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Λ-scheme feedback spectroscopy

V.A. Tomilin[a,b,*], L.V. Il'ichov[a,b]

[a] Institute of Automation and Electrometry SB RAS, 630090 Novosibirsk, Russia
[b] Novosibirsk State University, 630090 Novosibirsk, Russia

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ABSTRACT

We investigate probe-pump spectroscopy of a Λ-system, with one of the fields' phase being controlled by a feedback loop. The feedback is trigged by modified photo-detection events organized by means of a special unravelling of master equations. The steady-state of the system is obtained and analyzed, and works of the fields per unit time are evaluated. It is shown that the properties of dark resonances can effectively be controlled by the choice of the events that trig feedback action and by the fields' amplitudes. There revealed surprising peculiarities of the fields' work as a function of their amplitudes.

1. Introduction

Non-linear spectroscopy, originating from early 60-s [1] with the invention of lasers, is nowadays a well-developed field of non-linear optics. One of its fundamental effects, particularly well-studied in Λ-systems [2], is coherent population trapping (CPT) [3,4].

Quantum control theory is now a rapidly evolving field [5,6] that has recently found many applications with the development of experimental techniques capable of studying elementary quantum objects, such as single atoms and ions [7,8]. Applications of feedback control techniques to simple quantum optical systems could lead to novel behavior such as manipulation of the steady-state of dissipative two-level system [9], enhancing the squeezing of resonance fluorescence from a two-level atom [10], or stabilizing the outcome of a quantum measurement performed on the controlled system [11], and hence is certainly of interest for potential applications. When dealing with the systems of elementary emitters, such as atoms and molecules, interacting with electromagnetic fields, the most natural choice of feedback control is detection-based feedback, i.e. performing control action on the systems upon detecting the radiation coming from the system. In our earlier works [12–15] we have shown that controlling the phase of the field that interacts with two-level atoms is a powerful tool to change the form of resonance fluorescence spectrum, and the statistics of spontaneous photoemission.

In the present paper we aim to study a somewhat similar feedback scheme introduced into probe-pump spectroscopy setup. Modification of CPT phenomenon is the main topic of this work. Instead of simple photodetection, we propose to use a modified photodetection events as triggers for feedback action. We study how the characteristics of CPT phenomenon can be controlled by the choice of such events.

Introduction of feedback control of a different kind to spectroscopical setups was previously studied in [16], where the authors suggested to stabilize one of the system's responses by electronic feedback and study how the controlled parameters depend on the scanning frequency, which is a whole new approach to spectroscopy in general. The authors applied it to a Λ-scheme spectroscopy and showed that stabilizing the level of spontaneous fluorescence from a medium and controlling the amplitudes of the driving fields could dramatically increase the contrast of CPT resonances.

Because feedback control was initially developed for engineering purposes - namely, to make the system behave in the desired way, or to bring it to a given pre-defined state - its value is often reduced to a mere instrument for reaching some practical goals. Certainly, there is much more to it than that. Even when dealing with classical systems, it is sometimes impossible to predict with certainty the effect the chosen control strategy will have on the system. Needless to say that this point is even more valid for quantum control theory, with much more rich and complicated physics. Due to that, we are sure that feedback control may serve as a powerful tool for discovering new, previously unobserved physical effects. Squeezing [17–19] and entanglement [20–23] generation by use of feedback control could serve as excellent examples. The results reported in this paper, especially a peculiar structures in the field work's dependence on Rabi frequencies, could also back this statement. In this respect, we believe it is rewarding to study what this or that type of feedback control can do to the system, in search of new and interesting phenomena. This is the motivation behind the present work.

The paper is organized as follows: in Section 2 we introduce the

* Corresponding author at: Institute of Automation and Electrometry SB RAS, 630090 Novosibirsk, Russia.
E-mail address: 8342tomilin@gmail.com (V.A. Tomilin).

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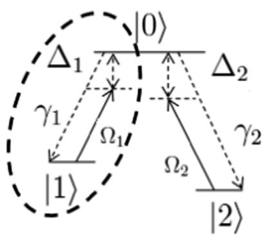

Fig. 1. Two-field spectroscopy of a Λ-system with the light field for 0–1 transition controlled by feedback loop.

theoretical model allowing for studying the stationary interaction of highly nonclassical light field with a three-level system; in Section 3 we present the results obtained both from analytical and numerical solution of the model; in Section 4 we summarize the results and make a conclusion.

