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Deep optical trap for cold alkaline-Earth atoms

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Abstract: We describe a setup for a deep optical dipole trap or lattice designed for holding atoms at temperatures of a few mK, such as alkaline-Earth atoms which have undergone only regular Doppler cooling. We use an external optical cavity to amplify 3.2 W from a commercial single-frequency laser at 532 nm to 523 W. Powers of a few kW, attainable with low-loss optics or higher input powers, allow larger trap volumes for improved atom transfer from magneto-optical traps. We analyze possibilities for cooling inside the deep trap, the induced Stark shifts for calcium, and a cancellation scheme for the intercombination clock transition using an auxiliary laser.

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1. Introduction

The study of cold atoms [1] led to many advances in our knowledge on atom physics and quantum optics. Today it is possible to precisely control and manipulate the internal and external states of atoms with laser light. Most laser cooling work has been performed with metal-alkaline atoms (such as Li, Na, K, Rb, or Cs), but it is also possible to cool and trap the alkaline-Earth atoms (such as Mg, Ca, Sr, or similar atoms such as Yb, Zn, Cd or Hg), which have been receiving increased attention due to their use in optical atomic clocks [2]. One feature of alkaline-Earth atoms is the lack of hyperfine structure for the most abundant bosonic isotopes. This simplifies both theory and experiment, and provides electronic transitions which are good approximations to actual two-level systems. The lack of hyperfine structure, on the other hand, prevents the use of well-known sub-Doppler cooling schemes [1], so that the lowest temperatures for these atoms is usually a few times the Doppler limit of their strong 1S_0 - 1P_1 resonant cooling transition (834 μ K for Ca, 2.2 mK for Mg). For heavier elements (Sr, Yb), the weak 1S_0 - 3P_1 intercombination transition has significant scattering rate, and can be used in a second stage of Doppler cooling [3]. For lighter elements (Ca, Mg), this does not happen and second stage cooling is considerably more difficult, requiring an additional laser to artificially increase the rate of this transition [4], [5].

In this context, it is worth to investigate the option of directly transferring atoms, previously trapped in a magneto-optical trap (MOT) [1] at a few mK, into a deep optical dipole trap or lattice. Among approaches that have been proposed to reach lower temperatures in alkaline-Earth atoms, we are interested in two options applied for calcium: a second stage of Doppler cooling in a MOT, using a three-level transition excited by two-photons [6], and resolved sideband cooling performed in a dipole trap [7] or optical lattice [8]. In this paper we propose and analyze a deep optical trap that uses a low-noise, single-frequency green laser at 532 nm, amplified in an external optical cavity. Such trap takes advantage of the commercial availability of single-frequency lasers at 532 nm with output powers up to 18 W. Optical dipole traps have been demonstrated for calcium [9], using an argon laser at 515 nm and a CO₂ laser at 10.6 μ m. Ref. [10] also demonstrates a trap for Lithium, produced by a single-frequency laser at 1064 nm amplified into an optical cavity to a few hundred Watts. Optical traps are essential in an all-optical route towards Bose-Einstein condensation, which for two-electron atoms has been obtained so far only for Ytterbium [11].

2. Theory

When atoms interact with light they experience a force that can be separated in two contributions: $\vec{F} = \vec{F}_{\text{spr}} + \vec{F}_{\text{dip}}$. The first term is the radiation pressure force, used for example to cool and trap atoms in a MOT. The second term is the dipole force, resulting from the interaction between the induced electric dipole momentum and the field. The dipole force depends on the light intensity gradient and can be used to trap atoms. The potential for a 1D-lattice obtained for a Gaussian beam in a stationary-wave is given by:

$$U(x, y, z) = -\frac{\alpha}{2} |E(x, y, z)|^2 = -\frac{4U_0}{1 + \left(\frac{z}{z_r}\right)^2} \exp\left[-\frac{2(x^2 + y^2)}{\omega(z)^2}\right] \cos^2 kz \quad (1)$$

