Optics Communications 283 (2010) 2705–2715

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Radio-frequency control of spontaneous emission from a coherently driven multilevel atom

Chunling Ding, Jiahua Li *, Xiaoxue Yang

Wuhan National Laboratory for Optoelectronics and School of Physics, Huazhong University of Science and Technology,Wuhan 430074, People's Republic of China

ARTICLE INFO

Article history:
Received 5 January 2010
Received in revised form 22 February 2010
Accepted 25 February 2010

Keywords:
Spontaneous emission
Radio-frequency (RF) fields
Spectral-line enhancement and narrowing

ABSTRACT

The spontaneous emission properties of radio-frequency(RF)-driven multilevel atomic systems with three different configurations are investigated in details. It is demonstrated that, due to the presence of the RF-induced coherence in the multilevel system, a few interesting phenomena such as spectral-line narrowing, spectral-line enhancement, spectral-line suppression, and fluorescence-quenching can be realized under realistic experimental conditions. By inspecting single-RF-driven, double-RF-driven, and triple-RF-driven atomic systems, we find that (i) when only one RF-driven field is applied, there are two fluorescence-quenching points and four spectral lines; (ii) in the case of applying two RF-driven fields, there are three fluorescence-quenching points and five spectral lines; (iii) when applying three RF-driven fields, there are four fluorescence-quenching points and six spectral lines; and (iv) as expected, when the atomic system coupled by N RF-driven fields, there will be $N+1$ fluorescence-quenching points and $N+3$ spectral lines. Interestingly enough, the spectral-line enhancement, the spectral-line suppression, and the selective cancellation of fluorescence-quenching can be well controlled just by appropriately modulating the intensities and frequencies of the applied RF fields, respectively. The proposed schemes can be achieved by use of RF-driven fields into hyperfine levels in rubidium atomic systems. These investigations may find applications in high-precision spectroscopy.

1. Introduction

Spontaneous emission in atomic systems, is recognized as one of the best-known fundamental processes based on the interaction of atomic systems with the environmental modes. As usual, spontaneous emission is believed to result in the decay between atomic levels, which can also be used to produce atomic coherence as long as there exist two close-lying levels with non-orthogonal dipoles in an atomic system. Atomic coherence due to spontaneous emission is usually referred to as vacuum-induced coherence (VIC) or spontaneously generated coherence (SGC). This type of coherence has become an active research topic and lies at the heart of many novel quantum phenomena. However, the rigorous conditions of near-degenerate close-lying levels and non-orthogonal dipole matrix elements are rarely met in real atoms, therefore few experiments have been reported [1,2]. Recently it has been pointed out that quantum interference similar to SGC could be achieved in the dressed-state picture without any stringent requirements [3–5]. As is well known, for atoms in free space, laser-induced quantum interference and atomic coherence are the basic methods for controlling the spontaneous emission [6,7]. As a result, efficient control and modification of spontaneous emission [8–21] based on atomic coherence and quantum interference has attracted much attention in quantum optics mainly because of its wide and potential applications in lasing without inversion [22–25], coherent population trapping [26,27], transparent high-index materials [28,29], high-precision spectroscopy and magnetometry [30–32], quantum information and computing [33–35], and so on.

There are two main mechanisms to control the spontaneous emission of atoms. In the first mechanism the spontaneous emission of a multilevel atomic system can be modified just by putting atoms into different environments, such as in free space, in photonic crystals and in optical cavities, which have different densities of electromagnetic modes interacting with atoms. On the other hand, in the second mechanism the manipulation of spontaneous emission can be achieved by using external coherent fields to couple atoms. In recent years, based on the second mechanism, a lot of theoretical works and considerable efforts have been devoted to discuss the control of atomic spontaneous emission. Paspalakis and Knight [36] proposed a phase control scheme in a four-level atom driven by two lasers of the same frequencies in the presence of the SGC effect, where the relative phase of the two lasers was used to obtain partial cancellation in the spontaneous emission spectrum. Ghafoor et al. [37] investigated the amplitude and phase control of spontaneous emission and obtained a wide variety of spectral behaviors. Joshi et al. [38] have studied the effect of SGC on population dynamics of three excited states decaying

* Corresponding author. Tel./fax: +86 2787557477.
E-mail address: huajia_li@163.com (J. Li).

