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Optical delay with spectral hole burning in Doppler-broadened cesium vapor

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ABSTRACT

The full frequency dependence of the optical delay in the Cs D_1 ($6^2S_{1/2} - 6^2P_{1/2}$) line has been observed, including all four hyperfine split components. Pulse delays of 1.6 ns to 24.1 ns are obtained by scanning across the hyperfine splitting associated with the lower $^2S_{1/2}$ state. Optical control of pulse delays in cesium vapor was demonstrated by pumping the D_2 ($6^2S_{1/2} - 6^2P_{3/2}$) transition and observing resulting holes in the D_1 delay spectrum. For a pump at four times the saturation intensity, the pulse delays are reduced by a maximum of 78% in a narrow region of 110 MHz. The frequency dependence of the delays of the probe laser in the vicinity of the spectral holes agrees with a Kramers–Kronig model prediction.

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1. Introduction

Numerous applications from communications to interferometry for remote sensing stand to benefit from the tunable delay of optical pulses. Several methods seek to achieve a rapidly tunable optical delays of multiple pulse widths with minimal loss of signal amplitude and no pulse dispersion. Coherently coupled fields can produce slow light through electromagnetically induced transparency (EIT) [1–3]. Alternatively pulse delays may be controlled by scanning through the rapidly varying frequency-dependent absorption near atomic transitions [4–7]. We previously reported controlling optical delay by tuning a single laser across the D_2 ($6^2S_{1/2} - 6^2P_{3/2}$) absorption spectrum of cesium vapor [7]. By extending the spectral analysis to include Voigt profiles with the Doppler component, the full frequency dependence of the observed delays was adequately described. In this paper we extend the analysis to the Cs D_1 ($6^2S_{1/2} - 6^2P_{1/2}$) spectrum where the hyperfine splitting is large enough to resolve all four components.

Agarwal and Dey proposed producing pulse delays with hole burning in a Doppler-broadened atomic vapor using a counter propagating pump beam to saturate the media and achieve group indices of about 10^3 [8]. Narrower resonances may be achieved using quantum coherence effects [9]. Shakhmuratov et al. extended the technique to persistent spectral hole burning and slow light in inhomogeneously broadened solid materials [10]. Most recently, Camacho et al. experimentally realized these concepts in hot rubidium vapor [11]. The pump laser induces transparency by moving population from the probed hyperfine state to the other hyperfine component, not by coherent effects. This previous

work focused on frequency modulation of the pump beam to tune delays of up to 45 ns [11].

In the current experiment we use a continuous wave (cw) D_2 pump laser to depopulate a given velocity group in the Cs ground state and probe the full frequency dependence of the delays observed in the D_1 absorption spectrum. Monitoring pulse delays as a function of probe frequency clearly revealed a pump intensity dependent hole.

2. Experimental setup

The experimental apparatus for hole burning delay measurements shown in Fig. 1 is a modified sub-Doppler absorption spectroscopy experiment where counter propagating beams intersect in the hot cesium vapor cell. A New Focus VelocityTM model 6316 20-mW tunable diode laser with a linewidth less than 300 kHz serves as the pump laser on the D_2 Cs transition (852 nm). The pump laser is directed through a pellicle beam splitter where a beam sample is sent to a Bristol model 621A wavelength meter with 0.075 GHz (0.0025 cm^{-1}) accuracy for frequency reference. The main pump beam is directed through a 5-cm-long, low-pressure cesium vapor cell enclosed in a machined aluminum heater block maintained at a constant temperature of $\pm 2^\circ\text{C}$ between 40°C and 120°C . Pump power is adjusted using neutral density filters as changing diode current causes a subsequent shift in pump laser frequency.

A New Focus VelocityTM model 6318 6-mW tunable diode laser with less than 300-kHz linewidth is used as the D_1 probe laser at 894 nm. The probe beam is directed through an optical isolator and a pellicle beam splitter. A probe beam sample is sent to a second Bristol model 621A wavelength meter while the main probe beam continues to a EOSPACE fiber-coupled Mach–Zehnder interferometric lithium niobate (LiNbO_3) electro-optic intensity modulator (EOM). A Picosecond Pulse Labs 1.6-GHz pulse/pattern generator drives the EOM to create a Gaussian 7.5-ns full-width at half-maximum (FWHM) pulse with 133-Hz repetition rate.

