Compact, filtered diode laser system for precision spectroscopy

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Stable, narrow-linewidth optical sources are necessary in modern atomic physics. An appealing approach to achieving ~10 kHz frequency stability is optical feedback. We have designed a compact external cavity diode laser with optical feedback to a filter cavity mounted on a single baseplate and enclosed inside a vacuum sealed box. The design was implemented for three wavelengths addressing the 422 nm cooling, 1091 nm repumping, and 674 nm clock transition lines of Sr^+. We are able to cool a single, trapped strontium ion to ~2 mK and observe motional sidebands of the $5S_{1/2} \leftrightarrow 4D_{5/2}$ transition. © 2007 Optical Society of America

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Semiconductor lasers are increasingly popular in atomic physics experiments, thanks to their compactness and reliability. While a typical extended cavity diode laser (ECDL) setup is often sufficient, there are numerous experiments that call for better frequency stability and spectral purity. Several techniques have been applied to improve the stability, including negative electronic feedback via current injection,[1,2] optical feedback,[3,4] or a combination of the above.[5] However, these schemes do not filter out the large fluorescent background extending by many nanometers from the diode center line, which can pump the sample to a dark state[6] (though some similar experiments were not affected[7]) or reduce the lifetime of metastable states.[8] Because of the small emitter area of single-mode diodes, such fluorescence is well collimated and cannot be spatially filtered. An additional step using a grating and a pinhole[8,9] or an interferometric filter[6] is necessary. In this paper, we present a very compact and robust design that simultaneously stabilizes the laser frequency and removes the fluorescent background, with reliable single-mode operation longer than 10 h at a time. To illustrate the performance of this design, we have cooled a single Sr^+ ion to ~2 mK and investigated the narrow $5S_{1/2} \leftrightarrow 4D_{5/2}$ transition.

A detailed schematic of our 674 nm laser design, based on Roithner RLT6715MG InGaAs diode (no antireflection coating, threshold current of 29 mA) is shown in Fig. 1; the other two setups are virtually identical. At the heart of the design is a triangular running-wave cavity with finesse ~200 and 1 GHz free spectral range, which acts as a spatial and frequency filter for both the optical feedback and output laser light. We employ a standard ECDL setup with grating reflectivity of ~20% to roughly select the lasing wavelength.

Two cylindrical lenses circularize the elliptical diode output. Two spherical lenses set the beam size and waist in between the tilted cavity mirrors for proper mode matching. The cavity consists of two 99% reflectivity mirrors at a 42° angle to the cavity axis and a 200 mm concave high-reflectivity mirror. The mirror is mounted on a single-layer piezo to allow for frequency tuning. We use a nonconfocal cavity to separate the resonant frequency for the TEM_{00} mode from higher-order modes, allowing us to remove them from the laser beam. The coupling into the cavity is ~60%. Due to significant scatter on the cavity mirrors, the cavity efficiency is ~75%, resulting in ~45% of the total incident light coupling through the cavity. Part of the light leaks through the HR mirror, allowing us to measure the power in the cavity. A glass plate reflects 4% of transmitted light, exciting the reverse-going mode that provides optical feedback. Slight misalignment of this plate allows us to adjust the coupling strength to that mode. A mirror

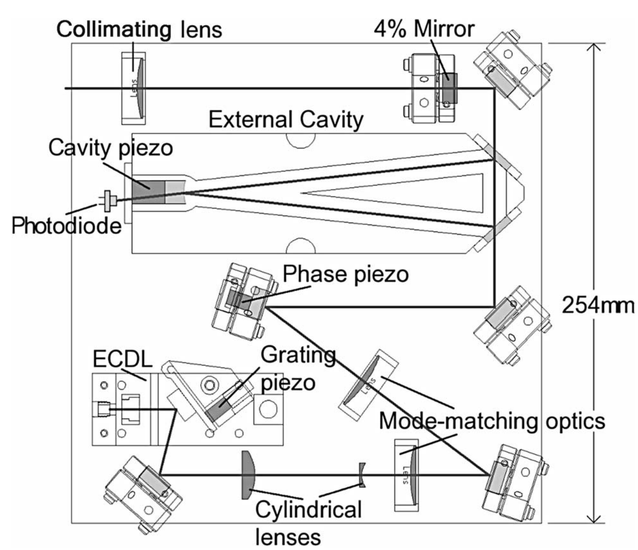

Fig. 1. Schematic of the laser setup with a superimposed laser beam.

