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Towards passive and active laser stabilization using cavity-enhanced atomic interaction

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Abstract. Ultra stable frequency references such as the ones used in optical atomic clocks and for quantum metrology may be obtained by stabilizing a laser to an optical cavity that is stable over time. State-of-the-art frequency references are constructed in this way, but their stabilities are currently limited by thermally induced length fluctuations in the reference cavity. Several alternative approaches using the potential for frequency discriminating of highly forbidden narrow atomic transitions have been proposed in, e.g., [1] and [2]. In this proceeding we will present some of the ongoing experimental efforts derived from these proposals, to use cavity-enhanced interaction with atomic ^{88}Sr samples as a frequency reference for laser stabilization. Such systems can be realized using both passive and active approaches where either the atomic phase response is used as an error signal, or the narrow atomic transition itself is used as a source for a spectrally pure laser. Both approaches shows the promise of being able to compete with the current state of the art in stable lasers and have similar limitations on their ultimately achievable linewidths [1, 2].

1. Introduction

Quantum metrology and ultra-stable optical atomic clocks rely on the frequency stability of reference lasers [3, 4, 5]. These lasers have been demonstrated with linewidths down to tens of mHz [6], relying heavily on stabilization to ultra-stable reference cavities [7] whose fractional frequency stability is currently limited by the Brownian motion in the mirror substrates [8]. The possibility of using cavity-enhanced non-linear spectroscopy on narrow transition lines has been studied extensively over the years. In the context of laser stabilization recent experimental studies in [9, 10] have demonstrated the potential for a stability comparable to the state of the art. It has also been proposed to use the direct emission of radiation from atoms with narrow transition linewidths [2, 11]. Such radiation emitted directly from a narrow transition requires unrealistically large atomic samples due to the small decay rate, which renders it impractical for reference purposes. However, when operated as a laser in the bad cavity regime, not only can the emission rate be significantly increased, the laser linewidth can also experience a further spectral narrowing compared to the natural linewidth [2, 12, 13]. These effects arise if one considers the case of superradiant or superfluorescent emission of light. In this case the photon emission flux can be considerably increased by collective atomic decay, while simultaneously achieving a spectral narrowing of the emitted light inversely proportional to the single atom cooperativity [12, 13]. Pioneering advances have already been made in connection with proof-of-principle quasi-continuous superfluorescent systems [12, 14] using atoms loaded into an optical lattice at very low temperatures, as well as high temperature gas active laser systems [13, 15].

In this proceeding we will present recent experimental advances in both the passive and active approaches using ^{88}Sr. The passive approach follows [10] but uses an optimized system with an increased

cavity finesse. For improved noise characteristics of the measured signals we employ the heterodyne detection technique, NICE-OHMS [16]. Here the atom-cavity system acts as a passive frequency reference in the bad cavity regime, and we show recent results concerning the maximally obtainable phase-response.

Additionally, we report the observation of superfluorescent-like behaviour of an ensemble of thermal strontium atoms freely moving at temperatures of about 5 mK. The atoms have a strong collective coupling to a single cavity mode, significantly enhancing their collective cooperativity, and allowing them to emit a burst of photons into the cavity mode. In this approach the atoms act as the active part of the laser allowing enhanced emission intensity on a narrow atomic transition. This system may also be important for entanglement studies of atomic ensembles [17, 18] as it can move easily between interesting regimes.

Before delving into the specifics of the passive and active approach respectively we will characterize the experimental system under investigation, which is common to the two cases.

