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ARTICLES

Suppression of the high-frequency recoil component in optical Ramsey-fringe spectroscopy

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The high-frequency recoil component is suppressed in the optical Ramsey resonance by utilizing optical pumping from the ground state to one of the magnetic sublevels of the upper state. This method requires no extra laser for suppression. With a moderate pump power and an exact tuning of the magnetic field, the high-frequency recoil component of the Ca intercombination line ${}^1S_0$-${}^3P_1$ was suppressed completely.

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The calcium intercombination line (${}^1S_0-{}^3P_1$ $m_J=0\rightarrow 0$, $\lambda=657$ nm) is an excellent candidate for an optical-frequency standard and is extensively and precisely studied [1–4]. Using optical Ramsey-fringe spectroscopy, which provides the highest resolution, a 23-kHz separated photon recoil doublet of the intercombination line was clearly resolved. However, this doublet structure causes a serious problem in the determination of the exact center frequency of the transition. First, the line shape of the Ramsey fringe is distorted due to the second-order Doppler effect of the thermal atomic beam [5]. If a monochromatic atomic beam provided by laser cooling [6,7] or by velocity selection [8,9] is used, this effect will be removed. But the increased number of fringes of the two components owing to the monochromatic beam will overlap each other and will alter the line shape in a resolution-dependent manner. Therefore, the suppression of one of the recoil components is necessary in order to determine the exact transition frequency.

To suppress the low-frequency recoil component, Bordé has proposed to observe crossover resonance between the transitions to the $m_J=\pm 1$ upper states using a σ-polarized laser beam [10]. Recently, Riehle, Ishikawa, and Helmcke presented a method and demonstrated the suppression of the low-frequency recoil component in both saturation spectroscopy and optical Ramsey-fringe spectroscopy by removing the upper-state population using optical pumping [11]. However, this method needs one extra laser for suppression. The high-frequency recoil component also should be suppressed for precision measurement of the frequency separation between the

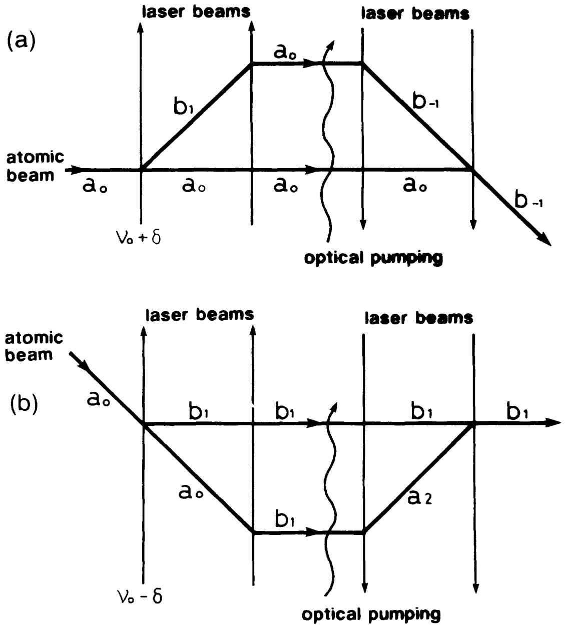

FIG. 1. The interaction geometry of the atom and the four traveling waves which contribute to the Ramsey fringe. (a) shows the paths which contribute to the high-frequency recoil component. After the second excitation wave, the atoms are in the ground state. (b) shows the paths which contribute to the low-frequency recoil component. The atoms are in the upper state after the second wave. Ramsey fringes are suppressed with an optical pumping beam at the zone between the second and the third interaction zones.

recoil doublets.

In this paper, we present a simple technique to suppress the high-frequency recoil component utilizing optical pumping from the ground state to the other Zeeman sublevel of the upper state. The main principle of this method is the same as the method presented by Riehle, Ishikawa, and Helmcke [11]. However, the present method needs no extra laser for suppression and is applicable only for optical Ramsey resonance, because the requirement for the saturation spectroscopy is more stringent [11].

