Optical trapping and manipulation of atoms near surfaces
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We discuss the several components of our experimental setup. The preparation of the laser beams with different frequencies is discussed and experimental parameters are presented. It is explained how these beams are used in the experiments. A very accurate method to determine the critical angle of a laser beam is presented. The vacuum system is discussed extensively insofar it has been altered with respect to previous descriptions of the setup [89, 90]. This concerns an alternative prism geometry, a quartz cell to provide optical access for the numerous laser beams used in the experiments, and the use of a dispenser that is used as the Rb source.
4.1 Laser park

This section discusses the laser setup that is used in the experiments described in this thesis. Several laser frequencies are necessary in the experiments. An overview of these is shown in Fig. 4.1. The purpose of these lasers will be explained in the following sub-sections. Fig. 4.2 schematically shows the setup of the lasers that are used near an atomic resonance.

4.1.1 Frequency locked diode lasers: master and repumper

There are two diode lasers locked to a $^{87}\text{Rb}$ spectral feature. One to the $F = 2 \rightarrow F' = (1, 3)$ cross-over of the $D_2$ line, and the other to the $F = 1 \rightarrow F' = 2$ transition of the $D_1$ line. Both lasers are 50 mW diode lasers with grating feedback [91, 92] in Littrow configuration [93]. A small fraction of the available optical power is used to obtain a Doppler-free saturation spectroscopy signal.

In order to frequency lock these laser diodes to a spectral feature a small RF signal is added to the laser current, which results in frequency sidebands on the laser light. A dispersive spectroscopy signal is obtained by mixing the spectroscopy signal with the RF oscillator [94, 95]. The resulting signal is used as feedback to the laser current in order to compensate for fast fluctuations. Furthermore it is integrated and sent to the piezo on which the grating is mounted, in order to compensate for long term drift.

The laser that is locked to the $D_2$ line is called the master laser, and is used as a frequency reference for two laser diodes that will be injection locked. These will be discussed in the next two sub-sections. The laser that is locked to the $D_1$ line is called the repumper, and is used to prevent atoms from ending up in the $F = 1$ ground state during the MOT and molasses stages of the experiment. Later in an experimental run it can also be used to pump all atoms to the $F = 2$ state by pulsing it on for a short time. A total power of 8 mW was obtained behind a single-mode (SM) optical fiber. It can be switched on and off within 100 μs by a mechanical shutter (Vincent Associates, Uniblitz, LS2T2), which is placed in the focus of a 1:1 telescope, in order to reduce the switching time.

4.1.2 MOT/molasses

Some light of the master laser is frequency shifted using a double-pass AOM setup. The frequency shifted light is injected into a the MOT/molasses laser diode through the unused output port of the second polarizing beam splitter (PBS) of the optical isolator behind this diode laser. We adjust the AOM frequency such that the injection locked laser diode operates at an optical frequency suitable for magneto-optic trapping ($\delta \approx -1.5 \Gamma$ with respect to the $F = 2 \rightarrow F' = 3$ transition of the $D_2$ line) or for polarization-gradient cooling ($\delta \approx -10 \Gamma$ with respect to the same transition). The final power of the beam can be reduced by the combination of an electro-optic modulator with a PBS. This combination has an extinction ratio of $\sim 10^{-3}$. To fully extinguish the beam a mechanical shutter is used. Just as mentioned before, it
is placed in the focus of a 1:1 telescope in order to reduce the switching time. The beam is finally injected into a SM optical fiber.

Initially we used a 50 mW laser diode [89]. This concerns the experiments described in chapter 6. Typically 100 µW of frequency shifted light was necessary for injection locking. A maximum power of 17 mW was realised behind the SM fiber. The fiber output was collimated to a waist of 4 mm. The beam is split in 3 parts. The 6 MOT beams were created by retro reflecting the original 3 beams. A disadvantage of this setup is that there is a power imbalance between the retro-reflected beams, both by the reflections from the glass cell surfaces and the absorption of the cloud of cold atoms, but it is very economical in terms of laser power.

