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AMPLITUDE AND PHASE CONTROL OF ABSORPTION AND DISPERSION IN A KOBRAK-RICE 5-LEVEL QUANTUM SYSTEM

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Abstract—The absorption and dispersion properties of a Kobrak-Rice 5-level quantum system are investigated. It is shown that the dressed states of such a system are phase-dependent. It is also demonstrated that the absorption, dispersion and group index can be controlled by either the intensity or relative phase of driving fields. Moreover, we have shown that by applying an incoherent pumping field the absorption doublet switches to gain doublet, and the absorption free superluminal light propagation appears which can be used in the transfer of information process.

1. INTRODUCTION

The optical properties of an atomic or molecular system may be controlled by the coherent or incoherent fields [1]. Atomic coherence

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and quantum interference are the basic mechanisms for controlling these properties. Coherent control of atomic systems can be used in numerous applications in optical physics, such as lasing without inversion [2], enhanced index of refraction [3], electromagnetically induced transparency [4, 5], optical bistability [6] and superluminal light propagation [7]. It is well known that the optical properties of a closed atomic system interacting with laser fields are completely phase dependent [8–12]. Recently, it has been shown that the phase-dependent behavior, in a closed-loop system, is only valid in the multi-photon resonance condition, so the phase-dependent process contributing to the probe field susceptibility only occurs at a specific frequency [13]. The effect of the relative phase on transient and steady state behavior of a four-level atomic medium in a closed-loop configuration has been discussed [14–16]. In view of many proposals, we note that the two-photon resonance condition has been employed to obtain the phase dependent behavior of the systems.

In this paper, we investigate the quantum coherence and optical properties of a Kobrak-Rice 5-level (KR5) atomic system (Fig. 1). This system was introduced by Kobrak and Rice to establish complete population transfer to a single target of a degenerate pair of states [17]. In this system, a four-level diamond-shape atomic system in closed-loop condition is coupled to lower ground state via a laser field. The quantum coherence effects in a four-level diamond-shape atomic system have been studied, and it has been shown that the system contains rich quantum interference features [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, a new quantum control scheme using intense laser fields together with quantum measurement has been applied to the (KR5) system [20]. It has been found that one can control the stationary population distribution by varying the intensity of laser fields. In particular, we study the absorption, dispersion and group index in the (KR5) system and explain the obtained results via a dressed basis. We show that the optical properties of such system can be controlled by either the intensity or the relative phase of the applied fields. In addition, we show that the dressed states of the system are also phase-dependent. If, however, an incoherent pumping field is applied to the system, we find that, around zero detuning, subluminal and superluminal light propagation as well as negative group velocity is available without absorption or gain. So, the group velocity of the probe field as well as the speed of information transfer can be controlled by either intensity or relative phase of the applied fields.

One interesting application of quantum coherence is the modification of light pulse propagation in an atomic medium which depends on its dispersive properties. The original study on the light propagation was presented by Lord Rayleigh [21] at the end of 19th century. He has remarked that a pulse of light inside a medium travels at the group velocity. In a dispersive medium, the frequency components of a light pulse experience different refractive indices and the group velocity of a light pulse in such a material can exceed the speed of light in vacuum which leads to the superluminal light propagation [22]. This process can be described in terms of superposition and interference of different frequency components of the traveling plane waves to form a narrow-band light pulse [23, 24].

2. MODEL AND EQUATIONS

Consider a (KR5) quantum system as depicted in Fig. 1. The scheme consists of 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 $|2\rangle$. 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, to establish a diamond-shape closed-loop system. A tunable coherent probe field with Rabi frequency $g_p = g_{35}$ is applied to the dipole-allowed transition $|3\rangle$–$|5\rangle$ that couples diamond-shape system to the metastable state $|5\rangle$. The spontaneous decay rates from the upper level $|i\rangle$ to the lower level $|j\rangle$ are denoted by $2\gamma_{ij}$. The spontaneous emission from the excited state $|4\rangle$ to the lower states $|3\rangle$, $|5\rangle$ are ignored.

The total Hamiltonian in bare state basis and in interaction picture is given as

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

where ϕ_{ij} shows the initial phase of the laser field which is applied to the transition $|i\rangle$–$|j\rangle$. It is assumed that all of the applied fields are in exact resonance with the corresponding transitions. The master equation of the motion for the density operator in an arbitrary multi-level atomic system can be written as:

$$\frac{\partial \rho}{\partial t} = \frac{1}{i\hbar}\,[\mathrm{H}, \rho] + L\rho, \quad (2)$$

