Doppler-free Adiabatic Self-Induced Transparency

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We demonstrate that a Doppler broadened two-level medium can be made transparent to a laser pulse by an appropriate adiabatic variation of the laser field amplitude and its nominal detuning. This new technique of adiabatic self-induced transparency (ASIT) is compared with the well known self-induced transparency (SIT) phenomenon, showing that the adiabatic method is much more robust to variations of the system parameters. We also discuss a possible experimental implementation of ASIT using ^{87}Rb atoms.

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I. INTRODUCTION

The ability to tailor the optical properties of a medium in such a way that it becomes transparent to a resonant laser field while its index of refraction is shaped at wish has been used for a wide range of applications, e.g., from slow light [1, 2] and dark-state polariton physics [3] to light-matter interfaces [4]. These investigations are mainly motivated by the fast development of quantum information technologies and have been carried out in different types of media from atomic vapours, either cold [1] or at room temperature [2], to solid state materials [5, 6], photonic crystals [7, 8] and optical fibers [9].

For practical implementations it would be desirable to work at room temperature but often this implies the presence of inhomogeneous broadening that tends to reduce the transparency. Explicitly, in hot atomic vapors, the atomic motion leads to Doppler broadening due to the velocity-dependent shift of the laser field frequencies. If so, one direct approach to avoid inhomogeneous broadening consists of using cold atomic samples although it involves demanding technological requirements. In fact, albeit there are some proposals on how to reduce the negative role of the Doppler broadening in a hot vapor [10], a fully satisfactory solution is still challenging. Here we will focus on avoiding the adverse effects of the Doppler broadening to obtain on-resonance transparency for two-level hot atomic vapours. However, our results could be extended to other inhomogeneously broadened systems, e.g., solids with non-uniform crystalline fields [11].

In a two-level system, there exists a simple approach for achieving Doppler-free transparency named *self-induced transparency* (SIT) [12], which consists in shaping a resonant optical pulse propagating in the medium such that an integer number of Rabi oscillations is performed. This occurs in the coherent regime whenever the pulse area is an integer multiple of 2π. Therefore, SIT requires a very precise temporal control of the Rabi frequency. Analogously to SIT, when the pulse area is a multiple of an odd number of π, self-induced absorption (SIA) occurs.

An alternative approach to achieve resonant transparency consists in using induced atomic coherences in three- or multi-level atomic systems, e.g., by means of the coherent population trapping (CPT) [13] and the electromagnetically induced transparency (EIT) [14] phenomena or via a double-STIRAP process [15]. In most cases, an intense laser field, the so-called control field, couples to an atomic transition while modifying the optical properties of the medium for a weak laser field, the probe, acting on an adjacent transition. However, the fact that all these atomic coherence effects, CPT, EIT, STIRAP and double-STIRAP, operate in the so-called two-photon (or Raman) resonance condition means that, in the presence of Doppler broadening, the two laser fields must have near identical frequencies which severely restricts the range of applications of atomic coherence effects in hot atomic vapors [10].

In this paper, we present a novel approach that gives rise to Doppler-free transparency in a two-level (2L) system resembling a double-STIRAP process in a three-level (3L) system. To achieve self-transparency we will appropriately modify in time the amplitude and detuning of the laser pulse. It will be shown that this technique, which we name *adiabatic self-induced transparency* (ASIT), operates for a larger parameter range than SIT and is much more robust against fluctuations of the parameter values.

The paper is organized as follows: in Section II the nature of the ASIT phenomenon is described in the framework of the topological equivalence between density matrix equations for a 2L system and the Schrödinger equation for a 3L system. In Section III, the time evolution of the 2L system under conditions for ASIT is studied in the inhomogeneously (Doppler) broadened case. Section IV is devoted to the comparison between the proposed ASIT process and the already known SIT phenomenon.

II. ADIABATIC SELF INDUCED TRANSPARENCY

We consider a two-level atom (Fig. 1 (a)) interacting with a classical electromagnetic field (EM), $\vec{\epsilon}(t) = \vec{e}E(t)\cos(\omega t)$ in the electric dipole approximation. Under the rotating wave and slowly varying envelope approximations, the coherent dynamics of the two-level atom is given by the following density matrix or optical Bloch equations:

$$\frac{d}{dt}\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} 0 & \Delta & 0 \\ -\Delta & 0 & -\Omega \\ 0 & \Omega & 0 \end{pmatrix}\begin{pmatrix} U \\ V \\ W \end{pmatrix} , \qquad (1)$$

where we have introduced the real-valued variables that define the coordinates of the Bloch vector moving in a 3D space

$$U = 2\,\mathrm{Re}\,(\sigma_{12}) \ , \quad V = 2\,\mathrm{Im}\,(\sigma_{12}) \ , \quad W = (\sigma_{22} - \sigma_{11}) \ ,$$

σ_{ii} and σ_{ij} with $i, j = 1, 2$ account for the corresponding populations and coherences. $\Delta \equiv \omega - \omega_{21}$ is the frequency detuning of the field with respect to the instantaneous atomic transition frequency ω_{21}. $\Omega(t) \equiv -\vec{d}_{12}\vec{e}E\,(t)/\hbar$ denotes the time dependent Rabi frequency with $\vec{d}_{12}$ being the electric dipole moment of the atomic transition. The Rabi frequency, without loss of generality, is taken real and positive. Throughout the paper, we will consider that both the detuning and the optical field envelopes are time dependent. We name the temporally shaped detuning as *D pulse*, and the temporally shaped amplitude field as *EM pulse*.

