Controlled steady-state switching in optical bistability

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Optical switching has been achieved between two steady states of optical bistability generated in a system with three-level atoms inside an optical cavity. The optical power switching is controlled by adding short positive (switching up) or negative (switching down) pulses to the input intensity. The coupling laser beam in the three-level atomic system is used to control the threshold value and the width of the hysteresis cycle, which can adjust and optimize the optical switching process. © 2003 American Institute of Physics. [DOI: 10.1063/1.1600833]

Optical bistability in atomic systems has been extensively studied both theoretically and experimentally since the early 1980s. The quantitative comparisons between the detailed experimental results and theoretical calculations with various experimental parameters provided good understanding of the underlying physical mechanisms for optical bistability in two-level atomic systems. Such bistable behavior between the input and output intensities of an optical resonator with two-level atoms is the result of nonlinearity of the intracavity atomic medium, such as saturation and Kerr nonlinear effects, and feedback of the optical intracavity field from the cavity mirrors. Driving the interest in such bistable behavior was the possibility of using it for applications in optical switching, optical transistors, and optical storage elements, which are essential for optical computing and communications. Optical bistability has also been observed in semiconductor and other materials. Optical switching in optically bistable multiple-quantum-well semiconductors and other systems has been demonstrated, which made use of the bistable transmission behavior of thin film structures.

In recent years, optical bistability in systems with three-level atoms inside optical cavities has been theoretically studied and experimentally demonstrated. The major advantages of using three-level, instead of two-level, atoms as the nonlinear medium inside an optical cavity can be threefold. The first one is to make use of the atomic coherence induced in the three-level atomic systems, which can greatly modify the absorption, dispersion, and nonlinearity of the system, thereby reducing the cavity input threshold power for optical bistability. The second advantage is the controllability added by the coupling laser beam for such three-level atomic systems, as shown in the bubble of Fig. 1. By changing the intensity or the frequency detuning of the coupling beam, one can control the threshold value and the hysteresis cycle width of the bistable curve. The last one is the simpler experimental setup with a three-level atomic system compared to a two-level atomic system. Due to severe Doppler effect, atomic beams or cold atomic samples were needed to observe optical bistability in two-level atomic systems. However, by using the two-photon Doppler-free configuration in the three-level atomic system, e.g., the two laser beams copropagate in the $\Lambda$-type three-level atomic medium, the first-order Doppler effect is eliminated. Therefore, one can easily observe optical bistability in an atomic vapor cell without the need for a complicated vacuum system for atomic beams.

These advantages provide us with a unique opportunity to make optical switching between the two steady states of the bistable curve by adding positive and negative pulses to the cavity input intensity. In this letter, we describe such experimental demonstration carried out in a rubidium atomic vapor cell inside an optical ring cavity. Although optical switching was previously demonstrated in the three-level atomic system, the actual switching action happened outside the bistable region, and the switching was controlled by the coupling laser beam, instead of by the cavity input beam, as will be shown here. The physical mechanisms for these two types of optical switching are very different.

The atomic medium used for the experiment is $^{87}$Rb in the three-level $\Lambda$-type configuration, as shown in the bubble of Fig. 1. Level $|1\rangle$ ($F=1, S^{1/2}$) and level $|2\rangle$ ($F'$ $S^{1/2}$) of $^{87}$Rb.

FIG. 1. The experimental setup, M1–M3 are mirrors of optical ring cavity; LD1 and LD2 are coupling and probe lasers, respectively; PB1–PB5 are polarizing cubic beam splitters; $\lambda/2$, half-wave plates; FR, Faraday rotators; D1, detector; APD, avalanche photodiode detector; SAS represents the saturation atomic absorption setup. Inside the bubble is the three-level $\Lambda$-type atomic system in the D$_1$ lines of $^{87}$Rb.
Two typical input-output intensity bistable curves for $\Delta_\nu=0$ MHz, $\Delta_\nu=42.8$ MHz, $T=67.6 ^\circ C$, and (a) $P_c=1$ mW; (b) $P_c=7$ mW.

