Observation of transient gain without population inversion in a laser-cooled rubidium lambda system

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We have observed clear Rabi oscillations of a weak probe in a strongly driven three-level lambda system in laser-cooled rubidium for the first time. When the coupling field is non-adiabatically switched on using a Pockels cell, transient probe gain without population inversion is obtained in the presence of uncoupled absorptions. Our results are supported by three-state computations.

In the last decade there has been growing interest in the study of atomic coherence effects in multilevel atoms, especially coherent population trapping [1], electromagnetically induced transparency (EIT) [2], slow light propagation [3], and optical gain without inversion. Reviews of lasing without inversion have been given by Kocharovska and Scully [4] and more recently by Monpart and Corbalán [5]. Most of this work has been in the steady state regime and the fast picosecond pulsed regime [6], but there have been several studies of transient effects where the coherence is switched on or off rapidly in a time that is short compared to decay rates and Rabi frequencies, i.e., in the non-adiabatic regime. An early experiment by Fry et al. [7] demonstrated several transient effects in a three-level lambda system realized in a sodium vapor cell. Their observations included transient gain of a strong field when a weak field was switched on by a Pockels cell in the presence of incoherent pumping to the upper level, but without population inversion. Subsequently, several theoretical studies of non-degenerate three-level lambda, V, and cascade systems have predicted transient ringing of a probe beam with gain when a strong coupling beam is switched on [8,9]. This predicted transient gain can occur without population inversion on the probe transition, and occurs with and without incoherent pumping. This ringing has also been explained by Vaccaro et al. [10] via stochastic wavefunction diagrams. Transient ringing of a three level system with gain has been observed in the radio-frequency regime in nitrogen-vacancy centres in diamond samples [11] but not yet in the optical region. Since the ringing occurs at approximately the Rabi frequency of the strong field, experiments in the optical region would need to be carried out in a Doppler-free configuration or ideally in a laser-cooled sample to avoid the Doppler effects masking the coherent effects.

In our previous work [12] we observed the transient approach to EIT in a cold rubidium lambda system in a magneto-optical trap (MOT). When the coupling field was switched on by a Pockels cell, the rapid rise in probe transparency exhibited an overshoot before settling down to the steady state. This overshoot was interpreted as the first Rabi half cycle in the transient ringing, but it did not reach gain owing to absorption on uncoupled Zeeman transitions and two-photon dephasing effects. In the experiments reported in this paper the coupling field intensity has been increased to the point where a clear Rabi ringing cycle reaching well into gain is observed. The results are supported by density matrix computations of a three level lambda system supplemented by observational data on the strengths of uncoupled absorptions and the effects of the MOT fields.

The lambda system we have studied is formed by the weak probe field P and the strong coupling field C shown in Fig. 1. The 87Rb sample was cooled in a standard MOT with trapping field T and repumping field R, similar to the one used in our previous work on EIT [13]. All laser fields were derived from external-cavity grating-controlled 780 nm laser diodes in master and master-slave arrangements, acting on the hyperfine transitions of the 5S1/2 to 5P3/2 D2 line, with the exception of the trap’s repumping beam R, which is locked to the 5S1/2 to 5P1/2 D1 line at 795 nm. The frequency of each master laser is monitored by saturated absorption in a Rb cell at room temperature and can be locked via electronic feedback. In all master-slave arrangements, there is an acousto-optic modulator which shifts the frequency of the slave relative to the frequency of the master.

The trapping lasers T are derived from a master-slave system. They are locked and detuned by −13 MHz from the F = 2 to F′ = 3 transition. Their diameter is ≈1 cm and the total average intensity in the cold sample is ≈50 mW/cm². The repumping beam R is locked to the F = 1 to F′ = 2 transition and has a diameter of ≈1 cm and an intensity of ≈0.2 mW/cm². The probe beam P can be locked to or scanned across the F = 2 to F′ = 2 transition by piezo-control of the external cavity. P has an average intensity ≈0.03 mW/cm² in a
beams are detuned by transition of the $D_2$ line. The probe propagates at an angle of about $20^\circ$ with respect to $C$, which was found to give a good overlap of the probe with the coupling field in the cold sample. It can be shown that this arrangement of polarizations is equivalent to three separate sets of Zeeman levels in $\Lambda$ configurations plus Zeeman transitions of the probe uncoupled by $C$. A Pockels cell and a polarizer are placed in the path of $C$ so that this beam can be switched on and off.

Figure 3(a) shows the steady state probe absorption versus probe detuning $\Delta_p$ for different coupling field Rabi frequencies $\Omega_C$ as the probe beam is scanned across the $F = 2$ to $F' = 2$ transition. It is seen that the spectrum consists of a central peak situated between the two Autler-Townes peaks of a standard EIT profile and a small peak to its red side. The central peak in the spectrum is caused by $P$ probing Zeeman sublevels that are not coupled by $C$. We identified this peak as the uncoupled absorption peak in our previous work. The trapping beams form a V-type EIT system with $P$, splitting each peak in two, which gives rise to the small red-detuned peak. We note that, in the present work, it was necessary to shift the frequencies of $C$ and $P$ to take account of the light shifts caused by the strong coupling of $P$ to the $F = 1 \rightarrow F' = 2$ transition with an average intensity of about $100 \text{ mW}/\text{cm}^2$ in a roughly elliptical profile $2 \text{ mm} \times 4 \text{ mm}$.