In later experiments (chapter 7) the 50 mW diode was replaced by a 150 mW diode (Semiconductor Laser International corporation, SLI-CW-9mm-C1-783-0.15s-PD). Although this device was specified as SM, all tested specimen were multi mode, both spectrally and spatially. The spectral multi-mode behavior was removed by injection locking it with ~ 3 mW of frequency shifted light from the master laser. The spatial multi-mode character limited the incoupling efficiency of the polarization maintaining (PM) fiber to ~ 45%, which corresponds to ~ 40 mW behind the fiber. This is sufficient to create 6 independent beams with a waist of 4.5 mm. This way the power imbalance between the beams is solved.

The MOT is loaded from the background $^{87}$Rb pressure for 3 s. During the loading stage two coils in anti-Helmholtz configuration produce a magnetic field gradient of approximately 10 G/cm. The 6 MOT beams are circularly polarized, the beams that propagate perpendicular to the coil axis are orthogonally polarized.
from the beams that propagate parallel to the coil axis. The repumper light is overlapped with 2 of the 3 sets of counterpropagating MOT beams. When the MOT is saturated, the temperature of the trapped cloud of atoms is further decreased by a short period of 3 ms polarization-gradient cooling. During this stage the magnetic field coils are switched off, the detuning of the MOT light is increased to $\delta \approx -10 \Gamma$ with respect to the $F = 2 \rightarrow F' = 3$ transition of the $D_2$ line and the power of the beams is decreased to approximately half the initial power by the EOM and PBS combination.

Typically $2 \times 10^7$ atoms were trapped and cooled to $T \approx 5 \mu K$. In order to reach these low temperatures it proved very important to cancel all stray magnetic fields in the trapping region. This was done by three pairs of Helmholtz coils. After the molasses stage all light beams are switched off and the atoms fall ballistically towards the prism that is mounted inside the vacuum under the trapping region.

### 4.1.3 Probe and depumper

The **probe/depumper** laser diode is injection locked directly with light from the master laser. Its light is split in two beams and each is frequency shifted by a double-pass AOM setup and subsequently coupled into a SM fiber.

One of the beams is frequency shifted to the $F = 2 \rightarrow F' = 2$ transition of the $D_2$ line and is called the **depumper**. It will be totally internally reflected from one of the 45° surfaces of the prism that is mounted inside our vacuum system. The two prism configurations that are used are best visible in Figs. 4.5 and 4.7. This way the depumper beam will propagate vertically upwards, along the trajectory of cold atoms falling towards the surface. A short pulse of $\sim 1$ ms duration and a power of 100 $\mu W$ is sufficient to pump all atoms to the $F = 1$ ground state by a spontaneous Raman process.

The second beam is frequency shifted close to the $F = 2 \rightarrow F' = 3$ transition of the $D_2$ line and will be called the **probe**. It is used for all probing purposes in the experiment: e.g. the evanescent-wave probing technique that will be discussed in chapter 6, but also for absorption imaging [89, 90, 96] in order to characterize the cloud of falling atoms.

### 4.1.4 Non-resonant lasers

Several higher power lasers are used in the experiments. These lasers are not frequency locked, since their detuning from an atomic resonance is relatively large and their frequency drift is sufficiently slow to be able to compensate manually.

We use a tapered amplifier system (**Toptica, TA100**) that is used to create a repulsive EW potential to load a standing-wave (SW) dipole trap in experiments described in chapter 6. The tapered amplifier gives powers up to 300 mW behind an optical isolator, but due to a bad spatial profile only approximately 100 mW is transferred through a SM optical fiber. In these experiments it is blue detuned by 0.2-1 GHz with respect to the $F = 1 \rightarrow F' = 2$ transition of the $D_1$ line.
The SW laser is a Ti:sapphire laser (Coherent, MBR-110) that is pumped by a 10 W Verdi laser (Coherent). This system gives up to 1.4 W of optical power near the $D_2$ line and is red detuned by 85 GHz in these experiments. In the experiments described in chapter 7 this Ti:sapphire laser is used for the EW dark-state trap, where it is tuned close to the $D_1$ line. This wavelength is closer to the optimum wavelength of the mirror set we use, which results in a power up to 1.8 W.