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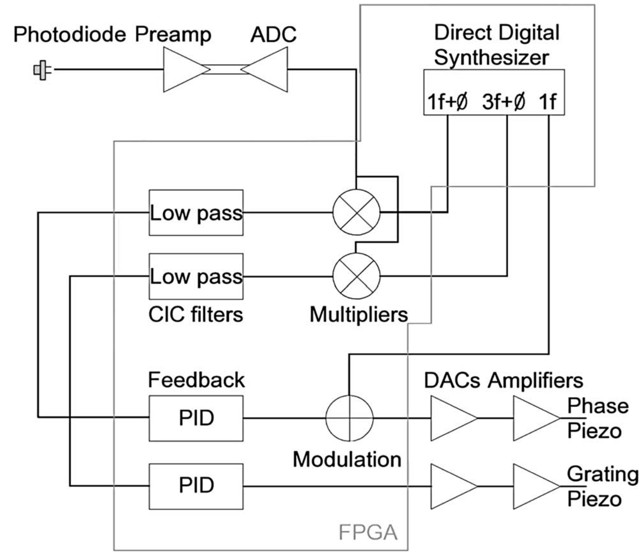

Fig. 2. Schematic of the digital lock system. The gray box denotes components implemented digitally using a field-programmable gate array (FPGA).

mounted on a piezoelectric transducer (phase piezo) controls the distance to the cavity and the phase of the optical feedback. The power at the system output was 3.6 mW (9 mW at the ECDL) at 56 mA operating current.

The ECDL and optics are mounted on a custom-machined and temperature-stabilized aluminum plate. For increased stability, we enclose the entire setup in a vacuum-tight box and pump it down to $<10^{-5}$ Torr. Based on the drift of the cavity frequency, we estimate the temperature stability of the baseplate to be better than 1 mK over 1 h.

Optical feedback requires stabilization of both the phase of the returning light and the free-running ECDL frequency. While the phase can be locked by maximizing the amplitude through the cavity using a simple lock-in technique, stabilizing the ECDL frequency requires measuring the asymmetry in the cavity transmission as the phase is scanned.[10–13] That asymmetry generates a $3f$ component when the feedback phase is dithered at frequency f. Due to the relative complexity of the locking method, we digitized the input and used a field-programmable gate array for signal processing. A schematic of the lock loop is presented in Fig. 2.

We use a 600 kHz, 18 bit analog-to-digital converter (ADC, Texas Instruments ADS8382) with 100 μV_{pp} of noise to digitize the ~3 V photodiode signal. This signal is mixed with 10 and 30 kHz variable-phase sine waves from a direct digital synthesizer to pick up the respective frequency components. Two low-pass, three-stage cascaded-integrator-comb (CIC) filters with cutoff at 100 Hz remove high-frequency noise. The filtered signal is fed to proportional-integral-derivative (PID) circuits, the 10 kHz component controlling the phase and the 30 kHz component controlling the free-running ECDL frequency via the grating piezo. The total gain was set to 0.1 (P) and 10 s^{-1} (I) for the 10 kHz circuit and 10 (P) and 1000 s^{-1} (I) for the 30 kHz one. As the last step, a 10 kHz modulation is added to the phase output. The digital output is converted to analog using two low-noise, 100 kHz, 16 bit digital-to-analog converters (DACs, Linear Technology LTC1592).

The lock is stable with 0.2% amplitude modulation (~300 kHz frequency modulation) for more than 10 h at a time. The frequency dither is undesirable, and while there are locking methods that reduce or eliminate it, we opted for turning the modulation off during experimental runs.[13,14] We are able to turn the lock off ~10 min before a 1% change in output amplitude is observed. The response times of the lock circuit are 100 and 1 Hz for phase and grating lock, respectively, allowing for a 25 MHz/s scan rate. The slow grating response is caused by very weak third-harmonic signal at the low modulation levels that we used. The maximum scan range is 1 GHz, limited by the cavity piezo travel range.

The fluorescent background of the diode was measured at the ECDL with a grating spectrum analyzer connected via a single-mode APC fiber and observed at −50 dBc level (see Fig. 3). This background was reduced by the filter cavity to below the analyzer's sensitivity of −80 dBc. The residual background is expected to have a periodicity equal to that of the cavity, or ~1 GHz. Because the usual linewidths of strong atomic transitions, which could be affected by this background, have ~10 MHz width, the chance of a residual background peak aligning with a parasitic transition is ~1%.

We used a single Sr^+ ion trapped in a linear Paul trap identical to that described by Furukawa *et al.*[15] to characterize the 674 nm laser. The trap was driven at 18.3 MHz, 800 V_{pp}, with endcap voltages at 50 V. At these values, the secular frequencies are 600 kHz (axial) and 800 kHz (radial). We measured the laser linewidth and frequency stability by using electron shelving to a metastable $D_{5/2}$ state.[16] Initially, the ion was Doppler cooled with 422 and 1091 nm radiation. Then, with the 422 nm laser off, a 100 μs pulse of 674 nm radiation was applied to shelve the ion to the $D_{5/2}$ state (see Fig. 4). Finally, the 422 nm radiation was turned on again for 2 ms to read out whether the ion made the transition to the $D_{5/2}$ state. The process was repeated 50 times to obtain a shelving probability. The spectrum of the quadrupole-allowed $S_{1/2} \leftrightarrow D_{5/2}$ line was taken by scanning the laser fre-

