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Coherent Interaction of Frequency-Modulated Laser Pulses with Rb Atoms

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Abstract. We investigate the behavior of Rb^{85} atoms in the field of a sequence of frequency-chirped short laser pulses for coherent manipulation of the Rb atomic beam. The analysis is based on numerical solution of equations for the density matrix elements of the hyperfine levels of the $5S_{1/2}$–$5P_{3/2}$ transition in Rb^{85} atom. We analyze two different regimes of interaction including relatively short laser pulses (when the width of the pulse envelope spectrum is of order or exceeds frequency interval between the hyperfine levels resulting in effective mixing of them) and relatively long ones (when the ground hyperfine levels are resolved but the excited ones are not resolved). We show that in all regimes considered, the interaction of a frequency-chirped laser pulse with the multilevel Rb^{85} system is similar to the interaction with an effective two-level atom at sufficiently large peak intensities of the pulses. It allows us to perform efficient excitation of the multilevel atom by transferring populations of two hyperfine ground states to the excited ones and back to the ground states using a pair of frequency-chirped laser pulses. We present experimental results of utilizing this scheme of population transfer for coherent manipulation of an ensemble of Rb^{85} atoms in a magneto-optical trap.

Keywords: coherent manipulation of atoms, rapid adiabatic passage,
frequency-chirped laser pulses, magneto-optical trap
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1. Introduction

Coherent manipulation of atoms without heating them in a process of changing their velocity or position is an important problem to be addressed in atomic interferometers, during transportation of atoms between different stages of a laser

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cooling system, and other applications where conservation of the atomic phase is an important issue [1–3]. Deflection and splitting of atomic beams using trapped (dark) atomic states was realized in [4]. Coherent manipulation of atomic beams was proposed and demonstrated in counter-propagating laser beams in the scheme of stimulated Raman adiabatic passage (STIRAP) (see [5] and references therein) and also in multilevel Zeeman systems [6]. Another way of coherent manipulation of atomic beams is stimulated excitation and de-excitation of atoms by counter-propagating pairs of short frequency-chirped laser pulses in the adiabatic passage (AP) regime of interaction [7–10].

In this paper, we analyze coherent interaction of frequency-chirped short laser pulses with Rb^{85} atoms. The aim of the investigation is to develop a simple, effective and robust scheme for coherent transfer of population of Rb^{85} atom from the hyperfine electronic ground states to the manifold of excited hyperfine states and back to the ground states by acting with pairs of frequency-chirped short laser pulses. We investigate different regimes of interaction including relatively short and relatively long laser pulses. In the case of short laser pulses, the width of the pulse envelope spectrum is of order or exceeds frequency interval between the hyperfine levels that results in effective mixing of them. We refer to this case as "broadband pumping". In contrary, the two ground hyperfine levels of the Rb model atom are resolved in the case of relatively long pulses with relatively narrow width of the pulse envelope spectrum referred to as "narrowband pumping".

The working level system of the Rb^{85} atoms is chosen to be its hyperfine levels manifold of the $5S_{1/2}$–$5P_{3/2}$ transition. The decay time of the excited level $5P_{3/2}$ is $\tau = 27$ ns [11]. One of the main results of the analysis performed in this paper is that the interaction of frequency chirped laser pulses with the multilevel Rb^{85} system in both cases mentioned above leads to effective excitation and de-excitation of the atom at sufficiently high peak intensities of the frequency-chirped laser pulses.

The experimental part of this paper consists of investigation of the action of the frequency-chirped laser pulses on slow Rb atoms collected in a magneto-optical trap (MOT). A pair of the counter-propagating frequency-chirped laser pulses with durations shorter than the decay time of the excited levels of the hyperfine structure $5S_{1/2}$–$5P_{3/2}$ of Rb^{85} atoms coherently excite and de-excite the Rb atom. As a result, the atom receives momentum equal to $2\hbar k_p$. If the atoms are coherently accelerated by the sequence of the counter-propagating pulses to kinetic energies larger than the depth of the potential well of the MOT, the atoms will be pushed from MOT and a coherent Rb atomic beam with a variable velocity will be produced.

