Manipulation of ultracold Bose gases in a time-averaged orbiting potential
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Chapter 3

Lasers and Imaging

In this chapter a description is given of the improvements of the laser and imaging systems in preparation for the experiments described in this thesis. These improvements were driven by new requirements on the power and stability of the lasers and the necessity of imaging along the cloud axis. Further, to facilitate detailed imaging and better analysis of the atomic clouds, greater position resolution and improved signal/noise were imperative.

An improved laser stabilization was required to realize a better shot-to-shot reproducibility in absorption imaging. For this purpose a stable sub-1 MHz linewidth external cavity diode laser (ECDL) stabilization was developed using Zeeman sideband spectroscopy. New higher powered laser systems were needed as a result of the decision to put all stabilized lasers on separate optical tables in order to decouple them from the sources of acoustic vibration caused by switching of trap currents and various shutters on the main table. This decision also allowed a very flexible mode of operation in which improvements could be developed alongside an operational system on the main table. To enable this approach insertion losses caused by the optical fibers bridging the optical tables had to be compensated. For this purpose tapered amplifiers were introduced in the system and a temperature stabilized mount was developed inhouse to make best use of the increased laser power. For the less critical purposes, such as optical pumping and repumping, a distributed feedback laser (DFB) was found to be a conveniently suitable alternative. The lasers were situated on two side tables, one containing the DFB laser and the other the ECDL master laser and tapered amplifier (TA). All optics on the side tables were enclosed in a metal casing thus avoiding stray light, thermal fluctuations and air turbulence disturbances to experiments.

The detection and imaging system was adapted to image both along the axis of the cloud and perpendicular to the cloud in order to investigate structure in the condensate introduced when rotating the cloud about its axis. This required a new system for absorption imaging, which again was cast in a modular concept. The new imaging directions overlap with the paths of the MOT beams and so required
an overhaul of all optics about the upper cell to integrate the imaging optics with those of the MOT. Researching the best way to proceed with this integration lead to several insights into the operation of the camera and key properties of detection such as optical resolution and signal to noise optimization. Polarization maintaining optical fibers were employed for their advantages of compactness and well-defined polarization. Investigating the performance of the imaging system, gains were also made in both optical resolution and imaging noise reduction with the aim of allowing finer detail examination of the clouds than was hitherto possible on this system. The limiting components for both resolution and imaging noise were identified and replaced resulting in better resolution and a signal to noise ratio.

3.1 Laser Systems

3.1.1 Master Laser

The master laser for this experiment is locked to a crossover line of the D2 transition and is based on a higher power version of the DL100 laser (Toptica). The locking system uses Zeeman sideband spectroscopy, explained at length in [52] and mentioned in [44], with some improvements here to help stability. The optical paths of the setup is shown in Fig. 3.1. Linearly polarized light is retroreflected through a small Rb-vapour saturation spectroscopy cell located between two coils connected in series in Helmholtz configuration (not shown in the figure). The current to these coils is
3.1. LASER SYSTEMS

modulated creating an AC magnetic field in the cell.

The Rb atoms in the cell can make $\sigma$ or $\pi$ transitions by absorbing photons from laser light at the transition frequency creating a dip in the transmission of the light through the cell [53, 54]. In the presence of a magnetic field the $\sigma^+$ and $\sigma^-$ transitions become non-degenerate and are frequency shifted in opposite directions proportional to the magnetic field due to the linear Zeeman effect. Thus the dips in the transmission of the light through the cell with a modulated magnetic field become frequency modulated just as if the laser light itself were modulated. This induces sidebands on the light through the cell without having the sidebands on the light directly from the laser. A combination of a Wollastonite prism and a $\lambda/4$ plate allow $\sigma^+$ to be detected on one photodiode of a high speed differential detector and $\sigma^-$ to be detected on the other. The combined (differential) signal is then amplified and multiplied on a mixer with the drive frequency of the coil current to produce a DC error signal which can be converted to feedback to the grating and power supply of the laser. The signal from a single photodiode could in fact be used individually to lock the laser but subtracting the two allows us to cancel laser noise as well as reducing greatly the effect of external magnetic fields, increasing stability [52].

Additional stability was gained by shielding the cell from external magnetic fields with a soft iron mount. The error signal is sensitive only to noise in a narrow band at the specific drive frequency. The result is a laser which can be stabilized to well below 1 MHz as measured by beat experiment between two such lasers. It shows excellent isolation from magnetic, electrical and vibrational noise but without creating sidebands on the laser as in other modulation methods.

This stabilization method is used for the imaging laser. Following amplification and additional detunings imparted with acousto-optical modulators (AOM) it also used for magneto-optical trapping and optical pumping. As can be seen in Fig. 3.1, a part of the beam is double passed through an AOM and sent as seed laser to the tapered amplifier (TA) which produces the upper MOT. A second beam goes to the main table at the crossover frequency $\nu_2$ and a third at frequency $\nu_3$ corresponding to a detuning of two linewidths (12 MHz) from the $F = 2 \rightarrow F' = 3$ transition.

3.1.2 DFB laser

The distributed feedback laser (DFB) is a 50 mW GaAs semiconductor laser diode with an integrated grating structure. For applications not requiring sub-natural linewidth accuracy in wavelength, the DFB laser was a useful tool introduced to the apparatus. The main advantage over the external cavity diode is that instead of an external grating, the DFB incorporates a grating into the active region of the semiconductor, which then via Bragg scattering provides optical feedback to the laser. By construction it is made near single mode in frequency (highly favouring modes in a narrow region). This is done by concatenating two such gratings, thus in effect creating a periodic structure with a phase change in the middle. The incorporated grating
Figure 3.2: Comparison of mode behaviour of DFB (open circles) and EDCL (solid squares). Temperature was varied from 14-40°C and detuning from D2 line of 87Rb plotted. Note the continuous wavelength property of DFB laser shows no modehops over a 15°C temperature change while the EDCL is stable over about 4-5°C and makes large mode hops.

