A Violet Extended Cavity Diode Laser for Laser Cooling and Atomic Diffraction

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An extended cavity diode laser significantly narrows the linewidth and improves the tunability of a diode laser through optical feedback. The cavity can be established with the use of a diffraction grating where the first order reflection travels back to the diode and again reflects off of the face of the diode. This can be constructed using an optics mount which provides for very precise control over the length of the cavity and angle of the diffraction grating. With temperature control as well as adjustment of the grating angle, the laser can be tuned to specific frequencies with a small linewidth.

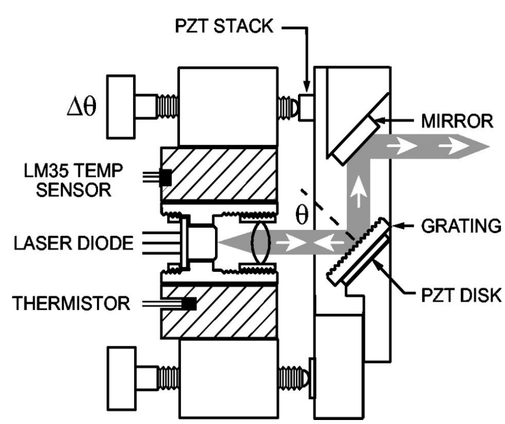
I. Introduction

Extended cavity diode lasers are very well suited for laser cooling and atomic diffraction because their wavelengths can be precisely tuned to values very near to those of atomic transitions. In conjunction with other techniques, laser cooling can be used to cool atoms to very low temperatures at which many quantum mechanical effects become apparent and can be more easily studied. Laser cooling uses three orthogonal pairs of counter propagating beams to slow atoms by taking advantage of the Doppler shift in the frequencies of the light seen by a moving atom. Atomic diffraction is used to give atoms precise momenta through the absorption and emission of photons from two laser beams. This can be used to make accurate measurements through sensitive interferometry using cold atoms.

II. Construction

I have constructed an extended cavity diode laser (ECDL) that will be used for atomic diffraction as well as atom cooling. To use a diode laser for such purposes, the frequency of the laser should be easily tunable and the linewidth should be relatively small. Without an extended cavity, the frequency of a diode laser has quite a large linewidth, poor tunability, and is very sensitive to temperature. The natural frequency scale in laser cooling is the atomic linewidth which is typically 1MHz. However, the linewidth of a diode laser by itself is about 50 MHz. Additionally, the laser diode tends to mode hop which means that it skips certain wavelengths when being tuned. The behavior of diode lasers is discussed in more detail in the paper "Using diode lasers for atomic physics" by Wieman and Hollberg. The diode that I used is a Nichia NOV4313.

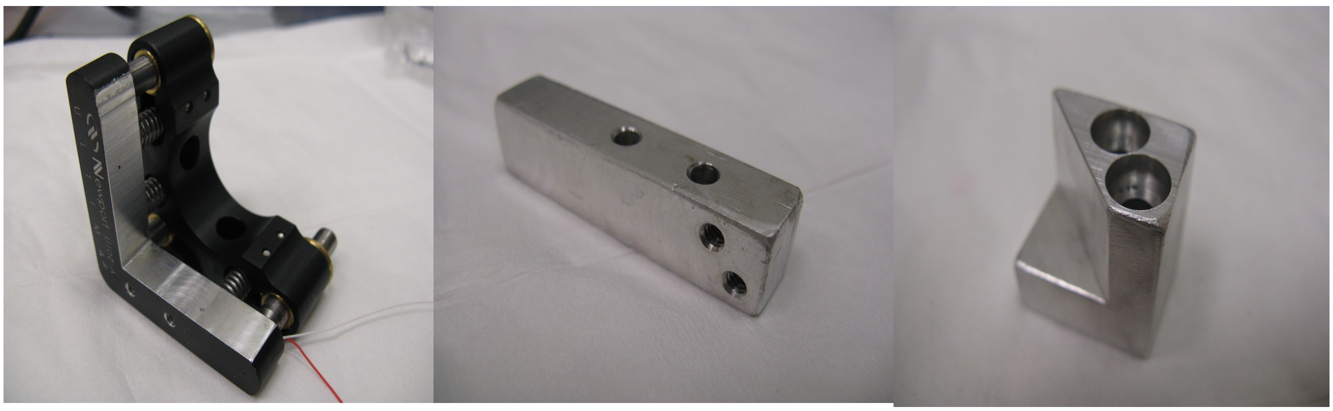
Figure 1 The design of the cavity is based off of the following configuration presented by Hawthorn, Weber, and Scholten



