Appl. Phys. B 76, 805–808 (2003)
DOI: 10.1007/s00340-003-1223-6

Applied Physics B
Lasers and Optics

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Doppler cooling a single Ca$^+$ ion with a violet extended-cavity diode laser

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Received: 31 March 2003

ABSTRACT We present a scheme for employing a violet extended-cavity diode laser in experiments with single, trapped ions. For this the grating-stabilised laser is spatially and spectrally filtered and referenced to a Fabry–Pérot cavity. We measure an upper limit to the line width by observing a 305-kHz FWHM beat note with the second harmonic of a titanium sapphire laser. The laser is subsequently used to optically cool a single ^{40}Ca$^+$ ion close to the Doppler limit.

PACS 03.67.Lx; 32.80.Pj; 42.55.Px

1 Introduction

The advent of diode lasers operating in the ultraviolet (UV) has brought with it the possibility of replacing cumbersome, expensive and complicated laser systems typically required to generate such wavelengths with smaller, cheaper and simpler systems. One application requiring narrow-band, frequency-stable, UV laser radiation is Doppler cooling of trapped ions for applications in precision spectroscopy [11, 12], frequency metrology [1, 3, 9] and quantum optics. In the last field, laser cooling is one of the basic experimental requirements for implementing quantum algorithms with trapped ions [5]. Since several ionic transition wavelengths lie in the UV, the radiation required for such experiments is typically generated by frequency doubling the output from a titanium sapphire (Ti:Sa) or dye laser, which itself is either pumped by an argon-ion laser or a high-power solid-state device. The replacement of such a complex system by a simple diode laser is of obvious benefit. Indeed, Hayasaka et al. [7] demonstrated the laser cooling of several calcium ions with a compact extended-cavity diode laser (ECDL) on the $4\,^2S_{1/2} \rightarrow 4\,^2P_{1/2}$ transition at 397 nm (see Fig. 1) and observed the phase transition from an ion cloud to a crystallised state. However, it was noted by Toyoda et al. [16] that the broad spontaneous emission from such a diode laser also excited closely lying transitions at 393 nm, thereby invoking quantum jumps to the $3\,^2D_{5/2}$ metastable state via the $4\,^2P_{3/2}$ state. With the ion in this state, Doppler cooling is halted and so the inclusion of an interference filter to eliminate this radiation was necessary. In addition, if such a laser is to be used in the implementation of quantum algorithms in which sequences of short pulses cool, prepare and read out the states of the qubits, then the ability to shutter the light field on and off in the microsecond regime is necessary. Here we detail a scheme fulfilling all of these requirements. We measure the line width of the ECDL by a beat measurement with the second harmonic from a Ti:Sa laser at 397 nm. To assess the diode laser's performance, a single calcium ion is Doppler cooled and the resulting mean phonon number measured.

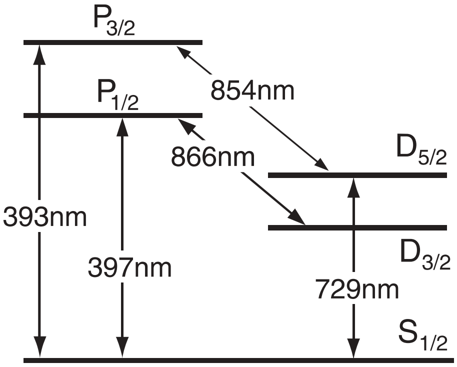

FIGURE 1 Partial energy-level scheme of ^{40}Ca$^+$. Note that the nuclear spin is zero

2 Experimental setup

The diode laser used in this work is a Nichia Corporation (NLHV3000E) device with the manufacturer's specifications giving a nominal CW output power of 30 mW at 397 nm. The threshold current is measured to be 42.2 mA. The laser is collimated and mounted in the Littrow geometry with the design being based upon a commercial 25-mm mirror mount. Details of this setup can be found elsewhere [2, 8, 13]. A 3600 lines/mm holographic grating (Edmund Industrie Optik GmbH) is used as the feedback element returning approximately 20% of light incident on the grating back to the diode. Once aligned, the threshold current fell to 38.6 mA. The mirror mount sits upon a Peltier temperature-stabilised baseplate ($\Delta T < 5$ mK) within an air-tight box. Wavelength tuning to 396.8 nm is achieved by altering the grating angle, operation

