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Stabilization of laser diodes frequency for cooling ^{133}Cs atoms in a magneto optical trap

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Results regarding the stabilization of laser radiation involved in a ^{133}Cs atoms magneto optical trap (MOT) operation are reported. The linewidth of the laser diodes was reduced using Littrow extended cavity configuration. For stabilizing the laser frequency, we used lock-in negative feedback loops. The atomic frequency references were obtained by means of saturated absorption spectroscopy. The amplification of the laser cooling power was realized by means injection locking, a master-slave optical method. We also briefly present the magneto optical trap operation.

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1. Introduction

Many applications of laser diodes require high frequency stability. Laser cooling of neutral atoms [1], Bose Einstein condensation [2] and high resolution laser spectroscopy [3] are some examples of research fields involving stabilized laser diodes. In this type of applications, despite of using highly stabilized current sources and precision temperature controllers, the laser diode emission wavelength will slowly vary in time. Some of the best frequency references used for locking laser diodes are atomic transitions; in this context, high resolution atomic spectroscopy becomes a valuable tool for building very stable frequency references.

In this paper we will present laser diodes stabilization methods used in a magneto optical trap (MOT), intended for cooling ^{133}Cs atoms. The magneto optical trap developed by us is the first step toward an atomic fountain clock based on cold atoms [4].

2. The magneto optical trap: general presentation

The most widely used trap for neutral atoms is a hybrid one, the magneto-optical trap (MOT) [5]. It consists of three orthogonal pairs of circularly polarized, counter propagating laser beams and an inhomogeneous magnetic field (see Fig. 1). Due to momentum transfer from the laser field during the photons absorption processes, atoms will experience an optical force directly opposed to their moving direction, since the spontaneous re-emissions of photons take places in random directions. The movement of the atoms in the lasers intersection region is strongly damped, resulting in slowing and collection of a large number of cold atoms in a small volume. The cold atoms cloud obtained at the intersection of the laser beams is named "optical molasses" (OM). The temperature of the cold atoms is of several μK above absolute zero. Because the optical force in OM is dependent only on the atomic velocity, the cold atoms can diffuse from the cooling region. By adding to the laser cooling configuration an inhomogeneous magnetic field, the optical force become, through the Zeeman shifts of the atomic energies levels, dependent on the atoms position in the trap. By proper choosing of the laser cooling beams polarizations (σ^+-σ^-, like in Fig. 1), the atoms moving away from the cooling region will be driven toward the center of the trap, where the magnetic field is zero. In our ^{133}Cs MOT design, the magnetic field presents a gradient of 10^{-3}T/cm and it is obtained by means of a coils pair mounted in anti-Helmholtz configuration.

The cooling laser beams are tuned $\Delta_1=2.5\Gamma$ ($\Gamma=5.2$ MHz is the natural transition linewidth) below the cyclic $F=4\rightarrow F'=5$ transition of the ^{133}Cs (see Fig. 2). The mentioned values of the magnetic field gradient and of the cooling laser detuning Δ_1 leads to a maximum concentration (10^8cm^{-3}) of ^{133}Cs cold atoms in the MOT [6]. An optical pumping laser beam, tuned on the $F=3\rightarrow F'=4$ transition, is superimposed over at least one of the cooling laser beams, depleting the F=3 level so that all atoms can participate at the cooling process; without this laser beam, the cooling optical radiation will pump all the atoms on the F=3 level, canceling in short time the atom slowing process. The detection laser beam, used for cold atoms temperature measurement is tuned $\Delta_2=0.5\Gamma$ below the $F=4\rightarrow F'=5$ transition in order to obtain a maximum number of fluorescence atoms.

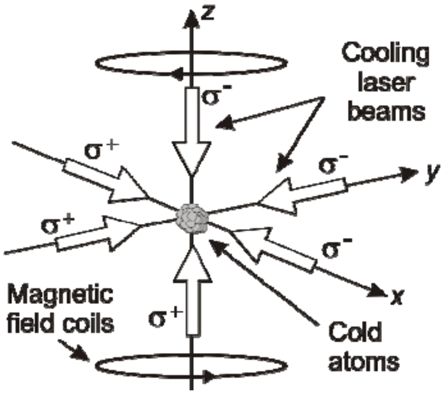


Fig. 1. MOT simplified schematic.

