Control of group velocity by phase-changing collisions

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We discuss the influence of phase-changing collisions on the group velocities in Doppler-broadened, cycling, degenerate two-level systems where $F_e=F_g+1$ and $F_g>0$, interacting with pump and probe lasers, that exhibit electromagnetically induced absorption (EIA). Two model systems are considered: the *N* system where the pump and probe are polarized perpendicularly, and EIA is due to transfer of coherence (TOC), and the double two-level system (TLS) where both lasers have the same polarization, and EIA is due to transfer of population (TOP). For the case of Doppler-broadened EIA TOC, which occurs at low pump intensity, there is a switch from positive to negative dispersion and group velocity, as the rate of phase-changing collisions is increased. For the case of EIA TOP at low pump intensity, the dispersion and group velocity remain negative even when the collision rate is increased. Pressure-induced narrowing, accompanied by an increase in the magnitude of the negative dispersion and a decrease in the magnitude of the negative group velocity, occurs in both EIA TOC and EIA TOP, at low pump intensity. When the pump intensity is increased, a switch from negative to positive dispersion and group velocity, with increasing collision rate, also occurs in the double TLS system. However, the effect is far smaller than in the case of the *N* system at low pump intensity.

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There have been several studies [1–11] of systems in which the group velocity of light can be switched from "slow" to "fast" [12,13] by changing an external parameter. For example, Kim *et al.* [7] showed that in a Doppler-broadened system which exhibits electromagnetically induced absorption (EIA), the magnitude and sign of the group velocity can be controlled by varying the pump laser intensity. The source of the effect is that in the regime of low pump intensities, the Doppler-broadened EIA peak develops a dip at line center as the pump intensity increases [14]. Thus the dispersion, which is negative at low intensity [15], becomes positive as the pump intensity increases. Recently, we showed [16] that the dip that occurs in the Doppler-broadened EIA spectrum can be eliminated by introducing phase-changing collisions, induced by a buffer gas. Thus it is reasonable to expect that phase-changing collisions can control the sign and magnitude of the dispersion and group velocity in systems that exhibit EIA. In related work, Mikhailov *et al.* [11] demonstrated that the group velocity in a Λ system in the presence of a buffer gas can be controlled by changing the one-photon detuning of the pump laser.

In this paper, we show that phase-changing collisions can control the magnitude and sign of the group velocity in two Doppler-broadened model systems: the *N* system [17] where the polarizations of the pump and probe lasers are perpendicular, and the double two-level system (TLS) [16] where the pump and probe lasers have the same polarization. The *N* system, shown in Fig. 1(a), corresponds to a cycling degenerate TLS, where $F_e=F_g+1$ and $F_g>0$, driven by a σ_+-polarized pump laser and probed with a π-polarized laser. The double TLS corresponds to the same atomic system, interacting with a pump and probe that are both σ_+ polarized. It has been shown that the EIA effect that occurs in the *N* system, at low intensity, derives from transfer of coherence (TOC), via spontaneous emission, from the excited to ground states [14,17–19]. By contrast, in the double TLS [16], shown in Fig. 1(b), EIA is due to transfer of population (TOP), due to optical pumping, from the first TLS to the lower level of the second TLS. The net EIA peak in the absorption spectrum is the sum of a small dip contributed by the first TLS and a larger peak contributed by the second TLS [16,20].

In both systems (see Fig. 1), a resonant pump laser of frequency $\omega_1=\omega_0$, where ω_0 is the transition frequency, couples level g_1 to e_1, and level g_2 to e_2, with Rabi frequencies V_1 and V_2. The e_2 to g_1 transition is forbidden by selection rules. In the *N* system [Fig. 1(a)], the probe laser of frequency ω_p couples levels g_2 to e_1 with Rabi frequency V_p. In the double TLS [see Fig. 1(b)] the probe laser of frequency ω_p couples both level g_1 to e_1 and level g_2 to e_2, with Rabi frequencies V_{p_1} and V_{p_2}.

We first consider a Doppler-broadened *N* system at low pump intensity. In the absence of phase-changing collisions, there is a dip in the center of the EIA TOC peak, which is accompanied by positive dispersion. As the collision rate in-

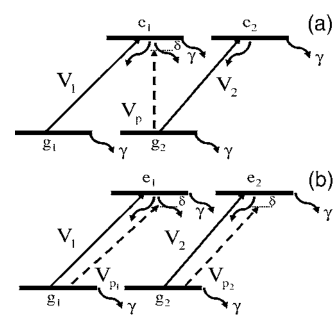

FIG. 1. (a) Energy-level scheme for the four-level *N* configuration interacting with two resonant pumps V_1 and V_2 and a tunable probe V_p. (b) Energy-level scheme for the double TLS interacting with two resonant pumps V_1 and V_2 and two tunable probes V_{p1} and V_{p2}.

