Slow light with large fractional delays by spectral hole-burning in rubidium vapor

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(Received 28 February 2006; published 6 September 2006)

We report on the experimental realization of large fractional pulse delays in a hot, Doppler-broadened rubidium vapor. A pump laser burns a deep spectral hole in the inhomogeneously broadened vapor. The delay is shown to be widely tunable by both power broadening the resonance and frequency modulating the pump laser. The simplicity of the scheme opens up the possibility for practical optical delays and buffers.

DOI: 10.1103/PhysRevA.74.033801 PACS number(s): 42.50.Nn, 42.50.Md

In addition to the intrinsic scientific interest in "slow" light, there are many applications benefiting from light with slow group velocities: optical delay lines [1], optical pattern correlation, precision measurements (such as magnetometery [2]), quantum measurements, and low light level nonlinear optics [3]. Several methods have been used to achieve slow group velocities: electromagnetically induced transparency (EIT) [3–6], population oscillations [7,8], nonlinear magneto-optics [2], gain resonances [9,10], and photonic lattices [11–13].

Though most researchers have used coherently prepared media (e.g., EIT) to produce slow light, it is well known that slow light may be achieved in any medium with frequency dependent absorption. In particular, Agarwal and Dey [14] proposed that a doppler broadened two level system may produce slow light in the configuration of saturated absorption spectroscopy. Shakhmuratov *et al.* [15] extended the work of Agarwal and Dey by proposing that an additional trapping state with a long radiative lifetime may be used to increase the group index even further and may be realized in many solid materials. Shakhmuratov *et al.* pointed out that such slow light using persistent hole burning has the advantage over most coherently prepared systems of having transparency windows of a more arbitrary shape.

In this paper, we report on a modified experimental realization of the proposals of Agarwal and Dey and Shakhmuratov *et al.* in an inhomogeneously (Doppler) broadened hot rubidium vapor. This system has several desirable features. First, the inhomogeneously broadened line is much larger than the homogeneous linewidth. Second, one can burn deep spectral holes by optically pumping population centered around the pump frequency into a trapping state of the light [15]. As shown in Fig. 1(a), a pump beam burns a hole in velocity classes near resonance with the pump frequency. Once in the $|F=2\rangle$ state, the atoms remain trapped until a Rb-Rb or wall collision causes them to flip back to the resonant ground state. A probe field with a center frequency near the pump frequency is then transmitted with little absorption. It should be noted that this is different from electromagnetically induced transparency in its typical sense, since no coherence exists between ground states; the atoms have simply been shelved in a way to prevent an interaction with the probe. Third, the system is robust to environmental fluctuations such as magnetic fields. We show that this system can achieve large fractional delays, and have measured up to ten fractional delays.

A schematic for the experiment is shown in Fig. 1(b). The pump beam is generated by seeding a tapered amplifier with a master oscillator laser near the $|F=1\rangle \rightarrow |F'=2\rangle$ Rb^{87} D_1 transition at 795 nm. It has a maximum output power of approximately 200 mW and a $1/e^2$ diameter of 2.6 mm. The probe pulse is generated by a passing a weak (<100 μW) continuous-wave (cw) beam through a fast modulator. Both 5.8 ns and 8.1 ns, full width half maximum (FWHM) pulses are used in the experiment. The pump beam (vertically polarized) is split into four equal intensity branches by cascading three 50/50 beam splitters. The pump beams then enter four Rb vapor cells counter-propagating relative to the probe beam (horizontally polarized) via the use of a series of polarizing beam splitters. The polarizing beam splitters also serve to eject the pump beams after traversing only one cell. Using multiple cells at lower temperatures reduces pump power and increases pump uniformity, resulting in less off-resonant pumping and less pulse distortion. As a note, the experiment was also performed in one cell heated to higher temperatures. However, as the number density of the vapor was increased, significant pump absorption limited the depth

