Optik 126 (2015) 530–535

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Controlling the optical bistability via quantum interference of incoherent pump in a four-level atomic system

H. Jafarzadeh [a,b,c,*], M. Sahrai [b,c], K. Jamshidi-Ghaleh [d]

[a] Sama Technical and Vocational Training College, Islamic Azad University, Tabriz Branch, Tabriz, Iran
[b] Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran
[c] Aras International Campus, University of Tabriz, Tabriz, Iran
[d] Department of Physics, Azarbaijan Shahid Madani University, Tabriz, Iran

ARTICLE INFO

Article history:
Received 22 January 2014
Accepted 16 January 2015

Keywords:
Optical bistability
Incoherent pump
Quantum interference
Absorption

ABSTRACT

Optical bistability is investigated in a four-level atomic system via direct and indirect incoherent pump fields. The threshold of optical bistability has substantially been decreased by the rate of direct and indirect incoherent pump processes. In addition, quantum interference of spontaneous emission and incoherent pump field affect the bistabile behavior of the medium.

1. Introduction

Nonlinear response of an atomic medium to the intense laser field can lead to important phenomenon such as nonlinear absorption, Kerr nonlinearity, and the optical bistability (OB). OB is an important mechanism in all optical switches and optical transistors, which is necessary for quantum computing and quantum communications. OB has extensively been studied from both experimental and theoretical point of view in the past few years [1–11]. The influence of quantum interference on OB has widely been discussed, and is shown that the threshold required for a bistable behavior can substantially be decreased due to quantum interference effects [7]. In addition, the effect of the phase fluctuation [12], squeezed vacuum field [13–15], and spontaneously generated coherence (SGC) [16–21] on OB have been discussed. In some recent studies, multi-level atomic systems are proposed to investigate the bistable and multi-stable behavior of the atomic systems [22–24]. In such systems, the absorption, dispersion, and nonlinearity of the medium have been modified due to the quantum interference, which may affect the optical bisability [25].

However, an incoherent pump processes are also another candidate for creation and even modification of the nonlinear response of an atomic medium. In recent years, there are a lot of interests to control the optical response of the atomic systems by the quantum interference of incoherent pump field. Fleischhauer et al. [26,27] demonstrated that the interference of incoherent pump processes lead to gain without inversion and even enhancement of refractive index without absorption. The effect of an incoherent pump process on modification of spontaneous emission spectrum is also proposed [28]. Quantum interference arising from incoherent pump process has been used for modifying the spontaneous emission [29,30], phase dependence of collection fluorescence [31], and coherent population trapping [32]. The effect of incoherent pump field on phase control of group velocity [33], and the dynamical behavior of the absorption and dispersion [34] have also been studied. Moreover, the effect of quantum interference arising from incoherent pump field on controlling the light pulse propagation from subluminal to superluminal has been investigated [35].

Now, intriguing question arises whether one can create optical bistability via quantum interference of incoherent pump field and quantum interference of spontaneous emission? In this paper, we show that the optical bistability can be controlled by the quantum interference of direct incoherent pump field and spontaneous emission processes. No coherent laser field is used at the pumping processes of the system. It is shown that the quantum interference of direct incoherent pump field can dramatically modify the nonlinear response of the medium; thus optical bistability can be controlled by the quantum interference arising from direct incoherent pump field and the spontaneous emission. Moreover, we find that the rate of an indirect incoherent pump field reduces the threshold of optical bistability.

* Corresponding author at: Sama Technical and Vocational Training College, Islamic Azad University, Tabriz Branch, Tabriz, Iran. Tel.: +98 9144170663; fax: +98 4113321256.
E-mail address: h_jafarzadeh56@yahoo.com (H. Jafarzadeh).

http://dx.doi.org/10.1016/j.ijleo.2015.01.013
0030-4026/

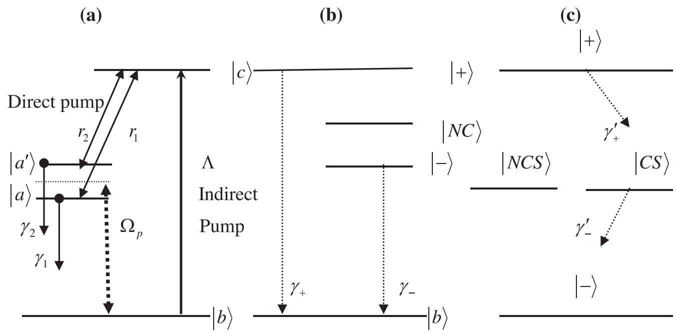

Fig. 1. (a) Energy levels diagram of a four-level atomic system interacting with two incoherent pump fields (solid) and a weak probe field (dashed). The direct incoherent pumping rates are shown by r_1 and r_2, while indirect incoherent pump rate is denoted by Λ. The decay rates from doublet to ground state are displayed by γ_1 and γ_2. Equivalent level schemes in terms of the new state basis for $\Lambda = 0$ (b), and $\Lambda \neq 0$ (c) are also displayed.

