PHYSICAL REVIEW A VOLUME 52, NUMBER 3 SEPTEMBER 1995

Transparency and dressing for optical pulse pairs through a double-Λ absorbing medium

Elena Cerboneschi and Ennio Arimondo
Dipartimento di Fisica, Università di Pisa, Piazza Torricelli 2, 56100 Pisa, Italy
(Received 16 November 1994)

Through numerical simulations we show that the propagation of pairs of optical pulses in a double-Λ configuration is favorable for the attainment of electromagnetically induced transparency with matched pulses, even through a long absorbing sample. The double-Λ configuration allows a flexible and precise control of the amplitudes and phases for the propagating pulses. Different atomic and field configurations based on a double-Λ system in rubidium atoms have been explored.

PACS number(s): 42.50.Gy, 42.25.Bs, 42.50.Hz

The phenomenon of electromagnetically induced transparency (EIT) in the propagation of laser radiation through an absorbing medium has been recently investigated and explained in terms of quantum coherence and interference for three-level atomic systems in Λ, V, and cascade configurations [1–5]. In the Λ configuration, if the atomic medium is prepared in a quantum superposition of states, matched pulses, i.e., a pair of optical pulses whose amplitude and phase have a well defined relation, propagate without absorption [2,4]. The mechanism of coherent population trapping [6] is responsible for EIT in a Λ system [4]. Pulse matching takes place owing to the nonlinear interaction between the pair of time-varying envelope fields and the atoms, prepared in the coherent population trapping superposition. The two fields, each one resonant with one transition of the Λ system, while propagating through the absorbing medium, experience reshaping until, after a characteristic penetration depth, temporal pulse matching of the field envelope shapes and transparency take place.

The propagation of matched pulses may be described as the spatiotemporal transparency for a linear superposition of optical electric field amplitudes. That transparent superposition of optical fields, or dressing [7], is fixed by the amplitudes in the atomic coherent trapping superposition and the preparation of the atomic quantum superposition allows a handle on the choice of the matched pulse characteristics. Thus atomic preparation represents the first stage in the realization of pulse matching. The question of the preparation of the coherent population trapping superposition state has been addressed by Agarwal [3] and Harris [4]. They assume that the time-varying fields of the pulse pair are superimposed onto constant electric field components, resonant with the atomic transitions, which produce the trapping superposition. If this assumption is renounced, numerical simulations show [4] that pulse matching is attained as well, but pulses undergo leading-edge preparation losses as they prepare the trapping state. Therefore, a completely lossless propagation cannot be achieved.

In this Rapid Communication we show, through numerical simulations, how, in a double-Λ four-level atomic system like that of Fig. 1, a separate pulse pair can be used to prepare the atomic superposition. Our numerical simulations report completely lossless propagation of shape matched pulses within long penetration distances inside an absorbing medium. Moreover, the transparency and dressing of the pulse matched pair can be controlled very precisely and with a large degree of freedom. In the double-Λ system atomic preparation and matching take place on different atomic transitions, so that a very flexible control of the amplitude and phase for the two electromagnetic fields composing the transmitted pulse is realized. The introduction of a short time delay between the preparation pulses, to be denoted as coupling, and the matched pulses, denoted as probe, allows us to separate the phases of atomic preparation and pulse matching. Furthermore, we have found that the assistance between simultaneously propagating coupling and probe pulses is responsible for an enhancement of the lossless propagation and pulse shape preserving. This electromagnetic assistance on the pulse matching is produced by the coherence between the two upper states of the four-level system. A similar electromagnetic assistance was reported before in the context of simulton theory [8].

The double-Λ scheme has already been investigated in the context of amplification without population inversion [9–11]. In [9] amplification without inversion became feasible if a high degree of coherence between the lower states was established and a definite condition on the population difference between the upper states was fulfilled. In the analysis reported in [11], the coherence between the two upper levels was shown to provide an additional mechanism for inversionless amplification. However, in our simulations we

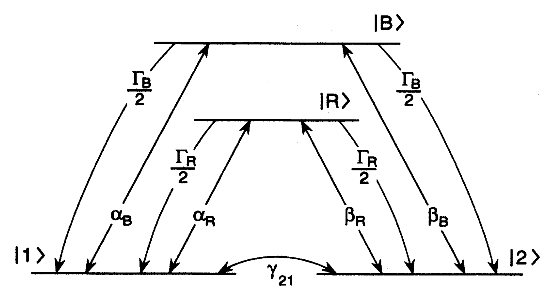

FIG. 1. Atomic energy levels in the double-Λ configuration. Optical transitions and spontaneous decays from $|B\rangle$ and $|R\rangle$ states are indicated. A nonradiative coupling γ_{21} between ground states is introduced. In the simulations, we investigated both cases with strong pulses and weak probe pulses acting on the transitions to states $|B\rangle$ and $|R\rangle$, and vice versa.

do not obtain amplification without inversion, because the characteristic requirements on the upper state populations are not fulfilled.

