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Unveiling the relationship between optical bistability and vacuum Rabi splitting

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Abstract – The relationship between optical bistability (OB) and vacuum Rabi splitting is experimentally demonstrated in an atomic ensemble confined in a three-mirror optical cavity. The vacuum-induced splitting and bright states can effectively affect the bistable behaviour by manipulating multiple parameters such as atomic density and detuning. Also, we observed another kind of “∞”-shape OB by scanning the probe/cavity detuning. The study can make a contribution to better understand the OB and other dynamical behaviours in a composite atom-cavity system.

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Introduction. – The optical bistability (OB) in multilevel atoms confined inside an optical cavity [1–4] has been the subject of many recent studies because of its broad applications in all optical logic and memories performance [5–7]. Generally, the OB based on atomic coherence mainly results from the enhancement and modulation of the nonlinearity such as the intra-cavity dark state [8] and Kerr nonlinearity [9,10], and is demonstrated via a hysteresis loop on the cavity transmission spectra of the input light by scanning the input intensities with a definite range [11]. The coherence-enhanced nonlinearity is usually introduced and controlled by the electromagnetically induced transparency (EIT) [12–15] technique. Consequently, the investigated OB in multilevel (EIT) atomic systems can be potentially extended to solid-state atomic-like media [16], where the EIT-related effects are already observed, to provide a platform to realize the all-optical device. Moreover, vacuum Rabi splitting (VRS) [17] characterized as a double-peaked transmission spectrum has been reported in a strongly coupled multilevel atom-cavity system under EIT regime [18]. The VRS phenomenon represents the dynamical behaviors in the cavity-atom system and can be explained through the multiple dressed-state theory [19].

This letter focuses on the relationship between OB and VRS in a three-level atomic ensemble confined in a three-mirror optical ring cavity. The atom-cavity coupling strength $g\sqrt{N}$ and the added pump field play the roles of controlling and dressing fields. We find that the OB can be clearly obtained and amplified when the splitting of a bright state is observed in the cavity transmission spectrum. Here the bright state corresponds to the electromagnetically induced absorption (EIA) [20] condition and can be affected by the cavity dressing field and pump field. Also, we demonstrate another kind of “∞”-shape OB in this setup by scanning the detuning of the probe and cavity fields.

Experimental setup and basic theory. – The experiment is performed in a composite atom-cavity system as shown in fig. 1(a), which is composed of a three-mirror optical ring cavity containing a rubidium vapor cell with Brewster windows. The cavity with a length of 38 cm consists of two plate-concave mirrors $M_1$ and $M_2$ (with a reflectivity of 99.9% and 97.5% at 780 nm, respectively) and one plate mirror $M_3$ (97.5% at 780 nm). $M_1$ and $M_3$ act as the input and output mirrors, respectively. A piezoelectric transducer (PZT) is mounted on mirror $M_1$ to control the cavity length. The spatial arrangement of the lasers for connecting the energy level is shown in fig. 1(b), where a weak 780 nm beam $E_1$ (frequency $\omega_1$, wave vector $k_1$)
k, and Rabi frequency $G_1$) probes a lower transition $|0⟩$ (5S$1/2$, F = 3) to $|1⟩$ (5P$3/2$), while a strong 776 nm pump beam $E_2$ ($ω_2$, $k_2$ and $G_2$) connects the upper transition $|1⟩$ to $|2⟩$ (5D$3/2$). Here $G_i$ is the Rabi frequency between $|i⟩ → |j⟩$ and it is defined as $G_i = μ_{ij}E_i/(i = 1, 2)$, where $E_i$ is the electric field of laser $E_i$ and $μ_{ij}$ is the dipole momentum. The resonant frequencies for transitions $|0⟩ ↔ |1⟩$ and $|1⟩ ↔ |2⟩$ are defined as $Ω_1$ and $Ω_2$, respectively. The frequency detuning of each field is given as $Δ_1 = Ω_1 − ω_i (i = 1, 2)$. Beam $E_1$ (horizontally polarized) counterpropagates with $E_2$ (vertically polarized), and an EIA window satisfying $Δ_1 + Δ_2 = 0$ is introduced into the probe field due to the two-photon resonance. The probe beam with $E_1$ then circulates inside the ring cavity and partially transmits through the output mirror $M_3$. The output cavity mode is detected by an avalanche photodiode detector (APD).

