Steep dispersion and group velocity below $c/3000$ in coherent population trapping

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We have measured the index of refraction in the region of a coherent population trapping resonance in a cesium vapor cell with an interferometric technique. We find very high normal dispersion (up to $dn/df = 9.7\times10^{-12}$ Hz^{-1}) at low absorption. From our spectra we obtain very small group velocities below $c/3000$. This corresponds to a delay time of more than 200 ns for a cesium cell 20 mm in length, equivalent to more than 60 m of propagation in vacuum.

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Since the first observation of nonabsorbing (dark) resonances in a Λ system of a ground-state doublet coupled to a common excited state by two coherent light fields [coherent population trapping, (CPT)] [1–3] this effect has been analyzed in a number of experimental and theoretical papers [4–9]. The cancellation of absorption gives rise to the effect of apparent amplification without inversion (AWI) [10] and is used as an efficient cooling mechanism in velocity-selective coherent population trapping (VSCPT) [11]. The properties of the refractivity at the CPT resonance lead to the prediction of an enhanced index of refraction without absorption [7,12], steep dispersion [13] with important applications in the detection of small frequency or phase shifts, the proposal of high sensitivity magnetometers [14], and to group velocities that are more than two orders of magnitude smaller than the vacuum speed of light [13]. Here we report on the simultaneous measurement of absorption and dispersion in the vicinity of a CPT resonance. We find low absorption and extremely steep dispersion corresponding to group velocities of $c/3000$ and less.

In the experiments two laser diodes frequency-stabilized by optical feedback [15,16] were used to excite the cesium D_2 transition [Fig. 1(a)] in a magnetically shielded vapor cell of length $L=20$ mm. One laser (frequency f_1), called the pump laser, is locked to the Doppler-broadened $^2S_{1/2}(F=4)\rightarrow{}^2P_{3/2}$ transitions. The second laser (frequency f_2), called the probe laser, is superposed with the pump beam and propagates through the cell in the same direction and with the same linear polarization. Its output is phase locked [17,18] to the pump laser with a tunable frequency offset around 9.192 631 770 GHz, the cesium ground-state hyperfine splitting. The offset frequency is derived from a stable rf synthesizer so that the detuning $\Delta f = f_2 - f_1 - 9.192\,631\,770$ GHz is known to within 10 Hz, while the relative linewidth δf of the lasers (i.e., the residual phase error accumulated during the integration time of 20 ms per data point) is much less than 1 Hz. Since the width of the CPT resonance cannot be smaller than δf we are left with transit time broadening (30 kHz for the spectra discussed here), power broadening, and residual Doppler broadening (8 kHz for $f_2 - f_1$ in the case of parallel beams, and 600 kHz for an angle of 1 mrad between the beams [4]). The last source of error can be eliminated by coupling both lasers into the same single-mode optical fiber, giving a perfect overlap with a good-quality Gaussian mode at the fiber output.

When the synthesizer frequency is stepped the probe-laser frequency is scanned across the $^2S_{1/2}(F=3)\rightarrow{}^2P_{3/2}(F')$ transitions. Since the Doppler width at room temperature is about 370 MHz the medium is inhomogeneously broadened, and depending on their velocity individual atoms couple to different excited levels for given laser frequencies. For the two velocity classes where both ground states are coupled to a common excited level ($F'=3$ or $F'=4$) by the two light

