Pis'ma v ZhETF, vol. 110, iss. 7, pp. 435 – 436 © 2019 October 10

Possibility of direct observation of the Bloch–Siegert shift in coherent dynamics of multiphoton Raman transitions

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Submitted 8 August 2019
Resubmitted 28 August 2019
Accepted 28 August 2019

DOI: 10.1134/S0370274X19190019

Modern studies of the resonant matter-light interaction evolve toward the ultrastrong coupling regime where the coupling strength is comparable to the transition frequency of a two-level system (qubit). The rotating wave approximation (RWA) is broken and the contribution of the counter-rotating (non-RWA) terms to the coupling Hamiltonian must be taken into account [1–4]. The well-known manifestation of the non-RWA terms is the Bloch–Siegert effect [5].

The ultrastrong regime is extremely important for quantum information processing [6] and is widely studied for various quantum objects [6–9]. In this regime, the Rabi oscillations have been investigated [10–22]. The dressing of qubit by the resonant electromagnetic field gives rise to new energy levels of the coupled field-qubit system and the Rabi frequency characterizes the splitting of each bare level [7]. The second field with the frequency closed to the Rabi frequency excites effectively transitions between the dressed states. This phenomenon, called the Rabi resonance, has been observed in electron paramagnetic resonance [23–25], NMR [26, 27] and in optics [28, 29]. The ultrastrong regime and the Bloch–Siegert effect becomes significant in the coherent dynamics of the doubly dressed states [24, 25, 30]. This dynamics finds applications in quantum information technologies [31, 32] and radio-frequency magnetometry [33]. Additional multiphoton resonances occur at the subharmonics of the Rabi frequency [28, 34]. Recently, so-called Floquet Raman transitions at multiphoton Rabi resonances have been observed for NV center in diamond driven by the amplitude-modulated microwave field [35]. It was shown [36] that the ultrastrong regime is reached in [35] resulting in the significant Bloch–Siegert shift. Here, we propose the method for direct observation of the Bloch–Siegert oscillation in the coherent dynamics of the second-order Raman transition.

We use the semi-classical Rabi model and the nonsecular perturbation theory based on the Bogoliubov averaging method [37]. We show that the co-rotating component of the low-frequency modulation field excites virtual multiple photon processes between the dressed states and forms the Rabi frequency in the RWA. The counter-rotating modulation component also gives a significant contribution to the Rabi frequency owing to the Bloch–Siegert effect. It is shown that for properly chosen parameters of the modulation field and qubit, the Rabi oscillations in the RWA vanish due to destructive interference of multiple photon processes (Fig. 1). In this case the Rabi oscillation results exclusively from the Bloch–Siegert effect and is directly observed in the time-resolved coherent dynamics as the Bloch–Siegert oscillation. Correspondingly, in Fourier spectra of the coherent response, triplets are transformed into doublets with the splitting between the lines equal to twice the Bloch–Siegert shift. We demonstrate these features by calculations of the qubit's evolution in the conditions of experiments with a NV center in diamond. The direct observation of the Bloch–Siegert oscillation offers new possibilities for studying driven quantum systems in the ultastrong regime. Non-RWA effects of atom-bath interactions [38] and propositions of two-photon Raman transition for a heat-powered maser [39] are mentioned.

Full text of the paper is published in JETP Letters journal. DOI: 10.1134/S0021364019190019

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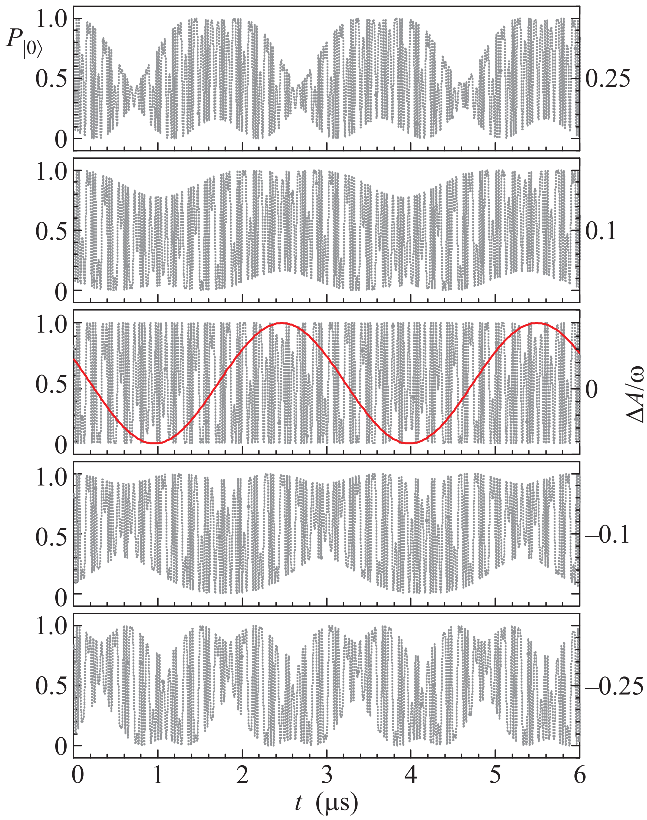

Fig. 1. (Color online) The state population of the excited level $|0\rangle$ of the NV center for the second-order Raman transitions [35] as a function of the evolution time at the modulation frequency $\omega/2\pi = 5.22$ MHz. The strength of the modulation field is $A = A^* + \Delta A$, where $A^*/\omega = 2.68$ is the strength at which the RWA Rabi frequency is equal to zero, and $\Delta A/\omega = 0.25$, 0.1, 0, −0.1, −0.25. The red line shows the Bloch–Siegert oscillation

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