Electromagnetically induced transparency controlled by a microwave field

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We have experimentally studied propagation of two optical fields in a dense rubidium (Rb) vapor in the case when an additional microwave field is coupled to the hyperfine levels of Rb atoms. The Rb energy levels form a close-lambda three-level system coupled to the optical fields and the microwave field. It has been found that the maximum transmission of a probe field depends on the relative phase between the optical and the microwave fields. We have observed both constructive and destructive interference in electromagnetically induced transparency (EIT). A simple theoretical model and a numerical simulation have been developed to explain the observed experimental results.

I. INTRODUCTION

Electromagnetically induced transparency (EIT) is based on quantum coherence [1, 2, 3, 4, 5] that has been shown to result in many counter-intuitive phenomena. The scattering via a gradient force in gases [6], the forward Brillouin scattering in ultra-dispersive resonant media [7, 8, 9], controlled coherent multi-wave mixing [10, 11], EIT and slow light in various media [12, 13, 14, 15, 16, 17, 18], Doppler broadening elimination [19], light induced chirality in a nonchiral medium [20], a new class of entanglement amplifier [21] based on correlated spontaneous emission lasers [22] and the coherent Raman scattering enhancement via maximal coherence in atoms [23, 24] and biomolecules [25, 26, 27, 28, 29] are a few examples that demonstrate the importance of quantum coherence.

Usually, the EIT has been observed in atoms that have a three-level configuration such as Λ, V, and Ladder schemes [1, 2]. For these schemes several theoretical approaches have been developed to provide clear physical insights. For example, the EIT can be understood in the bare state basis using quantum coherence, or in the dressed state basis involving Fano interference, or using the so-called dark and bright states [1, 2].

Natural generalization of the three-level schemes is the so-called double-Λ, double-V, double-Ladder, and Λ-V schemes [30], where two relatively strong optical fields applied to the atomic system to create coherence, and then a probe field propagates through the gas of such atoms together with an additional strong drive field. The probe propagation depends on the parameters of the medium and the fields preparing coherence. On the other hand, let us note that the effect of these two optical drive fields is equivalent to an effective microwave driving field applied to the system. Furthermore, in some regard, the schemes that involve two optical fields and a microwave field can be related to the double-Λ scheme.

The systems involving interaction with two optical fields and a low frequency microwave field coupled to the hyperfine levels have been in a focus of recent studies [31]. For example, microwave interaction [32] has been used to excite the Raman trapped state and it was shown that there is influence of the microwave field on the CPT in a Λ system; four-wave mixing (FWM) of optical and microwave fields has been demonstrated [33] in Rb vapor. A microwave field has also been used to study double dark resonances [34]. It has been shown [35] that, in a V-scheme three-level system of Pr3+:YAlO3 that was excited by a microwave driving field and two optical probe fields, the probe transmission was either constructively or destructively affected by the phase of the microwave field.

Recently, the phase effects in EIT systems has been studied [36, 37, 38], where the transient times of the refractive Kerr nonlinearity have been studied and it has been shown that the refractive Kerr nonlinearity is enhanced using EIT. Besides, these close systems also have broad range of applications that stimulated our interest to this system. For example, they have been considered as perspective candidates for realization of stop-and-go slow light [39, 40], backward scattering [10, 11]. Furthermore, the interest to this topic is stimulated by recent work [41] in which a quantum storage based on electromagnetically induced transparency has been predicted. The first experiments in support of the theoretical predictions have also been performed [41]. In [42], it was shown that the quantum state of light can be stored and retrieved in a dense medium by using the different regimes of switching on and off a control field. A quantum state of light having one polarization and carrier frequency can be transferred to the same state of light but having a different carrier frequency, polarization, or direction of propagation. These systems with microwave field have better controlled probe transparency because the absorption of the microwave field is much smaller than optical fields, which is important for improving and...
optimizing quantum storage efficiency. Slow light produces delay that can be used in optical buffers, the delay time is limited by the absorption of probe field. Using an auxiliary microwave field can improve the important parameter for broadband systems, the product of delay time and bandwidth of the pulse, which shows the effective number of communication channels.

In this paper, we report the study of EIT in a three-level \( \Lambda \) scheme interacting with two optical fields and a microwave field coupled with hyperfine levels. “Perturbing” (due to a microwave field) the coherence of two ground states leads the change of maximum transmission of probe field. Either constructive or destructive EIT peak can be obtained depending on the relative phase between the optical fields and the microwave field. The paper is organized by starting with a simple theoretical model of a close-\( \Lambda \) scheme. Then, we describe experimental details and obtained results. At the end we present numerical simulations that reproduce experimental results.

II. THEORY

Let us consider a closed lambda scheme shown in Fig. 1 in which a three-level atomic medium is coupled with two optical fields and a microwave field between two ground states.