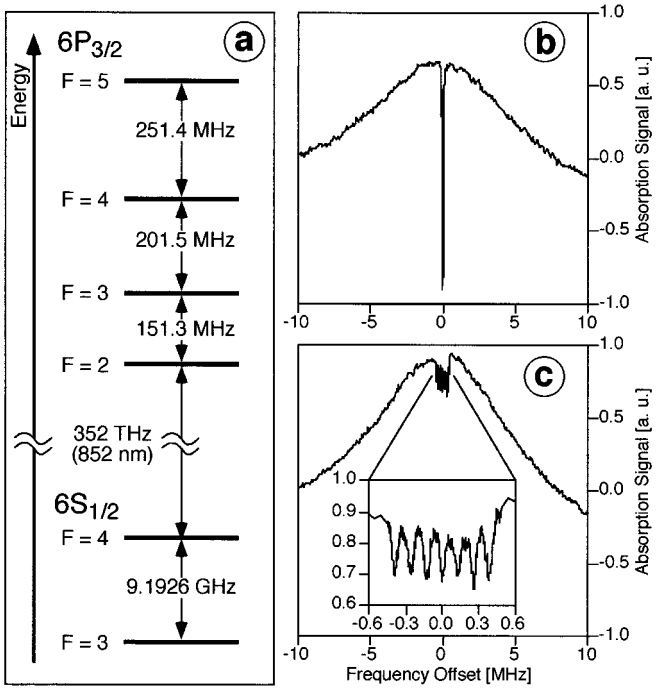

FIG. 1. (a) Relevant energy levels of the cesium D_2 line. (b) Absorption spectrum of the coherent population trapping dip on a hyperfine repopulation pumping peak in zero magnetic field. The absorption is reduced below the usual Doppler absorption. (c) High-resolution spectrum of the coherent population trapping resonance, split into seven components by a longitudinal magnetic flux density of 200 mG, showing a linewidth of 66 kHz for each component ($I_{\text{pump}} \approx I_{\text{probe}} \approx I_{\text{sat}}/10$).

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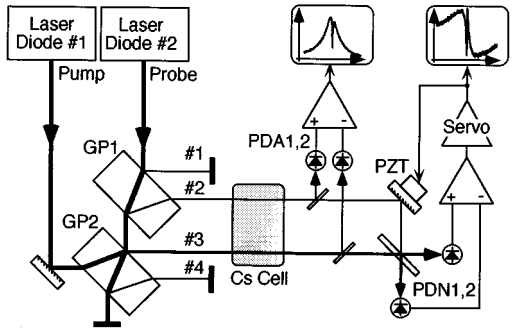

FIG. 2. Experimental setup for simultaneous measurement of the absorptive and the dispersive line shape of the coherent population trapping resonance.

fields CPT occurs, whereas transitions to $F'=5$ and $F'=2$ lead to additional absorption. The absorption spectrum [Fig. 1(b)], measured with a photodiode behind the cesium cell shows the center of the hyperfine repopulation resonance [19], where the pump laser optically pumps population into the $F=3$ ground state so that the probe laser is absorbed more strongly than without the presence of the pump beam. The sharp dip is the CPT resonance at $\Delta f=0$. Note that not only is the enhanced absorption due to hyperfine repopulation pumping compensated but that the total absorption is even less than the normal Doppler-broadened absorption level due to all allowed transitions combined.

Most of the theoretical work on CPT has dealt with a three-level Λ system. In cesium vapor the situation is complicated by the Zeeman substructure (48 levels all in all) and by the fact that Doppler broadening is more than 30 times larger than the natural linewidth and comparable to the spacing of different fine-structure components of the D_2 line. As a result, in a small longitudinal magnetic field and for linear laser polarizations the CPT dip splits into seven components [Fig. 1(c)], each of them representing several Λ systems that are formed between different Zeeman sublevels. The width of the CPT dips is only 66 kHz, or 1% of the natural linewidth of the $F=3\rightarrow F'=4$ transition. The sum of the amplitudes of the seven components equals the dip depth of the zero-field case [Fig. 1(b)]. This is not obvious since all of the ground-state sublevels are part of several Λ systems and are coupled by the σ^+ and σ^- components of the incident linearly polarized laser light. This provides experimental evidence that even for the case of a longitudinal magnetic field the CPT Λ systems interact with each other such that their effects add up only incoherently. Therefore the three-level Λ theories can be expected to describe the system properly when the signal strength is adjusted in accordance with the degree of degeneracy and the relative transition probabilities.