An extended cavity greatly improves upon the performance of a diode laser. The cavity in this case was created by mounting a diffraction grating about two centimeters from the diode. The grating I used has 3600 lines per millimeter. The grating is mounted in such a way that the zeroth order reflection leaves the cavity while the first order is reflected back into the diode. The face of the diode acts as the other end of the cavity, reflecting the beam back to the grating. In between the diode and the grating is a collimating lens. The cavity is built on a mirror mount where the diode and collimating lens are mounted on the back piece of the mount and the grating is connected to the front piece. This allows for precise control over the distance between the grating and the diode as well as the angle of the grating.

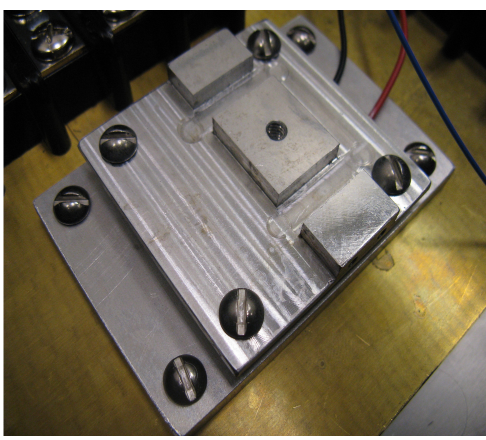
Within the cavity, destructive interference tends to cancel out all but those frequencies for which the length of the cavity is an integer number of half wavelengths, in which case, the light interferes constructively since the waves are in phase with each other. In this way, the length of the cavity can be tuned to allow only certain modes of light and therefore only specific wavelengths. Since the angle of the first order reflection is dependent on the wavelength, a specific wavelength can be selected by changing the angle of the grating. To provide fine adjustments to the angle of the grating, a piezoelectric transducer is mounted under one of the three pins of the mirror mount. The frequency of the light emitted from the diode changes with the temperature of the diode. For this reason, a thermoelectric cooler (TEC) and thermistor were installed below the cavity. The TEC sets the temperature while the thermistor measures the temperature