![Diagram of a closed lambda scheme](image)

**FIG. 1:** (Color online) Energy levels of a closed \( \Lambda \) scheme three-level system.

The Hamiltonian of the system can be written as

\[
H = H_0 + H_1;
\]

\[
H_0 = \hbar \omega_a |a\rangle \langle a| + \hbar \omega_b |b\rangle \langle b| + \hbar \omega_c |c\rangle \langle c|;
\]

\[
H_1 = -\hbar (\Omega_1 e^{-i\nu_1 t}|a\rangle \langle b| + \Omega_2 e^{-i\nu_2 t}|a\rangle \langle c| + \Omega_\mu e^{-i\nu_\mu t}|c\rangle \langle b| + h.c.);
\]

where \( \Omega_1, \Omega_2 \) and \( \Omega_\mu \) are rabi frequencies of the optical probe field, the optical driving field and the microwave field respectively; \( \nu_1, \nu_2 \) and \( \nu_\mu \) are angular frequencies of corresponding fields. The density matrix equation of motion is given by

\[
\dot{\rho} = -\frac{i}{\hbar} [H, \rho] - \frac{1}{2} (\Gamma, \rho)
\]

where \( \{\Gamma, \rho\} = \Gamma \rho + \rho \Gamma \), and \( \Gamma \) is the relaxation matrix. The non-diagonal elements of the density matrix equations are found as the following,

\[
\dot{\rho}_{ab} = -\Gamma_{ab} \rho_{ab} - i\Omega_1 (\rho_{aa} - \rho_{bb}) + i\Omega_2 \rho_{cb}
\]

\[
-\hbar \mu e^{i(\nu_1 - \nu_2 - \nu_\mu) t} \rho_{ac}
\]

\[
\dot{\rho}_{ac} = -\Gamma_{ac} \rho_{ac} - i\Omega_2 (\rho_{aa} - \rho_{cc}) + i\Omega_1 \rho_{bc}
\]

\[
-\hbar \mu e^{i(\nu_1 - \nu_2 - \nu_\mu) t} \rho_{ab}
\]

\[
\dot{\rho}_{cb} = -\Gamma_{cb} \rho_{cb} - i\Omega_2 \mu e^{i(\nu_1 - \nu_2 - \nu_\mu) t} (\rho_{cc} - \rho_{bb})
\]

where \( \Gamma_{ab} = \gamma_{ab} + i(\omega_{ab} - \nu_1) \), \( \Gamma_{ac} = \gamma_{ac} + i(\omega_{ac} - \nu_2) \) and \( \Gamma_{cb} = \gamma_{cb} + i(\omega_{cb} - \nu_2 - \nu_\mu) \). We consider the case in which the driving field is on resonant (\( \nu_2 = \omega_{ac} \)), while the probe field and microwave field have the same detuning \( \Delta \equiv \omega_{ab} - \nu_1 = \omega_{cb} - \nu_\mu \), thus \( \nu_1 - \nu_2 - \nu_\mu = 0 \). In the steady-state regime (\( \rho_{ab} = \rho_{ab} \), \( \rho_{ac} = \rho_{ac} \)), assuming that the driving field is much stronger than the probe field (\( \|\Omega_2\| \gg \|\Omega_1\| \)) so that almost all of the population remains in the ground state \( |b\rangle \), i.e. \( \rho_{bs} \approx 1 \) and \( \rho_{aa} = \rho_{cc} \approx 0 \), we can solve equations (5-7) for \( \rho_{ab} \),

\[
\rho_{ab} = \frac{i\Gamma_{cb} \Omega_1}{\Gamma_{ab} \Omega_{ch} + |\Omega_2|} - \frac{\Omega_2 \Omega_{ab}}{\Gamma_{ab} \Omega_{cb} + |\Omega_2|}^2
\]

with \( \Gamma_{ab} = \gamma_{ab} + i\Delta \) and \( \Gamma_{cb} = \gamma_{cb} + i\Delta \). The propagation equation of probe field is given by

\[
\frac{\partial \rho_{ab}}{\partial z} + i\kappa_{1} \rho_{ab} = -i\eta \rho_{ab};
\]

where \( \eta = \nu_1 N \gamma^2_{ab} / (2\epsilon_0 c \hbar) \) is the coupling constant, \( N \) is the atomic density, \( \gamma^2_{ab} \) is the dipole moment of the transition \( |a\rangle \leftrightarrow |b\rangle \), \( \epsilon_0 \) is the permittivity in vacuum. Consider optical fields as plane waves:

\[
\Omega_i(z,t) = \tilde{\Omega}_i(z,t) e^{-i k_i z},
\]

where \( \tilde{\Omega}_i(i = 1, 2) \) are slowly varying amplitudes in the envelopes of optical fields in space, and \( k_i(i = 1, 2) \) are wave numbers of optical fields. With these expressions and equation (8), the propagation equation of probe field can be written as

\[
\frac{\partial \tilde{\Omega}_1}{\partial z} = -\frac{\Gamma_{cb} \tilde{\Omega}_1}{\Gamma_{cb} \Omega_{ab} + |\Omega_2|} - i\eta \Omega_\mu \Omega_{cb} \tilde{\Omega}_2 e^{i(k_1 - k_2) z}
\]

where \( \Delta k = k_1 - k_2 \).