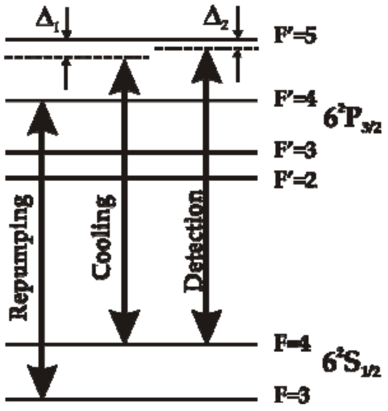


Fig. 2. The ^{133}Cs energy level diagram, presenting the laser frequencyes used in MOT operation.

For proper operation of the MOT, the laser radiations frequencies must be stabilized on the corresponding transitions, presented in Fig. 2. In our MOT design [7], both cooling and detection laser beams are obtained from the same laser diode, named master; the corresponding detunings, Δ_1 and Δ_2, are obtained by means of two acousto optical modulators. The optical pumping laser beam is obtained from the repumper laser diode.

3. The magneto optical trap: laser radiation sources

For an efficient cooling process, the linewidth of laser radiation must be smaller than Γ [8], [9]. AlGaAS Fabry Perot laser diodes present typically linewidths of tens of MHz [10]. For reducing this parameter, the laser diodes used in our MOT were mounted in Littrow extended cavity configuration (ECLD), represented schematic in Fig. 3. The “0” order beam reflects off the grating, for experimental use, while the “-1” order beam diffracts back into the laser diode chip. This optical feedback narrows the linewidth of the laser to about 1 MHz, forcing the emission frequency to that of the feedback beam[11]. The laser is tuned at a rate of 60MHz/V by changing the angle α of the grating, by means of a piezoelectric transducer. Over long periods, despite of using high stable electric current sources and temperature controllers, the laser frequency drifts at a rate of 100-200 MHz/hour due to current, temperature and mechanical fluctuations. For avoiding this, we locked both ECLD (master and repumping) to external atomic references, by means of negative feedback lock-in loops.

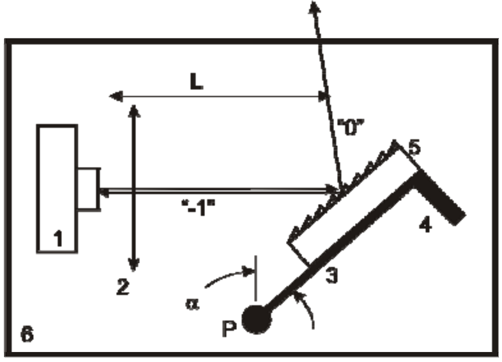


Fig. 3. Schematic of an extended cavity laser diode in Littrow configuration: 1- laser diode; 2-collimation lens; 3 - kinematic mount; 4 - piezoelectric transducer; 5- diffraction grating; 6- base plate.

The master ECLD use a SDL 5422 laser diode ($P_{max.}$=150 mW, λ=852±4 nm) while the repumper ECLD use a Q PHOTONICS 12SPO5LD-123 laser diode ($P_{max.}$=50 mW, λ=852±2 nm). Both laser diodes were collimated using Thorlabs C330TM-B aspheric lenses while the optical feedback was realized by means of Thorlabs GR13-1205 diffraction gratings (1200 mm^{-1} traces, blazed for λ_B=500 nm). Using reasonable values for laser chip temperature and injected electric current, we obtained 6 mW of optical power emitted from the repumping ECLD and only 14 mW from the master ECLD. For increasing the laser cooling optical power, we used a free medium power laser diode, locked on the master emission wavelength by means of an optical master-slave technique, named injection locking.