Figure 2 Laser components

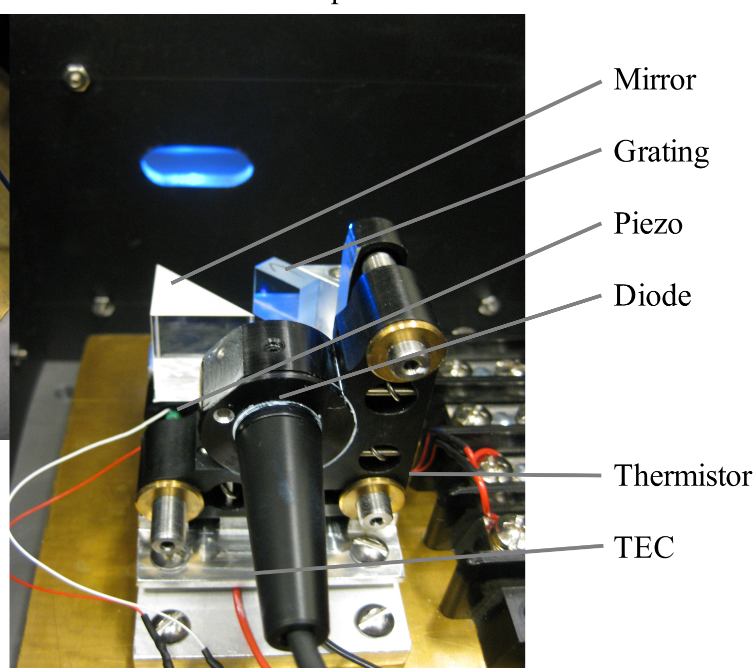


Mirror Mount

Machined pieces



Mounting plates with Thermoelectric cooler (TEC) underneath

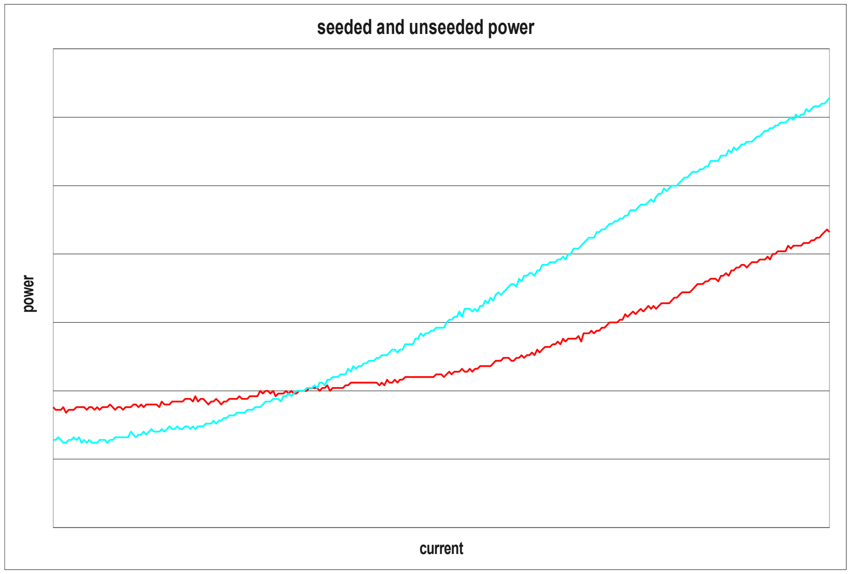


III. Alignment and Performance

To align the laser, the beam was first collimated and then seeded. To seed the laser, the position of the grating was adjusted so that the first order reflected back into the diode. This was done roughly by sight. The reflection of the light from the diode was aligned with the main zeroth order reflection beam. A power meter placed after the mirror was then used to finely adjust the position until the power was maximized and the threshold current was minimized (see figure 3).

Some additional optics were installed to further refine the beam, including a series of telescoping lenses to shrink the beam size, an optical isolator to prevent a beam from traveling back into the diode and possibly damaging it, and a waveplate to adjust the linear polarization of the light.

Figure 3
The plot shows the output power of the laser with increasing current around the threshold value of 40 mA. The blue line is the seeded power and the red is the unseeded power. The effect of seeding the laser can be seen from the slightly lower current threshold needed to lase when seeded and the larger power output.



IV. Atomic Diffraction

The violet laser that I have constructed will be used for both atomic diffraction of ytterbium atoms and atomic cooling of ytterbium atoms. Kapitza Dirac and Bragg scattering of atoms can be used to give the atoms certain, precise momenta while keeping the atoms in the same internal energy level. Knowing the momentum change as well as the change in energy as a result of the change in momentum, fine determinations of atomic properties can be made. To do such experiments, it is advantageous to start with a Bose Einstein Condensate which is a collection of atoms that are all in the ground energy state with zero average momentum. To give these atoms a nonzero momentum, Kapitza Dirac diffraction can be used. For this type of diffraction as well as Bragg diffraction, a standing wave is created from two counter propagating plane waves of equal magnitude, each of which has a frequency slightly less than the atomic transition frequency ωo.

$$\vec{E}(z,t)=E_o f(t)\sin(kz-\omega t)\hat{e}+E_o f(t)\sin(kz+\omega t)\hat{e}=2E_o f(t)\sin(kz)\cos(\omega t)\hat{e}¿$$

Here k is the wavenumber $k=\frac{2\pi}{\lambda}$ Since the frequency of the waves is far less than ωo, there is a very low probability of spontaneous emission. In order to diffract the atoms from the standing wave, it is easier to move the wave than the BEC. To do so, one of the two waves is slightly detuned from the other. Some of the atoms will absorb a photon from one wave and then re-emit a photon with the same frequency to the other wave, thus changing their momentum by $2\hbar k$ since the momentum of each photon is $\hbar k$. If starting from the ground state, an atom which undergoes this process will end up with a momentum of $\pm 2\hbar k$ and will have thereby gained energy. The energy gained by the change in momentum is called the single-photon recoil energy: $E_{rec}=\hbar\omega_{rec}=\frac{p^2}{2m}=\frac{\hbar^2 k^2}{2m}$ This transition is achieved by taking advantage of the energy-time uncertainty principle: $\Delta E\,\Delta t\geq\frac{\hbar}{2}$ If the pulse length is short, and therefore the uncertainty in the time is small, the uncertainty in the energy will be large. Thus, some atoms will be given enough energy to transition from the ground state with zero momentum to the ground state with $\pm 2\hbar k$ momentum by absorbing a photon with a higher frequency than the photon that is re-emitted. The pulse length as well as its energy can be engineered to result in different proportions of the various momentum states. This is the basis of Kaptiza Dirac diffraction.

