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Optics Communications 247 (2005) 367–379

OPTICS COMMUNICATIONS

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Four-level Hamiltonian model with an additional Kerr medium and multiphoton processes

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Received 7 August 2004; received in revised form 27 October 2004; accepted 18 November 2004

Abstract

The dynamics of the Q-function for a four-level system coupled to one mode cavity field via multiphoton processes in the presence of a Kerr-like medium are investigated. Starting the field mode in a coherent state and the atom in a coherent superposition of its ground and upper states, the atom-field wave function and the reduced density matrix of the field are obtained. The cavity field statistics are investigated through Mandel Q parameter. The influence of the detunings and the Kerr medium on the evolution of the Q parameter and the Q-function is analyzed numerically for single- and two-photon processes. It is shown that splitting, rotation and broadening phenomena have occurred in the evolution of the Q-function.

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PACS: 03.65.Ge; 32.80.−t; 42.50.Ct; 42.50.Dv
Keywords: Jaynes–Cummings model; Kerr-like medium; Multiphoton interactions; Cavity QED

1. Introduction

The Jaynes–Cummings model (JCM) [1] has been recognized as the simplest and most effective model on the interaction between radiation and matter in quantum optics. It is described by a two-level atom interacting with a single radiation mode. Despite the simplicity of JCM, it is of great significance because recent technological advances have enabled one to experimentally realize this rather idealized model [2,3] and to verify some of the theoretical predictions. The radiation–matter interaction currently used is based on some relevant approximations that are still well verified in current experiments. Among them, it is assumed that the dipole approximation holds, that is, the wavelength of the radiation field is much larger than the atomic dimensions. Also, the rotating wave approximation (RWA) is always assumed, meaning by this that just near resonant terms are effective in describing the interaction between radiation and matter, these terms being also described

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doi:10.1016/j.optcom.2004.11.068

as energy conserving. It is sometimes believed that without the above two approximations no two-level atom approximation can really holds [4]. Actually, in the optical regime, that statement can be supported and widely justifies the success of the JCM both theoretically and experimentally. The JCM can be implemented in two representative scenarios in quantum optics, namely ion traps and cavity QED. In ion traps the centre-of-mass motion of the trapped ion is harmonic, and it couples to an internal atomic transition when the ion is irradiated by a laser [5]. In cavity QED, the harmonic oscillator is a mode of the quantized radiation field, coupled to a resonant electronic transition of atoms sent through the resonator and undergoing the JCM dynamics [6].

Stimulated by the success of the JCM, many people have paid special attention to extending and generalizing the model in order to explore new quantum effects [7–9]. Two exactly solvable generalizations of the JCM have been proposed by Sukumar and Buck [10], one involving intensity dependent coupling and the other involving multiphoton interaction between the field and atom. Also, possible generalizations are the consideration of multimode and multiphoton instead of single mode and single photon [11], addition of Kerr-like medium, and Stark shift [12] have been performed. Also, extensive studies of a three-level atom with different configurations under RWA interacting with quantized fields inside an ideal cavity were carried out in detail by Yoo and Eberly [9]. Later on several more studies on dynamical evolution and field statistics were reported on the similar type of models [13]. These models could be experimentally tested by utilizing three-level atoms in various configurations in the micromaser systems. Based on the JCM and its various extensions, a multitude of interesting nonclassical effects, such as the collapse and revival of Rabi oscillations, antibunched light, squeezing, inversionless light amplification, electromagnetic-induced transparency, etc., have been extensively studied [8,9,13,14]. These effects have found wide applications in micromaser, microlaser and quantum nondemolition measurements [3,15].

In the present paper, we shall consider a generalization of the JCM and investigate the dynamics of the quasiprobability distribution Q-function of a four-level atom interacting with a single mode field in a cavity containing a Kerr-like medium. Also, we involve multiphoton interaction between the field and atom. Moreover, we investigate the cavity field statistics through Mandel Q parameter. The cavity mode is coupled to the Kerr medium as well as to the four-level atom. The Kerr medium can be modelled as an anharmonic oscillator. We shall examine the influence of the Kerr medium, the detunings and the multiphoton processes on the time evolution of the Mandel Q parameter, measuring the deviation from Poissonian photon statistics, and on the evolution of the quasiprobability distribution Q-function of the field. In order to study the quantum statistical properties of the field it is instructive to examine the quasiprobability distribution of the field. The field evolution is most conveniently presented in terms of the quasiprobability distributions. These distributions have become especially important in recent times as one could use them to demonstrate interference effects which are of quantum origin [16]. For example, for a Schrödinger cat state the Wigner function, which is one out of the many possible quasiprobability distributions becomes negative and exhibits oscillations in certain regions of phase space. The quasiprobability distributions have not remained merely the theoretical tools but we now have many theoretical proposals and experimental measurements of the quasiprobability distributions [17]. We shall present here the Q-function of the field for the considered atomic system.

The organization of the paper is as follows. In the following section, we introduce the multiphoton Hamiltonian model. Including Kerr medium, we show that the atomic system is exactly solvable in the RWA and obtain the atom-field wave function and the reduced density matrix of the field when the atom is initially prepared in a coherent superposition of the ground state $|1\rangle$ and the upper state $|4\rangle$ and the field is initially in a coherent state. In Section 3, we investigate the evolution of the Mandel Q parameter. We show numerically the influence of the Kerr medium and the detunings on the evolution of the Q parameter for single- and two-photon processes and for the case when the atom starts in the ground state $|1\rangle$. In Section

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