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temperature (typically 17 °C) and diode-laser current (typically 51.5 mA). The diode is run at an output power of 9.5 mW, well below its maximum operating parameters, in order to extend its lifetime. Anamorphic prisms (Toptica, APP J 405) reduce the aspect ratio of the beam until it is nearly circular before it passes through an optical isolator (Linos, FR390/420) giving 40 dB isolation. At this stage a small fraction of the light ($\approx 100\,\mu$W) is split off and used to frequency lock the laser to a temperature-stabilised Fabry–Pérot cavity using the Pound–Drever–Hall method, which acts on the grating setting and laser current with a bandwidth of ≈ 1 MHz. The cavity is built in-house and has a free-spectral range of 705 MHz, a finesse of 780 at 397 nm and a line width of 900 kHz. The laser is locked to the cavity with a r.m.s. error of 3 kHz. The remainder of the beam is incident upon a second grating. This has 1200 lines/mm and is blazed for 400 nm giving $\approx 75\%$ diffraction efficiency into the first order [1]. Its function is to filter spontaneous emission from the diode, particularly at 393 nm which has been shown to produce quantum jumps in calcium ions [16, 17]. The beam is focussed through an acousto-optic modulator (AOM) (Brimrose, QZF-80-20) and the first diffracted order is coupled into a 1.5-m length of optical fibre. Switching the radio frequency to the AOM allows the transmission through the fibre to be switched with microsecond accuracy and with 25 dB suppression. The fibre cleans the spatial mode of the laser output leading to an approximately Gaussian intensity profile, and also acts as a pinhole for spectral filtering upon receiving diffracted light from the second grating. With the apparatus optimised it is possible to obtain $\approx 300\,\mu$W after the fibre optic. This is commensurate with a coupling efficiency of 30%, which is due to the poor spatial profile of the diode output.

The suitability of the ECDL for Doppler cooling trapped ions is verified by two experiments. The first experiment measures the ECDL line width by a beat measurement and shows it to be much narrower than the cooling transition line width. In the second, a single ion is cooled with the ECDL and the frequency-doubled Ti:Sa laser alternately and the resulting mean vibrational phonon numbers are compared along each of the trap axes.

3 Line-width measurement

To obtain a value for the line width of the laser a beat measurement is performed. A frequency-doubled Ti:Sa laser [10] which has been previously used successfully to cool single or strings of ions is taken as a reference to beat against the diode laser. Both the Ti:Sa laser and the diode laser are locked to independent temperature-stabilised reference cavities. The beams are overlapped and directed onto a fast UV-sensitive photodiode (Hamamatsu, S8591). The signal is recorded using an RF spectrum analyser. Figure 2 shows a typical beat signal. The FWHM line width of the signal is measured to be 305 ± 7 kHz when fitted to a Lorentzian curve. With a Ti:Sa laser line width of 250 kHz [10], the ECDL line width is placed at below 200 kHz.

4 Phonon-number measurement

For initialising an ion-based quantum processor for logic operations the thermal motion of the ion must be reduced to its motional ground state. Typically, Doppler pre-cooling is followed by resolved sideband cooling [4, 14] to reach this state. To verify the ECDL's Doppler cooling performance and to compare it to that of the Ti:Sa laser, a single $^{40}\mathrm{Ca}^+$ ion is cooled, firstly with the ECDL and secondly with the Ti:Sa laser, and its mean phonon number measured. The relevant energy-level scheme of $^{40}\mathrm{Ca}^+$ is shown in Fig. 1. The trap frequencies are 1.2 MHz and 5.0 MHz for axial and radial axes respectively. Further details of the trap setup can be found elsewhere [6]. For each laser source, the temperature of the ion is measured both in the axial and in the radial modes immediately after Doppler cooling. This is done by applying pulses of 729-nm laser radiation to the ion's carrier, blue axial and blue radial sideband frequencies and observing the evolution of the excited-state population as a function of 729-nm pulse length.

