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Broadband cavity electromagnetically induced transparency

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Abstract: Cavity electromagnetically induced transparency (EIT) is created in a three-level atomic system confined in a cavity and coupled to a free-space control laser, and is manifested as a narrow transmission peak of a probe laser coupled into the cavity mode and tuned to the two-photon Raman resonance with the control laser. Cavity EIT can be observed with a control laser detuned from the atomic transition frequency in a range limited by the vacuum Rabi splitting of two cavity-atom normal modes. This leads to the broadband cavity EIT obtained in the coupled cavity-atom system with a free space, broadband control laser. We report an experimental observation of broadband cavity EIT in cold Rb atoms with a frequency-modulated control laser and discuss its application in multichannel and multi-frequency light memory.

PACS numbers: 42.50.Pq, 42.50.Gy, 32.80.-t, 42.65.-k

Electromagnetically induced transparency (EIT) and related applications has been a subject of many recent studies [1]. An important application of EIT is for optical information processing [2]. EIT provides a practical way to produce and manipulate the group velocity of light pulses. By adiabatically turning on and off of a control laser, the light pulses can be coherently stored in an EIT medium and later retrieved [3]. In optical information network, it is desirable to be able to store, route, and interface various information lines at different frequencies and with multiple channels. Building reliable light memories and performing multi-frequency and multichannel functions are important current research topics in classical and quantum information network. EIT is manifested by quantum interference and has a narrow linewidth in the light transparent window, which severely limits the bandwidth of the light pulses that can be slowed and stored in the atomic medium. Several schemes have been proposed to overcome the bandwidth limitation of the basic EIT system and extend the EIT technique to broadband applications [4-8].

Here we report an experimental observation of broadband EIT in a coupled cavity-atom system that may be used for applications in a multi-frequency, multi-channel light information network. The cavity EIT is created in a three-level Λ -type atomic system confined in a cavity and coupled to a free-space control laser (Fig. 1a), and is manifested as the narrow transmission peak of a weak probe laser coupled into the cavity mode [9-12]. Due to the collective coupling of the cavity mode and the multiple atoms, the narrow transmission peak of the cavity-EIT can be observed with a control laser detuned from the atomic transition frequency. Nearly equal amplitude of the cavity EIT peak is obtained when the control detuning Δ is within the vacuum Rabi sidebands and the probe laser detuning Δ_p matches the intra-cavity two-photon Raman resonance condition, $\Delta_p = \Delta + \delta \approx \Delta$ ($\delta \ll \Delta$ and accounts for the effects of the AC Stark shift and the probe frequency offset from the empty cavity frequency). With a broadband control laser and a broadband probe laser, when the frequency components of the control laser and the probe laser are within the vacuum Rabi sidebands (with each EIT pair of the control and the probe

components satisfying the two-photon resonance condition ($|\Delta_p| \approx |\Delta|$), the multichannel cavity EIT is established. The control and the probe frequency components among different pairs of the cavity EIT can be independent and have no phase correlations. That is, each cavity EIT channel can be made independent from others (with a control Rabi frequency Ω smaller than the channel frequency separation).

2. Experimental method

The experiment was done with cold ^{85}Rb atoms confined in a standing-wave cavity consists of two mirrors of 5 cm curvature with a mirror separation ~ 5 cm. The trapped ^{85}Rb atom cloud was ~ 1 mm in diameter and had an optical depth $n\sigma_{\text{ea}}\ell$ of ~ 3 . The schematic experimental set-up is shown in Fig. 1b and a detailed description of the experimental procedure can be found elsewhere [13-14]. Briefly, an extended-cavity diode laser was used as the free-space control laser and drives the atomic transition $|b\rangle \rightarrow |e\rangle$ (the ^{85}Rb D1 $F=3 \rightarrow F'=3$ transition) with Rabi frequency 2Ω and frequency detuning $\Delta = \nu_{\text{cont}} - \nu_{\text{eb}}$. Another extended-cavity diode laser was used as the probe laser. $\Delta_p = \nu_p - \nu_{\text{ea}}$ is the probe frequency detuning and $\Delta_c = \nu_c - \nu_{\text{ea}}$ is the cavity-atom detuning. The control laser is circularly polarized while the probe laser is linearly polarized parallel to the propagation direction of the control laser as shown in Fig. 1(b). The attenuated probe laser was coupled into the cavity and the transmitted probe light was coupled into a single mode fiber, the output of which was collected by an APD single-photon counter (PerkinElmer SPCM-AQR-16-FC). The experiment was run with a repetition rate of 10 Hz. All lasers were turned on or off by acousto-optic modulators (AOM). For each period of 100 ms, ~ 98 ms was used for cooling and trapping of the ^{85}Rb atoms, during which the cooling laser and the repump laser were turned on while the control laser and the probe laser were off. The time for the data collection lasted about 2 ms, during which the repump laser was turned off first; and after a delay of ~ 0.2 ms, the trapping laser was turned off (the current to the anti-Helmholtz coils of the MOT was always kept on), and the control laser and the probe laser were turned on. For the measurements of