2. Cavity enhancement

Since both the passive and the active systems we are investigating here can operate on essentially the same cavity-enhanced system, this section is dedicated to the description of such a system and the physical parameters of it. In figure 1 a sketch of the atom-cavity system can be seen. It consist of an ensemble of ^{88}Sr atoms that are laser-cooled and trapped in a Magneto-Optical Trap (MOT) inside an optical cavity. The atomic transition of interest to us is the narrow $(5s^2)^1S_0 - (5s5p)^3P_1$ dipole transition at 689 nm. This transition is dipole-forbidden and has a natural linewidth of $\Gamma/2\pi = 7.5$ kHz making the requirements on the probing laser relatively relaxed, while simultaneously providing very promising results for the final laser stability. The cavity decay rate is given by $\kappa/2\pi = 539$ kHz and the free spectral range is $\Omega/2\pi = 781$ MHz resulting in a cavity finesse of $\mathcal{F} = 1450$. The coupling between the atom and the cavity field is characterized by the coupling parameter $g/2\pi = 815$ Hz. Here $g = d/\hbar \sqrt{\hbar\omega/2\epsilon_0 V_{\text{eff}}}$, where d is the transition dipole moment, ω is the transition frequency, ϵ_0 is the vacuum permittivity, and V_{eff} is the effective mode-volume of the cavity field.
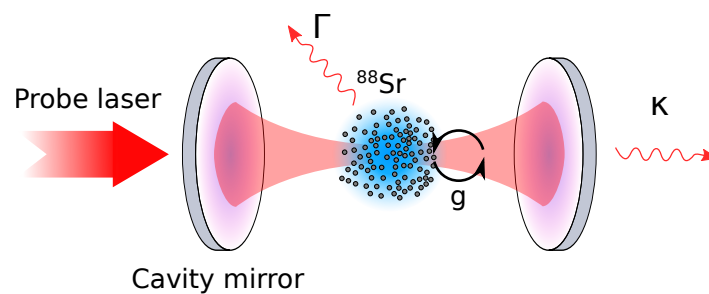
Figure 1. ^{88}Sr atoms are cooled and trapped inside a large-waist optical cavity. The atoms couple to the intra-cavity field with the coupling strength g. Cavity losses are given by the rate κ and the natural decay rate of the $(5s^2)^1S_0 - (5s5p)^3P_1$ atomic transition is given by Γ. During experiments the cooling light is switched off while cavity is kept in resonance with the probe light.

We wish to operate the system in the bad cavity regime, where the cavity linewidth κ is much larger than the natural linewidth of the atoms Γ. This ensures that the transition linewidth becomes decisive in terms of frequency discriminating properties and suppresses any line-pulling effects that may arise due to fluctuations in the cavity mirror positions. This bad-cavity limit is thus instrumental in obtaining the narrow laser linewidths we are targeting. The dynamics of the atom-cavity coupling in the system can be quantified by the single atom cooperativity $C_0 = 4g^2/\kappa\Gamma$ representing the cavity-field mediated interaction of an atom with itself, or the coherence buildup in the system relative to the coherence

decay. This quantity can also be expressed by geometrical considerations as $C_0 = \frac{6}{\pi^3}\mathcal{F}\lambda^2/w_0^2$ where λ is the cavity field wavelength on resonance with the atomic transition, and w_0 is the waist radius of the cavity mode intensity. Since we are considering large atomic samples the system dynamics may be represented by the collective cooperativity $C_N = C_0 N$ where the total number of atoms in the cavity mode is typically $N = 2 \cdot 10^7$. In the following experiments we investigate a regime where we have strong collective coupling $C_N\Gamma \gg \Gamma_{\text{decoherence}}$, but weak single-atom coupling $C_0\Gamma \ll \Gamma_{\text{decoherence}}$. By fulfilling these requirements we can simultaneously achieve large collective effects, and good suppression of cavity noise effects. Ideally then, we would want a high number of atoms N and a low cavity finesse $\mathcal{F}$.

Here the system behaviour is recorded by observing the field leaking out of the mirrors, with either a seeding field incident on the cavity, or by using a probe laser to record the absorption and phase response. The cavity length is controlled in order to ensure resonance conditions with the seed or probing laser at all times.

