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CONTROLLING THE OPTICAL BISTABILITY IN A KOBRAK-RICE 5-LEVEL QUANTUM SYSTEM

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Abstract—Optical bistability (OB) behavior of a Kobrak-Rice 5-level quantum system is investigated. It is demonstrated that the OB of the system can be controlled by either the intensity or relative phase of driving fields. We have also shown that by applying an incoherent pumping field, the OB behavior of the system changes and the considerable output is obtained for zero input in the gain region induced by incoherent pumping field.

1. INTRODUCTION

The optical properties of the atomic or molecular system can be controlled by the coherent or incoherent fields [1]. It can be changed by intensity or relative phase of applied fields [2–4]. Coherent light-matter interaction already provides numerous applications in quantum optics, quantum memories, qubits and quantum computations. Atomic coherence has a major role in establishing the various phenomena, i.e., Coherent population trapping (CPT), lasing without inversion (LWI), electromagnetically induced transparency (EIT), fast light and all optical switches. OB has been extensively studied both theoretically and experimentally because of its wide applications in optical transistors, memory elements and all optical switches [5]. In bistable optical system, the system has two output states for a single input [6]. By using the atomic coherence, several techniques have been introduced to control the OB in the atomic system [7–9]. The intensity controlling of OB in the three-level [10–12] and four-level [13, 14] atomic

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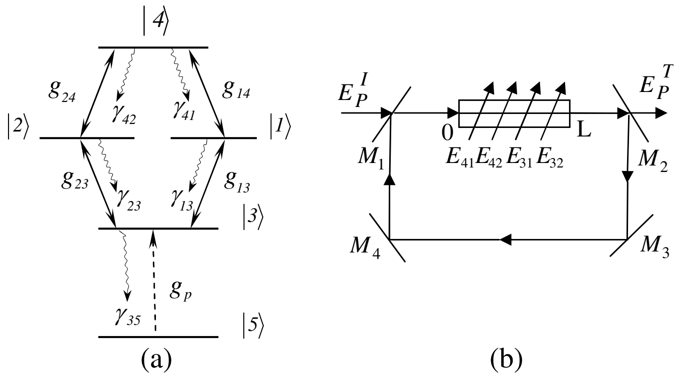

Figure 1. (a) Schematic diagram of the Kobrak-Rice 5-level (KR5) quantum system. The solid arrows show the coupling fields and the dashed one shows the probe field. (b) Unidirectional ring cavity with atomic sample of length L. E_P^I and $E_P^T$are the incident and transmitted fields, while $\vec{E}_p$, $\vec{E}_{31}$, $\vec{E}_{32}$, $\vec{E}_{41}$, $\vec{E}_{42}$ are the probe and four coherent laser fields, respectively. For mirror 1 and 2 it is assumed $\bar{R}+\bar{T}=1$ and mirrors 3 and 4 have perfect reflectivity.

system have been investigated. It was shown that the OB behavior in the three-level [15] and four-level [16] atomic system, containing closed-loop interaction can be controlled by either intensity or relative phase of applied fields.

Recently we have investigated the quantum coherence and optical properties of a Kobrak-Rice 5-level (KR5) atomic system (Fig. 1(a)) [17]. It was demonstrated that the absorption, the dispersion and the group index can be controlled by either the intensity or relative phase of driving fields. This system was first introduced by Kobrak and Rice to establish complete population transfer to a single target of a degenerate pair of states [18]. The Kobrak-Rice 5-level (KR5) system was also employed to show the advantages of the measurement in coherent control of atomic or molecular processes [19]. Moreover, by using intense laser fields a new quantum measurement has been introduced in the (KR5) system [20].

In this letter, we investigate the OB behavior of a (KR5) atomic system. We show that the OB behavior of the system is phase-dependent and it can be controlled by either intensity or relative phase of applied fields. Moreover, the phase-controlled OB threshold reduces with respect to three-level and four-level closed-loop atomic system. It is demonstrated that the incoherent pumping field introduces an additional tool for controlling the OB in this system and the considerable output is obtained for zero input.