### 4.2 Evanescent wave alignment procedure

In order to accurately adjust the decay length of an evanescent wave, the angle of incidence of the incident beam must be carefully controlled. This is especially important for angles of incidence close to the critical angle, since the dependence of the decay length on the angle of incidence is very steep as is obvious from Eq. (2.19).

The setup with which we control the angle of incidence is depicted in Fig. 4.3. Two lenses L1 and L2, both with focal distance $f$, are separated by a distance $2f$. Also the distance from lens L2 to the top surface of prism P is $2f$. The lens L2 images the beam at the position of L1 on the prism surface. If the height of lens L1 is changed, the angle of incidence of the beam is changed, but its position on the prism surface remains unaltered.

The angle of incidence $\theta_i$ as a function of the lens displacement $d$ is given by

$$\theta_i(d) = \frac{\pi}{4} + \arcsin \left( \frac{1}{n} \sin \left( \theta_0 - \arctan \frac{d - d_0}{f} \right) \right),$$

with $n$ the index of refraction of the prism and $\theta_0$ an angle to compensate for the angle of mirror M. The term $d_0$ is the lens position for which $\theta_i(d_0) = \theta_c$.

In order to calibrate the lens position $d_0$, we need to describe the incident beam as a diffraction limited beam, as described in section 2.2. The transmitted power, light coupling out of the prism at grazing angles, is compared with a calculation based on Eqs. (2.29) and (4.1) for different positions of the micrometer on which

![Figure 4.3](image)

**Figure 4.3:** The setup used to control the angle of incidence. The distance between lenses L1 and L2 and between lens L2 and the top surface of the prism P is $2f$, with $f$ the focal distance of the lenses. Lens L2 images the position L1 on the prism surface. If the height of lens L1 is changed, the angle of incidence of the beam is changed, but its position on the prism surface remains unaltered.
4.3 Vacuum setup

Figure 4.4: Measured (□) and calculated (line) transmission versus the vertical position of the first lens as shown in Fig. 4.3 for a TE polarized beam with a waist $w = 500 \mu m$ and lens focal distance $f = 80 mm$. The calculation is based on Eqs. (2.29) and (4.1). The angle of incidence $\theta_i$ of the beam is equal to the critical angle $\theta_c$ for a lens position of $d_0 = 4.89 mm$.

The accuracy with which the lens height $d$ can be adjusted is approximately 5 $\mu m$. The accuracy with which the lens position $d_0$ can be determined from the fit, as shown in Fig. 4.4 is approximately 10 $\mu m$. Combining this with Eq. (4.1), leads to a maximum value for the accuracy of the angle of 120 $\mu rad$. This is below the divergence angle of 500 $\mu rad$ of a diffraction limited beam with an experimentally realistic diameter of 0.5 mm.

4.3 Vacuum setup

The experiments described in this thesis have been performed in two similar vacuum setups. The experiments described in chapter 6 are performed in a setup described extensively in [89]. Therefore this setup will be only briefly discussed in this section. The experiments described in chapter 7 are performed in a modified version of this setup. This setup will be discussed in more detail.

4.3.1 Setup for EW absorption experiments (chapter 6)

The main part of the vacuum setup is an uncoated glass vacuum cell with outside dimensions $42 \times 42 \times 130 mm^3$ and a wall thickness of 4 mm. It is glued to a stain-
less steel platform, using low vapor pressure epoxy resin (Varian, TorrSeal). This platform is connected to a CF40 flange. This glued connection limits the bakeout temperature of the system to approximately 115 °C, which subsequently limits the achievable pressure in the system. This configuration provides us with excellent optical access for the numerous laser beams that are used in the experiments.

