Observation of transient electromagnetically induced transparency in a rubidium Λ system

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(Received 13 January 1998)

Observation of transient effects in electromagnetically induced transparency (EIT) is reported in Rb^{85} cooled in a magneto-optical trap. The transmission of a weak probe beam in resonance with the $5S_{1/2}(F=3)$ to $5P_{3/2}(F=3)$ hyperfine transition increased transiently when a relatively strong coupling field in resonance with the $5S_{1/2}(F=2)$ to $5P_{3/2}(F=3)$ hyperfine transition was switched on rapidly using a Pockels cell. The probe transient showed an initial Rabi half-cycle overshoot before settling down to steady-state EIT. The results agreed well with computations using a three-state model of the Λ system. The computations also suggest that transient gain should be observed with coupling field power only four times larger than that presently available to us. [S1050-2947(98)03308-3]

PACS number(s): 42.50.Gy, 32.80.Pj, 42.50.Md

The steady-state absorption of a weak resonant probe beam can be reduced or even eliminated by the presence of a strong coherent coupling beam exciting a linked transition. This effect, known as electromagnetically induced transparency (EIT), was first observed in 1991 [1,2]. Related work on coherent population trapping in three-level systems dates from the mid-1970s and has been recently reviewed [3]. In the last few years steady-state EIT has been widely studied in vapor cells and more recently in laser-cooled samples, see reviews [4,5]. Transient EIT effects, however, have received relatively little explicit attention. In the first EIT experiments [1,2] the coupling field was provided by a high power pulsed laser with pulse rise and fall times that were slow compared with the Rabi period of the field. The transient approach to transparency in this adiabatic regime has been analyzed by Harris and Luo [6] from the point of view of energy requirements for the establishment of the transparency. We are interested in the nonadiabatic regime where the coupling field is switched on in a time that is short compared with Rabi periods and relaxation times. The only reported experimental study in this regime is that of Fry *et al.* [7], who observed transient absorption of a probe pulse in a Λ system immediately after the coupling beam was rapidly switched off. This is the converse of our experiment where the coupling field is rapidly switched on. Three-state models of transient effects in probe transmission when the coupling field is switched on nonadiabatically have been reported [8,9]. In these models the transmission of a weak resonant probe approaches the steady-state EIT via damped oscillations characterized by the Rabi frequency of the relatively strong coupling field Ω_C and the excited state decay rate Γ, and for a sufficiently strong coupling beam there are intervals of probe gain without inversion, even without incoherent pumping. Thus there are possible applications to fast optical switching and lasing without inversion.

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We report an observation of transient EIT effects in the nonadiabatic regime, using a ^{85}Rb sample cooled in a magneto-optical trap (MOT). A three-level Λ system was chosen comprising the $F=3$ to $F'=3$ and the $F=2$ to $F'=3$ hyperfine components of the $5S_{1/2}$-$5P_{3/2}$ transition. See Fig. 1(a). Details of the MOT are described elsewhere [10]. Both probe and coupling field were provided by grating-controlled external-cavity diode lasers with linewidths of a few hundred kilohertz. The coupling field was switched on by a Pockels cell with a rise time of 3 ± 1 ns and remained on without substantial variation in transmission for more than 1 μs. The arrangement is shown in Fig. 1(b). After passing through the sample, the probe beam was detected using a Thorn EMI 9828b photomultiplier tube. The detected signal was stored in a Tektronix TDS 520B digital oscilloscope. The overall instrumental rise time of about 15 ns is illustrated in Fig. 1(c), which shows the recorded signal from a test beam switched on by the Pockels cell and passing straight to the photomultiplier tube.

