Scientific Report
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Introduction

In this report I will present the results that I got thanks to the six-month research grant offered to me by the QUDEDIS project of the European Science Foundation. My activity took place in the research group of the Professor Cristophe Salomon at the Kastler–Brossel laboratory (LKB) in Paris.

Taking advantage of the extremely high control over atoms, namely Lithium atoms, Salomon's group is able, tuning the strength of the interaction[1], to sweep from the weakly-interacting BCS regime to the strongly-interacting BEC regime. The efforts are mostly focused to the crossover between these two regimes, which is known as *crossover BEC–BCS* or *unitary regime*. It occurs when the Feshbach resonance makes the scattering length a diverge to infinity. Far from the unitary regime the system is strongly dependent on the scattering length, but, on the contrary, at the unitary regime it happens that the system is not characterized anymore by the scattering length, and it shows a universal behavior. This universality is particularly remarkable also outside the atomic physics, because its full explanation would provide important clues about other strongly interacting Fermi systems, such as high-temperature superconductors, neutron stars, and hopefully also quark systems.

An alternative and improved master laser system

According to what was planned in the submitted project, I devoted myself to the development of an upgrade of the master laser system, following the scheme

[1] The Feshbach resonance permits to select at one's pleasure the scattering length a.

proposed by the "Observatoire de Paris" [1]. Nowadays, in atomic physics, in metrology and in telecommunications as well, the semiconductor diode lasers represent the most convenient solution to produce a single-mode laser signal with narrow linewidth and good tunability. Up to now, the research group has adopted diode lasers stabilized in a external cavity constituted by a grating in the usual Littrow configuration. In this setup, as it is well-known, both the optical feedback and the wavelength discrimination are provided by the grating. On the contrary, in the new setup, that I will present in the following, an intracavity interference filter performs the wavelength discrimination and a partially-reflective mirror (out-coupler) performs the optical feedback. A more detailed description of this setup is presented in Fig. 1.

The use of two distinct optical components in a linear external cavity to perform wavelength discrimination and optical feedback turns out to be an important advantage. In fact, in this way, we operate the coarse wavelength selection acting on the interference filter, without affecting the alignment of the optical feedback, which is guaranteed, separately, by the optimization of the reflection onto the out-coupler back into the laser diode. I emphasize that, on the contrary, Littrow-configuration-tuned extended-cavity lasers do not easily permit[2] to select the wavelength without misaligning the optical feedback.

There exists another relevant advantage, which is strictly specific to this new alternative extended-cavity diode lasers. As pointed out in [2], the only parameter which determines the sensitivity of the optical feedback to misalignment is the waist of the beam onto the out-coupler. The separation of the out-coupler from the wavelength discriminator allows to focalize the beam onto the out-coupler itself (see the "cat's eye" telescope in Fig. 1), avoiding therefore large collimated beams, as it is required by the use of gratings[3]. Such a smaller beam waist onto the out-coupler guarantees a much greater robustness to misalignments induced by thermal and mechanical stresses. As a consequence of this improvement in stability, the extended cavity can be built longer, reducing therefore the free spectral range ($= c/2nd$), and consequently, for the same *finesse*, reducing also the extended-cavity linewidth. Usually, Littrow-grating extended-cavity diode lasers are 1 cm long, and the laser that I built is 10 cm long, which means that we shrinks the linewidth roughly up to a factor $10^2 = 100$ (the factor 100 instead of 10 arises from the Schawlow-Townes linewidth that also goes down by a factor 10, corresponding to the increase of the total energy inside the cavity).

[2] A fully-orthogonal rotation of the grating would allow to preserve the optimized optical feedback and to select broadly the wavelength at the same time, but this ideal configuration of the mechanical components is hard to realize in practice.

[3] When the out-coupler and the wavelength discriminator coincides with the grating, it turns out that beam waist is essentially determined by the wavelength selectivity requirement, and is usually of the order of 1 mm.