On the right hand side of equation (11), the first term is due to the standard Lambda scheme EIT, and the second term is the contribution from the microwave field. The transmission of probe field is determined by the interference of these two terms. The second term is interesting because of the strong dependence on the relative phase of optical fields and microwave field. This gives us several ways to control coherence and the transmission of the probe field. For instance, one can use microwave phase shifter to change the phase of microwave field; one can also use optical delay line, like the one used in Ref[32], to change the phase of optical field. An alternative way
is simply changing the position of the Rb cell, which is described as the following.

Assume that the driving and probe fields are phase-locked, they form a wave package along propagation direction with the frequency which is the frequency difference of two fields. For $^{87}$Rb, this frequency is 6.835 GHz, and corresponding wavelength is about 4.4 cm. If we put the Rb cell in a microwave cavity which is excited by a microwave with frequency 6.835 GHz, the phase of the microwave in a cavity does not change when we move the cell and the microwave cavity together. However, the relative optical phase changes since the relative position of the cell with respect to the wave package of optical fields changes. In other words, we are able to change the phase $\Delta k z$ by moving the cell and microwave cavity along the propagation direction of optical fields.

III. EXPERIMENT

A. Experimental setup

The experimental setup is schematically shown in Fig. 2. A diode laser is tuned to the $D_1$ resonance line of $^{87}$Rb atoms, specifically at the $5S_{1/2}(F = 2) \leftrightarrow 5P_{1/2}(F = 2)$ transition. The laser beam passes through an electro-optic modulator (EOM) which is driven by a microwave with frequency 6.835 GHz, and two sidebands are generated. One of them is working as probe field at the $5S_{1/2}(F = 1) \leftrightarrow 5P_{1/2}(F = 2)$ transition. Another sideband is 6.835 GHz frequency downshifted with respect to the drive field, this downshifted field is far from resonance and has negligible effect on experiment. Another beam is shifted 200 MHz by an acousto-optic modulator (AOM).

The output laser beam from EOM is circularly polarized by a quarter wave plate, and is directed into a glass cell with the length of 25 mm. The cell is filled with $^{87}$Rb vapor and 5 Torr of Neon buffer gas. The cell is installed in a microwave cavity made of aluminium and copper. The resonant frequency of microwave cavity is 6.835 GHz, and the loaded quality factor is $Q \approx 2000$. The microwave injected into the cavity comes from the same signal generator which also provides the driving microwave for EOM. The microwave cavity with Rb cell is installed in a magnetic shield. A non-magnetic heater is used to control the temperature.

With the optical fields (drive and probe) coming out from EOM and the microwave field in the cavity, we have a closed-Lambda system as shown in Fig. 1. During the experiment, the microwave generator is 200 kHz frequency modulating around 6.835 GHz. Therefore, the probe laser field and the microwave field are synchronized to be 200 kHz frequency scanning. The transmitted probe field is detected by the heterodyne detection described in Ref[13]. The transmitted light is beating with an additional optical field which is 200 MHz frequency shifted by an acousto-optic modulator (AOM), two sidebands (one of them is the probe field) are separated by 400 MHz in the beating signal which is detected by a fast photo detector with the bandwidth of 25 GHz. The signal from photodetector is acquired by a spectrum analyzer which is synchronized with the modulation of microwave generator, and the center frequency is set at the hyperfine splitting frequency plus 200 MHz. The amplitude of beating signal at this frequency is proportional to the transmission of probe field.

B. Experimental results

Without applying microwave field, as we vary the detuning, the transmission is varying. The EIT transmission peak is shown in Fig. 3(b). Applying a microwave field changes the transmission of probe field. As discussed above, we change the relative phase between optical fields and microwave field by changing the position of cell and microwave cavity along the optical axis. Due to the interference of two terms on the right hand side of equation (11), the transmission of probe field could be either con-
STRUCTURE OF THE NATURE OF THE TAIL OF THE BEATING SPECTRUM}

We also have a small dip on the top which indicates that the length of the Rb cell be \( L \). As varying the detuning, the maximum transmission appears at zero detuning.

An interesting feature needs to be pointed out for the case of destructive transmission (Fig. 3c). In this case, the amplitude of EIT peak decreases as we expected, and we also have a small dip on the top which indicates that one (the one due to presence of microwave field) of interfering terms has relatively narrower width. Its width is narrower than EIT width.

