Optical Multistability in Three-Level Atoms inside an Optical Ring Cavity

Amitabh Joshi and Min Xiao*
Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701, USA
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Optical multistability in an optical ring cavity filled with a collection of three-level Λ-type rubidium atoms has been experimentally demonstrated. The observed multistability is very sensitive to the induced atomic coherence in the system and can evolve from a normal bistable behavior with the change of the coupling field as well as the atomic number density. The underlying mechanism for the formation of such multistability is also discussed.

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Atomic optical bistability (AOB) in two-level atomic systems has been extensively studied both experimentally and theoretically in the past 20 years [1–5]. Such optical bistable behavior arises from the nonlinear interaction between a collection of two-level atoms and the field mode inside an optical cavity. Because of the Doppler effect, atomic beams were used for observing such AOB in these two-level atomic systems [2,3,5]. Many interesting phenomena in these AOB systems such as dynamic instabilities, squeezed states, cavity QED, and higher-order quantum correlation were all experimentally observed [6]. Also, bistable behaviors were predicted [7] and observed [8] in three-level atomic systems in recent years. Typically, those observed AOB phenomena were divided into two distinct categories, i.e., absorptive and dispersive bistability which have quite different characteristics [1–5].

Optical multistability (OM) was predicted and observed in systems involving interactions between nonlinear media and two different optical cavity field modes [9–12]. In particular, Kitano *et al.* [9] calculated optical tristability in a three-level Λ configuration under the limiting condition of large atomic detuning with no saturation, which was experimentally observed by Cecchi *et al.* [10]. This work was generalized by Savage *et al.* to include saturation in the dispersive limit [11]. Later, Arecchi *et al.* included the effect of ground-state coherence and reported not only tristability but also higher-order bistability [12]. The tristability generated here [12] involved a two-photon process via the cooperation of a bistability generation process. Several groups reported the observations of multistable/multiple hysteresis behaviors in a Fabry-Perot cavity filled with atoms having several degenerate or nearly degenerate sublevels in the ground state and driven by linearly polarized light [13–15]. In the transmitted light polarization switching occurs and three different states of polarization can dominate, giving rise to a transition from tristability to symmetry breaking bifurcation attributed to a change in cavity length or atomic density in the experiment of Giacobino [13]. The intricate multistable behavior, as observed by Nalik *et al.* [14], was a combined effect of Zeeman pumping and electronic excitation. Most of these experiments used magnetic fields and buffer gases, and relied on the Zeeman coherence as an efficient mechanism for the observed AOB/OM.

In this Letter, we report the experimental observation of a new kind of OM in a three-level Λ-type atomic system in a Rb vapor cell inside an optical ring cavity under different conditions. A simple physical model is given for understanding the appearance of such OM in this interesting system of electromagnetically induced transparency (EIT) [16,17] inside an optical cavity, in which AOB and dynamic instability were observed previously [8]. By varying the frequency detuning of the coupling laser beam or the atomic number density, transition from normal optical bistable behavior to the multistable one is achieved and controlled. Our ability of observing such OM stems from the enhanced Kerr nonlinearity due to atomic coherence in such a composite system [18] and the controllability of the coupling laser beam. Another advantage of our experimental setup is the use of an atomic vapor cell inside the optical cavity instead of atomic beams or a cold atomic sample, so we can increase the atomic density to a high value, which is essential for observing such OM. Because of the two-photon Doppler-free configuration used in our experiment, i.e., copropagation of the cavity field and the coupling field for the EIT transition, the first-order Doppler effect is eliminated [17]. With controllability of the intensity and frequency detunings of the coupling and cavity fields, as well as the atomic density, we can manipulate the absorption, dispersion, and nonlinear optical properties of the atomic medium inside the optical cavity, which provides us a unique opportunity for studying the OM in this system.