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creases, the dip in the EIA peak gradually disappears, leading to a decrease in the dispersion and an increase in the group velocity. Once the dip has been totally eliminated, and the dispersion has changed its sign from positive to negative, a further increase in the collision rate leads to pressure narrowing of the EIA peak, accompanied by an increase in the magnitude of the negative dispersion and a decrease in the magnitude of the negative group velocity. In order to understand the origin of these effects, we should recall [17] that the probe laser that interacts with the N system of Fig. 1(a) sees four distinct dressed states at the pump-probe detuning $\delta = \omega_p - \omega_{1,2} = \omega_p - \omega_0 = \pm(V_1 \pm V_2)$. It can be seen from Fig. 2 of Ref. [17] that, for a sufficiently strong pump, all four peaks are resolved in the probe absorption spectrum, both in the absence and presence of TOC. At low pump intensities, only the outer two peaks are resolved in the absence of TOC, whereas in the presence of TOC, all the peaks coalesce to give a single sharp EIA peak at $\delta=0$. The Doppler-broadened spectrum derives from interference between the contributions to the spectrum from different pump detunings. As shown in Fig. 3 of Ref. [17], this results in a dip at the center of the EIA spectrum which becomes deeper with increasing pump intensity until all four peaks are clearly resolved. If the pump intensity is very low, no dip is obtained and the EIA peak is very narrow. As we showed previously [16], introducing phase-changing collisions is in a sense equivalent to reducing the pump intensity. Thus as the rate of phase-changing collisions increases, the dip becomes less deep until it eventually disappears.

Unlike the Doppler-broadened N system, the Doppler-broadened double TLS does not exhibit a dip in the center of the EIA TOP peak in the absence of collisions. At low pump intensity, the EIA peak exhibits pressure narrowing accompanied by an increase in the magnitude of the negative dispersion and a decrease in the magnitude of the negative group velocity. At a certain collision rate, this trend is reversed: the EIA TOP peak becomes wider and there is a decrease in the magnitude of the negative dispersion and an increase in the magnitude of the negative group velocity. At high pump intensity, the Doppler-broadened absorption spectrum resembles that of a simple TLS [16,21], namely, a dead zone with a small EIA at the center, accompanied by negative dispersion. Phase-changing collisions destroy the dead zone, replacing it by a wide dip, accompanied by positive dispersion. Thus in this case the group velocity switches from negative to positive with increasing collisions. However, the collision-induced changes in the EIA TOP spectra are much smaller than those in the EIA TOC spectra.

The Bloch equations for the N system and the double TLS are given in Refs. [17,16]. For each of these systems, we calculate the probe absorption coefficient $\alpha(\omega_p)$ and refraction $n(\omega_p)-1$ from the relevant probe susceptibility, using the relations

$$\alpha(\omega_p) = (4\pi\omega_0/c)\mathrm{Im}\,\chi(\omega_p), \tag{1}$$

$$n(\omega_p) - 1 = \mathrm{Re}\,\chi(\omega_p), \tag{2}$$

where ω_0 is the transition frequency. The susceptibility for the N system, shown in Fig. 1(a), is given by [17,19]

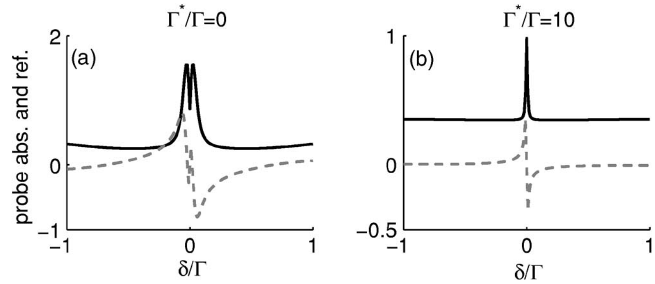

FIG. 2. Doppler-broadened probe absorption (black solid lines) and refraction spectra (gray dashed lines) for the N system, (a) without, $\Gamma^*/\Gamma=0$, and (b) with, $\Gamma^*/\Gamma=10$, phase-changing collisions. The refraction spectra have been multiplied by 10^6 in both (a) and (b). Parameters are $V_1/\Gamma=0.408$ and $V_2/\Gamma=0.5$.

$$\chi(\omega_p) = \frac{N\mu_{e_1g_2}^2}{\hbar}\rho_{e_1g_2}(\omega_p)/V_p, \tag{3}$$

whereas the probe susceptibility for the double TLS, shown in Fig. 1(b), is given by [16,19]

$$\chi(\omega_p) = \frac{N\mu_{e_2g_2}^2}{\hbar}[A^2\rho_{e_1g_1}(\omega_p)/V_{p_1} + \rho_{e_2g_2}(\omega_p)/V_{p_2}], \tag{4}$$

where N is the density of the atoms, $\mu_{e_jg_i}$ the transition dipole moment, and $\rho_{e_jg_i}$ the off-diagonal density matrix element, for the g_i to e_j transition.