Vitanov *et al.* [17] have recently shown that Eqs. (1) are topologically equivalent to the Schrödinger equation for a three-level atom in a Λ configuration interacting with two resonant laser fields (Fig. 1 (b)) under the following identifications: $U \Leftrightarrow \overline{C}_3$, $V \Leftrightarrow \overline{C}_2$, $W \Leftrightarrow \overline{C}_1$, and $2\Delta\,(t) \Leftrightarrow \Omega_S\,(t)$, $2\Omega \Leftrightarrow \Omega_P$, where $\overline{C}_{1,3} = C_{1,3}$ and $\overline{C}_2 = -iC_2$, with C_i being the probability amplitude to find a three-level atom in state $|i\rangle$. $\Omega_{P,S}$ denote the Rabi frequencies of the two applied fields. One should remark that for a 2L system the variables U, V and W are real quantities, while for a 3L system the variables $\overline{C}_i$ are, in general, complex numbers. The analogy between the 2L and the 3L systems is shown in Fig. 1(c).

In a 3L system, STIRAP is a widely used technique for transferring the atomic/molecular population between the two lower levels of a Λ-scheme and it is based on adiabatically following one of the three energy eigenstates of the system given by $|\Phi(t)\rangle = \cos\Theta(t)\,|1\rangle - \sin\Theta(t)\,|3\rangle$, with the mixing angle defined as $\Theta(t) = \arctan\left[\Omega_P(t)/\Omega_S(t)\right]$. In a 2L system and according to the previous analogy, the equivalent to the former energy eigenstate is the following combination of the population difference and the real part of the atomic coherence $\phi(t) = \cos\theta(t) \times W(t) - \sin\theta(t) \times U(t)$, with the mixing angle being now $\theta(t) = \arctan\left[\Omega(t)/\Delta(t)\right]$. Indeed, this analogy opens the possibility to directly extend

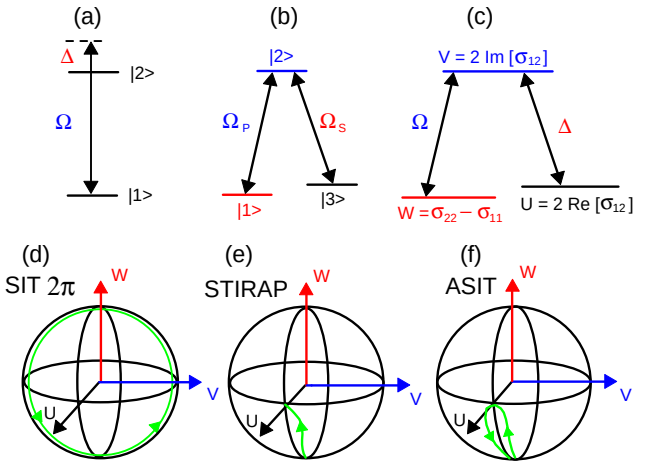

FIG. 1: (Color online) (a)Two-level system under consideration where Ω and Δ are the Rabi frequency and the field-atom detuning; (b) Three-level system interacting with two fields with Rabi frequencies Ω_P and Ω_S; (c) equivalence between the density matrix variables of the two-level system and the three-level picture. Schematic representation, for the two-level case, of the Bloch vector evolution on the Bloch sphere of the (U, V, W) variables, under (d) SIT with 2π pulses, (e) STIRAP and (f) ASIT processes.

the results that were known previously for 3L systems, obtained from the adiabatic temporal variation of the Rabi frequencies of the two coupled fields, to 2L systems, by appropriately engineering the temporal profile of the detuning and the Rabi frequency of a single EM pulse. We note that the temporal variation of the field amplitude and the detuning can be accomplished for instance by chirped pulses, and that chirped pulse excitation to achieve population inversion in a 2L system has been discussed via Stark Chirped Raman Adiabatic Passage (SCRAP) [16].

Such analogy between STIRAP and chirped two-state excitation has been studied in [17] in the complete coherent case, e.g., without spontaneous emission, and in the absence of Doppler broadening. From that study it follows that for the 2L-STIRAP case the Bloch vector moves from the south pole ($W = -1$, $U = 0$ and $V = 0$) to the equator ($W = 0$, $U = 1$ and $V = 0$) [see Fig. 1(e)] on the Bloch sphere. Starting with the population in the lower level and by applying first a D pulse and later on, and with an appropriate overlap, the EM pulse, the system ends up in a coherent superposition of the two states. In this process, the variable V accounts for EM field absorption (positive values) and stimulated emission (negative values), U describes the dispersion properties of the transition, and W gives the transfer of population.