The probe used for EIT studies was a 3 μW beam of diameter 1.2 mm and profile-averaged Rabi frequency 0.1Γ, where $\Gamma=5.86\times2\pi$ MHz, the spontaneous decay rate of the $5P_{3/2}$ level. The maximum power available to us for the coupling field was 1.5 mW, prepared in a beam of diameter 2.1 mm at the 1/e points of a Gaussian profile. This gave a profile-averaged Rabi frequency after passing through the Pockels cell of 1.7Γ. Figure 2 shows the steady-state EIT profile obtained when the probe frequency is slowly swept across the $F=3$ to $F'=3$ resonance with a steady coupling field of frequency fixed at the center of the $F=2$ to $F'=3$ line. The dashed curve is the theoretical EIT profile computed from a three-state model using the dephasing rate Γ_P of the two-photon transition as a fitting parameter. The main effect of Γ_P on the profile is to reduce the EIT at the line center. Good agreement is obtained with $\Gamma_P=0.6\Gamma$. We assume that this value of Γ_P describes the effects of laser linewidths, inhomogeneous light shifts, and Zeeman shifts due to the MOT trapping fields, which are on throughout the experiments, as well as the effects of probe absorption on Zeeman

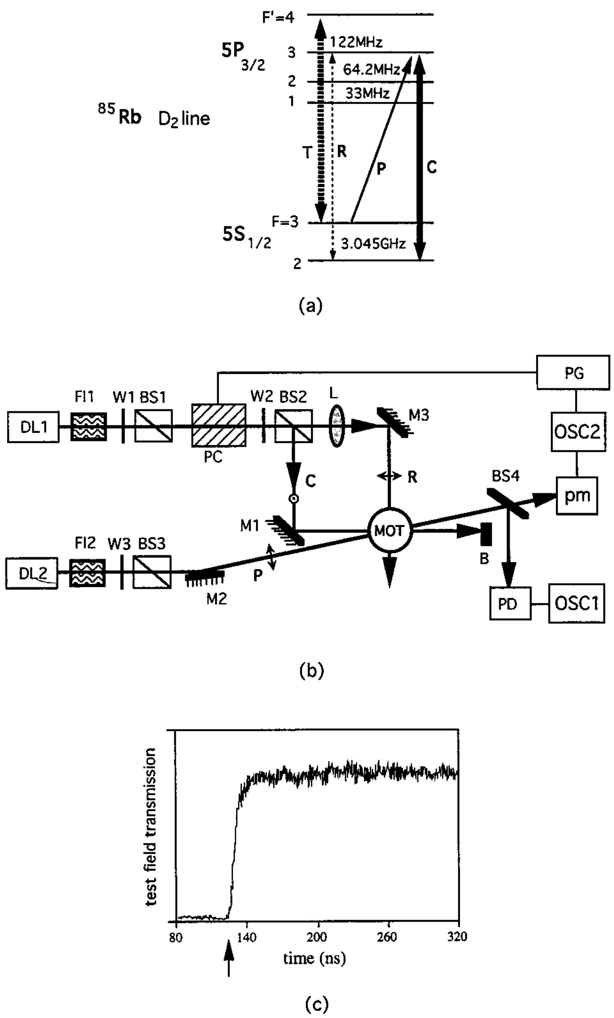

FIG. 1. (a) Hyperfine levels for Λ-type EIT in Rb^{85}. P is a weak probe field resonant with the $F=3$ to $F'=3$ transition, C is a strong-coupling field resonant with the $F=2$ to $F'=3$ transition. T and R are the MOT trapping and repumping fields. P and C are linearly and orthogonally polarized. (b) Pockels cell switching. DL, 1,2 diode lasers for beams C/R and P; FI, 1,2 Faraday isolators; W, 1-3 half-wave plates; BS, 1-3 prism beam splitters; BS4, 50:50 glass plate beam splitter; PC, Pockels cell; L, lens to expand beam to provide weak repumping beam R; pm, photomultiplier detector; PD, photodiode; PG, pulse generator; OSC1, oscilloscope; OSC2, digital oscilloscope. When the Pockels cell is off it passes R and blocks C. When the cell is on it blocks R and passes C. The directions of linear polarizations of C, P, and R are indicated. (c) Recording of a test field transmission with the MOT off showing the overall instrumental rise time of about 15 ns. The arrow indicates the Pockels cell switch-on time.

sublevel transitions for which there is no effective Λ coupling. Off-resonant excitation to hyperfine levels outside the three-level system is negligible with the coupling field power used. The dotted curve in Fig. 2 is the computed probe transmission profile with the coupling field switched off.

