

Controlling optical bistability in a three-level atomic system

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We have experimentally studied the optical bistable behavior in an optical ring cavity filled with a collection of three-level Λ -type rubidium atoms, interacting with two collinearly propagating laser beams. The bistability so observed is very sensitive to the induced atomic coherence in this electromagnetically induced transparency system or consequently to the altered nonlinearity in the system and, thus, can easily be controlled by changing the intensity and the frequency detuning of the coupling field.

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In the recent past, a great deal of attention has been paid to observing and understanding the phenomenon of optical bistability (OB) in two-level atoms confined in an optical cavity, due to its potential applications in all-optical switches, memories, and optical transistors [1]. The saturation of atomic transition and intensity-dependent refractive index of the media are attributed to two different physical mechanisms for absorptive OB and dispersive OB, respectively [1–3]. The bistable states of the optical cavity output appear only for a definite range of input intensities [4] and the intensity of the upper branch of the bistable curve shows an instability behavior for some parametric conditions [5]. The cold atomic cloud of cesium atoms is yet another system which shows OB as well as instability in which the Zeeman sublevels in the $6S_{1/2}$, $F=4$ to $6S_{3/2}$, $F=5$ transition of cesium atoms interact with a circularly polarized laser beam in an optical cavity. However, there are limitations to this experiment because of the lack of control due to only one laser beam being employed for both optical pumping and saturation, and the optical cavity was not locked in observing OB and instability [6].

Recently, electromagnetically induced transparency (EIT) and related effects in multilevel atomic systems have attracted great attention [7–9]. The induced atomic coherence in multilevel atomic systems can not only modify the linear absorption and dispersion properties, but can also enhance the nonlinear optical processes such as four-wave mixing [10,11], harmonic generation [12,13], and two-photon absorption [14]. More recently, the enhanced third-order Kerr-nonlinear index of refraction (n_2 , in the expression of $n = n_0 + n_2|E|^2$) was measured near the EIT condition, as well as near the more general coherent population trapping (CPT) conditions in three-level Λ -type rubidium atoms inside an optical cavity [15]. It is interesting to note that at the exact EIT or CPT condition, i.e., when both the coupling and probe frequency detunings are zeros, n_2 is zero. However, if one of the frequency detunings is even slightly tuned to be nonzero, the value of n_2 is greatly enhanced as compared to the situation when there is no coupling beam present (as in a two-level situation). Detailed studies of the variations of n_2 with

intensities and frequency detunings of both coupling and probe beams were reported earlier [15], which motivated us to further explore the bistable characters in this EIT system with the help of the enhanced nonlinearity due to atomic coherence.

The present work is built upon our preliminary observation (which mainly studied the instability behavior) [16] and is a further experimental investigation of the OB as functions of various parameters in the composite system consisting of three-level Λ -type Rb atoms and an optical ring cavity. The aim of this work is to experimentally demonstrate the controllability of OB behaviors in this system by varying the intensity and the frequency detuning of the coupling laser beam. These additional experimental controls provided by the coupling laser beam do not exist in the previous systems using two-level atoms for OB [1–5] or in the system with multi-Zeeman-levels but using only one laser beam [6]. Another advantage of our experimental setup is its simplicity with atoms in a vapor cell (no atomic beam or cooled atomic sample under vacuum is needed) in two-photon Doppler-free configuration to overcome the first-order Doppler effect [9]. The enhanced nonlinearity here due to atomic coherence can relate to the effect reported in an earlier experiment with sodium vapor filled in a Fabry-Perot cavity [17], where the two different frequencies for the atoms in a particular group of velocity distribution is provided by counterpropagating beams. Controlling OB can have practical applications in all-optical switches, memories, transistors, and logic circuits, which have no need for optical-electronic-optical conversion of signal information. Due to the enhanced Kerr nonlinearity in the three-level atomic system owing to atomic coherence, the switching thresholds of such devices can reduce down considerably, and hence controlling becomes easier and more efficient, which is also essential in order to process optical signals faster and reliably at very low intensity levels of light. Some interesting theoretical results for OB have been reported for three-level atoms confined in an optical cavity under various conditions [18].