2. Results of the Numerical Simulations

As show the results of numerical solution of Bloch equations (for details see [12,13]) for the density matrix elements of the quantum system under consideration, all population of the Rb atoms is being transferred from the ground states to the excited ones by a sufficiently strong frequency-chirped laser pulse in both cases

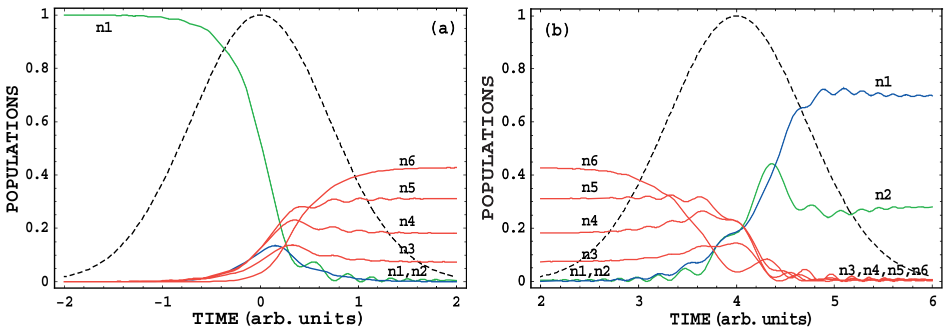

Fig. 1. The population dynamics for the case of "broadband pumping". Time is normalized by duration of the laser pulse. The dashed line is the normalized intensity profile of the laser pulse. The parameters applied are: the duration of the pulse intensity $2\tau_p = 10^{-1}$ ns, the peak Rabi frequency is between $\Omega_{\mathrm{R}} = 42$ GHz and $\Omega_{\mathrm{R}} = 120$ GHz for transitions between the two ground and four excited states; the chirp speed $\beta = 200$ GHz/ns. (a) During the first pulse; (b) During the second pulse

of the "broadband" and "narrowband" pumping independently on the (complex) value of the initial coherence between the ground states of the Rb atom. Similarly, all population of the atom is being transferred to the ground states as a result of interaction with a second frequency-chirped laser pulse, see Fig. 1. It means that the behavior of the multilevel Rb atom is similar to that of a two-level atom in the field of the frequency-chirped laser pulse. This result is an important one from the point of view of the mechanical momentum transfer to the atoms from the laser beam. It shows that the translational motion of multilevel atoms may be effectively manipulated by stimulated excitation and de-excitation of the atoms using pairs of coherent counter-propagating frequency-chirped short laser pulses. In some important applications, the temperature of the atomic ensemble must be not changed considerably during the laser manipulation of the atomic translational motion. This puts a restriction on the duration and period of repetition of the laser pulses, both of them have to be much shorter than the spontaneous decay time of the working excited states of the atom.

3. Experimental Results

The main goal of our experimental investigation was to obtain a coherent beam of Rb^{85} atoms from the cloud of Rb atoms cooled and trapped in the magneto-optical trap (MOT).

The Rb atoms from an oven with temperature about 100 C° move through diaphragms forming an atomic beam with average velocity about 300 m/sec, see Fig. 2. The atomic beam arrives to the place of MOT location in the middle of a

