Iraqi Journal of Physics, 2008 *Vol. 5, No. 1, PP 71-74*

Investigation of Electromagnetically Induced Transparency in the Rubidium Vapor

Baha T. Chiad, Abass H. Al-Wattar and Ahmed N. Abdullah
Department of Physics, College of Science, University of Baghdad

Abstract:

We have studied theoretically the response of atomic three- level cascade scheme of rubidium vapor to a strong laser under conditions in which electromagnetically induced transparency would be induced on a weak probe beam. We show that the medium that is an opaque to a probe laser can, by applying both lasers simultaneously, be made transparent.

تحقيقات الشفافية المحتثة بالمجال الكهرومغناطيسي في بخار الريبديوم

بهاء طعمة جياد، عباس جاسم حمادي الوتار و أحمد نجم عبد الله
قسم الفيزياء / كلية العلوم /جامعة بغداد

الخلاصة:

تمت في هذه الدراسة دراسة بخار الريبديوم لاستجابته لنظام ذري ليزري ثلاثي تحت شروط الشفافية المحتثة بالكهرومغناطيسية مولدة حزمة مجس ضعيفة محتثة، أثبتت الدراسة إن استخدام الأوساط المعتمة كمجسات ليزرية ممكن بكلا الليزرين أن تكون شفافة.

Introduction

Over the past 20 years coherence and interference in atomic physics have often led to the observation of many novel and interesting effects. In recent years, effects associated with quantum interference in multi-level atomic systems have been studied extensively, leading to the prediction and observation of a variety of unexpected phenomena such as Lasing without inversion, electromagnetic-induced transparency (EIT) and enhancement of the refractive index with no absorption [1].

EIT is a phenomenon that can occur in atomic systems as result of destructive interference between excitation pathways to the upper level [2]. A three-level atomic system coupled to two laser fields exhibits interference effects that can result in cancellation of absorption at a resonance transition frequency and other modifications of the optical response like dispersion. This happens because according to quantum mechanics the amplitudes must be added rather than the probabilities and they must be summed to obtain the transition probability of a process [3].

Theory

We consider a three level cascade system consisting of ground level |1> and excited levels|2> and |3> as shown in Fig. (1).

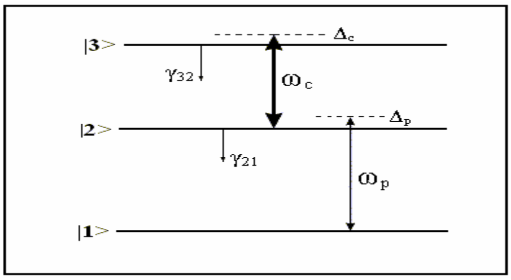

Fig. (1): Three level cascade scheme with the coupling field applied between levels |2> and |3> and the probe field between levels |1> and |2> [4].

The usual atomic dipole selection rules normally require that the transitions between two pairs of levels are allowed while the transition between the third pair is transition forbidden. So in this scheme the transition |1>-|2> and |2>-|3> are transition allowed but |1>-|3> is forbidden [3].

If we consider the system shown in Fig. (1), upon levels found in atomic rubidium we have for level |1> the $5S_{1/2}$ state, for level |2> the $5P_{3/2}$ state and for the upper level we have the $5D_{5/2}$ state. Now that if we apply a laser with appropriate energy between levels |1> and |2> then it will be absorbed and the atom in level |1> undergoes a transition to level |2> as it absorbs the energy of the light. If we then apply a second, somewhat stronger, laser between levels |2> and |3> we can then set up an alternative pathway for the atom to move from level |1> to |2>. This can be demonstrated as follows: the first route involves absorption of a photon moving the atom from level |1> to |2> and the second by absorbing another photon from the second laser moving the atom from level |2> to level |3>, and by the process of *stimulated emission* the atom may also be moved by the second laser from level |3> back to level |2>. Thus two pathways are possible for the atom to move from level |1> to level |2> (the pathways are denoted by |1> - |2> and |1> - |2> - |3> - |2> as shown in the figure (2)). Destructive interference between these two pathway can occur under appropriate condition and causes cancellation of the absorption of the light on the |1> - |2> transition. This interference effect, rendering an opaque medium transparent, is the essence behind EIT [5].