The experiment was carried out in a three-level Λ -type system of ^{87}Rb atoms using the D_1 lines of $5^2S_{1/2} \rightarrow 5^2P_{1/2}$ transitions as depicted in the bubble of Fig. 1. The probe laser beam (i.e., the cavity field with frequency ω_p) is tuned to the atomic transition $|1\rangle$ ($F=1, 5^2S_{1/2}$) to $|2\rangle$ ($F'=2,$

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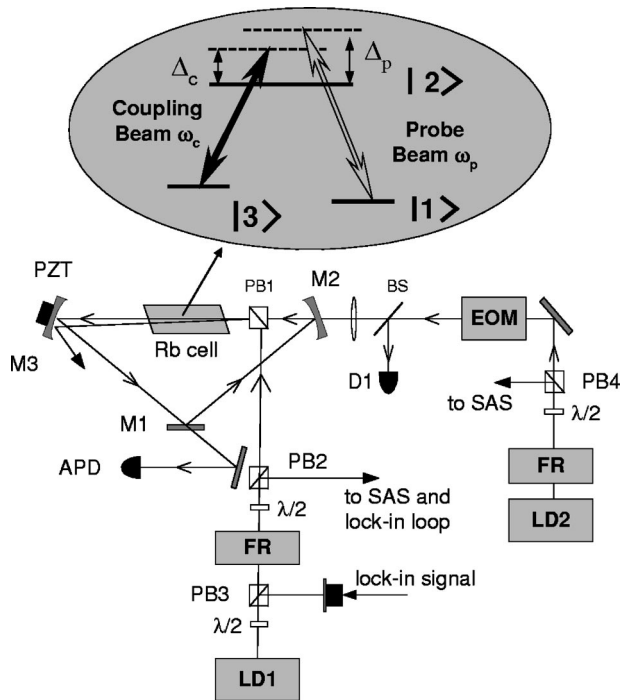


FIG. 1. The experimental setup: $M1$ - $M3$ are mirrors of the optical ring cavity; $LD1$ and $LD2$, coupling and probe lasers, respectively; $PB1$ - $PB4$, polarizing cubic beam splitters; $\lambda/2$, half-wave plates; FR , Faraday rotators; $D1$, detector; APD , avalanche photodiode detector. SAS is a saturation atomic spectroscopy setup. Bubble, a three-level Λ -type system in the D_1 lines of ^{87}Rb .

$5^2P_{1/2}$) with frequency ω_{12} , while the coupling beam (frequency ω_c) is tuned near the atomic transition $|3\rangle$ ($F=2$, $5^2S_{1/2}$) to $|2\rangle$ with frequency ω_{23} . The frequency detunings of the probe laser beam and the coupling laser beam are defined as $\Delta_p = \omega_p - \omega_{12}$ and $\Delta_c = \omega_c - \omega_{23}$, respectively. The rubidium atomic vapor is contained in a 5-cm-long cell having Brewster windows which is wrapped in a μ -metal sheet and heated to about 67.5°C in our experiment. The cell is placed in an optical ring cavity comprising of three mirrors. The flat mirror $M1$ has a reflectivity of 99%, while the concave mirrors $M2$ and $M3$ (both having $R=10$ cm) have reflectivity of 97% and 99.5%, respectively. The mirror $M3$ is mounted on a piezoelectric transducer (PZT). The cavity finesse (\mathcal{F}) with the Rb atomic vapor cell is measured to be about 55 (far from any resonant absorption line) and the free spectral range to be 822 MHz (for the total cavity length ~ 37 cm). The probe laser beam enters through mirror $M2$ and circulates in the cavity in a single direction. The coupling beam is introduced through a polarizing beam splitter with an orthogonal polarization with respect to the probe beam and does not oscillate in the cavity. A third laser has been used as a reference beam to lock the frequency of the optical cavity to a Fabry-Perot cavity. All three diode lasers used in the experiment are home-built extended-cavity diode lasers with current and temperature stabilization. All the three lasers are frequency locked to their respective Fabry-Perot resonators. The measurement of frequency detuning Δ_c or Δ_p can easily be carried out by another Fabry-Perot cavity in conjunction with a saturation absorption spectroscopy