The transmitted cavity mode formed by the probe field indicates that the cavity interacts with confined atoms with a strength of $gN^{1/2}$, where $g$ and $N$ represent the single-atom-cavity coupling strength and the atomic density, respectively. By assuming that all the atoms initially locate at state $|0⟩$ (5S$1/2$, F = 3), the cavity mode under the weak-cavity field limitation can be derived from the master equation based on the atom-cavity coupling picture [19], and be expressed as (see details in the Supplementary Information Supplementary material.pdf)

$$a = -g\sqrt{N}G_1 \left[ d_c \left( d_1 + \frac{|G_2|^2}{d_2} + \frac{g^2N}{d_c} + \frac{|G_{F}|^2}{Γ_{00}} \right) \right]^{-1},$$

(1)

where $d_1 = Γ_10 + iΔ_1$, $d_2 = Γ_20 + i(Δ_1 + Δ_2)$, and $d_c = γ + i(Δ_1 − Δ_{ac})$ with $γ$ defined as the cavity loss; $Δ_{ac} = Ω_1ω_3$ with $ω_3$ being the resonant frequency of the cavity; $G_F$ is the intensity of the cavity feedback. The term $Γ_{ij} = (Γ_i + Γ_j)/2$ is the decoherence rate between $|i⟩$ and $|j⟩$, and $Γ_i$ is the decay rate of level $|i⟩$. $Γ_{00} = Γ_0 ≈ 0.1$ MHz results from the collisions of particles at two hyperfine levels ($F = 2$ and $F = 3$) of the ground states 5S$1/2$.

With both fields turned on but the probe field not oscillating inside the cavity (namely, the case in the free space), only the dressing effect $|G_2|^2/d_2$ from the pump field $E_2$ is involved in the output intensity of the probe field. Clearly, the transmitted probe cavity mode, which is different from the case in the free space, can be affected by the feedback from the output intensity $|G_{F}|^2/Γ_{00}$ and the dressing effect $g^2N/d_c$ from the cavity field. The OB caused by the strong feedback effect and the self-dressing effect vs. the input power ($I_{in}$) or frequency ($ω_1$) of the probe field can be understood as

$$\frac{I_{out}}{I_{in}} ∝ |g\sqrt{N}d_c \left( d_1 + \frac{|G_2|^2}{d_2} + \frac{g^2N}{d_c} + \frac{|G_{F}|^2}{Γ_{00}} \right) |^{-1}^2,$$

(2)

where the intensity $I_{out}$ of the cavity output and the intensity $I_{in}$ of the input field are proportional to $|a|^2$ and $|G_1|^2$, respectively.

Figure 1(c) shows the theoretical simulations of VRS and OB according to eqs. (1) and (2). Next, we will experimentally investigate the relationship between OB and VRS by changing the density of the atomic vapour and the detuning of the probe or cavity field.

Results and analysis. – At first, we turn the pump field off and observe the OB resulted from the Rabi splitting as shown in fig. 2. With the temperature of the medium set at 50 °C, there is no splitting appearing on the transmission spectrum from the cavity when the probe detuning $Δ_1$ is periodically modified. By settling $Δ_1$ at the point corresponding to the transmitted peak (marked by an arrow, where $Δ_{ac} = Δ_1 = 0$) in fig. 2(a1), the cavity output by continuously changing the input power is shown in fig. 2(a2), where it has no clear OB phenomenon. Then we keep detuning at $Δ_1 = 0$ and increase the cavity detuning to $Δ_{ac} = 10$ MHz, the OB phenomenon is still not observed, as shown in fig. 2(a3). Next, we heat up the vapor to 70 °C and obtain the VRS shown in fig. 2(b1) by scanning $Δ_1$. The cavity-atom coupling is so strong
that the sides of the generated double peaks are nearly vertical in the middle zone. We modify the detuning as \( \Delta_1 = -70 \text{MHz} \) (corresponding to the left peak marked by an arrow in fig. 2(b1)) and observe the OB by increasing the cavity detuning. As a result, fig. 2(b3) depicts the strong OB phenomenon vs. the input power. So we conclude that the VRS can dramatically enhance the intensity-induced OB behavior, which can also be controlled by the cavity field.

The OB effect in the atom-cavity system is caused by the modification of the Kerr nonlinearity, which is effectively influenced by the self-dressing term \( |G_F|^2 / |I_{\text{in}}| \). The observed VRS phenomenon is induced by the term \( g^2 N \), which represents the atom-cavity coupling effect. Considering the cascade relationship between \( I_c \) (which proportionally determines the feedback effect) and \( g^2 N \) [19] on the right-hand side of eq. (2), term \( g^2 N \) can establish the internal physical relationship between OB and VRS. Actually, the generated VRS and OB effect both result from the modification of the dispersion properties in the EIT medium.