where $L\rho$ represents decay part of the system. By expanding Eq. (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} \\
&\quad + 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} \\
&\quad - 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} \\
&\quad - 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} \\
&\quad - 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} \\
&\quad + ig_{14}^{*}(\rho_{44} - \rho_{11}) - ig_{24}^{*}\rho_{12}, \\
\dot{\rho}_{15} &= -(i(\Delta_{13} + \Delta_{p}) - \gamma_{13})\rho_{15} + ig_{13}\rho_{35} + ig_{14}^{*}\rho_{45} - ig_{p}\rho_{13}, \qquad (3) \\
\dot{\rho}_{23} &= (i(\Delta_{42} - \Delta) - \gamma_{23})\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}))\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}_{35} &= -(\gamma_{35} - i\Delta_{p})\rho_{35} + ig_{23}^{*}e^{i(\Delta t+\delta\phi)}\rho_{25} + ig_{13}^{*}\rho_{15} \\
&\quad + ig_{p}(\rho_{55} - \rho_{33}), \\
\dot{\rho}_{45} &= (i(\Delta_{41} + \Delta_{13} + \Delta_{p}) - (\gamma_{41} + \gamma_{42}))\rho_{45} + ig_{14}\rho_{15} \\
&\quad + ig_{24}\rho_{25} - ig_{p}\rho_{43},
\end{aligned}
$$

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.

The response of the atomic system to the applied fields is

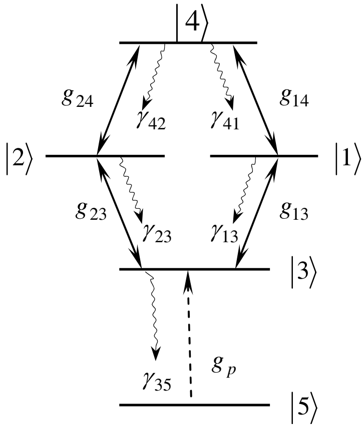

Figure 1. A schematic diagram of the Kobrak-Rice 5-level (KR5) quantum system. The solid arrows show the coupling fields and the dashed one shows the probe field.

determined by the susceptibility χ, which is defined as [25]:

$$\chi(\omega_p) = \frac{2Nd_{35}}{\varepsilon_0 E_p}\rho_{35}(\omega_p), \tag{4}$$

where N is the atom number density in the medium. The real and imaginary parts of χ correspond to the dispersion and the absorption of a weak probe field, respectively. For further discussion, we introduce the group index $n_g = \frac{c}{v_g}$ where c is the speed of light in the vacuum and the group velocity v_g is given by

$$v_g = \frac{c}{1 + 2\pi\chi'(\omega_p) + 2\pi\omega_p \dfrac{\partial}{\partial\omega_p}\chi'(\omega_p)}. \tag{5}$$

The group velocity of a light pulse can be determined by the slope of the dispersion. In our notation the negative (positive) slope of dispersion corresponds to superluminal (subluminal) light propagation. In addition, negative (positive) values in the imaginary part of the susceptibility show the gain (absorption) for the probe field.

3. DRESSED STATES ANALYSIS

We assume that all of the applied fields are in exact resonance with the corresponding transitions. Then the multi-photon resonance condition, i.e., $\Delta = 0$, is fulfilled. So, the coefficients of the Eq. (3) do not have an explicitly time dependent terms. First, we assume the probe field is switched off (or weak), then the phase dependent dressed states $|D_i\rangle$ ($i = 1$–4) for $\delta\varphi = 0$ are given by [18]

$$
\begin{aligned}
|D1\rangle &= \frac{\sqrt{y-\sqrt{z}}(x+\sqrt{z})}{\sqrt{2}(w-g_{14}\sqrt{z})}\,|1\rangle - \frac{\sqrt{2}(g_{13}g_{23}+g_{14}g_{24})\sqrt{y-\sqrt{z}}}{(w-g_{14}\sqrt{z})}\,|2\rangle \\
&\quad + \frac{(v-g_{13}\sqrt{z})}{(w-g_{14}\sqrt{z})}\,|3\rangle + |4\rangle\,, \\
|D2\rangle &= -\frac{\sqrt{y-\sqrt{z}}(x+\sqrt{z})}{\sqrt{2}(w-g_{14}\sqrt{z})}\,|1\rangle + \frac{\sqrt{2}(g_{13}g_{23}+g_{14}g_{24})\sqrt{y-\sqrt{z}}}{(w-g_{14}\sqrt{z})}\,|2\rangle \\
&\quad + \frac{(v-g_{13}\sqrt{z})}{(w-g_{14}\sqrt{z})}\,|3\rangle + |4\rangle\,, \\
|D3\rangle &= \frac{\sqrt{y+\sqrt{z}}(x+\sqrt{z})}{\sqrt{2}(w+g_{14}\sqrt{z})}\,|1\rangle - \frac{\sqrt{2}(g_{13}g_{23}+g_{14}g_{24})\sqrt{y-\sqrt{z}}}{(w+g_{14}\sqrt{z})}\,|2\rangle \\
&\quad + \frac{(v+g_{13}\sqrt{z})}{(w+g_{14}\sqrt{z})}\,|3\rangle + |4\rangle\,, \\
|D4\rangle &= \frac{\sqrt{y+\sqrt{z}}(x+\sqrt{z})}{\sqrt{2}(w+g_{14}\sqrt{z})}\,|1\rangle + \frac{\sqrt{2}(g_{13}g_{23}+g_{14}g_{24})\sqrt{y-\sqrt{z}}}{(w+g_{14}\sqrt{z})}\,|2\rangle \\
&\quad + \frac{(v+g_{13}\sqrt{z})}{(w+g_{14}\sqrt{z})}\,|3\rangle + |4\rangle\,,
\end{aligned}
$$

