



Magnetically assisted optical gain in Zeeman degenerate two-level systems of cold atoms

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ABSTRACT

We report on the observation of magnetically assisted narrow band probe beam amplification in Zeeman degenerate closed two-level system associated with cold cesium atoms. In the experiment the closed cesium D_2 hyperfine transition $F_g = 3 \rightarrow F_e = 2$ is coherently excited by a probe and an orthogonally polarized coupling beam in the presence of a transverse dc magnetic field. Single pass gain of 80% is observed for moderate values of the magnetic field and coupling beam power. The gain mechanism can be understood in terms of population transfer between the different Zeeman ground-state levels induced by the external magnetic field. We have developed a simple theoretical model using a simpler atomic transition $F_g = 1 \rightarrow F_e = 0$, which accounts reasonably for the main experimentally observed results.

1. Introduction

Quantum interference is associated with many intriguing phenomena observed with coherently prepared atomic systems and has been investigated now for more than four decades [1,2]. Phenomena such as electromagnetically induced transparency (EIT), coherent population trapping (CPT) and laser without inversion (LWI) are well known examples where quantum interference play a fundamental role in modifying the optical properties of an atomic system [3,4]. Usually, these phenomena are observed in three-level Λ , V or Ξ atomic systems driven simultaneously by a strong coupling field and weak probe field. On the other hand, a degenerate two-level system (DTLS) associated with hyperfine transitions of alkaline atoms can provide different configurations of three-level system depending on the relative polarizations of the coupling and probe fields and the coherent optical spectroscopy of DTLS has shown other unexpected phenomena such as the observation of Raman absorption and gain in laser cooled atoms as well as the resonant increase in the absorption of the medium, an effect coined as electromagnetically induced absorption (EIA) [5–7]. As it is well known, the spectroscopic behavior of a DTLS is strongly dependent on the relative values of the angular momentum associated with the ground (F_g) and excited (F_e) levels. For instance, for the case where $F_g = F_e + 1$ the system is pumped into dark states and usually one observes the EIT or CPT effects. However, for the case $F_g = F_e - 1$ ($F_g \geq 1$) the system can present either the EIA effect or Raman amplification and absorption of the probe beam, which are associated with Raman transition between differently populated Zeeman sublevels [8].

In the present work we revisit the topic of optical gain observation in coherently driven atomic systems [9,10]. In the context of LWI,

previous works have demonstrated that a Λ three-level system can present gain and lasing in the presence of incoherent pumping [11–13] and gain without population inversion in the atomic bare states induced by coherent pumping or ground state collisions in a Doppler broadened system [14–16] were also reported. More recently, our group has also observed gain in the DTLS associated with the D_2 hyperfine transition $F_g = 3 \rightarrow F_e = 2$ of cold cesium atoms induced by an optical pumping mechanism and used this gain to obtain the amplification of light carrying orbital angular momentum [17]. Transient gain without population inversion was also investigated theoretically in a three-level system interacting with an oscillating coherent magnetic field [18]. Although previous theoretical work have investigated the effect of an arbitrary dc magnetic field on the two-field spectroscopy of DTLS, within their approximations, no gain was predicted in the corresponding spectrum [19,20]. In the present work we demonstrate experimentally that a DTLS associated with the cesium $6S_{1/2}, F_g = 3 \rightarrow 6P_{3/2}, F_e = 2$ hyperfine transition, interacting with a coupling and a probe beam having opposite circular polarizations can present gain when a transverse magnetic field is applied to the system. Moreover, we developed a simple theoretical model considering a $F_g = 1 \rightarrow F_e = 0$ transition, in the limit of weak magnetic field, that predicts the existence of the observed gain. Moreover, the model also predicts gain in the probe transition even in the absence of population inversion both between the excited and ground state levels as well as between the ground state levels, therefore eliminating also the possibility of Raman gain and offering a new mechanism to obtain LWI. Thus, we have demonstrated a new scheme to obtain optical gain, which is based on magnetically assisted optical pumping in DTLS.

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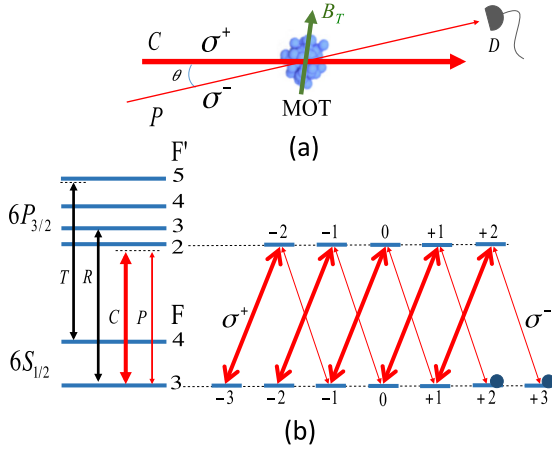


Fig. 1. (Color online) (a) Simplified experimental scheme, showing the coupling and the probe beam interacting with cold atoms in the presence of a *dc* transverse magnetic field B_T . The applied magnetic field is perpendicular to plane defined by the coupling and probe beams. (b) Hyperfine levels of cesium D_2 line, showing the hyperfine transitions interacting with the trapping (T) and repumping (R) beams of the MOT, and the coupling (C) and probe (P) beams having orthogonal circular polarizations interacting with the manifold of transitions between Zeeman sublevels.

