Quantum Jump Approach in a Λ System with a Close Lying Excited Level

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A medium of atoms in a Λ configuration with a closely placed excited level is investigated in the framework of quantum jump approach. This approach provides useful insight into the underlying mechanism of absorption and amplification observed in the system.

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Quantum coherence and interference in driven multi-level atomic systems are central to a number of interesting phenomena. The Master equation (density matrix) approach is generally used to study such systems. Quantum jump analysis is a complementary approach which is relatively simpler and provides useful insights in the understanding of subtle effects in coherent atom-photon interactions [1]-[3]. In this paper we investigate a four level atomic system consisting of two ground levels that are connected to a pair of closely spaced excited levels by a strong control and a weak probe [4]. Near two-photon resonance, this system is observed to exhibit amplification without inversion (AWI) in D_1 transition as opposed to absorption in D_2 transition of alkali atoms. Hyperfine manifold of D_1 and D_2 transition of ^{87}Rb is used as a model system to discuss this behavior. We use quantum jump approach to show that the coherent periods involving superposition of the excited states play a crucial role in determining the response of medium. This method enables to clearly identify the processes responsible for amplification and absorption in the medium.

The level scheme considered here is the hyperfine manifold of $D_1(D_2)$ transition of ^{87}Rb as shown schematically in Fig. 1(a). A strong pump laser is used to dress the hyperfine transitions $F = 2 \to F' = 1, 2$ and a weak probe is tuned across $F = 1 \to F' = 1, 2$ transition [4]. The excitation scheme thus consists of two simultaneous Λ resonances, $\Lambda^{(1)}$ ($|1\rangle$, $|2\rangle$, $|4\rangle$) and $\Lambda^{(2)}$ ($|1\rangle$, $|2\rangle$, $|3\rangle$) excited by the same pair of coherent fields. The Rabi frequencies (α) and detunings (Δ) corresponding to probe and pump lasers are denoted by subscripts 1 and 2 respectively. Further the unprimed and primed quantities correspond to $\Lambda^{(1)}$ and $\Lambda^{(2)}$ resonances respectively.

The essence of the quantum jump approach lies in categorizing the total system into different coherent manifolds [1]-[3]. For the system under consideration we define the manifold $\xi(N_1, N_2)$ of atom + laser system such that

$$\xi(N_1, N_2) = \{|4, N_1, N_2\rangle, |2, N_1, N_2 + 1\rangle, \\ |3, N_1, N_2\rangle, |1, N_1 + 1, N_2\rangle\} \qquad (1)$$

Here N_1 and N_2 represent the number of photons associated with the probe and pump fields respectively. Different manifolds $\xi(N_1, N_2)$ relevant for the present discussion are shown in Fig. 1(b). The interesting aspect of the present system is that the degeneracy of the system requires the manifolds of the system to be cyclic. The coherent evolution where the system enters the given manifold in a state $|i\rangle$ and leaves the same manifold via quantum jump from state $|j\rangle$ is called a coherent period [1]. Out of all the possible sixteen periods only four periods (1,2), (1,3), (1,4) and (2,1) contribute to change in probe field photon number. The average change in the number of probe photons is given by

$$\langle \Delta N_1 \rangle = P(1, 2) - P(2, 1) + P(1, 3) + P(1, 4) \\ - P_i(1, \{3, 4\}) \qquad (2)$$

where P(i,j) is the probability of period (i,j). The last term in (2) is the probability of period $(1, \{3, 4\})$ which represents the coherent evolution in which the system enters the given manifold in state $|1\rangle$ and leaves the same manifold from the superposition of excited states $|3\rangle$ and $|4\rangle$. The contributions of the individual probabilities in (2) are shown in Fig. 2(a) and 2(b) for D_1 and D_2 transition of ^{87}Rb.

We see in Fig. 2(a) that while P(1,2), P(2,1), P(1,3), P(1,4) are positive, $P_i(1, \{3, 4\}$ is negative and this particular contribution is responsible for the observation of AWI in the system for D_1 transition. In the counter example of D_2 transition, $|P_i(1, \{3, 4\}| < P(1, 3) + P(1, 4)$ at $\Delta_1 = \Delta_2$, which results in absorption instead of AWI. Thus this approach shows that the coherent periods involving superposition of the excited states play a crucial role in AWI, which means that the interference in one-photon absorption processes is primarily responsible for the observation of absorption and AWI in ^{87}Rb. A similar behavior is observed for other alkali atoms also.

