Slow light in narrow paraffin-coated vapor cells

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Alkali vapor cells with antirelaxation coated walls can have long atomic coherence times. However, using such coated cells in the hyperfine configuration for electromagnetically induced transparency (EIT) requires longitudinal atomic motion to be confined to less than the hyperfine wavelength. We employed a narrow (1 mm) coated cell geometry to study hyperfine EIT and slow and stored light in warm ^{87}Rb vapor, with results comparable to those in buffer gas cells and showing the promise of such cells for several applications. © *2009 American Institute of Physics*.
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Control of optical-pulse propagation via slow and stored light has applications in both quantum information[1] and photonics and optical communications.[2,3] Long atomic coherence times are a key requirement for effective use of slow and stored light as produced by electromagnetically induced transparency (EIT). In thermal vapor cells, buffer gas and wall collisions often provide a limit to atomic coherence. Antirelaxation coatings (e.g., paraffin) on the walls of buffer-gas-free vapor cells can prolong spin coherence lifetimes.[4] Such coated cells have been used in magnetometers,[5] squeezing,[6] entanglement,[7] and atomic clocks,[8] typically with cell diameters of order 1 cm.

EIT arises when a strong, optically resonant control field makes a medium transparent to a weak resonant signal field. The narrow transmission peak in an EIT spectrum corresponds to steep resonant dispersion resulting in reduced pulse group velocity and hence slow light. Slow light using EIT between nondegenerate ground state hyperfine levels in alkali atoms has the potential for low incoherent losses and improved optical depth in comparison to degenerate Zeeman EIT.[9] However, hyperfine EIT in a paraffin-coated cell requires a careful choice of cell geometry. First, a high optical depth is required for large delay-bandwidth product in slow light and good efficiency in stored light, necessitating a long cell, as deleterious effects such as spin exchange and radiation trapping limit absolute densities. Second, atomic motion must be confined to less than the hyperfine wavelength, to avoid differential phase evolution between the two light fields in the medium, which would increase decoherence and absorption. Third, rapid motional and velocity averaging is necessary for most thermal, Doppler-shifted atoms to interact with the monochromatic optical fields, requiring short mean times between velocity-changing wall collisions and thus a small cell diameter.

Here, we report investigations of hyperfine EIT and slow light in a high-aspect-ratio coated vapor cell. Results compare favorably to those of standard (uncoated) buffer gas cells and indicate that narrow coated cells could serve as an asset for several applications.

We employed Rb vapor cells (Fig. 1) made of 25 mm long, 1 mm inner diameter Pyrex capillary tubing with optical flats fused to the ends. A 1 mm hole was drilled perpendicular to the length of each cell and a larger glass sidearm was fused to the cell to hold metal Rb and to connect to a vacuum system during fabrication. The 1 mm diameter ensured that, on the timescale of typical slow-light experiments, few atoms traveled a significant fraction of a hyperfine wavelength (4.4 cm for the ^{87}Rb D_1 transition)

Each cell was coated with tetracontane ($C_{40}H_{82}$), a derivative of paraffin.[10] Tetracontane flakes were placed in the sidearm before evacuating and heating the cell above the paraffin vaporization temperature of $\approx 200\ ^\circ$C. The cell walls were uniformly cooled to coat the entire cell. Isotopically enriched ^{87}RbCl salt and CaH_2 were crushed and mixed together, then heated to $\approx 500\ ^\circ$C to produce ^{87}Rb metal (along with CaCl salt and H_2 gas). The metal was distilled into the sidearm, which was then sealed.[11] Two narrow cells were employed in the experiments reported here: a cell with a "good" wall coating, which provided an intrinsic hyperfine EIT full width at half maximum (FWHM) linewidth of 20 kHz and Zeeman EIT FWHM linewidth of 750 Hz; and a cell with a "moderate" quality wall coating, which provided a hyperfine EIT linewidth of 45 kHz and Zeeman EIT linewidth of 9 kHz.[12]

An outline of our apparatus follows. An amplified diode laser produced light at 795 nm, which was frequency modulated to produce sidebands (signal and reference fields) at 5% of the carrier (control field) intensity. The control and signal fields drove the $F=2 \rightarrow F'=2$ and $F=1 \rightarrow F'=2$ transitions, respectively. A 500 μm diameter beam with circular polar-

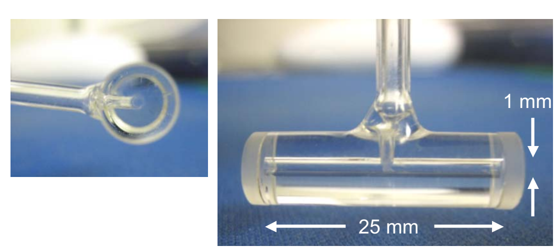

FIG. 1. (Color online) Photographs of the narrow (1 mm) paraffin-coated ^{87}Rb vapor cell (see text).