Equation (4) is derived assuming that $\mu_{e_1g_1}=A\mu_{e_2g_2}$ so that $V_1=AV_2$ and $V_{p_1}=AV_{p_2}$. In our calculations we take A $=0.816$ which is the value that corresponds to the $F_g=2 \rightarrow F_e=3$ cycling transition in ^{87}Rb [16,19].

The probe group velocity at line center, where the pump-probe detuning $\delta=0$, can be calculated from the susceptibility using the expression

$$v_g = \frac{c}{1 + 2\pi\omega_p[d\,\mathrm{Re}(\chi)/d\omega_p]_{\omega_p=\omega_0}}, \tag{5}$$

provided that $\mathrm{Re}[\chi(\omega_p)]=0$ at $\delta=0$.

In Fig. 2, we plot the Doppler-broadened absorption and refraction spectra for the N system, as a function of the pump-probe detuning δ/Γ, in the absence $(\Gamma^*/\Gamma)=0$ and presence $(\Gamma^*/\Gamma)=10$ of phase-changing collisions, where Γ is the decay rate of the excited states due to spontaneous emission ($\Gamma=5.89$ MHz for ^{87}Rb) and Γ^* is the rate of phase-changing collisions. The calculations in Fig. 2 show the spectra for low pump intensities, while the spectrum at high pump intensities does not display EIA behavior [16,17]. In all the calculations presented here, we take the atomic density to be $N=10^{10}$ atoms/cm^3, the Doppler width to be $D=50\Gamma$ which corresponds to the experimental Doppler width in a ^{87}Rb vapor cell, and set $\gamma/\Gamma=0.001$, where γ is the rate of transfer to and from the reservoir due to time of flight of the atoms through the copropagating laser beams. Although γ decreases with increasing buffer-gas pressure, we found the dispersion at line center to be almost independent of the value of γ. Figure 2(a) confirms the well-known result that, in the absence of phase-changing collisions, the Doppler-

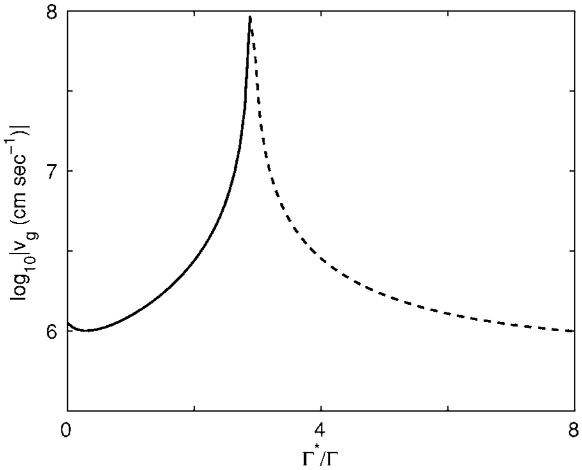

FIG. 3. $\log_{10}|v_g|$ as a function of Γ^*/Γ for the N system. The dashed part of the curve corresponds to negative v_g. The parameters are the same as in Fig. 2.

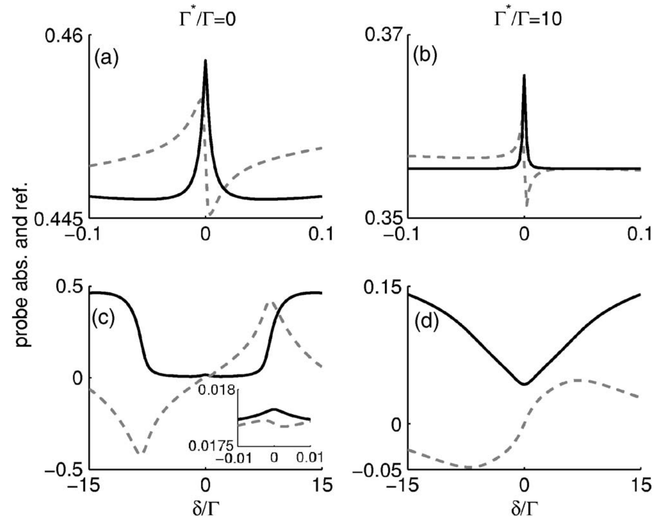

FIG. 4. Doppler-broadened probe absorption (black solid lines) and refraction spectra (gray dashed lines) for the four-level double TLS, (a) and (c) without phase-changing collisions, $\Gamma^*/\Gamma=0$, and (b) and (d) with phase-changing collisions, $\Gamma^*/\Gamma=10$. In (a) and (b), $V_1/\Gamma=0.0816$ and $V_2/\Gamma=0.1$, and in (c) and (d), $V_1/\Gamma=3.264$ and $V_2/\Gamma=4$. The refraction spectra have been multiplied by 10^6 in all the figures and have been moved to the center of the absorption in (a) and (b).