makes the DFB laser very insensitive to sources of acoustic noise. Wavelength tuning is realized by altering the refractive index of the semiconductor by changing the temperature or the operating current. Changing the temperature causes, via thermal expansion, a change to the bandgap of the semiconductor and hence also to the refractive index of the grating. This in turn causes a change to the pitch of the grating and thus the wavelength of the light produced, providing a wavelength tunable diode laser (TDL). The tuning range or free spectral range (FSR) is usually of the order of 6 nm for a 50 K change in temperature. Significantly though, in contrast to an ECDL a DFB there is no competition between the external and internal cavities to produce a most favourable mode and thus the familiar step-wise mode-hop behaviour of the ECDL is avoided as shown in Fig. 3.2. The output wavelength changes with temperature due to thermal expansion of the cavity. Altering the current to the diode also changes the temperature of the laser and hence the wavelength. This property can be used for frequency stabilization. The thermal coefficient is 0.06 nm/K and the current coefficient is 0.003 nm/mA corresponding to 300 MHz/K and 15 MHz/mA respectively. Frequency stabilization to better than 1 MHz requires temperature stabilization in the millikelvin range and current stability to better than 0.05 mA. It has been shown previously [55] for this particular DFB laser that the observed linewidth of a few MHz is not due to a single cavity resonance, but in fact consists of a lot of fluctuating resonances of about 300 kHz in width, which persist typically for times of about 0.5 μs and together provide a time-averaged envelope. The jumps are thought to be due to inhomogeneities in charge carrier density caused by spatial hole burning and leading to changes in the preferred mode. In our case this envelope was measured with a beat experiment and found to be around 6 MHz, comparable to the natural linewidth of the Rb transition.

We designed a temperature-stable mount with temperature regulation via Peltier
3.1. LASER SYSTEMS

Figure 3.3: DFB locking set-up employing polarization spectroscopy to produce a difference signal on photodiode Pd1 and Pd2 which are used to lock the laser.

elements (based largely on the mount for the tapered amplifier discussed in the next section). We then set up a DC polarization Zeeman spectroscopy configuration (see Fig. 3.3). Linear polarized light is sent through a Rb saturation spectroscopy cell which has a coil of manganine heating wire wrapped around it. Another coil is used to create a static magnetic field of some 4 G which separates the Zeeman sublevels for $\sigma^+$ and $\sigma^-$ polarized light, shifting them in opposite directions. A second beam (split off from the first) is reflected back through the cell as a probe beam, allowing detection of a doppler-free saturated absorption spectrum. A combination of quarter waveplate and polarization cube allows us to direct $\sigma^+$ and $\sigma^-$ polarized light components onto separate photodiodes. These are then electronically subtracted to create a dispersive signal used for locking. Feedback to the current supply of the DFB allows compensation of thermal drifts as well as suppression of the effects of electronic noise.

3.1.3 Tapered amplifier

The total laser power needed for laser cooling and trapping in this experiment is of the order of 120 mW after outcoupling from a polarization maintaining fiber. This increased requirement with respect to the previous use of bulk optics, could not be met by the DL100 (Toptica) alone and was only marginally fulfilled by other lasers used previously [44] so an optical amplifier was introduced to the set-up. The tapered amplifier (TA) operates much as a diode laser and can be similarly seeded with incoupled light. However, in the absence of seeding of light, the TA emits only amplified spontaneous emitted light, while suitable seeding leads to stimulated emission and up to 50 times amplification of the incoming beam. It also has a quite different geometry comprising an index-guided straight section and a gain-guided tapered section with AR coated facets at either end. In our experiments the tapered amplifier was variously seeded by a DFB or ECDL. The emission of these lasers can be amplified if the laser wavelength falls within the gain profile of the amplifier. The
seed laser is coupled into the narrow straight section. The amplified laser light is emitted at the facet of the tapered section. Since both sides have to be accessible and the electrical power input is of the order of 4.5 W (2.2.5 A and 1.8-2 V), mounting of the TA is not trivial. Some 1 W of this power is produced in the form of light when correctly seeded, so about 3.5 W is dissipated as heat. This heat load is considerable compared to standard diode lasers and requires careful design to prevent excessive heating of the diode or loss of alignment both on inject side and on the output side where the light is coupled into a single mode fibers.

Diode and Housing

The tapered amplifier diode used in these experiments was the EYP-TPA-0780-01000-3006-CM03-0000 (Eagleyard Photonics), supplied in a 2.75 mm C mount package and inspected under a microscope for defects upon in-take. To ensure stability of beam power and direction we developed a housing which could deal with the thermal load produced with minimal translation due to thermal expansion. The housing is made of aluminium and contains a copper cross-shaped block mounted on 4 springs and screwed in place with nylon screws to the aluminium housing (see Fig 3.4). This mounting block functions as a cooling plate temperature-stabilized by two Peltier elements (Eurcer Messtechnik GmbH TEC 1H-30-30-44/80-BS) as well as a beam direction stabilizer. The innovative spring mounted construction has the result that any differential thermal expansion in the mounting plate will cause to first order only a rotation and not a translation of the tapered amplifier. This holds for both facets of the TA, so not only is good coupling maintained with the seed beam, but the outgoing beam remains coupled to the optical fiber. In our design two small lenses (Thorlabs C230TME-B) are mounted in PEEK cylinders which can be screwed in and out for
3.1. LASER SYSTEMS

accurate semi-permanent positioning of the foci. To protect against overheating the diode, an interlock was included to shut down in the current controller if the diode temperature exceeds 40 °C.

Seeding and Alignment

Alignment of the seed laser is critical for stability and lifetime of the TA diode and this was a difficulty with commercially available self-seeded lasers. In these designs the spontaneously emitted light produced from the rear facet is reflected back into laser but limits seed power and complicates alignment. Both power and alignment are much more flexible with the introduction of a dedicated seed laser. Additionally the tapered amplifier then takes on the spectral properties of the seed laser, which can be tailored to be superior to the spontaneous emission spectrum of the TA diode itself.