The proposed level structure is a four level atomic system in a Λ configuration. This system was already employed to control the spontaneous emission [29], and to control the group velocity of a light pulse from subluminal to superluminal via interference of incoherent pump field [35]. The paper is organized as follows: in Section 2, we present the model and equations. The results are discussed in Section 3, and the conclusion can be found in Section 4.

2. Model and equations

Consider a four-level atomic system in a Λ configuration as shown in Fig. 1(a). Two closely lying intermediate levels $|a\rangle$ and $|a'\rangle$, for instance, with magnetic quantum numbers $m = 1$ and $m = -1$, are pumped to the excited state $|c\rangle$ by a linear polarized incoherent field with a spectral width greater than the separation of the doublet states. Under this condition both transitions $|a\rangle \to |c\rangle$ and $|a'\rangle \to |c\rangle$ interact with the same excited mode establishing a coherence between $|a\rangle$ and $|a'\rangle$. Therefore, a direct incoherent pump process generates the atomic coherence [29]. The spontaneous decay rates from level $|a\rangle$ and level $|a'\rangle$ to the ground level $|b\rangle$ are denoted by γ_1 and γ_2, respectively. For simplicity, the spontaneous emissions from the excited level $|c\rangle$ to the lower levels are ignored. In order to establish the steady state population in the excited states, an incoherent pump process with pump rate Λ is applied to the transition $|b\rangle \to |c\rangle$ via some auxiliary states. We apply a weak tunable linear polarized coherent probe field with central frequency υ_p to doublet-ground states transition. There are three major dynamical processes occurring in the system: (I) incoherent pump processes through r_1, r_2, and Λ (II) interaction with the reservoir governing the decay processes from the levels $|a\rangle$ and $|a'\rangle$ to the level $|b\rangle$ (III) interaction with a weak coherent probe field. We describe the processes by three interactions Hamiltonian terms H_1, H_2 and H_3, respectively. Thus, including the free energy terms, the total Hamiltonian is [29,35]

$$H = H_0 + H_1 + H_2 + H_3, \tag{1}$$

where

$$H_0 = \hbar\omega_1|b\rangle\langle b| + \hbar\omega_2|a\rangle\langle a| + \hbar\omega_3|a'\rangle\langle a'| + \hbar\omega_4|c\rangle\langle c|, \tag{2a}$$

$$H_1 = -p_1E_p|c\rangle\langle a| - p_2E_p|c\rangle\langle a'| - pE'_p|c\rangle\langle b| + c.c, \tag{2b}$$

$$H_2 = -\hbar\sum_k g_k^{(1)}e^{i(\omega_{ab}-\upsilon_k)t}|a\rangle\langle b|\hat{b}_k - \hbar\sum_k g_k^{(2)}e^{i(\omega_{a'b}-\upsilon_k)t}|a'\rangle\langle b|\hat{b}_k + c.c, \tag{2c}$$

$$H_3 = -\hbar\Omega_{p_1}e^{-i\upsilon_p t}|a\rangle\langle b| - \hbar\Omega_{p_2}e^{-i\upsilon_p t}|a'\rangle\langle b| + c.c. \tag{2d}$$

where $\hbar\omega_i$ gives the energy of the state $|i\rangle$ ($i = a, a', b, c$). Here Ω_{p_1} and Ω_{p_2} are the Rabi-frequencies of the weak probe field corresponding to the transitions $|b\rangle \to |a\rangle$ and $|b\rangle \to |a'\rangle$. $g_k^{(1)}$ and $g_k^{(2)}$ are the coupling constants between the kth vacuum mode of frequency υ_k and the atomic transition from levels $|a\rangle$ and $|a'\rangle$ to level $|b\rangle$.p_1, p_2 and p are the dipole moments of atomic transitions corresponding to the pumping from the levels $|a\rangle$, $|a'\rangle$ and $|b\rangle$ to the level $|c\rangle$, respectively. E_p and E'_p are the amplitude of direct and indirect incoherent pump fields. $\hat{b}_k(\hat{b}_k^+)$ is the annihilation (creation) operator for the kth vacuum mode with frequency υ_k; k here represents both the momentum and polarization of the vacuum mode.

