ESF – QUDEDIS grant

Scientific report

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Duration of stay : October 15th, 2004 until January 31th, 2005.

Active locking of optical trap oscillations frequencies. A step toward interspecies Feshbach resonances in a Bose-Fermi mixture

Abstract: Since Feshbach resonances require trapping potential insensitive to the different Zeeman sublevels, a far off resonance optical trap is used to store the ultracold gazes. However this trapping technique is sensitive to the laser's intensity fluctuations that should be corrected to achieved sufficiently long trapping times. Due to the short time of my stay at the LENS and the experimental difficulties encounters at that moment, I took in charge the realisation of the intensity stabilisation electronic device. Apart from the standard technique, the original concept lies on the implementation of proper ground isolation to assure very high efficiency even at low frequencies.

1. Introduction and motivation

The initial research project was dealing with the experimental investigation of interspecies Feshbach resonances in a Bose-Fermi mixture of Rb and K atoms. Tuning of the relative position of atomic and molecular levels via Zeeman effect in the neighbourhood of a resonance between an open and a closed molecular channel makes possible a precise control of the elastic and inelastic scattering between ultracold atoms. This phenomenon has been studied so far mainly for homonuclear systems. The aim of this project was then to investigate the phenomenon in a heteronuclear system. The position of various 40K-87Rb Feshbach resonances has been calculated in [A. Simoni, et al., *Phys. Rev. Lett.* **90**, 163202 (2003)] and some ground-state resonance have been observed at JILA [S. Inouy, et al., *Phys. Rev. Lett.* **93**, 183201 (2004)] and also at LENS in thermal samples, by studying inelastic losses. We plan now to continue the investigation at lower temperatures, by studying the elastic scattering properties. The possibility of controlling the elastic interaction in this system might have important application towards boson-induced superfluidity of fermions. In addition, we plan to investigate the possibility of heteronuclear molecule formation by means of adiabatic magnetic-field sweeps across the resonances.

To access the Feshbach resonances, a key feature is the ability to trap the ultracold atomic mixture in a potential insensitive to the tunable magnetic field. This is realized using a far off resonance optical trap, for which the conservative potential results from the light shift associated with the dipolar interaction. At the moment, the light source is provided by a commercial Ti:Sa laser tuned at 820nm and a crossed beam trap is produced with two intense beams (of 200 mW) focused on the atomic cloud (with a 50 μm waist). This yields to a quasi spherical attractive potential with oscillation frequencies of (200 HZ, 200 Hz, 300 Hz).

However a drawback of the optical trap is that the fluctuations of the intensity as well as the pointing direction can cause heating of the atomic cloud and dramatically reduce the trapping times. For instance, the intensity noise will heat the atomic cloud via parametric processes, since the fluctuations modulate the trapping oscillations frequencies (ν_{tr}). Clearly, the spectral intensity noise density at twice the natural oscillation frequency of the trap is then of particular relevance. Indeed T. A. Savatar et al. [Phys. Rev. A, 56, R1095, 1997] have demonstrated that the heating is exponential in time, with a time constant given by: $\tau^{-1} = \pi^2 \nu_{tr}^2 S(2\nu_{tr})$. Here $S(\nu)$ is the relative intensity noise (RIN) define as:

$$S(\nu) = 2\int_{-\infty}^{+\infty} d\tau \frac{\langle \delta I(t) \delta I(t+\tau) \rangle}{\langle I \rangle^2} e^{-i2\pi\nu\tau}$$

In addition they have shown that the beam pointing noise will cause heating at a constant rate, the energy doubling time being given by: $T = \pi^2 \nu_{tr}^2 S_x(\nu_{tr}) / \langle x^2 \rangle$.

It is therefore of absolute importance to estimate and correct these noise sources in order to achieved sufficiently long trapping times. However the Ti:Sa exhibits important intensity fluctuations at low frequencies (due to both pumping noise and mechanical vibrations) that could reduce the trapping time below one seconds. Furthermore the crossed beams geometry for the optical trap is very sensitive to pointing fluctuations and need also to be improved for the experiments.

In order to overcome these problems, the team directed by Massimo Inguscio and Giovanni Modugno have decided to buy a new laser source, i.e. an Yb:YAG laser at 1030 nm (Versadisk-1030-30 by ELS) that delivers 15 Watts in single mode operation. The confinement can be then sufficient enough to trap the atoms using only one beam, limiting the heating due to pointing fluctuations. However this new laser was also found to be very noisy below a few kHz and in particular around 50 Hz. These noise characteristics are of course not acceptable since the trapping oscillations frequencies range typically between 10 Hz and a few kHz, depending on the optical power of the trapping beam. For these reasons we decided to build an active locking loop to reduce these fluctuations.