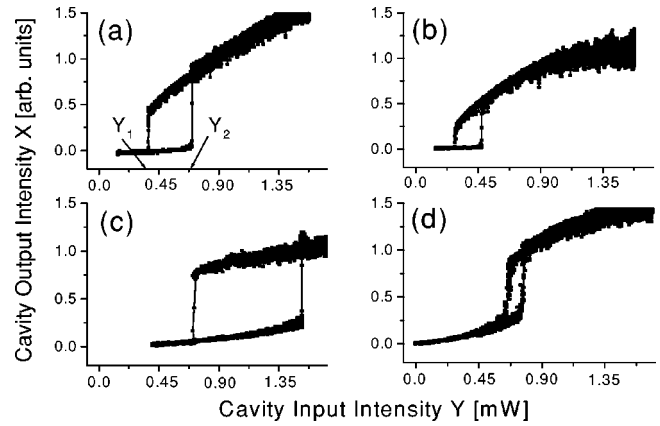


FIG. 2. The input-output intensity characteristics of the optical cavity with $\Delta_p=0$. (a) is for $P_C=1.5$ mW, $\Delta_C=51.4$ MHz; (b) is for $P_C=1.5$ mW, $\Delta_C=25.7$ MHz; (c) is for $P_C=8.4$ mW, $\Delta_C=85.6$ MHz; and (d) is for $P_C=8.4$ mW, $\Delta_C=256.8$ MHz.

copy (SAS) setup. The cavity input intensity is controlled by an electro-optical modulator (EOM) that produces a nearly triangular modulation of the cavity input intensity.

We first stabilize the temperature of the rubidium vapor cell around 67 – 68°C . The probe laser is tuned near the desired transition of D_1 line of ^{87}Rb . The coupling laser frequency is also tuned to observe EIT. We then lock the laser frequencies ω_p and ω_c to certain desired detuning values by their respective Fabry-Perot cavities and scan the optical ring cavity around its resonance by scanning the PZT on $M3$ with a ramp voltage. In the absence of the coupling laser beam the cavity transmission profile is basically symmetric. In the presence of the coupling beam this transmission profile becomes asymmetric indicating the existence of the Kerr nonlinearity which is a sensitive function of Δ_c [15]. After these initial settings, we lock the frequency of the optical ring cavity onto the transmission peak of the reference laser beam. The EOM in the path of the probe beam ($LD2$) is then switched-on, and a triangular modulation of cavity input intensity with a duration of 5 ms is applied. Without the coupling beam we could not observe any OB, but some kind of optical-transistor-like behavior is obtained. Also, when the coupling beam is on, but both $\Delta_c=0$ and $\Delta_p=0$, even with a quite high P_C there is no OB observed. As soon as one of the frequency detunings (Δ_p or Δ_c) is set to a nonzero value (few MHz), we start to observe OB for a wide range of P_C .

Figure 2 displays several experimentally observed OB curves controlled by coupling beam (Δ_c and P_C) keeping other parameters (like atom number density, cavity detuning, and Δ_p) fixed. Figure 2(a) represents a typical OB under the conditions of $\Delta_p=0$, $\Delta_c=51.4$ MHz, $P_C=1.5$ mW, and cavity detuning of about 40 MHz. The next figure [Fig. 2(b)] clearly shows how we can control the OB by simply changing the parameter Δ_c to 25.7 MHz. Both switching thresholds (Y_1 and Y_2) and width (Y_2-Y_1) of OB can be controlled by changing Δ_c alone and keeping P_C fixed. We define switching threshold intensities Y_1 (the lower one) and Y_2 (the upper one) at $dY/dX=0$ in the OB hysteresis curve. In next two figures [Figs. 2(c) and 2(d)] we keep $P_C=8.5$ mW fixed, but tune Δ_c to 85.6 MHz and 256.8 MHz,