In a 2L system, a functional definition of transparency is that the two-level atom evolves coherently from $W(t_{initial}) = -1$ (population in the lower level) back to $W(t_{final}) = -1$. This coherent evolution should

be fast enough such that spontaneous emission becomes negligible, which in turn, means that there is not irreversible EM absorption. Such definition of transparency is equivalent to state that the time averaged imaginary part of the atomic coherence weighted by the Rabi frequency is equal to zero, i.e., $g\langle \Omega V\rangle = 0$, where $g = \frac{N\omega_{12}d_{12}^2}{2\hbar\epsilon_0 c}$ is the gain parameter per unit length with N the atomic density, ϵ_0 the electric permitivity and c the speed of light. Hereafter the brackets $\langle ...\rangle$ mean time averaging.

As it has been mentioned above, a well known method to obtain transparency in a 2L system is the SIT phenomenon [12], i.e., coherent induced absorption of pulse energy during the first half of the pulse followed by coherent induced emission of the same amount of energy back into the beam direction during the second half of the pulse. In this case, the complete transfer of the population from the lower to the upper state and back can be realized with a fully resonant excitation whenever the pulse area is a multiple of 2π. Pulse areas multiple of an odd number of π result in complete absorption (SIA). The SIT/SIA phenomena have an absorptive nature, which means that in the Bloch sphere the evolution occurs predominantly in the plane (V, W) with $U = 0$ [see Fig. 1(d)], i.e. the transfer of the population is due to the EM absorption and emission processes involved and, therefore, $g\langle \Omega V\rangle = 0$ with $g^2\left\langle (\Omega V)^2\right\rangle / \left\langle \Omega^2\right\rangle^2 \neq 0$.

The novel method to obtain Doppler-free transparency in a 2L system, which we propose here, i.e. ASIT, consists in a process that resembles a double-STIRAP sequence in a 3L system. In a 3L system (Fig. 1(b)), a double-STIRAP process starts and ends in the ground state $|1\rangle$ since the mixing angle starts at $\Theta = 0$, goes to $\Theta = \pi/2$, and ends back again at $\Theta = 0$. To produce a double-STIRAP process, a first Stokes pulse has to be applied at the beginning of the process, then a partially overlapping pump pulse, and finally a partially overlapping second Stokes pulse. Alternatively, a relatively longer Stokes pulse that overcomes the pump pulse can be also used. In a similar manner, ASIT can be produced in a 2L system by applying an EM pulse in between two D pulses. The ASIT phenomenon is mainly of dispersive nature, since the evolution occurs predominantly in the plane (U, W), with much weaker relative excitation of the variable V related with absorption and of variable W [see Fig. 1 (f)] and, therefore, $g\langle \Omega V\rangle = 0$ and $g^2\left\langle (\Omega V)^2\right\rangle / \left\langle \Omega^2\right\rangle^2$ takes values smaller than in the SIT case.

Up to now we have not considered the incoherent processes that might be present in the system. In fact, there are no analogies between the 2L and 3L systems regarding incoherent processes like spontaneous emission or dephasing. In the 3L case, the spontaneous decay rate of the excited state does not play any role either in the STIRAP or in the double-STIRAP processes, because the whole adiabatic process occurs without coupling the excited state. In contrast, in the 2L case, spontaneous emission plays an important role because the exited state is always involved in the process. We will assume that the population difference decays at a rate γ while the decay of the real and imaginary parts of the coherence is $\Gamma/2$. In general, Γ accounts for several incoherent processes like spontaneous emission, collisions, dephasing or phase fluctuations. Here we only consider the effect of the spontaneous emission in the decay of the coherences and therefore $\Gamma = 2\gamma$. The requirement of full coherence for ASIT to work imposes a maximum time duration of the process limited by the lifetime of the levels, i.e., $T\gamma \ll 1$, where T is the total time for the ASIT process. Under these conditions, comparison between the three just above described processes of SIA, SIT and ASIT is shown in Fig. 2 where the time evolution of the variables (W, U, V) in a homogeneously broadened 2L medium is

