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Sub-Doppler and sub-natural narrowing of an absorption line

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Abstract

We experimentally demonstrate the double dark resonance windows characteristic of a four level tripod system such as the D_2 line of ^{87}Rb where the $F_g = 1$, $m_g = -1, 0, 1$ Zeeman sublevels form the bottom three levels and the $F_e = 0$ state is the upper level. Between the double dark resonance windows, a very narrow absorption resonance is observed whose line-width is shown to be sub-Doppler and sub-natural. The sharp absorptive resonance is characterized as a function of applied magnetic field and pump laser power.

Keywords: Atomic coherence; Optical pumping; Level crossing

1. Introduction

The phenomenon of "electromagnetically induced transparency" (EIT) has been extensively explored since its first observation in 1991 [1]. In addition to being an interesting quantum interference phenomenon, EIT has also become an important and efficient tool in various applications such as the slowing and storage of light via quantum coherence [2], quantum information processing [3], lasing without inversion [4], magnetometry [5] and EIT based atomic clocks [6].

The probe absorption spectrum of a four level tripod system, formed when a moderately intense σ polarized pump and a tunable π polarized probe laser interact with an $F_g = 1 \rightarrow F_e = 0$ transition (see Fig. 1), in the presence of a weak transverse magnetic field, is characterized by two electromagnetically induced transparency (EIT) windows which are separated by a sharp absorption peak [7,8]. The tripod system has been discussed in the context of the reduced group velocity experienced by a probe when it is tuned to one of the EIT windows [8], storage and release of the probe pulse [9], magneto-optical rotation with negligible absorption [10], all-optical switching and optical bistability in a ring resonator [11], the production of a phase gate due to the large Kerr cross-phase modulation between the pump and probe fields [12] and controllable atomic localization [13]. In this paper we report on the experimental observation of the double dark resonances characteristic of the tripod system and compare our observations to theoretical predictions. The paper is organized as follows. In Section 2, we review the essential results of the theoretical work relevant to the atomic system we study. In Section 3 we describe the experimental setup, and in Section 4, we present the experimental results and their interpretation and compare them with the theoretical predictions.

2. Theory

Recently, we studied [7] the probe absorption spectrum in the tripod system in the absence and presence of Doppler broadening (see Fig. 2). In particular, we are interested in a configuration in which the pump and probe lasers co-propagate perpendicular to an applied magnetic field and the pump laser is σ polarized while the tunable probe laser is π polarized. The probe absorption is proportional to the imaginary part of the off-diagonal density matrix element,

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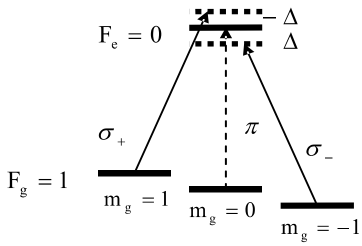

Fig. 1. $F_g = 1 \rightarrow F_e = 0$ transition when the degeneracy is lifted by a magnetic field whose direction is perpendicular to the optical propagation axis. The polarizations of the pump beam (solid line) is σ and the probe beam (dashed line) is π and they are perpendicular to each other and to the optic axis.

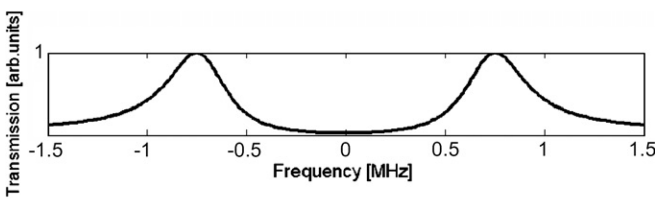

Fig. 2. Theoretical probe transmission versus probe detuning, δ, for the ^{87}Rb energy level system shown in Fig. 1. The pump and probe are σ and π polarized, respectively, with pump power of 747 μW, a weak probe field and magnetic field 1×10^{-4} T. The spectrum shows two EIT windows.

