Laser Enhancement by External Optical Signal

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This article is mainly a summary of what I have done during the summer. We used "injection locking" technique to amplify the power of a well performed master laser. With multi-mode and single-mode[a] laser diodes, we achieved the maximum amplification of 10 and 66 respectively. Some interesting properties of injection locking phenomenon are shown in the paper and some information about erbium experiment is also provided.

I. INTRODUCTION

A. Laser Performance

The main task when designing an experimental setup for quantum gas experiment is to cool and trap atoms effectively. To achieve extremely low temperature, the laser cooling technique is needed. At the same time, we can confine the atoms by the laser. To collect more atoms, the power of the laser needs to be high enough; To achieve the extremely low cooling temperature, the line-width of the laser spectrum line should be narrow. But the high power output indicates the emission process to be severe, which causes the happening of unwanted emission process, and the output laser will be mixed with undesired emission line. It means that it is hard (which is equivalent to "expensive") to create laser source with high output power and at the same time maintain the purity of the output frequency.

One strategy is to amplify the laser with a seeding laser source which has good frequency spectrum. And injection locking is one of the cheapest method for such amplification.

B. Injection Locking

Injection locking is a general phenomenon for coupled oscillator. A commonly used example to explain this phenomenon is the synchronization of two clocks with different initial phase and frequency. In laser injection locking technique, we control the behavior of one laser source by injecting another laser source. The injected laser, which we call "master laser", has pure frequency spectrum and low power, and the laser been controlled , which we call "slave laser", can output quite high power. Under the effect of external master laser, the slave laser is supposed to generate high power laser with the same frequency spectrum as the master laser. For a rapid laser cooling of erbium atom one needs laser diode which can emit blue light (∼ 401nm). It was a big challenge to produce such kind of laser diode in the past, and after the invention of blue light emitting diode (2014 Noble prize in physics), the injection-locking technique became available for erbium experiment.

II. APPARATUS

The experimental setup for master laser and slave laser are shown separately in this part.

A. Master Laser

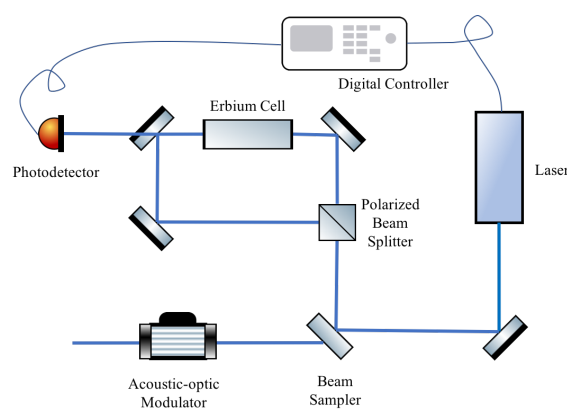

FIG. 1. Experimental setup for master laser. The main laser source and the digital controller are bought from Toptica. In the real apparatus totally three paths of the laser beam are produced from the master laser part.

The frequency of the master laser was locked by the spectral line of erbium atoms. The beam sampler reflected a small part of the power for spectroscopy and the remaining power was used as the master laser. Notice that several acoustic-optic modulators(AOM) were applied for frequency shifting of the master laser (by

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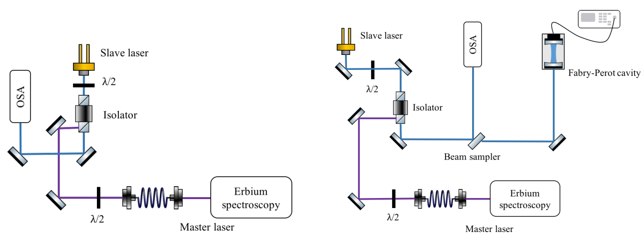
[a] In this paper, "mode" all refers to transverse mode, or beam profile of the laser.

80MHz) because of the Doppler effect of the moving erbium atoms.