and the corresponding eigenvalues are

$$
\Lambda_1 = -\frac{\sqrt{y-\sqrt{z}}}{\sqrt{2}},\ \Lambda_2 = \frac{\sqrt{y-\sqrt{z}}}{\sqrt{2}},\ \Lambda_3 = -\frac{\sqrt{y+\sqrt{z}}}{\sqrt{2}},\ \Lambda_4 = \frac{\sqrt{y+\sqrt{z}}}{\sqrt{2}}, \tag{6}
$$

where

$$
\begin{aligned}
x &= g_{13}^2 + g_{14}^2 - g_{23}^2 - g_{24}^2, \\
y &= g_{13}^2 + g_{14}^2 + g_{23}^2 + g_{24}^2, \\
z &= -4(g_{14}g_{23} - g_{13}g_{24})^2 + y^2, \\
w &= g_{13}^2 g_{14} + g_{14}^3 - g_{14}g_{23}^2 + 2g_{13}g_{23}g_{24} + g_{14}g_{24}^2, \\
v &= g_{13}^3 + g_{13}g_{14}^2 + g_{13}g_{23}^2 + 2g_{14}g_{23}g_{24} - g_{34}g_{24}^2.
\end{aligned}
$$

We have not considered the normalization coefficient for simplicity. All four dressed states contain all four bare states $|1\rangle$, $|2\rangle$, $|3\rangle$ and $|4\rangle$ and all eigenvalues are non-zero. But, if the Rabi frequency of the applied fields satisfy the following relation,

$$
g_{14}g_{23} = g_{13}g_{24}, \tag{7}
$$

two dark states are established. Then the eigenvectors and eigenvalues of the system are given by

$$\begin{aligned}
|d1\rangle &= \frac{g_{24}}{g_{23}}|3\rangle + |4\rangle\,,\\
|d2\rangle &= -\frac{g_{23}}{g_{13}}|1\rangle + |2\rangle\,,\\
|d3\rangle &= -\frac{g_{13}g_{23}G}{g_{24}\left(g_{13}^2+g_{23}^2\right)}|1\rangle + \frac{g_{23}^2+g_{24}^2}{g_{24}G}|2\rangle + \frac{g_{23}}{g_{24}}|3\rangle + |4\rangle\,,\\
|d4\rangle &= \frac{g_{13}g_{23}G}{g_{24}\left(g_{13}^2+g_{23}^2\right)}|1\rangle - \frac{g_{23}^2+g_{24}^2}{g_{24}G}|2\rangle + \frac{g_{23}}{g_{24}}|3\rangle + |4\rangle\,,\\
&\lambda_1 = 0, \quad \lambda_2 = 0, \quad \lambda_3 = -G, \quad \lambda_4 = G,
\end{aligned} \tag{8}$$

where

$$G = \sqrt{\frac{\left(g_{13}^2+g_{23}^2\right)\left(g_{23}^2+g_{24}^2\right)}{g_{23}^2}}.$$

Note that the dressed states and eigenvalues of a diamond shaped closed-loop atomic system are phase-dependent, then by changing the relative phase of the applied fields, the dressed states and the eigenvalues of the system will dramatically be changed.

The interesting situation are obtained for $\delta\phi = \pi$ when the following condition is satisfied by the applied fields,

$$g_{23} = g_{13}, \quad g_{24} = g_{14}. \tag{9}$$

In this case, the eigenvectors and eigenvalues can be written as

$$\begin{aligned}
|d1\rangle &= \frac{1}{\sqrt{2}}|1\rangle - \frac{1}{\sqrt{2}}|2\rangle + |3\rangle\,,\\
|d1\rangle &= -\frac{1}{\sqrt{2}}|1\rangle + \frac{1}{\sqrt{2}}|2\rangle + |3\rangle\,,\\
|d1\rangle &= -\frac{1}{\sqrt{2}}|1\rangle - \frac{1}{\sqrt{2}}|2\rangle + |4\rangle\,,\\
|d1\rangle &= \frac{1}{\sqrt{2}}|1\rangle + \frac{1}{\sqrt{2}}|2\rangle + |4\rangle\,,\\
\lambda_1 = -\sqrt{2}g_{13}, \quad &\lambda_2 = \sqrt{2}g_{13}, \quad \lambda_3 = -\sqrt{2}g_{14}, \quad \lambda_4 = \sqrt{2}g_{14}.
\end{aligned} \tag{10}$$

Second, we switch on the probe field and the Kobrak-Rice system is established. The phase dependent atom field dressed states and the corresponding eigenvalues of such system for $g_{13} = g_{23} = g_{14} = g_{24} = g$,