The incoupling facet is only 3 × 3 μm in size which provides an obvious difficulty for introducing the seed beam. Alignment was done with current running through the diode. The TA then produces light from both facets. From the rear facet the beam of light produced is close to circular and can be collimated with a single lens. The 3 × 190 μm front facet produces a beam with differing divergences in the long and short directions. The power of the seed laser should be in the range from 10 mW to 50 mW. Exact focussing into the active region of the tapered amplifier is very important in order to achieve the maximum output power of the tapered amplifier. This difficulty is solved by focusing the incoming light onto this opening by use of a 4.5 mm focal length lens which is adjustable in position relative to the diode as described in the previous section. This alignment uses the light from the free running amplifier. By placing the lens at the position which collimates the emitted light, we simultaneously ensure that a collinear collimated incoming beam is properly focused at the depth of the opening.

Due to the tapered geometry of the chip, the outgoing light not only has a different divergence in the long and short direction of the front facet but also considerable astigmatism. The divergences were measured to be 10.5° and 26.2°, respectively. Our solution to the astigmatism was to first collimate the tapered direction (horizontal in our design) with a 4.5 mm focal length lens as with the incoupling facet and to then use a f = 60 mm cylindrical lens to collimate the non-tapered (vertical) direction. As shown in Fig. 3.5, we found collimated beam widths of 1.52 mm and 1.77 mm in the vertical and horizontal directions, respectively, for the lenses selected, the resultant aspect ratio of 1.18 gives a near round beam which helps coupling to an optical fiber.

This collimation must be carried out without an optical isolator after the TA and so is done at low light intensity (without seeding) to reduce the chance of damage from back reflection. Once the laser beam has been collimated, a 60 dB optical isolator is put in place as shown in Fig 3.1 after which the TA can be safely seeded and the intensity increased to full specification. We used a telescopic pair of lenses to
Figure 3.5: Collimation of the outgoing beam of the TA is achieved by placing a lens of focal length 4.51 mm in front of the diode collimating the beam in the horizontal direction and thereafter a cylindrical lens of focal length 60 mm collimating the vertical direction.

decrease the size of the beam to one suitable for in coupling to a fiber. The focused point between the lenses also serves as a convenient location to spatially filter the beam using a pinhole, or as a place to position a shutter for rapid switching of the beam.

Stability Tests and Results

The tapered amplifier was tested with a DFB laser as seed laser [50] which allowed the seed power to be easily varied. The light from the DFB laser was sent to the tapered amplifier via a fiber and a beam splitter was placed in the beam path to allow a pick-off so that the seed power could be monitored. With a seed power of 12.5 mW, it was found that ramping up the current from the power supply we could reach the specified maximum power of 1 W (Fig. 3.6). At an input current of 2 A, we measured 1 W directly from the tapered amplifier. Of this 1 W we found that 640 mW remained after passing through an optical isolator and 440 mW after spatial filtering through a 50 μm pinhole. After coupling into input A of our octopus fiber distributor (described in section 2.5) 30 mW was emitted from each of the six branches of the distributor. We thus had 180 W of usable spatially filtered light. While not particularly impressive from a starting power of 1 W directly from the tapered amplifier, this was comfortably more than our requirements and was considered a successful modification given the
resulting stability. This power was monitored along with the temperature at various parts of the housing. It was found that the temperature of the housing rose 4°C over a period of five hours before stabilizing. However, the effect on the power coupled out of the fiber after an initial settling period was slight (Fig. 3.7) and the power was stable to within 1% over longer periods of time. The $M^2$ value, a measure of beam quality, was measured to be 1.7, which is a quite good result in comparison with other possibilities for this power and wavelength.

3.1.4 Implementation and usages of stabilized lasers

Our ECDL master laser provides the majority of frequencies in our system with narrow linewidth stabilized power; 10 mW from an ECDL is amplified to up to 1 W of stable, narrow linewidth optical power using the Tapered Amplifier (TA 1) described above. This was used to provide light for cooling and trapping in the upper MOT throughout our experiments while two further tapered amplifiers (TA 2 and TA 3) were used to amplify the trapping light for the lower MOT and repumping light for the entire system. The DFB laser was used for repumping and optical pumping purposes.

3.2 Imaging

3.2.1 Integration with MOT optics

A set of anti-reflection coated glass doublet lenses corrected for spherical aberration, coma and astigmatism (Melles Griot 06LAC101) was placed close to the cell at focal length from the center of the central axis. MOT, optical pumping and imaging
beams all passed through these four lenses. This configuration is mapped in Fig. 2.9 and Fig. 3.8. The lens chosen has the diameter of the MOT beams (30 mm), a focal length of 100 mm and a numerical aperture of $\text{NA} = 0.15$ capturing as much of the solid angle as possible from an aberration free commercial lens of this diameter. This provided an advantage in terms of both space and resolution (see Section 3.2.2). The lenses are positioned one focal length away from the cloud so that the image can be relayed to the camera. MOT and imaging beams free expand from fiber heads which are located one focal length the opposite side of the lens so that they are collimated after passing through the lens. Imaging beams and MOT beams arrive orthogonally at a polarization cube and are combined before passing through the cell. Note that the imaging beam is linearly polarized. The resulting main imaging line along the axis of the trap is shown in Fig. 3.8. A similar line of imaging is situated perpendicular to the axis of the cloud. Although the MOT beams arrive on the beam splitting cube with opposite polarization to the imaging beams, ensuring that 99% of the light of the MOT beam intensity is not incident on the CCD chip, the remaining 1% is still enough to saturate the camera. The camera is thus shuttered directly in front of the microscope objective where the collected light is brought to a focus. With this configuration and very careful timing, the MOT can be absorption imaged after a very short time-of-flight.