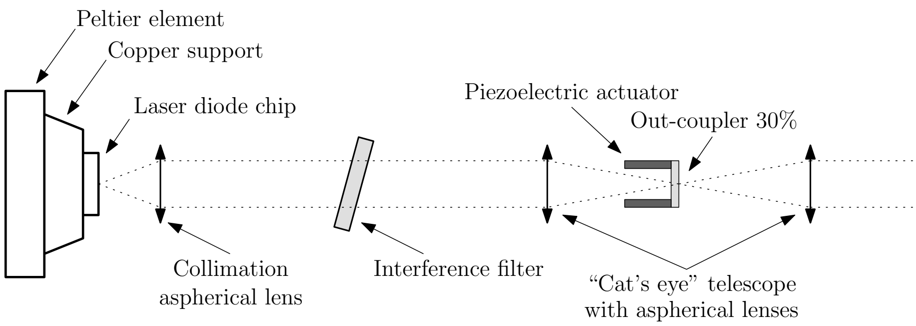

Figure 1: A schematic description of the main components of the interference-filter extended-cavity diode laser. A $30\,mW$ diode laser is heated and temperature-stabilized by a Peltier element to $\sim 60^{\circ}C$, in order to bring the wavelength from the free running ~ 664 nm to ~ 671 nm (the Lithium $S \rightarrow P$ line). The laser beam, diverging with 22° and 9°, is collimated by an aspherical lens with $f = 3.1$ mm and $NA = 0.68$. The collimated beam passes through an interference filter (90% maximal transmittance and FWHM $= 0.3$ nm which is about twice the f.s.r. of naked diode) which acts as a intracavity wavelength discriminator. The interference filter has the maximum transmittance at 671 nm when tilted at an angle of 30° to avoid the small amount of reflected light from going back into the diode. Then, the beam passes through a "cat's eye" telescope ($f = 18$ mm) and it is focalized over a partially-reflective (30%) out-coupler which provides the optical feedback (auto-injection of the diode laser). The out-coupler is mounted over a piezoelectric actuator which gives an active stabilization, and fine tunability over ~ 1 GHz (the extra cavity length is ~ 10 cm). This fine tunability is large enough to sweep over all the ground-state hyperfine structure of either the ^{7}Li (width ~ 800 MHz) or the ^{6}Li (width ~ 230 MHz).

The interference filter

The interference filter deserves a greater attention, because of its key role in this alternative extended-cavity diode laser. The filter is formed of a series of dielectric coatings on an optical substrate with anti-reflection coated back face. The filter is characterized by 90% maximal transmission and $\sim 0.3\,\mathrm{nm}$ FWHM at near infra-red and visible wavelengths, which is sufficiently narrow to depress under threshold all the naked-diode modes but one (which are usually separated by $\sim 0.15\,\mathrm{nm}$). The wavelength discrimination of the filter is based on multiple reflections within its dielectric coatings, and behaves as a thin Fabry-Perot etalon with effective index of refraction n_{eff}:

$$\lambda = \lambda_{\max} \sqrt{1 - \frac{\sin^2(\theta_{\mathrm{tilt}})}{n_{\mathrm{eff}}^2}} \qquad (1)$$

where θ_{tilt} is the angle at which the filter is tilted.

Operation of the laser

The interference-filter external-cavity diode laser is used as a master laser, thanks to its remarkable spectral purity. Master lasers are the ones that give the reference (in frequency) laser signal, which is opportunely amplified (in intensity) by other slaves naked-diode lasers (or either by a MOPA amplifier).

The laser diode temperature is fixed around 60° C, in order to bring the free-running wavelength of the naked diode laser (at room temperature around 664 nm) to approximately 671 nm, which corresponds to the $S \to P$ transition for Lithium. The temperature stabilization is performed thanks to an active feedback which acts over a Peltier element mounted under the laser chip. Furthermore, the temperature stabilization avoids slow drifts of the wavelength, which would bring the laser either out of single-mode operation (i.e. to multimode operation), or to a mode hop.

By changing the angle of the etalon, which is mounted over a 0.5 inch mirror mount, it is possible to operate the coarse wavelength selection within a window of $\sim 0.3\,\mathrm{nm}$, according to (1).