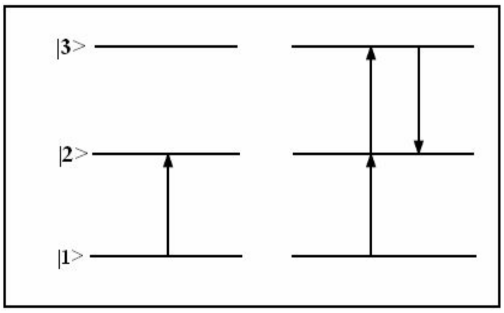

Fig. (2): Alternate quantum-mechanical pathways for the |1> → |2> transition.

Solving the density-matrix equations for this system in steady state and applying the rotating-wave approximation yields the following set of equations [6]:

$$\rho_{21} = \frac{i/2[\Omega_p(\rho_{22}-\rho_{11})-\Omega_c^{*}\rho_{31}]}{\gamma_{21}-i\Delta_p} \quad \text{....} \quad (1)$$

$$\rho_{32} = \frac{i/2[\Omega_c(\rho_{33}-\rho_{22})-\Omega_p^{*}\rho_{31}]}{\gamma_{32}-i\Delta_c} \quad \text{....} \quad (2)$$

$$\rho_{31} = \frac{i/2(\Omega_p\rho_{32}-\Omega_c\rho_{21})}{\gamma_{31}-i(\Delta_p+\Delta_c)} \quad \text{.........} \quad (3)$$

$$\rho_{22} = \frac{i}{2\Gamma_2}(\Omega_p^{*}\rho_{21}-\Omega_p\rho_{12}) \quad \text{.......} \quad (4)$$

$$\rho_{33} = \frac{i}{2\Gamma_3(\Omega_c^{*}\rho_{32}-\Omega_c\rho_{23})} \quad \text{..........} \quad (5)$$

Where Ω_c and Ω_p are Rabi frequency of coupling and probe laser respectively and are given by:

$$\Omega_c = \frac{2\mu_{32}E_c}{\hbar} \quad \text{..............................} (6)$$

$$\Omega_p = \frac{2\mu_{21}E_p}{\hbar} \quad \text{............................} (7)$$

Gea-Banacloche *et. al* [7] showed that the solution for ρ_{21} is given by the relation:

$$\rho_{21} = \frac{i\Omega_p/2}{i\Delta_p-\gamma_{21}+\dfrac{\Omega_c^{2}/4}{i(\Delta_p+\Delta_c)-\gamma_{31}}} \quad \text{.....} (8)$$

This displays the essence of (EIT). The response of the system to the probe field is determined by the above expression through the proportionality between the susceptibility and ρ_{21}, that is, [6]:

$$\chi_{21} = -\frac{2N\mu_{21}^{2}}{\hbar\Omega_{p}}\rho_{21} \qquad ....(9)$$

Substituting equation (8) into equation (9) we get expression of the susceptibility for cascade scheme:

$$\chi_{21} = -\frac{N\mu_{21}^{2}}{\hbar}\frac{i}{i\Delta_{p} - \gamma_{21} + \dfrac{\Omega_{c}^{2}/4}{i(\Delta_{p}+\Delta_{c}) - \gamma_{31}}} \qquad ..(10)$$

Where:

χ_{21} : is the electric susceptibility.
N: is the number of atoms within our system.
μ_{21}: is the dipole matrix element for the transition from level 2 to level 1.
ħ=h/2π; h: is Plank constant.
γ_{ij}: the decay rates for transition i→j.

Results and discussion

The medium that is used in our calculation in the present work is rubidium vapor (^{87}Rb). We chose the atomic number density of the rubidium vapor is equal to 1×10^{14} atom/cm^3 and the (^{87}Rb) is held at a fixed temperature about 75°C. The transparency of the media is determined by the imaginary part of susceptibility (χ) [8] in the relation (10). Two cases are considered: when the coupling field is absent (Fig. (3)) and when the coupling field is present (Fig. (4)). We have chosen the parameters of the first case (normal absorption profile) for (^{87}Rb) vapor as: Ω_c=0 MHz, the atomic number density N=1×10^{14} atom/cm^3, Ω_p=1 MHz, γ_{21}=6 MHz ,γ_{32}=0 MHz, $\mu_{21}=1.76\times10^{-21}$ (coul.cm). But in the second case we chose as before, but with Ω_c=40 MHz and Δ_c=0. The results of our calculations are display in the Figs. (3) and (4).