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Fig. 1. Experimental setup for hole burning delay measurements.

The modulated probe is split exiting the EOM fiber to a silicon photodiode detector with 2.3-ns response time providing initial intensity reference before the alkali-metal vapor cell. The probe beam is aligned overlapping but counter propagating to the pump beam in the Cs cell enclosed in the heater block. Probe pulse delay is measured after the alkali-metal vapor cell by a silicon photodiode detector with a 1-ns response time.

Pulse delay temporal waveforms of 2000 pulse averages were recorded on a 3-GHz oscilloscope triggered by the pulse generator signal. The cw D_2 pump is set at a fixed power and frequency detuned from an absorption peak. Neutral density filters were placed in the D_2 pump beam path to vary pump power at 0 mW (blocked), 5 mW and 16 mW. The probe laser is scanned across the full D_1 absorption spectrum. For the hole burning experiment the probe laser was scanned with greater sampling near $F'' = 4$ to $F' = 3$ or 4 components as depicted on the Cs energy level diagram in Fig. 2. Simulated absorption coefficients for Cs D_1 and D_2 at 50 °C are shown in Fig. 3. The x-axis is labeled using both nanometer (nm) and detuning frequency $\nu_{\Delta 1}$ and $\nu_{\Delta 2}$ (GHz) scales. The frequencies $\nu_{\Delta 1}$ and $\nu_{Delta 2}$ represent detuning from the central atomic transition frequency $\nu_{D_1} = 335.116049$ THz and $\nu_{D_2} = 351.725718$ THz. The simulation is performed at zero buffer gas pressure and modeled including Doppler broadening. At 50 °C with Doppler width of 393 MHz, the cesium concentration is $\sim 4.6 \times 10^{11}$ atoms/cm³ and the peak D_1 absorption coefficient is quite high, $\alpha \approx 3.5$ cm⁻¹ and the absorbance is $A_\lambda = 17.3$. At 100 °C the cesium concentration increases by a factor of ~ 35 [12].

3. Results

3.1. Optical delay and hyperfine structure

The pulse/pattern generator produced a nearly Gaussian 7.5-ns pulse as shown in Fig. 4. Sample pulses at three D_1 detuning frequencies $\nu_{\Delta 1}$ for the cell at $T = 109.5$ °C are depicted where pulse (1) is farthest

Fig. 2. Energy level diagram depicting the pump D_2 transitions and probe D_1 transitions.

Fig. 3. Simulated absorption coefficients for the (a) D_1 and (b) D_2 transitions at 50 °C. Single hyperfine transition absorption lineshapes are shown in the D_2 spectrum as thin black lines.

from the absorption peak while pulse (3) is closest to the resonant transition frequency. As expected the pulse amplitude decreases for pulses closer to the peak absorption while the pulse width increases due to dispersion broadening. Peak time for each Gaussian fit is recorded as the pulse arrival time. Zero-delay time is determined when the probe is detuned far off resonant frequency and the value is subtracted from the arrival time for each pulse to calculate the pulse delay. Maximum error in delay time measurement is ± 0.15 ns with average error ± 0.03 ns. Within 2 GHz of the resonant transitions the pulse amplitude is entirely attenuated, and relative delay cannot be determined. The observed delays for the $T = 109$ °C cell as a function of probe detuning are illustrated in Fig. 5. Delays of up to 24.1 ns are observed near the two resonant frequencies associated with the ground state hyperfine splitting. However, the absorbance is too high to observe the hyperfine splitting of the upper $^2P_{1/2}$ state. A few “stray” data points are indicated where transmitted pulse intensity is highly attenuated and barely discernible. The present results represent higher frequency sampling with 200 samples over 20 GHz compared to the prior observations for the Cs D_2 line with 90 samples over 20 GHz [7].

Fig. 4. Transmitted pulses at three D_1 detuning frequencies $\nu_{\Delta 1}$ are depicted as gray shapes. Solid black lines show Gaussian fit curves, and the peak of the fit curve is marked for reference. (1) $\nu_{\Delta 1} = 7.44$ GHz, peak at 4.66 ns, width 7.37 ns (2) $\nu_{\Delta 1} = 6.73$ GHz, peak at 12.04 ns, width 8.60 ns and (3) $\nu_{\Delta 1} = 6.5$ GHz, peak at 19.84 ns, width 11.83 ns.