2. MODEL AND EQUATIONS

We consider a (KR5) quantum system as shown in Fig. 1(a). The system has an excited state $|4\rangle$, two non-degenerate metastable lower states $|3\rangle$ and $|5\rangle$ as well as two intermediate degenerate states $|1\rangle$ and $|2\rangle$. To establish a diamond-shape closed-loop system, the transitions $|1\rangle$–$|3\rangle$, $|2\rangle$–$|3\rangle$, $|1\rangle$–$|4\rangle$ and $|2\rangle$–$|4\rangle$ are driven by four coherent laser fields with Rabi frequencies g_{13}, g_{23}, g_{14} and g_{24}, respectively. A tunable coherent probe field with Rabi frequency $g_p = g_{35}$ is applied to the dipole-allowed transition $|3\rangle$–$|5\rangle$ and couples diamond-shape system to the metastable state $|5\rangle$. The spontaneous decay rates of transitions $|1\rangle \to |3\rangle$, $|2\rangle \to |3\rangle$, $|4\rangle \to |1\rangle$, $|4\rangle \to |2\rangle$ and $|3\rangle \to |5\rangle$ are denoted by $2\gamma_{13}$, $2\gamma_{23}$, $2\gamma_{41}$, $2\gamma_{42}$ and $2\gamma_{35}$ respectively. The spontaneous decays from the excited state $|4\rangle$ to the lower levels $|3\rangle$ and $|5\rangle$ are ignored.

The total Hamiltonian of the system is given by

$$H_5 = \begin{pmatrix} 0 & 0 & |g_{13}|\,e^{i\phi_{13}} & |g_{14}|\,e^{i\phi_{14}} & 0 \\ 0 & 0 & |g_{23}|\,e^{i\phi_{23}} & |g_{24}|\,e^{i\phi_{24}} & 0 \\ |g_{13}|\,e^{-i\phi_{13}} & |g_{23}|\,e^{-i\phi_{23}} & 0 & 0 & g_{35} \\ |g_{14}|\,e^{-i\phi_{14}} & |g_{24}|\,e^{-i\phi_{24}} & 0 & 0 & \\ 0 & 0 & g_{35} & 0 & 0 \end{pmatrix} \tag{1}$$

The equation of the motion for the density operator can be written as:

$$\frac{\partial \rho}{\partial t} = \frac{1}{i\hbar}\left[\mathrm{H}\,,\rho\right] + L\rho, \tag{2}$$

where $L\rho$ represents decay part of the system. By expanding Equation (2), we can easily arrive at the density matrix equation of the motions:

$$\begin{aligned}
\dot\rho_{11} =& 2\gamma_{41}\rho_{44} - 2\gamma_{13}\rho_{11} + ig_{13}\rho_{31} - ig_{13}^*\rho_{13} + ig_{14}^*\rho_{41} - ig_{14}\rho_{14},\\
\dot\rho_{22} =& 2\gamma_{42}\rho_{44} - 2\gamma_{23}\rho_{22} + ig_{23}e^{-i(\Delta t+\delta\phi)}\rho_{32} - ig_{23}^*e^{i(\Delta t+\delta\phi)}\rho_{23}\\
&+ig_{24}^*\rho_{42} - ig_{24}\rho_{24},\\
\dot\rho_{33} =& 2\gamma_{13}\rho_{11} + 2\gamma_{23}\rho_{22} - 2\gamma_{35}\rho_{33} - ig_{13}\rho_{31} + ig_{13}^*\rho_{13}\\
&-ig_{23}e^{-i(\Delta t+\delta\phi)}\rho_{32} + ig_{23}^*e^{i(\Delta t+\delta\phi)}\rho_{23} - ig_p^*\rho_{35} + ig_p\rho_{53},\\
\dot\rho_{44} =& -2(\gamma_{41}+\gamma_{42})\rho_{44} + ig_{14}\rho_{14} - ig_{14}^*\rho_{41} - ig_{24}^*\rho_{42} + ig_{24}\rho_{24},\\
\dot\rho_{12} =& (i(\Delta_{42}-\Delta_{41}) - (\gamma_{13}+\gamma_{23}))\rho_{12} + ig_{13}\rho_{32} + ig_{14}^*\rho_{42}\\
&- ig_{23}^*e^{i(\Delta t+\delta\phi)}\rho_{13} - ig_{24}\rho_{14},\\
\dot\rho_{13} =& (i\Delta_{13} - \gamma_{13} - \gamma_{35})\rho_{13} + ig_{13}(\rho_{33}-\rho_{11}) + ig_{14}^*\rho_{43}\\
&-ig_{23}e^{-i(\Delta t+\delta\phi)}\rho_{12} - ig_p^*\rho_{15},\\
\dot\rho_{14} =& -(i\Delta_{41} + (\gamma_{13}+\gamma_{41}+\gamma_{42}))\rho_{14} + ig_{13}\rho_{34} + ig_{14}^*(\rho_{44}-\rho_{11})\\
&-ig_{24}^*\rho_{12},
\end{aligned}$$