The double-Λ system is composed of two Λ subsystems, which share the lower energy levels $|1\rangle$ and $|2\rangle$ with upper levels $|B\rangle$ "blue" and $|R\rangle$ "red." We treat a configuration where a pair of strong coupling fields is coupled to one of the two Λ subsystems and a pair of weak probe fields interacts with the other (see Fig. 1). Since the coupling pair is several orders of magnitude stronger than the probe pair, the subsystem concerned with the coupling fields is nearly decoupled from the other. Thus the intense coupling fields trap the atoms in the nonabsorbing coherent trapping superposition of $|1\rangle$ and $|2\rangle$ ground states; the probe pulses, on the other hand, by interacting with thus prepared atoms, experience amplitude and phase shape matching. The following expressions for the applied electromagnetic fields are considered:

$$E_{R_1}(z,t)=\mathrm{Re}\{\mathscr{E}_{R_1}(z,t)\exp(-i\omega_{R_1}t+ik_{R_1}z)\},$$

$$E_{R_2}(z,t)=\mathrm{Re}\{\mathscr{E}_{R_2}(z,t)\exp(-i\omega_{R_2}t+ik_{R_2}z)\},$$

$$E_{B_1}(z,t)=\mathrm{Re}\{\mathscr{E}_{B_1}(z,t)\exp(-i\omega_{B_1}t+ik_{B_1}z)\},$$

$$E_{B_2}(z,t)=\mathrm{Re}\{\mathscr{E}_{B_2}(z,t)\exp(-i\omega_{B_2}t+ik_{B_2}z)\}, \qquad (1)$$

where we assume that each field component interacts with one atomic transition only. We suppose also that exact resonance conditions are fulfilled. The time- and space-dependent Rabi frequencies, defined respectively for the transitions $|1\rangle$-$|R\rangle$ and $|2\rangle$-$|R\rangle$, are $\alpha_R=\mu_{R_1}\mathscr{E}_{R_1}/2\hbar$ and $\beta_R=\mu_{R_2}\mathscr{E}_{R_2}/2\hbar$, with μ_{R_i} $(i=1,2)$ dipole matrix elements. α_B and β_B are the analogous quantities for the transitions involving the state $|B\rangle$. If we propose using the excitations to the $|B\rangle$ state as coupling transitions, the $|NC\rangle$ noncoupled state is given by

$$|NC\rangle=\frac{\beta_B|1\rangle-\alpha_B|2\rangle}{\sqrt{\alpha_B^2+\beta_B^2}}. \qquad (2)$$

$|NC\rangle$ is an eigenstate of the field-atom interaction Hamiltonian and is decoupled from the coupling fields acting on the transitions to the $|B\rangle$ state: atoms in the $|NC\rangle$ state do not absorb radiation from the coupling fields. The coupled state, given by the orthogonal superposition, allows transitions to the upper state. In general, in a double-Λ system, the $|NC\rangle$ state is nonabsorbing with respect to the coupling fields that generate it, but it does couple to the probe fields. However, if the noncoupled quantum superposition for the probe fields coincides with that of the coupling fields, the probe fields also are not absorbed and they propagate freely. It is immediately verified that the two nonabsorbing superpositions coincide if the probe pulses have their Rabi frequencies in the same ratio as the coupling pulses. The following condition results:

$$\frac{\alpha_B}{\beta_B}=\frac{\alpha_R}{\beta_R}. \qquad (3)$$

Shape matched pulses satisfying this condition are stable solutions for the propagation in the double-Λ scheme. The condition of Eq. (3) is independent of which transitions of the double-Λ system are used for the coupling fields and which are used for the probe fields.

