Subkilohertz enhanced-power diode-laser spectrometer in the visible

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We report on a high-performance diode-laser spectrometer operating near 657 nm with narrow linewidth (<0.6 kHz), enhanced power (as much as 40 mW), and low drift (<10 Hz/s). The spectrometer comprised an extended-cavity diode-laser frequency stabilized to a high-finesse optical resonator and a broad-area antireflection coated laser diode as an amplifier with a single-lobe emission pattern of good spatial purity. The spectrometer was used to record time-domain optical Ramsey spectra of laser-cooled Ca atoms with a resolution of 0.6 kHz.

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Tunable lasers of narrow linewidth, high frequency and mode stability, and sufficiently high power are prerequisites for a variety of current research areas such as high-resolution laser spectroscopy, atom interferometry,[1] and optical frequency standards and optical clocks.[2] The small size, low power consumption, and long-term operation required by the two last-named applications and by portable devices can be provided at present by diode lasers only. In the visible part of the spectrum, however, which is home to some of the most prominent atomic transitions,[2,3] high-resolution diode-laser spectrometers are capable of supplying only a few milliwatts of power.[4–6] This power level is clearly not sufficient for efficient pulsed excitation of the relevant weak transitions in cold atoms[7] that are frequently needed for atom interferometry and optical frequency standards.

Several methods to raise the power of the required phase-coherent light pulses, e.g., cavity dumping the power stored in a buildup resonator[8] or employing broad-area diode lasers, are currently been explored. The increased widths of the active areas of these laser diodes necessary to generate the high output power, however, lead to poor spatial and spectral brightness. In the infrared region injection locking of broad-area laser diodes[9] and amplification in broad-area laser diodes[10] have been employed to capitalize on the power of broad-area diode lasers while retaining the high spatial and spectral purity of low-power single-mode devices. These systems, however, have not yet been used for high-resolution measurements in the kilohertz range.

In this Letter we report on a diode-laser spectrometer (DLS) operating near 657 nm with a linewidth below 0.6 kHz, an enhanced power of as much as 40 mW, and low drift (<10 Hz/s). The DLS was employed to record time-domain optical Ramsey spectra of laser-cooled Ca atoms with a resolution as fine as 0.6 kHz. Basically, the DLS (depicted in Fig. 1) consists of a master oscillator, a traveling-wave amplifier, and a high-Q cavity used to prestabilize the laser frequency. The master oscillator was a slightly modified version of an extended-cavity diode laser in the Littman arrangement described in Ref. 11. An intracavity $LiNbO_3$ electro-optical modulator with a bandwidth of more than 1 MHz controlled the frequency of the extended-cavity diode laser, whose maximum output power at 657 nm was 6 mW. A broad-area laser diode (Philips SQL-822/D; width of active area, 50 μm) was used as a traveling-wave amplifier. To suppress its lasing modes we antireflection coated the front facet, thereby increasing the threshold current from 130 to 220 mA. A Dove prism, an astigmatic telescope (comprising two cylindrical and one spherical lens), and a half-wave plate were used to match polarizations and beams of the two lasers, whose waveguides were perpendicularly oriented to each other.

To investigate the influence of the master beam on the spatial characteristics of the amplifier output we recorded the far-field pattern of the broad-area

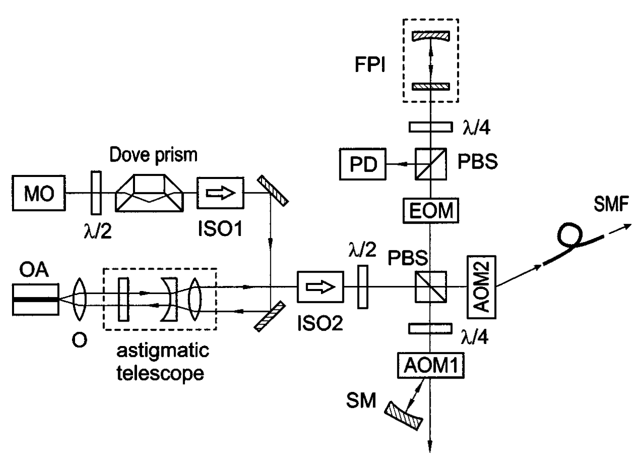

Fig. 1. Optical schematic of the experimental setup: MO, master oscillator; OA, optical amplifier; O, collimating objective; ISO1, ISO2, 40-dB optical isolators; SM, spherical mirror; PD, photodiode; PBS's, polarizing beam splitters; SMF, single-mode fiber delivering laser radiation to the magneto-optical trap. Other abbreviations defined in text.

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laser diode in the plane of the laser junction. Data were taken for the amplifier biased slightly below its own threshold (215 mA; Fig. 2(a)] and above threshold [250 mA; Fig. 2(b)]. The initial far-field pattern in the absence of the injected beam (dotted curves) displays a two-lobe emission with an angle of ~4 deg between the lobes. The solid curves were taken in the presence of the injected beam.