3. Passive approach

In a first approach to laser stabilization we will discuss passive stabilization which centers on the idea of having an external laser stabilized to a narrow frequency discriminator. This frequency discriminator should be able to provide a signal with high signal-to-noise ratio while simultaneously being very sensitive to any frequency-deviations. Here we follow [10] in using direct spectroscopy on the $(5s^2)^1S_0$ – $(5s5p)^3P_1$ transition in ^{88}Sr. The cavity enhances the effective interaction length with the atomic sample, by order of the finesse $\mathcal{F}$, while simultaneously increasing the saturation parameter by about a factor of 500. This places us deep in the saturated regime whose behaviour close to resonance was described in [10]. By sending in a probing laser and using the NICE-OHMS technique [16] we can record the phase-response of the system with good signal-to-noise ratio, see figure 2. We modulate the probing light in order to induce sidebands on the carrier frequency. These sidebands are used as reference in the heterodyne beating as they are far detuned from atomic resonance and do not interact with the atoms. They are separated by one free spectral range (FSR) of the cavity ensuring that they are transmitted through the cavity together with the carrier signal. A photodiode (PD) records the beat-signal, which is then demodulated using a mixer, thus producing the phase measurement. The antisymmetric phase-response acts as an error signal close to resonance where it has a linear dependence on the frequency detuning of the probing laser. In our case the probing laser is prestabilized to a linewidth of $\Gamma_{\text{probe}}/2\pi = 800$ Hz on the 100 μs timescale of a single measurements. By feeding the error signal obtained back to the laser it can thus be stabilized to the atom-cavity system. By ensuring that we are deep in the bad-cavity regime, the system resonance is primarily dictated by the atomic resonance, and all fluctuations on the cavity resonances are strongly suppressed.
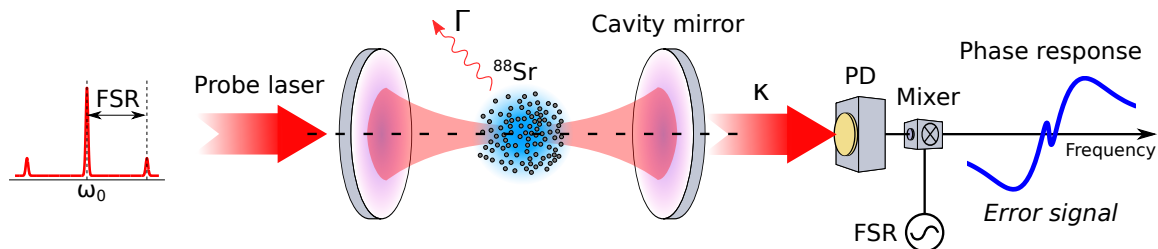
Figure 2. Sketch of a passive system where atoms inside the optical cavity are probed with an external laser having sidebands at ±FSR. The frequency sidebands are used for the NICE-OHMS technique, and the beat-signal recorded on a photodiode (PD) is then demodulated. The phase-response is recorded, producing an error signal that can be used to act back on the probing laser, correcting the probe laser frequency.

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The atoms are trapped using a MOT with an anti-Helmholtz coil configuration and six beams of $I = 1.5$ mW/cm^2 blue light, red-detuned by about 40 MHz from the strong $(5s^2)^1S_0 - (5s5p)^3P_1$ transition in strontium-88. We then map out the phase response of the system by first turning on the trap for up to 800 ms in order to accumulate atoms, which will then have a temperature of typically $T = 5$ mK. The atoms are then released by shutting off the trapping light, and a single measurement at a given probe detuning is recorded over 100 μs. Reiterating this procedure while varying the probe laser detuning then produces traces such as the ones shown in figure 3. A theoretical model from [10] using our experimental parameters is also plotted. The signal-to-noise ratio is currently limited by the shot-to-shot variations in the atom number N, as well as the stability of the cavity field intensity.