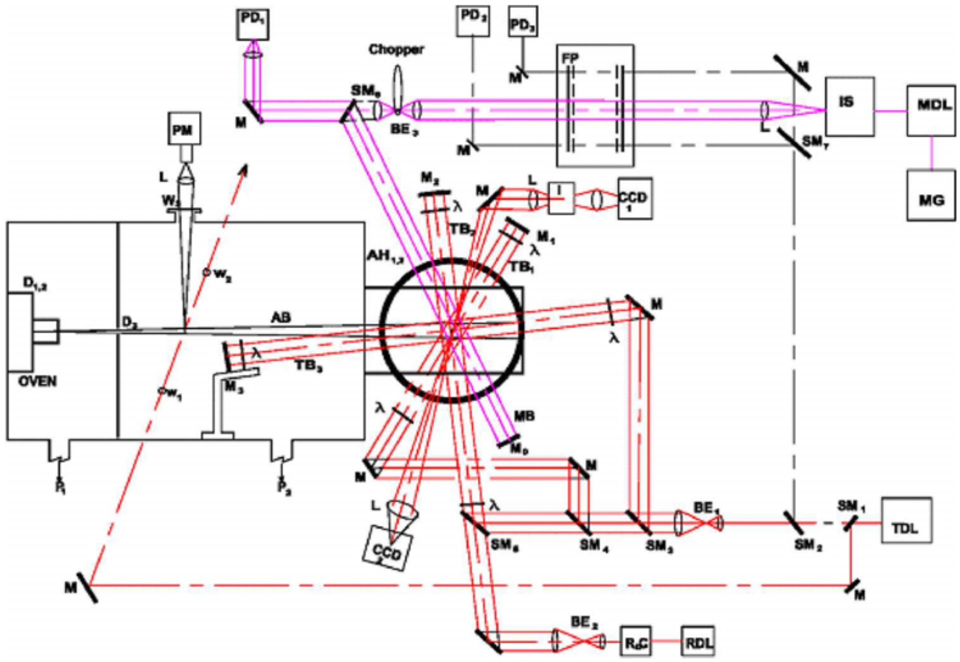

Fig. 2. Experimental setup. TDL: trap diode laser, RDL: repumping diode laser, MDL: modulating diode laser, MG: modulating generator, RbC: rubidium cell, FP: Fabry–Perot interferometer, I: image intensifier, PD1-3: photodiodes, PM: photomultiplier, L: lenses, M0-3: dielectric mirrors, M: metal mirrors, SM1-8: semi-transparent mirrors, BE1-3: beam expanders, W1-3: windows, AH1-2: anti-Helmholz coils, λ1-6: $\lambda/4$ plates, D1-3: diaphragms

quadratic prism made from glass plates and connected to a vacuum system. The vacuum has a residual pressure about 10^{-7} mbar. MOT consists of an anti-Helmholtz (AH) pair of magnetic coils located on both sides of the glass prism. The magnetic coils produce an inhomogeneous spherically symmetric magnetic field. This magnetic field along with three pairs of counter-propagating circularly polarized laser beams force the atoms to move to the central region of the MOT where the magnetic field has minimum value [14]. The counter-propagating laser beams are made up by reflecting three mutually perpendicular laser beams from three mirrors; all laser beams are crossed at the central point of the MOT, see Fig. 2. The source of the laser radiation for MOT is a diode laser with frequency red shifted from the working transition (transition $5S_{1/2}$–$5P_{3/2}$) by two-three natural line-widths of the transition. The effective diameter of the MOT performed was about 1 mm.

The frequency-chirped laser pulses for the manipulation of the Rb atoms referred to as manipulating laser are obtained using another cw diode laser with frequency tuned to the resonance with transition $5S_{1/2}$– $-5P_{3/2}$ of the Rb^{85} atom and with the pumping current modulated with frequency equal 20 MHz. The output radiation of the laser is focused into the MOT after propagation through a Faraday isolator and a Fabry–Perot (FP) interferometer. The free spectral range of the FP is about 20 GHz that is wider than the spectral width of the modulated diode laser radiation (about 3 GHz). The width of the FP transmission range is 500 MHz around the resonance. The output radiation (Fig. 3.) consists of a sequence of frequency-chirped pulses each having duration of 5 ns, the time interval between the pulses of 50 ns, and the duration of the sequences of about 30 ms. The latter (along with the number of the chirped laser pulses in the sequence) is governed by a mechanical chopper.