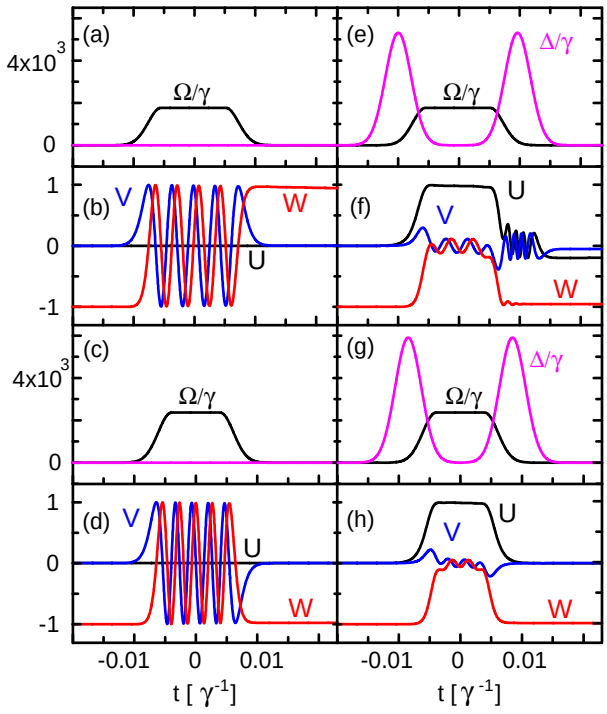

FIG. 2: (Color online) Temporal profiles of the EM (black line) and D (magenta line) pulses (a,c,e,g). Time evolution of the population difference (W) and the medium coherence (U, V) (b,d,f,h) in a homogeneously broadened two-level system under the SIA (a,b), SIT (c,d) and ASIT (e-h) processes. The areas of the pulses are equal to $A = A_\Omega = A_\Delta = 9\pi$ (a,b,e,f) and $= 10\pi$ (c,d,g,h). The D pulses and the rise and fall parts of the EM pulses have gaussian profile. The temporal width of the D pulses is $\tau_\Delta = 0.003\gamma^{-1}$, $\Delta_0 = 0$. $\overline{\Delta}/\gamma = 5318$ (e,f) and $= 5909$ (g,h). $\Omega_0/\gamma = 1772$ (a,b,e,f) and $= 2363$ (c,d,g,h). The rise τ_r and fall τ_f time of the EM pulses is equal to $\tau_{r,f} = \tau_\Delta/2$. The D pulses are shifted away by $\Delta\tau = 1.5\tau_\Delta$ from the top flat part of the EM pulse. The time duration of the top flat part of the EM pulses is set to keep the EM pulse area indicated above. In all cases represented, the detuning of the EM pulses during the top flat part is close to zero value.

represented. It should be mentioned that in the case we consider here Figs. 2 (b,d,f,h) represent the temporal response of a single 2L atom as well as of a homogeneously broadened medium composed of such 2L atoms. In contrary to the SIA and SIT processes (see Figs. 2 (a-d)) where the final state of the system strongly depends on the EM pulse area, under the ASIT phenomenon the population returns back to the lower level, giving rise to the transparency of the 2L medium, independently on the area of the exciting EM pulse as demonstrated in Figs. 2 (e-h). Although the strength of the light-atom interaction is larger for the SIA and SIT processes than for the ASIT process, but it is strong in all cases.

III. ASIT IN INHOMOGENEOUSLY BROADENED MEDIA

Now we focus on the role of the Doppler broadening in the 2L system under consideration by assuming a Maxwell distribution for the projection of the atomic velocities on the light propagation direction. We will solve the ASIT process for different atomic velocity classes and sum up the total response along the Maxwell distribution. For an atom moving with some velocity v along the direction of the propagating laser field (with wavenumber k = ω/c), the instantaneous field detuning will be $\Delta(v,t) = \Delta(t) - kv$, where $\Delta(t)$ is the nominal detuning for atoms at rest. For definiteness we choose temporal Gaussian profiles for the D and the EM pulses:

$$\begin{aligned} \Delta(t) &= \Delta_0 + \overline{\Delta}\left(e^{-(t-\Delta\tau)^2/\tau_\Delta^2} + e^{-(t+\Delta\tau)^2/\tau_\Delta^2}\right) , \\ \Omega(t) &= \Omega_0 e^{-t^2/\tau_\Omega^2} , \end{aligned} \tag{2}$$

where $\overline{\Delta}$ defines the amplitude of the temporal variation of the detuning with respect to the constant detuning offset Δ_0, Ω_0 is the amplitude of the EM pulse, $\tau_{\Delta,\Omega}$ are the time durations of the D and EM pulses, and $\pm\Delta\tau$ are the delays of the D pulses with respect to the center of the EM pulse.

For a complete transfer of the atoms, the double-STIRAP process should be performed adiabatically, condition that for atoms moving with velocity v reads [17]:

$$T\sqrt{\Omega_0^2 + \Delta^2(v,t)} > 10 . \tag{3}$$

Let us assume, for simplicity and without losing generality, that Δ_0 and $\overline{\Delta}$ are both positive. Then for the homogeneous case or for a small Doppler width, i.e. for $\Delta\omega_D < \Delta$, the adiabaticity condition (3) can be fulfilled for all atoms simultaneously, provided that appropriate values for the parameters, in particular for Ω_0, are chosen. This might not be the case, however, for hot atomic vapours, where the velocity-dependent Doppler shift can strongly modify the D pulse offset during the ASIT process for some atomic velocity classes. The largest reduction in the instantaneous values of the detuning $\Delta^2(v,t)$ will occur for atomic velocities verifying $kv > \Delta_0$ and in particular for $kv \sim (\Delta_0 + \overline{\Delta})$, where the detuning will remain close to zero during significant time intervals (those where the D pulse passes near its maxima values). This can break the adiabaticity condition (3) for atoms with such velocity, so that they can be transferred to the excited state breaking the transparency under the double-STIRAP process. One needs to note that to maintain adiabaticity of the process for small detuning $\Delta(v,t)$ the Rabi frequency Ω_0 should be increased substantially, see for instance [17].