Inside this cuvet an uncoated BK7 glass prism, with dimensions $10 \times 10 \times 4$ mm$^3$ (Melles Griot, 01PRB009, cut in half) is mounted. Fig. 4.5(a) shows a picture of this prism mounted in the glass cell. The surface flatness is specified to be better than $\lambda/8$ at a wavelength of 632.8 nm, with a surface quality of 20-10 scratch-dig. The 45° face of this prism is used as the entry face for the beams that will create the evanescent fields, as discussed in section 4.2.

During the experiments a low pressure of Rb atoms is maintained in the cell. In order to get the Rb vapor into the system, a small oven containing a Rb reservoir is heated. This oven can be sealed off from the main vacuum by means of an UHV valve when the Rb pressure in the cell is sufficiently high. The vacuum is maintained by a continuously pumping ion pump with a pumping speed of 15 l/s ($N_2$). This creates a background pressure of $10^{-9}$ mbar. In order to prevent the Rb from being pumped away too quickly during the experiments, the cell is differentially pumped through an aperture with a diameter of 1.5 mm. This allowed for experiment runs up to several hours without a noticeable decrease of the Rb pressure.
4.3 Vacuum setup

4.3.2 Setup for EW trapping experiments (chapter 7)

The experiments described in chapter 7 are performed in a modified/improved setup. An outline of this vacuum system is presented. The elements that are altered with respect to the setup described in [89] are discussed in more detail.

**General vacuum setup**  Drawings of the setup are shown in Fig. 4.6(a). The central part of the vacuum system is the “5-cross”, all major components are connected to this cross. On the top port a hexagonal section (Kimball physics, spherical hexagon, MCF275-SH206C-B) and a cell to provide optical access for the experiments, are mounted. The four side flanges of the “5-cross” will be discussed counter clockwise. One of the side ports is used for roughing the system. A turbo-molecular pump can be connected to this port in order to pump down from atmospheric pressure. It is usually sealed off by a UHV valve (Granville Phillips, gold seal type 204), so that the turbo-molecular pump can be detached from the system. To the second flange an ion pump (Varian, Vaclon Plus20 StarCell with ferrite magnets, 15 l/s N$_2$) is connected. A “T-cross” is placed in between the “5-cross” and the ion pump to reduce the ion pumps magnetic field in the cell region. The ion pump can be sealed off by a gate valve (VAT, series 010 mini UHV gate valve DN40, manual actuator) so that the ion pump is not exposed to atmospheric pressure when the system is vented. The third flange on the “T-cross” is used for an ion gauge (Varian, Bayard-Alpert type UHV-24p). The third flange of the “5-cross” is closed with a blind flange, to be used in the future to connect a titanium sublimation pump. The last port is used for electric feedthroughs. Two 100 W halogen lamps are connected to this using wires of OFHC copper. They are carefully positioned in the centers of the “5-cross” and the “T-cross”, as shown in the photograph in Fig. 4.6(c). There is also an electric feedthrough in the hexagonal section. A 100 W halogen lamp positioned in the center of the hexagon is connected to it. These lamps are used for baking the system from inside, instead of wrapping heater tapes around the setup.