B. Slave Laser



(a) Multi-mode (b) Single-mode

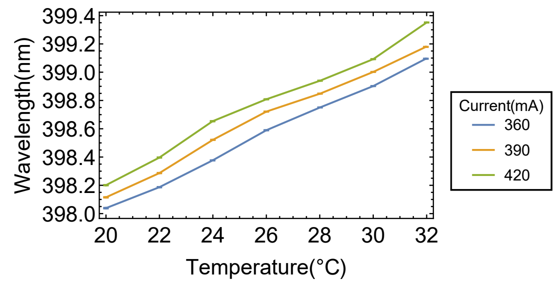
FIG. 2. Experimental setup for two different laser diodes. They shared the same master laser system.

The usages for two laser diodes were different. The single-mode one were used for construction of 3-dimensional magneto-optical trap (MOT) which needs to have nearly Gaussian beam shape; while the multi-mode one was used to pre-cool the erbium gas before loaded into the 3D MOT. Two additional mirrors were placed in front of the isolator in the single-mode setup. These mirrors were used to adjust the light path so that the slave laser beam became parallel to the optical table before going into the isolator. The optical spectrum analyzer (OSA) and Fabry-Perot cavity were used to obtain the output wavelength and frequency spectrum.

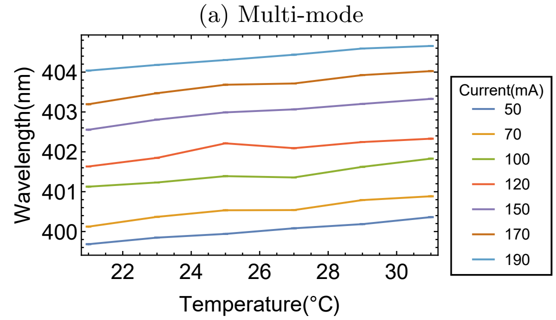
III. METHODS

To get the injection locking signal, two problems need to be concerned : first is to know whether the injected beam truly spatial covers the lasing region inside the slave laser diode; second is to make sure the wavelength/frequency difference between slave and master laser is not too large. For the first issue, we tried to make the beam paths and shapes between slave and master laser overlap with each other outside the diode as a time-reversal operation of the light propagation. During the experiment, only the positions were matched. That is, the injected beam reached the lasing material, but did not cover the whole region. This imperfect matching might increase the instability of the injection locking, and limit the injection locking behavior under higher output power.

For the second issue, we measured the temperature and current dependence of the wavelength of the two laser diode. Because the output power of the laser is linearly dependant on the driven current value when above the threshold, so we tried to find a suitable temperature value so that the wavelength difference remained small enough under high driven current. Notice that the single-mode diode was more sensitive to the change of the current, we had to go down to some quite low temperature like 5^oC to get a high output power (see more details about available frequency/wavelength difference in Appendix A).



(a) Multi-mode



(b) Single-mode

FIG. 3. Temperature and current dependence of the multi-mode and single-mode laser diode. The power differences between successive current value are roughly the same for the two laser diodes. All the data was taken above threshold.

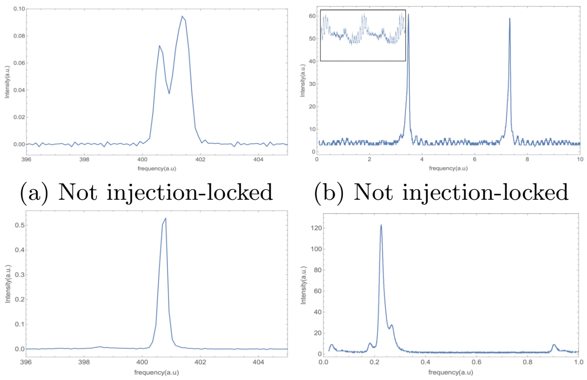
IV. RESULTS AND DISCUSSIONS

A. Efficiency

One of what we most concerned is how much power we can get with the master laser. For the multi-mode one we got about 80mW of the output power at the desired frequency with 7mW injected; for the single-mode one we got 106mW with 1.6mW injected. One of the possible limitation could be the difference beam shapes between slave and master laser.

