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Temperature-induced optical bistability with Kerr-nonlinear blackbody reservoir

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ABSTRACT

We investigate both absorptive- and dispersive optical bistability (OB) phenomena for a homogeneously broadened two-level atomic medium interacting with a single mode of the ring cavity in the presence of the Kerr-nonlinear blackbody reservoir. We predict the temperature-induced switching phenomenon with near resonance conditions, as well as lower cooperativity parameter to observe OB due to such reservoir.

1. Introduction

Optical bistability (OB) phenomenon is of profound importance in nonlinear optical sciences, and has been investigated both experimentally and theoretically over past many decades [1–14]. This is because the phenomenon could provide a break-through in some important technological advances in the high speed all-optical switching, all-optical signal processing, and all-optical computing. Optically bistable systems are usually based on the generation of two output stable electromagnetic field states when excited by the same input electromagnetic field state, and hence can provide applications to all-optical logic gates, memory devices, switches, differential amplifiers, components in optical computers and communication systems [8,11,12]. Some other noteworthy applications of such bistable systems in all optical telecommunication networks, optical computing based on nonlinear semiconductor lasers and laser amplifiers are also of current interests for the optics community [13]. Hence any further advancement of the OB systems can bring radical changes and innovations in the novel quantum computational devices, quantum information processing networks and efficient realization of entanglement in situations, when system is behaving in a cooperative manner. Another related phenomenon in the context of OB is the optical chaos generated in nonlinear optical systems, which could provide the communication information at enhanced data rates along with its application in the random number generation [15].

One of the simplest models of optical bistability using two-level atomic or molecular systems [2–4] placed in a non-ideal optical cavity (either a ring cavity or a Fabry–Perot cavity) exhibits the control of threshold intensity of the bistability and the shape and sizes of hysteresis loop of bistability under different physical situations. A few such situations are (but not limited to) field induced transparency in basic OB system [12], phase fluctuations in the interacting electromagnetic field [16], spontaneously generated coherence in the basic OB system [17]. Some interesting studies using squeezed vacuum field on the OB phenomenon were carried out in both Fabry–Perot and ring cavity configurations with two-level atomic vapor systems [18–26]. Also, some dispersive switching effects interconnecting the output field and atomic detuning for different kind of OBs including mesoscopic systems were also studied in recent past [27–30].

Recently, the effect of Kerr-nonlinear blackbody (KNB) has been examined in some nonlinear optical system [31–37, and references therein]. The usual black body radiation is the electromagnetic radiation emitted by a blackbody. In turn, this blackbody is usually modeled as a solid cavity having a small aperture within it, kept at a constant temperature *T*, allowing us to maintain a thermal equilibrium of the electromagnetic fields sustained inside the

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cavity [38]. On the other hand, the KNB contains paired and nonpaired photons, responsible to make formation of the nonpolariton, a quasiparticle system that contributes to the free thermal radiation in such black body. In the KNB, the resulting radiation is found to be a squeezed thermal state below a transition temperature [32]. A KNB can be realized by simply filling the interior of a black body with a Kerr-like medium (usually a nonlinear crystal in rectangular or cylindrical kind of shape) with the condition that the thermal radiation and the Kerr-like medium are in thermal equilibrium with each other and maintains a fixed temperature for the cavity. In a KNB, the photon–phonon interaction gives rise to an effective interaction of attractive nature responsible for creating bound photon pairs in photonic superguiding state moving unattenuated [35]. The significant change occurring when a normal blackbody is replaced by a KNB in matter-electromagnetic field interaction is that the usual vacuum state of the electromagnetic field is replaced by the photon pair state. This results in the replacement of infinite energy of the field vacuum by the finite energy of photon pairs [33,35]. The spectral energy density and radiation pressure of the KNB are larger as compared to the normal black body [32]. Few important studies in the presence of the KNB reservoir are the suppression of spontaneous emission from a two-level atom below a transition temperature [35] and the preservation of quantum entanglements of atoms [37]. The concern of the present work is to study effects of KNB reservoir on an OB systems and compare it with previously studied radiation reservoir cases, namely, the normal vacuum, thermal field and squeezed vacuum reservoirs. Advantages of the OB system with KNB reservoir effects are the temperature-induced switching, reduction in the threshold cooperative parameter to observe OB, etc., compared with earlier cases.

The paper is presented as follows. In Section 2, we present the model OB equations and the general input–output state equation in the KNB reservoir case and then compare it with input–output state equations of other radiation reservoir cases. In Section 3, we discuss the computational results, followed by conclusion in Section 4.