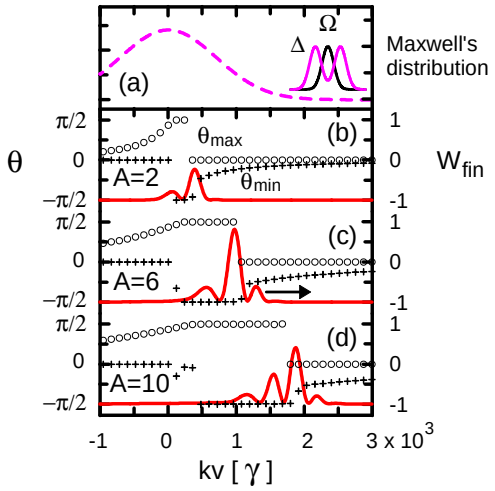

FIG. 3: (Color online) Distributions for the final value (red solid line) of the atomic population inversion, W_{fin}, and of the maximum (empty circles) and minimum (crosses) values for the mixing angle θ with respect to the Doppler shift kv at different amplitudes of the EM and D pulses (b-d). The areas of the EM and D pulses, defined as $A_\Omega = \Omega_0\tau_\Omega/\sqrt{2}$ and $A_\Delta = \overline{\Delta}\tau_\Delta/\sqrt{2}$, are equal to each other $A = A_\Omega/\pi = A_\Delta/\pi$ = 2 (b), = 6 (c), = 10 (d). The Maxwell distribution of the atomic velocities is shown in (a) (dashed line). The inset in (a) presents the time evolution of the exciting EM (Ω) and D (Δ) pulses. Abrupt decrease in the θ_{max} corresponds to the velocity class for which $kv \sim \Delta_0 + \overline{\Delta}$. The temporal widths of the input pulses are $\tau_\Delta = \tau_\Omega = 0.01\gamma^{-1}$, $\Delta_0 = 0$ and $\Delta\tau = 1.5\tau_\Omega$. The Doppler width is fixed at $\Delta\omega_D = 10^3\gamma$ and $\Gamma = 2\gamma$. Macroscopic response of the inhomogeneously broadened 2L medium is given by the integration of the atomic response [shown by red solid lines in figures (b-d)] weighted by the probability density for the atomic velocities of the Maxwell distribution [shown by the dashed line in figure (a)].

We have studied in detail the response of 2L atoms with different values of the Doppler shift kv along the Maxwell distribution by exciting them with D and EM pulses of the form given in (2). Some of the results are presented in Figs. 3 and 4, for a specific Doppler frequency profile and a specific temporal pulse profile [see Fig. 3 (a)]. Fig. 4 shows the total atom-field detuning (sum of the D-pulse value plus the Doppler shift kv) [see, Figs. 4 (a), (c) and (e)], and the atomic-state evolution

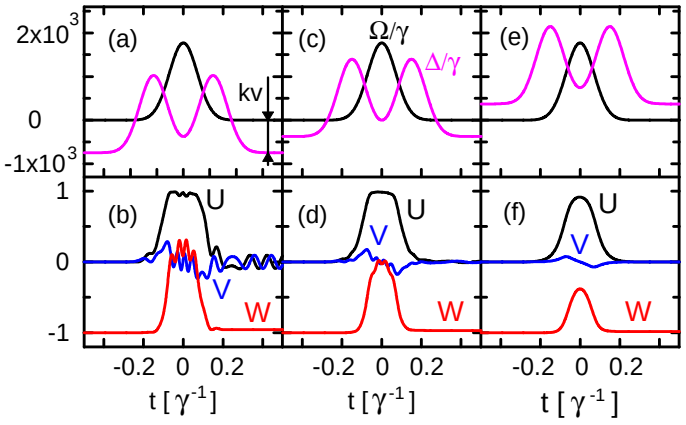

FIG. 4: (Color online) Temporal profiles for the EM pulse (black line) and the total detuning seen by the atom (magenta line), for three different atomic velocity classes (a,c,e): $kv = \Delta\omega_D 3/4$ (a,b), $kv = \Delta\omega_D/3$ (c,d) and $kv = -\Delta\omega_D/3$ (e,f). Figs. (b), (d) and (f) represent the time evolution of the atomic variables W, U and V. The pulse areas are $A_\Omega = A_\Delta = 10\pi$. The other parameters are the same as in Fig. 3