Figure 2 shows the experimental setup for the measurement of the dispersive properties of the CPT resonance. The basic idea is to compare the phase of the weak probe beam in the presence of the CPT-inducing stronger pump beam to the phase of an undisturbed beam. This comparison is done with a Mach-Zehnder interferometer, where in one arm there is only the probe beam, and in the other arm both the pump and probe beams are present and copropagating. Since we are mainly interested in the behavior of the CPT resonance the cesium vapor cell is placed into both arms simultaneously so that effects due to the usual Doppler absorption and dispersion are largely suppressed. This is, however, only true if the probe intensities in both arms are equal and if the beam combiner at the interferometer output is completely symmetric (50% splitter). The first condition can be fulfilled by using an arrangement of two uncoated glass plates (GP1 and GP2 in Fig. 2). The 50/50 splitting ratio was achieved by carefully choosing the angle of incidence on a nominal "50/50" beam splitter. Two thin glass plates with antireflection coated back sides are inserted into the beams to monitor the power transmitted through the cesium cell using photodiodes PDA1 and PDA2. The difference of their photo currents yields the Doppler background corrected absorption spectrum. The intensities at the two interferometer outputs are detected on the photodiodes PDN1 and PDN2. Their difference signal S_n can be written as

$$S_n = \text{const}\times\exp(-\alpha_l L)\exp(-\alpha_{\text{nl}}L/2)\times\cos\left[\frac{2\pi f_2}{c}Ln_{\text{nl}}+\Phi\right], \tag{1}$$

where α_l is the Doppler absorption, α_{nl} and n_{nl} are the pump beam-induced nonlinear absorption coefficient and nonlinear index of refraction, and Φ is an overall phase angle. From Eq. (1) n_{nl} can be determined provided the absorption factors are known. Since these vary strongly across the resonance, S_n is used in a servoloop to control the length of one interferometer arm such that the intensities at both outputs are kept equal, which means that phase changes in arm No. 3 due to a changing index of refraction are compensated by a change in the length of arm No. 2. n_{nl} is then obtained from the control signal of the loop. Since S_n is always zero, changes in absorption (and therefore the scale factor for S_n) during the frequency scan do not cause distortions of the dispersion profile. The servoloop ensures that

$$\Phi=\frac{2m+1}{2}\pi-\frac{2\pi f_2}{c}Ln_{\text{nl}}, \tag{2}$$

which can be solved for n_{nl}. Φ is proportional to the control signal U_{PZT} of the servoloop: $\Phi(U_{\text{PZT}})=\Phi_0+\kappa U_{\text{PZT}}$. Here we neglect the error due to the nonlinearity and hysteresis of the piezoelectric transducer's (PZT's) response, which is less than 1%. The proportionality constant κ is determined by ramping the PZT voltage and noting which voltage is necessary for a full interferometer fringe. The phase shift due to slightly different arm lengths gives rise to a linear background. For a frequency span of typically 5 MHz, this background is more than three orders of magnitude smaller than the dispersion signal of the CPT resonance.

A representative result for a power-broadened dispersion and absorption spectrum is shown in Fig. 3. The steep normal dispersion of $dn/df=8.5\times10^{-12}$ Hz^{-1} is more than 10^5 times higher than in glass while the absorption is essentially zero, except for the background of 50% due to the absorption on the Doppler-broadened transitions to the other F' levels. Since the vapor pressure is less than 10^{-5} mbar the dispersion per atom is about 16 orders of magnitude higher than in ordinary materials of low absorption. Around zero detuning the slope corresponds to a group velocity of $c/2975$.