B. Spectrum Change

The spectrum changes of partial and perfect injection-locking are shown in the FIG.4. Because of the limitation of the resolution of the optical spectrum analyzer, the wavelength distribution of the free running slave laser looks not that bad compared to the master laser. But from optical cavity which has a much higher resolution ($\sim$ 60MHz), the spectrum of the free running slave laser was not pure at all, and many side frequencies appeared around the desired frequency peak. Somehow the signal of side frequencies were weak, so the optical cavity signal could not show the real intensity distribution of the slave laser with injected master laser. However, when a nearly perfect injection-locking signal appeared from the OSA, cavity signal could provide a detailed information for finer adjustment.



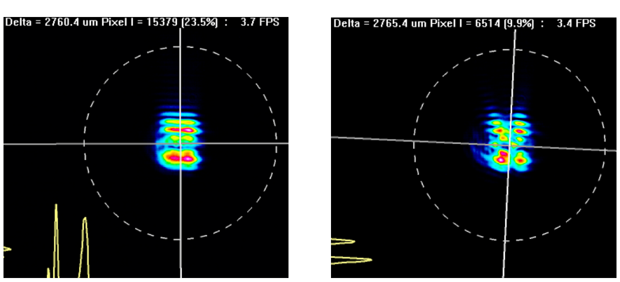
(a) Not injection-locked (b) Not injection-locked

(c) Injection-locked (d) Injection-locked

FIG. 4. The spectrum of the slave laser when partially and perfectly injection-locked . The small plot inside the black box in (b) shows the waveform of the running slave laser, and the intensity of the signal is roughly the same as those side peaks in (b). (d) shows the best waveform for injection locking, and part of the reason for the small side part might be the impurity of the master laser.

C. Beam Profile

The change of the beam profile of the multi-mode slave laser is shown in FIG.5. Because the beam shape of the master laser is just a circular spot, so the beam shape shown in plot (b) is not just the superposition of the two beam profiles. What we expected was that the beam profile of the slave laser was improved after injection-locked (that is, more Gaussian), but in the real experiment the slave laser just became higher order mode.



(a) Not injection-locked (b) Injection-locked

FIG. 5. Temperature and current dependence of the multi-mode and single-mode laser diode. The power differences between successive current value are roughly the same for the two laser diodes.

D. Injection-Locking Regions

One unexpected phenomenon was that more than one injection-locking region where almost perfect injection-locking signal can be obtained existed. The injection-locking regions were discrete, that is, at a specific current value a perfect injection-locking signal was observed, and after increasing the current value by several milliamperes the signal was lost, but after increasing the current value further the signal appeared again.

E. Future Work

Two issues still existed for the later construction of laser cooling and trapping system: stabilization of the signal and transferring of the laser. Because of some unstable factors like temperature fluctuation and mechanical vibration, the injection-locking signal could only last for less than one minute. One possible solution is adding a controlling circuit so that when the injection-locking signal disappears, the circuit will automatically scan the current value back and forth and find the new injection-locking region.

For the transferring issue, normally researchers will coupled the laser into a polarization-maintained fiber so that the laser can be transferred by a long distance (there will be a lot of optical elements placed around the vacuum chamber so normally the laser system will be placed far from the vacuum chamber). But because of the wired shape of the slave laser beam (see the plot in Appendix B), the coupling efficiency was less than 10% (even after using anamorphic prism pair which can make the beam shape more circular). We had tried several combinations of lenses to improve the beam profile but all failed. If we can not make any progress in the future, we will place the whole laser system close to the vacuum chamber and shine the laser directly into the chamber.

The next step is building a 2D MOT where only two directions of the erbium atom motion will be cooled (precooling process). The calculation and the measurement of the magnetic field had been done before my leaving. Hopefully the first attempt of trapping of erbium atoms will start before November.

V. CONCLUSIONS

For multi-mode and single-mode slave laser diodes, we could get the amplification of the power to be 10 and 66 respectively. According to the signals from optical spectrum analyzer and Farby-Perot cavity, we could make almost 100% of the slave laser power at the desired frequency. However, the bad beam profile of the slave laser resulted in an imperfect beam-profile matching between the slave and master laser, which strongly limited the stability of the injection-locking performance. This bad beam profile also caused the issue in transferring of the beam. Some methods like adding a current controlling system might be used if no improvement is achieved in the future.