The three-level Λ-type atomic system and the experimental setup used in the experiment are similar as in Ref. [8]. The lower two levels of the atomic system designated as $|1\rangle$ and $|3\rangle$ correspond to the $F = 1$ and $F = 2$ states of $5S_{1/2}$ in ^{87}Rb, respectively, and the upper level $|2\rangle$ corresponds to the $F' = 2$ state of $5P_{1/2}$. The probe laser (frequency ω_p) is tuned near the transition frequency of $|1\rangle$ to $|2\rangle$, and the coupling laser (frequency

ω_C) is close to the transition frequency of $|3\rangle$ to $|2\rangle$. Corresponding atomic detunings are defined as $\Delta_P = \omega_P - \omega_{21}$ and $\Delta_C = \omega_C - \omega_{23}$, respectively. The two Hitachi HL7851G tunable diode lasers are temperature and current stabilized. A feedback loop is used for each of these lasers for further stabilization. The rubidium atomic vapor is contained in a 5 cm glass cell with Brewster windows. Magnetic shielding of the cell is provided by a μ-metal sheet wrapped around it and the temperature of the cell is controlled by a heating tape outside the μ metal. The vapor cell is placed in the optical ring cavity, which is formed by three mirrors (one flat and two concave with $R = 10$ cm). The beam waists of the coupling and cavity fields at the center of the vapor cell are 700 and 80 μm, respectively. One of the concave mirrors (high reflector) is mounted on a piezoelectric transducer (PZT). The probe laser enters through the other concave mirror (transmissivity 3%) and circulates in the cavity. The flat mirror (with transmissivity of about 1%) serves as the output coupler. The coupling laser having orthogonal polarization to the probe laser enters the cavity through a polarizing beam splitter and does not circulate in the cavity. The finesse of the cavity is measured to be ~50 (with the cavity field tuned far away from the atomic transitions) and the free spectral range to be 822 MHz. In order to lock the optical cavity, a third diode laser is used. The three diode lasers used in the experiment are all frequency locked to their respective Fabry-Perot cavities. The triangular scan of the cavity field is provided by an electro-optical modulator (EOM).

We first set the probe laser near the desired transition ($|1\rangle$ to $|2\rangle$) and then tune the coupling laser to another transition ($|3\rangle$ to $|2\rangle$) in the three-level Λ-type system to meet the EIT condition. The optical cavity is scanned across its resonance by applying a ramp voltage to the PZT on one of the cavity mirrors. The cavity transmission profile is symmetric when probe laser frequency is far off from the atomic transition frequency ω_{21}. The cavity transmission peak becomes asymmetric as the frequency detunings of the probe and coupling fields are tuned near resonance, indicating enhanced Kerr nonlinearity in the atomic medium [18]. Next, the frequency of the optical cavity is locked to the reference laser and the EOM scans the intensity of the cavity input field. Without the coupling beam, or with Δ_C and Δ_P both zeros, we do not observe any bistability. At $\Delta_P = 0$ and Δ_C small with a reasonable coupling beam power ($P_C = 1.5$ mW), we observed typical absorptive AOB, which has a low lower-branch intensity due to strong absorption. The temperature of the vapor cell was at 67.5 °C which corresponds to an atomic density of about 6×10^{11} atoms/cm^3. When Δ_C is increased to a large value, a dispersive-type bistable curve appears, which is characterized by a relatively high lower-branch intensity [8]. Those absorptive and dispersive bistable curves are similar to the ones observed in two-level atomic systems [1–5].

However, with increased temperature and nonzero Δ_C and Δ_P, an interesting OM curve appears. Figure 1 displays a typical OM curve observed in such a system under the experimental conditions of $P_C = 8.5$ mW, $T = 90.5$ °C, $\Delta_C = 43$ MHz, and $\Delta_P = 64$ MHz. There are a pair of tristable steady-state points on the extended hysteresis cycle. The arrows marked on the curve show the paths taken by the cavity field intensity as the input field power is scanned from zero to about 4.5 mW and back down to zero again. Clearly, this observed OM phenomenon in the three-level atomic system inside an optical ring cavity is in marked contrast with what has been previously reported [13–15].

