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Fabrication of a Micro-Cavity for high precision Sensing of a Levitated Nanosphere

Semester Thesis

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Abstract

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1 Introduction

For the purpose of sensing very tiny masses, charges, magnetic fields or weak forces, recent developments in optomechanics have brought forth resonators with very high Q-factors which are potentially capable doing such measurements. Limitation of such resonators are that they are susceptible to temperature fluctuations, dissipation losses as well as thermomechanical noise. To omit those kinds of problems a different kind of resonator can be used, a levitated nanoparticle in high vacuum [nphys2798.pdf]. Such a particle can achieve a very high Q-factor that is only limited by the collision with residual air molecules. In order for the levitated nanoparticle to act as a resonator with high Q-factor the influence of thermal noise has to be mitigated by using feedback cooling. It has been shown that a very promising way of measuring the required parameters for said feedback cooling is the placement of the nanoparticle in an optical cavity which couples out the light of the fundamental mode hereby allowing to very precisely determine the influence of the nanoparticle on the light.

The goal of this work is to further improve the feedback cooling mechanism by developing a feasible method to fabricate microcavities for the nanoparticle to be put inside of. The advantage of very small cavities compared to larger ones is that the nanoparticle takes up more space in a small cavity ultimately leading to a bigger change of the optical properties of the cavity. With this increased change we hope to optimize the feedback cooling mechanism by being able to determine the exact state of the particle inside of the cavity more accurately.

2 Theory

2.1 Laser trapping

2.2 Cavity particle detection

2.3 Figures of merit

2.3.1 Sensing factor

$$S \propto \frac{\mathcal{F}}{L} \tag{2.1}$$

2.3.2 Information retrieval rate

2.3.3 Detection efficiency

3 Fabrication

3.1 Requirements

The main aspect of this project was concerned with finding a process to successfully fabricate a microcavity of medium-high finesse. For this purpose it is necessary to investigate what requirements are given for this cavity to be useful for the trapping experiment it will eventually be used in.

3.1.1 Cavity Length

As discussed in subsection 2.3.1, the sensing factor is a quantity which determines how strong the presence of a glass particle influences the optical properties of the cavity. Equation 2.1 is inversely proportional to the length of the cavity which was explained through the fact that a smaller mode volume will cause the volume of the nano-scaled, dielectric object inside of the cavity to become larger in comparison to the mode volume. Another consideration that has to be made is that the cavity dimensions cannot be made arbitrarily small. The limiting factor in this consideration is not the cavity itself but rather the trapping beam which hits the particle inside the cavity perpendicular to the cavity axis as discussed in section 2.1. Making the cavity too small would result in the cavity mirrors clipping the trapping beam which would dramatically reduce its efficiency and cause scattering of energy into undesired modes.

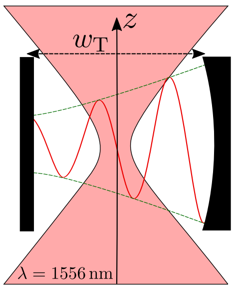

Figure 3.1: This figure shows the width of the trapping beam w_T which has to be taken into account when specifying the length of the cavity.

As discussed in section 2.1 the trapping beam can be approximated as a gaussian beam. This makes it easy to estimate what the value of w_T will be. We use the definition of the beam waist of a gaussian beam

$$w(z) = z\left[1 + \left(\frac{z_R}{z}\right)^2\right] \tag{3.1}$$

where z_{R} is the Rayleigh length. It is also important to note that $w_{\mathrm{T}} = 2 \cdot w(z)|_{z=z_{\mathrm{T}}}$ since $w(z)$ measures the beams radius and not its diameter. We can also determine z_{R} since it known that the beam width in the focus will be $d_0 = 2 \cdot w_0 \approx 0.5\mu$m.

$$z_{\mathrm{R}} = \frac{\pi w_0^2}{\lambda} \tag{3.2}$$

If the beam width in relation to the distance from the focus of the beam z is plotted we see the following picture.

Figure 3.2: The Figure shows the beam diameter $d(z) = 2 \cdot w(z)$ in relation to the distance of the beams focus.

4 Results

5 Summary and Outlook

The goal of this work was to design and build a narrow linewidth $\kappa < 2\pi \times 10\,\mathrm{kHz}$ optical cavity able to resolve the motional sidebands of an optically levitated nanosphere. Furthermore, the cavity resonance needed be stable enough to allow to lock a laser to the cavity in a stable manner.

During the design process, particular attention was put on obtaining a cavity with a stable resonance frequency, by minimizing the influence of environmental disturbances (in particular thermal and mechanical noise) to the cavity resonance. To this end, in the cavity construction, materials with low thermal expansion rates were employed and an active stabilization of the cavity temperature was implemented. Furthermore, a vibration isolation system as well as a vacuum setup were built.

A laser was successfully frequency locked to the cavity using the Pound-Drever-Hall locking technique. The laser was stabilized to the cavity resonance more precisely than κ and the lock remained stable against perturbations (knocking on the optic table, clapping), proving that the isolation of the cavity from environmental mechanical and acoustic noise was efficient enough. To this point it was not possible to quantitatively characterize the stability of the cavity resonance with respect to temperature fluctuations in the environment, i.e. determine the coefficient of thermal expansion of the mirror spacer. As soon as a stable (absolute) frequency source is available this value will become accessible. Being able to stabilize the laser to the cavity was a first step towards a frequency locked system consisting of microcavity, external cavity and optical field (Fig. **??**).

Finally, important parameters characterizing the cavity were determined. Among them, the cavity linewidth was found to be $\kappa \approx 2\pi \times 40.34(4)\,\mathrm{kHz}$, a larger value than the linewidth that was computed based on the mirror specifications. Consistently, the absorption in the cavity mirrors was measured to be higher ($\mathcal{A} \approx 122(6)$ ppm) than expected ($\mathcal{A} < 1$ ppm). Determining the reasons for the increased absorption $\mathcal{A}$ remains a task for the future.

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