0030-4018/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2010.02.052

to the same state. Antón et al. [39] investigated the resonance fluorescence and probe absorption spectra of a closed four-level system. In addition, the quenching of spontaneous emission in an open V-type atom was presented in Ref. [40]. Phase-dependent effects in spontaneous emission spectra in a Λ-type atom were studied in Ref. [41]. Recently, Wu et al. [42] studied the spontaneous emission properties of a 'tripod' configuration four-level atom with two external driving fields, and showed some interesting phenomena such as fluorescence-quenching, spectral-line narrowing, spectral-line enhancement and spectral-line elimination. They also pointed out that these phenomena could be observed in the experiment since the rigorous condition of near-degenerate levels with non-orthogonal dipole moments was not required. In the following research, Li et al. [43] studied a different four-level atomic model and arrived at similar conclusions. The control of spontaneous emission via an external coherent magnetic field in a cycle-configuration atomic medium is discussed by Li in Ref. [44] and later Gao et al. [45] studied the effects of SGC on spontaneous emission and dynamical evolution in a microwave-driven four-level atomic system. Li et al. [46] also investigated the features of spontaneous emission spectra in a coherently driven five-level atomic system by means of a radio-frequency (RF) or microwave field driving a hyperfine transition and further simulated multiple SGC reported by Fountoulakis et al. [47]. More recently, Dutta and Mahapatra [48] investigated the control of spontaneous emission in a driven M-type atom via microwave field induced low-frequency coherence. As far as we know, in Ref. [46] the two hyperfine levels which are driven by an RF field are within the ground and metastable states. While in Refs. [45,48] the two levels coupled by a microwave field are located in excited states, and the system is a closed-loop configuration. To the best of our knowledge, however, neither theoretical nor experimental works have been undertaken to study spontaneous emission properties and its control in such single-RF-driven, double-RF-driven, and triple-RF-driven atomic systems with the hyperfine cascade transitions.

Motivated by this, in the present work, we theoretically examine the spectral properties of spontaneous emission in coherently driven multilevel atomic systems with three different configurations, in which we respectively use the single, double, and triple-RF fields to couple the hyperfine cascade transitions within upper excited states. Of particular interest is the application of a few RF fields in the MHz range, since the RF sources are more readily available and also provide a coherent, homogeneous and readily controllable radiation fields in comparison with additional laser fields, and this is a situation considered in this paper. Compared with the previous works [44–46,48], the dynamics of our considered multilevel atomic system is disturbed by these additional RF fields, resulting in the formation of the multiple RF-induced coherence. Naturally the RF-induced coherence offers us further flexibility to manipulate the laser–matter interactions, including the control and modification of atomic spontaneous emission as discussed in this communication. By inspecting single-RF-driven, double-RF-driven, and triple-RF-driven atomic systems, we can observe some interesting phenomena, such as spectral-line narrowing, spectral-line enhancement, spectral-line suppression, and fluorescence-quenching under realistic experimental conditions. Interestingly enough, the spectral-line enhancement, the spectral-line suppression, and the selective cancellation of fluorescence-quenching can be easily operated just by properly adjusting the intensities and frequencies of the applied RF fields, respectively. In addition, we also give the possibility of realizing the proposed schemes in atomic rubidium where a seven-level scheme can be found with some of the levels being hyperfine levels.

The organization of this paper is as follows. In Section 2, the atomic models under study are presented. The corresponding basic dynamic equations of motion and their analytical solutions about the spontaneous emission spectra are explicitly derived for the single-RF-driven, double-RF-driven, and triple-RF-driven atomic systems. Besides, we analyze and discuss in detail their properties in three different configurations together with the differences among them. In Section 3, we provide a possible experimental realization of our scheme with cold ^{87}Rb atoms. Finally, we conclude with a brief summary in Section 4.