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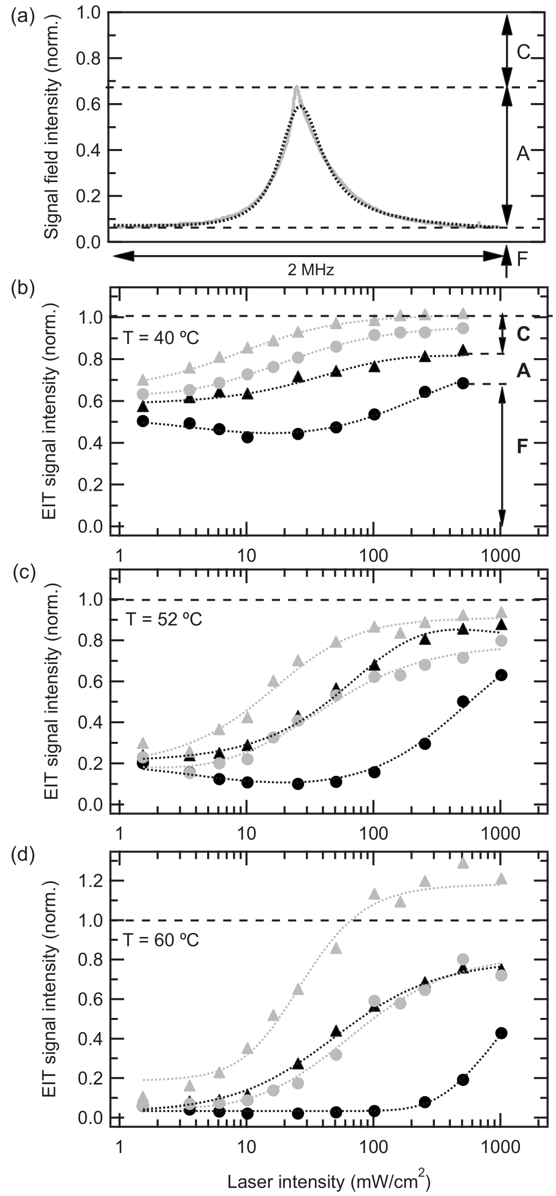

FIG. 2. Measured EIT behavior in small and narrow paraffin-coated cells. (a) Characteristic non-Lorentzian EIT lineshape, normalized to far off-resonant signal light transmission; dotted curve is a Lorentzian fit. Data from the cell with shorter coherence time is shown. $T=60$ °C and $I=100$ mW/cm^2. Contrast parameters are $F=0.08$, $A=0.60$, and $C=0.32$, and the linewidth is 180 kHz. [(b), (c), and (d)] EIT contrast parameters as a function of laser intensity for $T=40$, 52, and 60 °C, (respective Rb densities are 0.4, 1.2, and 2.5×10^{11} cm^{-3}). Black symbols are for the cell with the shorter coherence time and gray symbols for the longer coherence time cell. Dotted curves are fits to a four-level model (see text).

ization was sent into a narrow coated Rb vapor cell, which was heated by a blown-air plastic oven and housed inside layers of magnetic shields. A small fraction of the input signal light was measured just prior to entering the cell, providing a timing reference for slow-light measurements.

The measured EIT line shapes exhibited a non-Lorentzian shape typical of coated cells[13] [see Fig. 2(a)]. This non-Lorentzian line shape consists, in general, of (i) a narrow peak, which arises from atoms that repeatedly return to the laser beam with their phase coherence intact following wall collisions; (ii) atop a broad pedestal, which arises from atoms that interact coherently with the laser fields on only a single pass through the beam. The narrow feature indicates long coherence lifetimes and supports enhanced optical pumping in coated cells. For a beam size comparable to the cell size, such as employed here, these two components of the coated-cell EIT spectrum merge together into a single non-Lorentzian resonance.