$$
\begin{aligned}
\dot{\rho}_{15} &= -(i(\Delta_{13}+\Delta_p)-\gamma_{13})\rho_{15}+ig_{13}\rho_{35}+ig_{14}^*\rho_{45}-ig_p\rho_{13}, \\
\dot{\rho}_{23} &= (i(\Delta_{42}-\Delta)-(\gamma_{23}+\gamma_{35}))\rho_{23}+ig_{23}e^{-i(\Delta t+\delta\phi)}\rho_{33} \\
&\quad -ig_{23}^*e^{i(\Delta t+\delta\phi)}\rho_{22}+ig_{24}^*\rho_{43}-ig_{13}\rho_{21}-ig_p^*\rho_{25}, \\
\dot{\rho}_{24} &= -(i\Delta_{42}+(\gamma_{23}+\gamma_{41}+\gamma_{42}))\rho_{24}+ig_{23}e^{-i(\Delta t+\delta\phi)}\rho_{34} \\
&\quad +ig_{24}^*(\rho_{44}-\rho_{22})-ig_{14}^*\rho_{21}, \\
\dot{\rho}_{25} &= (i(\Delta_{23}-\Delta+\Delta_p)-\gamma_{23})\rho_{25}+ig_{23}e^{-i(\Delta t+\delta\phi)}\rho_{35} \\
&\quad +ig_{24}^*\rho_{45}-ig_p\rho_{23}, \\
\dot{\rho}_{34} &= -(i(\Delta_{41}+\Delta_{13})+(\gamma_{41}+\gamma_{42}+\gamma_{35}))\rho_{34}+ig_{23}^*e^{i(\Delta t+\delta\phi)}\rho_{24} \\
&\quad +ig_{13}^*\rho_{14}+ig_p\rho_{54}-ig_{14}^*\rho_{31}-ig_{24}^*\rho_{32}, \\
\dot{\rho}_{45} &= (i(\Delta_{41}+\Delta_{13}+\Delta_p)-(\gamma_{41}+\gamma_{42}))\rho_{45}+ig_{14}\rho_{15}+ig_{24}\rho_{25}-ig_p\rho_{43},
\end{aligned} \tag{3}
$$

where $\Delta_{13}=\omega_1-\omega_{13}$, $\Delta_{23}=\omega_2-\omega_{23}$, $\Delta_{41}=\omega_3-\omega_{41}$, $\Delta_{42}=\omega_4-\omega_{42}$, $\Delta_p=\omega_p-\omega_{35}$ are the one-photon resonance detuning transitions $|1\rangle$–$|3\rangle$, $|2\rangle$–$|3\rangle$, $|1\rangle$–$|4\rangle$, $|2\rangle$–$|4\rangle$ and $|3\rangle$–$|5\rangle$, respectively. The parameters $\delta\phi=\phi_{24}-\phi_{14}+\phi_{23}-\phi_{13}$ and $\Delta=\Delta_{42}-\Delta_{41}+\Delta_{23}-\Delta_{13}$ show the relative phase and multi-photon detuning, respectively. In this notation ω_i shows the central frequency of the corresponding laser field.