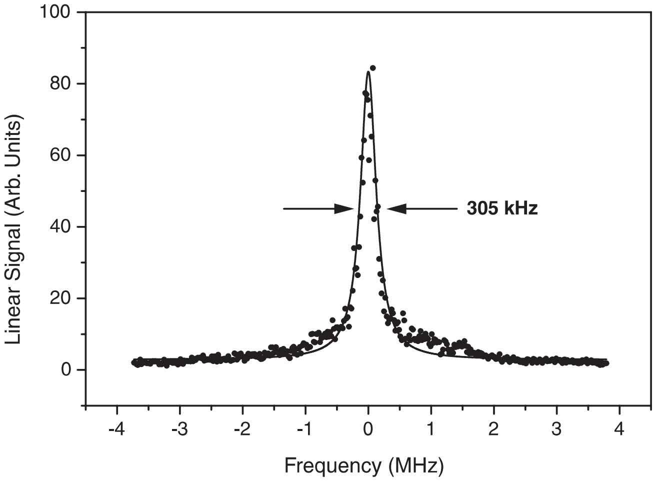

FIGURE 2 Beat-note data between extended-cavity diode laser and frequency-doubled Ti:Sa laser. *Points* are experimental data while the *line* shows a Lorentzian fit with a FWHM of 305 kHz. The resolution bandwidth of the RF spectrum analyser is 100 kHz

The time evolution of an excited-state population with vibrational modes of the ion occupied with a thermal distribution is given by

$$\varrho_{\mathrm{DD}}(t)=\sum_{n=0}^{\infty} p(n)\left(\frac{\Omega_{\mathrm{B}}}{\Omega_{\mathrm{B}\Delta}}\right)^{2} \frac{1}{2}\left(1-\cos(2\Omega_{\mathrm{B}\Delta}t)\right), \qquad (1)$$

where $p(n)$ is the occupation probability of the vibrational state $|n\rangle$,

$$p(n)=\frac{1}{\bar{n}+1}\left(\frac{\bar{n}}{\bar{n}+1}\right)^{n}. \qquad (2)$$

$\Omega_{\mathrm{B}}=\Omega_0\eta\sqrt{n+1}$ and $\Omega_{\mathrm{B}\Delta}=\sqrt{\Omega_{\mathrm{B}}^2+\Delta^2}$ are the blue sideband Rabi frequencies with no detuning and detuning Δ respectively. Ω_0 is the on-resonance carrier Rabi frequency while η ($\eta_{\mathrm{axial}}=0.033$, $\eta_{\mathrm{radial}}=0.028$) is the calculated Lamb–Dicke parameter from the measured trap frequencies and beam directions.

In short, the temperature of the ion is inferred from Rabi oscillations between the ground state and the $D_{5/2}$ state on the upper motional sideband. The experimental measurement cycle is outlined below:

1. Doppler cooling is performed for 2 ms on the $S_{1/2}$ to $P_{1/2}$ transition at 397 nm. This light is detuned $\Gamma/2$ below the transition frequency where Γ is the natural line width (20 MHz). Diode lasers at 866 nm and 854 nm prevent optical pumping into the D states. Prior to coherent manipulations the ion is initialised by optically pumping into the $S_{1/2}$ $(m = 1/2)$ state.
2. Measurements of the phonon numbers using the motional sideband $n \rightarrow n+1$ of the $S_{1/2}$ and $D_{5/2}$ transitions are carried out using a pulse of light from a Ti:Sa laser near 729 nm (line width ≤ 100 Hz).
3. State-detection analysis is achieved by applying light at 397 nm and 866 nm simultaneously and observing the fluorescence on a photomultiplier tube (electron-shelving technique). The internal state of the ion is determined with close to 100% accuracy within 3 ms [14].

This sequence is repeated 100 times to measure the excitation probability, ϱ_{DD}, to the $D_{5/2}$ state. To plot this as a function of pulse length the pulse in step 2 is incremented and the experimental cycle repeated. It should be noted that only the Doppler cooling pulse (step 1) uses either the diode or the Ti:Sa laser; all other experimental steps remain identical. The polarisation and the observed ion fluorescence from each 397-nm source are made equal. No quantum jumps as a result of background 393-nm spontaneous emission from the semiconductor laser medium were observed.

After measurement of the carrier Rabi frequency Ω_0, (1) is fitted to the measured data. These fits reveal the mean thermal phonon number, $\bar{n}$, for each axis. One such fit is shown in Fig. 3. This particular data set is for the axial mode of vibration when cooled with the ECDL. Using this method all phonon numbers for Doppler cooling with the ECDL/Ti:Sa laser are calculated and presented in Table 1, along with approximate theoretical values for the steady-state phonon numbers given by $\bar{n} \simeq \Gamma/2\nu$ [15, 18], where ν is the trap frequency.

