Frequency matching effect in electromagnetically induced transparency

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Abstract

The influence of the linewidth of the probe laser on the absorption reduction in a lambda-type three-level system of rubidium atoms is studied experimentally. We measure the transmission spectral profile of the probe laser and find that only the resonant frequency components of the probe field pass through the absorbing atomic medium. © 1997 Elsevier Science B.V.

1. Introduction

In recent years much interest has been focused on the effect of electromagnetically induced transparency (EIT) [1–3] because of its potential applications in lasing without inversion [4], pulse matching [5,6], modified dispersion properties [7,8], and nonlinear optics [9–11]. The continuous-wave EIT effect has been observed in ladder-type, lambda-type, and V-type three-level systems in atomic Rb vapor [2–4,8,12].

It is well known that coherent transparency in a Doppler-broadened three-level medium depends not only on the two-photon EIT position, but also on the positions of the Autler–Townes components for all velocity groups of atoms. In short, the Autler–Townes splittings induced by the pumping laser increase both the width and the amplitude of the transparency window of the probe field [13]. However, when the pumping field and the probe field have nearly the same wavelength, the two-photon resonance is almost Doppler free and occurs simultaneously for all atoms regardless of their velocities. In this case, the two-photon EIT effect dominates the transparency and determines the position of the transparency peak of the probe field. In this paper, we report an experimental investigation of the frequency matching effect in a lambda-type three-level EIT system of rubidium atoms using cw diode lasers. The linewidth of the probe laser is adjustable and can be broadened from less than the natural linewidth of the atomic transitions (~ 6 MHz) to be much larger than that (up to 200 MHz). By increasing the probe linewidth, the absorption reduction becomes successively smaller, which means that the EIT effect is degraded. The degradation in the absorption reduction is caused by the frequency components that are not matched with the frequency of the pumping laser and do not satisfy the EIT condition in the frequency domain. To confirm this, we measure the spectral profile of the probe laser after it has passed through a high-density (optically-thick medium) rubidium vapor cell. Our experimental results clearly show that the rubidium EIT system is transparent only for the frequency components that satisfy the two-photon resonance condition for a given linewidth of the pumping laser. In this case, the filtered probe field is locked in frequency relative to the pumping field.

2. Experimental arrangement

As shown in Fig. 1, our lambda-type three-level system consists of $^{87}$Rb atoms in a Doppler-broadened vapor cell.
The two hyperfine levels (F = 1 and F = 2), spaced by 6.8347 GHz, of the ground state 5S_{1/2} serve as the two lower states of the lambda system. The excited state 5P_{1/2} (F’ = 2) serves as the common upper state. The experimental arrangement is sketched in Fig. 2. Both the pumping laser and the probe laser are commercial diode lasers that are temperature and current stabilized and can be tuned, in the free-running condition, to the D1 lines of rubidium atoms. The free-running linewidths of these two diode lasers are about 5 MHz. After being polarized by a polarization cubic beam splitter, the two laser beams pass through the rubidium vapor cell with orthogonal polarization directions. The laser beams are focused onto the atomic vapor cell by a f = 10 cm lens. In order to control the linewidth of the probe laser, a random noise generator is used to modulate the current driver of this laser [14].

3. Results and discussions

First, a 5 cm long rubidium vapor cell (kept at room temperature of 24.6°C) is used as the EIT medium. The cell absorbs only about 3% of the weak probe beam resonant with the transition between states 5S_{1/2} (F = 1) and 5P_{1/2} (F’ = 2), so it can be regarded as an optically-thin medium. When both the strong pumping beam (about 12 mW) and the weak probe beam (about 18 µW) are applied to the rubidium cell, the absorption profile of the probe field is changed as shown in Fig. 3. The dip in the center of the absorption profile represents the absorption reduction due to the EIT effect under the two-photon resonance condition. For the probe linewidth of \( \gamma_p / \pi \approx 5 \) MHz (Fig. 3(a)), the absorption reduction is nearly 60%. However, when \( \gamma_p / \pi \) is adjusted to be about 82 MHz (Fig. 3(d)), the absorption reduction is reduced to about 10%. As we further broaden the probe linewidth to over 100 MHz, the EIT dip disappears. The degradation of the EIT effect caused by the increase of the probe linewidth seems to be the same as the case when the probe linewidth is unchanged while the pumping linewidth is increased. An existing theory has predicted that the linear susceptibility of the atomic system for the weak probe beam in the EIT case can be written in the following compact form [2]:

\[
\chi = \frac{4i \hbar g_{12}^2 N_0 \sqrt{\pi}}{\varepsilon_0 \omega_p \omega_p} \exp \left\{ (1 - \text{erf} \ z) \right\},
\]

with the argument

\[
z = \frac{c}{u \omega_p} \left[ \gamma + \gamma_p - i \Delta_1 + \frac{\Omega_c^2 / 4}{\Gamma_{31} + \gamma_p + \chi - i(\Delta_1 - \Delta_2)} \right],
\]

where \( \text{erf}(z) \) is the error function with a complex argument \( z \). \( \gamma_p / \pi \) and \( \chi / \pi \) are the linewidths of the probe laser and the pumping laser, respectively. Detunings \( \Delta_1 \) and \( \Delta_2 \) are defined as the nominal detunings of the probe laser and the pumping laser for an atom at rest. \( u / \sqrt{2} \) is the root-mean-square atomic velocity; \( 2\hbar g_{12}^2 \) is the dipole moment matrix element for the probe transition and \( \Omega_c \) is the Rabi frequency of the pumping field. \( \Gamma_{31} \) is the dephasing rate for the lower two levels of the lambda-type system. \( \gamma = (1/2)(\Gamma_{21} + \Gamma_{23} + \Gamma_{31}) \), where \( \Gamma_{21} \), \( \Gamma_{23} \) are decay rates from the upper state to the two lower states, respectively. \( N_0 \) refers to the number of atoms per unit volume, and \( \omega_p \) is the angular frequency of the probe laser. The imaginary part of the susceptibility leads to the absorption characteristics of the atomic medium, i.e., the absorption coefficient is given by \( \alpha = \omega_p n_0 \chi' / c \), where \( n_0 \) is the background index of refraction. From Eq. (2), we can see that both the probe linewidth and the pumping linewidth can affect the absorption coefficient. We use a simple fitting process [2] to fit the measured EIT curve (Fig. 3(a)) to determine \( \Omega_c \) (see Fig. 4). Using the \( \Omega_c \)
value and Eq. (1), we calculated the absorption reduction factor and the absorption profiles under different probe linewidths. The agreement between the theoretical curves and the experimental curves is quite good.

Although the existing theory is in good agreement with our experimental results, it cannot clearly tell us whether all the spectral components of the probe beam contribute to the EIT effect when the linewidth of the probe beam is much larger than that of the pumping beam. Intuitively, different spectral components should not play an equal role in the EIT process because their frequency detunings for two-photon resonance are different. We expect that only the resonant portion takes part in the EIT process and can pass through an optically-thick vapor cell with reduced absorption. To verify this, we need to measure the transmission spectrum of the probe field after it has passed through the medium. In our experiment, a longer rubidium cell (7.6 cm) is used and heated to about 331 K (58°C). Without pumping field, most of the probe field (85.8%) is absorbed by the vapor cell. When the pumping laser is applied to the atomic system, the absorption coefficient of the probe beam will be almost doubled due to the optical pumping effect. Thus only about 2% of the probe beam can pass through the rubidium cell. We first obtain an absorption profile like that in Fig. 3 while scanning the frequency of the probe laser. Then, we stop the frequency scanning to make the probe laser in the two-photon resonance condition ($\Delta_1 - \Delta_2 = 0$). Finally, we broaden the probe linewidth to about 82 MHz and analyze the transmission spectral profile using the F-P cavity. As shown in Fig. 5(b), two transmission peaks appear in one free spectral range of the F-P cavity. If the probe laser is blocked, the small peak in the right side disappears, which indicates that it comes from the probe field. The large peak on the left is, of course, from the pumping field, since the polarization of the pumping field has a slight change after passing through the lens and the vapor cell. When we block the pumping beam, the vapor cell acts as a conventional absorbing medium; about 14.2% of the probe beam passes through the vapor cell, which permits us to see its spectral profile, which is presented in Fig. 5(a). Note that the linewidth of the probe field is still much smaller than the full Doppler-width of the atomic medium (about 560 MHz at $T = 58^\circ$C). It is reasonable to assume that the absorption coefficient is almost a constant in the probe