The basic Ramsey fringe method is in principle identical to the stimulated photon echo, which is theoretically investigated by Mossberg and co-workers [12,13]. The optical Ramsey resonance composed of four traveling waves is well described by Bordé *et al.* [14]. According to their idea, interaction geometries for each recoil component of the Ramsey fringe are given as shown in Fig. 1 [13,15]. Since the photon has momentum $\hbar k$, the atom belongs to a different velocity group before and after the absorption (or emission) of the photon. Each segment is labeled by a given state a (ground state) or b (upper state) and by an integer m which indicates the net number of light quanta $\hbar k$ which have been exchanged from the initial momentum p_0. Figure 1(a) corresponds to the high-frequency recoil component of the Ramsey resonance which resonates at a frequency of $\nu_0+\delta$, where ν_0 is the transition frequency and $\delta=h\nu_0^2/(2Mc^2)$. Figure 1(b) corresponds to the low-frequency recoil component which resonates at $\nu_0-\delta$. At a dark zone after the second excitation wave, population grating in the v_z space is generated [12]. The atom populates only in the ground state in the dark zone in the geometry of the high-frequency recoil component and populates in the excited state in the geometry of the low-frequency recoil component. If the upper-state population grating is removed in the region between the two counterpropagating waves, the low-frequency recoil component will be suppressed. Riehle *et al.* used a second laser which was resonant at the transition ${}^3P_1-{}^3S_1$ ($\lambda=612$ nm) in order to optically pump the ${}^3P_1$ population into the ${}^3P_{0,2}$ metastable states through the short-lived ${}^3S_1$ state. In the same way, the high-frequency recoil component is suppressed if the lower-state population grating is removed. We planned to remove the lower-state population by pumping to the Zeeman sublevel $m_J=1$ (or $m_J=-1$) of the ${}^3P_1$ state using a σ-polarized wave. As the Zeeman sublevels have the same lifetime, optically pumped atoms are also detected when they fluoresce. But they do not affect the Ramsey fringe because they are out of Ramsey geometry and contribute only to the signal as background with a Doppler-broadened profile.

In order to select the $m_J=0$ to 0 field-insensitive transition, a transverse magnetic field (2.1 MHz/G) was superimposed on the interaction zone and the energy of the $m_J=\pm1$ level of the ${}^3P_1$ state was shifted from the $m_J=0$ level. Therefore, we shifted the frequency of the optical-pumping laser from the laser for the Ramsey fringe by a frequency shifter and adjusted the magnetic-field intensity so that the σ and π transitions occur at the same tuning of a single laser.

Figure 2 shows the present experimental setup used to suppress the high-frequency recoil component. In the absence of the third beam, this system is the same as the standard one used for Ramsey resonance in the optical domain [2]. In this case, a collimated Ca atomic beam passes two counterpropagating parallel pairs of traveling waves with an equal space D. A high-resolution dye laser

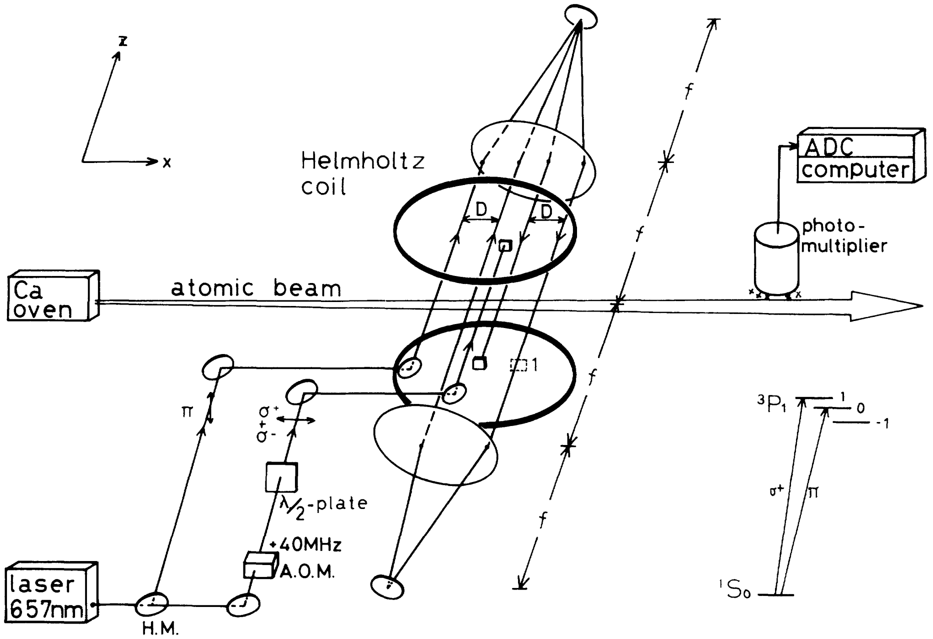

FIG. 2. Experimental setup for the detection of optical Ramsey fringe with only low-frequency recoil component, together with a partial energy diagram of Ca.