In the next two paragraphs we will present both locking techniques used in our MOT.

4. Frequency stabilization of external cavity laser diodes

4.1. Saturation absorption spectroscopy of ^{133}Cs atom

The most appropriate frequency references for locking laser diodes used in cooling ^{133}Cs atoms are the F=4→F’=5 and F=3→F’=4 atomic transitions. For resolving the hyperfine structure of the ^{133}Cs D2 line, masked by the Doppler broadening, we used the saturated absorption spectroscopy technique [11]. The experimental setup is presented in Fig. 4.

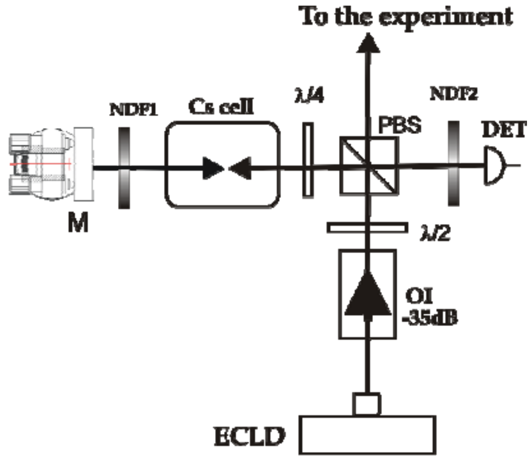
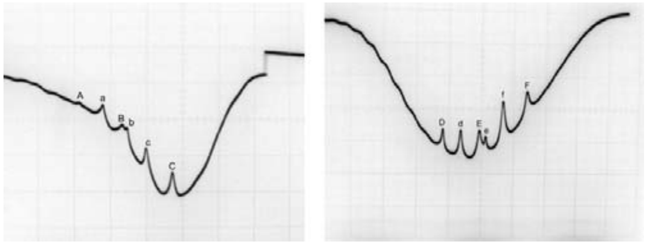


Fig. 4. Saturated absorption spectroscopy experimental setup.

After passing through a -35dB optical isolator (OI), a small part of the main laser beam is splited by means of a λ/2 retardation plate and a polarization beam splitter PBS, becoming the pumping beam; it pass through the ^{133}Cs vapors cell and, after retroreflection on mirror M and attenuation by means of the neutral density filter NDF1, it becomes the probe beam. By proper adjustment of the λ/4 retardation waveplate, the linear polarization of the probe laser is rotated with 90^O in respect with that of the saturating beam. After passing through the Cs cell and PBS, the probe beam is measured using the photodetector (Det). The intensity of the probe beam is adjusted by means of the neutral density filter NDF2. Scanning the atomic resonance was performed by applying a linear ramp to the ECLD piezoelectric transducer. For saturating the atomic transitions, the optical intensity of the pumping beam was adjusted to $I_{SB}=2.3mW/cm^2 \approx 2\cdot I_0$, where $I_0=1.1mW/cm^2$ is the saturation intensity of the D2 line of ^{133}Cs atom. The power broadening of the spectral lines was avoided by adjusting the probe beam power to $P_{PB}=8\mu W$, using the neutral density filter NDF1, while the contrast of the Lamb dips was adjusted by carefully superimposing the probe beam over the saturating beam.

In Fig. 5 are presented the saturated absorption spectra of the ^{133}Cs atom obtained using this experimental setup. The atomic lines labeled A, B, C, D, E, F correspond to Lamb dips burned in the Doppler spectrum by the allowed transitions ($\Delta F=0,\pm1$) between energetic levels (see Fig. 2). The saturated absorption spectra present also some supplementary Lamb dips (labeled with a,b,c,d,e,f in Fig. 5), the some named "crossover" lines, situated halfway between two Lamp dips caused by real transitions (for example, $\nu_f=(\nu_E+\nu_F)/2$). The crossover dips appear due to the simultaneous interaction of both probe and pumping beams with the ^{133}Cs atoms moving along the lasers direction.



a b

Fig. 5. The ^{133}Cs D2 line saturated absorption spectrums: a) Spectrum of the F=4→F' transitions (A=4→3', B=4→4', C=4→5'; a, b and c are the crossover lines). We can note the presence of a laser mode hope in the vicinity of the Doppler profile. b) Spectrum of the F = 3 → F' transitions (D = 3 → 2', E=3→3', F=3 →4';d, e and f are the crossover lines).