$g_{35} = g_p$, and $\delta\phi = 0$ are given by

$$
\begin{aligned}
|D1\rangle &= -|1\rangle + |2\rangle, \\
|D2\rangle &= \frac{gA^-}{g_pB^-}|1\rangle + \frac{gA^-}{g_pB^-}|2\rangle - \frac{\sqrt{B^-}}{\sqrt{2}g_p}|3\rangle + \frac{C^+}{\sqrt{2}g_p\sqrt{B^-}}|4\rangle + |5\rangle, \\
|D3\rangle &= \frac{gA^-}{g_pB^-}|1\rangle + \frac{gA^-}{g_pB^-}|2\rangle + \frac{\sqrt{B^-}}{\sqrt{2}g_p}|3\rangle - \frac{C^+}{\sqrt{2}g_p\sqrt{B^-}}|4\rangle + |5\rangle, \\
|D4\rangle &= \frac{gA^+}{g_pB^+}|1\rangle + \frac{gA^+}{g_pB^+}|2\rangle - \frac{\sqrt{B^+}}{\sqrt{2}g_p}|3\rangle + \frac{C^-}{\sqrt{2}g_p\sqrt{B^+}}|4\rangle + |5\rangle, \\
|D5\rangle &= \frac{gA^+}{g_pB^+}|1\rangle + \frac{gA^+}{g_pB^+}|2\rangle + \frac{\sqrt{B^+}}{\sqrt{2}g_p}|3\rangle - \frac{C^-}{\sqrt{2}g_p\sqrt{B^+}}|4\rangle + |5\rangle, \\
&\Lambda_1 = 0.0,\ \Lambda_2 = -\sqrt{\frac{B^-}{2}},\ \Lambda_3 = \sqrt{\frac{B^-}{2}},\ \Lambda_4 = -\sqrt{\frac{B^+}{2}},\ \Lambda_5 = \sqrt{\frac{B^+}{2}},
\end{aligned}
\tag{11}
$$

where,

$$
A^{\pm} = 8g^2 \pm 2\sqrt{16g^4 + g_p^4} \qquad B^{\pm} = \left(4g^2 + g_p^2 \pm \sqrt{16g^4 + g_p^4}\right)
$$
$$
C^{\pm} = -4g^2 + g_p^2 \pm \sqrt{16g^4 + g_p^4}.
$$

Note that a null eigenvalue appears, but for a small probe Rabi frequency, above eigenvalues can be written as

$$
\begin{aligned}
&\Lambda_1 = 0.0, \quad \Lambda_2 = -\frac{g_p}{\sqrt{2}} \approx 0, \quad \Lambda_3 = \frac{g_p}{\sqrt{2}} \approx 0, \\
&\Lambda_4 = -\sqrt{\frac{8g^2 + g_p^2}{2}} \approx -2g, \quad \Lambda_5 = \sqrt{\frac{8g^2 + g_p^2}{2}} \approx 2g.
\end{aligned}
\tag{12}
$$

Now the system is ready to show the double-dark resonance structure. A characteristic feature of this phenomenon is the appearance of a very narrow structure, due to the multi-photon resonances in optical spectra. It is shown that the resonance associated with the double-dark states can make the medium absorptive or transparent [26]. The double dark resonance, in a four level system, has been theoretically studied [27] and experimentally observed [28]. It has been demonstrated that the double-dark resonance is a powerful mechanism for establishing the high efficiency four-wave mixing [29], high resolution spectroscopy [30], sub-wavelength atom localization [31], and controlling the group velocity of a light pulse in a dispersive medium [32]. Recently, we have employed the double-dark resonance for controlling the optical bistability in a four-level mercury atom [33].

It is worthwhile to note that for $\delta\phi \neq 0$ the system does not show a double-dark resonance structure. For example, if $\delta\phi = \pi$, the dressed states and the eigenvalues of the system are given by

$$\begin{aligned}
|D1\rangle &= -\frac{g_p}{2g}|1\rangle - \frac{g_p}{2g}|2\rangle + |5\rangle, \\
|D2\rangle &= -\frac{1}{\sqrt{2}}|1\rangle - \frac{1}{\sqrt{2}}|2\rangle + |4\rangle, \\
|D3\rangle &= \frac{1}{\sqrt{2}}|1\rangle + \frac{1}{\sqrt{2}}|2\rangle + |4\rangle, \\
|D4\rangle &= -\frac{g}{g_p}|1\rangle + \frac{g}{g_p}|2\rangle - \frac{\sqrt{2g^2+g_p^2}}{g_p}|3\rangle + |5\rangle, \\
|D5\rangle &= -\frac{g}{g_p}|1\rangle + \frac{g}{g_p}|2\rangle + \frac{\sqrt{2g^2+g_p^2}}{g_p}|3\rangle + |5\rangle, \\
\Lambda_1 &= 0,\ \Lambda_2 = -\sqrt{2}g,\ \Lambda_3 = \sqrt{2}g,\ \Lambda_4 = -\sqrt{2g^2+g_p^2},\ \Lambda_5 = \sqrt{2g^2+g_p^2}.
\end{aligned} \tag{13}$$

Even for a weak probe field Rabi frequency, the double-dark resonance structure is not established and just two side peaks in the absorption spectrum are expected.