The semiclassical description of the interaction between electromagnetic fields and a homogeneously broadened material medium, in the configuration represented in Fig. 1, leads to a set of Maxwell-Bloch coupled nonlinear partial differential equations [9]. We have used, in the simulations, the parameters of a double-Λ system in a ^{87}Rb atomic beam with states [12] $|1\rangle=|5^2S_{1/2}F=1,m_F=1\rangle$, $|2\rangle=|5^2S_{1/2}F=1,m_F=-1\rangle$, $|R\rangle=|5^2P_{3/2}F=1,m_F=0\rangle$, $|B\rangle=|6^2P_{3/2}F=1,m_F=0\rangle$. The electric fields of Eq. (1) are supposed to be σ^- and σ^+ polarized. The spontaneous emission decay rates of the ^{87}Rb excited states, at wavelengths of 780.0 and 420.2 nm, respectively, are $\Gamma_R=3.77\times10^7$ s^{-1} and $\Gamma_B=8.93\times10^6$ s^{-1}. The nonradiative coupling γ_{21} between the two ground states determines the finite lifetime of the coherent trapping superposition: the value $\gamma_{21}=5\times10^4$ s^{-1} has been assumed. Such a value for γ_{21} results in a lifetime of the noncoupled state that is much longer than the time duration of the pulses, so that the loss in coherence of the ground-state superposition is not a limitation.

We have solved numerically the partial differential equations in the moving frame, along the propagation direction, defined by the variables $\zeta=z$ and retarded time $\tau=t-z/c$, where c is the velocity of the light in the medium. Given the time evolution at the entrance of the medium as an initial condition for the field envelopes, and the initial conditions of thermal equilibrium for the atomic variables throughout the medium, we determine the temporal profiles of field and atom variables at any fixed ζ position. The ζ coordinate values are expressed as multiples of α^{-1}, the Beers law absorption length for the transitions from each ground state to the excited state, which involve the probe pulses. In the simulations the amplitudes of the electromagnetic fields have been chosen real, before they enter the medium; since we assume conditions of exact resonance with the atomic transitions, they remain real during the propagation.

Figures 2 and 3 refer to the case where the coupling preparation is based on the excitations of the $|B\rangle$ state and the probe takes place on the transitions to the $|R\rangle$ state. In Fig. 2, the coupling field amplitudes are shown as a function of the time at different penetration distances through the atomic medium. They are compared with the occupations of the noncoupled trapping state and the coupled state, $\rho_{NC,NC}$ and $\rho_{C,C}$, respectively. The strong coupling blue pulses, while propagating through the medium, excite the $|B\rangle$ state and pump the atoms into the noncoupled state. In the simulations reported in Fig. 2, the maximum population in the noncoupled state is only about 90%, since the coupling fields have been switched off before the full accomplishment of the trapping process. Such a preparation of the medium does not provide the optimum conditions for pulse matching, but allows us to distinguish between different physical mechanisms concerned with pulse matching. The transmitted coupling fields, together with the population of the coupled superposition, display Rabi oscillations. The population of

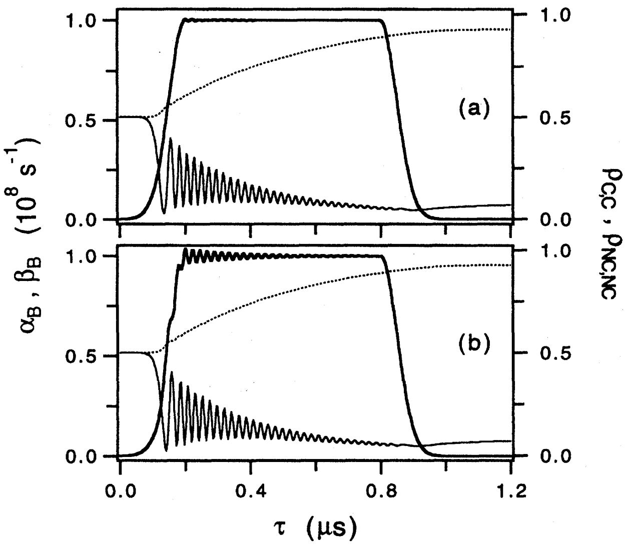

FIG. 2. Snapshots of the α_B and β_B coupling pulse amplitudes and of the occupation of the coupled and noncoupled superpositions at different penetration depths ζ through the medium. The thick solid line indicates the identical coupling amplitudes α_B and β_B with the left axis. Thin solid and dotted lines indicate the coupled $\rho_{C,C}$ and noncoupled $\rho_{NC,NC}$ occupations with the right axis. Penetration depths in (a) $\zeta\alpha=3$ and in (b) $\zeta\alpha=30$. At $\zeta\alpha=0$, α_B and β_B are as in (a), without the tiny oscillations, and $\rho_{C,C}$ and $\rho_{NC,NC}$ are equal to 0.5, their thermal equilibrium value.