In our MOT we used the next atomic hyperfine lines as frequency references:

- F=4→F'=5 (the C line in Fig. 5.a) for locking the master laser diode;
- F=3→F'=4 (the F line in Fig. 5.b) for locking the repumper laser diode.

4.2. Locking the laser diode by direct modulation of the emitted wavelength

Let suppose that the laser frequency used in a saturated absorption spectroscopy experiment is modulated around the atomic resonance frequency ω_A:

$$\omega(t)=\omega_A+A\sin\omega_m t \qquad (1)$$

If the modulation depth A is much smaller than the transition linewidth and the modulation frequency is much smaller than the atomic resonance frequency ($\omega_m \ll \omega_A$), the photodetector response is an amplitude modulated electrical signal [12]:

$$I_T(\omega)=I_T(1+m\sin\omega_m t) \qquad (2)$$

where I_T, m and ω_m represents the d.c. component, the modulation index and the angular frequency of the detected signal. Due to the small frequency modulation depth, the modulation index m<<1, so that the photodetector response can be expressed like:

$$I_T(\omega)=I_T(\omega_A)+m\sin\omega_m t\left.\frac{dI_T(\omega)}{d\omega}\right|_{\omega=\omega_A}+\ldots\ldots \qquad (3)$$

If the photodetector response $I_T(\omega)$ is synchronous detected by multiplication with the modulation signal $\sin(\omega_m t)$, followed by low pass filtering in order to eliminate all the time dependent terms, the resulting signal is:

$$\varepsilon(\omega)=\frac{m}{2}\left.\frac{dI_T(\omega)}{d\omega}\right|_{\omega=\omega_A} \qquad (4)$$

This is the error signal used to feed the servo loop in order to stabilize the laser diode on the top of a specific Lamb dip. In Fig. 6 is presented the schematic of experimental setup used for locking the ECLD involved in our MOT operation.

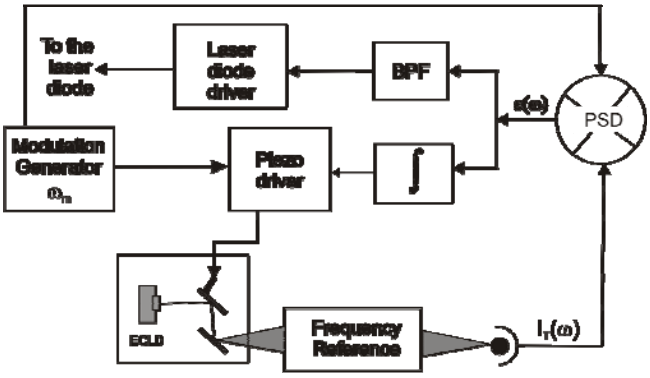


Fig. 6. Schematic of the ECLD locking system.

The modulational signal ω_m is applied on the ECLD piezo transducer, resulting the modulation of the laser frequency. The response of the saturated absorption spectrometer (frequency reference) is synchronous detected by means of the phase sensitive detector (PSD), resulting the error signal ε(ω), used for correcting the laser frequency fluctuations. The rapid fluctuations are corrected by means of a low pass filter (LPF), adjusting the laser diode current, while the slow variations are corrected by means of an integrator, adjusting the length L of the ECDL, using the piezo transducer. The parameters used in the locking system are: modulation frequency ω_m=50 kHz, modulation depth $A=2\pi \times 10$ MHz, cutting frequency of the low pass filter f_c= 1.6 kHz and the integrator gain-bandwidth GBW=1.6Hz. Using this parameters, both ECLD used in our MOT were locked on the desired wavelengths for long time (several days).