Bragg diffraction works in a similar way but uses longer pulse lengths so that the energy uncertainty is low enough that the majority of atoms never gain energy in the reference frame of the moving standing wave. This means that the energy state of the atoms is preserved and only the direction, not the magnitude of the momentum may change. Solving the Schrödinger equation for an atom with momentum $-\bar{h}k$ in the standing wave gives the probability of the transition from $\langle|g,-\bar{h}k\rangle$ to $\langle|g,+\bar{h}k\rangle$ as a function of the pulse length, τ: $P(\tau)=\sin^2(\frac{\omega_R^2\tau}{4\Delta})$ where ω_R is the single photon Rabi frequency and Δ is the detuning between the standing wave frequency and the frequency of the atomic transition. For a group of atoms with initial momentum $-\bar{h}k$ this probability becomes the fraction of atoms to make the transition in a given time period. In order to avoid populating additional, neighboring momentum states, the pulse length needs to be long enough so that the uncertainty in the energy is relatively low. Additionally, the interaction duration needs to be short enough to avoid spontaneous emission which would result in random momentum changes.

It should be possible to diffract Ytterbium atoms using the violet laser that I have built. For Bragg diffraction of a BEC of Ytterbium atoms, in order to produce a pulse that will result in most of the atoms transitioning from one momentum state to another, the function $P(\tau)=\sin^2(\frac{\omega_R^2\tau}{4\Delta})$ should be about equal to one. The square of the Rabi frequency for Ytterbium is $\omega_R^2=2s\Gamma^2$ where $\Gamma=2\pi\times30\,MHz$ $s=\frac{I}{I_{sat}}$ I is the intensity of the laser, I_{sat} is the saturation intensity of Ytterbium equal to about 60 mW/cm^2, beyond which the atoms cannot absorb photons any more rapidly. The power will be approximately 50 mW and the beam size about 2 mm. $\Delta=\omega-\omega_o$ is the relative detuning, where ω is the frequency of the laser and ω_o is the Ytterbium resonant frequency equal to about 399 nm. To avoid populating neighboring momentum states, the interaction time must meet the requirement: $\tau>\frac{\pi}{\omega_{rec}}$ where ω_{rec} is the recoil frequency $\omega_{rec}=\frac{2\pi^2\bar{h}}{m\lambda^2}$ m is the mass of a Ytterbium atom and λ is the wavelength of the standing wave. For Ytterbium, this lower bound on the pulse length is about 69 µs. The upper bound on the interaction time, set in order to prevent spontaneous emission, is about 100 µs. When the equation for the probability of the transition is set to one and the above values are substituted, the appropriate laser wavelength can be calculated. For an interaction duration of 69 µs, the wavelength should be about 406 nm and for a pulse of 100 µs about 409 nm. More information about atomic diffraction can be found in "Coherent manipulation of atoms with standing light wave" by Gupta, Leanhardt, Cronin, and Pritchard.

V. Laser Cooling

In addition to being used for atomic diffraction, the violet laser will be used for laser cooling of ytterbium atoms. The method of laser cooling uses three orthogonal standing waves to slow the atoms of a gas. Each of these standing waves is formed by a pair of counter-propagating beams from the laser. For a stationary atom, the effect of the beams will tend to cancel out and it will remain stationary. In order to slow a moving atom, the frequency of the laser is slightly red shifted from the atomic resonance frequency. In the reference frame of a moving atom, the Doppler effect causes the frequency of a wave traveling toward the atom to increase. Photons moving toward the atom will then have a frequency closer to the resonant frequency and will more likely be absorbed, causing the atom to transition to an excited energy state and also slowing the atom. The atom will later spontaneously emit a photon in a random direction. The atom's resulting velocity will be slower unless a photon is spontaneously emitted in the opposite direction it was absorbed, which is unlikely.

VI. Conclusion

The methods of optical cooling and atomic diffraction both require very precise and tunable lasers. The extended cavity diode laser that I have constructed should fulfill both of these requirements. Through temperature variation and grating position, the wavelength of the laser should be tunable to a value very close to the resonant frequency of ytterbium. The extended cavity should also narrow the linewidth of the laser enough so that the majority of the light has a frequency very close to the desired frequency.

References

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