Below threshold, the spatial and spectral properties of the amplifier were completely determined by the radiation of the master laser, with 92% of the total power concentrated in the narrow lobe [Fig. 2(a)]. The balance, 8%, is due to imperfect coupling; additional small diffraction maxima are also visible. Above threshold, the output characteristics of the amplifier result from a competition between the field of the slave and the injected field, because the two share gain in the active region of the amplifier. As a consequence, the injected field suppressed self-oscillation of the amplifier [Fig. 2(b)]. However, above a certain current level, depending on the master power of the master laser and on the frequency separation between the master laser and the amplifier, both the original and the amplified fields coexisted. The high spatial purity of the output beam was demonstrated by its coupling into the single-mode polarization-preserving fiber with an overall efficiency of $\eta = 43\%$.

The linewidth of the amplified radiation of the free-running master laser was determined to be ~30 kHz from a measurement of the beat note with a high-resolution dye-laser spectrometer. To reduce further the frequency fluctuations of the DLS we used a phase-modulation technique[12] to stabilize the laser frequency to an appropriate resonance frequency of a Fabry–Perot interferometer (FPI). For better stability the FPI was made of two Zerodur mirrors of 1- and 10-m radius optically contacted to a Zerodur spacer suspended in a temperature-stabilized vacuum chamber. The FPI had a finesse of $F = 5800$ and a 3-GHz free spectral range. The frequency of the spectrometer was controlled by an acousto-optic modulator (AOM1; Fig. 1), which introduced an adjustable offset between the frequency of the laser and a resonance frequency of the monolithic FPI. Double-passing AOM1 permitted frequency tuning with stable beam direction, independently of the driving frequency. We used a half-wave plate and a polarizing beam splitter to determine the optimum ratio of powers for stabilization and spectroscopy. For frequency stabilization[12] the beam coming from AOM1 passed an electro-optical modulator (EOM) and was coupled to the FPI. The reflected beam was directed to a detector to generate an error signal, which was integrated and fed back to the intracavity EOM of the master laser. With the EOM response of 2 MHz/V the dynamic range was high enough to keep the DLS in lock for hours. The beat note between the spectrally narrowed DLS and a highly coherent dye laser demonstrates a spectral linewidth of the DLS of 0.6 kHz or less (Fig. 3).

We used the laser to investigate the intercombination transition $^1S_0$–$^3P_1$ of ^{40}Ca atoms (natural linewidth, 400 Hz). The frequency of this transition[13] is known with a relative uncertainty of 2.5×10^{-13} and was recently recommended as the most accurate optical frequency standard for the realization of the length unit.[14] We prepared a slowly expanding cloud ($v_{\mathrm{rms}} <$ 1 m/s) of typically 10^6 cold Ca atoms[7] by releasing the atoms from a switched off magneto-optical trap. The laser radiation ($\lambda = 423$ nm, power $P > 30$ mW) required for trapping the Ca atoms was generated by a frequency-doubled diode-laser system similar to the one described in Ref. 5. Three pulses of a standing wave ($P = 4$ mW) for interrogating the transition were generated from the cw DLS beam by a second AOM (AOM2; Fig. 1). The pulses, of ~2-μs duration, were separated by the dark-time intervals T. The fluorescent decay of the excited Ca atoms was detected by a photomultiplier. The pulsed interaction scheme represents the time-domain equivalent of an optical Ramsey excitation or an atom interferometer,[1,7] in which the number of excited atoms and hence the fluorescence signal includes a term that varies with

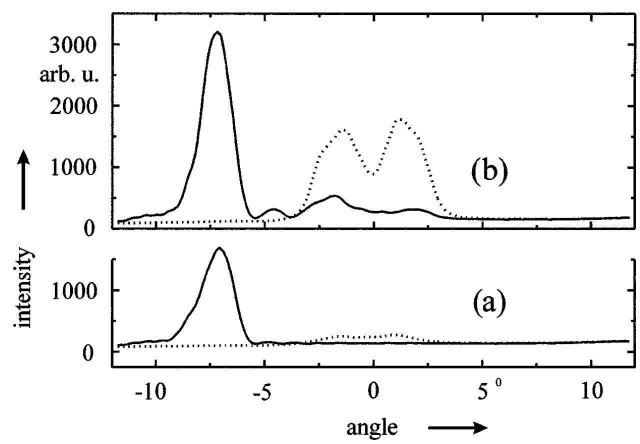

Fig. 2. Far-field distribution of the amplified output with (solid curves) and without (dotted curves) injected light from the master laser for amplifier currents of (a) 215 mA and (b) 250 mA.