Figure 3.7: Thermal properties of the TA found for a fixed current and seed power over a period of 5.5 hours. Note that while the housing reaches steady state 5 K above the initial temperature (dashed line), the copper plate is well regulated (dot-dashed line) and the diode changes temperature by less than 0.5 K (solid line.) The power loss due to these temperature changes is only a few percent and occurs mainly in the first minutes (black circles).
3.2. IMAGING

3.2. Resolution Tests

Introduction

As shown in Fig. 3.8, a pair of lenses between the cell and the CCD camera separated by the sum of the focal lengths of the lenses relay the image to the camera. The relaying telescope was the limiting factor in the optical resolution of the previous setup [39]. This telescope consisted of two high quality achromats of 100 mm and 200 mm focal length (Melles Griot 06LA011 and 01LAO189). At 780 nm these lenses provide a near-diffraction limited performance. Following the approach in [39], the optical system was assembled on a single rail away from the setup with a Ronchi ruling (USAF 1951). Later these rails were mounted on modular breadboards so that performance could be easily monitored after installation. To compare various imaging systems, we measure their resolution, i.e. the limit or minimum size of a feature which can be identified. Before introducing our findings it is expedient to consider the various definitions which are used to describe resolution values:

- The Sparrow criterion measures resolving power as the contrast cut-off distance, a logical definition since when the contrast between two features is zero they are no longer resolved (distinguishable). As soon as the contrast between
two feature is non-zero, they are considered to be resolvable. For a system of
optical elements however this excludes the effects of diffraction and for the case
of a lens more appropriate definitions consider the Airy disc, the ring-shaped
diffraction pattern which occurs when light from a lens interferes.

- The Rayleigh criterion requires that the first minimum (zero crossing) of the
  Airy disk of a feature is aligned with the central maximum of the Airy disk of
  an adjacent feature for two features to be considered just resolved. Extending
  this idea to an optical source which can be considered as a point light source,
  the point spread function is considered - two point sources are regarded as just
  resolved when the principal diffraction maximum of one image coincides with
  the first minimum of the other. Finding sub-resolution radiating sources or
  Airy maxima is problematic so for practical purposes a contrast value of 26.4%
  is considered necessary to satisfy this condition.

- The $1/e^2$ width is commonly considered for Gaussian optics such as that of laser
  beams. This is the distance where the intensity falls to $1/e^2$ times the maximum
  value, thus a minimum contrast of 13.5\% is necessary. This measurement is
  thus a weaker condition than Raleigh’s criterion and hence will give a smaller
diffraction-limited spot size or linewidth.

In this work we will use the more conservative Raleigh criterion which for an ideal
lens gives the resolution as

$$\Delta L = 1.22(\lambda/D),$$  \hspace{1cm} (3.1)

where $f$ and $D$ are the focal length and diameter of the lens and $\lambda$ the wavelength
of the incident light. In general, Sparrow’s resolution limit is about half the length
of Rayleigh’s resolution limit.

Tests
The resolving power of a set of Melles Griot microscope objectives was tested by
imaging a USAF resolution plate backlit with 780 nm laser light via a microscope
objective onto the CCD camera described in Section 3.3.2. The contrast between
the sets of vertical and horizontal bars is measured and compared to the Rayleigh
criterion. The notation for the smallest resolvable feature is read from an accompa-
nying table showing the cycles/mm value for each set of lines. The $\times 2.5$ microscope
objective (m.o.) was found to resolve features from 16 \(\mu\)m. The $\times 4.0$ m.o. resolves
from 10 \(\mu\)m and the $\times 6.3$ m.o. resolves from 6 \(\mu\)m. The $\times 10$ Olympus microscope
objective resolves to better than 4 \(\mu\)m, the smallest feature size available on the
resolution plate. These results are shown in Fig. 3.9.

Two lens telescop ic systems were tested using the same method. With the $1\times$
transfer telescope (i.e. two 06LAB011 lenses), a resolution of 16 \(\mu\)m was measured.
Testing the $2\times$ telescope (Melles Griot 06LAB011 and 01LAO189), the resolution was
3.2. IMAGING

Figure 3.9: Imaging of USAF gratings using microscope objectives of magnification \times 10 (left), \times 4 (top right) and \times 6.3 (bottom right). Note that on the left all sets of lines are resolved, top right the 4th smallest and bottom right the 3rd smallest lines are just resolvable.

found to be 12 \ \mu m, so it appears that the resolution of the 2\times telescope is superior. However when we combine the lens system with a microscope objective we get the opposite result: as low as 5.5 \ \mu m for the 1\times telescope, but no better than 8.8 \ \mu m for the 2\times telescope.

Resolution of a lens system

The results indicate that the magnifying power of the lens system is important and also that we cannot ignore a key property of the camera used to measure; the pixel size \( r_{\text{pixel}} = 15 \ \mu m \). These two effects combine so that when measuring with magnification \( M \), an area of width \( \Delta x_{\text{pixel}} = r_{\text{pixel}}/M \) is imaged on each pixel. When resolution measurements are taken in this manner what is measured is in fact a convolution of this effective pixel size with the actual resolution limit of the lens. Thus for a single lens of resolution \( \Delta x_1 \) we approximate the measured resolution by

\[
\Delta x_{\text{meas}} \approx \sqrt{\Delta x_1^2 + \Delta x_{\text{pixel}}^2}. \quad (3.2)
\]

For a telescopic lens system consisting of two lenses of resolution \( \Delta x_1 \) and \( \Delta x_2 \), the total resolution of the system is obtained from a convolution of the point spread function of each lens and can be approximated by

\[
\Delta x_t \approx \sqrt{\Delta x_1^2 + \Delta x_2^2}. \quad (3.3)
\]
CHAPTER 3. LASERS AND IMAGING

Table 3.1: Resolution achievable with a system of two lenses for two 100mm lenses and a 100mm, 200mm pair. Each system was tested without additional microscope objective (m.o), with a x10 olympus m.o and with an intermediate m.o. Tabulated are the respective net magnifications, effective pixel size, diffraction limited resolution (dlr) as calculated with the Rayleigh condition as well as the actual measured resolution using a Ronchi grating and the resolution of the telescope implied by this measurement.