4. RESULTS AND DISCUSSION

We now summarize our results for the steady state behavior of the system by using Eq. (3). For simplicity, all parameters are reduced to dimensionless units through scaling by $\gamma_1 = \gamma_2 = \gamma$ and all figures are plotted in the unit of γ. It is difficult to solve analytically, Eq. (3), then we are trying to solve, numerically, to obtain our interesting results shown in Figs. 2–6. We assume that all of coupling fields are in exact resonance with the corresponding transitions to establish the multi-photon resonance condition. First, we are interested in studying the effect of the intensity of the coupling fields on the dispersion and absorption spectrum when $\delta\phi = 0$. In Fig. 2, we show the absorption (solid) and dispersion (dashed) of a weak probe field for different values of the intensity of the applied fields. The selected parameters are (a), (b) $g_1 = g_{23} = g_{14} = g_{24} = g = 2\gamma$, (c), (d) $g_{13} = g_{23} = 2\gamma$, $g_{14} = g_{24} = \gamma$ and (e), (f) $g_{13} = g_{24} = 3\gamma$, $g_{23} = 2\gamma$, $g_{14} = \gamma$ for all of which, we have $\gamma_{13} = \gamma_{23} = \gamma$, $\gamma_{41} = \gamma_{42} = 0.1\gamma$, $\gamma_{35} = 0.01$, $\Delta_{13} = \Delta_{23} = \Delta_{41} = \Delta_{42} = 0$, $g_p = 0.01\gamma$. In Figs. 2(a)–(d) the condition (7) is satisfied and an interacting dark states resonance is expected. The central peak in these figures shows a double-dark resonance structure, while two side peaks located at $\pm 2g$ show a one-photon transition due to the usual dynamical Stark effect. By decreasing the Rabi frequency of two upper diamond closed-loop transitions, the central absorption peak is decreased. Moreover the slope of the dispersion around zero detuning is steep negative, corresponding to the superluminal light propagation while in the electromagnetically induced transparency (EIT) windows the slope of dispersion is positive which shows the normal dispersion.

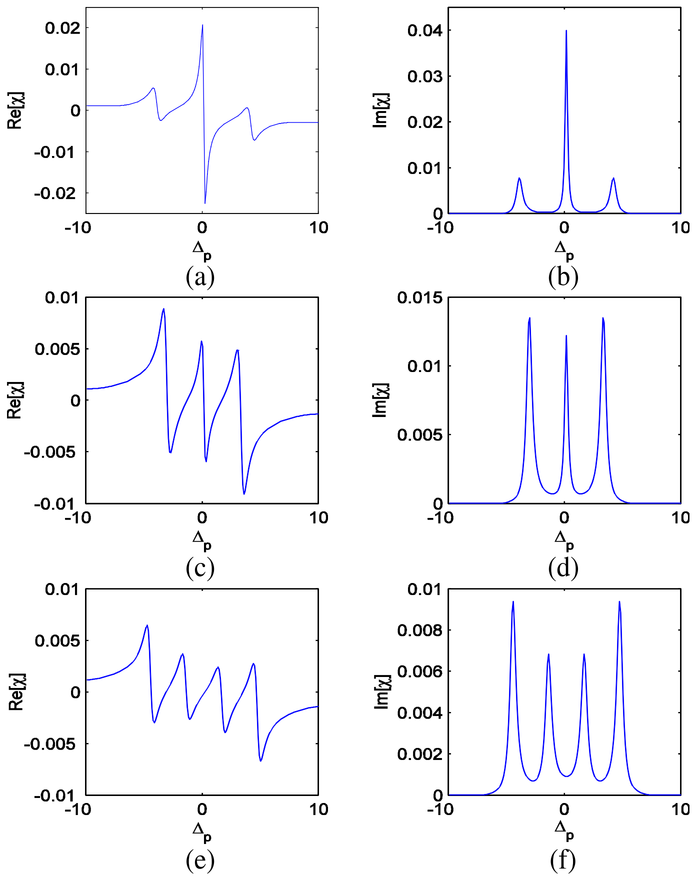

Figure 2. Real (left column) and imaginary (right column) part of susceptibility are plotted versus probe field detuning for $\delta\phi = 0$. The selected parameters are $2\gamma_{13} = 2\gamma_{23} = 2\gamma$, $2\gamma_{41} = 2\gamma_{42} = 0.2\gamma$, $2\gamma_{35} = 0.02$, $\Delta_{13} = \Delta_{23} = \Delta_{41} = \Delta_{42} = 0$, $g_p = 0.01\gamma$ (a), (b) $g_1 = g_{23} = g_{14} = g_{24} = g = 2\gamma$, (c), (d) $g_{13} = g_{23} = 2\gamma$, $g_{14} = g_{24} = \gamma$ and (e), (f) $g_{13} = g_{24} = 3\gamma$, $g_{23} = 2\gamma$, $g_{14} = \gamma$.