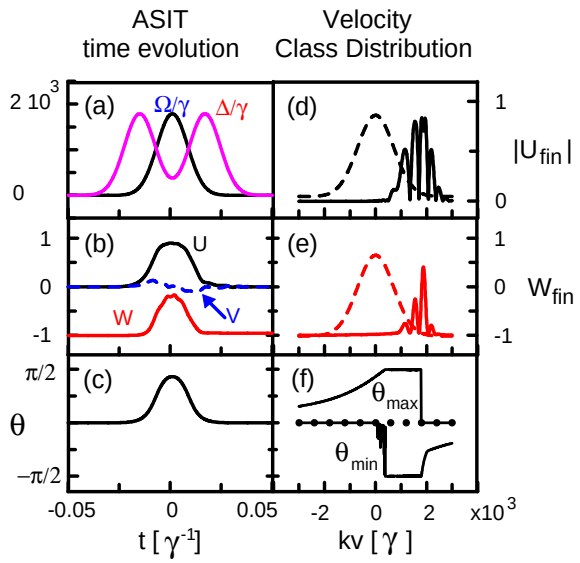

FIG. 5: (Color online) Time evolution of the macroscopic population difference (W) and the medium coherence (U, V)) (b) in the inhomogeneously broadened two-level system under excitation of EM and D pulses shown in (a). (c) shows the evolution of the mixing angle, θ, for atoms with zero projection of the velocity onto the light propagation direction. The pulse areas are $A_\Omega = A_\Delta = 10\pi$. Distribution of the final amplitude for the single atom variables U and W on the Doppler shift kv is shown in (d) and (e), respectively. Dashed lines in (d) and (e) are plotted to visualize the Maxwell distribution of the atomic velocities. The maxima (upper line) and minima (lower line) for the variable θ are shown in (f), where dots represent its zero final value. The other parameters are the same as in Fig. 3

for three different atomic velocity classes v [see, Figs. 4 (b), (d) and (f)]. It is clear from Fig. 4 that in all cases the light-atom interaction is quite strong [it is less strong in the case of Figs. 4 (e) and (f) because in that case the total field detuning is largest], but always the final state of the population difference W is the same as the initial state, i.e., $W = -1$. This is due to the adiabaticity of the ASIT process. The dependence of the final value of the atomic population inversion, W_{fin}, i.e. the response of a single 2L atom, with respect to the Doppler shift kv is presented in Figs. 3 (b-d), red solid line, for different values of the area of D and EM pulses at a constant temporal duration of the pulses. It is clearly shown in the figure that, in the velocity domain pointed out above, with $kv \sim (\Delta_0 + \overline{\Delta})$, the 2L atoms are strongly perturbed by the pulses and they do not end at the initial state $W = -1$.

Therefore, the macroscopic response of the inhomogeneously broadened 2L medium considered is provided predominantly by atoms in the velocity domain of nonadiabatic response. As known the macroscopic absorption of atoms within a particular velocity domain of the Doppler profile is defined by absorption of individual atoms [represented by W_{fin}, see red solid lines in Figs. 3 (b-d) and Fig. 5 (e)] weighted by the probability density for these atoms to belong to this particular velocity domain within the Maxwell distribution (shown by the dashed lines in Fig. 3 (a) and Fig. 5 (e)). Therefore, the absorption of the 2L medium considered could be reduced either by decreasing the absorption of individual 2L atoms or by moving the velocity domain of nonadiabatic response to the wings of the Maxwell distribution where the probability density for atomic velocities is strongly reduced. We found that by increasing the amplitude $\overline{\Delta}$ of the D pulse (increasing simultaneously the amplitude of the EM pulse to keep the same pulse areas) the domain of nonadiabatic response could be shifted to the wing of the Doppler profile, as it is clearly shown in Figs. 3(b-d). In this way its negative role is reduced due to the much lower relative atomic population at the wing of the Maxwell distribution shown by the dashed line in Fig. 3(a), almost all the atoms undergo an adiabatic process and, consequently, the medium becomes essentially transparent.

In order to verify the previous statement, we present in Fig. 5 further results corresponding to the case considered in Fig. 3(d), which describes an inhomogeneously broadened system of 2L atoms excited by D and EM pulses of the form given in (2) with area of $A = 10\pi$. Fig. 5(a) shows the sequence of the exciting D and EM pulses in such case. The time evolution of the macroscopic variables (U, V, W) (obtained at each time step by the summation of single atom response weighted in accordance with the Maxwell distribution of the atom velocity) and of the mixing angle θ (the latter is presented only for atoms with $kv = 0$) for the ASIT process is plotted in

Fig. 5(b) and Fig. 5(c), respectively. One can see that the ASIT phenomenon has predominantly a dispersive nature, since the quantity V takes values much smaller than those taken by U [Fig. 5(b)]. In Fig. 5 the amplitude of the D pulses has been chosen two times larger than the Doppler width of the inhomogeneous transition. In such a case, the spectral components of the EM pulse induce almost identical evolutions in 2L atoms from different velocity classes of the Maxwell distribution (except for the perturbed domain mentioned above at $kv \sim (\Delta_0 + \overline{\Delta})$). Indeed, we found that a given exciting pulse in the inhomogeneously broadened 2L system will produce almost the same response that would be induced in a homogeneously broadened 2L system. It should be mentioned that for small values of the amplitude of the D pulse, the perturbed domain is moved to the center of the Maxwell distribution, as shown in Fig. 3. This strongly modifies the response of the inhomogeneously broadened 2L atoms because large part of them are transferred to the excited state, making the ASIT process ineffective.