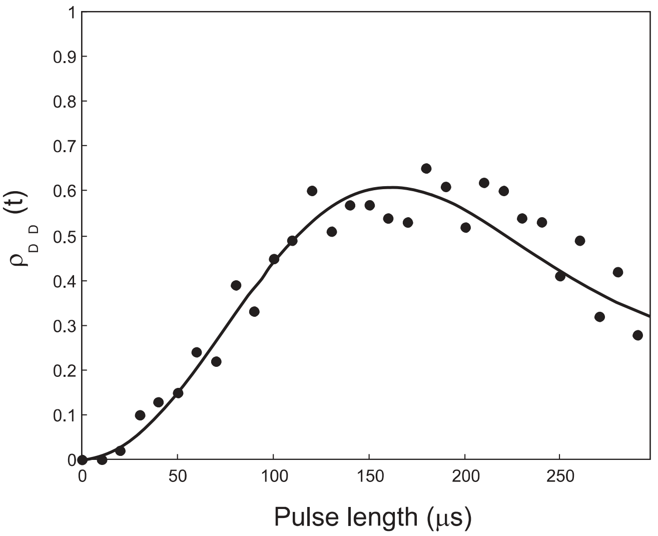

FIGURE 3 A Rabi oscillation on the blue axial sideband (trap frequency = 1.2 MHz) following 2 ms of Doppler cooling using the ECDL. *Circles* are measured data points while the *line* is obtained from (1) with $\bar{n} = 12$ and $\Delta = 1.5$ kHz

	$\Gamma/2\nu$	Ti:Sa	ECDL
Axial (1.2 MHz)	8.3	14 ± 4	12 ± 3
Radial (5 MHz)	2	4 ± 1	3 ± 1

TABLE 1 Table showing the theoretical and experimental mean phonon numbers after Doppler cooling

The discrepancy in resulting phonon numbers between the Ti:Sa laser and the diode laser is attributed to non-identical power incident on the ion and frequency of the cooling beams in each case. Nevertheless, the fact that the diode laser can cool to, or even below, the phonon number achieved by cooling with a conventional Ti:Sa laser indicates that it possesses the required characteristics for replacing larger, more expensive laser systems in this type of experiment. Why the experimental values did not reach the theoretically predicted Doppler limit in either case may be explained by the presence of intensity or polarisation gradients and the applied magnetic field of 2.6 G. As a further test of the ECDL a two-ion cloud was cooled and crystallisation was observed. A measurement of such an ion crystal's phonon number is intended for future study as well as using such a system for the preparation of ions for implementing quantum algorithms.

5 Conclusion

In conclusion, an extended-cavity UV diode laser has been successfully incorporated into an existing ion-trap experiment. The laser output has been spatially and spectrally improved for use as a Doppler cooling laser. An absolute upper limit for its line width was obtained by conducting a beat measurement between it and a frequency-doubled titanium sapphire laser. This revealed a FWHM line width of 305 ± 7 kHz. The diode laser was subsequently used to cool a single trapped $^{40}\mathrm{Ca}^+$ ion in a linear Paul trap. By fitting to blue sideband Rabi oscillation data taken immediately after Doppler cooling, the phonon numbers for each of the trap axes were measured. These values were compared to those obtained from a proven, reliable tool for Doppler cooling, namely a frequency-doubled titanium sapphire laser. Both Doppler cooling light sources reveal similar phonon numbers and, as a result, it is indicative that such an ECDL can be used successfully in a quantum computation experiment based upon trapped ions.

ACKNOWLEDGEMENTS This work is supported by the Austrian 'Fonds zur Förderung der wissenschaftlichen Forschung' (SFB15), by the European Commission (TMR networks 'QI' and 'QSTRUCT' (ERB-FRMX-CT96-0087 and -0077), IHP network 'QUEST' (HPRN-CT-2000-00121) and IST/FET program 'QUBITS' (IST-1999-13021)) and by the 'Institut für Quanteninformation GmbH'. H. Häffner is supported by the European Commission with a Marie Curie Fellowship.

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