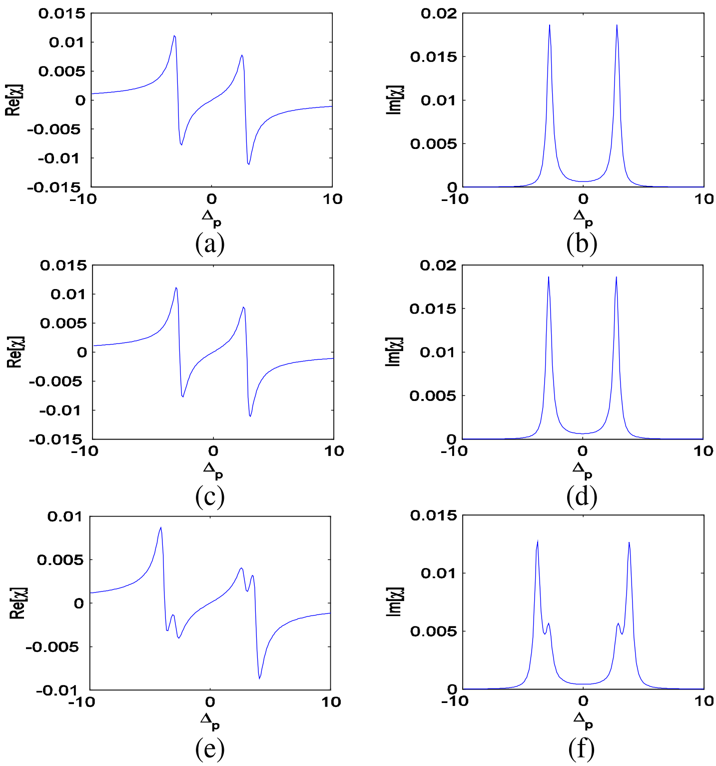

Figure 3. Real (left column) and imaginary (right column) part of susceptibility are plotted versus probe field detuning for $\delta\phi = \pi$. The other parameters are same as in Fig. 2.

In Fig. 2(e) and Fig. 2(f) the Rabi frequency of the applied fields exceed the condition (7) and the central double-dark resonance peak disappears Four peaks in the absorption spectrum can be explained by Eq. (6).

The other interesting aspect of this system is the phasedependent dressed states. In Fig. 3, similar plots are shown for $\delta\phi = \pi$. An investigation of Fig. 3 shows that the double dark resonance structure does not establish. Generally, two peaks observed in the absorption spectrum located at $\pm\sqrt{2}g$ can be explained by Eq. (13). Similarly, the slope of dispersion around the absorption peaks is negative, while in EIT regions the slope of dispersion is positive. Note that Fig. 3(c) and Fig. 3(d) are similar to the Fig. 3(a) and Fig. 3(b), respectively. This point can be explained by Eq. (10). When the applied fields satisfy the condition (9), the eigenvectors are not depending on the

Rabi frequency of the applied fields. On the other hand, the atomic bare state $|3\rangle$ can be written versus first two eigenvectors $|d1\rangle$ and $|d2\rangle$. Then the probe field excites two $|5\rangle$–$|d1\rangle$ and $|5\rangle$–$|d2\rangle$ transitions and two absorption peaks are established at $\Delta_p = \pm\sqrt{2}g_{13}$ which do not depend on the parameter g_{14}.

Now we are interested in the dynamical behavior of the population distribution of each level and the probe field absorption. In Fig. 4, we plot the dynamical behavior of the population and the absorption for $\delta\phi = 0$ and $\delta\phi = \pi$. We assume all five lasers satisfy the exact resonance condition. The other used parameters are same as in Fig. 2(a). An investigation on the Fig. 4 shows that the population distribution of levels as well as the optical properties of the system is completely phase-dependent. For $\delta\phi = 0$, all of the levels are populated