In the absence of the coupling field, the trap operates with a repumping beam to give about 95% of the cold $5S_{1/2}$ ground-state atoms in the $F=3$ level and $5\pm1\%$ in the $F=2$ level, as determined by probe absorption measurements. These populations are in agreement with the predictions of the three-state model, which also gives the probe-induced

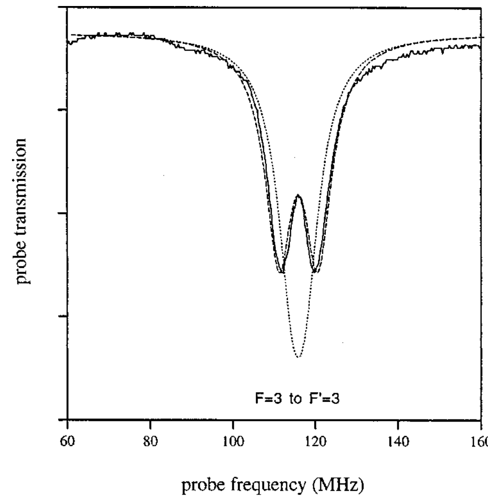

FIG. 2. The solid curve shows the steady-state EIT profile recorded by slowly sweeping the probe frequency across the $F=3$ to $F'=3$ transition with the coupling field frequency fixed at the center of the $F=2$ to $F'=3$ transition resonance. The dashed and dotted curves show the three-state computations with $\Gamma_P=0.6\Gamma$, with and without the coupling field.

($F=3$ to $F'=3$) optical coherence. The two ground-state populations and the optical coherence specify the initial conditions for the EIT transients.

In the transient experiments, the probe and coupling field are tuned to the line centers of their respective transitions [Fig. 1(a)] with the probe passing through the sample and the coupling field controlled by the Pockels cell, which is switched on for 10 μs with a repetition rate of 10 Hz. The

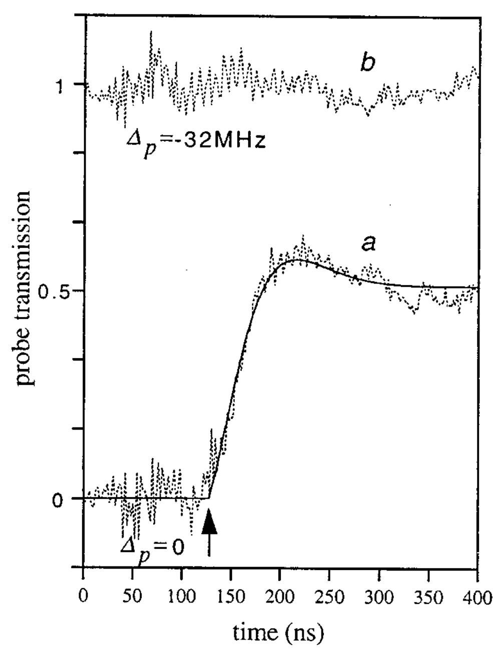

FIG. 3. Transient EIT. Trace a (dotted curve) shows the transient probe transmission signal (averaged over 100 shots) with the coupling field switched on at the time indicated by the arrow. rf noise from the Pockels cell switching circuit is seen just before the coupling beam is switched on. The solid curve is the computed transient using the three-state model with $\Gamma_P=0.6\Gamma$. The Rabi frequencies are $\Omega_P=0.1\Gamma$ and $\Omega_C=1.6\Gamma$. Trace b shows the nearly 100% transmission when the probe is red-detuned by 32 MHz.