2. Model

We consider a Λ-type three-level system interacting with two classical electromagnetic fields (see Fig. 1). The energy of $|0\rangle$ is set at zero. The feedback action is fairly simple: the phase of the field driving one of the transitions (we will always choose 0–1 transition) is changed by π. The phase switching is activated by detecting photoemission of a special type. By such a feedback, the atom governs its own evolution. Although not very sophisticated, we will see that this provides a set of new phenomena. The essence of our work is the choice of the events that trig the feedback action. Let us first recall the familiar feedback-free case. In absence of feedback the master equation on the density matrix $\hat{\rho}$ reads

$$\partial_t\hat{\rho} = -\imath[\hat{H}_{tot}, \hat{\rho}] + \sum_{i=1,2}\left(\hat{L}_i\hat{\rho}\hat{L}_i^\dagger - \frac{1}{2}\{\hat{L}_i^\dagger\hat{L}_i, \hat{\rho}\}\right) \tag{1}$$

with

$$\hat{L}_i = \sqrt{\gamma_i}|i\rangle\langle 0|; \quad i = 1, 2, \hat{H}_{tot} = \hat{H}_\Lambda + \hat{V}_1 + \hat{V}_2, \hat{H}_\Lambda = \sum_{i=1,2}\Delta_i|i\rangle\langle i|, \hat{V}_i = \Omega_i|0\rangle\langle i| + h.c. \tag{2}$$

where γ_i is the spontaneous emission rate from $|0\rangle$ to $|i\rangle$, Δ_i and Ω_i are field detunings and Rabi frequencies for both transitions. The operators $\hat{L}_{1,2}$ describe the spontaneous transition from $|0\rangle$ to $|1\rangle$ and $|2\rangle$, respectively. The Hamiltonian is written in the rotating wave approximation (RWA). The most remarkable phenomenon observed in such a system is the mentioned coherent population trapping (CPT). If the detunings of the fields are equal ($\Delta_1 = \Delta_2$), there exists a state $|\Psi_{dark}\rangle$ that does not interact with the field, i.e. the system is trapped in a certain superposition of its ground states. It is hence called "dark state". Naturally, the superposition of ground states orthogonal to the dark

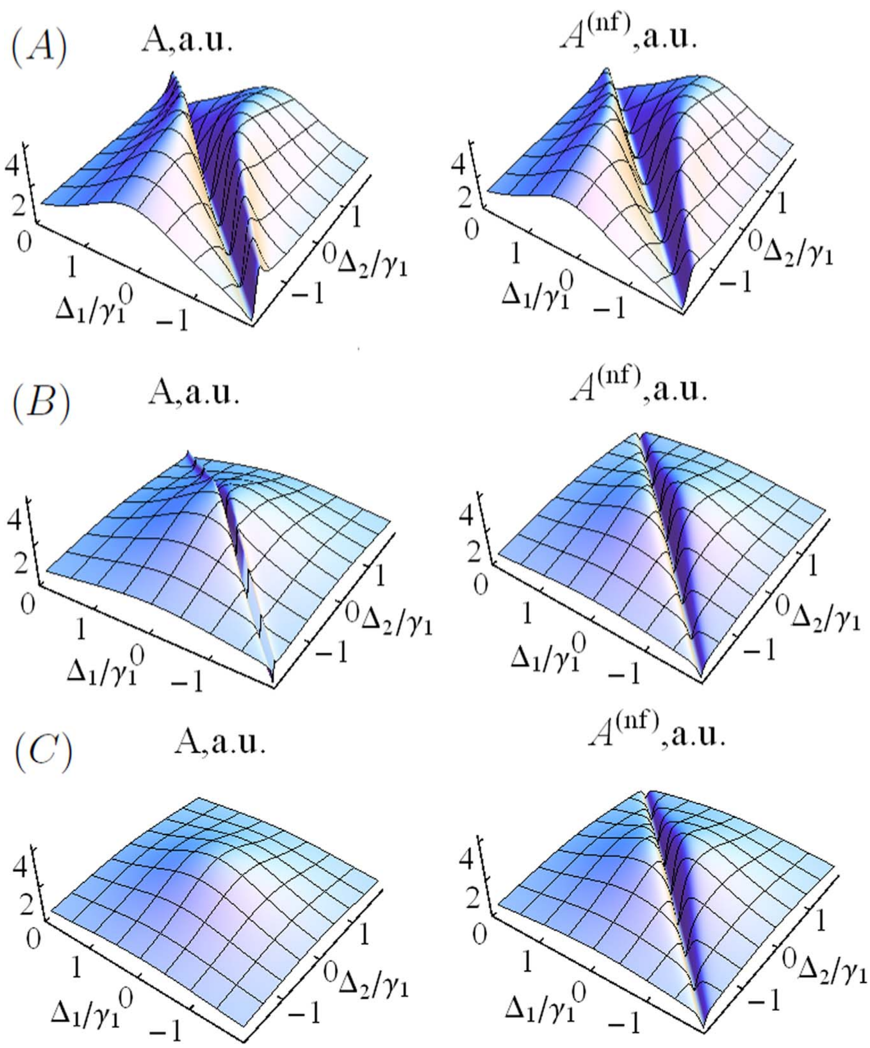

Fig. 2. Work done by the field per unit time with and without feedback (left and right, respectively). On all plots $\alpha = \beta = 1/\sqrt{2}$, $\gamma_1 = \gamma_2$. Other parameters of the system: (A) $\Omega_1 = 0.25\gamma_1$, $\Omega_2 = 0.67\gamma_1$; (B) $\Omega_1 = 0.25\gamma_1$, $\Omega_2 = 0.3\gamma_1$; (C) $\Omega_1 = \Omega_2 = 0.25\gamma_1$.