Phase-dependent electromagnetically induced transparency

E. A. Korsunsky, N. Leinfellner, A. Huss, S. Baluschev,* and L. Windholz
Institut für Experimentalphysik, Technische Universität Graz, A-8010 Graz, Austria

(Received 6 July 1998)

We report on the experimental demonstration of phase-dependent electromagnetically induced transparency (EIT). This effect is based on a quantum interference in closed-loop schemes of interaction of atoms with the radiation. It allows us to control optical properties of the medium by the phases of the laser fields. We discuss some of the possible applications of phase-dependent EIT. [S1050-2947(99)01003-3]

PACS number(s): 42.50.Gy, 32.80.Qk, 42.50.Hz

Quantum interference is a physical mechanism, which has recently brought many surprising innovations in modern quantum optics and laser physics. One of those innovations is the effect of electromagnetically induced transparency (EIT) [1]. The basic feature of EIT is a strong reduction of the light absorption of an atomic medium at a resonance transition frequency. Since other characteristics of the optical response are also modified, EIT can be used to manipulate properties of the medium and the e.m. radiation in a well-controlled manner. Generation of a medium with high dispersion [2] and refraction index [3] and vanishing absorption, enhancement of nonlinear optical processes [2,4], lasing without population inversion [5], laser pulse matching [6], solitonlike propagation of laser pulse pairs (adiabatons) [7], phase and intensity fluctuations correlation [8], and photon statistics matching [9] are some of the applications of EIT. The physical effect on which EIT is based is coherent population trapping (CPT) [10]. The central idea of CPT (and EIT) is a creation, through quantum interference, of a superpositional state, which is not excited by radiation, and preparation of atoms in this ''dark'' state. In conventional EIT/CPT situations, the dark state may exist for any laser phases and intensities. The only necessary condition is multiphoton resonance of the atom-radiation interaction. As long as the laser fields do not change or change adiabatically, the atoms can always be prepared in the dark state by optical pumping in the cw regime or by adiabatic following in the pulsed regime, independent of the laser phases. This is, however, not the case in situations where the radiation-induced transitions in atoms form a closed loop [11–20]. In closed-loop systems, as it has been shown by Kosachiov *et al.* [12], both dynamics and the steady state of the atoms depend on the relative phase Φ of the transitions. In particular, the dark state exists only for specific values of the phase Φ, even if the multiphoton resonance condition is satisfied. Therefore, the response of atoms to the e.m. radiation may be changed dramatically by a change of only the phase, at fixed frequencies of the radiation. This fact is the basis for a type of the control of medium properties—control by the phases of applied fields.

Previous investigations of closed-loop systems include theoretical studies of the phase control of photoionization [13], nonadiabatic losses in coherent population transfer process [14], spontaneous emission [15], subrecoil laser cooling, and localization of atoms [16]. Laser light propagation in an optically dense medium consisting of closed three-level atoms has been theoretically investigated in Ref. [17]. Experimentally, the phase sensitive population dynamics has been observed in three- [18] and four-level [19,20] closed-loop systems.

The effect of phase dependent CPT in an optically dense medium (phase dependent EIT) is especially interesting since both absorptive and dispersive properties of the medium may be controlled by the phase of laser light. Therefore, the properties of the propagating light may be manipulated in a more sophisticated way than in the conventional EIT effect. At the same time, phase dependent EIT provides an example of a highly entangled system atoms + radiation fields. The propagation of light through the medium of ''closed-loop atoms'' is governed by the Maxwell equations involving the medium polarization, which depends on the phases of laser light. But the phases themselves change during the propagation. Thus, refraction of the medium directly determines absorption (for fixed laser frequencies, not just through Kramers-Kronig relations).

In this paper we report on the experimental observation of phase-dependent EIT. For this observation we used a four-level double-Λ atomic system excited by a laser radiation (Fig. 1) consisting of four optical frequencies. The dark state in this closed-loop system can be considered as a common one for the two Λ systems. The dark superposition in a single Λ system is determined by the relative amplitudes $|g_1|/|g_2|$

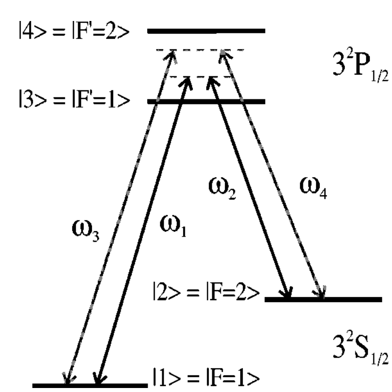

FIG. 1. Double-Λ system in sodium atoms used in our experiment.

