengths. The blue markers in Fig. 1(c) were the result of the measurement at 666 nm, green markers at 669 nm, red markers at 671 nm, and yellow markers at 672 nm, respectively. The angle of incidence of $\sim 9^\circ$ was used to obtain stable free-run lasing at 671 nm (indicated with the red shade in Fig. 1(c)). The output power obtained at 671 nm is also plotted in Fig. 1(b) with red circles. We observed more than 800 mW with the maximum pump power.

### 3. RESULT OF INJECTION LOCKING

After achieving the free-run lasing at 671 nm, we observed single-frequency lasing at 671 nm by injecting the single-frequency laser from the ECDL. At a pump power of 10 W, the Ti:sapphire laser output was more than 500 mW using injection locking with a seed power of 30 mW. According to [27], the seed laser power required to realize the injection locking depends on the difference between the seed laser frequency and the free-running lasing frequency of the Ti:sapphire laser, as expressed by the formula

$$|\omega_1 - \omega_0| = \sqrt{\gamma_1 I_0/\gamma_p}.$$  

Here, $\omega_1$ is the frequency of the seed laser, $\omega_0$ is the closest longitudinal mode of the Ti:sapphire laser to the seed laser, $\gamma_1$ is the energy decay rate of the cavity, $I_1$ is the input power of seed laser, and $I_0$ is the output power of free-running Ti:sapphire laser.

According to the discussion, the free-running oscillation wavelength of the Ti:sapphire laser needs to be as close as possible to reduce the required power of the seed laser. The relationship between the required power of the seed laser and the pump power of the injection locking will be discussed in detail in Section 4. The longitudinal mode of the output was picked up and monitored using a scanning Fabry-Perot interferometer with a free-spectral range.
Within the measurement resolution. These two measurements, indicate that the laser wavelength was stabilized to the resonance condition of the seed laser. With the increase in pump power, the lasing intensity increased. As the seed laser intensity increased, the lasing became more stable and the output power increased. When the seed laser intensity reached the threshold intensity, the lasing was observed to be stable. The output power at PD1 and PD2 decreased to almost zero when the seed laser was off-resonant. Furthermore, the output in the opposite direction to the seed laser was observed to be almost zero when the cavity was off-resonant.

4. REQUIRED POWER OF SEED LASER FOR INJECTION-LOCKING

As we already discussed in Section 3, we could quantitatively evaluate the degree of unidirectional lasing. Figures 3(a)-(c) show the peak signal intensities measured at PD1 (red circles) and PD2 (blue triangles) under the scanning conditions for pump powers of 9.5 W, 10.0 W, and 10.5 W, respectively. When the seed laser intensity was low, we observed the multidirectional lasing even though the Fabry-Perot signal showed single-frequency lasing. As the seed laser intensity increased, the lasing intensity in the opposite direction to the seed laser (observed at PD2) decreased to almost zero when the seed laser reached the threshold intensity. The lasing was also observed to be rather unstable when the seed laser intensity was below the threshold for the unidirectional lasing. The orange and blue shades in Figs. 3(a)-(c) show the stable and unstable regions of the parameters, respectively (seed and pump laser intensity). When the unidirectional and stable lasing conditions were satisfied, we could lock the cavity onto the seed laser to realize stable lasing. We obtained output power similar to that obtained at the free-running condition shown in Fig. 1(b). Figure 3(d)
summarizes the stability diagram of the Ti:sapphire laser for the seed laser and pump laser intensities. The result shows the linear relationship between the seed laser and pump laser intensities, indicating that the laser has not yet reached the saturated condition. However, we observed that 40 mW of the seed laser intensity was insufficient to realize the stable unidirectional lasing at 11 W pumping. We need to investigate further to understand the limitation of the output power of the Ti:sapphire laser developed in this work.

5. CONCLUSION

We have demonstrated an injection-locked, single-frequency Ti:sapphire laser. To operate the Ti:sapphire laser at a wavelength of 671 nm where the fluorescence gain of the Ti:sapphire crystal is quite low, a specially designed mirror was used as one of the cavity mirrors, and the free-running oscillation wavelength was adjusted by changing the angle of incidence at the mirror. With a seed laser power of 30 mW and a pump power of 10 W, the output power of the injection-locked Ti:sapphire laser exceeded 500 mW. The spectral property of the injection-locked Ti:sapphire laser was confirmed to be the same as that of the seed lasers with no discernible frequency noise. We experimentally determined the threshold power of the seed laser for unidirectional lasing by injection locking. Stable single-frequency and unidirectional lasing can be achieved without extra optical components. We also developed an injection-locked Ti:sapphire laser at the wavelength of 729 nm using the same structure presented in this paper. We have been able to obtain enough intensity and spectral qualities to drive a narrow $S_{1/2} - D_{5/2}$ transition of the $^{40}$Ca$^+$ ion in our various experiments.

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Data Availability Statement. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.