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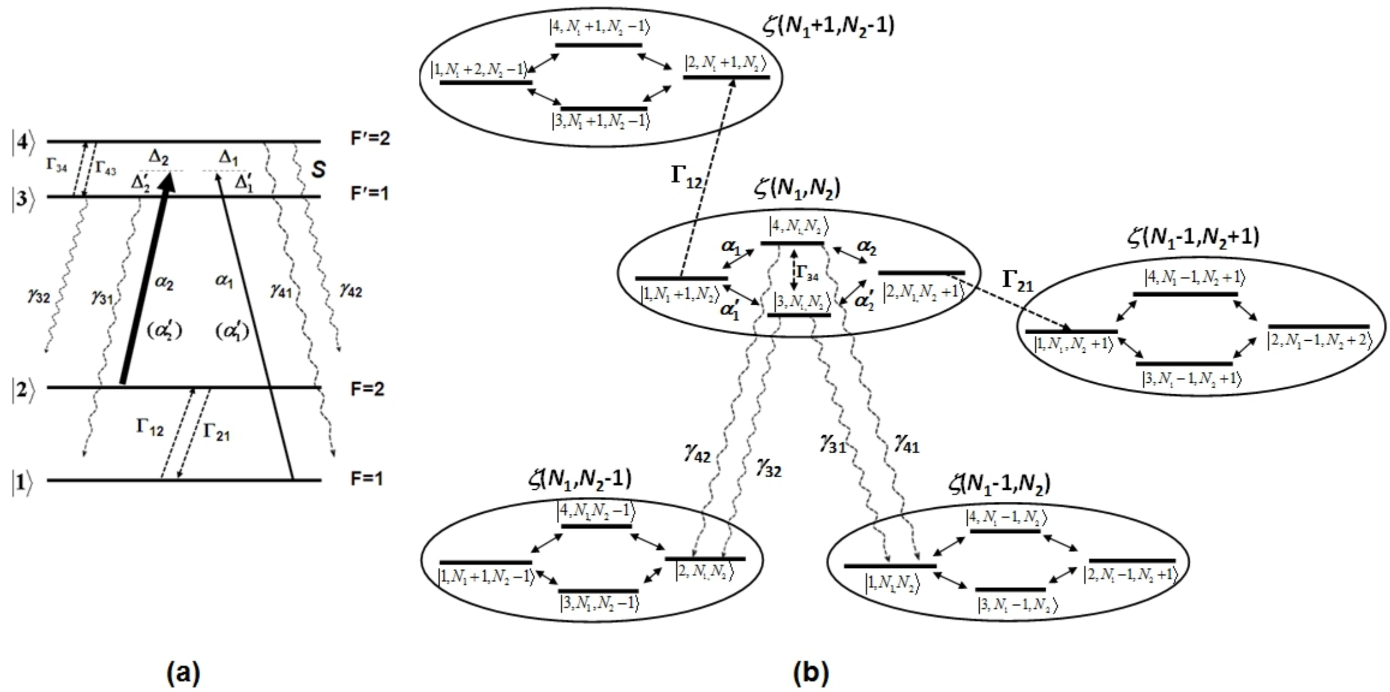

FIG. 1. (a) Schematic representation of energy levels in a four level system. For $\Lambda^{(1)}$ resonance the pump (probe) Rabi frequency and detuning are Δ_2 (Δ_1) and α_2 (α_1) respectively. Corresponding parameters for $\Lambda^{(2)}$ resonance are denoted by primed quantities. (b) Different manifolds of atom + photon system. The coherent coupling between different states within a manifold is characterized by the Rabi frequencies and is shown by solid arrows. Quantum jumps are governed by incoherent processes which cause jump of the system from one manifold to other. The radiative and non-radiative dissipative processes are shown by wavy and dashed lines respectively.

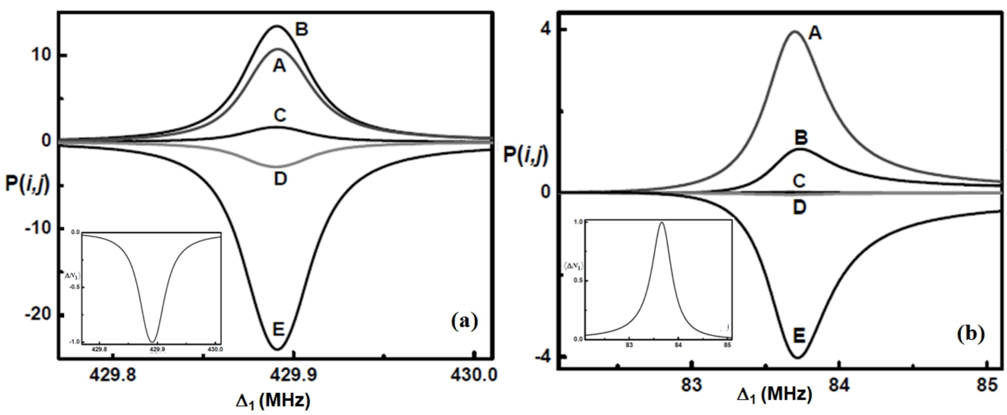

FIG. 2. Relative probabilities of coherent periods in the vicinity of two-photon resonance at $\Delta_1 = \Delta_2$ for (a) D_2 transition and (b) D_1 transition of ^{87}Rb. Inset shows relative absorption (in terms of $\langle \Delta N_1 \rangle$). Curves A, B, C, D and E correspond to P(1,4), P(1,3), P(1,2), P(2,1) and $P_i(1, \{3, 4\}$ respectively.For frame (a) S = 814 MHz, α_2 = 20 MHz, α_1 = 0.1 MHz, Δ_2 = 430 MHz which correspond to $\alpha_2^{'}$ = 20 MHz, $\alpha_1^{'}$ = 0.045 MHz,$\Delta_2^{'}$ = 384.5 MHz and for frame (b) S = 156.95 MHz, α_2 = 20 MHz, α_1 = 0.1 MHz,Δ_2 = 80 MHz, which correspond to $\alpha_2^{'}$ = 8.94 MHz, $\alpha_1^{'}$ = 0.1 MHz,$\Delta_2^{'}$ = 76.95 MHz.Here Γ_{ij} = 1 kHz, and all γ_{ij} are assumed to be equal and they all add to natural line width of 5.75 MHz [6.1 MHz] for frame (a)[(b)].