*Permanent address: Technical University of Sofia, Institute of Applied Physics, 1756 Sofia, Bulgaria.

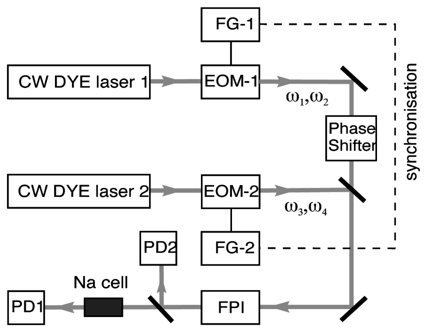

FIG. 2. Scheme of the experimental setup. EOMs, driven by FGs, synchronized to each other, FPI, PD1 and PD2, photodiodes with data acquisition system.

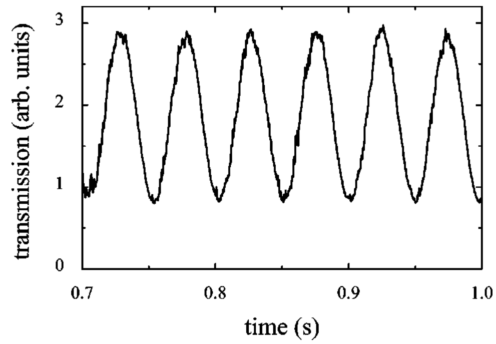

FIG. 3. Temporal dependence of the transmitted light power at the four-photon detuning $\Delta\omega = 20$ Hz and frequency difference $\delta_{12} = (\omega_1 - \omega_2) \approx (\omega_3 - \omega_4) = 1771.6$ MHz. Time translates to the phase as $\Phi(\mathrm{rad}) = 20\pi t(\mathrm{sec})$. Total input laser intensity $I = 200$ mW/cm^2. Temperature of the cell, 127 °C.

and phases $(\varphi_1 - \varphi_2)$ of the Rabi frequencies $g_m \equiv |g_m| e^{i\varphi_m} = d_m E_m / 2\hbar$, with E_m being the field strength of the e.m. wave with frequency ω_m, and d_m being the dipole moment of the transition excited by the ω_m field [10]. Therefore, the common dark state exists in the double-Λ system only if $|g_1|/|g_2| = |g_3|/|g_4|$ and $\Phi = (\varphi_1 - \varphi_2) - (\varphi_3 - \varphi_4) = 2\pi n$ [11,12,19]. This state is completely decoupled if both frequency pairs are tuned to the Raman resonance: $(\omega_1 - \omega_2) = (\omega_3 - \omega_4) = (\mathcal{E}_2 - \mathcal{E}_1)/\hbar$, where $\mathcal{E}_m$ is the eigenenergy of the state $|m\rangle$ [11,12].

Our double-Λ system is generated by the excitation of sodium atoms in a vapor cell. The lower states are the two hyperfine levels $F=1$ and $F=2$, spaced by 1771.6 MHz, of the ground state $3^2S_{1/2}$. The Doppler broadened excited state $3^2P_{1/2}$, with the unresolved hyperfine levels $F'=1$ and $F'=2$ (frequency splitting of 189 MHz, while the Doppler width is approximately 1 GHz), serves as the common upper state. We note that the effect under study appears in both cases of exciting two different upper states (''real'' double-Λ system) or a single one (degenerate double-Λ system) [19]. In the latter case, the condition $|g_1|/|g_2| = |g_3|/|g_4|$ is reduced to $|E_1|/|E_2| = |E_3|/|E_4|$, which is satisfied in our experiment. The four-frequency radiation is produced by two independent Ar^+-laser-pumped dye lasers, each of them having a linewidth of about 1 MHz (Fig. 2). Those lasers provide linearly polarized light, which is modulated by means of two electro-optical modulators (EOM-1, EOM-2). The modulators create first-order side bands with a frequency difference matching the splitting of the ground levels $|1\rangle$ and $|2\rangle$. The two frequencies, created in each of the EOMs are obviously perfectly correlated to each other. The EOMs are driven by two tunable rf generators (FG-1, FG-2), which are synchronized: FG-2 uses the internal oscillator signal of FG-1 as a reference. Therefore, there is a defined phase relation between the two frequency pairs (ω_1, ω_2) and (ω_3, ω_4), which excite the two Λ systems. Thus, all four frequencies are phase locked, and the bandwidths of the single lasers are not relevant anymore. The two combined laser beams pass an electronically controlled Fabry-Pérot interferometer (FPI) that acts as a mode filter by suppressing the carrier frequency. Finally, the laser beam passes the sodium cell, and the total transmitted intensity (of all four frequency components, each of them having an approximately equal intensity) is detected and recorded. Additionally, the total input intensity is detected by photodetector PD2 (see Fig. 2). The laser beam diameters are 0.6 mm each. The sodium cell is a cylindrical glass tube with 96 mm in length and 26 mm of diameter, filled with sodium without any buffer gas. It is placed inside an arrangement of three mutually orthogonal Helmholtz coil pairs (not shown in Fig. 2) in order to compensate stray magnetic fields. We have performed experiments for total input laser intensities ranging from 10 mW/cm^2 to 300 mW/cm^2, and the vapor temperature ranging from 110 °C to 160 °C, which corresponds to the vapor density from 8×10^9 cm^{-3} to 4×10^{11} cm^{-3}.