For low atom numbers we observe structures similar to what was shown in [10] where a higher atom number and a cavity with much lower finesse $\mathcal{F}_{low} = 85$ was used. As the number of atoms is increased to a similar level as used in [10], the phase shift induced by the atom-cavity system is effectively much larger due to the higher finesse, $\mathcal{F} = 1450$, of the cavity in the current system. This causes the total phase to increase beyond $\pi/2$ which is seen in the measurements as a mirroring around some maximal value. In figure 3 this can be seen for $N = 1 \cdot 10^7$ (shown in pink) at about ± 500 kHz, where two new peaks seem to have appeared. These features do not affect the slope at the center of the resonance feature which is decisive in order to provide a good error signal for laser feedback. This inversion for an absolute phase shift of π does, however, put a maximum bond on the amplitude of the error signal. As we require a significant output signal in order for a lock to not be limited by the photon shot noise on the detectors, simply increasing the finesse of these systems will thus not be an adequate solution.
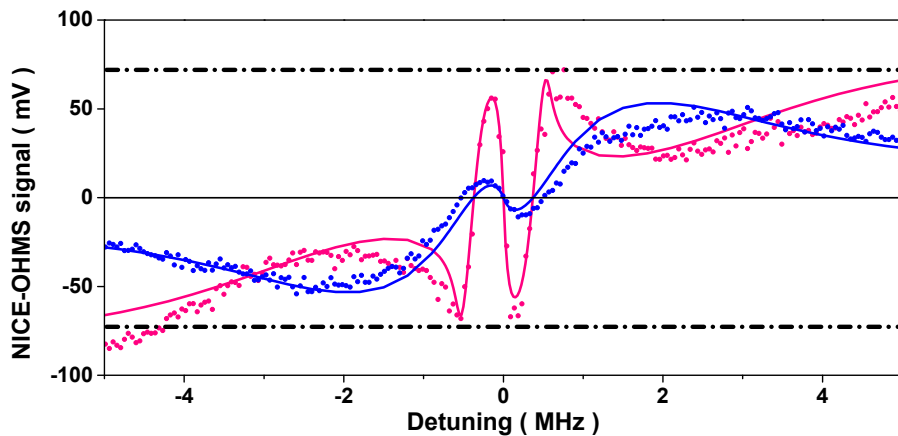
Figure 3. NICE-OHMS response of the passive system representing the phase for $N = 2 \cdot 10^6$ (blue) and $N = 1 \cdot 10^7$ (pink). Data is represented by dots whereas the full lines represents the theoretical model. For $N = 1 \cdot 10^7$ the phase shift becomes greater than $\pm\pi/2$ (corresponding to the black dot-dashed lines) at about ± 500 kHz resulting in a mirroring of the signal at about ± 70 mV. Both signals were recorded for $T = 7$ mK.

The shot noise limited linewidth of a laser perfectly locked to such a signal can be found following [1] and has been projected to be below 10 mHz [19] which is comparable with the state of the art in passive laser stabilization on empty optical cavities [6].

4. Active approach

Alternatively to a passively stabilized laser based on, e.g., a solid-state laser diode, the active approach seeks to use the narrow atomic transition directly as a lasing transition [2, 12, 14]. As an alternative to

having effectively stationary atoms in an optical lattice at μK temperatures, we consider here a simpler system with freely moving atoms at three orders of magnitude higher temperatures. The ultimate goal is to realize a so-called optical maser where collective effects can cause an ensemble of optical dipoles to synchronize and emit light of high spectral purity [20, 11] into the cavity mode. In a first generation of experiments pursuing these phenomena in our setup the atoms are pumped by an external source, say by applying a pi-pulse, and can coherently emit light into the cavity mode. This can happen spontaneously in a process known as superfluorescence, or by stimulation from a weak seed field inside the cavity mode. Although the introduction of a weak driving field is of less importance for the optical maser it has interesting applications for quantum optics schemes targeting entanglement of atomic ensembles. It turns out superradience or superfluorescence is not sufficient to guarantee entanglement, but the introduction of a weak seed field may generate entanglement of the atomic ensemble [17, 18].

