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Absolute optical frequency measurement of the cesium D_2 line

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We have performed an absolute optical frequency measurement of the cesium D_2 line at 352 THz (852 nm). This frequency is an important scaling parameter in atomic interferometry. The D_2 line has been compared with the fourth harmonic of a methane stabilized He-Ne laser at 88.4 THz (3.39 μm). A frequency mismatch of 1.78 THz between 4×88.4 THz$=354$ THz and the D_2 line was bridged with an optical frequency comb generator. We find $f_{D2}=351\,725\,718.50(11)$ MHz for the hyperfine centroid, improving previous results by almost two orders of magnitude.

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The cesium atom serves as the primary standard of time and it plays an important role in many experiments on laser cooling, trapping, and atom interferometry. Interferometric measurements of the local gravitational acceleration performed with cesium atoms [1], for example, rely on a precise value of the absolute frequency of the Cs D_2 line. Using an optical frequency comb generator [2,3], which allows the measurement of frequency differences in the terahertz (THz) range, we have determined the absolute frequency f_{D2} of the cesium D_2 resonance line near 852 nm to 3.1 parts in 10^{10}, surpassing the accuracy of the best previous measurements by almost two orders of magnitude [4]. In our experiment we compare the frequency of the cesium D_2 resonance line with the fourth harmonic of a transportable CH_4-stabilized 3.39-μm He-Ne laser [5].

The reference laser was calibrated in November 1995 against a second transportable He-Ne standard [7] and in June and July 1996 at the Physikalisch Technische Bundesanstalt (PTB) in Braunschweig against a microwave cesium atomic clock with their phase-locked harmonic laser frequency chain [6]. At that time its frequency was determined to $f_{HeNe}=88\,376\,182\,599\,937(23)$ Hz [8]. The measurement of the cesium D_2 line was performed shortly after this calibration from December 1996 to January 1997.

The frequency of the grating stabilized laser diode [9] at 852 nm, which probes the cesium D_2 line, is set as shown in Fig. 1. A color center laser is phase-locked to the second harmonic of the He-Ne standard by controlling the beat frequency between them with an electronic phase-locked loop. With an intracavity electro-optic modulator and a piezo-mounted folding mirror the frequency of the color center laser is forced such that the beat frequency oscillates in phase [10] with a precise radio-frequency reference of a few MHz (not shown in the figure). The frequency of the color center laser is then known as precisely as the He-Ne standard. At 848 nm a laser diode is phase-locked to the second harmonic of the color center laser. The beat frequency that is used for this lock is shifted first by mixing it with a radio frequency f_{rf} provided by a synthesizer. A double balanced mixer, used for this purpose, produces the sum and the difference frequency of the beat note and f_{rf}. This allows for an adjustable frequency offset in the GHz range between the laser diode at 848-nm and the fourth harmonic of the He-Ne standard ($4f_{HeNe}$). The 848-nm laser diode is then used to drive an optical frequency comb generator [2,3] that produces a few hundred sidebands by efficient electro-optic modulation in $LiNbO_3$. The comb generator consists of a monolithic optical cavity that is placed inside a microwave cavity that

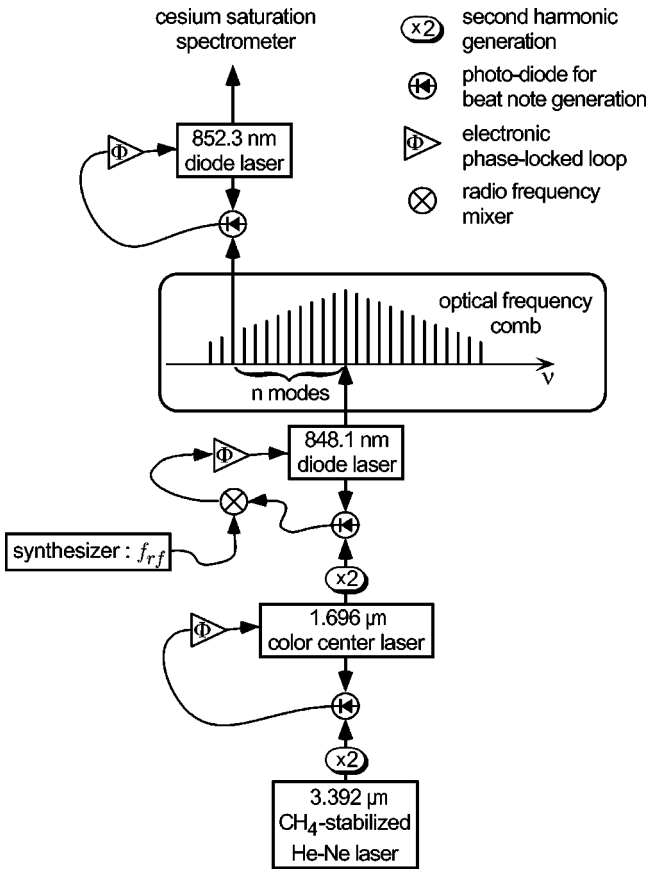


FIG. 1. Frequency chain that allows the comparison of the precisely known frequency of a methane stabilized He-Ne laser at 88.4 THz (3.39 μm), with the cesium D_2 transition at 352 THz (852 nm).