In fig. 3, we turn the pump field on and study the relationship between bright state and VRS as well as OB. In fig. 3(a1), the cell temperature is 50 °C and the transmitted spectrum shows a single peak. In figs. 3(a2)–(a4), we discrete increase the cavity detuning \( \Delta_{ac} \) and find that there is no OB occurring vs. the input power. Then the temperature is raised to 70 °C and the spectrum shows three peaks by scanning \( \Delta_1 \), as shown in fig. 3(b1). These three peaks are caused by the combined effects from the cavity field and the pump field. With \( \Delta_1 \) tuned to the point of the left peak (marked by the arrow in fig. 3(b1)), we can observe OB phenomena in figs. 3(b3), (b4) by growing \( \Delta_{ac} \). Here the OB is the result from the term \( g^2 N / d_c + |G_2|^2 / d_2 \) in eq. (2), where the first term \( g^2 N / d_c \) corresponds to the cavity field and the second one \( |G_2|^2 / d_2 \) to the pump field. By comparing the size of unstable regions in figs. 3(b3) and (b4), we can conclude that the cavity detuning can change the term \( g^2 N / d_c \) and further influence the unstable region (which visually represents the degree of OB) as expressed in eq. (2). Next, we tune the probe detuning to the point of the right peak (marked by the arrow in fig. 3(c1)) and find that the unstable region diminishes when the cavity detuning increases as shown in figs. 3(c2)–(c4), contrary to the tendency in figs. 3(b2)–(b4). Evidently, the region size is also shifted due to modification of the probe and cavity detuning by considering the term \( d_c = \gamma + \Omega (\Delta_1 - \Delta_{ac}) \) in eq. (2). The observations show that the bright state can impose influence on the VRS and further on the OB behavior.

In fig. 4, we demonstrate a new kind of OB. The feedback effect in the cavity also introduces a dressing effect and further induces greatly modulated nonlinearity, which can also result in the OB by scanning the cavity/probe detuning. Generally, the nonoverlapped region of OB is related to the nonlinear refraction shift \( \Delta n \) described as

\[
\Delta n = N (n_2^h I_{\text{out}}^h - n_2^l I_{\text{out}}^l),
\]

where \( n_2^h (n_2^l) \) is the nonlinear refraction index corresponding to the output intensity \( I_{\text{out}}^h (I_{\text{out}}^l) \) in the frequency-increasing (frequency-decreasing) ramp of the scanning triangle wave. Compared to the situation in free space, \( n_2 \) is greatly enhanced by the dressing feedback of \( I_{\text{out}} \) inside the cavity. Differently from the cases in figs. 2 and 3 (where OB shows the square unstable region), the new OB phenomenon is majorly reflected as the frequency difference between the generated signal peaks. In fig. 4(a1), we obtain the transmission spectrum by scanning the cavity detuning (by using a triangle wave with a repetition of 10 Hz) and observe the frequency difference of the cavity modes in one scanning period consisted of one rising ramp and one falling ramp. The feedbacks of the cavity output in the rising ramp and falling ramp are different in intensity. Such difference can result in different nonlinear refraction \( \Delta n \), and further produces the “\( \infty \)”-shape OB vs. the detuning.

Figures 4(a2)–(a4) show the evolution of the nonoverlapping region by increasing the pump power vs. \( \Delta_{ac} \).
The observations show that the frequency difference can grow with the input power $P_2$. Additionally, we scan the probe detuning and obtain the “∞”-shape OB in the spectrum shown in figs. 4(b1)–(b4), which indicate that the frequency gap between two peaks can increase rapidly with the temperature at a definite range, and then decrease slightly at higher temperature. Theoretically, the frequency difference should increase with atomic density, namely, temperature. However, a higher temperature means more absorption as well as weaker feedback, which indicates the shrink of the frequency gap.

Conclusions. – In summary, we have investigated the relationship between OB and VRS as well as the coherence-induced bright state in a cavity-atom composite system. Multiple parameters, such as atomic density and probe/cavity detuning can control the size of the unstable region corresponding to the degree of OB. Also, by scanning probe/cavity detuning, another kind of frequency-induced OB is observed under different experimental conditions. The study could potentially provide a way to improve the applications related to the normal OB such as logic-gate devices and optical information processing.

REFERENCES


