Coherent manipulation of atoms using partially overlapping laser pulses - Final report

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The goal of the project was to consider the application of partially overlapping pulses for the coherent manipulation of atoms in various settings. An interesting class of results were discovered recently, where it was shown that a pair of overlapping laser pulses, one member of which arrives with a distinct time delay, can induce multiphoton adiabatic passage processes [1, 2, 3]. In these processes changes in the internal state of the atoms are accompanied by multiple photon exchanges between the driving fields. This makes it possible for the atoms to, for example, receive $2N\hbar k$ mechanical momentum from the fields in a single interaction and be returned to the ground state at the end. (N is the order of the process, $N = 1$ is the usual interaction with separated pulses where a single photon is absorbed from one field and emitted into the other.) The primary aim of the project was to explore the possibility of realizing and applying such multiphoton processes under various circumstances.

The first step was to investigate the effect of overlapping chirped pulses on atoms with a Λ-level scheme. It was previously shown before, that it is possible to transfer the atomic populations between the two metastable states of the atoms in the adiabatic regime using a single frequency-chirped laser pulse [4]. This population transfer has the important property that population of the excited state can be suppressed during the population transfer, thus making the scheme immune to the adverse effects of spontaneous emission. I investigated the application of two overlapping chirped laser pulses with the aim of transferring $2N\hbar k$ momentum to the atoms in a single interaction cycle, with the additional property that the excited state is not populated during the process. However, I found that this was not possible. Either excitation of the atoms can be suppressed, but then there is no net momentum transfer to the atoms. Or, pulses can be such that $2N\hbar k$ momentum is transferred to the atoms, but this process is always accompanied by excitation during the interaction, just as in the two-level atom case. I found that by using four laser pulses it is possible to achieve both goals at once - but as this is much more problematic to realize in an experiment, this line of research was not pursued any further.

In conjuction with the experiments performed at the laser laboratory of the Department of Plasma Physics, I have performed numerical simulations to investigate the momentum transfer to a cloud of cold atoms by counterpropagating, overlapping chirped pulses. In this simulation I considered two-level atoms, took exact consideration of the pulse generation technique used in the experiment, and also included the effects of spontaneous emission of the excited state. The counterpropagating pulses used in the calculation were taken to be generated by passing the light of a frequency-modulated diode laser though a Fabry-Perot etalon [5] and retroreflecting it from a mirror. Spontaneous emission was included using the Monte-Carlo Wave-Function technique. The curves calculated for the momentum transfer and the heating of the atomic ensemble showed good agreement with the experimental data [6, 7], but also proved, that the intensity used in the setup was not sufficient to realize multiphoton adiabatic passage.

I have investigated the effect of spontaneous emission on the manipulation schemes with multiphoton adiabatic passage when the interaction continues for longer than the spontaneous lifetime of the atoms. This is an important case, as even though the interaction with a single laser pulse pair can be much shorter than the spontaneous lifetime, the whole interaction of repeated pulse pairs will often persist for much longer. For the case of two separated chirped laser pulses that induce population transfer in the adiabatic regime, this question has already been studied using a simple model [8]. I have now shown that similarly to the separated pulse case, the force exerted on the atoms, as well as the heating of the atomic ensemble converges to constant values as the interaction time exceeds the spontaneous lifetime. A simple model was also devised and the dependence of the average force and the diffusion constant on the order N of the process derived. The results were corroborated with numerical simulations using a density matrix approach. I have also investigated multiphoton adiabatic passage processes using a Floquet formalism and compared the cases of two chirped pulses as opposed to two symmetrically detuned pulses. I have shown that the use of chirped pulses simpler, in that the two pulses are identical apart from the delay of the second pulse, so it can be formed simply by retroreflecting the first one. I have also shown, that the process induced by chirped pulses requires intensities about an order of magnitude smaller than that induced by the symmetrically detuned pulses[9].