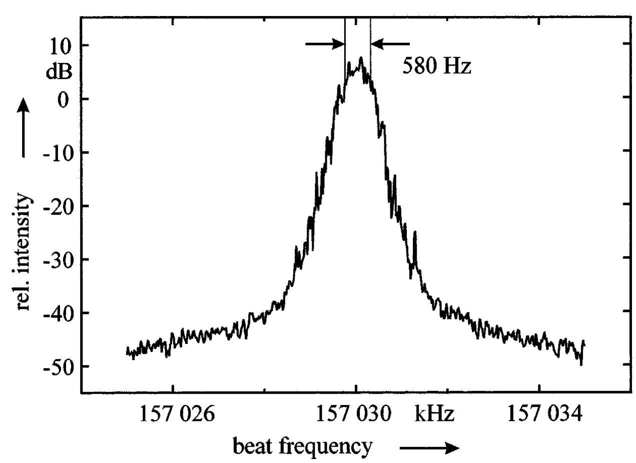

Fig. 3. Beat note between the DLS and a dye-laser spectrometer when the master laser is locked to the high-Q cavity. Resolution bandwidth, 300 Hz; video bandwidth, 10 Hz; seep time, 10 s.

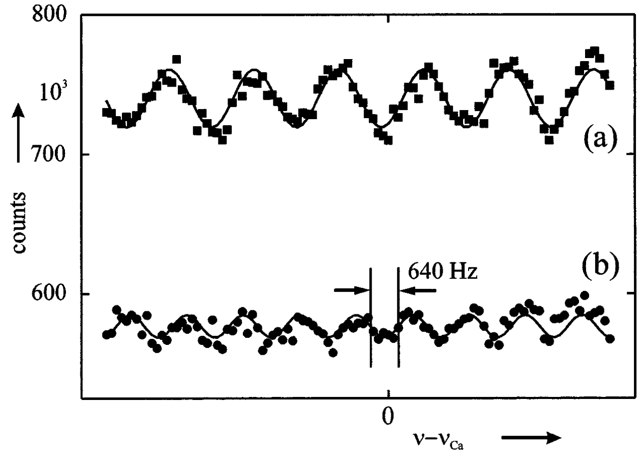

Fig. 4. Optical Ramsey fringes taken with slow Ca atoms for resolutions of 960 Hz (filled squares) and 640 Hz (filled circles) corresponding to pulse separations of $T = 260\ \mu$s and $T = 390\ \mu$s and fits (solid curves) according to relation (1).

the laser frequency ν according to

$$I(\nu) \propto a_1 \cos\left[4\pi\left(\nu - \nu_{\mathrm{Ca}} - \frac{\Delta}{2}\right)T\right] + a_2 \cos\left[4\pi\left(\nu - \nu_{\mathrm{Ca}} + \frac{\Delta}{2}\right)T\right]. \quad (1)$$

The two corresponding fringe systems that result from the photon recoil are separated by $\Delta = h{\nu_{\mathrm{Ca}}}^2/(\mathrm{mc}^2) =$ 23.1 kHz. The spectral resolution $\delta\nu$, defined as half of the period of the interference system of relation (1), is $\delta\nu = 1/(4T)$.

We have taken spectra with time intervals of $T = 260\ \mu$s and $T = 390\ \mu$s [Fig. 4, curves (a) and (b)], corresponding to a resolution of 960 and 640 Hz, respectively, for which the fringe patterns of the two recoil components add constructively for optimum visibility. Each point of the spectra corresponds to an average of 20 trapping–excitation–detection cycles. During the measurements a temporal drift of the resonance frequency of the FPI owing to temperature fluctuations was observed of ~7 Hz/s, corresponding to a fractional frequency instability of 1.5×10^{-14}/s. From the reduced signal-to-noise ratio (S/N) of the high-resolution spectrum of Fig. 4 and the fact that for resolutions below 600 Hz the interference pattern vanished, we conclude that this limit is currently set by the linewidth of the laser. The laser has been stabilized for several hours to the central minimum of a spectrum similar to the ones presented in Fig. 4, representing an optical frequency standard at $\nu = 455\,986\,240\,494.1$ kHz.[13,14] The relative frequency instability described by the two-sample variance (Allan variance) is ${\sigma_y}^2(\tau) \cong [(\mathrm{S/N})Q]^{-2}\tau^{-1}$ if we assume that the signal is shot-noise limited.[15] From the S/N and the experimental quality factor $Q = \nu/\Delta\nu$ of Fig. 4 we derive $Q = 5 \times 10^{11}$, S/N = 5, and $\sigma_y(\tau) \cong 4 \times 10^{-13}\ \tau^{-1/2}$. This instability compares well with other optical and microwave frequency standards and can even be increased by the use of other pulse schemes.

In summary, we have utilized a completely diode-laser-based high-resolution spectrometer to measure the Ca intercombination transition with nearly lifetime limited resolution as low as 0.6 kHz. The Ca standard represents the current optical frequency standard for the most accurate realization of the meter. In connection with a frequency-measurement chain[13] and simpler and more reliable chains at the horizon, the solid-state diode-laser system represents the heart of an optical clock, permitting long-term operation. Furthermore, the DLS serves as the crucial part of a certain class of atom interferometers that now can be made portable for a variety of field investigations.

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