2. The model

Consider a single mode ring cavity containing a homogeneously broadened two-level atomic medium of length L and transition frequency ω_0, interacting with an electromagnetic field of amplitude E_P and frequency ω_P. The upper and lower levels are given by the states $|1>$ and $|2>$ with the corresponding ladder operators defined as $A_{12} = |1><2|$, $A_{11} = |1><1|$, and $A_{22} = |2><2|$. The cavity contains mirrors with transmission coefficient T along with N atoms all in the ground state. The coherent interaction between atoms and field that propagates along the longitudinal axis induces macroscopic polarization and changes in the level population of the atomic system. Here the transverse field effects are not taken into account for the sake of simplicity. The total internal field inside the ring cavity is composed of the incident field and the radiated field due to the induced polarization. The longitudinal and transverse decay rates of the upper atomic level are characterized by $\gamma_{\|}$, $\gamma_{\perp}$, respectively. The equations describing population and polarization of the atomic system (the Bloch equations) [14] are given by

$$\langle \dot{A}_{11} \rangle = -i\Omega_P[\langle A_{12}\rangle - \langle A_{21}\rangle] - \gamma_{\|}(n_1+1)\langle A_{11}\rangle + \gamma_{\|} n_1 \langle A_{22}\rangle,$$

$$\langle \dot{A}_{22} \rangle = i\Omega_P[\langle A_{12}\rangle - \langle A_{21}\rangle] + \gamma_{\|}(n_1+1)\langle A_{11}\rangle - \gamma_{\|} n_1 \langle A_{22}\rangle,$$

$$\langle \dot{A}_{12} \rangle = -i\Omega_P[\langle A_{11}\rangle - \langle A_{22}\rangle] - \gamma_{\perp}(2n_1+1)\langle A_{12}\rangle + i\Delta_P\langle A_{12}\rangle. \tag{1}$$

Here, $n_1 = 1/(e^{\hbar\omega/k_B T_B} - 1)$ is the average photon number of the heat bath (thermal reservoir) maintained at a fixed temperature T_B, with central frequency ω, Boltzmann constant k_B and the parameter $\Delta_P = \omega_P - \omega_0$ represents the atom-field detuning. The Rabi frequency of the system is $\Omega_P = d_{12}E_P/\hbar$ and transition dipole matrix element is d_{12}. The field propagation along the cavity axis (z-direction) is given [14] by the Maxwell equation

$$\frac{\partial E_P}{\partial z} + \frac{1}{c}\frac{\partial E_P}{\partial t} = \frac{2\pi i d_{12}\omega_P}{c}P(\omega_P). \tag{2}$$

Under the steady-state conditions, the boundary conditions for the field at different positions are given by [9,14]

$$E_P^T = \sqrt{T}E_P(L),$$
$$E_P(0) = \sqrt{T}E_P^I + (1-T)\exp(-i\theta_0)E_P(L), \tag{3}$$

in which, the subscripts I and T represent incident and transmitted field on and from the cavity, respectively. θ_0 is the cavity detuning of the nearest mode of the cavity close to the atomic transition frequency. Alternatively, the steady-state behavior of OB can be obtained by allowing $\langle \dot{A}_{ij}\rangle = 0$ $(i,j=1,2)$ and $\partial E_P/\partial t = 0$, which provide the following equation [9]:

$$\frac{\partial E_P}{\partial z} = -\alpha\chi(|E_P|^2)E_P. \tag{4}$$

The quantity χ is called the complex dielectric susceptibility having the following expression:

$$\chi = \frac{\alpha[(2n_1+1)+i\delta]}{(2n_1+1)[(2n_1+1)^2+\delta^2+|E_P|^2/I_S]} \tag{5}$$

with $\delta = \Delta_P/\gamma_{\perp}$, $\alpha = \pi\omega_P d_{12}^2 N/\hbar c\gamma_{\perp}$ and $I_S = \hbar^2\gamma_{\|}\gamma_{\perp}/4d_{12}$. By defining $x = E_P^T/(I_S T)^{1/2}$, $y = E_P^I/(I_S T)^{1/2}$ with $X = |x|^2$, $Y = |y|^2$, we get from Eqs. (4) and (5), the following state equation

$$Y = X([1+2C\tilde{\chi}_a(X)]^2 + [\theta - 2C\tilde{\chi}_d(X)]^2), \tag{6}$$

where $C = \alpha L/2T$, $\theta = \theta_0/T$ and have used the spatial mean field approximation to get Eq. (6). The expressions for $\tilde{\chi}_a(X)$ and $\tilde{\chi}_d(X)$ for the thermal reservoir condition are given by

$$\tilde{\chi}_a(X) = \frac{1}{[(2n_1+1)^2+\delta^2+X]},$$
$$\tilde{\chi}_d(X) = \frac{\delta}{(2n_1+1)[(2n_1+1)^2+\delta^2+X]}. \tag{7}$$

In the case of KNB reservoir [35,37], the radiation is in a squeezed thermal state below a transition temperature T_c (dependent on the Kerr nonlinear crystal), which results in atomic spontaneous emission suppression due to formation of photon pairs via lattice vibrations. Above the temperature T_c, the KNB behaves like a normal blackbody (ordinary thermal radiation of temperature T_B). The formation of photon pairs is physically understood as follows [32]: if one photon (first photon) is surrounded by a cloud of lattice vibrations (phonons) then with another photon nearby this polarization cloud, it experiences a force of attraction with the first photon and a photon pair is then formed. Not all KNB photons paired where unpaired forms a new kind of quasiparticles, the nonpolaritons.

Hence, spontaneous emission of atomic system coupled to a KNB reservoir (i.e., a thermal reservoir with KNB medium) is