I have investigated adiabatic passage processes induced by chirped laser pulses using the full hyperfine level structure of the ^{85}Rb atoms that are used in the laser laboratory of the Department of Plasma Physics. Applying results obtained from a two-level model calculation are far from trivial, because the ground state contains two hyperfine states with 12 rotational substates altogether, and the excited state has 2 (for the D_1 line) or 4 (for the D_2 line) hyperfine states with 12 or 24 rotational substates. Furthermore, the transition strengths between various rotational substates are different [10], so applying various laser manipulation schemes to an ensemble of atoms whose initial state is some random mixture of rotational substates can be problematic.

I have shown that using adiabatic processes induced by frequency chirped pulses, it is possible to transfer the whole of the atomic population from one selected hyperfine ground state level to a single excited state hyperfine level, regardless of the initial distribution over the rotational substates. This is very useful, because when excitation of multiple hyperfine excited state levels takes place, dephasing between these levels hinders further coherent manipulation. Since this dephasing takes place on a timescale shorter than the spontaneous lifetime of the excited state, excitation to multiple hyperfine levels should be avoided when manipulation with a series of laser pulses is envisioned. I have also shown that partially overlapping laser pulses can drive multiphoton adiabatic passage processes regardless of the initial distribution over ground-state substates and that such processes are also advantageous because even if multiple excited state levels are populated during the interaction, these processes are immune to the effects of dephasing between them. Furthermore I have shown that in certain cases it is possible to apply two partially overlapping chirped laser pulses in such a manner, that each ground state rotational substate experiences a multiphoton adiabatic process with a different order N, which makes it possible to entangle the atoms' rotational states with discrete center-of-mass-momentum states [11].

As the final stage of the current project, I have started studying the interaction of partially overlapping laser pulses with rare-earth ion dopants in crystals. Crystals doped with rare-earths play a significant role in studying various coherent optical phenomena such as self-induced transparency, electromagnetically induced transparency, slow light and various other effects. These ions have long lived excited states, but the transitions couple to local oscillation modes of the ion within the crystal [12, 13]. The theory of optical transitions in such crystals is very complex, but the system is well worth studying, considering the enormous possibility of applications in quantum computation and quantum optics. As a first step, we have developed a simple model that contains a two-level quantum system, whose center of mass motion is constrained by two harmonic potentials, one for the ground state ion and another one for the excited state ion [14]. As the two potentials are displaced and possibly also distorted with respect to one another, this yields a set of vibrational transitions in conjunction with electronic ones. This simple model of the rare-earth ion dopants in crystals describes the local oscillation modes coupled with the excitation of the ions, but is simple enough to be tractable even if coherent optical phenomena are to be considered.

As the second step, I have used this model system to consider the propagation of a pair of partially overlapping laser pulses in an inhomogeneously broadened ensemble of rare-earth ions. The primary difficulty in the calculations was the inclusion of inhomogeneous broadening, which is always present in solid state systems. Computer simulations with realistic parameters were achieved with the use of the relatively new technology of GPGPU - General Purpose computing on Graphics Processing Units), which allows the massive parallelization of computational tasks to a large number of processors (in our case several hundred on two modern GPU-s). This technology lends itself very well to the problem of calculating the response of a large number of ions to the fields of the laser pulses and allows the calculation of coherent optical phenomena in a medium of inhomogeneously broadened rare-earth ions.

Using this technology I investigated how pulses resonant with the various vibrational sidebands of the frequency of the fundamental electronic transition propagate on their own (as a single pulse), and how two pulses of relatively small amplitude interact when injected into the medium simultaneously. In particular, I have investigated the scattering of a “seed pulse” on the well known Self-Induced Transparency soliton which propagates slowly. I also investigated how high intensity pulses interact to generate Raman sidebands of the input radiation in the medium that are then able to propagate losslessly. The efficiency of sideband generation was mapped as several parameters were varied (input pulse amplitudes, pulse lengths, delay of the second pulse). This line of study is highly promising for the future.

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