Dispersion and the absorption of the weak probe field are determined by the real and imaginary parts of ρ_{35} respectively. In our notation, for $\mathrm{Im}(\rho_{35})\langle 0$ the system exhibits gain, while for $\mathrm{Im}(\rho_{35})\rangle 0$ the probe field will be attenuated.

Optical Bistability (OB) is a result of the nonlinearity of the interactivity atomic medium and the feedback of the optical interactivity field from the cavity mirrors. The bistable behavior of the system is investigated in the optical ring cavity as shown in Fig. 1(b). For simplicity, we assume that mirrors 3 and 4 have perfect reflectivity, and the intensity reflection and transmission coefficients of mirrors 1 and 2 are $\bar{R}$ and $\bar{T}$ (with $\bar{R}+\bar{T}=1$). A collection of N homogeneously broadened (KR5) atomic systems is assumed inside a cell of length L. The total electromagnetic field seen by these atoms is

$$\vec{E}=\vec{E}_pe^{-i\omega_pt}+\vec{E}_{41}e^{-i\omega_{41}t}+\vec{E}_{42}e^{-i\omega_{42}t}+\vec{E}_{31}e^{-i\omega_{31}t}+\vec{E}_{32}e^{-i\omega_{32}t}+c.c, \tag{4}$$

where the probe field circulates in the ring cavity and the other fields do not circulate in the cavity. Then under slowly varying envelope approximation, the dynamic response of the probe field is governed by Maxwell's equation [21]

$$\frac{\partial E_p}{\partial t}+c\frac{\partial E_p}{\partial z}=i\frac{\omega_p}{2\varepsilon_0}P(\omega_p), \tag{5}$$

where ε_0 is the permittivity of free space. $P(\omega_p)$ is the induced polarization in the transition $|3\rangle-|5\rangle$ and is given by $P(\omega_p)=N\mu_{35}\rho_{35}$.

For a perfectly tuned ring cavity, in the steady-state case, the boundary conditions between the incident field E_p^I and the transmitted field E_p^T lead to

$$E_p(L) = E_P^T/\sqrt{\bar{T}}, \quad E_P(0) = \sqrt{\bar{T}}E_P^I + \bar{R}E_P(L), \tag{6}$$

Both atomic coherence and the feedback mechanism of the probe field due to the mirrors for the nonlinear atomic medium are responsible for the behavior of OB. It means that for R= 0 or $\rho_{35} = 0$ no bistability can occur. According to the mean-field limit and by using the boundary conditions, i.e., Equations (6), the steady state input-output relation of probe field is given by

$$y = x - iC\gamma_{35}\rho_{35}(x), \tag{7}$$

where

$$x = \frac{\mu_{35}E_p^T}{\hbar\sqrt{\bar{T}}}, \quad y = \frac{\mu_{35}E_p^I}{\hbar\sqrt{\bar{T}}}.$$

The usual cooperation parameter is denoted by $C = \frac{N\omega_p L\mu_{35}^2}{2\hbar\varepsilon_0 c\bar{T}\gamma_{35}}$.

According to Equation (7) the probe coherence ρ_{35} plays an important role in establishing of the OB behavior.

3. RESULTS AND DISCUSSION

Now, by solving numerically Equation (2) in steady state condition and substituting the results in Equation (7), we present the numerical results for obtaining the OB behavior under various parametric conditions. For simplicity, all parameters are reduced to dimensionless units through scaling by $\gamma_{13} = \gamma_{23} = \gamma$ and all figures are plotted in the unit of γ.