During my stay at the LENS, the ongoing experiments about the Feshbach resonances were undergoing technical difficulties due to several dramatics instruments breakdown (as the MOPA crystal that provided the optical power needed for both Magneto-Optical-Traps for Rubidium and Potassium). For this reason and because I had some background electronics knowledge via my previous studies in quantum optics, I decided to take in charge the project about intensity stabilisation.

2. Active locking system of the laser's intensity

2.1. Principle

The servo loop principle was to control the intensity diffracted at the output of an acousto-optic modulator by monitoring the radio frequency power (RF at 80 MHz). For that purpose the intensity fluctuations of the beam are recorded by a photodiode that delivers an output voltage used to drive, in a closed loop, the attenuation of the RF.

This technique used to actively control the intensity of a laser beam, is of course well known. However we had some stringent conditions due to the fact that we want to reduce the noise at low frequency and especially around 50 Hz. Since there exist a lot of technical noise at these frequencies, (mainly arising from ground loops problems that introduces noise via the fluctuations of the background magnetic field) special effort have been developed to isolate our system from external perturbations. To do so, I took advantage from the knowledge of

Robert Drullinger (in visit from the NIST – Boulder- USA) in the domain of very low noise electronics. The main idea was to develop special ground reference for each component of the locking loop, the PI (proportional, integrator) device, the RF driver for the acousto-optic modulator and the photo detector.

2.2 Detailed description

a) The Radio Frequency driver.

A standard Voltage Controlled Oscillator produces the reference frequency at 80 MHz, and the power is controlled using a variable attenuator (TFAS-2 from Minicircuits), driven by an input current. The RF is then send into at a power amplifier ZHL3A (from Minicircuits +24dB) in order to obtain sufficient power (around 1,5 Watt). An important feature of the TFAS-2 is the frequency bandwidth by which the attenuation can be modulated. We found a frequency cut around ν_c=100 kHz so that we can expect to correct the intensity up to this frequency. However this component does not act simply as a first order low pass filter but introduce a rapid phase shift of π around ν_c. This effect is of practical importance for the dynamic of the close loop system since it diminishes the feed forward gain at frequency below ν_c and induces an unwanted oscillation at this frequency. In practice the frequency bandwidth of the locking loop has been limited up to 50 kHz.

b) The photo detection stage

One part of the light diffracted by the acousto-optic modulator, about 100 μW, is directed towards a photo detector composed by BPX-65 photodiode (high speed photodiode) and a trans-amplifier stage that transform the input current into a voltage signal. The converting resistance has been chosen to 100 kHz, leading to a detection bandwidth of 800 kHz, far above the limiting bandwidth of the TFAS-2. The output voltage is then typically on the order of a few Volts. For insulating purposes, the ground reference of this electronic box is independent from the common ground of the experimental room and is provided by an AC (220V)-DC (+/-15V) converter. A particular attention has been paid in order to avoid any conducting contact from the electronic box to the optical table (connected to common ground).

c) The PI correction stage

The output of the photo detector is send (together with the +/15V and GND cables) into the PI electronic box. The four cables are rolled together in order to avoid the noise arising from the important magnetic field fluctuations at low frequencies. This signal is then compare to variable reference (derived from a low noise 10 V source AD581JH) in order to generate the error signal. The quality of this reference is ensured by a low pass filter (1 Hz cut off frequency), which reduces the noise at higher frequencies.
The efficiency of a locking loop system is related to the gain of the feed forward action. Higher is the gain, closer is locked signal from the reference. The error signal is then amplified with a controllable gain and separated into a proportional stage and an integrator stage. The proportional stage is set to unity. The integrator stage is made of two amplifiers in order to get a second order integrator (-40 dB/decade) at frequencies lower than 10 kHz followed by a first order integrator (-20 dB/decade) until 50 kHz. This solution gives a high gain at low frequency (around 10^5-10^6 at l Hz). This also provides the maximum gain around DC and prevents any drift from the DC reference signal.
Finally the corrected signal is send to the RF driver. However we need to insulate the ground reference of PI box (common to the photo detector box) from the ground reference of RF driver. This operation is realized with the help of a precision, unity gain differential amplifier AMP03GP (Analog Devices). Indeed the internal matched resistor of the amplifier enables a high common mode rejection (around 100dB) and is used to separate the two ground references, provided that the power supply (+/-15V) is related to the output signal. This component is then placed at the input of the RF driver box.

c) Results

Since the Yb :YAG laser was sent back to the ELS company (they try to improve the noise characteristics of their laser), we tested the performance of the locking loop on the Ti:Sa laser. As said above, this laser exhibits important noise at low frequencies, especially around 50 Hz. At this particular frequency, the fluctuations can be of the order of 3% rms, which corresponds to a RIN of: $S(50Hz) \approx 10^{-4}\,Hz^{-1}$. This amount of noise gives a lifetime smaller than one second for an oscillation frequency of 25 Hz in the optical trap.

