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Critical slowing down in an optical bistable model with Kerr-nonlinear blackbody reservoir

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ABSTRACT

We investigate switching response for an Optical Bistable (OB) device consisting of homogeneously broadened two-level atoms in a ring cavity supported by a Kerr Nonlinear Blackbody (KNB) radiation reservoir in the high-Q cavity regime for both absorptive and dispersive cases. In the resonant case and below a transition temperature, faster switching processes for OB devices with KNB can be triggered by a small perturbation of the incident field in the vicinity of the critical transition point. The switching time increases with increasing atomic detuning parameter. A thermal switching process is obtained for a fixed incident field and is triggered by small perturbation in the relative reservoir temperature, T_b say. The switching time is reduced considerably by slightly increasing the temperature T_b. Comparison with other cases of radiation reservoir is made, namely, normal, thermal and squeezed vacuum.

1. Introduction

OB is vitally important in nonlinear optical phenomena, due to its potential applications in different branches of science, optical computations, optical communications, biological and medical systems. It has been investigated theoretically and experimentally with dissipative two-level atomic systems placed in an optical cavity [1–4]. OB has attractive applications in all optical switches, memories, transistors and logic circuits [5,6] with normal vacuum field. These studies show that one can control the bistable threshold intensity and the hysteresis loop via many approaches, such as field induced transparency [7] and phase fluctuations [8]. Reversed (clockwise) and butterfly (closed loop) hysteresis structures [9] were predicted for the additional first harmonic output field component outside the Rotating Wave Approximation (RWA) *simultaneously* with the usual bistable (anti-clockwise) hysteresis for the fundamental output field component. The first harmonic output field component outside the RWA can be further controlled to show a one- or two-way switching processes when atomic inhomogeneous broadening and transverse input field features are taken into consideration [10]. There may be applications in optical information signal processing as well as simultaneous opposite coding.

The nonlinear atomic medium in optical bistable devices is affected by the quantum state of the radiation reservoir responsible for the atomic damping processes as follows:

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(i) The Thermal Field (TF) leads to the broadening of the longitudinal and transverse atomic linewidths [4].
(ii) The Squeezed Vacuum (SV) field induces narrowing in the transverse atomic linewidth associated with one quadrature component of the atomic polarization [11], as a result of the simultaneous creation or annihilation of photon pairs in the squeezed state.
(iii) In the KNB case, the natural atomic linewidth (the spontaneous emission) is suppressed as a result of the formation of photon pairs by the phonons of lattice vibrations under the condition that $T < T_c$, where T_c is the critical transition temperature [12,13].

Optical bistable systems with injected SV field [14–19], compared with the Normal Vacuum (NV) case [3,4] have their advantages of achieving OB at a lower threshold value of the atomic cooperative parameter ($C < 4$), as well achieving a one– or two– phase switching processes by adjusting the relative phase of the degree of the squeezing parameters (M).

On the other hand, an optical bistable system of a homogeneously broadened two-level atomic medium interacting with a single mode of the ring cavity in the presence of the KNB reservoir has been studied recently in both the absorptive and dispersive cases [20]. It is shown that OB is observed at even lower cooperativity parameter than that in the SV case [16]. Furthermore, a temperature induced switching process at a fixed input field is predicted near resonance conditions [20]. In the KNB, the resulting radiation is found to be a squeezed thermal state below a certain transition temperature [21]. The significant change occurring when a normal blackbody (thermal field) 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 and in turn the infinite energy of the field vacuum is replaced by the finite energy of the photon pairs [13,22].

The phenomenon addressed in this paper, namely, Critical Slowing Down (CSD), is associated with lengthening the time taken for the system to recover from a small perturbation or disturbance in one of its control parameters in the vicinity of a critical transition point. As a consequence, the large delay time leads to: (i) a large memory device, and (ii) a slow switching device. Earlier, within the RWA, CSD in the NV case was examined for absorptive OB [23] and later extended to the SV case [24]. A study of CSD would benefit (at some degree) the following:

(i) Decay rates of the transitional transient processes to stable steady-state can be measured.
(ii) There are possible device applications in optics [25–27].
(iii) It may be possible to achieve dynamical stabilization of the system in response to perturbations or fluctuations of the system parameters near the critical points [28].

Recently, we have examined the CSD of an OB model of two-level atoms placed inside a ring cavity outside the RWA in the high- and low-Q cavity cases [29]. The faster oscillatory behavior outside the RWA induces irregular oscillations with increased atomic detuning in the lower branch of the hysteresis curve of the first harmonic output field due to interference with atomic dispersion or Rabi oscillations. Effects of atomic inhomogeneous (Lorentzian) broadening and transverse (Gaussian) field variations on the CSD in the high-Q cavity limit has been discussed in [30]. The main result in [30], in the high-Q cavity regime, is that the switching time decreases with increasing the Lorentzian parameter in both absorptive and dispersive cases. In addition, the transverse field parameter increases the switching response of the optical bistable device significantly in the dispersive case with associated irregular oscillations in the lower branch.

Elsewhere [31,32], CSD was investigated for some bistable biological and environmental models. In [31] it was shown that the time-delay reduction is independent of the nonlinearity form and fits an inverse square root law $\beta^{-1/2}$, where $\beta$is a perturbation parameter (see e.g. [25,26] and refs. therein). In [32] it was suggested that CSD could provide universal indicators of how close a complex system such as the brain, the climate, ecosystems and the financial markets, are to a threshold. CSD applied to the optical properties of atoms is covered in papers such as [33,34].

The aim of the present work is to study the switching response of an optical bistable system of 2-level atoms in the presence of a KNB reservoir in the vicinity of critical transition point and compare it with previously studied radiation reservoir cases, namely, the NV, thermal field and squeezed vacuum reservoirs. This is achieved by showing the effect of perturbations of the incident field near a transition point. Furthermore, we investigate the thermal switching effects by perturbing the relative temperature T_b in the vicinity of critical value of T_c.

The paper is organized as follows: A review of our model is presented in Sec. II. Both incident field and thermal switching responses in the OB model in the high-Q cavity limit is examined in Sec. III and a summary is given in Sec. IV.

2. Model review

Consider a single mode ring cavity containing a homogeneously broadened two-level atomic medium in contact with a thermal reservoir of temperature T_B and of transition frequency ω_o and interacting with an electromagnetic field of frequency ω_L. 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. The c-number model Maxwell-Bloch equations in the plane wave, rotating wave and mean field approximations are given by [20]:

$$\frac{dx}{dt} = \kappa\left[Y - (1 + i\theta)x + 2\sqrt{2}Cr_-\right], \tag{1a}$$