respectively. Dramatic changes in the shapes of the OB hysteresis curves are apparent. Thus, the bistability range and the switching intensity thresholds Y_1 and Y_2 can be controlled very effectively by P_C and Δ_C . In general, the OB intensity threshold values are functions of many parameters such as Δ_p , cavity detuning, atomic number density (or cooperativity parameter), P_C , and Δ_C . At the exact condition of EIT or CPT ($\Delta_p=0$, $\Delta_C=0$), $n_2=0$, so the bistable behavior should be governed by the absorption. However, since absorption is greatly reduced at such EIT or CPT condition, the absorptive bistability is also inefficient and might need much higher input intensity. The moment we set nonzero Δ_C but $\Delta_p=0$ [Figs. 2(a) and 2(b)] the switching thresholds come down drastically from the situation where $\Delta_C=0$ and $\Delta_p=0$ with no OB. The reason of observing OB at quite low intracavity field intensity and low coupling intensity is a result of the enhanced Kerr nonlinearity near resonance due to induced atomic coherence by the coupling beam interacting with the nearby transition slightly off-resonance (i.e., $\Delta_C \neq 0$). This kind of OB is a mixture of absorptive and dispersive types where the dispersion (or phase detuning) is greatly enhanced by the Kerr nonlinearity, as measured in Ref. [15]. With the increase of Δ_C to further higher values [Fig. 2(c)] the nonlinearity in the system reduces down, and hence the switching intensity Y_2 as well as the width of the hysteresis cycle increase. For a very large coupling detuning [$\Delta_C = 256.8$ MHz, Fig. 2(d)] the nonlinearity sharply reduces in such three-level system and the dispersion due to frequency detuning dominates, which is similar to the two-level dispersive OB situation. As a result, the shape and width of OB curve modify considerably. These measured results are consistent with the previous work on the measurements of n_2 in this system [15]. The cooperativity parameter C , traditionally defined as $C = (\alpha_0 l / 4\pi) \mathcal{F}$ ($\alpha_0 l$ is single pass absorption) in two-level OB systems [1–5], can be estimated with the measured atomic absorption and cavity finesse under the EIT condition in the experiment.

In order to quantify the behaviors of the OB with variation of Δ_C at a given P_C , we have carried out further experimental measurements and present results in Fig. 3 where the switching threshold intensity ratio Y_2/Y_1 is plotted as a function of Δ_C for two different coupling intensities (curve A for $P_C=8.4$ mW and curve B for $P_C=1.5$ mW). At very small Δ_C , the ratio Y_2/Y_1 is small (indicating a lower OB threshold) because of the enhanced Kerr nonlinearity near resonance. With increasing Δ_C , there is an increase in Y_2/Y_1 because the nonlinearity reduces down substantially. However, a small drop near $\Delta_C=50$ is observed for both P_C values. Note that $\Delta_C=50$ is the point near where the change in the sign of n_2 takes place for a certain value of P_C [15]. For larger Δ_C there is also a reduction in Y_2/Y_1 , which could be a combined effect of dispersion due to Δ_C alone (at larger Δ_C , the Kerr nonlinearity n_2 drops down appreciably and the system behaves like a two-level atomic system) and a slight cavity drift [3]. We have also observed a similar dependence of the width of OB hysteresis cycle with the changing Δ_C .