The relative phase in our double-Λ case is equal to $\Phi = \Phi_0 + \Delta\omega t - (k_1 - k_2)z - (k_3 - k_4)z'$, where Φ_0 is the constant phase, $\Delta\omega = (\omega_1 - \omega_2) - (\omega_3 - \omega_4)$ is the multiphoton detuning, k_m are the wave numbers of the laser fields, and z and z' are the path lengths for the frequency pairs (ω_1, ω_2) and (ω_3, ω_4), respectively. In our experiment, we use two possibilities to vary the phase Φ. First, if we put the value of $\Delta\omega$ equal to a few Hz, the relative phase Φ changes linearly in time with the rate $\Delta\omega$. In such a way, the phase is scanned automatically over many periods. At the same time, the value of $\Delta\omega$ is so small, that the change of the phase is certainly adiabatic and the multiphoton resonance condition, necessary for establishment of the dark state, is sufficiently satisfied. Figure 3 shows a typical signal of the transmitted light intensity versus the time (phase). In the course of time, the phase Φ changes from $2n\pi$, when the dark state appears (and absorption is considerably reduced; the light is transmitted), to $(2n+1)\pi$, when there is no EIT so that the light is strongly absorbed. Thus, we have demonstrated that the laser light (having a carrier frequency of order of 5×10^{14} Hz) can be modulated with a frequency of only a few Hz by using the effect of phase-dependent EIT. The modulation strongly depends on the frequency splitting $\delta_{12} \equiv (\omega_1 - \omega_2) \approx (\omega_3 - \omega_4)$. The best result one gets for $\delta_{12} = 1771.6$ MHz corresponding to the two-photon resonance condition for both frequency pairs, necessary for establishing CPT. From the phase scans similar to Fig. 3 taken at different values of the splitting δ_{12}, we obtain the dependence of the transmitted intensity on δ_{12} for different phases Φ (Fig. 4). For $\Phi = \pi$ the transmission is nearly independent of δ_{12}, since no CPT is established. However, the typical transparency window of EIT (a narrow frequency range where EIT is established) appears for the phase $\Phi = 0$. This window is cen-

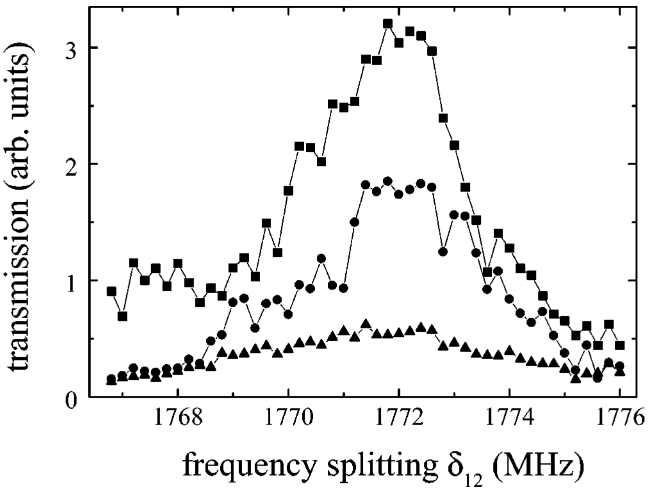

FIG. 4. Dependence of the transmitted light intensity on the frequency difference δ_{12} for different values of the phase Φ: squares, for the phase $\Phi=0$; circles, $\Phi=\pi/2$; up triangles, $\Phi=\pi$.