It is assumed that direct and indirect incoherent pump fields have a broad spectrum with effective δ-like correlation, i.e.

$$\langle E_p^*(t)E_p(t')\rangle = \Gamma_p\delta(t-t'),$$

$$\langle E'^*_p(t)E'_p(t')\rangle = \Gamma'_p\delta(t-t'). \tag{3}$$

However, the energy separation of the doublet states from the ground state is greater than the spectral width of the incoherent pump field E_p. We further assume that the incoherent pump process from the level $|b\rangle$ to the level $|c\rangle$ takes place via some unspecified auxiliary states; thus some terms corresponding to the inverse pumping from the level $|c\rangle$ to the level $|b\rangle$ and also the terms corresponding to the interference effect due to the pumping processes r_1, r_2, and Λ are all ignored.

The density matrix equations of motion in the rotating wave approximation and in rotating frame are:

$$\begin{aligned}
\dot\rho_{aa} &= -i\Omega_{p_1}\rho_{ab} + i\Omega_{p_1}\rho_{ba} - (\gamma_1 + r_1)\rho_{aa} + r_1\rho_{cc} - \frac{1}{2}(K_s\sqrt{\gamma_1\gamma_2} + K_p\sqrt{r_1r_2})(\rho_{a'a} + \rho_{aa'}),\\
\dot\rho_{a'a'} &= -i\Omega_{p_2}\rho_{a'b} + i\Omega_{p_2}\rho_{ba'} - (\gamma_2 + r_2)\rho_{a'a'} + r_2\rho_{cc} - \frac{1}{2}(K_s\sqrt{\gamma_1\gamma_2} + K_p\sqrt{r_1r_2})(\rho_{a'a} + \rho_{aa'})\\
\dot\rho_{bb} &= i\Omega_{p_1}\rho_{ab} + i\Omega_{p_2}\rho_{a'b} - i\Omega_{p_1}\rho_{ba} - i\Omega_{p_2}\rho_{ba'} - \Lambda\rho_{bb} + \gamma_1\rho_{aa} + \gamma_2\rho_{a'a'} + K_s\sqrt{\gamma_1\gamma_2}(\rho_{a'a} + \rho_{aa'}),\\
\dot\rho_{cc} &= -(r_1 + r_2)\rho_{cc} + r_1\rho_{aa} + r_2\rho_{a'a'} + \Lambda\rho_{bb} + K_p\sqrt{r_1r_2}(\rho_{a'a} + \rho_{aa'})\\
\dot\rho_{ab} &= \left[i\delta_{p_1} - \frac{1}{2}(r_1 + \Lambda + \gamma_1)\right]\rho_{ab} + i\Omega_{p_1}(\rho_{bb} - \rho_{aa}) - i\Omega_{p_2}\rho_{aa'} - \frac{1}{2}(K_s\sqrt{\gamma_1\gamma_2} + K_p\sqrt{r_1r_2})\rho_{a'b},\\
\dot\rho_{a'b} &= \left[i\delta_{p_2} - \frac{1}{2}(r_2 + \Lambda + \gamma_2)\right]\rho_{a'b} + i\Omega_{p_2}(\rho_{bb} - \rho_{a'a'}) - i\Omega_{p_1}\rho_{a'a} - \frac{1}{2}(K_s\sqrt{\gamma_1\gamma_2} + K_p\sqrt{r_1r_2})\rho_{ab},\\
\dot\rho_{a'a} &= \left[i(\delta_{p_2} - \delta_{p_1}) - \frac{1}{2}(r_1 + r_2 + \gamma_1 + \gamma_2)\right]\rho_{a'a} - i\Omega_{p_1}\rho_{a'b} + i\Omega_{p_2}\rho_{ba}\\
&-\frac{1}{2}(K_s\sqrt{\gamma_1\gamma_2} + K_p\sqrt{r_1r_2})(\rho_{aa} + \rho_{a'a'}),\\
&\rho_{aa} + \rho_{a'a'} + \rho_{bb} + \rho_{cc} = 1.
\end{aligned} \tag{4}$$

Here, the Weisskopf–Wigner approximation has also been used [36]. The detuning parameters are defined as $\delta_{p1} = \Delta - \omega_{a'a}/2$ and