$=2, S_1^2 P_{1/2}$) with transition frequency $\omega_1$ are coupled by the cavity (probe) field (frequency $\omega_p$). Level $|2\rangle$ and level $|3\rangle$ ($F=2, S_1^2 S_{1/2}$) with transition frequency $\omega_3$ are connected by the coupling beam (frequency $\omega_c$). Frequency detunings for the probe and coupling lasers are defined to be $\Delta_p = \omega_p - \omega_1$ and $\Delta_\nu = \omega_c - \omega_3$, respectively. The three-mirror optical ring cavity contains a rubidium atomic vapor cell with Brewster windows, as shown in Fig. 1. The cell is wrapped in $\mu$-metal sheet and heated to 67.6 $^\circ C$. The reflectivity ($R$) of flat mirror M1 is 99%, and the concave (radius of curvature=10 cm) mirrors M2 and M3 have $R = 97\%$ and $R = 99.5\%$, respectively. A piezoelectric transducer is attached to M3 for scanning and locking the cavity. The finesse of the cavity containing the Rb vapor cell is measured to be about 30, and the free spectral range is 822 MHz (length $\sim 37$ cm). The probe beam enters the cavity through M2 and circulates in a single direction. The coupling beam is injected into the cavity by a polarizing beam splitter so that it has orthogonal polarization with respect to the probe beam and does not circulate. The intensity of the cavity input beam can be controlled by scanning an electro-optic modulator (EOM) with a triangular wave form. The intensity of the coupling beam is adjusted by the halfwave plate before the cubic polarizing beam splitter. Each diode laser is current and temperature stabilized with extended cavity feedback. Frequency detunings of the cavity input beam and the coupling beam are determined by their respective Fabry–Pérot cavities together with a saturation absorption spectroscopy (SAS) setup. A third frequency-stabilized diode laser is used to lock the optical cavity.

The optical bistability in the input-output intensity plot is observed by setting one or both of the frequency detunings to be nonzero and a coupling power of a few milliwatts. Figure 2 shows two typical optical bistable curves with different coupling intensities. One can see that threshold and hysteresis cycle shape change dramatically due to the altered absorption and nonlinearity. Such controllability over the bistable curve can be very useful in optimizing the optical switching conditions for desired applications.

For a typical bistable curve, as sketched in Fig. 3(a), the cavity output intensity will stay on the lower branch when the input intensity is increased from zero or a lower value outside the bistable region until it reaches the threshold value $Y_1$, when it jumps to the upper branch. Similarly, when the input intensity decreases in upper branch from higher values outside the bistable region, the output intensity will stay on the upper branch until it reaches the threshold value $Y_1$, when it jumps down. An optical switch can be formed based on this property of the optical bistability. Let the initial input intensity be set in the middle of the bistable curve by increasing it from a low input intensity, so the output intensity is at the lower branch (point A) initially. We then add an intensity pulse which is higher than the threshold value $Y_1$, as shown in Fig. 3. This intensity pulse brings the output intensity to the upper branch (point C) and, as the pulse ends, the output intensity will end up on the upper branch position B and stays there. Then, as another negative pulse comes, the output intensity will be brought down to the lower branch A (through point D) again. So, the binary (high and low) values of the output intensity of the system are determined by the added positive or negative pulses in the input intensity, even when the input intensity returns to the same initial value.

Figure 4 depicts the experimental demonstration of such optical switching. For a typical bistable curve similar to the one shown in Fig. 2(a), we set the initial input power at 1.73 mW. The positive and negative pulses were formed by applying pulse voltages to the EOM. The amplitude of the intensity pulses is chosen to be just little bigger than the half width of the bistable hysteresis cycle. The initial output intensity is at lower branch (state A). As can be seen from Fig. 4, the output intensity is brought to the upper branch [state B in Fig. 4(b)] by the positive pulse [Fig. 4(a)] and stays there; then the negative pulse brings it down to the lower-branch value (state A) again. The initial spikes above the state B, as shown in Fig. 4(b), are the output intensity values at state C [Fig. 3(a)] of the upper-branch outside the bistable region where the peaks of the positive pulses reach. Similarly, the small dips at the beginning of the state A are due to the
negative pulses. The states A and B are very stable and the extinction ratio of this switching action reaches about 20:1. The switching speed in the current experiment was limited to a microsecond time scale by the speed of the EOM used to pulse the input intensity, which is only 200 kHz for a sinusoidal wave form.

We expect to have a much faster switching speed in this system with atomic coherence (in nanosecond time scale, possibly determined by the cavity response time and other factors). This switching action has a very different physical mechanism from the all-optical switching demonstrated by controlling the coupling beam, where the switching is mediated by the nonlinear optical process in the atom-cavity system. We are interested in investigating and comparing the ultimate switching speeds in these two different cases both theoretically and experimentally (with a much faster EOM). Such study will be important in understanding the dynamic processes in the interactions between three-level atoms with atomic coherence and an optical resonator, and in the potential applications for controlled optical logic gates. With the controllability of the bistable curve by the coupling beam intensity and frequency detuning, as shown in Fig. 2, one can make the threshold value very low and the hysteresis cycle small, which will reduce the required dc input intensity and the amplitude of the pulses for realizing such switching actions.

In summary, we have experimentally demonstrated optical switching between two steady states of the bistable curve generated in a system with three-level atoms inside an optical cavity. The cavity input intensity and the pulse heights can be changed by modifying the shape of the bistable curve with the coupling beam parameters. Such controllability can be very useful in optimizing the switching efficiency for desired applications.

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1 For example, see a review by L. A. Lugiato, in Progress in Optics, edited by E. Wolf (North Holland, Amsterdam, 1984), Vol. 21, p. 71; and H. M. Gibbs, Optical Bistability: Controlling Light with Light (Academic, New York, 1985).