In order to achieve the fine tuning and stabilization of the wavelength, the laser frequency is locked to an absolute reference provided by a suitable atomic spectroscopy, which is, in our case, on the same atomic species which is used in the experiment, namely ^{6}Li and ^{7}Li atoms. An electronic active feedback takes care to restore the laser wavelength to the absolute reference. The low/mid-frequency noise (up to a few tens of KHz) of the laser wavelength is attenuated by the feedback over the piezoelectric actuator, which holds up the out-coupler. A change of the cavity length Δd induces a change of the wavelength $\Delta\lambda/\lambda = \Delta d/d$. The maximum tunability that might be achieved operating with the piezoelectric actuator is roughly given by the free spectral range $c/2nd \sim 1\,\mathrm{GHz}$, that is wide enough to cover all the hyperfine structure of the ground state in the

$S \rightarrow P$ spectroscopy for both ^{6}Li and ^{7}Li (for instance, see Fig. 4). The higher-frequency noise (up to a few MHz) of the laser wavelength is attenuated by acting over the diode-laser current, in order to perform small and fast corrections of the wavelength.

The Fig. 2 shows a picture of the interference-filter extended-cavity diode laser which I personally built during the stage at the LKB laboratory.

In order to test the good operation of the laser, I also built a standalone pump-probe subdoppler spectroscopy system. Such a system is mainly composed by two counter-propagating laser beam, crossing a hot vapor ($\sim 300\,^{\circ}C$) inside a *heat pipe*, which is showed in Fig. 3. When one beam is resonant with atoms at velocity v, the other beam is resonant with atoms at opposite velocity $-v$. As soon as we pass through the resonance the two beams affect the same class of atoms, those with $v = 0$. In this special case, one beam, that we call the *pump*, depopulates the ground S level towards the excited P level, and the other beam, that we call the *probe*, experiences a smaller absorption due to the saturation effect induced by the pump beam. The transmission enhancement of the probe beam, which is called Lamb dip, allows to detect with subdoppler precision the transition resonance. In fact, the width of the dip is equal to the homogeneous broadening (a few MHz), and the inhomogeneous Doppler broadening cancels because the effect involves only atoms with velocity $v = 0$. The Fig. 4 presents the atomic signal that I got from the spectroscopy, for instance, of the $D2$ line of ^{7}Li.

Conclusions

The six-months stage at the LKB laboratory, which has been possible thanks to the QUDEDIS project, gave me the exclusive possibility to work with and to learn from one the most qualified research group in the field of ultra-cold quantum gases. I had the possibility to give my personal contribution to the development and improvement of their researches.

In the near future, the laser which I built will be used to probe ultra-cold Fermi gases in the strongly interacting regime. More precisely, the laser will be used in a new experiment with fermion ^{6}Li to study superfluidity with imbalanced populations, which is a very debated subject in the last few months [3].

After considering the advantages offered by this interference-filter extended-cavity diode laser, the ultra-cold atom group at the LKB laboratory is going to replace all the Littrow-configuration external-cavity diode lasers with this new master diode laser. The laser will be adapted to other wavelengths to fit the different atoms used in the Rubidium, Potassium, and Lithium as well experiments.

Before concluding, I really wish to thank once more Professor Christophe Salomon for having offered me a wonderful experience that I enjoyed with a great personal profit.

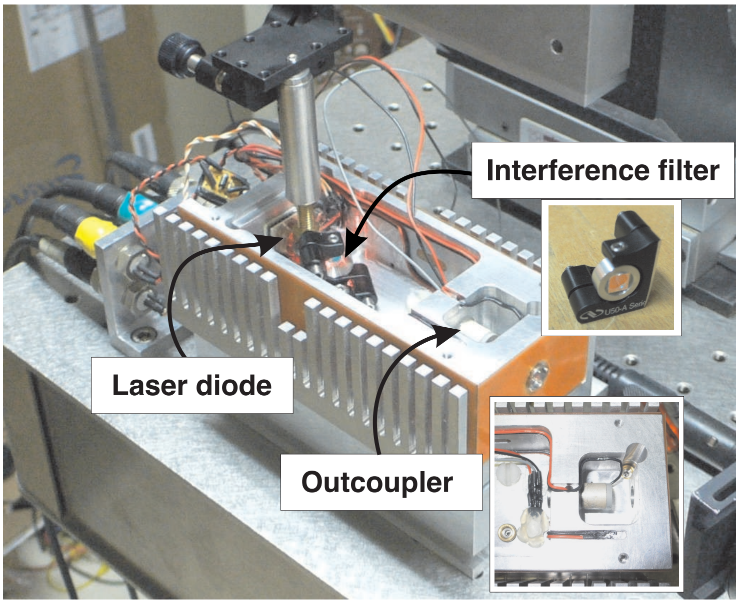

Figure 2: A picture of the interference-filter external-cavity stabilized diode laser. The main components, which were discussed in Fig. 1, are highlighted. The collimation lens is still hanging on translational stage, which has been used to optimize in the final step the auto injection of the diode laser (the optical feedback was improved by positioning the collimation lens in order to minimize the threshold current).