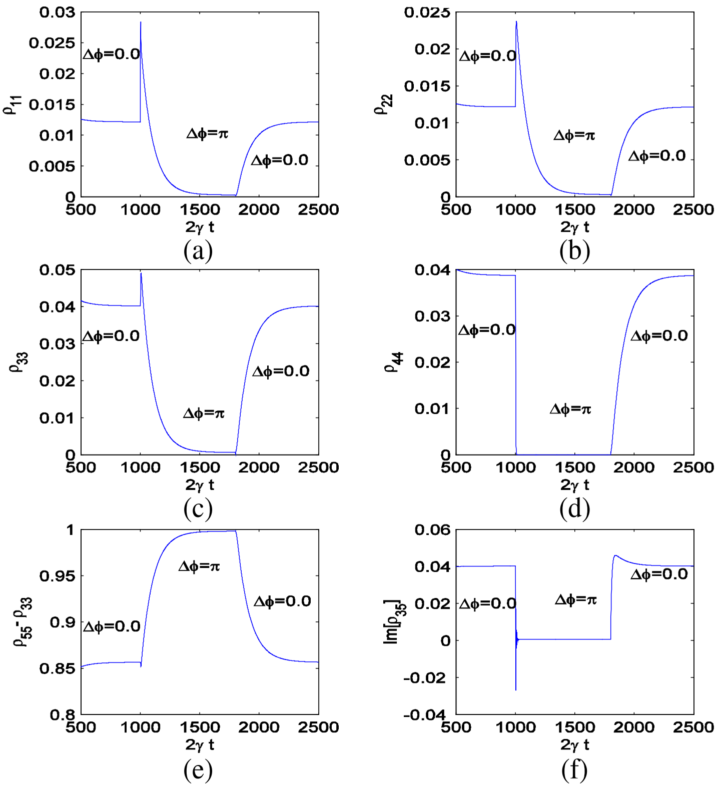

Figure 4. The dynamical behavior of populations (a)–(e) and absorption (f) of probe field are shown for $\delta\phi = 0, \pi$. The other parameters are same as in Fig. 2(a).

while by switching the relative phase of the applied fields to $\delta\phi = \pi$, the population distribution is changed and the excited state depopulated (Fig. 4(d)) Moreover, by comparing the population difference in probe transition (Fig. 4(e)) and the probe field absorption (Fig. 4(f)), it is shown that for $\delta\phi = 0$, the population of the lower level is larger than upper level, so the probe field will beabsorbed Note that for $\delta\phi = \pi$,the ground level $|5\rangle$ is populated, and the system becomes transparent, so the probe field does not attenuate as it passes through the medium. This is the result of destructive quantum interference of two $|5\rangle$–$|D4\rangle$ and $|5\rangle$–$|D5\rangle$ transitions defined in Eq. (13).

Now we are interested in studying the effect of the incoherent pumping field on the optical properties of the system. An incoherent pumping field, i.e., $E(t)$, has a broad spectrum with effective δ-like correlation, i.e.,

$$\left\langle E^*(t)E(t')\right\rangle = \Gamma\delta(t - t'). \tag{14}$$

We apply such incoherent pumping field with the pump rate $r = 2p^2/\hbar^2\Gamma$ to the transition $|4\rangle$–$|5\rangle$ where p shows the dipole moments of corresponding atomic transition.

In Fig. 5, we display the probe dispersion and probe absorption for $\delta\phi = 0$ and different values of the incoherent pump rate. The other parameters are same as in Fig. 2(a). Fig. 5 shows that for $r = 0.01\gamma$ the central peak, which is corresponding to the double dark resonance structure, switches to the gain dip, while the other two side peaks are still absorption peaks. Moreover, the slope of dispersion around the central dip is switched from negative to positive. By increasing the incoherent pumping rate to $r = 0.05\gamma$, two side peaks are also switched to gain dips. In Fig. 6, we plot the absorption (left column) and group index (right column) of the probe field. The parameters are $g_1 = g_{23} = g_{14} = g_{24} = 0.5\gamma$, $\delta\phi = 0$ (a), (b), π (c)–(f), $r = 0.0$ (a–d) and 0.03γ (e), (f). The other parameters are same as in Fig. 2. Fig. 6(a) shows the negative group index corresponding to the superluminal light propagation. However, according to Fig. 6(b), it is accompanied by strong absorption, so the pulse light will be attenuated. By changing the relative phase to $\delta\phi = \pi$, the two absorption peaks appear in the absorption spectrum as shown in Fig. 6(c). Similar to previous case, the superluminal light propagation is accompanied by strong absorption peak which is not an interesting case for light pulse propagation. In Fig. 6(e) and Fig. 6(f), we apply a weak incoherent pumping field to the transition $|4\rangle$–$|5\rangle$ so the doublet absorption peak changes to a doublet gain. Moreover, the slope of dispersion switches from positive to negative around zero detuning and then the group index becomes negative(see Fig. 6(f)). For used parameters, the absorption or gain around zero detuning is