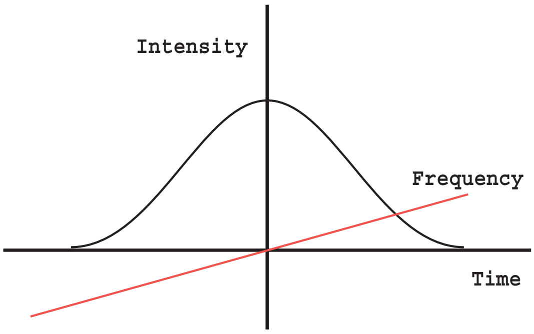

Fig. 3. The schematic shape of the frequency-chirped pulse

The position of the atomic cloud in the MOT which depends on the number of the acting on the atoms frequency-chirped pulses is followed with a video-camera by detecting the fluorescence of the Rb atoms. A mirror is used to reflect the manipulating laser pulses back into MOT to perform the counter-propagating sequences of the chirped laser pulses. To control the above-mentioned mechanism of manipulation of Rb atoms, the case of no reflecting mirror for the manipulating laser is also investigated in details. The signal of the video-camera is stored and processed by a computer.

The atoms receive some amount of mechanical moment when interacting with a resonant laser beam. The direction and amount of the transferred momentum depend on the parameters of the laser beam. An important requirement for generating a coherent atomic beam is that the velocity distribution of the atomic ensemble does not increase considerably during the interaction with the manipulating laser pulses. The reason of such heating are the spontaneous transitions from the excited atomic states: each act of such transition transfers to the atom a recoil momentum equal to the momentum of the spontaneously radiated photon (with stochastic direction of propagation). To avoid this kind of heating we use manipulating laser pulse pairs having duration and time interval between pulses shorter than the decay time of the excited working hyperfine states of Rb atoms. For such frequency-chirped

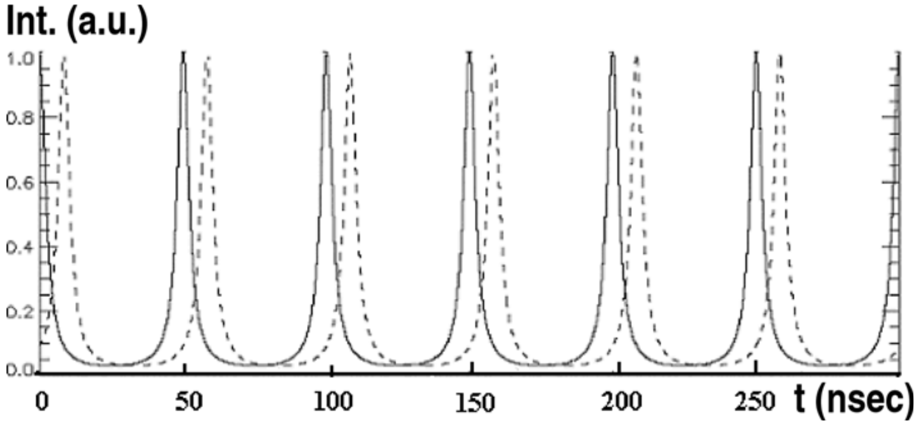

Fig. 4. Sequence of frequency-chirped pulses manipulating the trapped atoms (——) and the retro-reflected pulses from the mirror (– – –) delayed by 3 nsec

pulses (see Figs. 3 and 4), the transitions in the Rb atoms between the working states have stimulated character and the role of the spontaneous transitions is relatively small. Calculations show that using the laser pulse intensities achieved in the experiment, the adiabaticity conditions are fulfilled and the manipulating laser frequency-chirped pulse will produce transfer of the atomic population from the ground hyperfine states to the manifold of the excited hyperfine states by transferring a photon momentum $\hbar k_p$ to Rb atoms in direction of the pulse propagation. If the reflected from the mirror manipulating pulse arrives back in the MOT in a time shorter compared with the decay time of the Rb excited working hyperfine manifold, it will transfer another momentum $\hbar k_p$ in the same direction as the original one by transferring the atomic population from the excited manifold to the ground states. By measuring the intensity of the laser pulses and knowing the pulses' repetition rate, we can calculate the forces acting on the atoms and estimate the acceleration of the atoms taking into account the light pressure forces acting on atoms from the laser beams forming MOT.