In multi-photon resonance condition, i.e., $\Delta = 0$, the Equation (2) have the steady state solutions. Therefore we assume that all coupling fields are in exact resonance with the corresponding transitions to establish the multi-photon resonance condition. First we study the effect of intensity of applied fields on the OB behavior of system. In Fig. (2), we show the input-output relation for different values of Rabi frequency of applied fields. The input and output in OB diagram are calculated in the unit of γ. Used parameters are $\gamma_{13} = \gamma_{23} = \gamma$, $\gamma_{41} = \gamma_{42} = 0.1\gamma$, $\gamma_{35} = 0.01$, $\Delta_{13} = \Delta_{23} = \Delta_{41} = \Delta_{42} = 0$, $g_p = 0.01\gamma$, $g_{13} = g_{23} = g_{14} = g_{24} = g = 2\gamma$ (solid) $g_{13} = g_{23} = 2\gamma$, $g_{14} = g_{24} = \gamma$ (dashed) and $g_{13} = g_{24} = 3\gamma$, $g_{23} = 2\gamma$, $g_{14} = \gamma$ (dotted). An investigation on Fig. 2(a) shows that for equal values of Rabi frequencies the OB behavior is established. By decreasing the Rabi frequency of two upper diamond closed-loop transitions, the OB

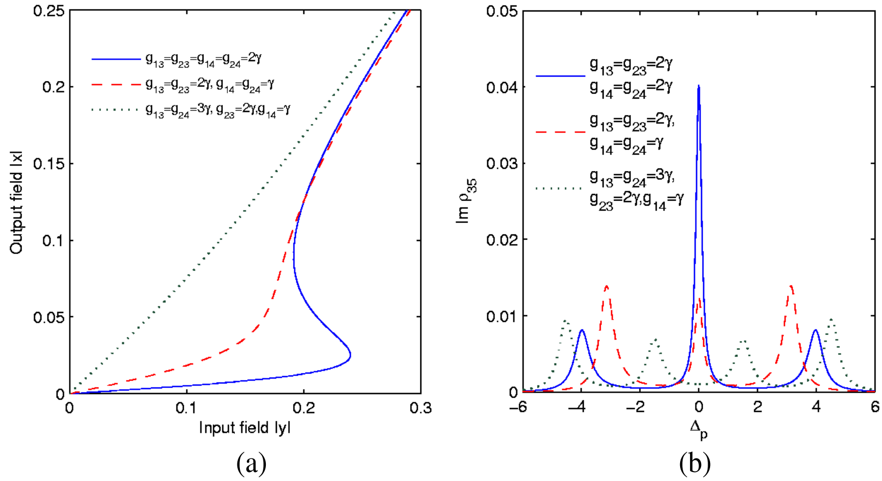

Figure 2. (a) The input-output relation in zero probe detuning and (b) absorption spectrum for different values of Rabi frequency of applied fields. Used parameters are $\gamma_{13} = \gamma_{23} = \gamma$, $\gamma_{41} = \gamma_{42} = 0.1\gamma$, $\gamma_{35} = 0.01$, $\Delta_{13} = \Delta_{23} = \Delta_{41} = \Delta_{42} = 0$, $g_p = 0.01\gamma$, $g_{13} = g_{23} = g_{14} = g_{24} = g = 2\gamma$ (solid) $g_{13} = g_{23} = 2\gamma$, $g_{14} = g_{24} = \gamma$ (dashed) and $g_{13} = g_{24} = 3\gamma$, $g_{23} = 2\gamma$, $g_{14} = \gamma$ (dotted).

behavior is decreased. Moreover, for Rabi frequencies correspond to dotted line, the optical bistability is completely disappeared.

The physics of phenomena can be explained via absorption spectrum which is plotted in Fig. 2(b). The solid line has a central absorption peak due to the double-dark resonance [22] and two side peaks located at $\pm 2g$ show a one-photon transition. The necessary condition to establish the double-dark resonance is given by $g_{14}g_{23} = g_{13}g_{24}$ [17] which are satisfied by solid and dashed curves of Fig. 2. In dotted curves, the Rabi frequency of the applied fields exceeds this condition and the OB behavior of system disappeared because of cancelling the central double-dark resonance absorption peak.

It is well known that the optical properties of a closed-loop atomic system interacting with laser fields are completely phase dependent [23–26]. We have shown that the phase-dependent behavior in closed-loop interacting system is restricted to the multi-photon resonance condition [27]. The phase-dependent behavior in closed-loop configuration is the result of coupling fields scattering into the probe field frequency in multi-photon resonance condition. In Fig. 3(a), we plot the OB behavior of the system for different values of relative phase of applied fields, i.e., $\delta\phi = 0$ (solid) and $\delta\phi = \pi$ (dashed).