The experimental setup is shown schematically in Fig. 2. The probe $P$ is linearly polarized in the horizontal plane whilst the coupling field $C$ is linearly polarized in the vertical direction. The probe propagates at an angle of about $20^\circ$ with respect to $C$, which was found to give a good overlap of the probe with the coupling field in the cold sample. It can be shown that this arrangement of polarizations is equivalent to three separate sets of Zeeman levels in $\Lambda$ configurations plus Zeeman transitions of the probe uncoupled by $C$. A Pockels cell and a polarizer are placed in the path of $C$ so that this beam can be switched on and off.

The transient experiments were performed with the probe field locked to the $F = 2$ to $F' = 2$ transition of the cold sample and non-adiabatically turning on the coupling field in less than 6 ns using a Pockels cell driven by a pulse $10 \mu\text{s}$ long with a repetition rate of 10 Hz. As the Pockels cell is switched on, it rotates the polarization of the coupling beam, which then passes through a polarizer that selects only the rotated polarization (see Fig. 2). The shifts of $C$ varied with $\Omega_C$ with a maximum value of $-7 \text{ MHz}$, while the shift of the probe was $4\text{ MHz}$. Finally, we note that the linewidths of our spectra are well modelled by inclusion of the broadening due to beam profile inhomogeneities, variations of Clebsch-Gordan coefficients between different Zeeman transitions, and the spread of intensity in the standing wave field of the counterpropagating trapping beams in the MOT which causes a spread in the detuning of the probe field due to the spatially varying light shifts.

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FIG. 3. (a) Steady state probe absorption spectra with $C$ on and locked to the light-shifted transition of the atoms in the MOT. (b) Probe transient transmission as $C$ is turned on at time $t = 0$. Each trace is an average over 200 scans.

$\Omega_c = 19.2 \pm 0.6 \text{ MHz}$

$\Omega_c = 30.0 \pm 0.3 \text{ MHz}$

$\Omega_c = 33.4 \pm 0.2 \text{ MHz}$

$\Omega_c = 39.3 \pm 0.2 \text{ MHz}$

$\Omega_c = 42.5 \pm 0.1 \text{ MHz}$

$\Omega_c = 43.6 \pm 0.1 \text{ MHz}$

$\Omega_c = 47.7 \pm 0.2 \text{ MHz}$
We have observed as much as 15% rubidium when the coupling field is non-adiabatically ringing of a three-level lambda system in laser-cooled trap \cite{16}, it should be possible to eliminate the broadening effects of the trapping fields and the uncoupled absorptions, thereby observe a larger gain.

We would like to thank the EPSRC for financial support on this project and Dr. T. B. Smith (Open University) for useful discussions. We would also like to thank Roger Bence, Fraser Robertson, and Robert Seaton (Open University) and Shahid Hanif (Imperial College) for technical assistance.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{The height $h$ of the first Rabi cycle peak plotted against $\Omega_C$ when $C$ is locked to the light-shifted transition of the atoms in the MOT. The solid line is a theoretical model.}
\end{figure}

ent heights $h$ of the first Rabi cycle as a function of $\Omega_C$. Gain is seen in this plot after a threshold Rabi frequency of $\Omega_C \approx 33$ MHz. Numerically subtracting the effects of the uncoupled absorptions would yield a maximum gain $\approx 45\%$ and a significantly lower threshold Rabi frequency. The solid line in Fig. 4 corresponds to a theoretical expectation derived from a three-level atom model with an initial population distribution of 75% in the $F = 2$ and 25% in the $F = 1$ ground levels, as established from independent absorption measurements. Our computations show that for these initial conditions there is no inversion at any time on either the one photon probe transition or the two photon transition $F = 1 \rightarrow F' = 2 \rightarrow F = 2$.

Theoretical modelling of our system was performed by numerically integrating the density matrix equations of motion presented earlier \cite{15} and incorporating the spread of probe detunings due to the spatial variation in the light shifts induced by trapping fields. It is difficult to fully model this spread in trapping field intensity as the standing wave pattern is critically dependent on the slowly varying, but unknown, relative phases of the component fields of the trapping beams. For a fuller description of these effects see \cite{11}. Experimentally, the mean light shift was corrected by shifting the frequency of the probe field accordingly, while in the numerical models, a truncated Lorentzian distribution of detuned probe fields was found to give good agreement with the experimental results. More accurate modelling of the actual trap configuration should, however, yield better fits to the data.

We have carried out experiments showing transient ringing of a three-level lambda system in laser-cooled rubidium when the coupling field is non-adiabatically turned on. We have observed as much as 15 ± 5% transient gain in the presence of uncoupled absorption. We note that by working with other configurations, for example, by reversing the roles of $C$ and $P$ in a dark SPOT trap \cite{16}, it should be possible to eliminate the broadening effects of the trapping fields and the uncoupled absorptions, thereby observe a larger gain.

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