Fig. 5. Pulse delay for full spectrum Cs D_1 scan. Cesium cell maintained at 109.5 °C with no D_2 pump.

A model of the Voigt absorption profile $\alpha(\nu)$ including the full hyperfine splitting and prediction of real index of refraction from the Kramers–Kronig relation

$$n_R = 1 + \frac{c}{2\pi^2} P \int_0^\infty \frac{\alpha(\xi)}{\xi^2 - \nu^2} d\xi \quad (1)$$

has recently been developed and applied to the Cs D_2 line [7,13]. Extending this model to the current D_1 spectra predicts delays of $t_d = l/v_g$ for cell length l where the group velocity is defined as

$$v_g = \frac{c}{n_R + \nu \frac{dn_R}{d\nu}}. \quad (2)$$

The predictions compare favorably with observations in Fig. 5.

Dispersion of the Gaussian pulse width is shown in Fig. 6. As the probe is tuned toward the transition frequency with no pump laser, pulses initially appear to broaden before pulse narrowing is briefly observed. At higher pump intensities, pulse dispersion appears more evident near resonant frequency peaks, however narrowing is not observed before pulse attenuation prevents accurate resolution of the pulse.

The optical thickness is reduced at lower cell temperatures due to the steep Cs vapor pressure curves. By reducing the cell temperatures

Fig. 6. Pulse width in the neighborhood of D_1 absorption peaks at $T=109.5$ °C. Gaussian pulse fit FWHM is shown for 0 mW (no pump) and 5.6 mW across the D_1 spectrum.

to 52.5 °C the spectral dependence of the delay reveals the hyperfine splitting of the excited $^2P_{1/2}$ state. Fig. 7a illustrates the delay spectrum in the vicinity of the $F''=4$ to $F'=3,4$ components. The spectral resolution is only slightly poorer than the Doppler limit, despite the peak absorbance exceeding $A_\lambda=21.1$. This appears to be the first report of optical delay spectra with sufficient resolution to discern the full hyperfine structure in an alkali-metal vapor.

Fig. 7(a) also illustrates the delays predicted from Eqs. (1) and (2) using the experimentally observed absorption coefficients $\alpha(\nu)$ reported in Fig. 8. The absorption spectrum of Fig. 8 was obtained using a lock-in amplifier using a cw probe signal chopped at 190 Hz. The frequency-sampling interval is sufficient for the numerical integration of Eq. (1). Rapid variations in the predicted delay near the absorption peaks are due to minor frequency instability of the laser. The Kramers–Kronig relations unify the absorption and delay spectra with no significant discrepancy.

3.2. Intensity-dependent delay and hole burning

Overall D_1 absorption decreases as D_2 pump laser power increases due to ground state depletion and spectral holes are evident in the D_1 absorption. The absorption spectra for a low-pressure Cs cell at 52.5 °C with a D_2 pump at a fixed frequency $\nu_{\Delta 2} = -3.84$ GHz (852.3566 nm, 11732.1790 cm^{-1}) at 0 mW (no pump), 5.7 mW and 16.4 mW are shown in Fig. 8. At the resonant frequency, the D_1 probe laser is less than 9% of the saturation intensity I_{sat} while D_2 pump intensity is approximately $4 \times I_{sat}$ at 5.6 mW and $12 \times I_{sat}$ at 16.4 mW. The pump and probe spot size diameter are 10 mm and 3 mm respectively. A hole is evident on the low frequency side of the $(F'', F') = (4, 3)$ and $(4, 4)$ components. The pump detuning frequency $\nu_{\Delta 2} = -3.84$ GHz is on the high side of the $F''=4 \rightarrow F'=3, 4$ components of the D_2 line (see

Fig. 7. Observed and predicted delay for Cs at 52.5 °C for $\nu_{\Delta 2} = -3.84$ GHz at three D_2 pump powers of (a) 0 mW (no pump), (b) 5.7 mW and (c) 16.4 mW. Predicted delay at each power is calculated using the observed absorption spectra and the Kramers–Kronig relations model.

