

Injection time effects on LWI with microwave driven non-degenerate ground states

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Abstract

We present an analytical calculation to determine the atomic injection time effects on lasing without inversion (LWI) in a three level lambda system with its ground state driven by an arbitrarily strong classical microwave field. We systematically take into account subtle effects associated with the injection times. We derive an expression for the optical coherences and show that one gets amplification of the field without population inversion which is governed by a temporal phase, in addition to the initial (random) phases of the ground state coherence.

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1. Introduction

More than a decade ago, it was demonstrated that atomic coherence induced by a microwave field, in the degenerate ground states of a three level lambda system, can show lasing without inversion [1]. In the following years, several works have been reported on microwave-driven systems with non-degenerate ground states [2], with

injected coherence [3] and also with initially prepared coherence [4].

The most important feature in the microwave-driven system is the ground state coherence associated with an initial phase ϕ , which gives a new control parameter that can be varied, e.g., by the phase of the microwave field. Many colleagues had concern that when atoms are injected into the interaction region, a ground state oscillation $e^{i\omega_{bc}t}$ at frequency ω_{bc} in the medium polarization could survive—that could wash out the coherence effects. However, with the condition that the microwave field Rabi frequency is made equal to

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the atomic frequency separation of the ground states, one can eliminate the time-dependent oscillations [1,3,4]. This essentially produces degenerate ground states. For variety of reasons, the case of non-degenerate ground state has never been published. One of the reason is because such a system is difficult to deal mathematically. Our aim here is to present the non-degenerate lasing without inversion (LWI) scheme considering the subtle effects associated with the injection time.

Before we proceed, we would like to note that such coherences also have applications in correlated emission laser with reduced noise [5]. It has been experimentally demonstrated that enhanced four-wave mixing could be obtained in a microwave-driven system [6]. Some of the most recent excitements in such a system are the demonstrations of efficient quantum Carnot engine [7] and “quantum afterburner” [4,8].

In this paper, we consider the driven ground state doublet system with arbitrarily strong microwave field and weak probe field is on resonance with the line center of the ground state. Atoms are assumed to be injected, at random times t_i , into the interaction region where both microwave field and the weak probe field are present. Here, we systematically take the injection time into account. We show that, the gain of the probe field is governed by a temporal phase, in addition to the phase ϕ of the ground state coherence.

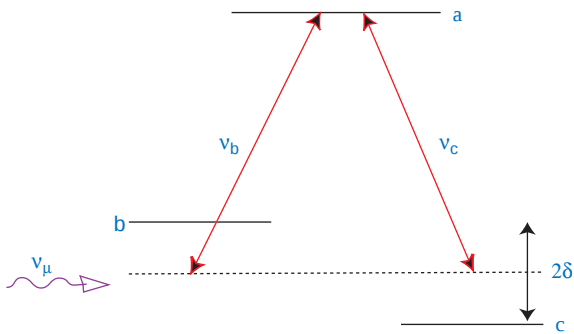


Fig. 1. The *A*-scheme with its ground states driven by a microwave field. Here, ν_μ is the frequency of the microwave field that couples the two ground states and the weak field couples the excited state *a* with the two ground states. 2δ is the ground state separation.

In Fig. 1 we show the system under consideration. Considering the dipole moments $\wp$ corresponding to both the optical transitions to be same and assuming the states *b* and *c* to be nearly degenerate, Maxwell's equation of motion for a weak field passing through the driven medium can be written as

$$\left(\frac{\partial}{\partial z} + \frac{1}{c} \frac{\partial}{\partial t}\right)E = i \sum_i \frac{k \wp^2}{\hbar \epsilon_0 V} (\rho_{ab}^i + \rho_{ac}^i). \quad (1)$$

Here, E is the weak probe field that couples both $a \rightarrow b$ and $a \rightarrow c$ transitions, k is the corresponding wave vector, $\rho_{\alpha\beta}^i$ are the coherences (between the optical transitions $\alpha \rightarrow \beta$) of the i th atom, and n is average number of atoms in the interaction volume V at any given moment of time. We calculate the conditions for which amplification of the weak probe field can be obtained.

The organization of the paper is as follows: We present the formulation of the dynamic equation in Section 2. In Section 3, we make transformations to keep track of the injection time and simplify the atomic density matrix equations. In Section 4, we derive the equations in the transformed frame, solve them and then transform back to original frame to discuss LWI in our driven system. We present a summary in Section 5.

2. The system dynamics

From Fig. 1, the total Hamiltonian of the system can be written as

$$H = H_0 + V_l + V_\mu, \quad (2)$$

where,

$$H_0 = \hbar(\omega_{ac}|a\rangle\langle a| + \omega_{bc}|b\rangle\langle b|), \quad (3)$$

$$V_l = \hbar(\Omega_b e^{-i\nu_b t}|a\rangle\langle b| + \Omega_c e^{-i\nu_c t}|a\rangle\langle c| + H.c.), \quad (4)$$

$$V_\mu = \hbar(\Omega_\mu e^{-i\nu_\mu t - i\phi}|b\rangle\langle c| + H.c.). \quad (5)$$

Here, Ω_b and Ω_c are the Rabi frequencies of the weak optical fields with frequencies ν_b and ν_c to the $a \leftrightarrow b$ and $a \leftrightarrow c$ transitions, respectively; Ω_μ is the microwave field Rabi frequency with frequency ν_μ , and ω_{ij} is the atomic transition frequency between levels i and j ($i, j \rightarrow a, b, c$). If t_i is the injection time of the i th atom into the interaction

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