We have numerically solved the density operator equations governing the dynamics of these three-level Λ-type atoms [17,18] inside an optical cavity including the Doppler effect to find out the polarization; we then integrated the Maxwell's equation [1] under steady-state conditions and obtained varieties of bistable and multistable characteristics of the system with different parameters. The steady-state polarization $P(\omega_P)$ solved from the density operator equations is a ratio of two polynomials of order 5 and 6 in Ω_P in the form of [7]

$$P(\omega_P) = \frac{\Omega_P[a_1 + a_2|\Omega_P|^2 + a_3|\Omega_P|^4]}{b_1 + b_2|\Omega_P|^2 + b_3|\Omega_P|^4 + b_4|\Omega_P|^6}, \qquad (1)$$

in which the complex numbers a_i and b_i are functions of Δ_C, Δ_P, P_C, atomic density, and decay constants. This form of $P(\omega_P)$, showing higher-order nonlinearities and complicated dependence of absorption/dispersion on system parameters, is responsible for the OM observed in this three-level atomic system. In the case of two-level atoms, $P(\omega_P)$ reduces to a ratio of linear to quadratic polynomial in Ω_P and, hence, only bistability can occur. Although we have obtained an analytical expression in the form of Eq. (1) for this system, we choose not to discuss this complicated expression further. Instead,

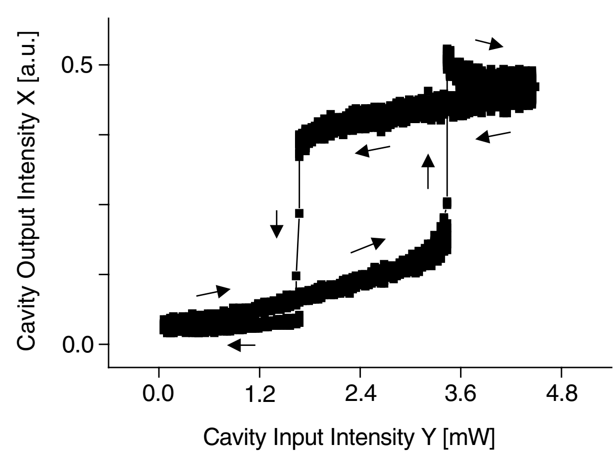

FIG. 1. Observed OM in the input-output intensity characteristics of the system with the parameters $\Delta_P = 64$ MHz, $\Delta_C = 43$ MHz, $T = 90.5$ °C, and $P_C = 8.5$ mW.

we provide a simple physical model to explain the observed OM.

During the experiment, we notice that the multistable behavior appears only between the typical absorptive and dispersive parametric regions. To see this more clearly, we plot two curves, (*i*) and (*ii*) in Fig. 2, which represent pure dispersive and pure absorptive bistability, respectively, for parameters close to our experimental conditions. In plotting curve (*i*) [(*ii*)], we artificially remove the contribution of absorption (dispersion) from the expression representing relation between cavity input and output intensities [1]. As indicated by the arrows on the curves, when the cavity input intensity increases, the cavity output intensity follows the dispersive bistable curve (*i*) to its upper threshold point *A*, where the output intensity jumps up to the upper branch of the dispersive curve at point *B*, and further increases on this dispersive bistable curve (*i*). However, when the input intensity is scanned down, the output intensity switches to the upper branch of the absorptive bistable curve (*ii*) at the crossing point *E* and follows it down to its lower threshold point *C*, where it jumps down to *D*, then back to zero. When one looks at the path (the solid curve *OABECDO*) taken by the cavity output intensity, it mimics the multistable curve observed in our experiment, as shown in Fig. 1. Notice that the new hysteresis cycle (solid line) stays on the stable parts of the two bistable curves (*i*) and (*ii*). Therefore, we can attribute the observed OM to the coexistence of both absorptive and dispersive optical bistabilities uniquely realized in this system. This seems not to be a simple transition from absorptive to dispersive behavior. The output intensity stays on one of the bistable curves, except it makes a switch at the high intensity point *E*.