**Cell**  The glass cell is replaced by a rectangular quartz cell (Optiglass, custom made) with outside dimensions 30 × 30 × 120 mm$^3$ and a wall thickness of 4 mm. A “wide angle” anti-reflection coating for 780 nm is applied to the outside surfaces. It is shown in Fig. 4.5(b). An UHV vacuum tight connection between the cell and the stainless steel of the rest of the vacuum was obtained using a Helicoflex Δ gasket (Le Carbonne-Lorraine, type HNV200Δ (DN25), spring Nimonic 90, lining aluminium/Inconel600). This connection and a successful test are extensively described in [89]. The quartz cell is mounted on two rings of increasing diameter of the same material. The bottom surface of the lowest ring is polished. This construction is connected to a specially prepared stainless steel CF40 flange with a polished top surface and fine thread of 1.2 mm/turn on its outer surface. A Helicoflex Δ gasket is placed between the two polished surfaces. The system is subsequently compressed with a single compression nut screwed on the threads on the flange. This connection allowed for much higher baking temperatures than using the previously used glued cell. Pressures below 10$^{-10}$ mbar are realized in this system.
Figure 4.6: (a) Drawings of the vacuum setup; from top to bottom: top view of the hexagonal section, side view of the entire setup, top view of the bottom section around the "5-cross". (b) Photograph of the hexagonal section. It is visible how the dispenser is mounted against the prism mount and how this mount is itself mounted in the hexagonal section using "groove grabbers". (c) Photograph of the electric feedthrough in the "5-cross" on which two halogen lamps are mounted.
Prism  The second major change is the geometry of the prism. Top and side views of this prism are shown in Fig. 4.7 and a photograph can be seen in Fig. 4.5(b). Although the shape of this structure does not resemble the geometrical shape of a prism, it will be called a prism throughout this chapter and chapter 7. It is effectively a pyramid that is cut in half and put upside down. The result is that it has three entrance faces at 45° with respect to the top surface, through which beams can enter that will totally internally reflect from the top surface and thus create evanescent waves “propagating” in different directions. The remaining entrance face, which is at 90° with respect to the top surface, can be used for a beam that will be internally reflected from the opposing 45° surface, which results in a beam propagating upwards through the top surface of the prism. The prism is created from the same basic rectangular prism (*Melles Griot, 01PRB009*) as the prism discussed in section 4.3.1. It is cut in half and an extra 45° face is grinded on one of the non-optical surfaces. Both the new 45° surface and the opposing 90° surface are subsequently polished. The resulting flatness of these surfaces is estimated to be \( \lambda \). The prism is clamped at its four corners. Using a construction with several rods the prism is mounted using “groove grabbers” (*Kimball physics, split axial clamping groove grabbers, MCF275-GG-CS03-A*) in the hexagonal section. This is visible in the photograph in Fig. 4.6(b).

Dispenser  The Rb oven is replaced by a Rb dispenser (*SAES getters, RB/NF/3.4/12 FT 10+10*). This is a small metal container that contains a mixture of rubidium chromates (\( \text{Rb}_2\text{CrO}_4 \)) with a reducing agent. The narrow exit slit of the dispenser is partially obstructed by a metal wire to shield the escape of loose particles. By (resistively) heating it, the reduction reaction is initiated above a threshold temperature of about \( \sim 400^\circ \text{C} \) and the rubidium will be released. Dispensers were first mentioned as an atom source for laser-cooling experiments in [97]. A description of how to handle these dispensers more sophisticatedly in atomic physics experiments is discussed in [98]. Recently a method was described to reduce the background pressure while operating a dispenser by collecting the atoms that are too hot to be trapped on a thermo-electrically cooled copper plate [99].

**Figure 4.7:** Top, front and side view of the prism used in the experiments described in chapter 7.
We have mounted the dispenser in a small tray made of a ceramic material (MACOR. $\text{Al}_2\text{O}_3$), that is screwed against the prism mount. This is visible in the photograph of Fig. 4.6(b). The MOT loading region is blocked from the line of sight of the dispenser by the prism, so that hot atoms emerging from it do not collide with atoms trapped in the MOT. The dispenser is electrically connected to the electric feedthrough in the hexagonal section using OFHC copper wires. During the three seconds MOT loading process, a current of $\sim 6$ A is run through the dispenser for the first two seconds. According to [98] the dispenser cools mainly by thermal radiation. During the short time that the current is switched off the temperature will not decrease significantly, so that the temperature will tend to a constant value, which results in a constant input rate of Rb atoms. During the experiments the pressure increased up to $5 \times 10^{-10}$ mbar measured on the ion gauge. We switch the dispenser current off in order to get rid of the magnetic fields due to this current. This spurious magnetic field is especially important during the polarization-gradient cooling stage and the actual experiments.