A picture of the atomic cloud in MOT is presented before and after the action of the manipulating laser pulses in Fig. 5. As it is clearly seen, the atomic cloud is moving in one direction (the direction of propagation of the manipulating laser pulses) when counter-propagating sequence of the pulses is present due to the reflecting mirror. It means that the above considered mechanism of excitation and de-excitation of the atoms by manipulating laser pulses is being performed in the experiment.

The time-dependent position of the atoms in the MOT is defined by the parameters of the manipulating laser pulse sequences and those of the MOT. We can measure parameters of the MOT by measuring the position and velocity of the atomic cloud and knowing the force acting on the cloud from the manipulating laser

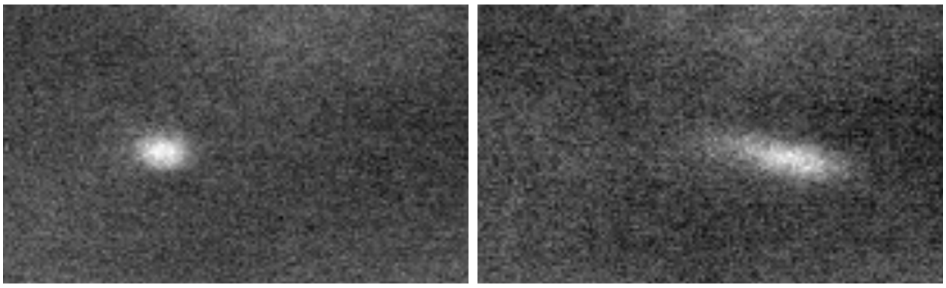

Fig. 5. Picture of the atomic cloud in MOT before (left panel) and after the action of the manipulating laser pulses (right panel)

pulses. A macroscopic model of the atomic cloud in the field of counter-propagating sequences of frequency-chirped short laser pulses in MOT has been developed and is being verified using the experimental results.

The fluorescence of the cloud of the Rb atoms trapped in the MOT is shown in Fig. 6 before the interaction and after 2 msec of interaction with the manipulating laser pulses. The density of the presented contour lines is proportional to the density

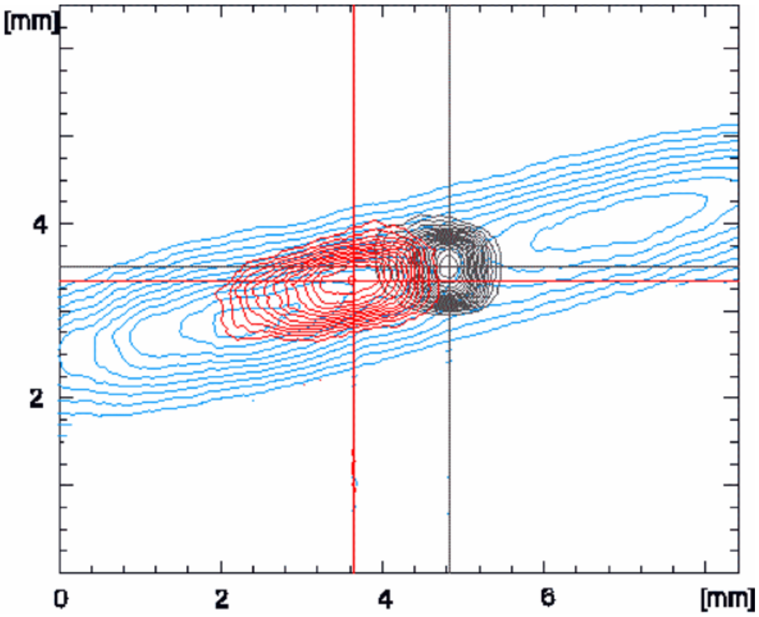

Fig. 6. The fluorescence spatial distribution from the cloud of the Rb atoms trapped in the MOT before the interaction and after 2 msec of the interaction with the sequence of the manipulating laser pulses

of the atoms in the cloud. The background contour lines indicate the distribution of the intensity and the direction of the manipulating laser radiation. Crossing points of the vertical and horizontal lines show the center of mass of the cloud before and after the interaction.

