Slow-light dynamics from electromagnetically-induced-transparency spectra

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We show how slow-light pulse delays in realistic electromagnetically-induced-transparency (EIT) media can be determined directly from static transmission spectra. Using only the measured EIT linewidth and off-resonant transmission, the absolute delay of a slow-light pulse in an optically thick, power-broadened medium can be simply and accurately determined, while capturing more complex optical pumping behavior.

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Slow light from electromagnetically-induced transparency (EIT) has many potential applications, including photonic delay lines [1], interferometry [2,3], quantum memories [4], and atomic spectroscopy [5]. These applications benefit from long pulse delay times, which arise from a reduced group velocity associated with steep dispersion from an atomic [4,6–10] or optical [11–16] resonance. Characterization of slow light for a particular medium often begins with the underlying static absorption resonance (e.g., Refs. [4,7,10,11,17]). However, extracting dispersive slow-light behavior from the associated absorption resonance via the Kramers-Kronig relations is often difficult. While these relations provide a direct connection between absorption and dispersion spectra, they can be solved analytically only for a very limited range of absorption functions and numerical solutions often diverge [18]. Other work [19] has taken a phenomenological Lorentzian absorption spectrum and calculated the resulting group velocity reduction. Here, we show that a simple realistic model of EIT spectra allows accurate prediction of slow-light pulse delay from two easily measurable parameters: the linewidth and off-resonant transmission level on a logarithmic scale. We find good agreement between the predictions of this model and experimental measurements of EIT and slow light in warm rubidium vapor. This technique should be applicable to a wide range of slow-light media.

EIT is a two-optical-field phenomenon in which a strong control field renders an otherwise absorbing medium transparent to a weak signal field via quantum interference between two alternate excitation paths from the ground to excited state [20]. Both static line shapes [21] and dynamic behavior [22,23] may be straightforwardly calculated. Here, we extract model parameters from the three-level-atom absorption resonance and determine the group velocity and effective optical depth, which together determine the absolute pulse delay.

We calculate steady-state signal absorption in EIT from the imaginary component of the susceptibility. For a three-level Λ system, the susceptibility as a function of two-photon Raman detuning, δ, is [21]

$$\chi''(\delta) = \frac{n\wp\omega}{2\hbar\epsilon_0}\frac{\delta^2(\gamma+\gamma_0) - \gamma_0(\delta^2 - \gamma\gamma_0 - \Omega_c^2)}{(\delta^2 - \gamma\gamma_0 - \Omega_c^2)^2 + \delta^2(\gamma+\gamma_0)^2}, \tag{1}$$

where n is the atomic density, $\wp$ and ω are the dipole matrix element and frequency between the ground and excited states, γ is the excited state decay rate, γ_0 is the ground-state decoherence rate, and Ω_c is the control field Rabi frequency. We characterize our EIT spectrum S by its linewidth γ_S, amplitude A, off-resonant floor F, and ceiling C (see Fig. 1). The normalized off-resonant transmission, F, is

$$F = [e^{-\chi''_{\max.}L/c}]^2 = e^{-2d_0}, \tag{2}$$

where L is the length of the medium, c is the vacuum speed of light, and d_0 is defined as the system's optical depth. $\chi''_{\max}$, determined from Eq. (1), is the absorption away from EIT resonance.

The delay of a slow-light pulse is proportional to the product of the optical depth and the slope of the medium's dispersion curve. Based on a first-principles dark-state polariton model of propagation in a three-level EIT medium, the maximum delay $\tau_{\max}$ for a pulse with bandwidth much smaller than the width of the power-broadened EIT resonance is given by [22,23]

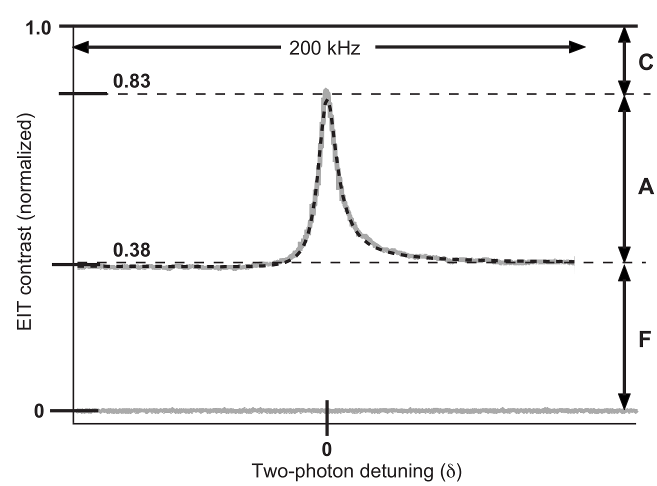

FIG. 1. Intensity spectrum with normalized contrast and background levels. Solid gray line is the data while the dashed dark line is a fit to a skew-Lorentzian. **F**: signal intensity above background away from EIT resonance (the "floor"); **A**: amplitude of EIT peak; **C**: difference between EIT peak and 100% transmission (the "ceiling"). Parameters are normalized so that **F**+**A**+**C**=1. (For data shown here, T=40 °C, in 25 torr N_2 buffer gas, and total laser power ≈490 μW.)