The term $U_0 = \frac{1}{4\pi\epsilon_0} \frac{4\alpha}{c\omega_0^2} P$ represents the depth of a single focus dipole trap [7] (α is the ground state polarizability [12], P is the laser power, the waist size is

$\omega(z) = \omega_0[1+(z/z_r)^2]^{1/2}$ and the Rayleigh length is $z_r = \pi\omega_0^2 / \lambda$, where ω_0 (spot size) is the $1/e^2$ radius). In the case of 1D lattice the depth is four times bigger (hence the factor 4 in Eq. (1)). To obtain a deep potential it is necessary to either increase the laser power or decrease the waist. We have chosen to increase the power using an optical cavity, while keeping the trap volume as large as possible to maximize the atom transfer efficiency from a MOT. While a linear, stationary-wave cavity will produce a 1D lattice with a TEM₀₀ mode, a ring cavity with travelling waves will produce a deep optical dipole trap. The cavity enhancement factor G , defined as the ratio of the intracavity power P_C to the incident power P_I , is given by:

$$G = \frac{P_C}{P_I} = \frac{T}{1 - 2\sqrt{(1-T)(1-L)} + (1-T)(1-L)} \quad (2)$$

where T is the transmissivity of the input coupler (IC) mirror and L represents all losses in the cavity, excluding the transmission of the IC. For fixed losses L in the cavity, the optimum transmission of the input coupler mirror which maximizes G , is simply $T = L$ (impedance matching). This maximum G will be $1/L$. For example, a cavity loss of 1 %, matched by an IC with 1% transmissivity, will result in an enhancement factor of 100. Enhancements higher than 1000 can be achieved with commercially available low-loss optics.

When the temperature of the trapped atoms is much lower than the trap depth, the vibrational levels can be approximated by those of a harmonic oscillator. For a 1D lattice, these harmonic trap frequencies in the radial and axial directions are $\omega_{\text{rad}} = (16U_0/m\omega_0^2)^{1/2}$ and $\omega_{\text{axial}} = (8U_0k^2/m)^{1/2}$, respectively, where $k = 2\pi/\lambda$ and m is the atomic mass. For a dipole trap the frequencies are four times smaller. Residual scattering from a far detuned atomic transition can still be significant for a deep optical trap or lattice, leading to heating or atom loss. This scattering rate is given by [7]:

$$\Gamma_{sc} = \frac{3\pi c^2 I}{2\hbar \omega_{at}^3} \left(\frac{\omega_L}{\omega_{at}} \right)^3 \left(\frac{\Gamma}{\omega_{at} - \omega_L} + \frac{\Gamma}{\omega_{at} + \omega_L} \right)^2 \quad (3)$$

where ω_{at} and Γ are the transition frequency and linewidth, respectively, and ω_L and I are the laser frequency and intensity.

Potential depths, trap frequencies and residual scattering rates from the strong 1S_0 - 1P_1 cooling transition of calcium atoms at 423 nm, are given in table 1 for a 1D lattice produced by a laser at 532 nm, considering different values of waist sizes and intracavity power. We note that for intracavity powers above 1 kW, trap depths above 1 mK are produced for waist sizes of 100 μm . This should allow efficient transfer from a MOT to a lattice of alkaline-Earth atoms that have undergone only Doppler cooling with the resonant 1S_0 - 1P_1 transition. Figure 1 shows the level diagram of calcium. The strong 1S_0 - 1P_1 , 423-nm resonant transition ($\gamma/2\pi = 34$ MHz) is used for laser cooling. The 1S_0 - 3P_1 , 657-nm “clock” transition ($\gamma/2\pi \approx 400$ Hz) can also be used for cooling using “quenching” lasers at 453 nm [4] or 552 nm [5]. The 1P_1 - 1S_0 , 1034-nm transition can be used for “2-photon” cooling if driven in cascade with the 423-nm transition [6]. To improve the atoms transfer from a MOT to a deep trap/lattice, “quench” cooling with the 657-nm transition could be used, but for this purpose 2-photon cooling might be a simpler option, even though the expected final temperature is higher [6], [9].