<table>
<thead>
<tr>
<th>optical system</th>
<th>calculated</th>
<th>measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>telescope</td>
<td>lenses</td>
<td>Δx\text{pixel}, ΔL</td>
</tr>
<tr>
<td>1× 100, 100 mm</td>
<td>2.4 μm</td>
<td>5.1 μm</td>
</tr>
<tr>
<td>with ×6.3 m.o</td>
<td>1.35 μm</td>
<td>4.7 μm</td>
</tr>
<tr>
<td>2× 100, 200 mm</td>
<td>7.5 μm</td>
<td>10.4 μm</td>
</tr>
<tr>
<td>with ×4.0 m.o</td>
<td>1.875 μm</td>
<td>7.3 μm</td>
</tr>
<tr>
<td>with ×10 m.o</td>
<td>0.75 μm</td>
<td>7.2 μm</td>
</tr>
</tbody>
</table>

Applying Eq. (3.2), we can estimate the measured resolution of the system as

\[ \Delta x\text{meas} \approx \sqrt{\Delta x^2 + \Delta x^2 \text{pixel}} = \sqrt{\Delta x^2 + \Delta x^2 + \Delta x^2 \text{pixel}}. \]  

(3.4)

To understand the results, experimental values for the resolution measurements found with Eq. (3.4) are compared with those calculated with the Rayleigh ideal lens formula Eq. (3.1). Substituting wavelength \( \lambda = 780 \text{ nm} \) and a lens diameter \( D = 30 \text{ mm} \), for the lens of focal length \( f = 100 \text{ mm} \), an estimated diffraction limited resolution of \( \Delta L = 3.2 \mu m \) is found. For focal length \( f = 200 \text{ mm} \), this value is \( \Delta L = 6.4 \mu m \). Combining each lens with a second lens of focal length \( f = 100 \text{ mm} \) we get diffraction limits of \( \Delta L = 4.5 \mu m \) and \( \Delta L = 7.2 \mu m \) for the 1× and 2× telescopes respectively. As Table 3.1 shows, we do not quite reach the estimated diffraction limited imaging. However the results are consistent, differing for each lens set on the scale of the 12% difference between successive elements of the test target, our effective measuring error level. The table clearly shows the advantage of the pair of 100 mm focal length lenses as the relaying telescope, used for all subsequent experiments.

3.2.3 Image blurring by the atoms

In the above tests resolution is measured by imaging the light blocked (absorbed) by the dark lines. In experiments with BECs however the incident resonant light on atoms will cause photons to be absorbed and some of the photon energy eventually turned into additional atomic kinetic energy; i.e., our measurement moves the atoms
3.3. ANALYSIS OF IMAGING NOISE

whose position we are trying to measure. We can calculate the blurring effect from the imaging photons to the atoms by considering the re-emission of this energy as a velocity kick in a random direction. This velocity is known as the recoil velocity and can be expressed as

\[ v_r = \frac{\hbar k}{m} \]  (3.5)

The net effect of these velocity kicks is an uncertainty in the release velocity of the atoms and hence a blurring in the effective pre-release position of the atoms within the cloud. Following the analysis in [56] we take the following measure for the mean blur of a cloud in a given direction:

\[ X_{\text{rms}} = \sqrt{\frac{N_p}{3} v_r \partial t} \]  (3.6)

where \( N_p \) is the number of absorbed photons per atom and \( \partial t \) is the length of the exposure.

Substituting typical values from our experiments in Eq. (3.5) using the shortest exposures that we typically make, we get a value of \( v_{\text{rec}} = 5.9 \text{ mm/s} \) for \(^{87}\text{Rb} \) atoms. Expressing \( N_p \) in terms of \( P \) the power density (mW/cm\(^2\)) of the incident light, \( E_p = \hbar c/\lambda \) the energy per photon and \( \sigma = 3\lambda^2/2\pi \) the absorption cross section of the atoms, with an exposure time of 40 \( \mu \text{s} \) the effect of blurring on resolution is 3 \( \mu \text{m} \).

3.2.4 Conclusions

Lens quality being equal, best resolution is achieved with the lens combination with the highest NA, so for the same diameter and lens quality \( f = 100 \text{ mm} \) is preferable to \( f = 200 \text{ mm} \). In particular with high magnification, camera pixel size becomes less important and lens quality and NA will dominate. The choice of \( f = 100 \text{ mm} \) also allows us to have a compact and modularized design. Blurring due to recoil velocities is minimized with short exposures. A recoil velocity with our parameters of 5.9 mm/s is low compared to lighter atoms, nonetheless it is a potential limitation on resolution causing a blurring of some 3 \( \mu \text{m} \). Combined with the lenses selected it will be possible to resolve features in atomic clouds above \( \sqrt{3^2 + 5.3^2} = 6.2 \mu \text{m} \) in diameter along or perpendicular to the long axis of the cloud.

3.3 Analysis of Imaging Noise

The information used to analyze sample cloud properties in the experiments of Chapters 4 and 5 is provided by absorption imaging, the standard method to detect and measure a BEC. A resonant or near-resonant laser beam is passed through an atomic cloud with the absorption shadow imaged onto a CCD camera. There, the transmission profile is measured and the amount of light absorbed by the atoms can be
determined. The 2D distribution of the transmission profile can be related to the 3D distribution of the cloud by considering the absorption of light by atoms along the direction of propagation of the light as a column density at each point on the CCD. To exclude external influences on the profile of the light, a dark background image is subtracted and the profile normalized to an image of the beam’s transmission without the atomic cloud present. The log of this normalized transmission profile at any point is known as the optical density (OD) and this can be related to the atomic density distribution $n$ of the cloud by the following relation

$$\text{OD}(x, y) = \sigma \int n(x, y, z) \, dz$$  \hspace{1cm} (3.7)$$

where $\sigma$ is the scattering cross-section of the light and $z$ the direction of propagation of the light [56]. The total number atoms is then calculated by summing over the profile of the cloud. The scattering cross section $\sigma$ depends on the detuning from resonance of the imaging light, the wavelength $\lambda$ and the Clebsch-Gordan coefficient of the transition. Estimating the latter when spin states are not well-defined is a source of uncertainty in determining an atom number from absorption imaging. This uncertainty can be reduced by ensuring a spin-polarized sample and imaging with circularly polarized light ($\sigma^+$) and a well-defined magnetic field along the direction of imaging. The other source of uncertainty can be the precise detuning from the resonance, so frequency stability of the lasers is also essential.

