Coherent population trapping resonances in thermal ^{85}Rb vapor: D_1 versus D_2 line excitation

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We have compared coherent population trapping (CPT) resonances, both experimentally and theoretically, for excitation of the D_1 and D_2 transitions of thermal ^{85}Rb vapor. Excitation of the D_1 line results in greater resonance contrast than excitation of the D_2 line and in a reduction in the resonance width, in agreement with theoretical expectations. These results translate into a nearly tenfold improvement in performance for the application of CPT resonances to a frequency standard or a sensitive magnetometer when the D_1 line, rather than the D_2 line, is used.

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Recent growing interest in miniature atomic frequency references[1] and precision magnetometers[2,3] has motivated detailed investigations of coherent population trapping (CPT) and its use in such applications. System designs that use CPT make possible substantial reductions in size, power, and cost for both atomic clocks and magnetometers. Coherent dark states that exhibit CPT[4] can be prepared in a Λ system in which the two hyperfine components of the $S_{1/2}$ ground state of an alkali atom are coupled to a common excited state by two laser fields that are nearly resonant with the two atomic transitions. If the frequency difference of the laser fields is close to the atomic hyperfine splitting, Δ_{hfs}, of the two ground states, quantum coherence between the two hyperfine components will be effectively generated. As a rule, this quantum coherence reduces the total absorption and fluorescence,[5] and, under certain conditions, atoms can be completely trapped in a dark state, where they cannot be excited by the applied light. Atomic clocks take advantage of the narrow transitions between long-lived magnetic-field-insensitive ground states ($m_F = 0$), whereas for magnetometers magnetic-field-sensitive states ($m_F \neq 0$) are used.

For applications to both atomic clocks and magnetometers it is important that the contrast of the CPT resonance line be large and its width be small. For our purposes the contrast is defined as the change in transmitted power that is due to the CPT effect, divided by the total absorbed power. Past experiments with the D_2 line of ^{133}Cs (Ref. 1) have shown that the signal contrast for atomic clocks that use the CPT effect is roughly 1%, almost an order of magnitude smaller than the typical signal contrast for conventional optical-microwave double-resonance designs.[7] Motivated by some general theoretical considerations, in our present study we compare the width and contrast of CPT in ^{85}Rb observed for D_1 excitation ($5S_{1/2} \rightarrow 5P_{1/2}$) with the results obtained for D_2 excitation ($5S_{1/2} \rightarrow 5P_{3/2}$).

One important difference between the two excitation lines is in the excited-state hyperfine structure [see Fig. 1(b) for the specific case of ^{85}Rb]. The $P_{1/2}$ excited state has only two hyperfine levels (labeled $F' = I \pm 1/2$, where I is the nuclear spin quantum number), both of which couple to both hyperfine ground states and contribute to the coherence preparation. The $P_{3/2}$ excited state, however, has four excited-state hyperfine levels ($F' = I \pm 1/2$, $I \pm 3/2$), only two of which

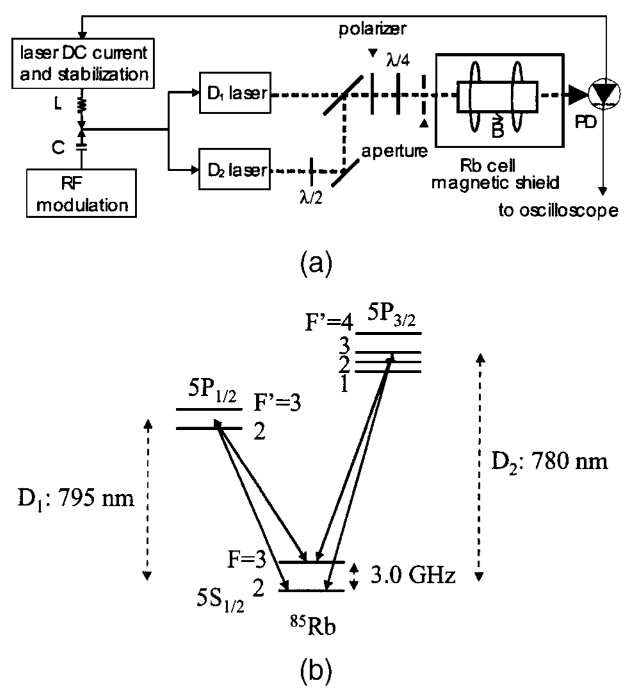

Fig. 1. Experimental setup for the comparison of the CPT resonances for excitation when the D_1 and the D_2 transitions are used.

