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Emission spectrum of a qubit under its deep strong driving in the high-frequency dispersive regime

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In the past decade, theoretical and experimental studies of the matter-light interaction evolve toward the ultrastrong ($0.1\omega < g < \omega$) and deep strong ($g > \omega$) coupling regime where the well-known rotating wave approximation (RWA) [1] is broken and the contribution of the antiresonant (non-RWA) terms in the coupling Hamiltonian cannot be omitted. In these regimes, the coupling strength g between the qubit and the electromagnetic field with frequency ω is comparable to, or exceeds, the transition frequency ε between two energy levels of the quantum system. The non-RWA terms results in complex field-qubit dynamics [2–7] and makes difficulties for its analytical description.

The strong and ultrastrong regimes of light-matter interaction have been studied both theoretically and experimentally in a variety of solid state systems [8–13]. Recently, the ultrastrong regime has been studied in time-resolved experiments with artificial atoms such as superconducting flux [14–16] and charge [17] qubits as well as with a single NV center in diamond [18, 19], radiation-dressed states of NV centers [20], nuclear spins [21] and mechanical driving of a single electron spin [22]. The unusual features of the deep strong regime have been reported [23–25]. Dissipative and decoherence processes limiting the observation of Rabi oscillations under the ultrastrong driving regime have been considered theoretically [26–31]. The ultra- and deep strong driving field induces the transitions between the levels of the qubit even when the driving frequency is far away from resonance ($\omega \gg \varepsilon$) [26, 27].

In the present paper, we study the steady-state first-order field correlation function and the photon emission spectrum of the qubit under its deep strong driving in the high-frequency dispersive regime ($\omega, g \gg \varepsilon$). An analytical description is realized in the framework of the non-secular perturbation theory based on the Krylov–Bogoliubov–Mitropolsky averaging method [32–34]. We have found that under such driving of the qubit its multiphoton emission spectrum $S(\Omega)$ [35] consists of the coherent and incoherent parts: $S(\Omega) = S_{\text{coh}}(\Omega) + S_{\text{inc}}(\Omega)$,

$$S_{\text{coh}}(\Omega) = \sigma_0^2 \sum_{n=1}^{\infty} J_{2n-1}^2(a) \times$$
$$\times \left[\delta\left(\Omega - (2n-1)\omega\right) + \delta\left(\Omega + (2n-1)\omega\right)\right],$$

$$S_{\text{inc}}(\Omega) = \frac{1}{4\pi}\left(1 + \sigma_0 J_0(a)\right)\Gamma_\perp \left\{ \frac{1 + J_0(a)}{\left(\Omega - \varepsilon_q\right)^2 + \Gamma_\perp^2} + \right.$$
$$+ \sum_{n=1}^{\infty} J_{2n}(a) \times$$
$$\left. \times \left(\frac{1}{\left(\Omega - 2n\omega - \varepsilon_q\right)^2 + \Gamma_\perp^2} + \frac{1}{\left(\Omega + 2n\omega - \varepsilon_q\right)^2 + \Gamma_\perp^2} \right) \right\}.$$

Here $\Gamma_\perp = \frac{5}{8}\gamma + \frac{3}{8}\eta + \frac{1}{8}(\eta - \gamma)J_0(2a)$, γ is the rate of photon radiative processes, η is the dephasing rate, $J_n(x)$ are Bessel functions, $a = \frac{2g}{\omega}$, $\varepsilon_q = \varepsilon J_0(a)$ is the qubit quasienergy, $\sigma_0 = -\frac{\gamma J_0(a)}{\Gamma_\parallel}$, $\Gamma_\parallel = \frac{3}{4}\gamma + \frac{1}{4}\eta + \frac{1}{4}(\gamma - \eta)J_0(2a)$. Fig. 1 depicts the emission spectra for two values of the driving strength. Narrow delta-like lines at odd harmonics of the driving field stem from coherent processes. Lorenzian peaks at frequencies equal to the quasienergy and the sum of the quasienergy and even harmonics of the driving field result from the incoherent scattering of photons.

It is shown that the widths of emission lines have the Bessel-function-like dependences on the driving strength. Moreover, the driving field can invert some Lorentzian lines of the emission spectrum and at the certain frequencies the absorption of photons by the qubit can take place instead their emission. The obtained new features of emission spectrum are fundamental and important to physics of open quantum systems at deep strong far-off-resonant driving as well as for potential practical applications, including nonlinear spectroscopy and multi-frequency processing.

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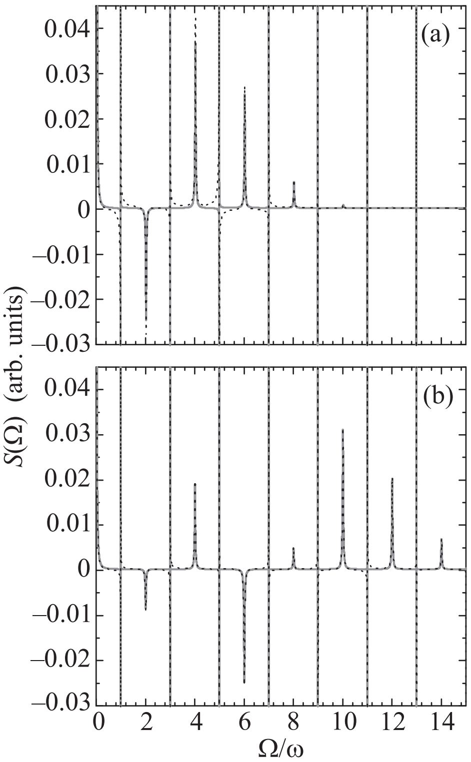

Fig. 1. The emission spectra for different values of the driving strength at $\gamma/\omega = 0.03$ and $\eta = 0$. (a) – $a = 6.0$, $\sigma_0 = -0.198$. (b) – $a = 8.6$, $\sigma_0 = 0$. The dotted lines show the numerical results

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