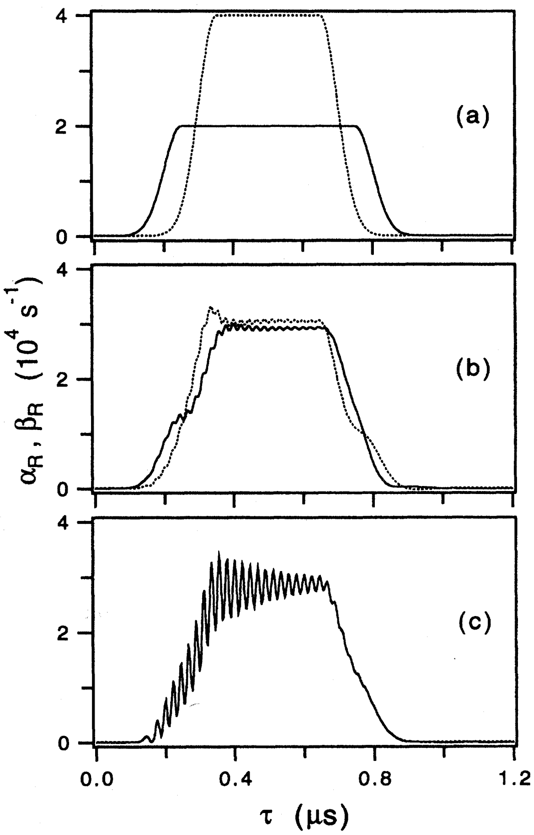

FIG. 3. Snapshots of the probe pulse amplitudes α_R (solid line) and β_R (dotted line) at different penetration depths, as they propagate simultaneously with the coupling pulses on the transitions to the $|B\rangle$ state (shown in Fig. 2). Penetration depths in (a) $\zeta\alpha=0$, in (b) $\zeta\alpha=3$, and in (c) $\zeta\alpha=30$.

the noncoupled state does not oscillate, since such a state does not interact with the fields, while it is filled by the spontaneous decay process.

We have chosen coupling blue pulses that are identical to each other to produce the noncoupled trapping superposition of Eq. (2) composed by both lower states in equal percentages. Figure 2 shows that the coupling pulses remain equal during the propagation. With such a preparation of the atomic system, from Eq. (3) we expect exact coincidence for the final amplitudes and phases of the probe pulses. As can be seen from Fig. 2, the atomic system, which interacts with the propagating coupling pulses, reproduces the same temporal behavior at any ζ position inside the medium: the curves of the populations, in Figs. 2(a) and 2(b), are almost identical to each other. Thus the system always undergoes the same atomic preparation, and constant conditions are encountered by the probe pulses. Such a stability in the preparation of the atomic medium is essential for pulse matching to take place, so that the probe pulses reach matched temporal profiles, as shown in Fig. 3. Further simulations have demonstrated that, if the noncoupled state changes in the course of the field propagation, then the matching process is inhibited.

Figure 3 reports the shape evolution of probe pulse amplitudes α_R and β_R, as they propagate through the medium, simultaneously with the coupling fields shown in Fig. 2. The input pulses, at $\zeta=0$, are different in amplitude and time duration. At a penetration depth of $\zeta\alpha=3$, pulse matching is already realized, with pulse amplitudes satisfying Eq. (3). Even though the trapping state is only partially occupied, pulse shape matching takes place. At longer propagation depths, pulse matching is not accompanied by transparency, because of the residual population in the coupled absorbing state. Figure 3 evidences the presence of Rabi oscillations on the transmitted probe pulses. Those oscillations are originated by the coupling pulses on the population of the coupled state.

Figure 4 refers to a situation where the coupling fields produce a complete pumping action into the population trapping noncoupled state, so that transparency of the probe pulses remains at longer penetration depths. The atom and field parameters are the same as those of the previous cases, except that the coupling preparation takes place on the transitions to the $|R\rangle$ state and the probing stage on the transitions to the $|B\rangle$ state. This choice corresponds to the purpose of illustrating a condition with perfect dressing and transparency. A large value of Γ_R allows a faster preparation of the atoms in the trapping state. Pulse matching is reached at a penetration depth around $\zeta\alpha=10$, longer than in the case of Fig. 3. In fact, in agreement with the normal mode analyses of [4,9], the pulse matching is reached exponentially with a characteristic penetration depth that depends on the ratio between the oscillatory strength of the transition and the spontaneous decay from the upper level. Once pulse matching is realized, the penetration length where pulse matching and transparency are conserved is determined by the slow absorption of the coupling pulses. For the case of Fig. 4 (b) the transparency of the matched pulses remains at penetration