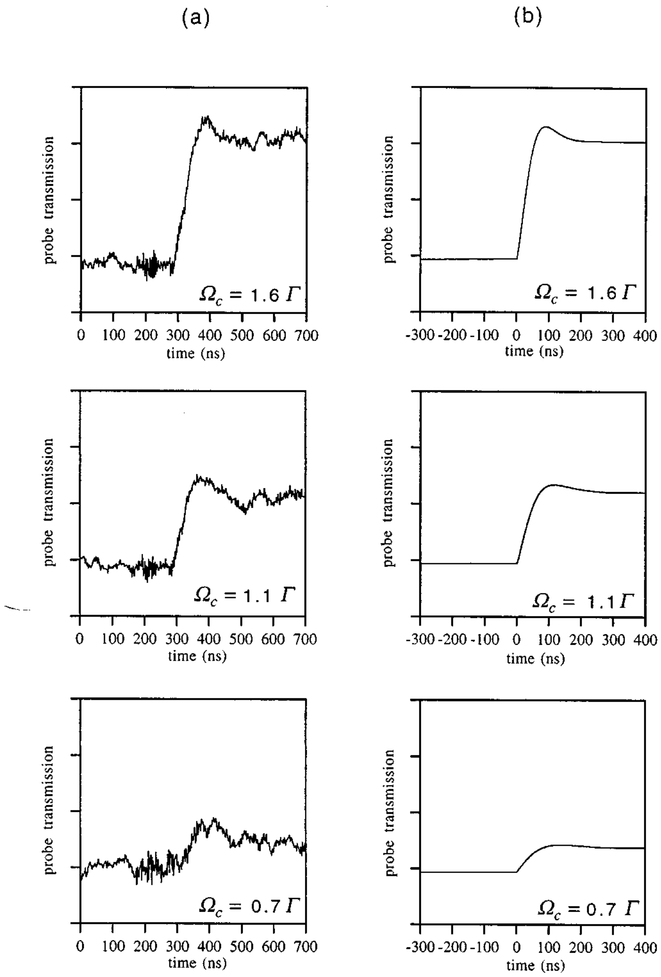

FIG. 4. The effect of reducing the coupling field intensity: (a) Experiment (averaged over 100 shots); (b) computations using the three-state model with $\Gamma_P = 0.6\Gamma$. $\Omega_P = 0.1\Gamma$, $\Omega_C = 1.6\Gamma$, 1.1Γ, and 0.7Γ.

observed EIT transient is shown by the dotted curve in trace *a* of Fig. 3, which is an average over 100 shots. We see that the steady state is reached via an initial rise and overshoot. These features represent the first half-cycle of oscillation at an effective Rabi frequency of $(\Omega_C^2 - \Gamma^2/4)^{1/2}$ for a weak probe, damped by the spontaneous decay rate Γ, as described by a first-order analysis, e.g., Ref. [8]. This interpretation is supported by agreement with the computed transient (solid curve in Fig. 3) obtained using the three-state model with $\Gamma_P = 0.6\Gamma$ as before. Significant features are the $\sim 7\%$ transmission overshoot and the slow rise time ~ 80 ns from zero to maximum [cf. Fig. 1(c)] corresponding to approximately half the effective Rabi cycle. Figure 4 shows the effect of reducing the intensity of the coupling field over a range of Rabi frequencies Ω_C from 1.6Γ to 0.7Γ. The observed steady-state transparency decreases as expected in agreement with the computations, while the observed rise time and overshoot are consistent with the computed values, which show the former increasing slowly and the latter decreasing slowly as the coupling field intensity is reduced.

