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Optical Ramsey fringes observed during temporal evolution of Zeeman coherences in Rb buffer gas cell

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Abstract

We experimentally studied the temporal evolution of Zeeman electromagnetically induced transparency (EIT) resonances induced by the laser resonant to hyperfine transition $F_g = 2 \rightarrow F_e = 1$ of ^{87}Rb in a rubidium buffer gas cell. We simultaneously modulated the laser beam intensity and polarization to achieve the repeated interaction of the laser beam with coherently prepared atoms. Our cell was placed in a homogenous magnetic field to obtain the Larmor precession of the phase of coherences. The weak laser beam was used to probe the atoms at the end of the Ramsey sequence. We measured the transparency of the probe pulse at different magnetic fields for a given excitation pulse and the period of free evolution of Zeeman coherences in the dark. From these data, we reconstructed the temporal evolution of EIT resonances. The Ramsey fringes that appeared on the EIT curves at the beginning of the second probing pulse disappeared at later moments due to various decay processes.

Keywords: electromagnetically induced transparency (EIT), Zeeman coherences, slow light, storage of light, Ramsey fringes

(Some figures may appear in colour only in the online journal)

1. Introduction

Electromagnetically induced transparency (EIT) is a phenomenon characterized by a narrow transparency resonance of a laser field through coherent media, such as alkali atomic vapor [1]. This effect is of special interest because it allows for fine control of pulse propagation. EIT-based slow and stored light observations [2] may benefit telecommunications and quantum memories.

EIT resonance in Hanle configuration is based on Zeeman coherences between magnetic sublevels of a given hyperfine state of an alkali atom electronic ground state. When such an atom is exposed to the external magnetic field, its magnetic dipole moment rotates around the field direction with a Larmor frequency. This allows the possibility for a Ramsey method of separated oscillatory fields [3]. For instance, in the interaction of an atom with a first light field, coherence between atomic levels is created. Under the influence of the magnetic field, the phase of the rotation of the magnetic dipole moment defines the coherence phase. The second light field, which can be either spatially or temporally separated from the first field, probes the coherence [4]. The result is an interferometric picture with Ramsey fringes in the probe transparency signal, due to the phase differences between the coherence and the probe field.

Ramsey-like measurements of Zeeman decoherence that determine the dumping rate of the oscillations are presented in [5]. The effects of Ramsey narrowing of EIT resonances due to atomic diffusion in and out from the interaction region were discussed in [6, 7]. High contrast Ramsey fringes in a double Λ atomic scheme were obtained in [8]. Raman–Ramsey fringes are also shown in vacuum Rb cells using time-delayed optical pulses [9] and a probe beam that was spatially enclosed by the pump beam [10].

In this work, we present the experimental study of the temporal evolution of the Zeeman EIT resonances based on repeated interaction of coherently prepared atoms with the laser beam. The obtained transparency of the σ^- probe at

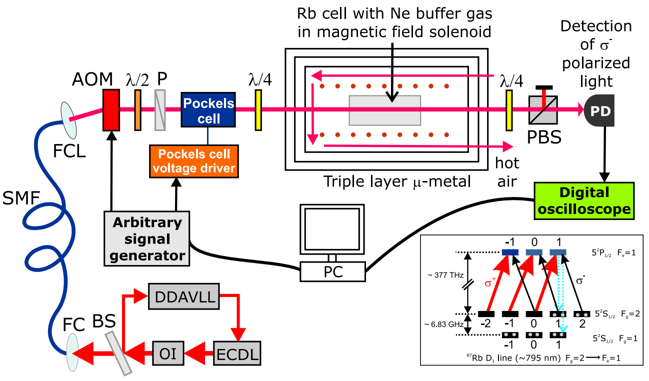

Figure 1. Experimental setup and atomic transition [15] used in the experiment. ECDL—external cavity diode laser; OI—optical insulator; DDAVLL—Doppler-free dichroic atomic vapor laser lock; BS—beam splitter; FC—fiber coupler; SMF—single-mode fiber; FCL—fiber collimator; AOM—acousto-optic modulator; P—polarizer; PBS—polarizing beam splitter; PD—photodetector. Hot air is used to heat the cell.

different magnetic fields was used to reconstruct the EIT resonances at different moments from the beginning of the probe pulse. The studies of dark states temporal behavior [11] and transient effects of EIT phenomenon [12–14] have been previously shown. In our work, the evolutions of (i) damped Ramsey fringes on the probe transparency and (ii) reconstructed EIT resonances during the probe propagation allowed for unique observation of the development and decay of Zeeman coherences.