($F' = I \pm 1/2$) couple to both ground-state hyperfine levels simultaneously, owing to selection rules. The uncoupled levels on the D_2 line ($F' = I \pm 3/2$) do not contribute to the coherence preparation and reduce the lifetime of the coherent dark state because they allow atoms to escape from the trapped state through direct (one-photon) absorption. This loss of atoms is expected to increase the CPT resonance width, and decrease its contrast, for excitation on the D_2 transition compared with excitation on the D_1 transition.

A second difference between excitation on the two transitions involves the Clebsch–Gordan (C–G) coefficients of the optical transitions. For example, in the case of σ^+ excitation each excited-state hyperfine level that couples (by means of single-photon electric-dipole transitions) to both ground states results in a unique dark state for the two $m_F = 0$ levels of the ground states. This dark-state composition depends on the ratio of the field Rabi frequencies and hence on both the ratio of the optical power in the two excitation fields and the ratio of the C–G coefficients of the transitions being excited. Because the excitation light at some level couples the ground states to both of the excited hyperfine levels (owing to the Doppler and buffer-gas broadening of the optical transition), a pair of dark states is simultaneously excited for each fine-structure line.[8] If these dark states are similar (i.e., the corresponding ratios of the C–G coefficients are equal), then the coherence will be maximized and the total resonance contrast of the dark line will be high. Unequal ratios of the C–G coefficients, however, will result in lower contrast. For all alkali atoms the ratios of the C–G coefficients are equal for excitation on the D_1 line and are not so for excitation on the D_2 line. Thus a higher contrast might be expected for D_1 excitation.

Guided by these theoretical considerations, we describe here experimental measurements carried out on ^{85}Rb vapor (Fig. 1). The bichromatic light field that forms the Λ system was generated through modulation of the injection current of a distributed Bragg reflector laser at half the ground-state hyperfine frequency, $f_{\mathrm{hfs}} = 3.0$ GHz.[1,9] The two first-order optical sidebands are therefore separated by the full hyperfine splitting, f_{hfs}, and form the Λ system.

For each set of measurements, one of two lasers was used. The first was tuned to the D_1 transition of ^{85}Rb at 795 nm, and the second to the D_2 transition at 780 nm. Both laser beams had the same diameter, and they were superimposed with a beam splitter such that they traveled along the same path in the cell (Fig. 1). Each laser beam was then circularly polarized, was passed through an aperture with a diameter of 5 mm and then through the vapor cell, and finally was detected with a photodiode (PD). The cell (length, 4 cm; diameter, 2 cm) contained a natural mixture of Rb isotopes at room temperature and 0.4 kPa of Ne buffer gas. The Rb cell was surrounded by a magnetic shield, and a small longitudinal magnetic field ($\sim$10 μT) was applied to shift the magnetically sensitive CPT resonances away from the magnetically insensitive resonance ($|F = 2, m = 0\rangle \rightarrow |F = 3, m = 0\rangle$). The diode laser frequency was locked near the center of the optical transition by an active servo. For measurement of the CPT resonance, the synthesizer that produced the microwave frequency was scanned over a range of a few kilohertz near 1.5 GHz, the first subharmonic of the hyperfine transition frequency.

Figure 2 compares the CPT resonance excited by the D_1 transition with that excited by the D_2 transition under the same experimental conditions. Each trace was normalized to the Doppler absorption value that was present when the fields were in optical resonance but out of CPT resonance. It is clear that the CPT width is smaller for D_1 excitation, and the contrast is larger: The contrast for D_1 excitation is close to 10%, whereas for D_2 excitation the contrast is near 2%. For comparison, Cs atoms excited on the D_2 line typically show a contrast of $\sim$1%, with a width comparable to that for Rb for similar buffer-gas pressure.[10] We normalize to the Doppler absorption profile for the following reason: For common operating parameters (cell length, buffer-gas pressure, etc.) the CPT signal slope is optimized when the cell temperature is adjusted such that approximately one half of the optical power is absorbed by the Doppler background.[11] Therefore, if we were to optimize the cell temperature for each of the two transitions independently, the relative signal amplitudes would be exactly those shown in Fig. 2. The Doppler absorption was measured to be 12% for the D_1 resonance and 39% for the D_2 resonance. Thus the height of the D_2 resonance is roughly optimized with respect to cell temperature, but some improvement might be obtained for the D_1 measurement by an increase of the cell temperature.

