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Effects of laser beam diameter on electromagnetically induced transparency due to Zeeman coherences in Rb vapor

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Abstract
We experimentally studied the effects of laser beam diameter on electromagnetically induced transparency (EIT) due to Zeeman coherences induced by a laser resonant with the hyperfine transition $F_g = 2 \rightarrow F_e = 1$ of ^{87}Rb in a rubidium buffer gas cell. We use two laser beams of Gaussian intensity radial profile for laser beam diameters of 6.5 and 1.3 mm, laser intensities in the range of 0.1–35 mW cm^{-2} and cell temperatures between 60 and 82 °C. The results show that the amplitude of the normalized EIT resonance has a maximum at a laser intensity which depends on laser beam diameter and cell temperature. The laser intensity corresponding to the maximum EIT amplitude is higher for a smaller laser beam and higher cell temperature. The linewidth of Zeeman EIT resonance varies nearly linearly with laser intensity, almost independent of cell temperature and laser beam diameter.

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

1. Introduction

Electromagnetically induced transparency (EIT) is a coherence phenomenon characterized by narrow transmission resonance of a laser beam through alkali atom vapor [1]. It is essential for fields such as slow and stored light [2], lasing without inversion [3], frequency mixing [4], etc. Important devices such as atomic frequency standards [5] and magnetometers [6] are based on EIT. The optimization of all these processes and devices is therefore directly conditioned on achieving better EIT properties.

The average time-of-flight of an atom through the laser beam limits the EIT amplitudes and linewidths. In order to prolong interaction time and thus the dark states lifetime, an inert buffer gas is added to atomic vapor to slow down the diffusion of the coherently prepared atoms through the laser beam. The linewidth, governed by the ground state relaxation and laser power, is reduced by several orders of magnitude due to the Dicke effect [7]. Linewidths as narrow as 30 Hz are obtained [8].

Hyperfine EIT resonance is formed as a coherent superposition of two ground hyperfine levels while EIT resonance in the Hanle configuration is based on Zeeman coherences between magnetic sublevels of a given hyperfine state of the alkali atom electronic ground state. Cell temperature affects differently hyperfine coherences than Zeeman coherences. For the former, it is found that linewidths vary inversely with density [9, 10]. The linewidth is a linear function of laser intensity and the slope of the linear curve decreases as the cell temperature increases. At lower temperatures than in [9, 10], in the range 30–60 °C, linewidth can be independent on cell temperature, as shown in [11]. On the other hand, EIT resonances due to Zeeman coherence are nearly independent of cell temperature [10]. In addition, the behavior of EIT as a function of laser beam diameter [12], optical depth [13], laser intensity [14, 15] and laser beam profile [16, 17] was investigated.

In this paper, we analyze the properties of Zeeman EIT resonances under different parameters in order to obtain optimum EIT contrast and linewidths, which is essential

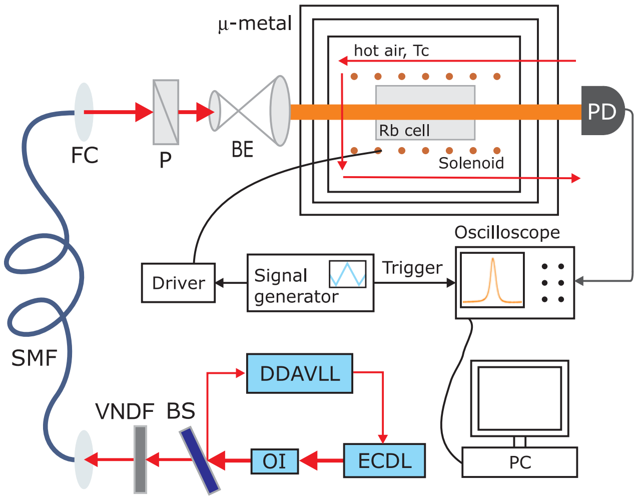

Figure 1. Experimental setup: ECDL—external cavity diode laser; OI—optical insulator; DDAVLL—Doppler-free dichroic atomic vapor laser lock; BS—beam splitter; VNDF—variable neutral density filter; SMF—single-mode fiber; FC—fiber coupler; P—polarizer; BE—beam expander; PD—large-area photodiode. Hot air is used for heating the cell.

for application of Zeeman coherences, like efficient slowing down of light pulses in the cell [18] as well as their storage. Zeeman coherences were induced by the laser locked to the $F_g = 2 \rightarrow F_e = 1$ transition in ^{87}Rb, contained in the cell with 30 Torr of Ne. We analyze EIT for two laser beam diameters and a wide range of laser intensity and cell temperature. Unlike the hyperfine EIT, there are no detailed studies on the behavior of Zeeman EIT when the main experimental parameters vary.