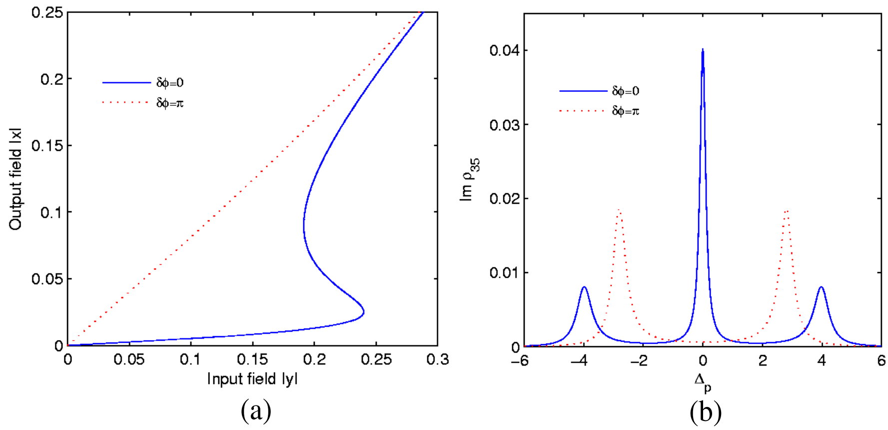

Figure 3. (a) The OB behavior and (b) absorption spectrum of the system for different values of relative phase of applied fields, i.e., $\delta\phi = 0$ (solid) and $\delta\phi = \pi$ (dashed). Other parameters are same as in solid line in Fig. 2.

Other parameters are same as in solid line in Fig. 2. By switching the relative phase of applied fields to $\delta\phi = \pi$ the OB behavior of the system is destroyed. It can be explained via the corresponding absorption spectrum which is shown in Fig. 3(b). By changing the relative phase from $\delta\phi = 0$ to $\delta\phi = \pi$, the double-dark resonance induced central peak, switches to the electromagnetically induced transparency window. Thus the probe atomic coherence becomes negligible and OB behavior disappeared.

Finally, we investigate the effect of incoherent pumping field on the OB behavior of system. The incoherent pumping field with rate Λ is applied to the transition $|4\rangle$–$|5\rangle$. The population of level $|5\rangle$ transforms to level $|4\rangle$ and then change the atomic coherence of system. In Fig. 4, we show the effect of incoherent pumping field on the OB behavior (a) of the system for $\Lambda = 0$ (solid), 0.0065γ (dashed), 0.01γ (dotted), 0.05γ (dash-dotted). The coupling Rabi frequencies are $g_{13} = g_{23} = g_{14} = g_{24} = 2\gamma$. The other parameters are same as in Fig. 2. By increasing the incoherent pumping rate, the central absorption peak switches to the gain around zero probe detuning [17]. It is worth to note that the gain-assisted OB is completely different from the OB due to the absorption. Fig. 4(b) shows the absorption (solid) and dispersion (dashed) of probe field versus incoherent pumping rate. It can be seen that for small values of incoherent pumping rate, the absorption of system reduces and the probe coherence becomes zero at point (A). By increasing the pumping rate, the system shows the gain. Thus

