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Slow Light in a Collection of Collisionally Broadened Two-Level Atoms

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Abstract—Slow light produced by means of the process of coherent population oscillations has been observed in room-temperature solids. The experiments performed to date have all been performed within the validity of the rate equation approximation, and the fractional delays that have been observed have been limited to a few tens of percent. Here, we show that, by operating with stronger pump fields, much larger fractional delays are predicted. This result could have important consequences for the development of slow-light methods for practical applications.

The two-level atom can, for good reason, be considered the basic material structure for the study of quantum optics [1]. The two-level atom has played a fundamental role in studies of physical processes, including self-induced transparency (SIT), photon echoes, optical nutation, saturation spectroscopy, and, most recently, slow- and fast-light research. This latter field has recently been the subject of great activity, as researchers have learned how to utilize various physical processes to exert control over the velocity of propagation of light pulses through material systems [2]. This interest stems both from the intellectual intrigue in situations in which the velocity of light can be speeded up or slowed down by many orders of magnitude and the promise that such techniques might be useful for applications in fields such as telecommunications and optical computing [3–6]. Most of the recent work in this field has made use of the process of electromagnetically induced transparency (EIT) to induce a narrow transparency region in an otherwise highly absorbing optical material [7, 8]. The rapid variation of the refractive index n associated with this transparency window then leads to a strong modification of the group velocity n_g in accordance with the standard relation

$$n_g = n + \omega\frac{dn}{d\omega}. \tag{1}$$

Under most laboratory situations, the conditions leading to EIT require that dephasing processes be avoided to allow the delicate balance between excitation pathways leading to EIT to occur. However, a different process [9–13] based on coherent population oscillations (CPO) has recently been shown to lead to ultraslow group velocities as well. The process of CPO is relatively immune to disruption by dephasing processes, and, as a result, it has been possible to observe slow light effects based on this process even in room-temperature solids [14, 15]. Many proposed applications of slow light require time delays considerably greater than one pulse length. However, thus far the fractional delays (time delay divided by pulse duration) achievable by this effect have been limited to only a few tens of percent. Since there appears to be no fundamental limitation on the time delay that can be achieved using EIT and related methods [16], one is motivated to try to find means for extending the range of time delays achievable using CPO. In the present paper, we present a detailed theoretical study of slow-light effects based on CPO. We find that, for low values of the pump intensity, the fractional delay is limited to a few tens of percent, consistent with current laboratory results. However, we find that, for larger values of the pump intensity, such that the Rabi frequency associated with the pump intensity becomes comparable to the T_2 dephasing time of the atomic transition, much larger values of the fractional pulse delay become achievable. In the results presented here, we find that delays as large as 30 pulse widths are predicted.

We consider the situation described pictorially in Fig. 1, in which a strong pump beam of frequency copropagates along with a weak probe beam at frequency $\omega + \delta$ through a collection of two-level atoms. The response of the probe field as modified by the presence of the pump field can be quantified in terms of an effective susceptibility defined by $P(\omega + \delta) = \chi^{(1)}_{\text{eff}}(\omega +$

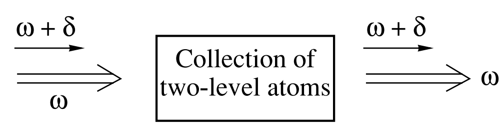

Fig. 1. A strong pump field propagating through a medium comprised of two-level atoms can modify the propagation velocity of a probe wave at frequency $\omega + \delta$.

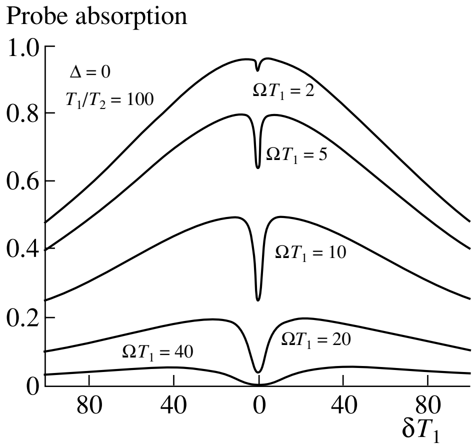

Fig. 2. Absorption profile experienced by the probe wave for a centrally tuned pump wave for several values of the pump-wave field strength. The quantity $\mathrm{Im}\chi_{\mathrm{eff}}^{(1)}(\omega + \delta)$ is plotted. The absorption coefficient experienced by the probe beam is related to this quantity by $\alpha = 4\pi(\omega/c)\mathrm{Im}\chi_{\mathrm{eff}}^{(1)}(\omega + \delta)$.