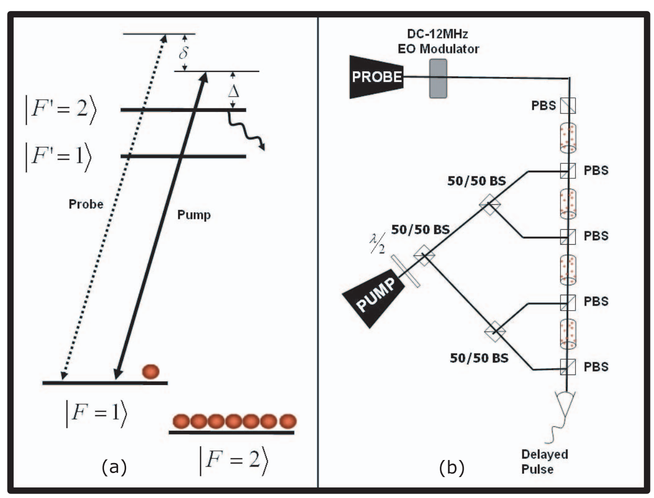

FIG. 1. (Color online) (a) Energy level diagram of Rb^{87} D_1. A cw pump laser detuned Δ from the $|F=1\rangle \rightarrow |F'=2\rangle$ transition drives a set of velocity classes from the $|F=1\rangle$ ground state to the $|F=2\rangle$ ground state, creating a transparency window for the probe centered at the same frequency. δ is the probe detuning from the pump center frequency. The atoms remaining in the $|F=1\rangle$ ground state near the pump frequency are driven to saturation, further reducing the absorption of the probe beam. The pump burns a hole in an inhomogeneously broadened spectrum. (b) Experimental setup.

of the spectral hole. As a result, the optimal number temperature and pump power for maximizing the delay bandwidth product changed, and the maximum observed delay was approximately four times less. Higher optical depths require more pump power to burn a spectral hole. However, increasing pump power also results in more power broadening of the resonance and more off-resonant absorption, effectively reducing the steepness of the dispersion curve and hence the group delay of the pulse.

A 1 GHz avalanche photodiode measures the transmitted probe field and a 300 MHz oscilloscope records the pulse data. The limited bandwidth of the oscilloscope resulted in a small (<10%) broadening of the pulses during measurement. All data in this paper are reported as measured by the oscilloscope. The oscilloscope is triggered by the arbitrary wave form generator (AWG) signal that drives the fast modulator. Since the scope is triggered by the AWG, the probe pulse is free to change center frequencies. To get a reference pulse the probe field is detuned many GHz away from the Doppler distribution. This gives both a zero delay and maximum transmission reference. The probe pulse frequency is then tuned to the same center frequency as the pump (placing it inside the spectral hole) to determine the relative pulse delay and transmission.

We estimate that the thermal distribution has an optical depth as high as 350 in the absence of the pump beam. The cells are heated to approximately 110 °C, which corresponds to a number density of approximately 6×10^{12} atoms/cm^3 [16]. Accounting for natural isotopic abundance (≈25%) and using the fact that the number of atoms per natural linewidth is approximately 1/150 of the total Doppler profile, we arrive at a Rb^{87} number density of $n=10^{10}$ atoms/cm^3 per natural linewidth. The small signal atomic absorption cross section σ for the $|F=1\rangle\rightarrow|F'=2\rangle$ Rb^{87} transition is $\sigma=8.4\times10^{-10}$ cm^2 [3]. The total interaction length of the four cells is $L=40$ cm. This leads to an estimated optical depth of $OD=N\sigma L\approx350$. This is somewhat higher than the optical depth of 63 in the cold atom EIT work [5], but much smaller than the optical depth of 6000 in the lead vapor EIT experiment [4]. As a note, we believe our temperature readings to be somewhat high and hence the optical depth may be lower than 300. Also, the presence of the pump beam reduces the optical depth of the entire ground state, further reducing the maximum pulse delay.

In slow light experiments, pulse distortion is closely related to the behavior of the derivatives of the spectral lineshape through which the light pulse passes [17]. In general, an ideal slow light medium would have a vanishing first derivative in absorption over the entire pulse bandwidth. We were able to achieve a flatter top for the transmission line shape by frequency modulating the pump laser. As is well known, the natural line shape for atomic resonances is an exponentiated Lorentzian, which has a pulse acceptance bandwidth on the order of its linewidth. Frequency modulation of the pump laser results in the convolution of several Lorentizans, which add to create a line shape with a flatter top and larger acceptance bandwidth. The instantaneous laser frequency may be written

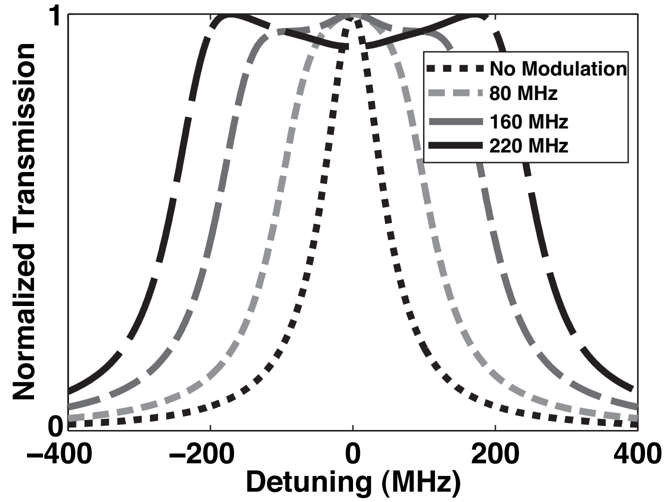

FIG. 2. The effect of laser modulation on atomic transmission resonance. The modulated laser spectrum [Eq. (1)] is convolved with an exponentiated Lorentzian line shape. As the modulation amplitude increases, the top of the resonance flattens and then sidebands begin to appear.