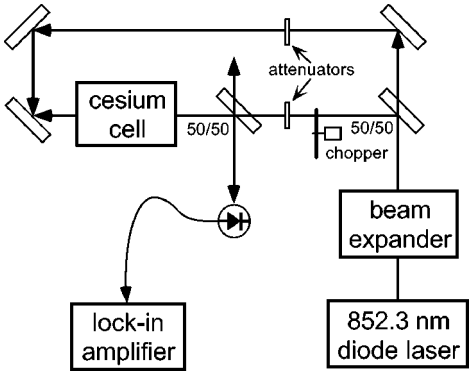


FIG. 2. Saturation spectrometer.

resonantly enhances the modulating field. The optical radiation is enhanced as well by locking one of the resonance fringes to the input from the laser diode. The free spectral range of the optical cavity is chosen such that twice its fringe separation coincides with the modulation frequency so that modulation sidebands are resonantly enhanced and can efficiently produce additional side bands. The comb generator was operated at a modulation frequency of $f_{OFC} = 6.3418$ GHz, which sets the separation of the sidebands. In the last step the probe laser is phase-locked to the nth sideband at the red side of the carrier. The probe laser is scanned over the hyperfine components of the cesium D_2 line by changing the frequency f_{rf}. The frequency chain described here is similar to parts of an existing chain that was used to determine the isotope shift of the hydrogen/deuterium $1s$-$2s$ transition frequency [11].

With the frequency chain phase-locked the frequency of the probe laser at 852 nm is related to other known frequencies by

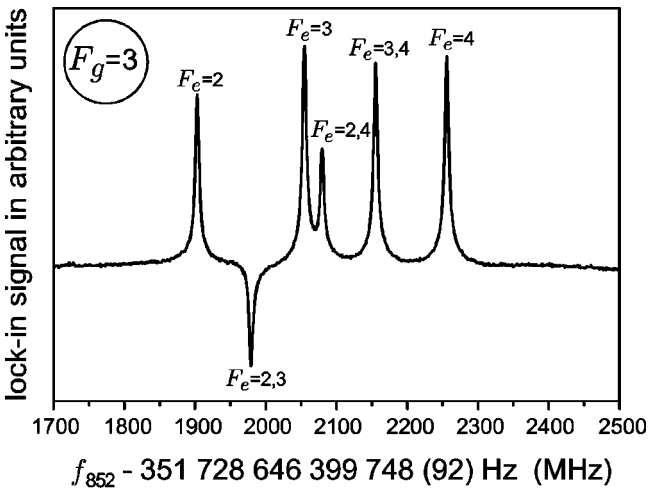
$$f_{852} = 4 f_{HeNe} - n f_{OFC} \pm f_{rf} - 380 \text{ MHz},$$

where the offset of 380 MHz is due to the reference frequencies used for phase-locking. The sign of f_{rf} is chosen by selecting the correct radio frequency at the output of the double balanced mixer with a bandpass filter.

The mode number n was determined by a coarse measurement of f_{852} with a wavemeter. To probe the hyperfine transitions starting from the $F_g = 3$ ground state we used $n = 280$ and the positive sign, while for the $F_g = 4$ ground state we used $n = 281$ and the negative sign of f_{rf}, so that f_{852} is derived from

$$\begin{aligned} f_{852} &= 351\,728\,646\,399\,748(92) \text{ Hz} + f_{rf} \quad \text{for } F_g = 3, \\ f_{852} &= 351\,722\,304\,599\,748(92) \text{ Hz} - f_{rf} \quad \text{for } F_g = 4. \end{aligned} \tag{1}$$

Here the 92-Hz uncertainty of the 852-nm probe laser is determined from the uncertainty of the frequency of the He-Ne reference laser only. All radio frequencies, including f_{rf}, are referenced to a commercial cesium atomic clock (Hewlett Packard model HP 5071A with a specified accuracy of 10^{-12}) and therefore contribute with a negligible uncertainty. The main source of uncertainty is introduced by the Cs spectroscopy.