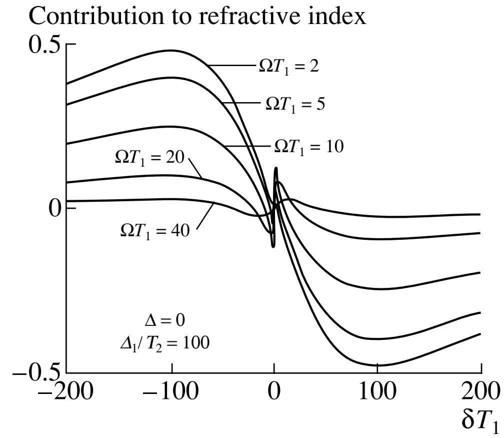

Fig. 3. Contribution to the refractive index experienced by the probe wave for a centrally tuned pump wave for several values of the pump-wave field strength. The quantity $\mathrm{Re}\chi_{\mathrm{eff}}^{(1)}(\omega + \delta)$ is plotted. The contribution to the refractive index of the probe beam is related to this quantity by $n = 2\pi\mathrm{Re}\chi_{\mathrm{eff}}^{(1)}(\omega + \delta)$.

$\delta)E(\omega + \delta)$, which has been shown to be given by the expression [17, 18]

$$\chi_{\mathrm{eff}}^{(1)}(\omega + \delta) = \frac{N|\mu_{ba}|^2 w_0}{\hbar D(\delta)} \times\left[\left(\delta + \frac{i}{T_1}\right)\left(\delta - \Delta + \frac{i}{T_2}\right) - \frac{1}{2}\Omega^2\frac{\delta}{\Delta - i/T_2}\right], \quad (2)$$

where

$$w_0 = \frac{w^{\mathrm{eq}}(1 + \Delta^2 T_2^2)}{1 + \Delta^2 T_2^2 + \Omega^2 T_1 T_2} \quad (3)$$

is the steady-state value of the population difference induced by the pump field of Rabi frequency $\Omega = 2\mu E/\hbar$ and detuning $\Delta = \omega - \omega_{ba}$ and where $D(\delta)$ is the function

$$D(\delta) = \left(\delta + \frac{i}{T_1}\right)\left(\delta - \Delta + \frac{i}{T_2}\right)\left(\delta + \Delta + \frac{i}{T_2}\right) - \Omega^2\left(\delta + \frac{i}{T_2}\right). \quad (4)$$

Here, T_1 is the population relaxation time and T_2 is the dipole dephasing time.

The transparency window predicted by these equations is illustrated in Fig. 2, where we plot $\mathrm{Im}\chi_{\mathrm{eff}}^{(1)}(\omega + \delta)$ as a function of the pump-probe detuning δ. For this example and for most of the cases treated in this paper, we treat the case of a pump field tuned to line center ($\Delta = 0$) and a highly collisionally broadened medium such that $T_1/T_2 = 100$. It has been shown earlier that no transparency window occurs for the case of radiative broadening; that is, $T_1/T_2 = 0.5$. The curves are labeled by the value of the Rabi frequency associated with the pump field. We see that, as the pump intensity is increased, the transparency window becomes deeper and (as a consequence of power broadening) becomes wider. Most crucially, we note that the absorption at the line center can be rendered arbitrarily small by using a large value of the Rabi frequency.

The collection of two-level atoms also produces a contribution to the refractive index of the material systems. This contribution is proportional to $\mathrm{Re}\chi_{\mathrm{eff}}^{(1)}(\omega + \delta)$ and is illustrated in Fig. 3 for the same conditions treated in Fig. 2. We see that, in each case, there is a rapid spectral variation of the refractive index near zero detuning. This feature is the refractive response associated with the narrow dip in the absorption profile, as required by Kramers–Kronig relations. This rapid spectral variation of the refractive index gives rise to a large contribution to the group index, as described by Eq. (1). This contribution is shown in Fig. 4. The group index normalized by the product ωT_1 is shown in the figure. It can be noted from any of Figs. 2–4 that the CPO feature displays significant saturation and significant power broadening. In fact, the power broadening of the CPO resonance can be desirable for many practical applications, since the width of this resonance limits the maximum modulation bandwidth of the probe wave that can be used under these conditions. The dependence of the CPO linewidth on the field amplitude of the pump wave is illustrated in Fig. 5. This linewidth was determined numerically from the CPO absorption spectra of the sort shown in Fig. 2.