An important parameter, especially for a deep optical trap or lattice, is the AC-Stark shift. It is of especial relevance for spectroscopy and clocks [12], [13], but will also affect the optimum detuning of any cooling laser. This shift, obtained by second order perturbation theory, can be expressed as [9]:

proper laser detuning by a few MHz. For a lattice, the atoms will be in a strong confinement regime, so that resolved sideband cooling can be achieved, e.g., when the trap frequencies are higher than the cooling transition linewidth. This happens for the axial direction, where trap frequencies of a few MHz (table 1) are higher than the linewidth of both the intercombination (~ 400 Hz) or the cascade transition used for 2-photon cooling (~ 5 MHz for ^{40}Ca). However, because the lattice potential is not harmonic, and the vibrational levels are not evenly spaced especially at higher energies, sideband cooling may require some controlled tuning (“chirping”) of the cooling laser wavelength. This is similar to initial experiments of atomic beam deceleration that used a chirped laser, when a “Zeeman slower” was not yet used to compensate for the Doppler shift of the atoms as they decelerated [1].

Finally we consider the possibility of Stark-free spectroscopy of the $^1\text{S}_0$ - $^3\text{P}_1$ intercombination “clock” transition of calcium in a deep potential. By working in a dipole trap or lattice at the “non-magical wavelength” of 532 nm, this cancellation could be done with an auxiliary laser. Ref. [15] investigates this option for improved loading of Rb in a deep trap. For a deep trap/lattice with mK depths, such laser also would need to have very high power. However, this cancellation by a second laser could be done after cooling to a few μK (by some of the above mentioned methods; see also [9]), which of course would allow reduction of the trap potential and Stark shifts. In Fig. 1 we show the AC-Stark shift of the $^1\text{S}_0$ and $^3\text{P}_1$ levels, associated with the intercombination transition, produced by a second laser in the presence of a weaker laser at 532 nm that produces a trap depth of 50 μK . The value indicated by the circle is the “magic wavelength” of a 613-nm laser with 1 Watt of power and waist size of 100 μm . For this wavelength, both $^1\text{S}_0$ and $^3\text{P}_1$ ($m=0, 1$) sublevels shift by the same amount (for the indicated laser polarizations, Fig. 1).

3. Experimental setup and results

To implement a deep 1D lattice, we have built a Fabry-Perot cavity (Fig. 2) formed by two concave mirrors (ROC = 30 cm). These are standard dielectric mirrors (coated at the optics shop of the Univ. of Sao Carlos - USP) separated by 40 cm, and placed outside the MOT chamber, whose optical viewports are also shown in Fig. 2. The input coupler (IC) transmits less than 1% at 532 nm. The other HR (high-reflecting) mirror reflects 99.6 % at 532 nm, and is mounted on a piezo stack for tuning the cavity resonance and locking it to the laser. For locking, we have used the Pound-Drever-Hall (PDH) scheme [16]. The cavity produced a waist size of 100 μm at its center. The mode-matching efficiency into the TEM_{00} mode of the cavity was optimized and measured to be better than 97 %. This cavity amplified light from a 5.5 W single-frequency laser at 532 nm (Coherent Verdi). We have verified that the free-running stability of the laser is very good, allowing stable lock of the cavity for long times. For stabilization of the optical lattice position, active stabilization of the laser path should be easily implemented with an external mirror (not shown in Fig.1). We also verified that the laser intensity noise is limited by the shot noise level, particularly at twice the axial trap frequencies given in Table 1. At lower frequencies, where laser intensity noise is usually higher, we have also not observed discrete spectral features near twice the radial trap frequencies. Parametric heating of the atoms is therefore not expected to be a problem.

Figure 2 also shows the intracavity power, measured without the viewports, as function of input power. This is deduced from the cavity power enhancement, measured by the ratio of the power transmitted through the second mirror, with and without the input coupler. The inset shows the cavity resonance, with frequency modulation sidebands (12 MHz), and the PDH error signal. Although the laser output power is 5.5 Watt, the cavity input power has been limited to 3.2 Watt due to losses in the optical setup. A power enhancement factor of 150 has been obtained, so that for 3.2 Watt of input power we reach 523 Watts, leading to a potential depth of 0.8 mK, which is near the calcium Doppler limit. Intracavity powers of a few kW, corresponding to enhancements of several hundreds, should be achieved with commercially available low-loss coatings for the mirrors and viewports.