Absorption imaging is most often employed in concert with time-of-flight (TOF). In this method the cloud is not imaged in the trap but after a given time after release from the trap. The cloud will then expand (ballistically for a thermal cloud) as each atom carries on with its velocity at the time of release. This expansion is measured as a function of time $T_{\text{TOF}}$. Assuming a Gaussian atomic density distribution and temperature $T$ the cloud width $w$ will evolve as

$$w(T_{\text{TOF}}) = \sqrt{w(0) + \frac{k_B T}{m} T_{\text{TOF}}}.$$  \hspace{1cm} (3.8)$$

To make an absorption image, at least three separate exposures are necessary. Firstly, exposure (A) is made with the cloud in the beam path. The profile of the laser beam on the CCD chip will then show a drop of intensity where light is absorbed by the atoms. With minimum delay a second flat field exposure (B) is taken with the same laser beam and beam path but without the cloud so that the profile of the light beam without the absorption from the atoms is reproduced as faithfully as possible. A third exposure (C) is taken to record the dark background without atomic cloud and without detection beam. The normalized difference is then calculated pixel-by-pixel, creating an $n \times m$ array

$$D = D_{ij} = \left\{ \frac{(A_{ij} - C_{ij})}{(B_{ij} - C_{ij})} \right\}, 1 \leq i \leq n, 1 \leq j \leq m$$  \hspace{1cm} (3.9)$$
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Figure 3.10: Noise measurements without a cloud: pixelwise division of images $A - C$ and $B - C$ (the background image $C$ is not shown) produce a resultant image $D$. Note that these images taken under identical conditions 1 s apart still leave residual concentric rings even after division.

where $X_{ij} \in \{A_{ij}, B_{ij}, C_{ij}\}$ is the pixel count of the pixel in the $i$th row, $j$th column and $n, m$ the number of pixel rows and columns. Accurately determining the atomic density distribution requires good reproducibility of imaging conditions and a low noise level on the images. Noise can come from the method of detection of the photons or from time-dependent disturbances of the wavefront at any of the optical elements in the optical path to the camera. Such disturbances give rise to interference fringes which are fluctuating in time for instance as a result of acoustic noise. Our aim will be to determine the theoretical limits of our imaging system imposed by the detection method and to minimize sources of noise.

3.3.1 Method

Since our cloud exposures are normalized to a flat field exposure, we will follow the same process of normalization in the analysis of the noise. In order to simplify matters, we will consider calibrated exposures in the absence of a cloud (see Fig. 3.10). To estimate the effect of multiple exposures at the same pixel, we measure the noise by considering a sub-array $M$ of the array $D$ of all pixel positions on the CCD chip. We choose $M = \{D_{ij} \mid x_1 \leq i \leq x_2, y_1 \leq j \leq y_2\}$ where $(x_1, y_1)$ and $(x_2, y_2)$ are pixel coordinates such that $M$ defines a square area of adjacent pixels where all pixels can be assumed to give identical response, avoiding any known bad pixels of the CCD chip. For a flat light field the average value over this sub-array should be 1. The variation in normalized pixel count can thus be measured by calculating the standard deviation

$$
\sigma(M) = \sqrt{\sum_{i,j \in M} (D_{ij} - \bar{D}_{ij})^2}.
$$

The value $\sigma(M)$ can be considered to be a good approximation for the variation over multiple exposures on a single pixel. It is thus a good measure of the noise ratio $\Delta N/N$ (standard deviation/mean) on processed images, which is the inverse of the commonly used signal to noise ratio (SNR). The quality of our imaging can be
improved by quantifying and achieving a reduction of the relative noise.

There are three limiting factors to achieving a low noise ratio for a given optical detection system: these are read-out noise, dark noise and photon noise. The first two are related to properties of the camera. Read-out noise is the noise introduced during the process of quantifying the electronic charge on the pixels. This noise originates from the on-chip preamplifier and analogue-to-digital conversion. Dark noise is due to the statistical variation of thermally generated charge on the pixels. Cooling the camera CCD from room temperature to $-25 \, ^\circ C$ reduces dark noise by a factor of 100.

The third and most important limiting factor is photon shot noise. The photon flux per pixel obeys poissonian statistics, which means that the pixel charge grows proportional to the number of photons while the photon shot noise increases with the square-root of the number of photons incident on a pixel. This means that in relative terms the shot noise becomes less significant for higher intensity. Taking these limiting contributions to the noise for a given exposure and detection system together, the best achievable noise ratio $\Delta N_0/\tilde{N}$ for our camera can be expressed as

$$\frac{\Delta N_0}{\tilde{N}} = \sqrt{\frac{\alpha \text{QE} \dot{N}_s + \dot{N}_d}{\alpha \text{QE} \dot{N}_d t + N_r^2}}$$

(3.11)

where $\dot{N}_s$ is the photon flux (photons/pixel/second), $\alpha \text{QE}$ is the quantum efficiency of the camera, and $t$ is the integration time (second); $\dot{N}_d$ (electrons/pixel/second) is the rate of increase of the dark count with time and is heavily temperature dependent. The read noise, $N_r$ (electrons/pixel) is independent of both photon flux and exposure time.

In the following tests, the integration time $t$ will be fixed and only the photon flux $\dot{N}_s$ will be varied so that $\Delta N_0/\tilde{N} \equiv \Delta N_0(\dot{N}_s)/\tilde{N}(\dot{N}_s)$. We will measure the constants $\dot{N}_d$, $N_r$ and $\alpha \text{QE}$ and so establish the lowest noise ratio which can be reached.

Eq. (3.11) gives the noise on a single image such as $A, B, C$ as described above and as such is arguably not directly applicable to the situation of the normalized array $D$, where multiple contributions from each of these noise sources should be included for a full error analysis. It nonetheless gives a good lower bound for the reproducibility of an exposure and is thus used to compare to measurement of the $D$ matrices with the method described above.

### 3.3.2 Camera

The camera used to produce the images is the TE/CCD-512EFT (Princeton Instruments) which functions in either a frame transfer or kinetics mode chosen by way of a switch. The CCD-chip type is EEV 512x512 FMTR and can operate as low as $-70 \, ^\circ C$ using a thermoelectric cooler. The chip has a full size of $7.7 \times 15.4 \, mm$ with 512 $\times$ 1024 pixels of size $15 \, \mu m \times 15 \, \mu m$. Half of the chip is shielded from incident light by a mask, so only a maximal surface of $7.7 \times 7.7 \, mm$ can be illuminated, i.e.
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an area of 512 × 512 pixels. The read-out procedure involves two steps. First the image information stored in the lower half is shifted under the mask. Then the actual read-out is done line-by-line. This procedure is chosen because the shift is fast (0.2 μs/line) and the read-out is slow (15 μs/line). In this way, exposure to light during read-out is minimized.