Fig. 8. Absorption coefficients for Cs D_1 with Cs D_2 pump at $\nu_{\Delta 2} = -3.84$ GHz (852.3566 nm, 11732.1790 cm^{-1}) for various pump powers at $T = 52.5$ °C.

Fig. 3). The pump blue shift of 170 MHz for the $F'' = 4 \rightarrow F' = 4$ transition matches the counter-propagating red shift of the probe beam and corresponds to a velocity group centered at approximately $v = 145$ m/s.

Observed and predicted delays for Cs at 52.5 °C $\nu_{\Delta 2} = -3.84$ GHz at three D_2 pump powers are shown in Fig. 7. In the presence of holes burnt in the D_1 absorption spectra, predicted delay is calculated from the observed absorption spectra using the Kramers–Kronig model of Eq. (1) to calculate group velocity and pulse delay. The maximum delay near resonance is reduced by as much as 78% in the presence of the high power pumpbeam and may produce a rapidly tunable optical delay mechanism.

The hole burning is further explored in Figs. 9 and 10. The transmittance of the probe near the D_1 $F'' = 4 \rightarrow F' = 3, 4$ components for a Cs cell at 52.5 °C is provided for the D_2 pump at 16.4 mW and tuned to $\nu_{\Delta 2} = -3.86$ GHz in Fig. 9. A reference spectrum with the pump beam blocked is also provided to better illustrate the location of the holes. The difference in the two spectra is interpreted as the sum of six Lorentzian lines associated with the three $F' = 3, 4, 5$ components of the D_2 transition. The Lorentzian lineshapes used in the differencing exhibit line center differences of 192 MHz and 285 MHz, which compares well with the hyperfine splittings of 201 MHz and 251 MHz shown in Fig. 2. The common Lorentzian width (FWHM) of 110 MHz is 21 times the

Fig. 9. Spectral hole observed in the transmittance with the D_2 pump laser at $\nu_{\Delta 2} = -3.86$ GHz for 16.4 mW and 52.5 °C while the D_1 probe was scanned across the absorption spectrum. A no-pump reference spectrum (dashed lines) is added to visualize the spectral holes. The difference in the absorption spectra is shown as a summation of Lorentzian line shapes (solid lines).

Fig. 10. Pulse delay illustrating the spectral hole effects. Observed delay is shown with predicted delay from a simulated absorption spectrum (solid lines).

natural linewidth of 5.32 MHz. Saturation broadening predicts a homogeneous linewidth at low pressure of

$$\Delta\nu_{\text{sat}} = \Delta\nu_{\text{nat}}(1 + I/I_{\text{sat}})^{1/2} \quad (3)$$

which is considerably less, $\Delta\nu_{\text{sat}} \approx 14$ MHz. The natural broadening limit is often not achieved in sub-Doppler saturation spectroscopy due to beam divergence and misalignment.

The simulated absorption curve may be used to predict the frequency dependence of the hole-burned spectra using Eqs. (1) and (2). The simulated and observed delays are compared in Fig. 10. In the neighborhood of the spectral hole, the delay changes rapidly across a narrow frequency range. Indeed, the observed delay is modulated by a factor of 2.8 in an interval of 50 MHz in the deepest hole. The observed delay in the region of the hole qualitatively matches the Kramers–Kronig prediction. A more precise prediction would require a complete analysis of the sub-Doppler lineshapes from saturation spectroscopy.

4. Conclusion

The frequency dependence of the optical pulse delay in cesium D_1 closely matches the previously developed model predictions using Voigt lineshapes and the full hyperfine structure. Delays up to 24 ns were achieved by detuning from resonance by 10 GHz. At lower cell temperature the hyperfine splitting of the excited $^2P_{1/2}$ is resolved in the pulse delay spectra.

Tunable optical delays were demonstrated with a Cs D_1 pulse by varying D_2 pump laser power. Increasing D_2 pump power reduced D_1 absorption overall. Observation of hole burning effects on delay close to the spectral hole was noted. Location of the holes and predicted delay from a modified absorption spectrum matched model predictions. For a pump intensity of four times saturation intensity I_{sat} observed delay is reduced by an average of 50% across the spectrum and reaches a maximum of 78% in a narrow 110 MHz spectral hole region.

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