The residual scattering rate (table 1) by the far-off-resonance 1S_0 - 1P_1 calcium transition (423-nm), detuned by 109 nm from the 532 nm trap laser, represents a negligible loss of only 3.8×10^{-20} for the 532-nm photons inside the cavity. Therefore it does not affect at all the cavity power enhancement. Also, in the high power regime of a deep trap/lattice, atom loss due to photoionization can be of concern. However, for calcium, we have verified that a laser at 532 nm is not near resonance with any level and the probability for direct ionization is negligible. In addition, we have made a test by sending 5.5 Watt at 532 nm into a calcium hollow-cathode lamp. Photonionization could be detected in this lamp with very high sensitivity via the optogalvanic detection, which is a change in the discharge impedance [17]. With this method, we have not observed any indication of photoionization.

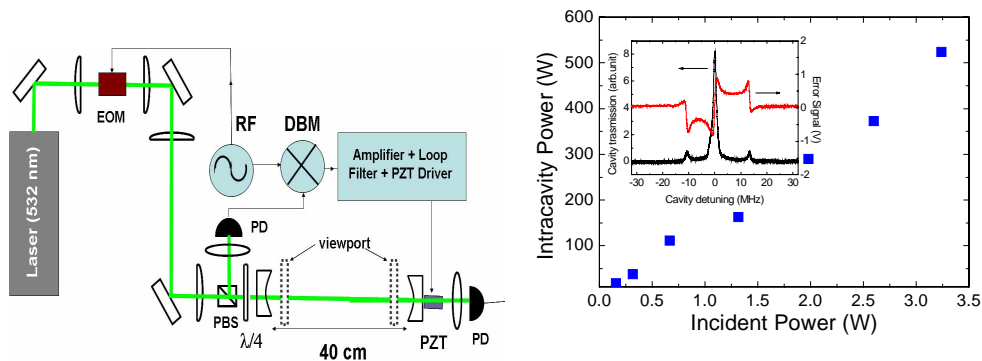


Fig. 2. Left: Schematic diagram of the Fabry-Perot cavity for a deep 532-nm lattice. The cavity is locked to the laser by the Pound-Drever-Hall technique [16]. EOM: electro-optical modulator (resonant at 12 MHz); PD: photodetector, PBS: polarizing beamsplitter; $\lambda/4$: quarter-wave plate; DBM: double balanced mixer; RF: RF oscillator at 12 MHz; PZT: piezo transducer. Right: Intracavity power, without the viewports, as function of input power at 532 nm. Inset: cavity resonance with FM sidebands (black), and corresponding Pound-Drever-Hall error signal (red).

Conclusion

We propose the use of a deep optical trap or lattice for direct loading of atomic species that have been previously cooled only to about one mK. This is particularly suitable for alkaline-Earth atoms which have undergone only Doppler cooling with their strong resonant transition. Because this transition is in the blue/UV region for Mg, Ca, Sr, Yb, or Hg, dipole trapping is possible with powerful commercial visible lasers, as for example at 532 nm. These low-noise, single-frequency lasers can have powers amplified into the kW range, by use of low-loss power-enhancement optical cavities. We demonstrate amplification of a 3.2 W, 532-nm laser up to 523 Watt, by using a Fabry-Perot cavity with standard dielectric mirrors. High power trap lasers will allow keeping the trap volume as large as possible, for improved transfer efficiency from a magneto-optical trap. Using calcium as an example, we estimate the trap depths for different powers and waist sizes, and calculate the AC-Stark shifts for some levels relevant for cooling and spectroscopy. Stark-free spectroscopy of the calcium intercombination transition into a 532 nm optical trap, should be possible using an auxiliary laser at 613 nm.

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