the cavity transmission spectrum, the probe laser frequency was scanned across the ^{85}Rb D_1 $F=2 \rightarrow F'=3$ transitions (after the control laser and probe laser were turned on for ~ 0.2 ms) and the cavity transmission of the probe laser was then recorded versus Δ_p .

3. Results and discussions

Fig. 2 shows the cavity transmitted intensity of the probe laser I_t (normalized to the resonant peak transmission of the empty cavity I_c) versus the probe frequency detuning Δ_p for a series of the control laser detuning Δ . Fig. 2(a) plots the experimental measurements and Fig. 2(b) plots the numerical calculations from a simple semiclassical model in which the atoms are confined in a Fabry-Perot cavity and coupled by a free space, classical control laser and a weak, classical probe laser circulating inside the Fabry-Perot cavity [9,11]. The empty cavity frequency is kept on resonance ($\Delta_c = \nu_c - \nu_{ea} = 0$). The cavity transmission spectrum exhibits three peaks. The two sidebands located at $\Delta_p \approx \pm 50$ MHz represent the multi-atom vacuum Rabi splitting and are given by $\Delta_p \approx \pm g \sqrt{N} = \pm \mu_{ca} \sqrt{N \omega_{ca} / 2 \hbar \epsilon_0 V}$ (μ_{ca} is the atomic dipole moment, N is the number of atoms in the cavity mode and V is the cavity mode volume), which represents the collective coupling of the cavity mode with the atoms confined in the cavity mode volume (when the control field is turned off) [15-17]. When the control laser is turned on, the splitting of the two vacuum Rabi sidebands becomes $2\sqrt{g^2 N + \Omega^2} \approx 2g\sqrt{N}$ (in our experiment, $g\sqrt{N} \approx 50$ MHz and $\Omega \approx 9$ MHz. So the effect of the control laser on the vacuum Rabi splitting is small) [14, 18]. The peak between the two sidebands (the normal modes) represents the cavity EIT and is located at $\Delta_p \approx \Delta$. At the free-space EIT resonance ($\Delta_p = \Delta = 0$), the cavity transmission spectrum is symmetrical. The measurement shows that when the control laser is detuned from the atomic resonance ($\Delta \neq 0$), the cavity EIT peak shifts away from the single-photon resonance but always matches the two-photon Raman resonance condition $\Delta_p \approx \Delta$. The positions of the two sidebands representing the two cavity-atom normal modes essentially are not affected by the control laser and are always located at $\Delta_p \approx \pm g\sqrt{N}$. Our measurements show that the peak amplitude of the cavity EIT

decreases rapidly for $|\Delta| > g\sqrt{N}$ and the practical frequency range of the cavity EIT is limited by the vacuum Rabi splitting $2g\sqrt{N}$ (~ 100 MHz under our experimental conditions). We note that the bandwidth of the cavity EIT can be varied by changing the number of atoms N in the cavity mode. This is in contrast from the fixed bandwidth of the free-space EIT in a homogeneously broadened Λ system that is limited by the natural linewidth of the atomic excited state (~ 6 MHz for the Rb system).

Fig. 3 plots the measured cavity transmission I_t (normalized to the peak transmission of the empty cavity I_0) versus the probe detuning Δ_p with a frequency-modulated (FM) control laser obtained by modulating the driving current of the diode laser at 15 MHz. The data were taken with three different modulation indices and the corresponding frequency spectra of the FM control laser are plotted in the inset figures of Fig. 3(a) to Fig. 3(b). The measurements present multiple peaks in the cavity EIT spectrum that matches the frequency spectrum of the FM control laser, and demonstrates the broadband characteristic of the cavity EIT with a broadband control laser.