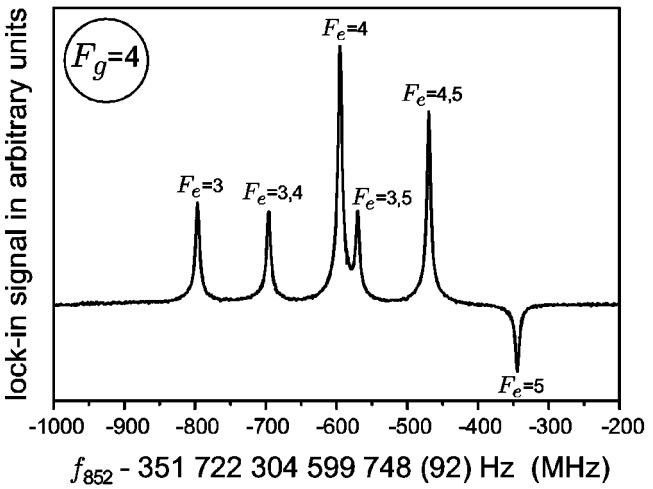


FIG. 3. Top: hyperfine components and crossover resonances (labeled with two angular momentum numbers F_e) of the cesium D_2 line starting from the ground state total angular momentum $F_g = 3$. Bottom: same with $F_g = 4$.

To probe the cesium D_2 line we used the same saturation spectrometer [13] as used for a recent determination of the cesium D_1 transition [12]. It consists of a cesium cell that is illuminated by two counterpropagating laser beams (Fig. 2). The pump beam redistributes the occupation number mainly by optically pumping the ground-state hyperfine levels. For most of the observed hyperfine components the atoms are pumped into the other ground-state hyperfine level so that the absorption of the probe beam is decreased. For some components the pumping fills up the probed level so that the line appears to be inverted [13]. The pump beam is chopped and the difference in absorption is detected with a lock-in amplifier. Because one beam can change the absorption of the other only through atoms whose Doppler shift is the same for both beams we detect only atoms that do not move along the laser beam axis. With this Doppler-free method we

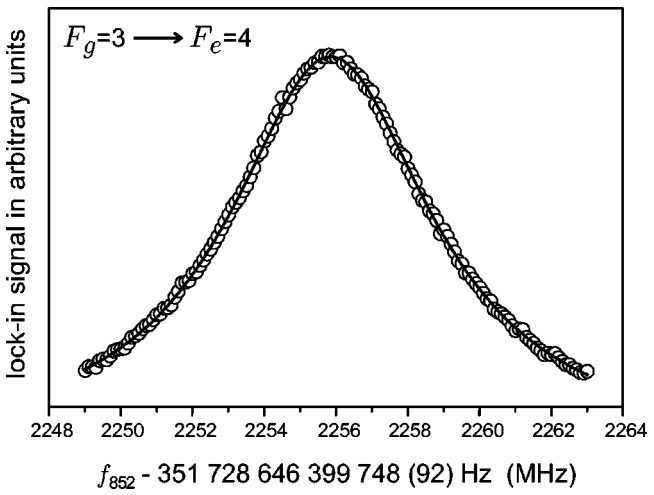


FIG. 4. The $F_g=3\rightarrow F_e=4$ resonance as in Fig. 3 with expanded frequency axis and fitted Lorentzian.

observe six hyperfine components of the single stable isotope ^{133}Cs for the transitions from the $6S_{1/2}$ ground states with total angular momentum $F_g=3$ and $F_g=4$ to the $6P_{3/2}$ upper states with $F_e=2$, $F_e=3$, $F_e=4$, and $F_e=5$ (see Fig. 3). In addition to the six hyperfine components we observe six crossover resonances. These resonances occur if two components within the Doppler width share a common level. In this case a velocity class of atoms with $v\neq 0$ is probed giving rise to a resonance that lies halfway in between the two transitions.

The two laser beams are polarized linearly in the vertical direction. The pump and the probe beam intensity was less than 15 μW/cm^2 and less than 4 μW/cm^2, respectively. The saturation intensity for the most intense component ($F_g=4$, $M_{Fg}=\pm 4\rightarrow F_e=5$, $M_{F_e}=\pm 5$) is 1.1 mW/cm^2 [13]. The 2-cm-long cesium cell was held at room temperature and shielded with two layers of μ metal, which reduced the longitudinal component of the magnetic field below $B=2$ μT. The observed linewidth of a single component was about 6.9 MHz full width at half maximum (natural linewidth is 5.2 MHz [14]).

We find the line center of the resonances by fitting the peaks separately with a Lorentzian and linear background, as shown in Fig. 4. Each of the 12 components was recorded twice so that a total of 24 values for the hyperfine centroid could be calculated from the known hyperfine splittings [15].