2. Experimental setup and results

The simplified experimental scheme is shown in Fig. 1(a) and uses cold cesium atoms obtained from a magneto-optical trap (MOT). In Fig. 1(b) we also show the hyperfine levels of cesium D_2 line. The atoms are initially prepared in the lower hyperfine ground state $6S_{1/2}$, $F_g = 3$ by switching the MOT repumping beam about 1 ms before the switching off of the trapping beams and the MOT quadrupole magnetic field. The optical density of atoms in the lower ground state can be varied in the range 1–3 and the typical trap size is about 2 mm. We use three pairs of Helmholtz coils together with a microwave spectroscopy technique, described previously in [21], first to cancel any stray magnetic field and then to calibrate the value of the applied external transverse magnetic field associated with the current in each pair of Helmholtz coils, we turn on the coupling and the probe beams for about 80 μ s, a time long enough for the system to reach steady state regime. These beams are obtained from a grating stabilized diode laser nearly resonant with the $F_g = 3 \rightarrow F_e = 2$ transition and can have their intensities and frequencies controlled by two independent acousto-optic modulators (AOM's). The coupling and the probe beams are then coupled to single mode optical fibers which send them through polarizing beam splitters and quarter wave plates before being incident on the cold atomic sample, forming a small angle $\theta \approx 2^\circ$, as indicated in Fig. 1(a). We define the quantization direction along the propagation direction of the coupling beam and the transverse magnetic field is then applied perpendicularly to this direction.

For coupling and probe beams with opposite circular polarizations, Fig. 1(b) also shows the manifold of Zeeman sublevels coupled to the coupling and probe beams. We are neglecting the small polarization contamination associated with the probe beam due to the small angle θ . The frequency of the coupling beam is kept fixed at a detuning $\Delta_C \approx 2\Gamma$ ($\Gamma/2\pi = 5.2$ MHz), while the frequency of the probe beam is scanned in steps of 5 KHz around the coupling beam frequency. Although we also were able to observe gain for smaller detunings, no gain was observed for the case of a resonant coupling beam, which can be attributed to probe absorption. We then detect the probe beam transmission as a function of the coupling-probe detuning δ . The detuning corresponding to $\delta = 0$ is monitored through the measurement of the coupling-probe beating in a fast photodetector. For a coupling and probe beam with approximate intensities of $I_C = 2$ mW/cm² and $I_P = 0.01$ mW/cm², respectively, in Fig. 2 we show the probe transmission spectra for two

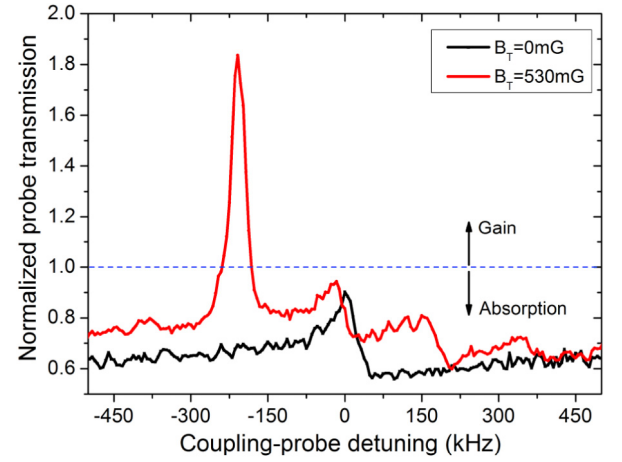


Fig. 2. Measured probe beam transmission spectra for two different values of the applied transverse magnetic field: $B_T = 0$ (black) and $B_T = 530$ mG (red), for the parameters given in the text. The probe transmission is normalized by the incident probe intensity, so transmission values higher than 1 in the vertical scale corresponds to gain. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

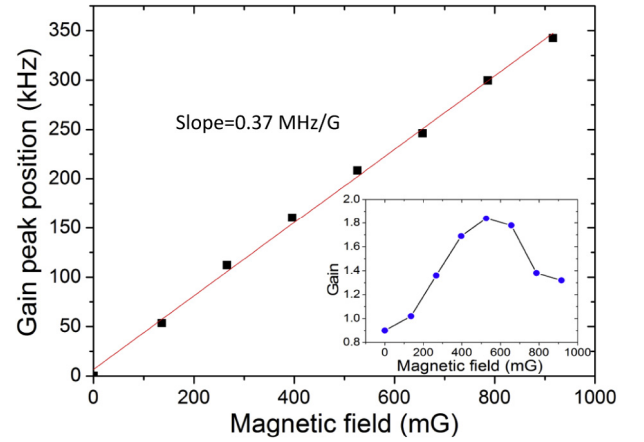


Fig. 3. (Color online) Dependence of the position of the gain peak with the magnetic field amplitude for the under the same experimental conditions as in Fig. 2. The red line is a linear fitting with a slope 0.37 MHz/G. Inset: The probe gain as a function of the magnetic field amplitude.

different values of the applied magnetic field, *i.e.*, for $B_T = 0$ and $B_T = 530$ mG. As can be observed a maximum single pass gain of about 80% is obtained in the presence of the transverse magnetic field. We believe the observed gain is mainly limited by the sample optical density. For this same polarization configuration and intensities, we have experimentally verified that the application of an external longitudinal magnetic field produces no observable gain. It is worth noticing that we have also measured comparable probe beam gain for the case where the coupling and probe beam have linear and orthogonal polarizations. In such case, it is more convenient to define the quantization direction along the polarization of the coupling beam and similar behavior is observed for an external magnetic field applied parallel or perpendicular to the quantization direction. Finally we also note that the application of a transverse magnetic field changes the hamiltonian of the system so that the Zeeman degeneracy is removed and this explains the fact that the two-photon resonance condition is obtained for a non zero coupling-probe detuning. The extra resonances observed in the spectrum can be attributed to the degeneracy of the $F_g = 3$ ground state, which can give rise to different two-photon resonances. Indeed, as shown in Fig. 3, we have experimentally verified that the position of the gain

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