$$\omega_L = \cos(\omega_c t + a\cos\omega_m t) = \sum_{n=0}^{\infty} J_n(a)\cos\left(\omega_c \pm n\omega_m + \frac{n\pi}{2}\right), \quad (1)$$

where ω_c is the laser carrier frequency, ω_m is the modulation frequency, $a\omega_m$ is the modulation amplitude, and J_n is the bessel function of order n. The result of modulation, then is a superposition of frequencies at $\omega_c\pm n\omega_m$, each with amplitude $J_n(a)$, and the atomic transmission resonance may be approximated by convolving each frequency component with an exponentiated Lorentzian.

Figure 2 shows an example of the effect of modulation with a frequency of 6 MHz convolved with transmission resonances of width 50 MHz. At low modulation amplitudes the effect is simply to broaden the resonance, but at higher modulation amplitudes distinct sidebands begin to appear. We note that by proper choice of the modulation frequency and amplitude, it is always possible to find an intermediate region with a relatively flat top. Although we observed the high modulation amplitude regime in which the frequency sidebands become pronounced, we report here only on the low amplitude regime.

The cw probe transmission with and without the pump beam is shown in Fig. 3. The curves show the transmission of the probe beam through all four vapor cells in the absence of the pump beam, and in the presence of the pump beam at three different pump modulation amplitudes. Two spectral transmission windows can be seen, corresponding to transitions from the $|F=1\rangle$ ground state to two excited states, $|F'=1\rangle$ on the left and $|F'=2\rangle$ on the right, separated by the excited state hyperfine splitting of 816 MHz. The resonances on the right were used for all pulse delay data reported here.

Experimentally, we observed that if the modulation frequency was slower than 1 MHz, there was significant shot-to-shot transmission instability. We ran the experiment at

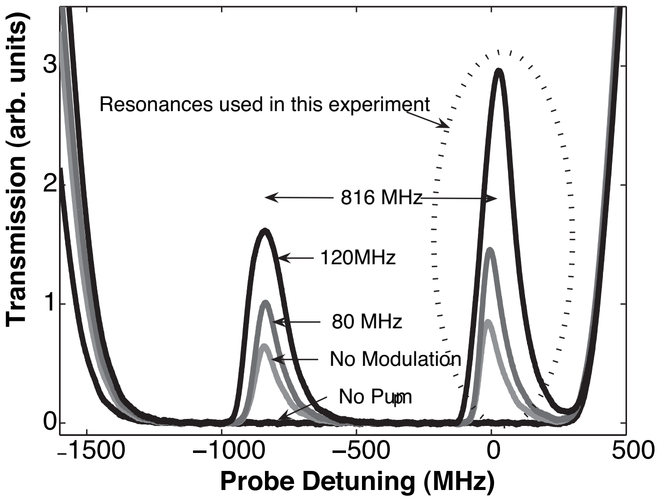

FIG. 3. Probe transmission at various pump modulation amplitudes as a function of probe detuning from the pump center frequency. The probe transmission in the absence of a pumping laser is shown in the lowest curve. The pump power is 35 mW for all scans.

6 MHz. The range of frequencies spanned by the pump in the 6 MHz dither were from 0 to 120 MHz. Frequency modulation allowed us to reduce the pump power while maintaining similar resonance widths, resulting in a flatter top and steeper wings. We also observed that the peak transmission increased as well.

Figure 4 shows the transmission of several 5.8 ns FWHM pulses in the presence of 15 mW of pump power at different pump modulation amplitudes. (The reference pulse amplitude has been divided by 4 for graph scaling.) For broadened pulses, the percent power transmission (pulse area) is higher than the relative peak transmission shown. With small modulation amplitudes, higher frequency components are not transmitted and the pulse broadens and the absorption is increased. A small amount of off-resonant amplified spontaneous emission from the diode laser can be seen in each pulse near the time origin, which we found to be removable by spectral filtering.