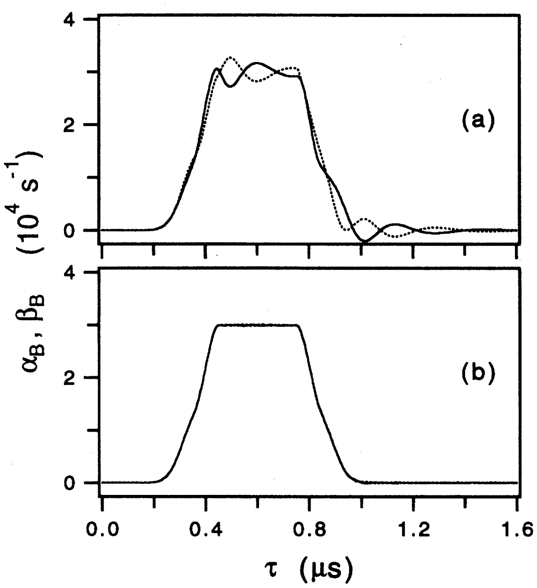

FIG. 4. Snapshots of the probe pulses α_B (solid line) and β_B (dotted line) as they propagate simultaneously with coupling lasers on the transitions to the $|R\rangle$ state. At the entrance of the medium, the probe shapes are as in Fig. 3(a). Penetration depths in (a) $\zeta\alpha=30$ and in (b) $\zeta\alpha=300$.

lengths longer than $\zeta\alpha=300$. The simulations reported in Fig. 4 evidence the joint effect of the full preparation of the atoms in the trapping superposition and of the electromagnetic assistance provided by the coupling fields. The way to accomplish that is to use coupling pulses that overlap the time envelopes of the probes and propagate through the medium enough in advance to complete the trapping process.

We have also numerically investigated the pulse matching process as a function of the time delay of the probe pulses with or without time overlap with the coupling laser pulses. Without simultaneous propagation of the two pulse pairs, at time delays where the ρ_{BR} coherence has died out, but the ρ_{21} coherence is still on, the atomic system is effectively a three-level Λ system prepared in the trapping state by the coupling pair. Investigation of this time delayed regime has allowed us to isolate the influence of the coherent population trapping preparation from the electromagnetic assistance provided, through the ρ_{BR} coherence, by the simultaneous presence of the coupling fields. We have verified that, even if pulse matching is realized in the time-delayed propagation, the electromagnetic assistance greatly enhances the pulse shape preservation.

In conclusion, we have studied the propagation of pairs of weak probe pulses through a double-Λ medium, prepared by a pair of strong coupling pulses. Exploration of the pulse matching process over the different transitions of the double-Λ system has allowed us to determine the influence of different atomic and laser parameters. Numerical calculations show completely lossless propagation of shape matched pulses: leading edge preparation losses have been avoided and conditions on the pulse areas ignored. Finally the electromagnetic assistance on the pulse matching process provided by the upper level coherence has been discovered.

The authors are grateful to Professor Neal Abraham for inspiring conversations and to Dr. Marina Mazzoni for her encouraging interest in experimental realizations in this field.

[1] S. E. Harris, J. E. Field, and A. Kasapi, Phys. Rev. A **46**, R29 (1992), and references therein.
[2] S. E. Harris, Phys. Rev. Lett. **70**, 552 (1993).
[3] G. S. Agarwal, Phys. Rev. Lett. **71**, 1351 (1993).
[4] S. E. Harris, Phys. Rev. Lett. **72**, 52 (1994).
[5] A. Weis, F. Sander, and S. Kanorsky (unpublished).
[6] See A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, Phys. Rev. Lett. **61**, 826 (1988); J. Opt. Soc. Am. B **6**, 2112 (1989), and references therein.
[7] J. H. Eberly, M. L. Pons, and H. R. Haq, Phys. Rev. Lett. **72**, 56 (1994).
[8] M. J. Konopnicki and J. H. Eberly, Phys. Rev. A **24**, 2567 (1981).
[9] O. A. Kocharovskaya and P. Mandel, Phys. Rev. A **42**, 523 (1990).
[10] O. A. Kocharovskaya, F. Mauri, and E. Arimondo, Opt. Commun. **84**, 393 (1991).
[11] C. H. Keitel, O. A. Kocharovskaya, L. M. Narducci, M. O. Scully, S.-Y Zhu, and H. M. Doss, Phys. Rev. A **48**, 3196 (1993).
[12] The cases of degenerate or split low-lying levels lead to equivalent results for the pulse matching.