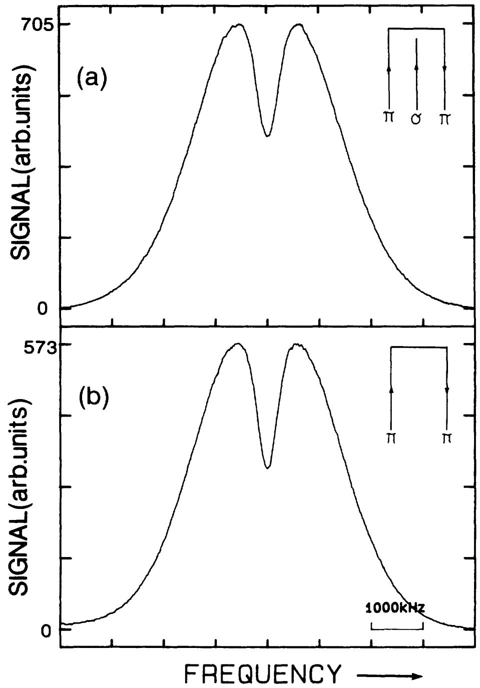

FIG. 3. Saturated absorption spectrum (obtained with the laser beam blocked at position 1, see Fig. 2) with the optical pumping beam (a) on and (b) off.

spectrometer [16] was tuned to the frequency of the Ca intercombination line. The output beam with a linear polarization parallel to the magnetic field (π beam) was used for the Ramsey excitation of the $m_J=0$ to 0 transition. The laser power was 3 mW. It should be mentioned that this power does not necessarily correspond to the $\pi/2$ pulse. The laser power required for a $\pi/2$ pulse was 0.6 mW for the atom with the most probable velocity of 780 m/s [17]. However, since the atomic beam has a large velocity distribution, the highest Ramsey-fringe contrast was obtained at a power level of ~3 mW. Part of the output from the laser was shifted 40 MHz up by an acousto-optic modulator and sent to the zone between the second and the third Ramsey excitation beams, after passing a $\lambda/2$ plate to turn the polarization plane 90° (σ beam). The diameter of each laser beam was 3 mm at the excitation zone. The excited atoms are detected about one decay length downstream by monitoring the resonant fluorescence. Correct phase alignment of two pairs of traveling waves was achieved by two cat's eyes.

The σ beam was aligned well parallel to the other beams by monitoring the Lamb dip pattern generated by using a retroflected beam. The shift frequency between the σ and π beams was perfectly compensated by tuning the magnetic field to a value at which the fluorescence signal became minimum in the Lamb dip generated by parallel π and σ beams. The condition required for the field homogeneity was not so rigorous because the resonance was broadened to ~480 kHz (full width of the Lamb dip) by the transit time. It was $\Delta B/B < \sim 1\times10^{-2}$ in a region of a few mm^2. This was easily satisfied by a Helmholtz coil of 20 cm in diameter and 15 cm in separation.

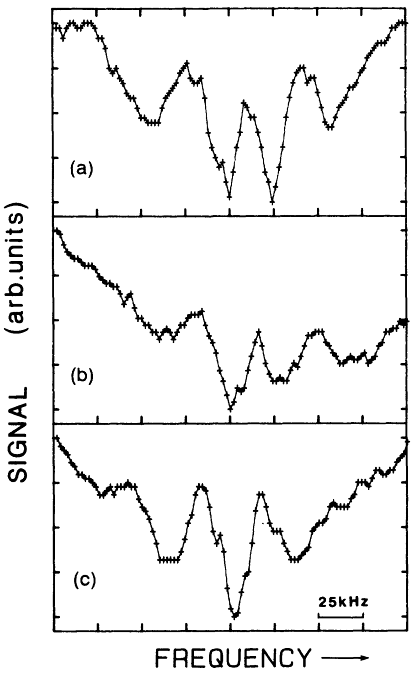

FIG. 4. Ramsey-fringe patterns with the field separation of $2D=23$ mm observed at different optical pumping power levels I_P: (a) $I_P=0$ mW, (b) $I_P=2$ mW, (c) $I_P=4.5$ mW (5 ms integration time for 1 point).