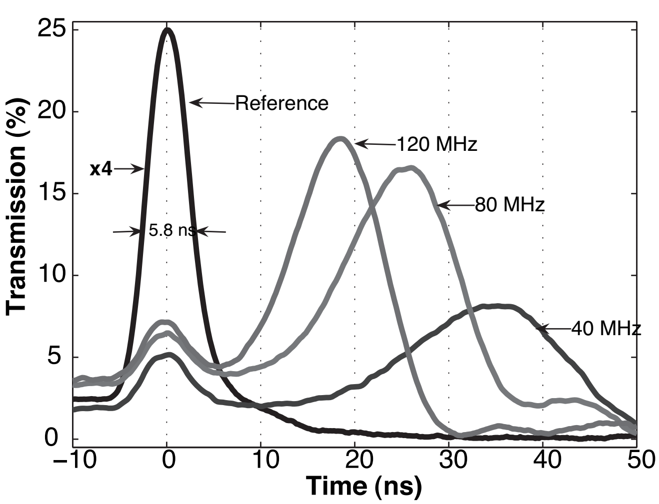

FIG. 4. Pulse delay at various pump modulation amplitudes. The input (reference) pulse is 5.8 ns FWHM in duration. The pump beam power is 15 mW for all scans.

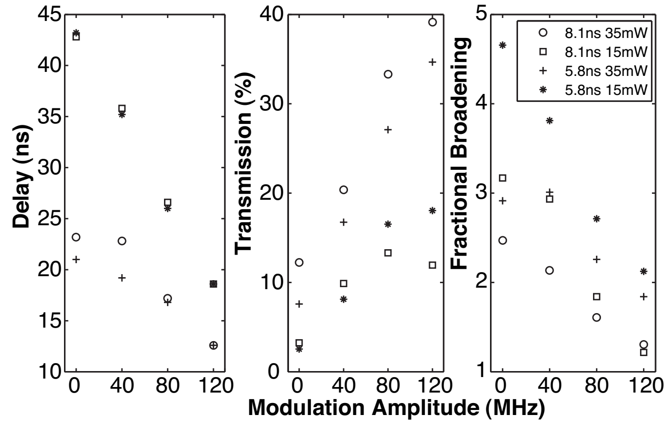

FIG. 5. Pulse delay trend data for two pulse durations and two pump powers. Plots show fractional delay (left), pulse peak transmission (middle), and fractional broadening (right) as a function of pump modulation amplitude. Pulse broadening is the pulse duration fraction of the reference pulse at full width at half maximum.

Figure 5 shows the delay, transmission, and broadening of the probe pulse for different pump powers and modulation amplitudes. For a given pump power, increasing the modulation amplitude decreases delay and broadening while increasing transmission. A few features of the data are worth noting: lower pump powers increase delay tunability, lower pump powers have more uniform transmission over their tunable range, and simultaneously decreasing pump power and increasing modulation amplitude produces greater pulse delays with less fractional broadening.

The tunability of the delay via frequency modulation is more sensitive at lower pump powers, as seen by the steeper slope in the delay plot for lower powers. With no pump modulation, lower pump powers result in narrower transmis-

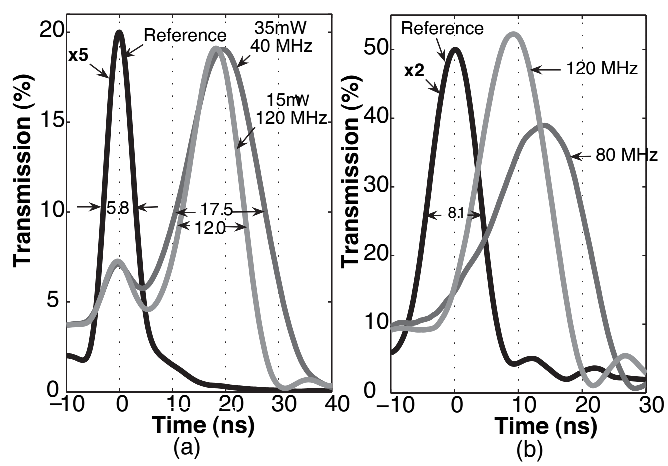

FIG. 6. (a) Comparison of delayed pulses at two pump powers and pump modulation amplitudes. Less pulse broadening is obtained by increasing the pump modulation amplitude. (b) Pulse delays showing greater than $1/e$ transmission and more than one pulse delay with less than a factor of 2 fractional broadening. The temperature has been reduced to 100 °C.

sion linewidths due to less power broadening. Therefore, when the pump is frequency modulated to increase the transmission linewidth, lower pump powers have a greater range of linewidths.