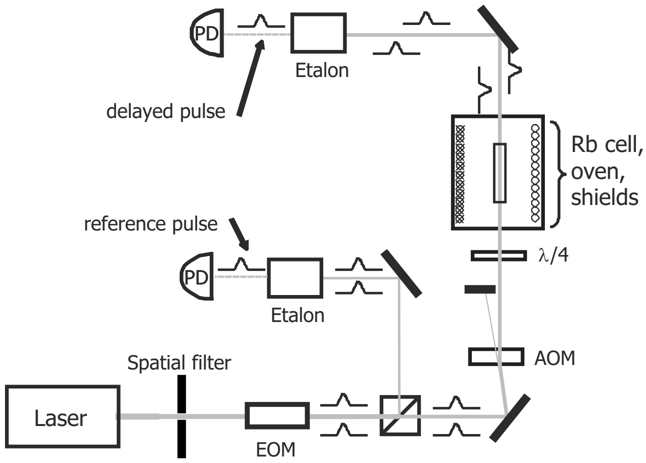

FIG. 2. Schematic of the apparatus used for our EIT and slow-light measurements. An electro-optic modulator (EOM) frequency modulates the laser light to generate signal and reference field sidebands, while an acousto-optic modulator (AOM) regulates the light intensity. Reference and output signal fields are sent into photodetectors (PD) for EIT line shape and slow-light delay measurements. See text for details.

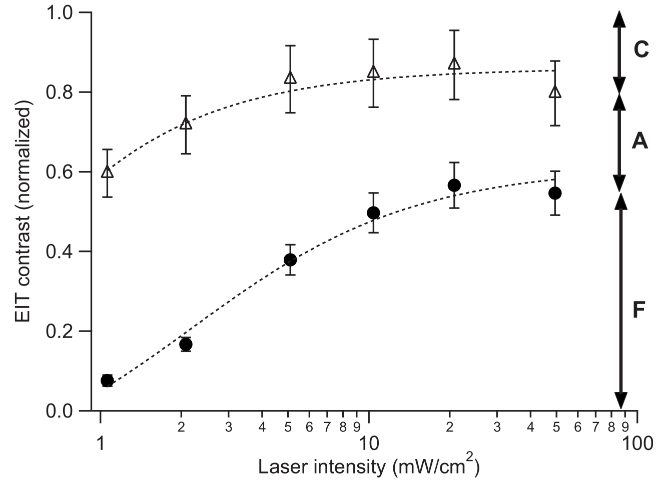

FIG. 3. Measured EIT floor (**F**, circles) and peak transmission (**F**+**A**, triangles) level vs total laser intensity for experimental conditions described in the text. Uncertainties in the measured contrasts in this figure are predominantly systematic. Dotted curves are fits of a four-level model to the data with good agreement between fit parameters and experimental conditions (see text).

$$\tau_{\max} = \frac{nL\wp\omega}{2\hbar\epsilon_0\Omega_c^2 c} = \frac{d_0\gamma}{\Omega_c^2}. \tag{3}$$

In an optically thin medium, Ω_c^2/γ equals the EIT transmission half-width half-maximum (HWHM), provided that the control field has both a uniform transverse profile [24] and intensity such that in combination with the given buffer gas pressure and beam size, reshaping by Ramsey narrowing is not present [25]. To generalize to optically thick media, we set Ω_c^2/γ equal to W, the HWHM of the logarithm of the EIT transmission spectrum, assuming the medium to be power broadened throughout [23]. The maximum delay for an optically thick medium is then

$$\tau_{\max} = \frac{-\ln(F)}{2W}, \tag{4}$$

where F is defined above [26]. A similar approach can be used to extract γ_0, the intrinsic decoherence rate [5]. The EIT amplitude, A, determines the fidelity of pulse transmission, but need not be measured directly in order to extract the pulse delay for narrow bandwidth pulses. The easily measurable off-resonant transmission, F, serves as a proxy for the optical depth which can be a function of system parameters as discussed below.