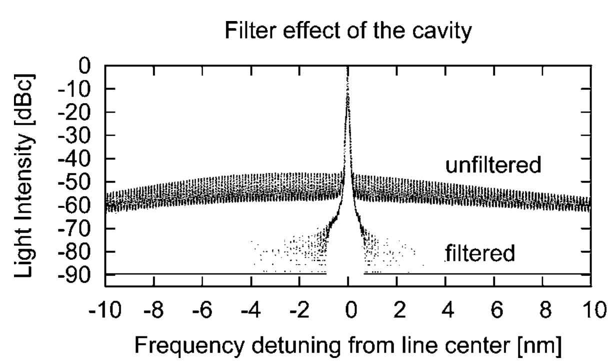

Fig. 3. Spectrum of the 674 nm laser at the ECDL (top trace) and after the filter cavity (bottom trace). −90 dBc indicates null intensity.

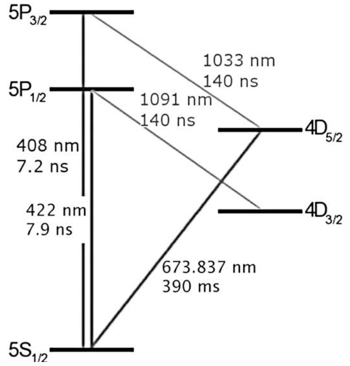

Fig. 4. Diagram of the relevant states of Sr^{+}.

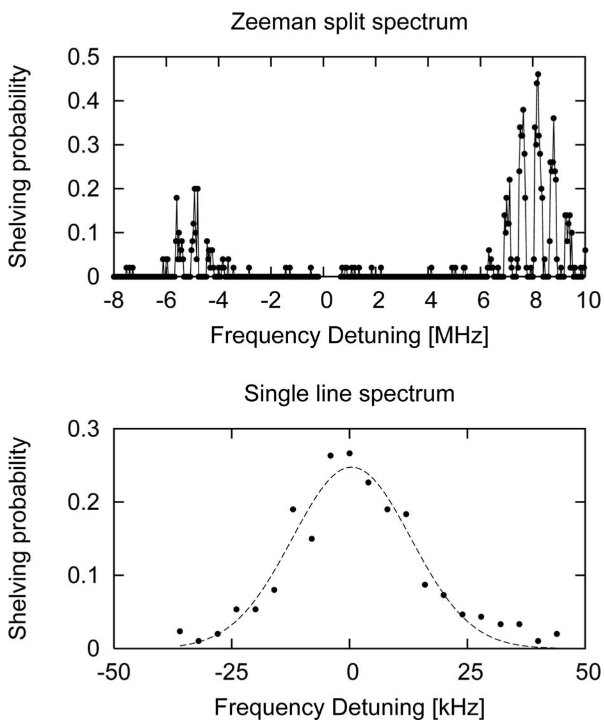

Fig. 5. Top: shelving probability spectrum for the two lowest-frequency Zeeman components of the $5S_{1/2} \leftrightarrow 4D_{5/2}$ line, $m=-1/2 \leftrightarrow m=-5/2$ and $m=1/2 \leftrightarrow m=-3/2$. The splitting indicates a magnetic field of 9 mT. Every peak is further split by the 600 kHz secular motion of the ion in the trap. Bottom: detailed scan across the central line of the $m=-1/2 \leftrightarrow m=-5/2$ line. The Gaussian fit to the spectrum has a 30 kHz FWHM. The lock circuit was turned off during this scan to avoid broadening due to the dither of the phase piezo.

quency in fixed intervals. With this method, we observed all 10 Zeeman components of this line and resolved the secular motion sidebands of each component. The strength of the sidebands indicates a Doppler cooled temperature of $\sim$2 mK. Based on the width of the peaks, we put an upper bound on the 674 nm laser linewidth at 30 kHz for a 30 s scan acquisition time (Fig. 5). The likely cause of such a broad line is residual acoustic vibrations of the filter cavity; the ac magnetic shifts should be negligible at this level.[17] By observing the position of the line, we were also able to evaluate the long-term stability of our setup. The laser frequency stayed within ±1 MHz of its initial value over a period of 3.5 h. The Allan deviation at 60 s averaging time was 1.3×10^{-10}. Given the similarity of the other lasers, we expect the respective linewidths and drifts to be similar.

In conclusion, we have developed a compact, stable laser system for precision spectroscopy. This system produces narrow-linewidth light in a TEM_{00} mode, with the diode fluorescence removed by a filter cavity. Long-term stability is entirely determined by cavity drifts and is measured to be less than ±1 MHz over several hours.

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