The condition for collective effects to be important is that the collectively enhanced emission rate is much larger than any decoherences of the system $C_N\Gamma \gg \Gamma_{\text{decoherence}}$. In the system investigated here the atoms are at a temperature of T = 5 mK resulting in the Doppler broadening of $\Gamma_{\text{Doppler}}/2\pi$ = 1 MHz as the most important decoherence in the system. With the parameters given above we obtain a collective cooperativity of C_N = $1 \cdot 10^4$ thus fulfilling the condition for strong collective coupling in the system, $C_N\Gamma/2\pi$ = 75 MHz. As a preliminary approach we have resonant seed-light in the cavity mode ensuring that the cavity and atomic resonances overlap. We inject a resonant pi-pulse of light at an angle of 45° with respect to the cavity axis, see figure 4. The pulse causes ground-state atoms to be excited, and collectively emit a burst of light into the cavity mode stimulated by the seed light with a delay τ_{D}.
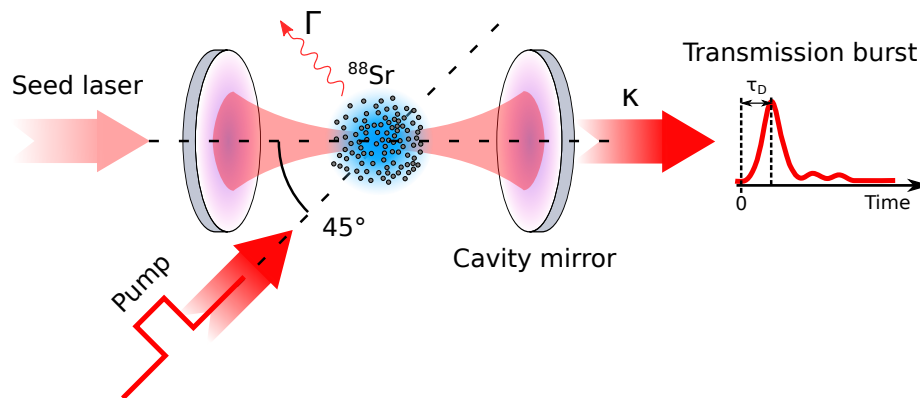

Figure 4. Sketch of an active system where ground state atoms are initially pumped into an excited state, and can subsequently be collectively stimulated to emit a burst of photons into the cavity mode after a time τ_{D}. The burst is observed on a photodetector through the field leaking out of the cavity.

The superfluorescent-like behaviour of the system with a seed-field in the cavity mode can be seen in figure 5 for a pump pulse of τ_π = 280 ns. The data was averaged over 128 data series, and retains its characteristic shape. The time τ_π corresponds to a 3π-pulse, and was chosen due to technical limitations. The delay of about τ_{D} = 1.5 μs is not limited by cavity leakage rate but attests the collective process that causes this emission of light. The decay rate of the burst can be seen to initially be far greater than the natural decay rate of the atomic transition, $1/\Gamma$ = 22 μs, and after the initial burst small oscillations in the field intensity, partially washed out by the averaging, can be observed. Both features are characteristic for collective effects taking place, and reveals some level of coherence. Notice that the oscillations following the primary burst sit on top of two slopes. The first one is clearly visible from 2 to 4 μs and is expected to be caused by the averaging process where shot-to-shot variations in the atom number and seed power wash out some of the oscillatory behaviour. The second one is that caused by some atoms spontaneously decaying with the natural decay rate, a characteristic time of $\tau = 1/\Gamma$ = 22 μs, and thus not participating

in the cooperative emission of light. This is attested by the fact that the final power in figure 5 is a few nW higher at 10 μs than the initial seed at -1 μs.