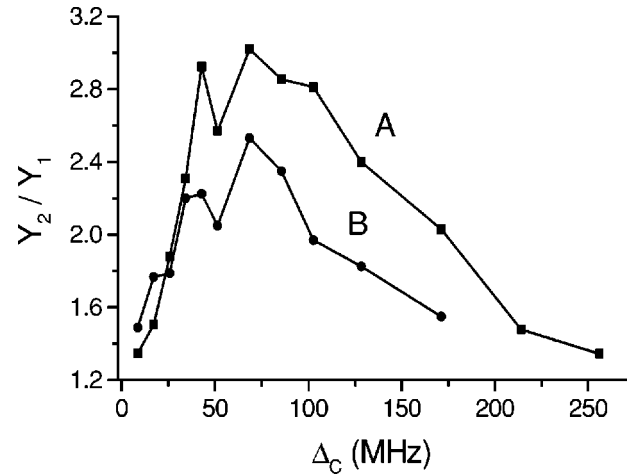


FIG. 3. Ratio of switching threshold intensities Y_2/Y_1 as a function of Δ_C . Curve A is for $P_C=8.4$ mW and curve B is for $P_C=1.5$ mW.

Next, we have studied the dependence of switching thresholds for a fixed Δ_C on the variation of P_C . The results are depicted in Fig. 4, in which curves A and B represent switching threshold ratio Y_2/Y_1 for $\Delta_C=42.8$ MHz and 17.1 MHz, respectively. The curve A rises with an increasing P_C which is most likely due to the decrease in the Kerr nonlinearity with increasing coupling power for this value of Δ_C , and is consistent with our measurements of n_2 [15]. However, we find an opposite behavior in curve B which is slightly descending with the increase of P_C and this is again because of the increasing nonlinearity with the increase of P_C at this particular frequency detuning Δ_C [15].

The observed OB behaviors in such three-level EIT system are quite different from the previously studied two-level atomic systems. Due to the induced atomic coherence near EIT resonance, the absorption, dispersion, and nonlinearity are all greatly altered [7–15]. For example, the absorption reduction [7–9] and the great enhancement of the Kerr-nonlinear index at near EIT resonance [15] make the distinction between absorptive and dispersive regions for OB impossible near resonance. It will be interesting to find the

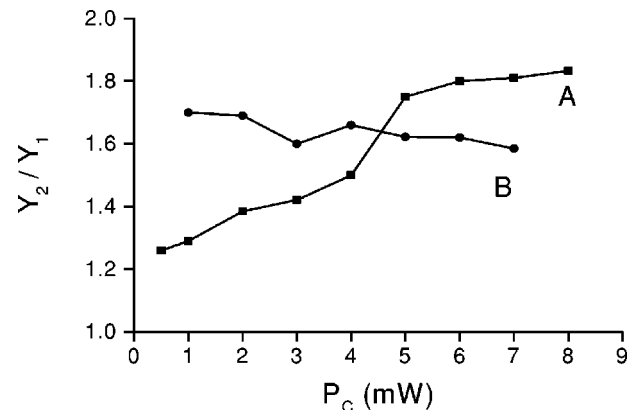


FIG. 4. Ratio of switching threshold intensities Y_2/Y_1 as a function of P_C . Curve A is for $\Delta_C=42.8$ MHz and curve B is for $\Delta_C=17.1$ MHz.

optimal conditions for achieving the desired OB behaviors for both fundamental studies and practical applications. Our experimental demonstration of controlled OB with the coupling beam intensity and frequency detuning provides an important step towards this goal.

In summary, we have experimentally demonstrated the controllability of atomic optical bistability in a three-level EIT system inside an optical ring cavity. This is, to our knowledge, the first detailed experimental study of OB in a three-level EIT system. By controlling the threshold intensities and the width of OB with the intensity and frequency detuning of the coupling beam, one can build more efficient all-optical switches and logic-gate devices for optical com-

puting and quantum information processing. Due to the reduced absorption and the enhanced Kerr nonlinearity via atomic coherence in this EIT system, the switching threshold value (Y_2) is greatly reduced to make the optical switches more efficient with the possibility to operate at much lower light intensities. Complete understanding of these interesting OB phenomena will require a proper and complete theoretical calculation matching our experimental conditions.

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