The displacement of the center of mass of the atomic cloud is shown in Fig. 7 as a function of the duration of the manipulating laser pulse sequence in the case when the laser pulse peak intensity is equal to 700 mW/cm^2 and the period of repetition of the counter-propagating pulse pairs is 50 nsec.

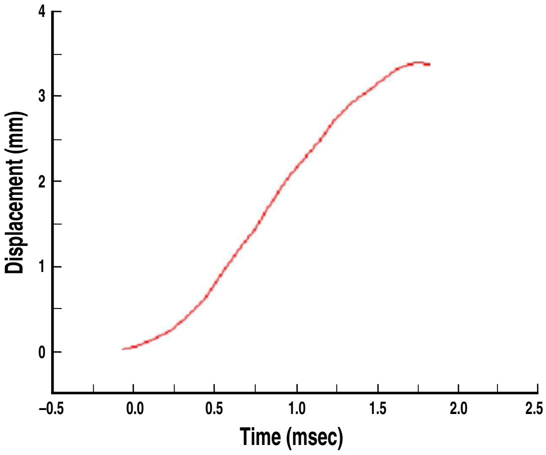

Fig. 7. Displacement of the atomic cloud center of mass as a function of duration of the manipulating laser pulse sequence

4. Conclusions

In conclusion, the results of theoretical and experimental investigation of population transfer in Rb^{85} atoms and of peculiarities of the motion of these atoms in MOT in the field of a sequence of frequency-chirped laser pulses are presented in this paper. We have shown that effective population transfer between two ground hyperfine levels of the atoms and the manifold of excited hyperfine levels may be achieved using frequency-chirped laser pulses of different durations: relatively short ("broadband" pumping) and relatively long ("narrowband" pumping).

As it follows from above consideration, interaction of a frequency-chirped laser pulse with Rb^{85} atomic system in the ground states initially, results in excitation of the atom in the case of sufficiently high Rabi frequency of the pulse: the all atomic population becomes distributed among the excited states with no population in the ground states. Second laser pulse applied to the atom with a time delay much shorter than the relaxation times of the atom, will transfer all atomic population into the ground states. This may be used for efficient coherent manipulation of beams of multilevel atoms, such as Rb atoms: the atoms will receive mechanical momentum equal to $2\hbar k_p$ (with k_p being the wave number of the laser pulse) after interaction with a pair of frequency chirped laser pulses, which propagate in opposite directions. Repetition of this cycle of excitation and de-excitation of the atoms by a sequence of counter-propagating laser pulses will result in effective coherent transfer of mechanical momentum from the laser field to Rb atoms and effective manipulation of the atomic beam. An important advantage of this system is that relatively large mechanical momentum may be transferred to the atomic beam from the laser field due to large number of the laser pulses interacting with the atoms. This number is defined by repetition rate of the laser pulse source and the time of flight of the atoms through the interaction region.

Preliminary results of experimental investigation of manipulation of Rb atoms are presented based on the theory developed in this paper. Cold Rb atoms collected into atomic cloud in MOT are used for manipulation utilizing counter-propagating frequency-chirped laser pulses. Coherent motion of the atomic cloud as a whole without considerable diffusion has been achieved, which is a first step toward obtaining a coherent atomic beam.

When the atomic cloud is accelerated to kinetic energies exceeding the depth of the MOT's potential barrier, a free coherent and monochromatic atomic beam will be generated with a given velocity. This velocity may be governed by changing the depth of the MOT's potential barrier. Such coherent monochromatic atomic beams with variable translational velocity may find interesting applications in different fields of the science and technologies.

Note that the case of the manipulating laser pulse sequence propagating in one direction (no reflecting mirror) is investigated too. At given experimental parameters, the force acting on the atoms was not enough to "kick" the atoms out of the MOT: the atomic cloud occupies a new equilibrium position after its center of mass made decaying oscillations in MOT.

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