Long slow-light pulse delays can be achieved in coated cells due to the extended spin coherence lifetime allowed by the wall coating.[13,14] However, high EIT contrast is crucial for good slow and stored light efficiency. EIT contrast is described with three parameters: signal light transmission off of two-photon resonance, which is a measure of the optical depth (floor, F); transmission amplitude of the EIT resonance, A; and the difference between the peak EIT transmission and full signal light transmission through the cell (ceiling, C). These three parameters (F,A,C) vary as a function of laser intensity, cell geometry and properties, and atomic density, enabling the optimization of slow light performance. See measurements and fits to a four-level model in Figs. 2(b)–2(d). The peak signal transmission level $(F+A)$ increases with laser intensity, as more atoms are optically pumped into the EIT dark state.[15] The off-resonant signal transmission level (F) is also laser intensity dependent. At modest laser intensity, atoms will be optically pumped out of the $F=2$ states and into $F=1$ states, increasing the effective optical depth for the signal field and thus reducing F; however, at high laser intensity, the signal field will optically pump atoms out of the $F=1$ states and into the $|F=2, m_F=2\rangle$ trapped state, reducing effective optical depth and increasing F. Numerical simulations using the full set of D_1 transition states[16] and variable input light intensity reproduced this effect. We also find good agreement between measured EIT contrast at all laser intensities and a simple four-level model including an extra optically inaccessible "trapping" level in the ground state,[17] which captures the physics of optical depth dependence on laser intensity.

We observed resonant transmission greater than the input signal level at high laser intensity for the cell with longer coherence lifetime [Fig. 2(d)]. We attribute this to gain in the signal field induced by four-wave mixing.[18] This process is more pronounced at high Rb density and high laser intensity, and its efficiency is enhanced by the long coherence lifetimes provided by the high-quality wall coating. Such amplification may improve slow light in classical information applications.[19]

There is a quantitative connection between experimentally measured EIT line shapes and slow light behavior.[20,21] Slow light fractional delay and transmission are both greater for larger EIT amplitude, A, and smaller floor, F. The measured EIT contrasts for coated cells, shown in Fig. 2, are comparable to similar experiments done in buffer gas cells,[21] even though our small cells' length of 25 mm leads to reduced optical depth, limiting the slow light delay.

EIT with conditions more favorable to slow light are found in the cell with the *shorter* coherence lifetime (black symbols), which has smaller F and larger A values for almost all laser intensities and Rb densities. This occurs because a longer coherence time leads to enhanced optical pumping into the trapped state $|2,2\rangle$, and, hence, greater reduction of the effective optical depth. The optimal decoherence rate (determined by wall coating) must balance against the optical pumping rate (determined by laser intensity), which sets the EIT contrast/slow light delay. Depopulating the $|2,2\rangle$ state

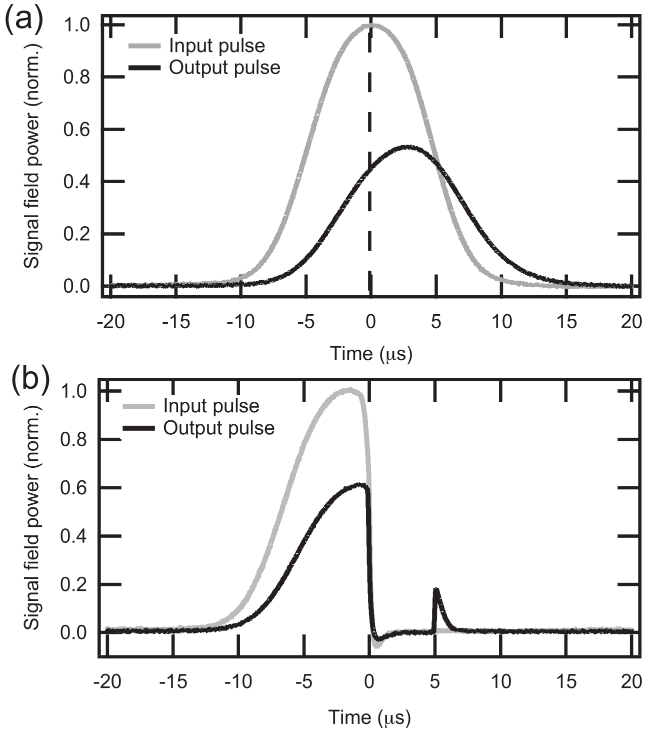

FIG. 3. (a) Measured slow light in the narrow coated cell with shorter coherence time. Fractional delay is 0.26 and transmission fraction is 0.53. $T=60$ °C and $I=250$ mW/cm^2. The transmission for the cell with longer coherence time, at the same fractional delay, is only 0.40. (b) Stored light under the same conditions, with a 5 μs storage time.

using an additional light field would be needed to properly take advantage of the longer coherence times allowed by higher quality wall coating and achieve high EIT contrast without suffering reduced optical depth.

Example slow and stored light pulses are shown in Fig. 3, and a width of 10 μs was chosen to fit within the EIT bandwidth. The storage time of 5 μs is equivalent to four beam crossings and efficiency was consistent with the slow light transmission and delay and measured decoherence rates. Both slow and stored light performance should improve with more refined state selection combined with better coating techniques for long narrow cells.