In the read procedure, the information is then processed by the camera controller ST-138 which has two modes of Analogue-to-Digital Conversion (ADC): 12 bit and 16 bit registers. These registers are full at $2^{12}$ and $2^{16}$ counts respectively, so the 16 bit can give greater accuracy but the 12 bit has the advantage of greater speed. To test the readout of the ADCs and also estimate dark noise, background images (no light on camera) were taken. With the 12 bit ADC a background count of 307(1) counts/pixel is found per exposure. The 16 bit ADC gives an offset of 230(1) counts/pixel per exposure. The background contribution can thus be subtracted from our images to an RMS accuracy of about 1 count/pixel which gives the read noise contribution for a divided image. This translates to $N_r \approx 20 \text{ electrons/pixel}$ using the calibrations in Section 3.3.2. These measurements were made with exposures of 40 μs, typical for measurements. Taking progressively longer exposures we can measure the dark count $N_d$. This value is found to be 10 electrons/pixel/second with a camera cooled to −40 C and for the 40 μs exposures a negligible contribution to the noise.

As in many cooled cameras, the fan of the thermoelectric cooler is a source of vibration, which affects the light field reproducibility and shows up as noise at the pixel level. This is removable by switching off the fan when imaging.

Controls

The camera software, WinView32 (Roper Scientific) works in concert with a Labview (National Instruments) visual interface. This works differently in frame transfer and kinetics mode and since both modes will be used in the experiments and tests, a brief description of the differences are given here.

For most of the tests we use the frame transfer mode. The camera is activated via WinView by means of an active-X command. This initiates a constant cleaning mode. Subsequently, a TTL-high pulse of maximum duration 0.5 ms starts exposure for a time specified in the WinView software, after which the exposed half of the chip (512 × 512 pixels) is read-out. The time to shift one line is 0.2 μs, the time to shift one line into the register is 15 μs and this is then followed by the digitization time. Either 12 bit or 16 bit may be selected under ADC conversion. The time to digitize one pixel is 0.9 μs for 12 bit and 10 μs for 16 bit. At 12 bit the overall frame capture cycle takes 0.6 s while for 16 bit this takes 2.7 s. A trigger pulse exceeding 0.5 ms results in read-out of the entire 1024 × 512 pixels, which includes the masked area.

In this case we acquire 4 images in 4 WinView frames. The timing of the first exposure was found to be unreliable. This is probably caused by differences in the termination of the cleaning cycle, the process by which accumulated charge on the
CCD before imaging is removed to begin measurements. Therefore, only the three subsequent exposures are used. The 2nd exposure is called the signal exposure \((A)\), the 3rd the flatfield \((B)\) exposure and the 4th the background exposure \((C)\). Only during the 2nd and 3rd exposure is the imaging beam on. Exposure during the shift stage of the read-out must be avoided.

The kinetics mode allows multiple shifts of a specified number of lines before read-out of the lower 512 lines of the chip as above. This allows multiple exposures at a repetition rate limited only by the shift time. To make use of this feature, the hardware set-up menu in WinView must have Kinetics mode selected as well as a number of lines \(n_k \leq 512\), required per exposure. In this mode the TTL pulse will finish the previous exposure of \(n_k\) lines and after the required shift time the next exposure will begin automatically. To avoid exposure beyond the selected \(n_k\) lines, an external mask must be put in place to block light to the rest of the chip.

Calibration and Quantum Efficiency

To calibrate the bit counts of the ADC to incident photon numbers, the CCD chip is exposed to laser beams of known intensity. The photons per pixel are then plotted against the counts recorded in the WinView software at both 12 bit and 16 bit ADC resolution. It should be noted that the count/photon ratio varies substantially with exposure time. For a fixed exposure time of 0.2 ms we find a good linear relation over a range of values. For 12 bit ADC we find 0.019 counts/photon (53 photons/count) and for 16 bit ADC: 0.063 counts/photon (16 photons/count). In 12 bit mode the ADC register is full at 4096 or \(2^12\) counts which corresponds to 20,000 photons/pixel. In 16 bit the ADC register would be full at 65536 or \(2^16\) counts but already at 20,000 counts the response becomes non-linear, reaching saturation at 30,000 counts (see Fig. 3.11).

This saturation effect gives a useful way to check the quantum efficiency of the camera. Each CCD-well is specified to collect up to 129,000 electrons. Thus in 16 bit, we can expect the electron well to saturate before the ADC register can be filled. The camera is specified with a quantum efficiency of 45\% at 780 nm, the wavelength of the imaging light. At high intensities, we can see the number of counts reach a saturation value of 340,000 photons/pixel. According to the specifications of the manufacturer, the end of the linear regime to corresponds to a full well (129,000 electrons). This gives a measured quantum efficiency of 38(2)\%.

\[
\alpha_{QE} = \frac{\text{electrons}}{\text{photons}} = \frac{\text{electrons in full well}}{\text{photons recorded at linear limit}} = \frac{129000}{340000} = 38(2)\%. \tag{3.12}
\]

Using this quantum efficiency we can compare the contributions from read noise and dark noise with that from photon noise using Eq. (3.11). For our camera, at \(-40^\circ C\), dark noise contribution is negligible, a factor of 1000 less than the read noise. For
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Figure 3.11: The Quantum Efficiency (QE) is found by measuring counts vs photons per pixel and noting the limit of the linear range which indicates a full electron well. Squares indicate measured values, solid line indicates a fit to the linear regime and the black ring shows the linear limit.