Asymmetric pumping of the M_F levels could lead to a systematic Zeeman shift of up to $\mu_B(g_{F_e}M_{F_e}-g_{F_g}M_{F_g})B$ of the line centers rather than a pure line broadening, as one would expect for symmetrical pumping. With Bohr magneton $\mu_B=14$ GHz/Tesla and the Landé g factors the maximum possible shift that is compatible with the selection rules for dipole transitions is between 9 and 51 kHz depending on the selected hyperfine component. Another systematic effect that was not controlled in this measurement is the fact that scanning the absolute optical frequency and reading the signal with a lock-in amplifier with a nonvanishing time constant could lead to a shift of the observed line centers. Because the $F_g=3$ components were scanned in the opposite direction than the $F_g=4$ components (f_{rf} was increased in both cases) we expect that this effect cancels when calculating the hyperfine centroid. For the separated components we estimate this effect to contribute a 40-kHz systematic uncertainty. An additional uncertainty is introduced because of a missing quantitative model for the actual line shape. As shown in Ref. [13] the line shape depends on various parameters such as the polarization and the laser power. Some lines can even be inverted just by changing the laser power in one of the beams. We tried to estimate this uncertainty by comparing the measured crossover resonances with their position relative to the expected mean of the two components that give rise to the crossover (see Table I). In addition, we check the observed ground-state hyperfine splitting and compare it to the defined value of the SI second (SI=international system of units). In contrast to a recent measurement of the Cs D_1 line [12] this cross check is not compatible with the largest possible Zeeman shift which is part of the line-shape uncertainties. Therefore we estimate the uncertainty of each component to 110 kHz, which is the

TABLE I. Result of the absolute frequency measurements of the cesium D_2 line in kHz. The measured radio frequencies of the line centers are given in the second column with their statistical uncertainty only. Two methods are used to check the consistency of the data: First the measured cross over resonances are compared with the frequencies calculated from the regular resonances that make up the particular crossover; and second by comparing the three different combinations that yield the ground-state hyperfine splitting with the definition of the SI second. We attribute the obvious inconsistency to the deficiency of our simple line-shape model and estimate the uncertainty of each component to 110 kHz, which is the average value of the above-mentioned discrepancies.

Transition	f_{rf}	Absolute frequency
$F_g=3\rightarrow F_e=2$	1 903 211(7)	351 730 549 611
$F_g=3\rightarrow F_e=2,3$	1 979 088(19)	351 730 625 488
$F_g=3\rightarrow F_e=3$	2 054 568(47)	351 730 700 968
$F_g=3\rightarrow F_e=2,4$	2 079 643(33)	351 730 726 043
$F_g=3\rightarrow F_e=3,4$	2 155 168(51)	351 730 801 568
$F_g=3\rightarrow F_e=4$	2 255 814(18)	351 730 902 214
$F_g=4\rightarrow F_e=5$	344 238(45)	351 721 960 362
$F_g=4\rightarrow F_e=4,5$	469 532(32)	351 721 835 068
$F_g=4\rightarrow F_e=3,5$	570 152(12)	351 721 734 448
$F_g=4\rightarrow F_e=4$	595 056(34)	351 721 709 544
$F_g=4\rightarrow F_e=3,4$	695 792(18)	351 721 608 808
$F_g=4\rightarrow F_e=3$	796 375(27)	351 721 508 225

TABLE II. Previous results for the frequency the cesium D_2 line.

Author	Cs D_2 frequency
Eriksson *et al.* (1964) [16]	351 725 742(30) MHz
Avila *et al.* (1986) [17]	351 725 769(12) MHz
Carlsson *et al.* (1996) [18]	351 725 757(9) MHz
this work	351 725 718.50(11) MHz

mean of the deviations mentioned. Other systematic effects, such as the ac-Stark effect, light-pressure-induced line-shape modifications [19], spurious selective reflection signals, and collisional shifts [20] shifts are estimated to be much smaller.

Accounting for the known hyperfine structure of the excited level [magnetic dipole coefficient $A=50.275(3)$ MHz, electric quadrupole contribution $B=-0.53(2)$ MHz [15]] and the defined hyperfine splitting of the ground level (9 192 631 770 Hz), we obtain 12 independent values for the hyperfine centroid. Their mean value is

$$f_{D_2}=351\,725\,718.50(11)\ \text{MHz}. \qquad (2)$$

The stated uncertainty is the same as for a single component because it may be due to a common systematic effect that does not average out. Our result is almost two orders of magnitude more precise than the previous measurements that are listed in Table II. In the future we may improve this result by using a better spectrometer. Then it may even be possible to derive new values for the excited-state hyperfine splitting.

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