Fig. 3. Absorption profile as a function of probe detuning $\Delta_1$. Pumping power is 12 mW ($\Omega_p = 115$ MHz). The linewidth of the pumping laser $\gamma_p / \pi = 5$ MHz. The linewidth of the probe laser is $\gamma_0 / \pi$: (a) 5 MHz, (b) 28 MHz, (c) 50 MHz, and (d) 82 MHz.

Fig. 4. Experimental curve of Fig. 2. (a) (solid line) and its theoretical fitting curve (dashed line). The fitting parameters are $\gamma_0 = \gamma_p = 5\pi$ MHz and $\Omega_0 = 114.6 \times 2\pi$ MHz.

Fig. 5. Transmission spectral profiles. (a) Without the pumping laser. (b), (c), and (d) With the pumping laser. The smaller peaks on the right side are attributed to probe transmission due to EIT effect while the large peaks on the left side represent the pumping laser.
s spectral range and hence the spectral shape of the probe field is not affected by the absorption of the vapor cell. As shown in Fig. 5(a), the linewidth of the probe field is still 82 MHz, which is the same as that of the probe field before it enters the vapor cell.

Fig. 5 presents the results of the probe transmission for different frequencies of the pumping laser. From Figs. 5(a) and 5(b), we can see that the probe transmission peak appears in the center of probe line shape, where the EIT occurs. The probe peak is definitely revived by the EIT effect. The width of the transmitted probe peak is basically equal to that of the pumping laser, but much smaller than the linewidth of the probe beam before entering the vapor cell. This indicates that the vapor cell is transparent only to the resonant spectral components that satisfy the EIT condition while is opaque to other frequency components. When EIT occurs, the frequencies of the pumping and the probe lasers have a definite spacing (6.8347 GHz) which is just the spacing between the two ground states of $^{87}\text{Rb}$. As shown in Fig. 5(b), this spacing appears as 95 MHz for a 749 MHz free spectral range F-P cavity. We found that, when the frequency of the pumping laser is shifted, the probe peak moves in the same direction and keeps the constant distance (95 MHz) from the pumping peak. However, its height changes across the spectral range of the probe field (see Figs. 5(c) and 5(d)). The probe peak disappears beyond this range.

Fig. 6 shows the resonant transmission peaks of the probe field for different probe linewidths. For the same input probe power, the intensity per unit frequency interval of the probe field increases with decreased linewidth. So the probe peak filtered through the vapor cell becomes larger from (a) to (c) as the linewidth of the probe beam decreases from about 127 MHz to about 22 MHz. However, the width of the transmitted peak has no change since the spectral width of the resonant components of the probe field is independent of the probe linewidth, and is determined only by the linewidth of the pumping field.

4. Conclusions

In summary, we have observed the degradation of the EIT effect due to the increase of the probe linewidth in the lambda-type three-level rubidium atomic system. We also confirmed that, for a probe field with a large linewidth, only the spectral components that satisfy the two-photon resonance condition take part in the EIT process and can pass through the optically-thick medium with reduced absorption. This result can be extended to answer the question of whether a thermal light as a probe beam can have the EIT effect. The filtered probe field has a locked frequency relative to the frequency of the pumping field and perhaps has potential applications in some optical experiments where frequency locking is needed. This study has significant implications in pulse matching, nonlinear optics, and frequency correlation effects.

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References