ρ_{eg_2}, where e refers to the excited hyperfine state $F_e = 0$, $m_e = 0$, and g_i with $i = 1, 2, 3$ refers to the ground Zeeman levels $F_g = 1$, $m_g = -1, 0, 1$, respectively. For a weak probe beam, we can write [7] the steady-state solution as

$$\rho_{eg_2} = \frac{V_2(\rho^0_{g_2g_2} - \rho^0_{ee}) + VV_2\left[\frac{\rho^0_{g_1e}}{\Delta_1-\Delta_2+i\gamma_{gg}} + \frac{\rho^0_{g_3e}}{\Delta_3-\Delta_2+i\gamma_{gg}}\right]}{(\Delta_2 - i\gamma_{eg}) + \frac{V^2}{\Delta_1-\Delta_2+i\gamma_{gg}} + \frac{V^2}{\Delta_3-\Delta_2+i\gamma_{gg}}} \quad (1)$$

where $\rho^0_{g_2g_2}$ and ρ^0_{ee} are the populations of the ground and excited $m = 0$ Zeeman sublevels, and $\rho^0_{g_1e}$ and $\rho^0_{g_3e}$ are the optical coherences when only the pump is present. The rates of decay of the optical and Zeeman coherences are γ_{eg} and γ_{gg}, respectively. The detunings of the $\sigma_\pm$ pumps are $\Delta_{1,3}$, and the detuning of the π polarized probe is Δ_2, where $\Delta_{1-3} = \omega_{eg_i} - \omega_i$. For the case where both pumps derive from the same σ polarized field, $\omega_1 = \omega_3$ and the Rabi frequencies $2V_1 = 2V_3 = 2V$. When the ground state degeneracy is lifted by a weak magnetic field of strength B, $\Delta_3 = -\Delta_1 = \Delta = g_F\mu_B B$ [7,14].

It can be seen from Eq. (1) that the probe absorption spectrum which is proportional to $Im\rho_{eg_2}$, is determined by the relative values of the two terms in the numerator. When the pump is too weak ($V/\gamma_{eg} < 1$) to optically pump all the population into the $m_g = 0$ level, both terms in the numerator contribute. It has been shown elsewhere [15] that, in this regime, the spectrum is characterized by two sharp stimulated emission peaks at the Raman resonances, separated by an absorption peak at line center. However, these features are very sensitive to collisions and Doppler broadening. At the opposite extreme, $V/\gamma_{eg} > 1$, we showed [7] that the $m = \pm 1$ levels are populated due to coherent population trapping (CPT) and that the spectrum is characterized by two EIT windows, separated by a very sharp absorption peak, whose height decreases with increasing pump Rabi frequency. As the pump Rabi frequency is increased further, the EIT windows move closer to line center until they coalesce to form a single EIT window. At even higher values of V/γ_{eg}, a sharp stimulated emission peak appears at the center of the EIT window.

At the moderate values of V/γ_{eg} investigated in this paper, all the population is pumped into the $m_g = 0$ state and the second term in the numerator is negligible. Then, we see from the denominator that the probe absorption has minima at $\Delta_2 = \pm\Delta$ (EIT windows), and maxima at exact line center, $\Delta_2 = 0$, and at $\Delta_2 = \pm(2V + \Delta^2)^{1/2}$ (Autler–Townes peaks). The positions of the EIT windows and central absorption peak are independent of the pump Rabi frequency, whereas the width of the EIT windows increases with increasing pump intensity. Because of such an increase in the EIT window width, increasing the pump intensity leads to a narrowing of the central absorption peak. Increasing the magnetic field, on the other hand, increases the distance between the EIT windows, which effectively broadens the width of the central absorption peak. The calculations performed included Doppler broadening and other relaxation mechanisms and perturbations contributing to the effect, but the inclusion of these broadening mechanisms did not affect the essential features predicted by Eq. (1): two EIT windows separated by a narrow absorption peak.

For moderate values of V/γ_{eg}, the tripod system has a number of features that are different from the features found in other four level systems [7,8] that exhibit similar spectra when the atoms are cold. For the tripod, the positions of the EIT windows and the central absorption peak do not change on Doppler broadening, so that the tripod system has an advantage when used as a magnetometer for small magnetic fields. Typical calculated probe absorption spectra are shown in Fig. 2, demonstrating that the central peak is narrowed on increasing the pump Rabi frequency. The width of this central peak is both sub-natural and sub-Doppler. In this paper, we confirm these theoretical results experimentally.

3. Experimental setup

In the experiment we probe the $F_g = 1 \rightarrow F_e = 0$ transition of ^{87}Rb (D_2 line), as shown in Fig. 1, with the pump and probe lasers both operating near the 780.241 nm resonance line. The pump beam is σ polarized, while the probe beam is π polarized and the degeneracy of the $F_g = 1$ ground state is lifted by a small magnetic field which has no first order effect on the $F_e = 0$ excited state.

The experimental setup is shown in Fig. 3. A single mode, linearly polarized, external cavity diode laser, was locked to the transmission resonance of a thermally stable Fabry–Perot interferometer. The absolute frequency position of the lock point was calibrated by Doppler free satu-