In conclusion, we investigated hyperfine EIT and slow light in narrow (1 mm) antirelaxation coated Rb vapor cells and found EIT results comparable to those in conventional buffer gas cells. The narrow coated cell geometry, dictated by the need for limited longitudinal atomic motion, could be an asset for a number of applications. Small vapor cells are used in atomic clocks[22,23] and magnetometry;[5] and a narrow cell allows for higher intensity light fields when needed. Quantum optics applications such as a coated cell "slow-light beamsplitter"[24] could see improved transfer of information between multiple channels in a narrow medium. Future work may also use narrow coated cells for single photon storage,[25] where a narrow coated cell could remove buffer-gas-specific collisional decoherence[26] since velocity-changing collisions would occur outside the laser beam; long optical pumping lifetimes could enhance measurement repeatability and atoms re-entering the beam after wall collisions maintain spin states.

[1]M. D. Lukin, Rev. Mod. Phys. **75**, 457 (2003).
[2]R. W. Boyd and D. J. Gauthier, Prog. Opt. **43**, 497 (2002).
[3]R. S. Tucker, P. C. Ku, and C. J. Chang-Hasnain, J. Lightwave Technol. **23**, 4046 (2005).
[4]D. Budker, V. V. Yashchuk, and M. Zoloterev, Phys. Rev. Lett. **81**, 5788 (1998).
[5]M. V. Balabas, D. Budker, J. Kitching, P. D. D. Schwindt, and J. E. Stalknaker, J. Opt. Soc. Am. B **23**, 1001 (2006).
[6]A. Kuzmich, L. Mandel, and N. P. Bigelow, Phys. Rev. Lett. **85**, 1594 (2000).
[7]B. Julsgaard, A. Kozhekin, and E. S. Polzik, Nature (London) **413**, 400 (2001).
[8]H. G. Robinson and C. E. Johnson, Appl. Phys. Lett. **40**, 771 (1982).
[9]A. B. Matsko, D. V. Strekalov, and L. Maleki, Opt. Express **13**, 2210 (2005).
[10]M. A. Bouchiat and J. Brossel, Phys. Rev. **147**, 41 (1966).
[11]W. E. Bell, A. L. Bloom, and J. Lynch, Rev. Sci. Instrum. **32**, 688 (1961).
[12]D. Budker, L. Hollberg, D. F. Kimball, J. Kitching, S. Pustelny, and V. V. Yaschuk, Phys. Rev. A **71**, 012903 (2005).
[13]M. Klein, I. Novikova, D. F. Phillips, and R. L. Walsworth, J. Mod. Opt. **53**, 2583 (2006).
[14]D. Budker, D. F. Kimball, S. M. Rochester, and V. V. Yaschuk, Phys. Rev. Lett. **83**, 1767 (1999).
[15]M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. **84**, 5094 (2000).
[16]M. Crescimanno and M. A. Hohensee, J. Opt. Soc. Am. B **25**, 2130 (2008).
[17]We used a model similar to that in J. Vanier, M. W. Levine, D. Janssen, and M. Delaney, Phys. Rev. A **67**, 065801 (2003).
[18]M. D. Lukin, M. Fleischhauer, A. S. Zibrov, H. G. Robinson, and V. L. Velichansky, Phys. Rev. Lett. **79**, 2959 (1997).
[19]I. Novikova, D. F. Phillips, and R. L. Walsworth, Phys. Rev. Lett. **99**, 173604 (2007).
[20]R. W. Boyd, D. J. Gauthier, A. L. Gaeta, and A. E. Willner, Phys. Rev. A **71**, 023801 (2005).
[21]M. Klein, M. Hohensee, Y. Xiao, R. Kalra, D. F. Phillips, and R. L. Walsworth, Phys. Rev. A **79**, 053833 (2009).
[22]L. A. Liew, S. Knappe, J. Moreland, H. Robinson, L. Hollberg, and J. Kitching, Appl. Phys. Lett. **84**, 2694 (2004).
[23]S. Knappe, V. Shah, P. D. D. Schwindt, L. Hollberg, J. Kitching, L. A. Liew, and J. Moreland, Appl. Phys. Lett. **85**, 1460 (2004).
[24]Y. Xiao, M. Klein, M. Hohensee, L. Jiang, D. F. Phillips, M. D. Lukin, and R. L. Walsworth, Phys. Rev. Lett. **101**, 043601 (2008).
[25]M. D. Eisaman, A. Andre, F. Massou, M. Fleischhauer, A. S. Zibrov, and M. D. Lukin, Nature (London) **438**, 837 (2005).
[26]S. Manz, T. Fernholz, J. Schmiedmayer, and J.-W. Pan, Phys. Rev. A **75**, 040101(R) (2007).