In order to have a better understanding of the observed OM, we carried out two different sets of experiments with the variations of parameters. Figure 3 shows the transition from AOB to OM as we increase the atomic number density by raising the temperature of the Rb vapor cell. At a low temperature ($T = 65.4\,^\circ$C), with other parameters set at $\Delta_P = 0$, $\Delta_C = 42.8$ MHz, and $P_C = 8.5$ mW, a typical AOB curve appears, as shown in Fig. 3(a). As the temperature is raised to $T = 74.5\,^\circ$C, the hysteresis cycle starts to develop into a multistable curve, as shown in Fig. 3(b). This tendency gets further amplified for $T = 85.3\,^\circ$C [Fig. 3(c)] and $T = 92.5\,^\circ$C [Fig. 3(d)]. This clearly indicates that to observe multistable behavior a high atomic number density is needed.

In Fig. 4, we display several experimentally observed curves, going from AOB to OM controlled by Δ_C alone. Figure 4(a) represents a typical absorptive AOB curve under the conditions of $\Delta_P = 0$, $\Delta_C = 17.1$ MHz, $P_C = 8.5$ mW, and $T = 91.5\,^\circ$C. By increasing Δ_C to 25.7 MHz, the system exhibits multistable behavior, as shown in Fig. 4(b). In the next two figures [Figs. 4(c) and 4(d)] we have further tuned Δ_C to 51.4 and 214 MHz, respectively. Dramatic changes in the shape of the hysteresis curve are apparent. Thus, the bistable to multistable behaviors can be controlled very effectively by the coupling laser beam. Notice that the threshold power is lowered as we increase Δ_C.

The observed AOB and OM behaviors in this system of three-level atoms inside an optical ring cavity are quite different from the previously studied atomic systems. Because of the induced atomic coherence in such an EIT medium, the absorption, dispersion, and nonlinearity are all greatly altered, which make this composite system more complicated and interesting. For example, it is Δ_C, and not Δ_P, that tunes the pure absorptive-type bistability to multistability with both absorptive and dispersive characteristics (Fig. 4). Also, the increase of atomic number

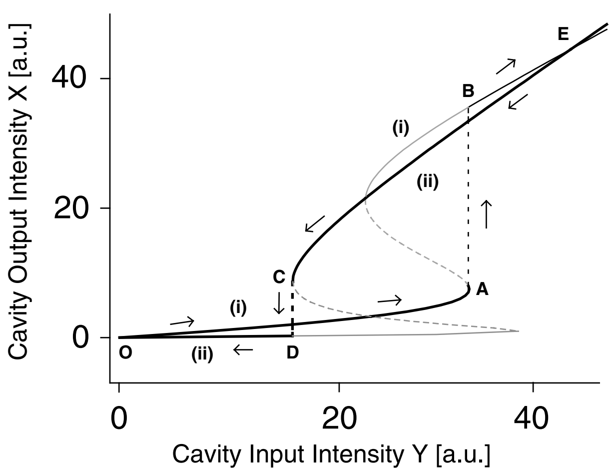

FIG. 2. Construction of optical multistable behavior (represented by the dark lines) with the help of a pure-dispersive [curve (*i*)] and a pure-absorptive [curve (*ii*)] optical bistability curve coexisted in the system with the similar parameters as in Fig. 1.