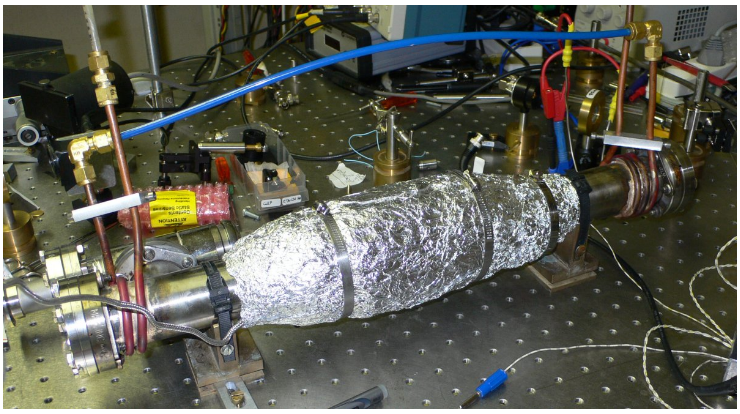

Figure 3: A picture of the heat pipe that I built to perform a pump-probe subdoppler spectroscopy of $S \rightarrow P$ lines of ^{6}Li and ^{7}Li. This heat-pipe reproduces the same standard that is currently used in the group. The Lithium vapor is produced heating the heat-pipe at $\sim 300\,^{\circ}C$. Its ends are cooled down by a cold water flow. A grid (0.15 mm step size) was positioned all over the internal surface in order to recycle the melted Lithium thanks to a capillarity effect and the temperature gradient. After filling the cell with a small amount of solid Lithium, a turbo pump emptied the cell itself, and finally ~ 10 mTorr of Argon were introduced to reduce the mean free path of Lithium vapor, in order to avoid collisions with the ending windows.

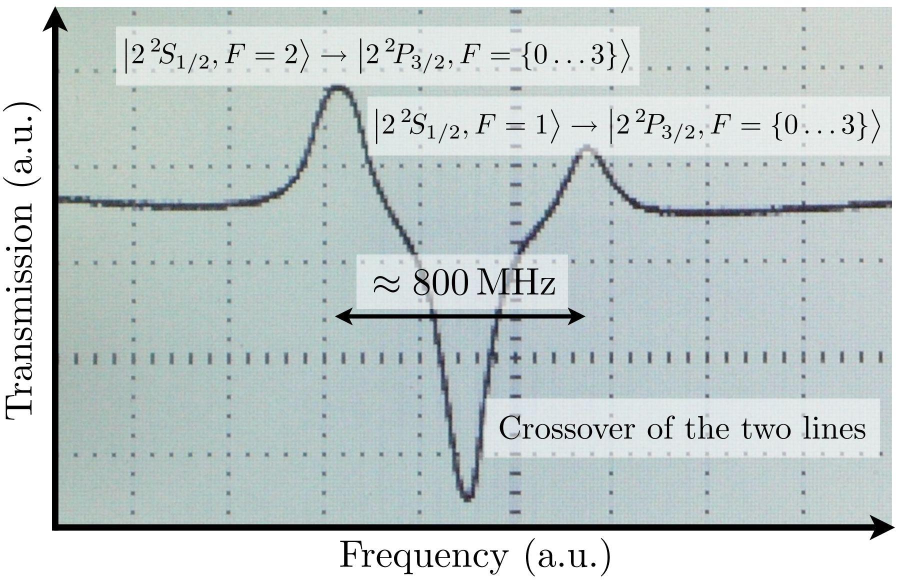

Figure 4: For illustration purpose, here is the measured intensity of transmitted probe beam after the heat-pipe sweeping over the $D2$ line of ^{7}Li. On the left and on the right they are visible the two Lamb dips of greater intensity, which refer to the two hyperfine levels of the ground state (the hyperfine levels of the excited state P are not distinguishable since they are separated by only a few MHz). In the middle it is visible the crossover Lamb dip of lower intensity, which is equally separated from the two sided dip, and arises because of the common upper level.

References

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