2. Experimental setup

The experimental setup is shown in figure 1. The external cavity diode laser is frequency locked to the hyperfine $F_g = 2 \rightarrow F_e = 1$ transition of the D_1 line in ^{87}Rb in vacuum cell using the Doppler-free dichroic atomic vapor laser lock (DDAVLL) method [16, 17]. Gaussian distribution of radial laser intensity is obtained using the single-mode optical fiber. To achieve the repeated interaction of the laser light with Rb atoms, the power of the acousto-optical modulator (AOM) first-order diffracted beam is modulated and transmitted through the cell. The linear polarization of the laser light is assured by the high-quality linear polarizer. The Pockels cell and the $\lambda/4$ plate are used to modulate the polarization of the laser beam, so that pure σ^+ circular polarization is obtained when no voltage is applied to the cell and some percent of the σ^- light is produced otherwise. The arbitrary signal generator is programmed by the computer, whereas its two synchronized outputs control the AOM and the Pockels cell. The Rb cell containing 30 Torr of Ne buffer gas is 8 cm long and 25 mm in diameter. The difference between the $F_g = 2 \rightarrow F_e = 1$ transition frequencies in a vacuum and our buffer gas cell is approximately −20 MHz [18], which in total gives one photon detuning of −90 MHz in the experiment, due to −110 MHz AOM frequency shift in the first diffraction maximum. The Rb cell was heated using hot air circulating around the cell. The Rb vapor is shielded from external magnetic fields by the triple μ-metal layers, which reduce stray magnetic fields below 10 nT. To obey two-photon detuning, a long solenoid placed around the Rb cell produces a controllable longitudinal magnetic field in the range of ± 40 μT. The estimated magnetic field error is on the order of 10 nT. The transmitted σ^- laser light is extracted with $\lambda/4$ plate and polarizing beam splitter (PBS). The σ^- laser intensity as a function of applied magnetic field is measured by the photodetector and recorded by the storage oscilloscope. The intensities of polarization pulses were 4.9 and 0.95 mW cm^{-2} and the cell temperature was set to 67 ° C.

The signals applied to the AOM and the Pockels cell are shown in figure 2(a). We first generate a 400 μs pulse, in which 15% of the optical power is carried by σ^- polarized photons. Two coherent light fields (strong σ^+ and weak σ^-) pump the Rb atoms into the nonabsorbing dark state. After completion, the voltage on the Pockels cell is set back to zero and the AOM is synchronously turned off for 60 μs. During this dark interval, Zeeman coherence makes a Larmor precession in the external magnetic field. After this dark interval, the Pockels cell again generates the same elliptically polarized pulse and the AOM is turned back on to produce five times weaker light. This second pulse, with 400 μs duration, probes the previously created Zeeman coherences. Finally, we return the full beam power and set circular σ^+ polarization during 5 ms to reset atoms back in the ground state before the next pulse train. In this way, we produced Ramsey-like measurements with two temporally separated polarization pulses.

3. Results and discussions

The σ^- transparency signals measured for three different values of the external magnetic field are shown in figure 2(b). As expected, in the case of zero magnetic field, we see no Ramsey fringes in the transparency curve. We measured the linear dependence of fringes' frequency on the applied magnetic field with a slope close to magnetic sublevels energy splitting factor of ^{87}Rb hyperfine state $5^2S_{1/2}$ $F_g = 2$ (not shown). Due to decoherence processes, the oscillations are dumped.

The noise in figure 2(b) comes from the low transparency of the σ^- signal and the photo detector's electronic noise. The measured value of signal to noise ratio is 12 dB in the 21 MHz bandwidth of the entire data acquisition system. From these data, we were able to reconstruct the EIT resonances at different times during the probe pulse propagation. First, we set $t = 0$ at the beginning of the second polarization pulse. Next, we take the values of the σ^- transparency at a particular time instant t for all magnetic field values and plot this data set using the B-spline routine. EIT resonances obtained this way, as shown in figure 3(a), show clean oscillations because the reconstruction process takes one transparency value at a time and therefore eliminates the noise itself. However, because of measurement uncertainty, these oscillations are not perfect, i.e., fringes of the same order have slightly different amplitudes. The reconstructed EIT resonances are shown in figure 3 for the Rb density of ~ 4.5·10^{11}