2. Theoretical models in three different systems

In this section, firstly we will focus on the properties of spontaneous emission spectra in a five-level atomic system driven by single-RF field. In this scheme, we give a detailed theoretical derivation for the basic dynamic equations of motion and the analytical expressions of the spontaneous emission spectra. Secondly, we turn to a six-level atomic system driven by double-RF fields to study the spontaneous emission and further compare with the five-level atomic system. Lastly, we extend them to a seven-level atomic system which is driven by triple-RF fields. We find that, due to the existence of these RF field-induced coherences in the multilevel system, the spontaneous emission behaviors can be easily controlled for various combinations of system parameters in each scheme mentioned above. In the given models, because of multiple interfering pathways, 'peak to peak'-compression effect as highlighted in some recent works (see e.g. [4,42,45,48]) is seemed to be achievable. At the same time, we would like to mention here that the proposed models can introduce the effect of superposition of dynamic Stark-splittings through the upper transitions in the spontaneous emission spectrum when the Rabi frequency of the optical field pumping the population from the ground to the upper state is strong. These detailed results will be presented in the following.

2.1. Five-level atomic system with single-RF-driven field

We begin with a study of a coherently driven five-level atomic system, which consists of three upper, excited levels $|1\rangle$, $|2\rangle$, $|3\rangle$ and two lower, ground or metastable levels $|g\rangle$ and $|e\rangle$ as depicted in Fig. 1(a). A coherent probe laser field with carrier frequency ω_p and Rabi frequency $2\Omega_p$ is used to drive the transition $|g\rangle \leftrightarrow |1\rangle$. At the same time, a coherent coupling laser field with carrier frequency ω_c and Rabi frequency $2\Omega_c$ is used to couple the transition $|1\rangle \leftrightarrow |2\rangle$. An extra coherent field drives a hyperfine transition between two hyperfine levels $|2\rangle$ and $|3\rangle$, which can produce strong dynamically induced coherence between them. The two levels are located in the excited-state hyperfine structure, therefore the

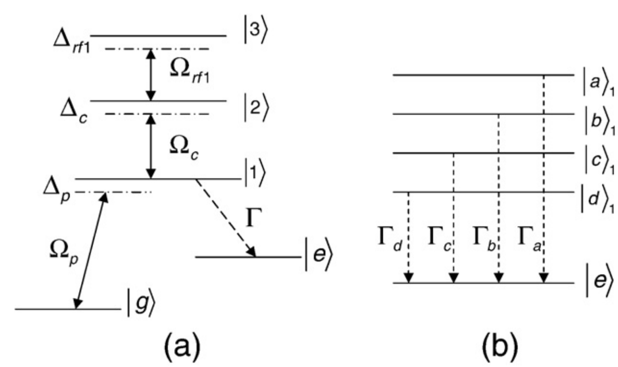

Fig. 1. (a) Schematic diagram of the five-level atomic system under consideration, which consists of the ground state $|g\rangle$, the intermediate state $|e\rangle$, and three excited states $|1\rangle$, $|2\rangle$, and $|3\rangle$ ($|2\rangle$ and $|3\rangle$ are hyperfine levels). The transitions $|g\rangle \xrightarrow{\Omega_p} |1\rangle \xrightarrow{\Omega_c} |2\rangle$ are driven by the coherent probe and coupling laser fields with Rabi frequencis $2\Omega_p$ and $2\Omega_c$, respectively. The hyperfine transition $|2\rangle \leftrightarrow |3\rangle$ is driven by an RF field with Lamor frequency $2\Omega_{rf1}$ which can produce strong dynamically induced coherence between them. While the transition $|1\rangle \leftrightarrow |e\rangle$ is coupled by the vacuum-field mode in the free space, Γ denotes the decay rate. Δ_p, Δ_c, and Δ_{rf1} are the frequency detunings of the corresponding probe, coupling, and RF-driven fields. (b) The corresponding dressed-state description of the probe, coupling, and RF-driven fields. The atomic system we considered can be regard as four dressed states decaying to a common state.