For low-light exposures the image quality is read noise limited. With an exposure time of 40 μs, the photon noise term in Eq. (3.11) becomes greater than the read noise for exposure intensities higher than 0.005 mW/cm². Thus, at the light intensities used in experiments with BEC clouds as described this thesis (0.1 mW/cm² - 1 mW/cm²), the image data is photon-limited and displays a near square-root relationship to the number of incident photons. The noise ratio $\frac{\Delta N}{\bar{N}}$ from the photon noise for a range of light intensities is plotted in Fig. 3.12 along with the camera limited noise ratio $\frac{\Delta \bar{N}}{\bar{N}}$ as calculated using Eq. (3.11). The measured noise in our experiments will be compared to these limits. The range 0.1 mW/cm² - 1 mW/cm² for a 40 μs exposure is also indicated in the figure as is the electron well depth.

3.3.3 Reducing the noise

The data points in Fig 3.12 show the results measured experimentally using the method mentioned in Section 3.3.1. Consecutive exposures of a calibrated collimated beam with a flat wavefront were imaged onto the Princeton Instruments TE/CCD-512EFT. The exposures were then processed using Eq. (3.9) to produce an image as in Fig 3.10. The standard deviation (sigma) inside the area of the light beam of the processed image is calculated and this number is the relative noise compared to unit average. Physical imperfections in the imaging optics produce undesired patterns in the images such as fringes. These patterns are minimized by the image processing procedure, but persist if the fringes move between exposures. It is thus essential to reduce time-dependent disturbances of the wavefront caused by vibrations. In practice this is done by minimizing the time between exposures. Further improvement can be made by image selection. This gives rise to a trade-off between image quality...
Figure 3.12: Plot of noise ratio versus signal on a log-log scale containing data points from three sets of measurements and systematic limits. The straight black line shows the photon shot noise $\Delta N/\bar{N}$ and the solid red curve shows the total limiting noise ratio $\Delta N_0/\bar{N}$ for the noise on a single image. The solid squares show noise measurements from images containing many fringes using the imaging system as received. The open circles show measurements with reduced noise following selection of optical elements. The crosses show the improvement of imaging quality to near poissonian-limited noise after selection of optical elements and after the replacement of the CCD window. The dashed vertical curves show 40 $\mu$s exposures representing 0.1 mW/cm² and 1 mW/cm², while the solid vertical line corresponds to the full electron well exposure (see Fig. 3.11).

and measurement time. In our case a discard rate of 40% was used, comparable to other authors [57].

Using the full imaging system as shown in Fig. 3.8 the measurement points taken with unselected optics in Fig 3.12 show a relative noise level $\Delta N = 0.08(1)$. This noise level is due to fringes which are not entirely divided out. Further improvement can be gained by taking a series of flat-field exposures and by post-processing the exposures are selected that best reproduce the fringes of exposure $A$ [58]. This results in a smaller discard rate but this was not employed here. Although the imaging processing results in a spectacular improvement in image quality as illustrated in Fig. 3.10, for best results it is important to eliminate - as good as possible - the sources of the wavefront distortions, for instance dust on the imaging optics or other blemishes. To trace such sources, one method is to rotate each optic to see if a feature moves and then cleaning the relevant optic. For inaccessible blemishes it is possible to identify the focal plane of the blemish and insert a pinhead to block the diffracted light. Dynamical sources of wavefront distortion such as dust in the air are minimized by enclosing the beam path. Using these methods we improve the relative noise for the highest exposure intensities from around to $\Delta N = 0.02$ for frame transfer and to $\Delta N = 0.015$ in kinetics mode (shorter time between exposures). This is illustrated by the points taken with selected optics (red circles) in Fig. 3.12. Note that the relative noise is essentially constant for intensities above 10,000 photons per pixel. As will be
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To test the camera, we made a reduced set up consisting of laser, single mode fiber, collimating lens and camera. Fig. 3.13 shows the images taken with and without a microscope objective in the left and middle panels, respectively. The left panel correspond to a diverging beam obtained by inserting the microscope objective used in imaging the gas clouds. The central panel is free of bull’s-eye shaped fringes but contains interference stripes both vertically and diagonally. The explanation was found with experiments varying the angle of the light incident to the chip as shown in Fig. 3.14. The CCD chip is a very reflective surface, and although the vacuum window is AR-coated, the incoming beam will interfere with the reflected beam from the chip. Depending on the angle, a larger or smaller fraction of the chip is exposed to the interference (see right panel of Fig. 3.13). By using a tilted

Figure 3.14: Slightly convergent collimated beams incident on the camera. Left: beams normal to ccd via original camera window results in circular interference pattern. Middle: beams at angle to original window result in interference pattern on part of ccd chip. Right: beams normal to ccd via angled camera window result in no interference on ccd.
camera window, the reflection between chip and window can be eliminated. For this purpose a camera window was custom made (LENS-optics) which could be fitted at 15° to the surface of the chip replacing the original. The results were essentially fringe-free images with and without microscope objective as in the right side of the right panel of Fig. 3.13. The best relative noise, $\Delta N = 0.003$, was observed with 16 bit ADC to accommodate exposures approaching 1 mW/cm$^2$. At this low noise the imaging becomes very susceptible to other disturbances in the optical path and the best results were obtained with a discard rate of 40%. Measuring under these conditions as a function of imaging intensity we obtain the results shown by the blue cross-shaped data points in Fig. 3.12, only slightly above the theoretical limit of shot noise, dark noise and read noise for a single exposure. The deviation from this limit may in part be attributed to our procedure of normalizing to a flat field exposure to produce an image as described in Section 3.3.1 resulting in an underestimate of the system noise limits where we consider only a single exposure.

3.3.4 Conclusion

In our experiments we demonstrated that we can approach the poissonian limit for the signal-to-noise of our images. In principle, this signal-to-noise ratio could even be improved by a factor of two by using a camera with a higher quantum efficiency. However these signal-to-noise ratios were only achieved on the test bench and could not be reproduced with the full imaging system including vacuum cell necessary to observe the gas clouds. With the latter a typical exposure is a factor of 3 worse than the camera limited noise. To achieve the poissonian limit on the full apparatus, extreme care is required in avoiding dust, in particular on the inside of the vacuum system, which means that mounting of vacuum components under cleanroom conditions seems indispensable. Also, in hindsight, combining the MOT optics with the imaging optics, results in more optical surfaces which can become contaminated or give rise to interferences and although essential for the measurements discussed in this thesis, this configuration is less favourable from a signal-to-noise point of view.