We note that the initial $5 \pm 1\%$ population in the $F = 2$ level is expected to give rise to an optical nutation signal, which adds incoherently to the EIT transient, but the effect

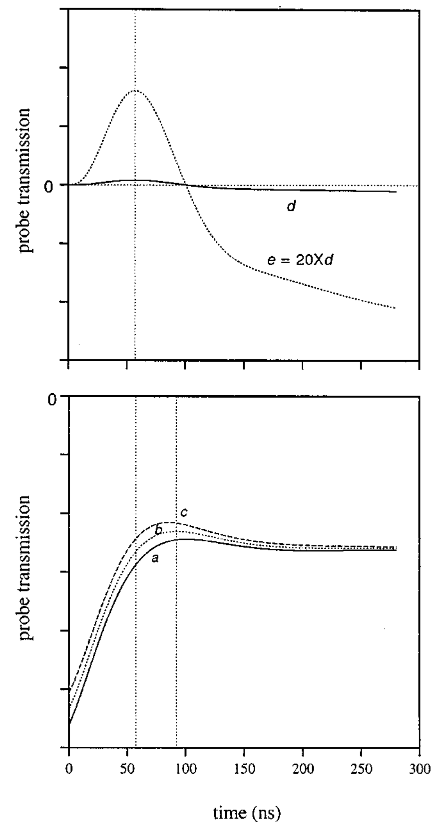

FIG. 5. The computed transients with $\Omega_P = 0.1\Gamma$, $\Omega_C = 1.6\Gamma$, $\Gamma_P = 0.6\Gamma$, and different initial ground-state population fractions in the $F = 2$ state: *a*, 0%; *b*, 5%; *c*, 10%. The coupling field is switched on at $t = 0$. The top curve *d* shows, on the same scale, the very small optical nutation contribution from a 5% initial population fraction in $F = 2$; curve *e* is a magnification of curve *d* by 20.

of this is very small. This is illustrated by the computations in Fig. 5 (traces *a* to *c*), which show the weak dependence of the overall transients on the initial $F = 2$ populations from zero up to 10%. The two top curves (*d* and *e*) show the very small contribution of the initial $5 \pm 1\%$ $F = 2$ population to the overall transient; note that this small contribution peaks near 60 ns while the EIT transient peaks near 80 ns. These computations support the idea that the observed transmission overshoot in Fig. 3 is due almost entirely to the EIT transient as discussed in the preceding paragraph with only a small

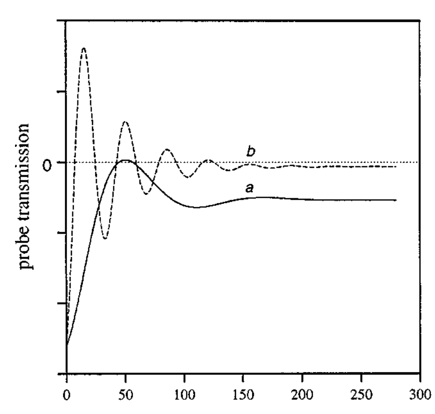

FIG. 6. Computed transients with $\Omega_P = 0.1\Gamma$, $\Gamma_P = 0.6\Gamma$; curve *a*, $\Omega_C = 3\Gamma$; curve *b*, $\Omega_C = 10\Gamma$.

contribution from the optical nutation signal due to the initial $F=2$ population driven by the coupling field.

In conclusion, we have observed EIT transient effects in a Rb MOT, showing that the transient probe transmission following the fast switching on of the coupling field is controlled by the Rabi frequency of the coupling field modified by the excited level decay rate. With the laser power we have available, we can trap only about 2×10^7 atoms. This limits the signal-to-noise ratio, and also the time resolution due to the need for signal averaging. Our three-state computations suggest that with a modest fourfold increase in laser power it should be possible to increase the coupling field Rabi frequency sufficiently to reduce the EIT switch-on time and drive the transmission overshoot into gain. This is illustrated by the computed curves in Fig. 6, which show that transient gain should be observable in this system with coupling field Rabi frequencies greater than 3Γ.

We are grateful to Christopher Dorman and Michael Mason for their assistance in the preparation of this experiment, and also to Shahid Hanif for his invaluable technical assistance.

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