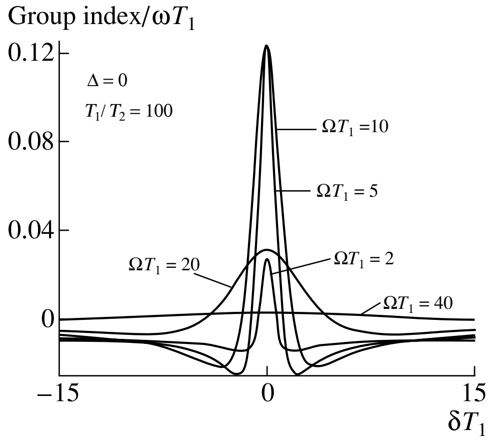

Fig. 4. The group index (divided by ωT_1) experienced by the probe wave for a centrally tuned pump wave for several values of the pump-wave field strength.

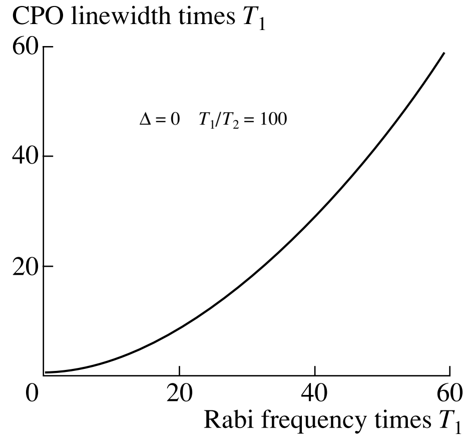

Fig. 5. Variation of the width of the transparency window with the field strength of the pump wave.

Often, the most important figure of merit for a slow-light interaction used as a controllable optical delay line is the maximum achievable time delay measured in units of the pulse width of the modulated input probe wave [16]. This quantity is also known as the normalized maximum time delay. As mentioned above, the minimum pulse length can be no smaller than the inverse of the spectra width of the transparency window. We can estimate the value of the normalized delay in terms of the quantities introduced above as follows. The material contribution to the group delay experienced in passing through a distance L of slow-light material is given by

$$T_{\mathrm{del}} = \frac{L}{c}(n_g - 1) \simeq \frac{n_g L}{c}. \tag{5}$$

Since L can be no greater than the inverse of the absorption coefficient α at the probe frequency, and since the input pulse duration T_0 can be no smaller than $\Delta\nu^{-1}$, we find that the maximum value of the normalized group delay is given by

$$\left(\frac{T_{\mathrm{del}}}{T_0}\right)_{\max} \simeq \frac{n_g \Delta\nu}{\alpha c}. \tag{6}$$

The quantities n_g, α, and $\Delta\nu$ are given above, and, from these quantities, we can calculate the normalized time delay. This quantity is shown in Fig. 6. We see that time delays of many pulse widths are predicted by the present model.

Candidate systems in which to study these effects include saturable absorber dyes of the sort used for laser mode locking and Q switching, bulk semiconductors, semiconductor heterostructures, and atomic vapors. Atomic vapors constitute a particularly attractive system for studying the fundamental features of this interaction, because the dipole dephasing time T_2 can be varied continuously by controlling the number density of the atomic species or of any buffer gas. We also note that, even though the absorption of the probe wave can be rendered negligibly small by the procedure described in this paper, the pump wave will undergo some absorption. It would thus be necessary to utilize an experimental geometry in which multiple pump beams are used or in which the probe beam passes many times through a region irradiated by a single pump beam. Such considerations could complicate the verification of the predictions of this paper but do not constitute any fundamental limitation on the method described here.

In summary, we have shown that, by using a pump beam sufficiently strong to render the material medium essentially transparent to a probe beam, much greater pulse delays than those observed thus far in a CPO system should be possible.

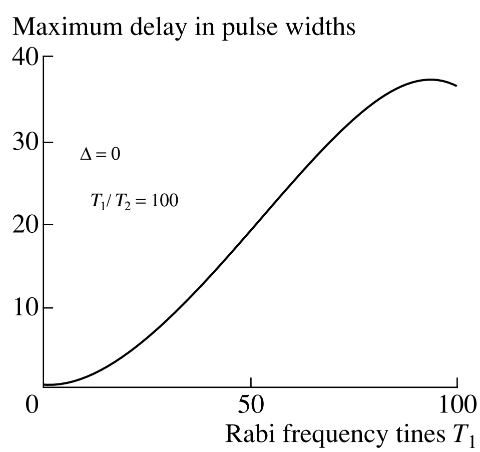

Fig. 6. Predicted maximum time delay experienced by the probe beam normalized by the input pulse width. Note that large time delays are predicted.

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