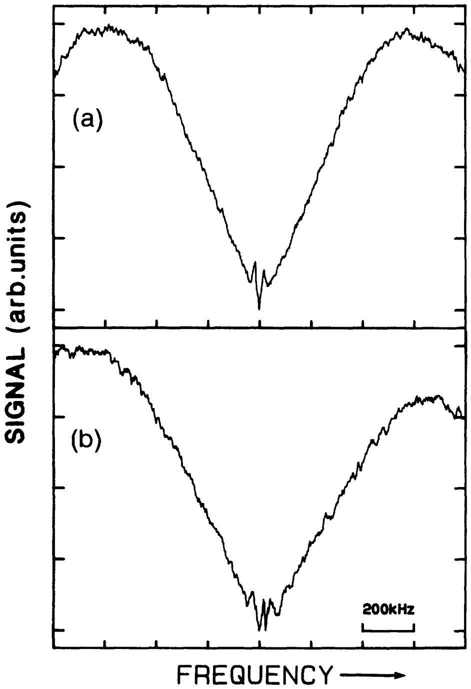

FIG. 5. Ramsey-fringe patterns with the optical pumping laser tuned to (a) on resonance and (b) off resonance, measured at $I_P=4.5$ mW. The tuning was performed by changing the current driving the Helmholtz coil. In (b), the detuning was 2.5 MHz.

Figure 3 shows the saturated absorption spectrum obtained by blocking the π beam at position 1 (see Fig. 2) with the optical pumping laser (a) on and (b) off. The power of the optical pumping laser was 9 mW. Since the optical pumping laser has a linear polarization perpendicular to the magnetic field, half the power was used to excite the $m_J=0\rightarrow 1$ transition. Hereafter, we call half the power I_P. When the optical pumping laser ($I_P=4.5$ mW) was on, the intensity increased approximately 1.25 times. The increment shows the effect of optical pumping. The width of the Lamb dip was 500 kHz, which is almost the same as that obtained without the optical pumping beam. This result shows that the field is sufficiently homogeneous and that both beams were well aligned parallel to each other.

We recorded Ramsey fringes at a field separation of $2D=23$ mm, corresponding to a Ramsey-fringe cycle of about 35 kHz. This is sufficient to resolve the recoil splitting. The fringe patterns obtained at different pumping power levels are shown in Fig. 4. The fluorescence signal was monitored with an integration time of 5 ms per point. At $I_P=0$, two peaks with a separation of 23.1 kHz and the same height are clearly visible [Fig. 4(a)]. At $I_P=2$ mW, the height of the high-frequency recoil peak clearly becomes smaller than that of the low-frequency recoil peak [Fig. 4(b)]. At $I_P=4.5$ mW, the high-frequency recoil peak disappeared completely and only the low-frequency component with the side fringes in both sides is observed, [Fig. 4(c)]. At this power level, the atoms related to the high-frequency component of the Ramsey fringe were pumped to the $m_J=1$ state perfectly (π pulse) and the suppression was achieved. If the power was further increased to generate a 2π pulse, the high-frequency recoil peak should appear again. But the measurement at higher power levels could not be made because of available laser power limitations.

In order to ascertain that the suppression of the high-frequency recoil component of the Ramsey fringes was not due to the distortion of the Lamb dip, but due to the optical pumping of the population in the ground state, we compared the two signals obtained with the optical pumping laser tuned to "on" resonance [Fig. 5(a)] and "off" resonance [Fig. 5 (b)]. When an optical pumping laser with a power of $I_P=4.5$ mW was detuned 2.5 MHz, the pattern of the Lamb dip became asymmetric and a doublet structure appeared again, as shown in Fig. 5(b).

In conclusion, we demonstrated the suppression of the high-frequency recoil component in Ramsey-fringe spectroscopy. The high-frequency recoil component could be suppressed well under a moderate pumping power, when both laser beams were aligned parallel and the frequency shift between π- and σ-polarized beams was canceled by tuning the magnetic field. Riehle *et al.* discussed the possibility of a broadband blue lascr to pump the ground-state population to a short-lived excited state ${}^1P_1$ in order to suppress the high-frequency recoil component [18]. The present technique requires no extra laser. It will simplify the determination of the line center when the laser-cooled atomic beam is in use for spectroscopy. Furthermore, precise measurement of h/M_{Ca} will be possible if two frequency-stabilized lasers are locked to each of the two recoil peaks, respectively.

Note added. After this work was completed, suppression of the high-frequency recoil component by using a blue laser was recently reported by Riehle *et al.* [18].

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