5. Injection locking of a medium power laser diode

As mentioned before, the optical power emitted from the master ECLD locked on the F=4→F'=5 transition was of only 14 mW. In order to obtain a higher power for generating the laser cooling configuration, we used an optical locking method [13],[14]. To that purpose we injected, through a beam splitter, the light emitted from the master ECLD, in a 150 mW laser diode chip (SDL5422 type), named slave laser. The schematic of the injection locking experimental setup is presented in Fig. 7.

In some operation conditions (in locking states), the slave laser will oscillate on the frequency imposed by the master laser, resulting in power amplification of the injected optical radiation. The locking bandwith Δf is the frequency range characterized by locking states, for which the phase difference between the master and slave optical waves varies from $-\pi/2$ to $\pi/2$ [13]. If we note with I_{in} the injected laser intensity and with I_{out} the slave laser intensity, then [15]:

$$\Delta f = 2\Delta\nu_{FSR}\sqrt{\frac{I_{in}}{I_{out}}} \qquad (5)$$

where $\Delta\nu_{FSR}$ is the free spectral range of the slave laser diode (typically, for medium power AlGaAS laser diodes, $\Delta\nu_{FSR}$=50GHz [10]).

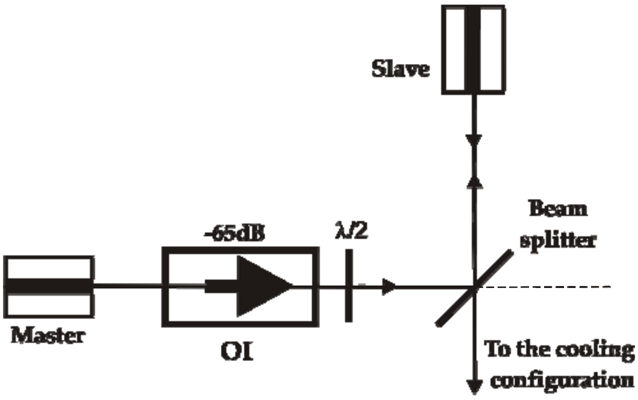


Fig. 7. Experimental setup for laser diode injection locking.

In the realization of the master-slave lasers system we considered some important requirements:

- The isolation of the master laser is the most critical point in the setup. An optical power of only 0.1μW retro-injected in the master ECLD is enough to perturb it. For avoiding this, we used a -65 dB optical isolator OI (note that master ECLD is already protected by a -35dB isolator; see Fig. 4);
- The linear polarizations of the master and slave was set to be identical because only the polarization parallel with that of the slave laser play an active role in the injection procedure. The master laser polarization was adjusted by means of a λ/2 retardation waveplate;
- For avoiding power losses, the injection beam splitter present a small reflection coefficient (10%); this represent a compromise between assuring enough power for the injection laser beam and a small attenuation of the emitted slave laser beam;

The injected optical power was P_{in}=600 μW for obtaining P_{out}=50 mW of slave laser optical power. As the master and slave laser beams presents the same diameters (Φ=2 mm), the locking bandwith is Δf=1 GHz, allowing scanning of the entire D2 line of the ^{133}Cs atom. Proper alignment of the master laser beam in the slave chip was obtained by adjusting the position of the injection beam splitter by means of a differential drive kinematic mount.

6. Conclusions

Operation of a ^{133}Cs magneto optical trap (MOT) developed in our laboratory was briefly presented. The laser beams involved in our MOT operation are generated exclusively from laser diodes. Reducing the linewidth of the laser radiation was obtained by mounting the laser diodes (master and repumper) in Littrow extended cavity configurations. The F=4→F'=5 and F=3→F'=4 hyperfine components of the ^{133}Cs D2 line, obtained by saturated absorption spectroscopy, were used as frequency references for laser radiation stabilization. We presented two stabilization methods involved in our MOT operation: the electronic feedback servo loop method, using phase sensitive detection, and an optical master-slave method, the injection locking of a medium power laser diode.

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