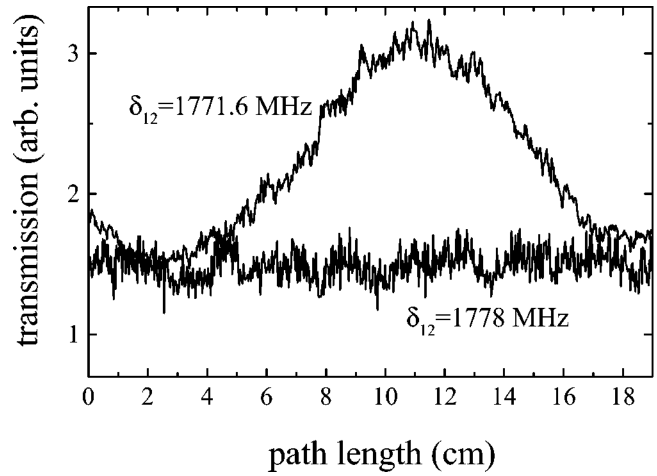

FIG. 5. Dependence of the transmitted light intensity on the path length change Δz of the first frequency pair (ω_1, ω_2) for two values of the frequency difference $\delta_{12}=1771.6$ MHz and $\delta_{12}=1778$ MHz. The path length translates to the phase as $\Phi(\mathrm{rad})=2\pi[\Delta z(\mathrm{cm})/16.9]$.

tered at $\delta_{12}=(\mathcal{E}_2-\mathcal{E}_1)/\hbar=1771.6$ MHz, and its width (of the order of 3 MHz, smaller than the natural width of sodium $3^2P_{1/2}$ state, equal to 10 MHz) depends on the input light intensity and the optical density of the vapor in the same manner as in conventional EIT [21]. A somewhat reduced transparency is obtained for the phase $\Phi=\pi/2$. These results clearly demonstrate that the modulation of the transmitted intensity in Fig. 3 is due to the EIT effect, and that the EIT may be controlled by the phases of the laser light in closed-loop interaction schemes.

A second possibility to control the phase is to alter the path length of one of the frequency pairs: $\Delta\Phi=(k_1-k_2)\Delta z$. It is performed in our experiment by means of a mechanical phase shifter consisting of three pairs of retroreflecting mirrors. One set of mirrors is mounted on a fixed plate while the other set, mounted on a gliding plate, is moved by an electric stepper motor. Therefore, the distance between the mirrors can be controlled accurately. With this phase shifter, the light path length can be stretched by a little more than a full wavelength λ_{HF} corresponding to the hyperfine splitting, which in the case of sodium atoms is $\lambda_{HF}=2\pi/|k_1-k_2|=16.9$ cm. The path-length dependence of the transmitted light intensity is shown in Fig. 5. The change of the transmission with phase $\Delta\Phi=(k_1-k_2)\Delta z$ is clearly seen for the frequency splitting $\delta_{12}=1771.6$ MHz, but is not observable for $\delta_{12}=1778$ MHz, which is outside the transparency window. In general, the behavior of the transmission is similar for both methods of the phase change. In the case of the mechanical shift, however, one can fix the phase to a particular value with high precision, which is necessary for future experiments. We note that the optical phase can also be controlled in some other ways. For example, the laser beam may be passed through a cell with dispersive gas so that the phase is varied by varying the gas density [22]. Another possibility is to use an electro-optic effect in some optical crystals where the refractive index is changed by a dc electric field.

The phase-dependent EIT may have some interesting consequences different from the conventional EIT effect. First of all, it is a possibility to control optical properties of the medium by the laser phases, without changing neither frequencies nor input intensities. This would not only provide an additional degree of freedom in the control, but also allow us to manipulate both the medium and the e.m. fields in a more sophisticated manner than in conventional EIT. In general, the behavior of the medium is much richer in the case of closed-loop interactions. For instance, the fact that light waves are not absorbed only if their frequencies, phases, and intensities satisfy particular relations means that the closed-loop medium filters out all noncorrelated field components [23]. Thus, the e.m. field amplitude, phase, and frequency matching may be realized both in nonadiabatic and adiabatic (including continuous-wave) regimes, which can be used, for example, for laser phase locking or for complete amplitude and phase fluctuations correlation. Interesting features are known for media prepared not in the dark state, but in a ''gray'' one that does interact with light but very weakly. In closed-loop systems, such gray states can be easily created, the degree of their interaction being controlled by the phase. Our theoretical calculations, to be published elsewhere, show that the gray media have very high ratio of refraction to absorption, and may be used for efficient frequency conversion [17,23]. We note also the possibility to use phase-dependent EIT for measurement of small frequency or phase shifts. We are planning to realize some of those fascinating applications of phase-dependent EIT in our future experiments.