Once the feed forward loop is closed, the fluctuations on the laser intensity are recorded with an independent photo detector to avoid any "closed loop effects" in the noise measurements. Thanks to efforts made for ground isolations, we found very good results since the spectral noise density was flat from below 1 Hz to around 40 kHz, without any peak around 50, 100 and 200 Hz (where the fluctuations are usually difficult to eliminate). The fluctuations were then reduced to the order of 10^{-4} rms. Since the noise is flat we can easily estimate the RIN: $S(1Hz \rightarrow 40kHz) \approx 10^{-12} Hz^{-1}$. This gives an improvement of 80 dB compare to the unlocked intensity fluctuations. Then one find a lifetime of 10^5 seconds (i.e. around one day) for a 1 kHz oscillation frequency. This value exceeds clearly the other source of heating, like beam pointing fluctuations, or collisions.

Note that we estimate here the RIN of the laser by measuring only a small portion of it (around 100 μW compare to 200 mW). If the noise in purely classical then the RIN measured for this part is equal to the one of the entire beam. However this is not true as we approach the quantum noise limit, so we should consider what are the limits of our locking loop.

2.3 Limits of the active locking loop system

One may wonder what is the limit of the locking loop with our system. Then we have to take into account the sources of uncorrelated noise that is not possible to correct: the shot noise and the electronic noise in the circuits. Let us estimate these different contributions.

a) Shot noise

The relative intensity noise corresponding to the shot noise level is given by $S^{SN}(\nu) = \frac{2\hbar\omega_L}{P}$ where P is the optical power and ω_L the laser pulsation. For P=100 μW, we found $S^{SN}(\nu) = 410^{-15} Hz^{-1}$. This is lower than the RIN measured in the experiment, so our approach is valid. Nevertheless we found that our servo loop is working not so far above shot noise, enlightening the good performances of our system. However a quantitative estimation of the limitation by the quantum fluctuations of light is beyond of the scope of this work.

b) Electronic noise

One also may ask if our noise level is limited by the electronic noise or by the finite gain in the feed forward loop. For that purpose let us estimate the noise of the photo detector. In our case the dark noise of the photodiode is negligible compare to noise arising from the transamplifier stage. The output voltage noise is given by:

$$S_{elec}(\nu) = \sqrt{S_{en} + S_{in} + \frac{4kT}{R}}\ (nV/\sqrt{Hz})\,.$$

The operational amplifier is a LF356N (from National Semiconductor) and we found (for R=100kΩ): $S_{elec}(\nu) = 30nV/\sqrt{Hz}$. Compare to the 5V DC signal, this gives a relative voltage noise around 4 10^{-17} Hz^{-1}. This contribution is then clearly negligible compare to the shot noise level.

c) Reference voltage noise

Ultimately, for infinite feed forward gain, the intensity noise should reproduce the noise of the reference voltage. This one can be evaluated at 5 Volts using the datasheet of the AD581 component. One find a relative voltage noise of 3 10^{-16} Hz^{-1} that is higher than the detection noise but still lower than the shot noise level. Then we can conclude that the main fluctuations sources are governed by the shot noise of the light. In order to improve the result we should then try to increase the gain at low frequency. However one may enter rapidly in a domain where a proper estimation of the quantum fluctuations of light will be needed.

3. Conclusion

To conclude, I develop during my stay at the LENS a low noise locking loop for laser's intensity fluctuations. I took in charge the conception as well as the complete realisation of the electronic box. The good performances achieved (especially around 50 Hz) are due to the efforts that have been made to design proper ground isolation. This system will likely improve the lifetime of the atomic cloud inside the optical trap and enables higher stability for further experiments; as the study of the heteronuclear Feshbach resonance or the study of mixture of degenerate gazes in optical lattices. Nevertheless the trapping time will be now limited by other sources like the beam pointing fluctuations. At the moment efforts are made in this direction by using fiber optics to bring the beam from the laser to the vacuum chamber.