We also observe that the transmission appears to be more constant for large modulation amplitudes at low pump powers. In addition, for a given delay, less fractional broadening may be obtained by reducing pump power and increasing modulation amplitude, as shown for one case in Fig. 6(a). For the case of three fractional delays, a 5.8 ns pulse broadens by a factor of 2 with 15 mW of pump power, while broadening by a factor of 3 with 35 mW of pump power.

Two important criteria highlighted in the literature for practical optical delay lines relate to fractional broadening and transmission. First, Boyd *et al.* [1] stated that for return-to-zero protocols with a 50% duty cycle, a pulse cannot temporally broaden by more than twice its input width. Second, Matsko *et al.* [18] stated that the peak transmission should exceed $e^{-\alpha L}$ with $\alpha L \leq 1$, where α is the absorption parameter on a line center (peak transmission). We found that by decreasing the cell temperature to 100 °C, we were able to meet both broadening and transmission criteria, as shown in Fig. 6(b).

The method we have used to achieve large fractional delays can be applied more generally to any system which has multiple ground states enabling it to trap population, and an inhomogeneously broadened line which is much larger than the homogeneous linewidth. We therefore believe that the general idea outlined in this paper can be of interest to the telecommunications community, as similar energy level structures can be found in other more desirable systems.

In conclusion, we have demonstrated that it is possible to achieve large fractional delays in atomic vapors. We have highlighted the importance of spectral line shapes in addition to optical depth and transparency in obtaining large delays. Specifically, frequency modulating the pump beam is an effective way to change the line shape and tune the delay while at the same time reduce pulse broadening. When modulated, the transmission line shape deviates from Lorentzian in that it has a flatter top and that the wings fall off faster as determined by pump power broadening. Multiple vapor cells allow us to achieve greater uniformity in pump intensity throughout the rubidium vapor and greater optical depth. We have shown that spectral hole burning is an effective method for achieving slow light. In particular, it seems suitable for many applications, including optical delays, buffers, and quantum information applications.

This work was supported by DARPA Slow Light, the National Science Foundation, and Research Corporation. We also thank Robert Boyd, Alex Gaeta, Dan Gauthier, and Steve Harris for helpful discussion.

[1] R. W. Boyd, D. J. Gauthier, A. L. Gaeta, and A. E. Willner, Phys. Rev. A **71**, 023801 (2005).
[2] D. Budker, D. F. Kimball, S. M. Rochester, and V. V. Yashchuk, Phys. Rev. Lett. **83**, 1767 (1999).
[3] D. A. Braje, V. Balic, G. Y. Yin, and S. E. Harris, Phys. Rev. A **68**, 041801(R) (2003).
[4] A. Kasapi, M. Jain, G. Y. Yin, and S. E. Harris, Phys. Rev. Lett. **74**, 2447 (1995).
[5] L. V. Hau, S. E. Harris, Z. Dutton, and C. Behroozi, Nature (London) **397**, 594 (1999).
[6] M. M. Kash, V. A. Sautenkov, A. S. Zibrov, L. Hollberg, G. R. Welch, M. D. Lukin, Y. Rostovtsev, E. S. Fry, and M. O. Scully, Phys. Rev. Lett. **82**, 5229 (1999).
[7] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, Science **301**, 200 (2003).
[8] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, Phys. Rev. Lett. **90**, 113903 (2003).
[9] J. E. Sharping, Y. Okawachi, and A. L. Gaeta, Opt. Express **13**, 6092 (2005).
[10] Y. Okawachi, M. S. Bigelow, J. E. Sharping, Z. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, Phys. Rev. Lett. **94**, 153902 (2005).
[11] X. Zhao, P. Palinginis, B. Pesala, C. Chang-Hasnain, and P. Hemmer, Opt. Express **93**, 7899 (2005).
[12] A. Uskov and C. Chang-Hasnain, Electron. Lett. **41**, 922 (2005).
[13] A. V. Turukhin, V. S. Sudarshanam, M. S. Shahriar, J. A. Musser, B. S. Ham, and P. R. Hemmer, Phys. Rev. Lett. **88**, 023602 (2001).
[14] G. S. Agarwal and T. N. Dey, Phys. Rev. A **68**, 063816 (2003).
[15] R. N. Shakhmuratov, A. Rebane, P. Megret, and J. Odeurs, Phys. Rev. A **71**, 053811 (2005).
[16] A. N. Nesmeyanov, *Vapor Pressure of the Chemical Elements* (Elsevier, New York, 1963), English ed.
[17] R. Boyd and D. J. Gauthier, *Progress in Optics* (Elsevier, New York, 2002), p. 497.
[18] A. B. Matsko, D. V. Strekalov, and L. Maleki, Opt. Express **13**, 2210 (2005).