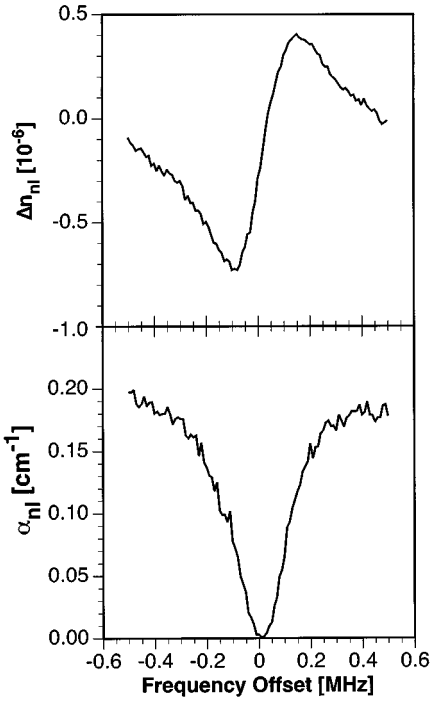

FIG. 3. Representative absorption and dispersion spectra of the CPT resonance for $I_{\text{pump}} \approx I_{\text{sat}}$ where I_{sat} is the saturation intensity of the one-photon $6S_{1/2} \rightarrow 6P_{3/2}$ transition. The dispersion of $dn/df = 8.5 \times 10^{-12}$ Hz^{-1} corresponds to a group velocity of $c/2975$.

In Fig. 4 the group-velocity reduction c/v_{group} is plotted versus the pump-laser intensity. The higher the intensity, the higher the percentage of atoms that are pumped into the CPT dark state, thereby steepening the resonance and thus increasing the group-velocity reduction. When the intensity approaches the saturation intensity of the one-photon $6S_{1/2} \rightarrow 6P_{3/2}$ transition, power broadening wins and leads to a decrease again. The lowest group velocity is $c/3400$. Our 20-mm-long cell then causes the same delay as 68 m of vacuum, i.e., 227 ns. So far the slowest measured pulse propagation is $c/1000$ for 2π pulses in self-induced transparency [20] and $c/14$ for ''ordinary'' pulses [21].

We have studied the dependence of the experimental line shapes from the angle between the beams, their diameters, intensities, detuning, Zeeman shift, and polarizations. These results, as well as a comparison with theoretical predictions, will be discussed in detail in a forthcoming presentation.

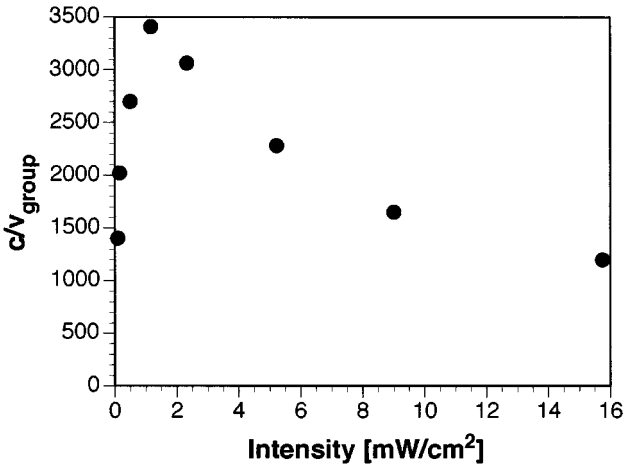

FIG. 4. Group-velocity reduction factor c/v_{group} vs pump beam intensity. Minimum group velocity is reached at about $I_{\text{pump}} = I_{\text{sat}}$.

Since the group-velocity dispersion is zero at $\Delta f = 0$ (linear slope), it is tempting to try to measure the low pulse propagation velocity directly. The region of normal dispersion is about 1 MHz wide so that the shortest pulses that should be able to propagate without too much distortion are a few μs long. In the experimental setup of Fig. 2 the probe-laser beam was sent through an acousto-optic modulator and the zero-order beam coupled into the interferometer. The probe intensity was then sine-, triangle-, or square-wave modulated with a modulation index of up to 10% at frequencies between 1 and 100 kHz. We tried to determine the delay directly from oscilloscope traces of the reference and probe intensity wave forms, using PDA1 and PDA2, respectively. However, depending on modulation frequency and detuning from the CPT resonance the transmitted pulse shapes were strongly distorted, similar to pulse-shape modifications seen earlier in Grischkowsky's experiments [22], where pulses were sent through rubidium vapor under conditions of group velocity around $c/4$. They saw evidence of the formation of an optical shock wave due to the spatial compression of the pulse when entering the medium. In our setup, where the pulse compression is even stronger by a factor of 850, a meaningful measurement of a unique propagation time was therefore not possible.

Note added. While finishing the manuscript we became aware of Ref. [23] where group velocities of $c/13.2$ are calculated from measured dispersion spectra under CPT conditions in rubidium.

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