Fig. 2 and Fig. 3 show that the cavity EIT is manifested by the two-photon Raman resonance of the free-space control light and the intra-cavity probe light. The transmission peak between the two vacuum Rabi sidebands (the normal modes) in Fig. 2(a) represents the intra-cavity dark state. The intra-cavity dark state is created at the two-photon resonance ($\Delta_p - \Delta \approx 0$) and its energy is shifted from the atomic resonance frequency by the detuning $\delta = \Delta_p \approx \Delta$. When $|\delta|$ approaches $g\sqrt{N}$, the control field interferes with the normal modes of the cavity-atom states and cavity EIT transmission peak disappears [19]. The probe transmission is maintained for δ values within the vacuum Rabi sidebands ($|\delta| \leq g\sqrt{N}$). The valid frequency range of the cavity EIT is therefore limited by the vacuum Rabi frequency $2g\sqrt{N}$. With a multi-frequency control field and a multi-frequency probe field, if each pair of the frequency components between the control and the probe satisfy the two-photon Raman resonance and the intensities of the components are moderate such that they do not cause the appreciable cross

coupling among different pairs, then the cavity EIT condition is kept for each pair and the multichannel cavity EIT with nearly equal amplitudes may be observed.

Since the transmission peak of the cavity EIT is accompanied by a steep normal dispersion, the probe light pulse with the cavity EIT propagates inside the cavity with reduced group velocity. Therefore, multi-frequency, multiple slow light pulses can be produced in the cavity EIT system. On the other hand, a short probe pulse with a large bandwidth ($< 2g\sqrt{N}$) can propagate with slow group velocity inside the cavity when a control laser matching the bandwidth of the probe pulse is present. Since the variation of the peak amplitudes of the cavity EIT in the frequency range $|\Delta| \leq \sqrt{N}g$ are small (unlike the free space, homogeneously or inhomogeneously broadened EIT system), the pulse distortion of the broadband slow light is minimized. It then appears that the cavity EIT system may be useful for studies of broadband classical and quantum light memories (with a tunable bandwidth determined by the number of atoms in the cavity mode) based on the well-established EIT technique [20-21].

4. Conclusions

In conclusion, cavity EIT is induced by the collective coupling of the cavity mode and coherently prepared multiple atoms inside the cavity mode and is manifested as a narrow transmission peak of a probe laser coupled into the cavity. The cavity EIT can be observed with the free-space control laser detuned from the atomic transition frequency when the free-space control field and the intra-cavity probe field satisfy the two-photon Raman resonance condition. We have observed the cavity EIT with nearly equal transmission amplitude in a frequency range within the vacuum Rabi sideband. With a FM modulated control laser, we observed the broadband cavity EIT, in which the probe transmission spectral features match that of the control laser. The broadband cavity EIT may be useful for applications in broadband, multichannel light memories.

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Figure Captions

Fig. 1 (Color online) (a) Λ -type three-level ^{85}Rb atoms coupled to a cavity mode with the collective coupling coefficient $\sqrt{N}g$ and interact with a free-space control field of Rabi frequency 2Ω . (b) Experimental set up. M: mirror; DL: extended cavity diode laser; $\lambda/2$ ($\lambda/4$): half (quarter)-wave plate; AOM: acousto-optic modulator; D: photon counter.

Fig. 2 (Color online) (a) Measured and (b) calculated cavity transmission spectra of the probe laser for a series of the control laser detuning. The two side peaks at $\Delta_p \approx \pm 50$ MHz represent the cavity-atom normal modes (vacuum Rabi sidebands). The peak between the two side peaks represents the cavity EIT and is located at $\Delta_p \approx \Delta$ (for the central peak from left to right, the corresponding control detunings are $\Delta = -30$ MHz, -10 MHz, 0 , 10 MHz, 14 MHz and 28 MHz, respectively). The parameters used in the numerical calculations are $\Omega = 1.5 \Gamma$ and $\gamma_{ab} = 0.01 \Gamma$ (the decoherence rate) with $\Gamma = 5.9$ MHz.

Fig. 3 (Color online) Measured cavity transmission spectra of the probe laser with a FM control laser (the modulation frequency is 15 MHz and the carrier frequency is resonant with the atomic transition). (a) to (c) correspond to different modulation index of the control laser. The inset figures plot the frequency spectrum of the FM control laser separately recorded with a Fabry-Perot spectral analyzer.

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