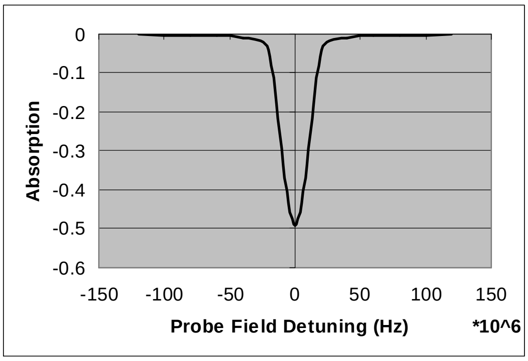

Fig. (3): Absorption profile for cascade scheme of the ^{87}Rb vapor when Ω_c=0 (a normal absorption profile).

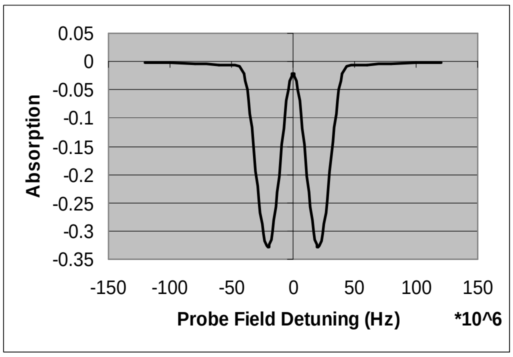

Fig. (4): Absorption profile for cascade scheme of the ^{87}Rb vapor when Ω_c=40 MHz.

Since the absorption and refractive index of a substance are linked via the Kramers-Kronig relations [9], we see that the modification of the absorption of a medium will result in a change in the refractive index as well as [10]. Examples of uses of this modification are high refractive index media with low absorption (phaseonium) [11].

This term summarizes the idea of the formation of a macroscopic medium consisting of phase-coherent quantum objects (atoms or molecules). The optical properties (both linear and nonlinear) of this (coherent) medium are very different from those of a normal (incoherent) medium [3].

The refractive index of the media is determined by the real part of susceptibility (χ) [8] in the relation (10).

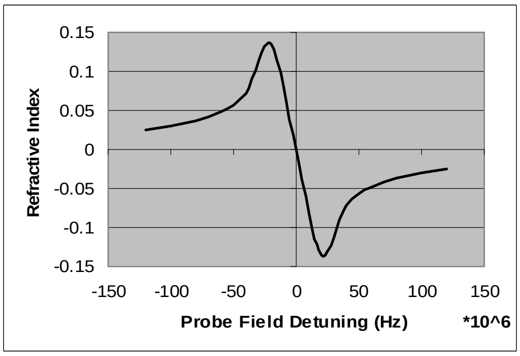

Fig. (5): Refractive Index profile for cascade scheme of the ^{87}Rb vapor when Ω_c=0.

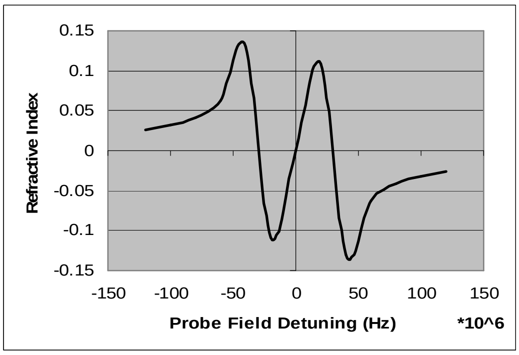

Fig. (6): Refractive Index profile for cascade scheme of the ^{87}Rb vapor when Ω_c=57 MHz.

Discussion

One of the strange interactions of light and matter is EIT. EIT can be used to modify the linear optical properties of the atomic medium such as absorption and refractive index.

When the coupling field is turned off we observe a maximum in absorption of the resulting trace for a zero probe field detuning as shown in the Fig. (3). While the absorption profile is markedly changed when the coupling field present, as shown in the Fig. (4), and the absorption profile is spilt into two components when a finite value of coupling field is introduced. This means the effect of medium on a propagating beam is eliminated.

If we examine the absorption profile of a probe field in Fig. (3) we find a maximum absorption occur at probe field detuning equal to zero. Accompanying this absorption will be a refractive index profile that has a zero value coinciding with the maximum absorption as shown in the Fig. (5). We also see a dispersive element of the refraction (variation of refractive index with frequency) around the maximum absorption point. By moving to a transparent medium we can modify this as shown in Fig. (6). We see that in a transparent medium we have high dispersion (rapidly varying refractive index).

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