Figure 3 shows the dependence of the normalized CPT resonance amplitude [Fig. 3(a)] and width [Fig. 3(b)] on the resonant laser intensity for both transitions. The Allan deviation, as a measure of a clock's frequency stability, or the magnetic sensitivity for a magnetometer is proportional to the value of $N/(\partial S/\partial f)$,[7] where N is the detected noise power spectral density, S is the detected signal, and f is the scanning microwave frequency, near $f_{\mathrm{hfs}}/2$. For an optimum detection configuration the slope at the center of the line is a useful figure of merit that can be estimated by the ratio $A_{\mathrm{cpt}}/\Delta f_{\mathrm{cpt}}$, where A_{cpt} and Δf_{cpt} are, respectively, the normalized amplitude

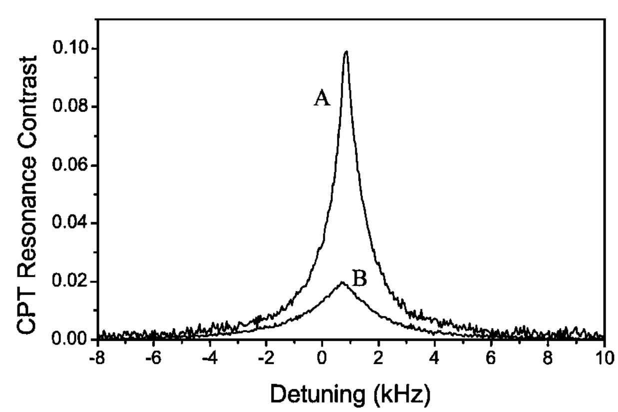

Fig. 2. CPT resonance for excitation on A, the D_1 transition and B, the D_2 transition with a resonant laser intensity of 160 μW/cm^2.

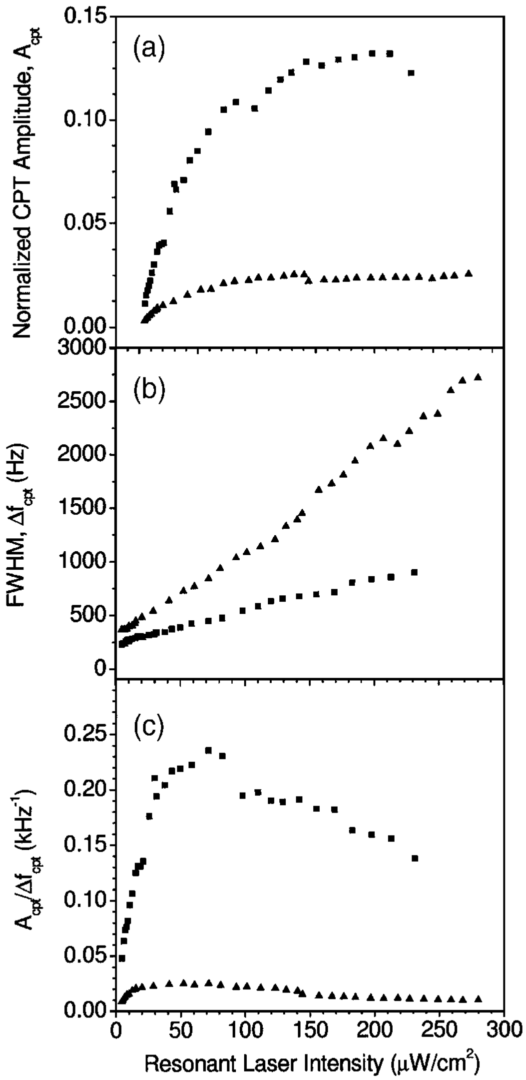

Fig. 3. CPT (a) amplitude, (b) width, and (c) quotient of both quantities, measured for excitation on the D_1 (squares) and the D_2 (triangles) transitions.

and width of the CPT resonance. The dependence of this value on the intensity is shown in Fig. 3(c). It can be seen that the slope in the center of a dark resonance taken with the D_1 transition is almost an order of magnitude larger than that taken with the D_2 transition, suggesting that a significant improvement in the performance of a clock or a magnetometer could be obtained. Indeed, Zhu and Cutler[6] have obtained high stabilities for a CPT clock operating on the D_1 transition of ^{85}Rb. Finally, we note that the performance of clocks and magnetometers that use CPT is 2–3 orders of magnitude worse than that obtained for atomic fountain clocks or superconducting quantum-interference device magnetometers. The advantages of the CPT systems, therefore, lie mainly in the potential for reduced size, power, and cost.

In conclusion, we have measured the contrast and width of CPT resonances excited on both the D_1 and D_2 optical transitions. Excitation of the D_1 transition results in both a narrower resonance width and a larger resonance contrast. It is expected that atomic clocks or magnetometers that use lasers tuned to the D_1 transition will demonstrate as much as a factor-of-10 improvement in performance compared with their D_2 counterparts.

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Note added in proof: Since the submission of this Letter, a patent was issued[12] that addresses many of the issues discussed here. The scientific conclusions in the patent correspond to those presented here.

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