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 by using the Doppler-free dichroic atomic vapor laser lock method [19, 20]. Gaussian distribution of laser intensity radial dependence is achieved by the single-mode optical fiber. For adjusting the laser beam diameter, a beam expander is used. The linear polarization of laser light is ensured by a high-quality polarizer. Laser beam intensity is controlled by the variable neutral density filter. A Rb cell with 30 Torr of Ne as the buffer gas is 8 cm long and 25 mm in diameter. The Rb vapor is shielded from external magnetic fields by the triple layer of μ-metal which reduces stray magnetic fields below 10 nT. In order to obey two-photon detuning in the Hanle experiment, a long solenoid placed around the Rb cell produces a controllable longitudinal magnetic field in the range of $\pm 20\,\mu$T. The intensity of transmitted laser light as a function of applied magnetic field was monitored by the photodiode and recorded by the storage oscilloscope. The Rb cell was heated up to a certain temperature by using circulating hot air around the cell. The advantage of this system in comparison with electrical heating is avoiding the stray magnetic field inside the μ-metal that is inevitably introduced by heating current.

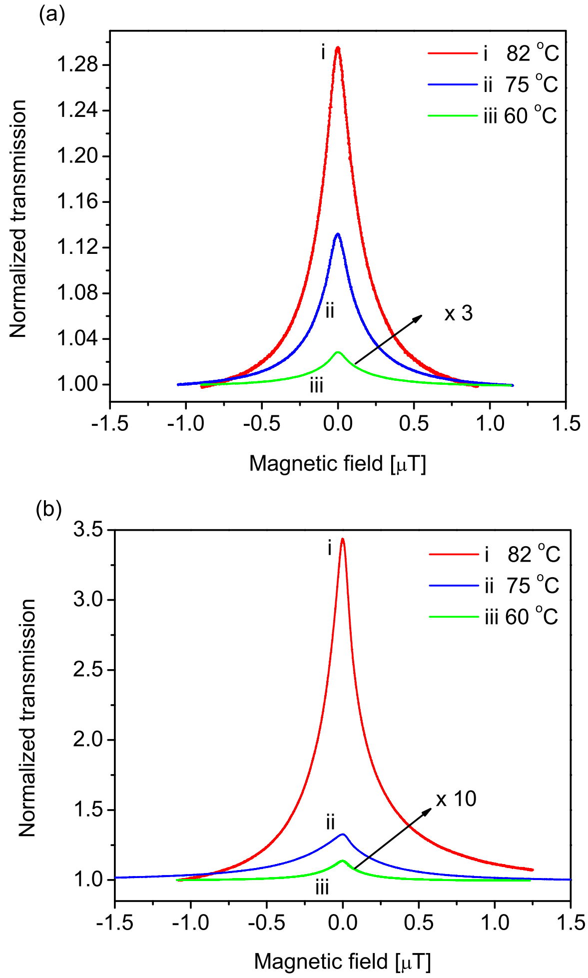

Figure 2. Measured EIT resonances for Gaussian laser beams of diameter (a) $D = 6.5$ mm and (b) $D = 1.3$ mm. Resonances are measured for an overall laser beam intensity of 3.3 mW cm^{-2} at temperatures of 60, 75 and 82 °C.

3. Results and discussions

We present measured EIT resonances in the Hanle configuration obtained with laser beams of Gaussian radial intensity profile for cell temperatures of 60, 75 and 82 °C and laser beam diameters of 1.3 and 6.5 mm. The intensity range covered in the experiment was 0.1–10 mW cm^{-2} for wide and 0.1–35 mW cm^{-2} for narrow laser beams. EIT resonances presented in this paper are obtained after normalizing measured resonances to the transmission signal away from Raman resonance. Examples of experimentally obtained EIT resonances for wide and narrow Gaussian laser beams at three temperatures are given in figure 2.

As can be seen in figure 2, the amplitudes of Zeeman EIT increase with cell temperature, and this effect is particularly strong for narrower laser beams.

The EIT amplitude dependence on overall laser beam intensity measured at different temperatures, for wide and narrow laser beams, is shown in figures 3(a) and (b), respectively. As can be seen, the highest cell temperature with the smaller laser beam diameter gives the strongest EIT resonances. Higher temperatures mean larger atomic density and number of atoms coherently prepared in the dark state. As the laser beam diameter gets smaller, the contribution of wings