We tested the efficacy of this simple technique for determining slow-light delay using measured hyperfine EIT resonances in warm Rb vapor. For an example spectrum, see Fig. 1. A schematic of our experimental apparatus appears in Fig. 2. An amplified diode laser produced light at 795 nm, which after spatial filtering passed through an EOM driven at 6.835 GHz, the Rb ground-state hyperfine transition frequency, producing sidebands with 4% of the carrier (control field) intensity. The +1 sideband served as the signal field, while the −1 sideband was far off resonance and served as a transmission reference. Adjusting the EOM frequency changed the two-photon detuning, δ. The laser field was circularly polarized with a quarter-wave plate and then expanded and shaped with a telescope and iris to approximate a flat-top profile with diameter 3.5 mm; this minimizes reshaping of the EIT resonance from an otherwise Gaussian transverse profile [24]. This beam then passed through a Rb vapor cell of length $L=15$ cm and diameter $D=1.2$ cm containing isotopically enriched ^{87}Rb and 25 torr of N_2 buffer gas to confine the Rb atoms. The cell was housed inside a blown-air oven and high-permeability magnetic shields, and heated to $\sim 40\ ^\circ$C, corresponding to an unpolarized optical depth of $d_0 \approx 2$. The output light was filtered using a temperature-stabilized etalon tuned to transmit only the signal light. A small amount of the input signal light, separated from the main beam with a beam splitter and measured through a second stabilized etalon, served as a reference for slow-light time delay measurements. We obtained EIT spectra by measuring the output signal power while sweeping the two-photon detuning δ across the hyperfine resonance. Similarly, we performed slow-light measurements at $\delta=0$ by varying the EOM drive power to shape a pulse of input signal light. We defined the slow-light delay as the difference in peak arrival times between the reference and output signal pulses.

Measurements of the EIT floor and amplitude are summarized in Fig. 3. The normalized signal transmission level $(F+A)$ increases with laser power as more atoms are optically pumped into the nonabsorbing dark state [22]. The measured EIT linewidth (not shown) conforms well to the expected linear power broadening: $\gamma_S \propto \Omega_c^2/\gamma$. The increase in signal transmission saturates at high power, whereas the off-resonant transmission level F increases, corresponding to reduced slow-light delay [see Eq. (4)]. We attribute this increased F to optical pumping into inaccessible "trapped" states at a rate dependent on buffer gas species and pressure as well as laser field intensity and polarization. For example, for σ^+-polarized light, atoms pumped into the $|F,m_F\rangle$

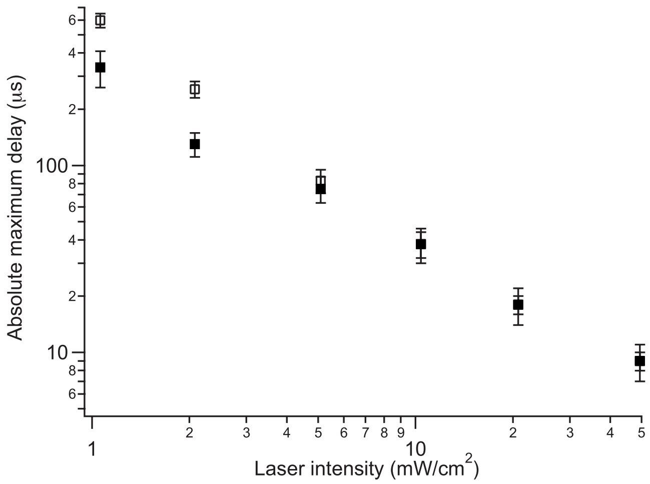

FIG. 4. Measured slow-light delays (solid squares) and predictions (hollow squares) based on accessible EIT line-shape parameters. Good agreement is shown over a large range of pulse delays and laser intensities.

$=|2,2\rangle$ state no longer participate in EIT. Thus, the *effective* optical depth decreases with increasing control power. The consequences of complex optical pumping processes are encapsulated in the measured F, illustrating the usefulness of this approach. We also find good agreement between our measured EIT contrast levels and a simple four-level model that includes the extra "trapped" level in the ground state [27].

We found quantitative agreement between directly measured slow-light pulse delays and predictions by the above method using measured EIT line shapes, over a large range of pulse delays and laser intensities (Fig. 4). Narrow-bandwidth pulses were employed, such that the pulse bandwidth was always small compared to the EIT bandwidth. We found discrepancies between prediction and observation at only the lowest laser intensities, where the approximation of power-broadened EIT began to break down (i.e., when the ground-state decoherence rate is no longer negligible compared to the two-photon pumping rate). More detailed modeling improved the agreement at low powers, but at the expense of the simple expressions of Eqs. (3) and (4) above [28]. Error bars in Figs. 3 and 4 were derived from the uncertainty in fit parameters for slow-light pulse delays and EIT contrast as well as systematic errors associated with laser power and etalon drift (leading to 5% overall uncertainty in maximum signal transmission). Systematic uncertainty dominated over statistical uncertainty in our EIT contrast data. Residual uncertainty due to nonuniform transverse beam profiles and Ramsey narrowing [25] was small.

We have presented a straightforward model of EIT in optically thick, power-broadened media that provides both a quantitative prediction of the slow-light delay and a measure of the effective system optical depth from easily derived static properties of the EIT line shape. We find good agreement between the EIT spectrum-based predictions and measured slow-light delay, and the approach captures more complicated optical pumping behavior present in many-level atomic systems. Slow light with large delay and high efficiency is obtained for small floor F and large amplitude A; hence static EIT line-shape measurements may be used to optimize slow light. These techniques should be applicable in other slow-light systems in which static resonance line shapes can be easily extracted.

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