IV. ASIT VERSUS SIT

In this section we compare the robustness of the ASIT technique with respect to the SIT one by studying the effect of the variation of the pulse parameters. We consider the evolution of an inhomogeneously (Doppler) broadened 2L system. Fig. 6 shows the numerical results for the final values of the macroscopic population difference W_{fin} [Figs. 6 (a) and 6 (b)] and for the time averaged quantity $g^2 \left\langle (\Omega V)^2 \right\rangle / \left\langle \Omega^2 \right\rangle^2$ describing the absorptive character of the process [Fig. 6(c) and Fig. 6(d)], in the parameter plane defined by the area of the D and/or EM pulses and the pulse width. Fig. 6(a) and Fig. 6(c) correspond to a SIT process and Fig. 6(b) and Fig. 6(d) correspond to an ASIT process.

Since the ASIT process is based on a double-STIRAP technique, and since the STIRAP mechanism is more effective when the exciting pulses have equal amplitudes, we have assumed that D and EM pulses have equal areas, $A_\Omega = A_\Delta$, and time durations in the simulations of Fig. 6. Moreover, it has been assumed that the delay time between consecutive D and EM pulses is $\Delta\tau = 1.5\tau$, for which it is known that STIRAP transfer by Gaussian pulses is most efficient [15]. For the SIT process we have considered only an EM pulse of area A_Ω ($A_\Delta = 0$).

White regions in Fig. 6(a) and Fig. 6(b) correspond to the domains with $W_{fin} \to -1$, which means that the final state is the same as the initial one and thus there is transparency. Fig. 6(a) shows that to achieve transparency in the SIT case the pulse area needs to be precisely controled (multiples of 2π), especially for short pulses. But even for these particular values of the pulse area, Doppler broadening and relaxation processes prevent from reaching complete transparency (the best values in Fig. 6(a) are obtained for pulse area equal to 2π and short pulse duration, where $W_{fin} \sim -0.973$ at $\tau_\Omega = 2 \times 10^{-3}\gamma^{-1}$).

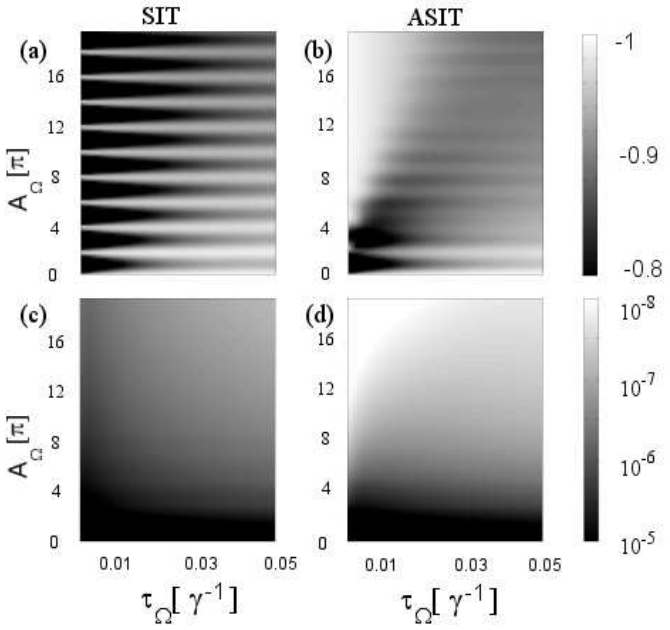

FIG. 6: Contour plot of the final values of the macroscopic population inversion, W_{fin}, after SIT (a) and ASIT (b) processes in a Doppler broadened 2L system as a function of the pulse area and duration. $A_\Delta = A_\Omega$ in (b) and (d), and $A_\Delta = 0$ in (a) and (c). Other parameters of the 2L system and of the pulses are the same as in Fig. 3. White regions in (a) and (b) correspond to the domains where $W_{fin} \to -1$. Plots for time averaged values of $g^2 \left\langle (\Omega V)^2 \right\rangle / \left\langle \Omega^2 \right\rangle^2$ in g^2 units indicate the pure absorptive nature of the SIT phenomenon (c) and the more dominantly dispersive nature of the ASIT process in the domain close to the left vertical axis (d).

For longer pulses (and thus with smaller peak amplitude) the broadening due to Doppler effect (and also due to spontaneous emission) is more present because its relative influence on the value of the generalized Rabi frequency increases. In contrast, Fig. 6(b) shows that in the ASIT case transparency is feasible with pulses of arbitrary area, provided this area is larger than a value (approximately 4π) which is almost equal to that required by the adiabaticity condition (3) in the double-STIRAP process. Note also in Fig. 6(b) that the degree of transparency is larger for smaller pulse durations (i.e., near the vertical axis), where values very close to -1 ($W_{fin} \sim -0.995$ at $\tau_\Omega = 2 \times 10^{-3}\gamma^{-1}$ for pulses of area $A_\Omega = A_\Delta = 10\pi$) are achieved. For larger pulse durations (and thus lower pulse amplitudes) it is progressively more difficult to push the velocity classes not fulfilling the adiabaticity condition (i.e., classes $kv \sim (\Delta_0 + \overline{\Delta})$) to the wings of the Maxwell distribution and larger pulse areas are required for that. Also the influence of spontaneous emission is larger for longer pulses. Note also in Fig. 6(b) that near the horizontal axis there is a second region with values of W_{fin} close to -1. Such region