In conclusion, we have experimentally demonstrated an effect of phase-dependent electromagnetically induced transparency. It is based on a quantum interference in closed-loop schemes of atom e.m. radiation interaction. This effect can be a basis for many interesting applications in atomic physics and nonlinear optics.

S.B. thanks the members of the Institut für Experimentalphysik, TU Graz, for their hospitality and support. The authors are grateful to D. Kosachiov for very stimulating and useful discussions, and to W. Scherf for technical assistance. This work was supported by the Austrian Science Foundation under Project Nos. S 6508 and P 12894.

[1] S. E. Harris, Phys. Today **50**(7), 36 (1997).
[2] S. E. Harris *et al.*, Phys. Rev. Lett. **64**, 1107 (1990); Phys. Rev. A **46**, R29 (1992).
[3] M. O. Scully, Phys. Rev. Lett. **67**, 1855 (1992); A. S. Zibrov *et al.*, *ibid.* **76**, 3935 (1996).
[4] K. Hakuta *et al.*, Phys. Rev. Lett. **66**, 596 (1991); G. Z. Zhang *et al.*, *ibid.* **71**, 3099 (1993); M. Jain *et al.*, Opt. Lett. **20**, 982 (1995); P. R. Hemmer *et al.*, *ibid.* **20**, 982 (1995); S. Babin *et al.*, *ibid.* **21**, 1186 (1996).
[5] O. Kocharovskaya and Ya. I. Khanin, Pis'ma Zh. Éksp. Teor. Fiz. **48**, 581 (1988) [JETP Lett. **48**, 630 (1988)]; S. E. Harris, Phys. Rev. Lett. **62**, 1033 (1989); A. S. Zibrov *et al.*, *ibid.* **75**, 1499 (1995); G. G. Padmabandu *et al.*, *ibid.* **76**, 2053 (1996).
[6] S. E. Harris, Phys. Rev. Lett. **70**, 552 (1993).
[7] R. Grobe *et al.*, Phys. Rev. Lett. **73**, 3183 (1994); A. Kasapi *et al.*, *ibid.* **74**, 2447 (1995).
[8] M. Fleischhauer, Phys. Rev. Lett. **72**, 989 (1994).
[9] G. S. Agarwal, Phys. Rev. Lett. **71**, 1351 (1993).
[10] For a review of CPT phenomenon, see, E. Arimondo, in *Progress in Optics*, edited by E. Wolf (Elsevier, Amsterdam, 1996), Vol. 35, p. 257.
[11] S. J. Buckle *et al.*, Opt. Acta **33**, 2473 (1986); D. Kosachiov *et al.*, Opt. Commun. **85**, 209 (1991).
[12] D. V. Kosachiov *et al.*, J. Phys. B **25**, 2473 (1992).
[13] G. X. Li and J. S. Peng, Phys. Lett. A **218**, 49 (1996); E. Paspalakis *et al.*, J. Phys. B **31**, 761 (1998).
[14] R. G. Unanyan *et al.*, Opt. Commun. **139**, 48 (1997).
[15] E. Paspalakis and P. L. Knight, Phys. Rev. Lett. **81**, 293 (1998).
[16] D. Kosachiov *et al.*, Europhys. Lett. **22**, 11 (1993); T. Pellizzari and H. Ritsch, *ibid.* **31**, 133 (1995).
[17] D. V. Kosachiov, Quantum Electron. **25**, 1089 (1995); Ph.D. thesis, St-Petesburg State Technical University, Russia, 1994 (unpublished).
[18] M. S. Shahriar and P. R. Hemmer, Phys. Rev. Lett. **65**, 1865 (1990).
[19] W. Maichen *et al.*, Europhys. Lett. **31**, 189 (1995); Phys. Rev. A **53**, 3444 (1996).
[20] N. Ph. Georgiades *et al.*, Opt. Lett. **21**, 1688 (1996).
[21] S. Baluschev *et al.*, Eur. Phys. J. D **2**, 5 (1998); N. Leinfellner *et al.*, Phys. Scr. **58**, 583 (1998).
[22] C. Chen *et al.*, Phys. Rev. Lett. **64**, 507 (1990).
[23] E. A. Korsunsky and D. V. Kosachiov (unpublished).