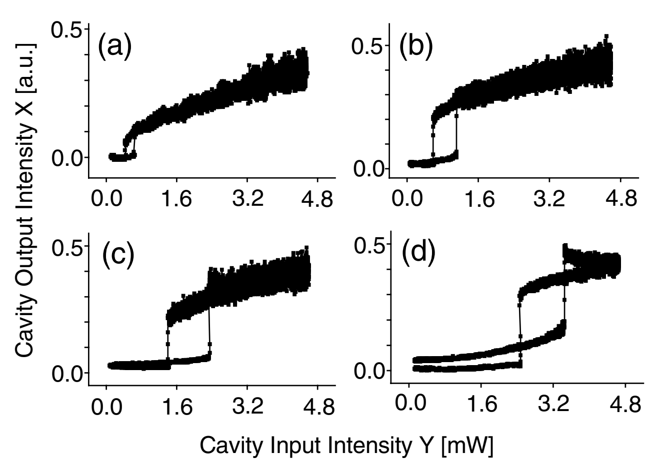

FIG. 3. The input-output intensity characteristics of the system for different atomic number densities. The parametric conditions are $\Delta_P = 0$, $\Delta_C = 42.8$ MHz, $P_C = 8.5$ mW, and (a) $T = 65.4\,^\circ$C, (b) $T = 74.5\,^\circ$C, (c) $T = 85.3\,^\circ$C, and (d) $T = 92.5\,^\circ$C.

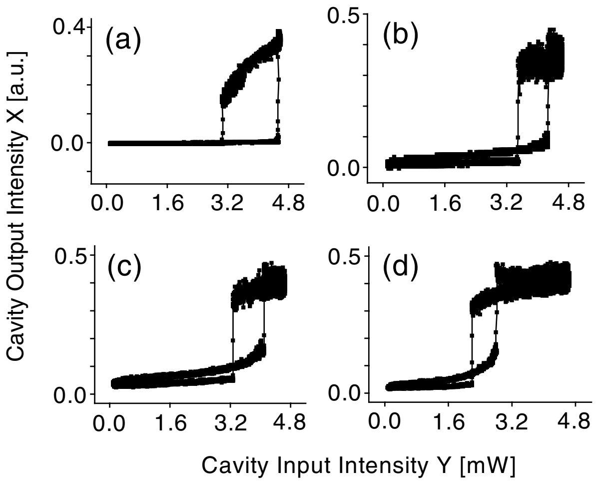

FIG. 4. The input-output intensity characteristics of the system for different frequency detunings of the coupling field. The parametric conditions are $\Delta_P = 0$, $T = 91.5\,^\circ\mathrm{C}$, $P_C = 8.5$ mW, and (a) $\Delta_C = 17.1$ MHz, (b) $\Delta_C = 25.7$ MHz, (c) $\Delta_C = 51.4$ MHz, and (d) $\Delta_C = 214.0$ MHz.

density pulls the dispersive-type bistability into multistability with added absorption (Fig. 3). One major advantage of using an atomic vapor cell with two-photon Doppler-free configuration is the ability to increase the temperature to a higher value, which is essential to observe such multistability in our experimental setup. It will be interesting to find the optimal conditions for achieving the desired bistable/multistable behaviors for both fundamental studies and practical applications. Multistability in conjunction with some phase coherent techniques [19] can be used to make improved optical transistors, memory elements, and all-optical logic gates. Our experimental demonstrations of controlling this behavior with the coupling beam frequency detuning and atomic number density provide an important step towards this goal.

In summary, we have observed a new type of OM in a three-level EIT medium inside an optical ring cavity. A simple physical model is presented to explain the observed OM phenomenon. By manipulating the absorption, dispersion, and nonlinear optical properties of this three-level EIT system via atomic coherence, one can get more interesting effects, including dynamic effects such as controlled instability and chaos. Quantum effects, namely, quantum tunneling and quantum correlation, can also be observed in such a system. The experimentally demonstrated controllability of AOB and OM with the additional (coupling) laser beam can be very useful in building all-optical switches and logic-gate devices for optical computing and quantum information processing.

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*Electronic address: mxiao@uark.edu

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