broadened EIA peak displays a dip at line center [14,16–18]. We also see that the dip is accompanied by positive dispersion. When phase-changing collisions are introduced, the background absorption is broadened, and the central EIA peak is narrowed. As the rate of dephasing collisions increases, the central dip narrows until it is eliminated [16] and only an EIA peak with negative dispersion remains, as shown in Fig. 2(b). This is expected since a high concentration of buffer gas is known to counteract the Doppler effect [22] which originally produced the dip.

In Fig. 3, we plot the group velocity as a function of phase-changing collisions for the same parameters as in Fig. 2. We see that the group velocity changes sign when $\Gamma^*/\Gamma \simeq 3$. It is interesting to compare the effect of phase-changing collisions on the magnitude of the dispersion and group velocity, before and after its sign reversal. When the EIA peak is characterized by a dip and positive dispersion, increasing the phase-changing collisions results in broadening of the dip which is accompanied by a decrease in the dispersion and a concomitant increase in the group velocity. However, when the EIA absorption peak no longer has a dip, increasing the phase-changing collisions further results in pressure narrowing of the EIA peak, accompanied by an increase in the absolute value of the negative dispersion and a decrease in the absolute value of the negative group velocity.

In Fig. 4, we plot the Doppler-broadened absorption and refraction spectra for the double TLS, in the absence $(\Gamma^*/\Gamma)=0$ and presence $(\Gamma^*/\Gamma)=10$ of phase-changing collisions, for low and high pump intensities. At low pump intensities, phase-changing collisions lead to a decrease in the overall absorption [compare Figs. 4(a) and 4(b)]. However, this is accompanied by a relative increase in the height of the EIA peak above the background absorption, pressure-induced narrowing of the EIA peak, and an increase in the magnitude of the negative dispersion, which leads to a decrease in the magnitude of the negative group velocity, as can be seen in Fig. 5(a). As the collision rate is further increased, the EIA peak becomes lower and wider, leading to a lower negative dispersion and an increase in the absolute value of the negative group velocity. At high pump intensities, the absorption spectrum of the double TLS, shown in Fig. 4(c), resembles that of the ordinary TLS [16,21], namely, a wide dead zone with a small EIA peak at line center, accompanied by negative dispersion (see inset). In the presence of phase-changing collisions, the dead zone is replaced by a broad dip, accompanied by positive dispersion [23], as shown in Fig. 4(d). In Fig. 5(b) we show the change in sign of the group velocity from negative to positive that results from an increase in the rate of phase-changing collisions. However, the change in magnitude of the group velocity is much smaller than in the case of the N system [compare Fig. 3 with Fig. 5(b)].

In conclusion, we have shown that phase-changing collisions can control the sign and magnitude of the dispersion and group velocity in Doppler-broadened systems that exhibit EIA. Two model systems have been considered: the N system [17] which corresponds to EIA TOC at low pump

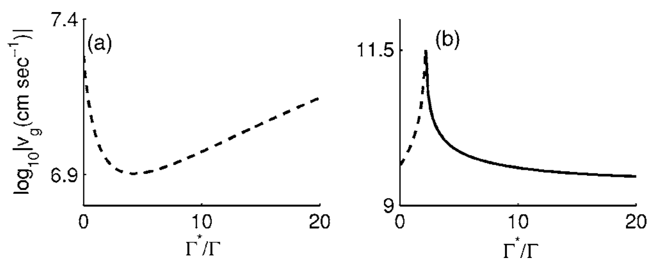

FIG. 5. $\log_{10}|v_g|$ as a function of Γ^*/Γ for the double TLS. The dashed part of each curve corresponds to negative v_g. In (a), $V_1/\Gamma=0.0816$ and $V_2/\Gamma=0.1$, and in (b), $V_1/\Gamma=3.264$ and $V_2/\Gamma=4$.

intensity, and the double two-level system (TLS) which corresponds to EIA TOP [16]. For the case of EIA TOC, there is a switch from positive to negative dispersion and group velocity as the rate of phase-changing collisions is increased. For the case of EIA TOP, at low pump intensity, the dispersion and group velocity remain negative as the rate of collisions increases. When the pump is more intense, a switch from negative to positive dispersion and group velocity occurs as the rate of collisions increases. However, the effect is far less important in this case than in EIA TOC.

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