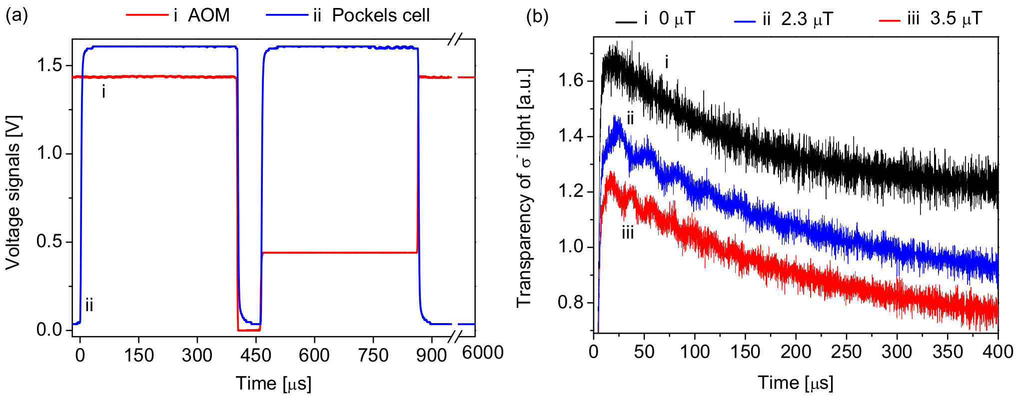

Figure 2. (a) The signals used in the experiment: AOM (i) and Pockels cell (ii). (b) Transparency of the σ^- light measured during the second probing pulse for various magnetic fields: 0 μT (i), 2.3 μT (ii), and 3.5 μT (iii).

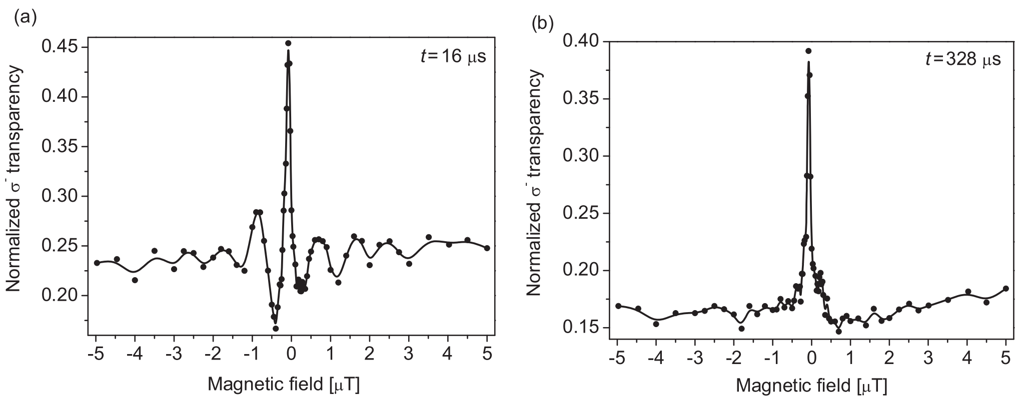

Figure 3. Reconstructed Zeeman EIT resonances from the σ^- transparency signal at different time moments t from the beginning of the second polarization pulse: (a) $t = 16\ \mu$s and (b) $t = 328\ \mu$s.

cm^{-3} and the laser beam diameter of 1.3 mm. Ramsey fringes were observed at EIT resonances for $t \lesssim 196\ \mu$s and vanish at later moments due to the finite lifetime of Zeeman coherence. The decay rate of Zeeman coherences γ_2 was obtained by fitting the σ^- transparency signal (ii) from figure 2(b) to function $y = A_1 e^{-\gamma_1 t} + A_2 e^{-\gamma_2 t} \sin(\omega t + \varphi_0)$ (not shown). The measured γ_2 value is on the order of $\sim 9000\ \mathrm{s}^{-1}$. In figure 3(a), an EIT resonance with oscillation pattern at $t = 16\ \mu$s is shown. In figure 3(b), an EIT curve at $t = 328\ \mu$s with no fringes is presented.

4. Conclusion

We experimentally studied the Zeeman coherence using Ramsey fringes obtained at the transparency signal of the probe σ^- laser field in the presence of the external magnetic field. Temporal evolution of Zeeman EIT resonances in Rb buffer gas cell were also presented. The first polarization pulse containing weak σ^- and strong σ^+ fields was used to create Zeeman coherences in Rb atoms. The subsequent weaker probe pulse with the same polarization state was produced to probe these coherences. The laser beam was completely turned off between the pulses to enable free evolution of the dark state in the magnetic field. The oscillatory pattern on the reconstructed EIT curves obtained soon after the second pulse generation disappeared at later times because of the various decoherence processes.

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