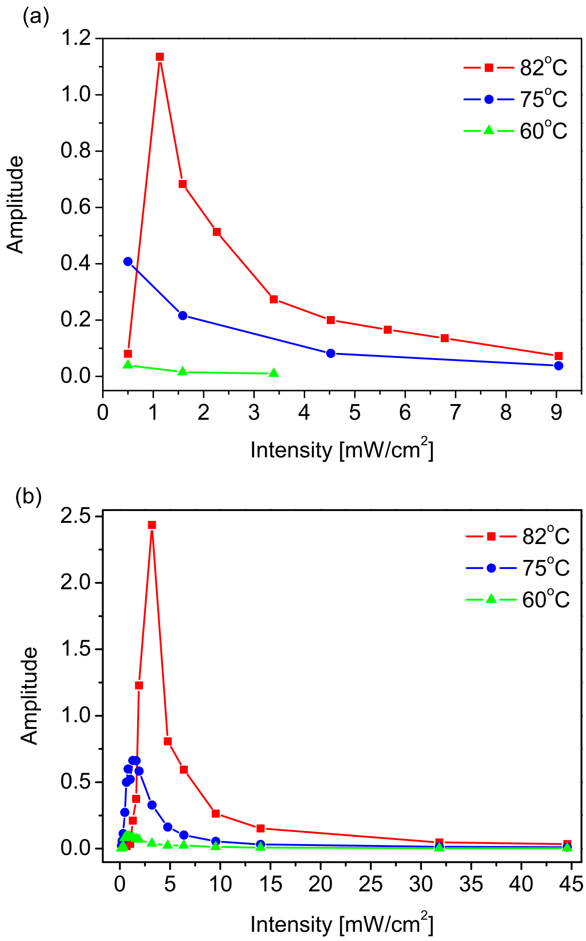

Figure 3. Experimental dependences of EIT amplitudes on overall light intensity for Gaussian laser beams of diameter (a) 6.5 mm and (b) 1.3 mm at temperatures of 60, 75 and 82 °C.

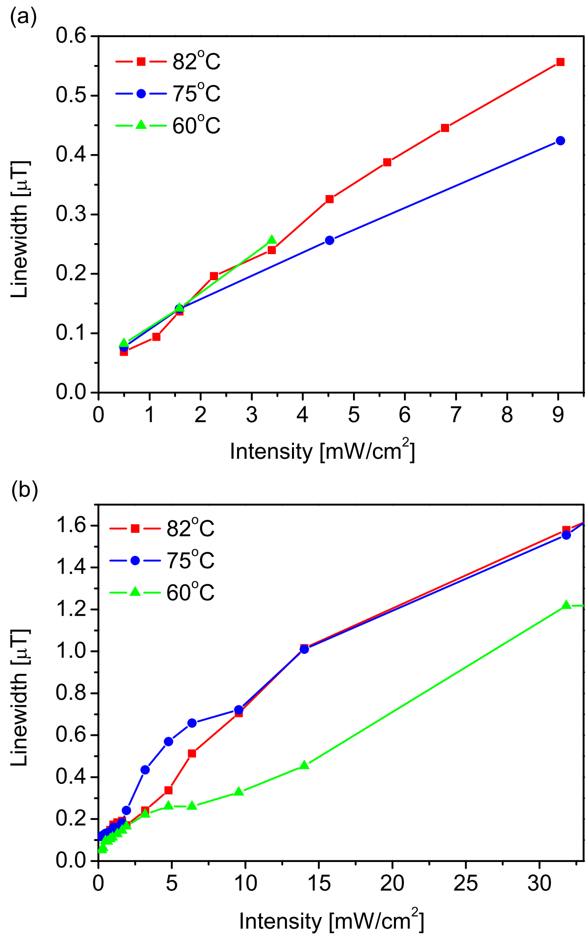

Figure 4. Experimental dependences of EIT linewidth on overall laser beam intensity for Gaussian laser beams of diameter (a) 6.5 mm and (b) 1.3 mm at three different temperatures.

of the Gaussian laser beam to two-photon type resonance like EIT is enhanced.

In figure 4 the EIT linewidth as a function of laser intensity at three different cell temperatures is shown for two Gaussian laser beam diameters. The dependence of EIT linewidths on laser intensity, for either wide or narrower laser beams, is apparently independent of cell temperature. Such behavior of Zeeman EIT with cell temperature is shown in the pump–probe laser configuration in [10]. Ultra narrow Zeeman EIT resonances with linewidths below 100 nT were achieved because of careful elimination of stray magnetic fields inside the triple antimagnetic shielding surrounding the Rb buffer gas cell.

4. Summary

We carried out an experimental study of the behavior of EIT resonances due to Zeeman coherences among sublevels of the ^{87}Rb hyperfine state $F_g = 2$ in a Rb buffer gas cell of 8 cm length, 25 mm diameter and 30 Torr of Ne buffer gas. The dependence of EIT on laser beam diameter (6.5 and 1.3 mm), laser intensity (0.1–35 mW cm^{-2}) and Rb cell temperature (60–82 °C) reveals that the highest contrast and amplitude to linewidth ratios are obtained with the narrower laser beam at about 5 mW cm^{-2}.

Acknowledgments

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