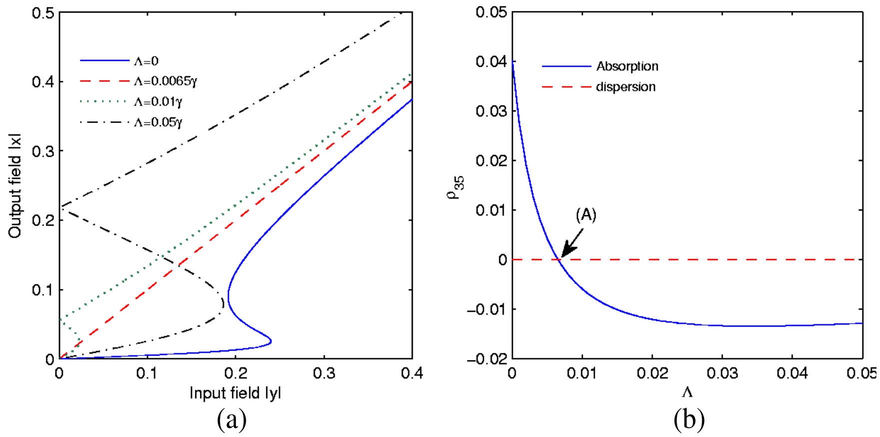

Figure 4. (a) The OB behavior of the system for $\Lambda = 0$ (solid), $\Lambda = 0.0065\gamma$ (dashed) 0.01γ (dotted), 0.05γ (dash-dotted). (b) Absorption (solid) and dispersion (dashed) of probe field versus incoherent pumping rate. The coupling Rabi frequencies are $g_{13} = g_{23} = g_{14} = g_{24} = 2\gamma$. The other parameters are same as in Fig. 2.

for the small values of incoherent pumping rate the OB behavior is generated by the absorption. For $\Lambda = 0.0065\gamma$ (point A) the OB (dashed in Fig. 4(a)) disappears, while for bigger values of pumping rate, i.e., $\Lambda = 0.01\gamma$, 0.05γ the gain-assisted OB is established (dotted and dash-dotted in Fig. 4(a)) in this system. Note that the incoherent pumping field reduces the OB threshold. Moreover the considerable output is obtained for zero input in the gain region induced by the incoherent pumping field.

One possible experimental candidate for proposed model is sodium atoms [28]. As a realistic example, we consider the D_1-line transitions, i.e., $3^2s_{1/2} \rightarrow 3^2P_{1/2}$ for probe transition. The decay rate and dipole moment are $\gamma \approx 2\pi \times 9.76\,\mathrm{MHz}$ and $\mu = 2.1 \times 10^{-29}\,\mathrm{C{\cdot}m}$, respectively [20]. Thus, by assuming the perfect reflection for mirrors 1 and 2, the amplitude of the input laser field is obtained as $E_p^I = 1935\,\mathrm{V/m}$ (corresponding to $0.5\,\mathrm{W/cm^2}$) for $y = 1$. The necessary variation range of y for switching in OB behavior is about $\Delta y = 0.05$ which corresponds to $0.001\,\mathrm{W/cm^2}$.

In our model the spontaneous jumps allow just by changing the input $|y|$ and the system may infinitely remain in upper or lower branch. However the intensity fluctuations larger than $0.001\,\mathrm{W/cm^2}$, may apply the unexpected OB switching.

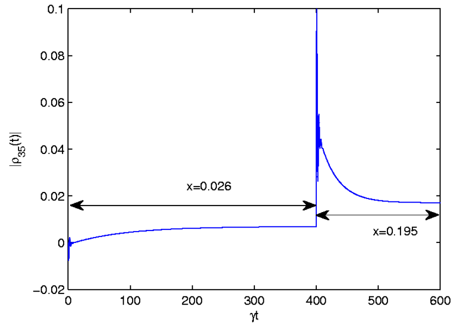

Figure 5. Dynamical behavior of atomic coherence, ρ_{35}, when the output jump from lower branch to upper branch of OB curve for $g_{13} = g_{23} = 2\gamma$, $g_{14} = g_{24} = \gamma$. The other parameters are same as in Fig. 2.

In Fig. 5 we display the dynamical behavior of atomic coherence, ρ_{35}, when the output jump from lower branch to upper branch of OB curve and introduce the required switching time for OB behavior. It is realized that as the intensity of output laser switches from $x_1 = 0.026$ to $x_2 = 0.195$ (Fig. 2(a)),the switching time becomes about $100\gamma^{-1} = 1.6\,\mu\text{s}$.

4. CONCLUSION

We studied the OB behavior of a Kobrak-Rice 5-level quantum system. It was shown that the OB of such system can be controlled either intensity or relative phase of applied fields. It was demonstrated that the incoherent pumping field adds an additional parameters to control the OB of the system. By applying an incoherent pumping field to the system, the nonzero output intensity was obtained even for negligible input intensity.

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