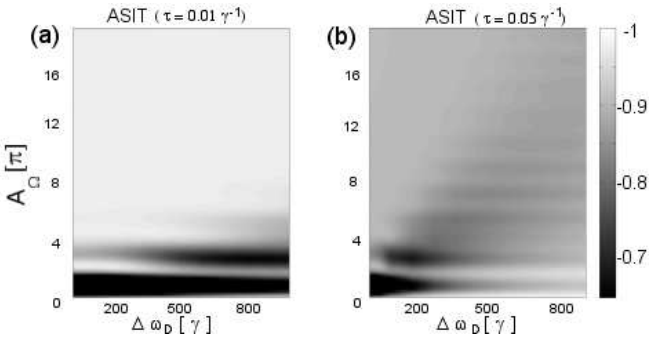

FIG. 7: Contour plot of macroscopic variable W_{fin} under conditions of ASIT in the plane $(A_\Omega = A_\Delta, \Delta\omega_D)$ for a Doppler broadened 2L system of ^{87}Rb atoms excited by EM and D pulses of equal areas for two values of the time duration $\tau_\Omega = \tau_\Delta = 0.01\gamma^{-1}$ (a) and $\tau_\Omega = \tau_\Delta = 0.05\gamma^{-1}$ (b). The considered transition of the ^{87}Rb atoms is $(\left|5^2S_{1/2}, F = 2, m_F = 2\right\rangle \leftrightarrow \left|5^2P_{3/2}, F = 3, m_F = 3\right\rangle$ with $\lambda_0 = 780$ nm, $\gamma = 5.83 \times 2\pi \times 10^6\ s^{-1}$ and $\Gamma = 2\gamma$.

does not correspond to pure ASIT, since the adiabaticity condition is not fulfilled; rather, it can be seen as a reminiscence of the SIT effect due to the EM pulse (compare with Fig. 6(a)), combined with the relaxation processes. Fig. 6(c) and Fig. 6(d), confirm the previous discussion. The absorptive character is smaller in the ASIT case than in the SIT case.

It is known that the Doppler width in optical transitions can be modified by cooling or heating the atoms. In such cases it is possible to change the Doppler width in a large range of values from below to few orders above the homogeneous width. In order to show the feasibility of ASIT for real hot atoms we have investigated the effects of the Doppler width in specific atomic transitions. The results are summarized in Fig. 7, where we plot the dependence of W_{fin} in a hot gas of ^{87}Rb atoms as a function of the amplitudes of the EM and D pulses and of the Doppler width of the inhomogeneously broadened transition $(\left|5^2S_{1/2}, F = 2, m_F = 2\right\rangle \leftrightarrow \left|5^2P_{3/2}, F = 3, m_F = 3\right\rangle$, for two values of the pulse width $\tau_\Omega = \tau_\Delta = 0.01\gamma^{-1}$ (Fig. 7(a)) and $= 0.05\gamma^{-1}$ (Fig. 7(b)). It is clear from Fig. 7 that nonadiabatic effects are negligible for pulses with large area and short time duration. In contrast they are pronounced for long pulses and also for short pulses with small area, when the amplitude $\overline{\Delta}$ of the D pulse becomes comparable to the Doppler width of the transition. By taking into account that at room temperature ($T = 300^0$K), the Doppler width is equal to $\Delta\omega_D = 530\gamma$ we can conclude, [see Fig. 7(a)], that the reported phenomenon of ASIT can be feasible experimentally in an atomic vapour cell of rubidium at room temperature and under excitation of nanosecond EM and D pulses with pulse area of few π.

In conclusion, we have demonstrated the feasibility of the adiabatic self induced transparency (ASIT) technique, which yields Doppler-free transparency for electromagnetic pulses in a 2L system. Our technique consists of driving the 2L system with a laser pulse whose detuning with respect to the atomic transition and whose EM field amplitude are temporally varied in a proper shape. The detuning modulation can be introduced either by using the Stark or the Zeeman effect to obtain time-dependent energy levels in the atom/molecule, which gives rise to time-dependent detunings, or alternatively by introducing a suitable chirp on the EM pulse. We have studied the robustness of the reported phenomena against modifications of the pulse parameters and we have shown that the ASIT process is much more robust than the conventional SIT, in the sense that the area of the pulses needs not to be adjusted with precision and it can be much less sensitive to Doppler broadening. Because of the adiabaticity condition, the pulse areas for ASIT need in general to be somewhat larger than for SIT, for which a 2π area is sufficient, but it could be implemented with no essential difficulty in real Doppler-broadened atomic systems such as for instance rubidium hot vapors. Although the results presented in this article have been obtained for Gaussian pulses we have also checked the validity of the ASIT technique for pulses with other forms of temporal profiles.

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