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Appendix A: More about the Locking Range

The laser injection locking phenomenon has been studied theoretically for several decades, and this part will provide a simplified mathematical model to describe this behavior quantitatively.

Consider both the master and slave laser are single-mode and each contains only one frequency (ω_m and ω_s respectively). The the set of rate equations describing the change of number of photon (output intensity), phase of the electric field and the number of the carrier (electron for semiconductor laser) inside the slave laser when operating with the injection of master laser is given by:

$$\frac{dP_s}{dt} = \left[G - \frac{1}{\tau_P} + \frac{c}{n_g L}\sqrt{\frac{P_m}{P_s}}\cos\theta\right] P_s \tag{A1}$$

$$\frac{d\phi}{dt} = \left[-\Delta\omega + \frac{c}{2n_g L}\sqrt{\frac{P_m}{P_s}}\sin\theta + \frac{\alpha}{2}(G - \frac{1}{\tau_P})\right] \tag{A2}$$

$$\frac{dN}{dt} = \frac{I}{e} - GP_s - \frac{N}{\tau_e} \tag{A3}$$

where P_s is the photon number of slave laser, ϕ is the phase of the field, N is the carrier number. G is the optical gain, τ_P is the photon lifetime, c is the light velocity in vacuum, n_g is the group index (then c/n_g gives the group velocity inside the material), L is the cavity length (laser diode can be simplified as a lasing material inside an optical cavity), P_m is the photon number of the master laser, $\theta = \phi_m - \phi_s$ is the phase difference between the master laser and the free-running slave laser (that is, without injected light), $\Delta\omega = \omega_m - \omega_s$ is the frequency difference between the master laser and free-running slave laser , α is the phase amplitude of the electric field, I is the current driving the slave laser, e is the electronic charge, τ_e is the electron lifetime. G can be obtained by $\Gamma A(N - N_o)$, where Γ is the confinement factor (ratio of light intensity within active layer, and normally semiconductor laser has multi-layer structure), A is the differential gain, N_o is the carrier number for transparency.

For the steady-state solution, that is, the time derivative terms all equal 0. Then from Eq.(A1) and Eq.(A2) we can get

$$\begin{aligned}\Delta\omega &= \frac{c}{2n_g L}\sqrt{\frac{P_m}{P_s}}\cdot(\sin\theta - \alpha\cos\theta)\\ &= \rho\sqrt{1+\alpha^2}\cdot\sin(\theta - \theta_o)\end{aligned} \tag{A4}$$

where $\rho = (c/2n_g L)\cdot(P_m/P_s)^{1/2}$ and $\theta_o = \tan^{-1}\alpha$. Then we can get the range for $\Delta\omega$:

$$-\rho\sqrt{1+\alpha^2} < \Delta\omega < \rho \tag{A5}$$

In the real life the frequency profile of the free-running slave laser is not pure. Treat the frequency component of the slave laser which is closest to the ω_m as ω_s, then if ω_s is within this range, the injection locking signal is supposed to be detected; and a perfect injection locking signal is possible if the whole spectrum is inside this range. However, this result is not comprehensive enough for our experiment and some factors are neglected like the beam profiles of master and slave laser.

Appendix B: Beam Profile of Slave Laser

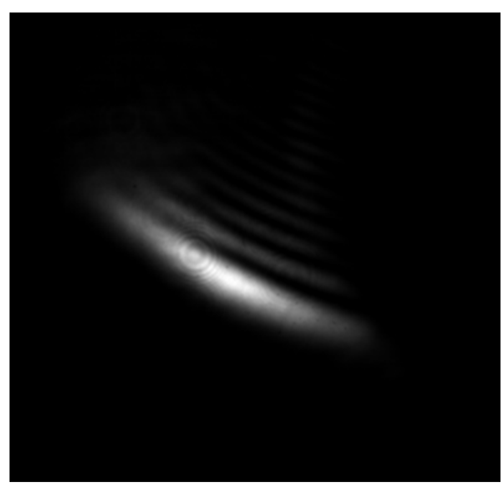

FIG. 6. The beam profile of the single-mode slave laser after injection-locked.

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