We have developed a theoretical description of the system allowing us to simulate the expected behaviour of the cavity transmission. This model relies on a Jaynes-Cummings approach with a classical pump-field and incorporates a constant thermal velocity distribution of the atoms. A simulation of the cavity transmitted field for typical parameters can be seen in figure 6, where a non-zero seed field is present in the cavity initially. The initial burst is seen to have similar behaviour and delay τ_{D} to the measured burst. It is followed by a series of oscillations that are much more pronounced than what we see experimentally. We expect that the great difference in these oscillations is caused by the spatial profile of our pump field which is narrower compared the spatial extend of the atomic cloud. This results in different Rabi frequencies for atoms at different positions and the effective population inversion obtained by the pump pulse is thus smaller in the experiment than what the simulation assumes.
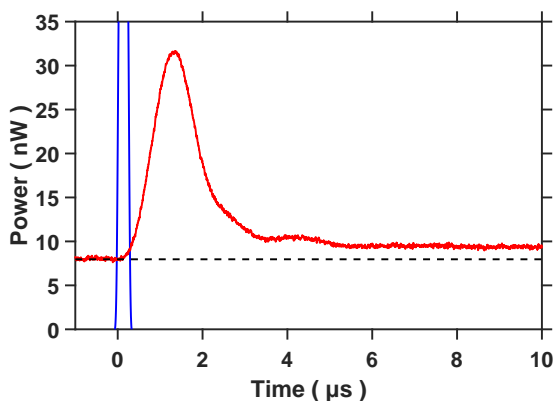
Figure 5. Recorded data of a light leaking out of the cavity (red) after a burst of light has been emitted by the atoms into the cavity mode. The initial pump-pulse (blue) is also shown. The initial decay rate of the flash is much faster than the natural decay rate Γ of the atomic transition. Though the signal is averaged over 128 data series, ringing effects are still visible. The non-zero start value is due to the seed field (dashed line) present in the cavity.
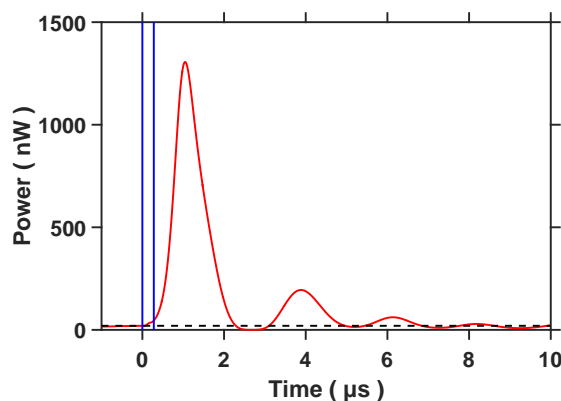
Figure 6. Simulation of a superfluorescent-like burst (red) following a 3π-pulse (blue). The initial decay of the pulse is much faster than the natural decay rate of the transition and is followed by coherent ringing characteristic for superfluorescence. Here no spatial effects of the system are included, resulting in a significant overestimation of the burst intensity. Notice that the initial value of the transmission curve is non-zero due to the seed field (dashed line).

The larger power predicted by the simulation is primarily caused by spatial dependences of the atoms and pump pulse in the system. When spatial distributions are included much better agreement between the predicted and experimentally observed power is expected. The detailed modelling of this will be the subject of future publications. The dynamical behaviour is quite similar and bodes well for a superfluorescent system with thermal atoms. By optimizing the spatial configurations of the setup, thus increased the number of participating atoms, and by better controlling some of the decoherence effects, we expect an improvement of the burst intensity by at least an order of magnitude may be obtained.

5. Conclusion

We have described our approach to and preliminary results from two of the novel methods that are currently receiving broad interest in the laser stabilization and quantum metrology communities. While these approaches rely on technically and experimentally very different approaches they have a great deal

in common when one considers the physical systems. Here we have presented the physical systems in a way that underline these similarities.

The passive approach boasts impressive predictions that should be comparable to and beyond the state of the art in laser stabilization technology. In the active approach, the emission line-narrowing effect expected by the single atom cooperativity can provide a laser with a linewidth much narrower than the natural linewidth of the lasing transition making superfluorescence in the bad cavity regime an interesting alternative approach towards an ultra narrow continuous laser source. The narrowing of the linewidth in the superfluorescent light means that such a device could significantly increase the stability and accuracy of reference lasers used in, say, optical atomic clocks.

Both techniques require a continuous system such as a beamline of ultra cold atoms in order to take full advantage of the potential for narrow laser linewidths. We are currently constructing such a beamline system in order to demonstrate both a continuous active laser as well as a passive continuously locked laser.

Acknowledgments

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