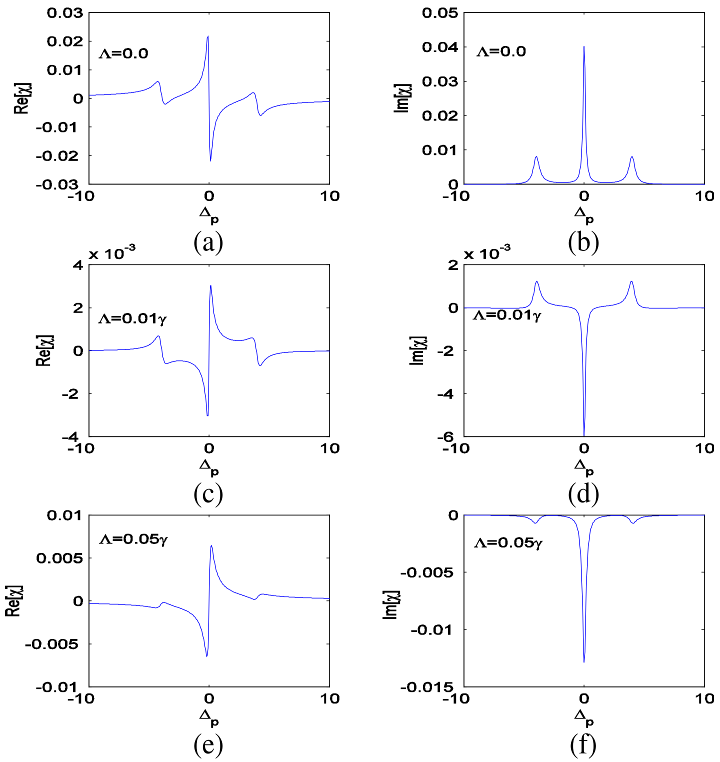

Figure 5. Real (left column) and imaginary (right column) part of susceptibility are plotted versus probe field detuning for$\delta\phi = 0$. The pump strength is (a), (b) $\Lambda = 0.0$, (c), (d) 0.01γ, (e), (f) 0.05γ. The other parameters are same as in Fig. 2(a).

negligible and the superluminal light propagation is also occurred in this region. Then, by applying an incoherent pumping field to our suggested system, the absorption-free superluminal light propagation is established. Note that the interesting region of the light propagation is a region that the system does not show the absorption or gain. This is due to the fact that a large absorption in the system does not permit the pulse propagation inside the medium. On the other hand, the gain also may add some noise to the system.

Although the group velocity of a light pulse can be propagated with a speed faster than the speed of light in vacuum c, i.e., superluminal, no information can be transmitted faster than the c. In fact, all the information encoded on the waveform is available to be detected at the pulse front (The waveform has a front, the moment of time when the intensity first becomes non-zero). When such a waveform passes through an anomalous dispersion medium, the peak of the pulse can move forward with respect to the front, but can never exceed the front. So the speed of the transmission of information is limited by the encoding/decoding method.

On the other hand, in many practical situations, we can perform reliable measurements of the information content only near peak of the

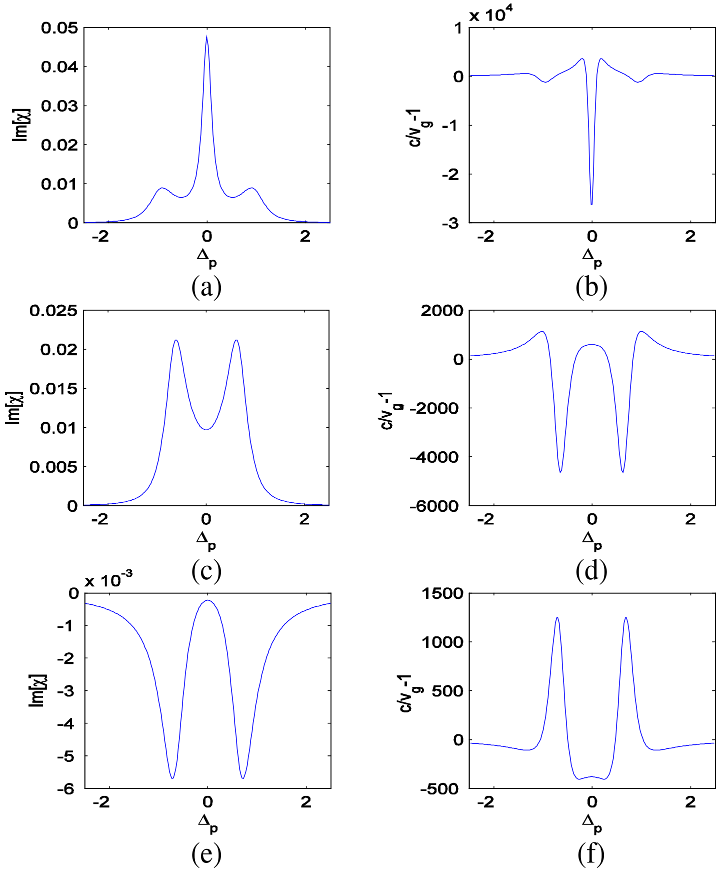

Figure 6. Absorption spectrum (left column) and corresponding group index (right column) of probe field are plotted versus probe field detuning for (a), (b) $\delta\phi = 0$, (c)–(f) π. The pump strength is (a)–(d) $\Lambda = 0.0$, (e), (f) 0.03γ. The coupling Rabi frequencies are $g_1 = g_{23} = g_{14} = g_{24} = 0.5\gamma$. The other parameters are same as in Fig. 2.

pulse. In this sense, useful information often propagates at the group velocity, but it always limited by traveling less than or equal to the speed of light in vacuum [34].

It is worthwhile to understand that the phase-dependent behavior of the system is obtained even in the absence of an incoherent pumping field. However, by applying an incoherent pumping field, a gain-assisted superluminal light propagation is established.

5. CONCLUSION

The absorption and dispersion properties of a Kobrak-Rice 5-level quantum system interacting with laser fields were investigated. It was shown that the dressed states of such a system are phase-dependent, and the optical properties of the system can be controlled by either intensity or the relative phase of the applied fields. Moreover, by applying a weak incoherent pumping field, the absorption-free superluminal light propagation is obtained.

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