The EIT peak is recorded at every 3 mm we move the cell along the optical axis. Fig. 4 shows how the EIT peak changes as we move the Rb cell. Fig. 4(a) is the result obtained with right circularly polarized input laser field, and Fig. 4(b) is the result obtained with left circularly polarized input laser field. The amplitude of EIT peak is oscillating with the change of cell position. The distance between two maximums (or minimums) next to each other is about 4.4 cm, which is exactly the wave-length of beating envelope of input optical fields. This periodicity is consistent with the theoretical prediction described above.

The oscillation is clearly shown in Fig. 5, where we plot the amplitude of EIT peaks as a function of relative phase (phase \( 2\pi \) corresponds the wavelength 4.4 cm). The dash lines are fittings of sinusoid function. Comparing the cases of right and left circularly polarized input laser fields, the behaviors are exactly opposite. This feature is very surprising, because the whole system is symmetrical about the optical axis, and there is no obvious way to tell the difference between left and right circular polarizations. However, atoms are smart enough to see the difference. Left and right circularly polarized fields are coupled with different Zeeman sub-levels, the corresponding magnetic moments have opposite signs which introduce a phase difference of \( \pi \) in our results.

IV. SIMULATION

To gain physical insights for the obtained results, we perform simulation based on the equation (11). Assume that the length of the Rb cell be \( L \), and the optical fields enter the Rb cell at position \( z_0 \) and leave at position \( z_0 + L \). With the probe field \( \Omega_{10} \) entering the cell, equation (11) gives the transmitted probe field \( \tilde{\Omega}_1 \) as the following,

\[
\tilde{\Omega}_1(z_0 + L) = \tilde{\Omega}_{10} e^{-\alpha L} - i \frac{\eta \Omega_{10} \tilde{\Omega}_2}{\Gamma_{cb} \Gamma_{ab} + |\tilde{\Omega}_2|^2} \cdot \frac{1}{i \Delta k + \alpha} \left[ e^{i \Delta k (z_0)} - e^{i \Delta k (z_0 - \alpha L)} \right],
\]

where \( \alpha \) is the absorption coefficient which is given by

\[
\alpha = \frac{\eta \Gamma_{cb}}{\Gamma_{cb} \Gamma_{ab} + |\tilde{\Omega}_2|^2}.
\]

The simulation result is shown in Fig. 6. The parameters we used in the simulation are the following: \( \gamma_{ab} = 5 \), \( \gamma_{bc} = 10^{-3} \), \( \Omega_{10} = 0.1 \), \( \Omega_2 = 1 \), \( \Omega_n = 0.02 \), \( \eta = 0.9 \), \( L = 2.5 \) cm and \( \Delta k = 1.5 \) cm\(^{-1} \). As varying the detuning, the maximum transmission appears at zero detuning. Meanwhile, the maximum transmission is oscillating when we change \( z_0 \) which determines the position of Rb cell, and the period of oscillation is about 4.4 cm. The simulation shows the similar behavior as the experimental results, except for the dip at EIT peaks in destructive cases.

This narrow feature, the dip in the EIT peak, could be used for EIT-based applications such as improving accuracy of atomic clock. Eventhough, the simple model described above do not predict this narrowing. A detail theoretical investigation of this feature should include four-wave mixing.

It is interesting to note that the obtained results can be considered for realization of the stop-and-go slow
The obtained results can be also applied to the backward scattering predicted in [10, 11]. By controlling dispersion of the medium with the optical fields, a microwave field can be produced. Its direction of generation is determined by the parameters of the fields, in particular, the detuning of the optical fields from the two-photon resonance.

Furthermore, the interest to this topic is stimulated by the recent work [41] in which a quantum storage based on electromagnetically induced transparency has been predicted. Because absorption of the microwave field is much smaller than optical fields, these systems have better controlled probe transparency, which is important for improving and optimizing efficiency of quantum storage [43, 44]. Slow light produces delay that can be used in optical buffers, the delay time is limited by the absorption of probe field. Using auxiliary microwave field can improve the product of delay time and bandwidth of the pulse [45]. The broad range of applications stimulated our interest to the atomic system with the optical and microwave fields.

V. CONCLUSION

In conclusion, we have experimentally studied EIT in Rb atoms coupled with two optical fields and a microwave field. The microwave is coupled to two hyperfine levels, and coherently “perturbs” the coherence of two hyper-
fine levels, thus change the transmission of probe field. It has been found that the maximum transmission of probe field depends on the relative phase between optical fields and microwave field, and both constructive and destructive EIT peaks have been observed. A simple theoretical model and a numerical simulation have been provided. The simulation shows the similar behavior as the experimental results. However, a more detailed theoretical model is required to explain the dip which occurs in destructive EIT peaks.

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