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The Impact of the Pulse Phase Deviation on Probability of the Fock States Considering the Dissipation

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Abstract. The probability of the Fock states in the Kerr non-linear dissipative systems driven by the sequence of Gaussian pulses is studied and estimated considering the phase deviation between any two successive pulses. Numerical calculations are made for the $\pi/2, \pi/4, \pi/8$ values of phase deviation.

Keywords: qubits, Kerr non-linear resonator, Fock states, probability

1. Introduction

The advantage of quantum information over the conventional one in the information processing such as calculations, modeling, transfer, coding and so on, is unquestionable especially if the system comprises hundreds of coherently correlated qubits. However, the physical realization of the latter brings about significant problems [1-3]. These problems are preconditioned both by the confirmation of the coherent correlation in the system of numerous qubits and by the issues related to the conservation of the latter in the given time period. It is the result of the necessary use of the open-system quantum dynamics when the irreversibility and decoherence occur due to the basic laws of nature and the “working” reasons (the input and output of the processed and controlled information into the quantum system). In certain issues (high level of insensitivity to external stimuli, information transfer, coding) the optical quantum systems are more advantageous than others, however non-sufficiently adapted for the information processing, namely modeling and calculations. In this respect the behavior of Kerr-type qubits represented by Fock. Photon-photon interaction, particularly the phenomenon of the photon blockade or dissipation, has been thoroughly investigated [4-5]. It is a conventional dynamics of the quantum system, since the presence of one photon in the system affects the probability of the second photon admission. One of the main conditions of the photon blockade is that the photon-photon interaction should be larger than the decay rate of the system. In this respect strong non-linearity on the few-photon level can be obtained in non-linear resonators by Kerr non-harmonic oscillators [6-10] and via a number of other modes [11-13]. For the photon blockade, G. Kryuchkyan and his scientific group has proposed to use the external field of Gaussian pulses, which lead to new quantum effects or enhance obtained effects [14]. The results obtained can be a basis for implementing a number of quantum gates and binary operations in case the control of the coherently correlated state of the Kerr system is expanded.

In this paper, we examine the impact of the pulse phase deviation on the probability of the Fock states and compare it with the results in [14].

2. Non-linear Kerr resonator in the pulsed regime driven by pulse phase

The Hamiltonian of Kerr nonlinear resonator under pulsed excitation in the rotating wave approximation reads as

$$H = \Delta a^{+} a + \chi (a^{+})^{2} a^{2} + \hbar f(t)\left(\Omega a^{+} + \Omega^{*} a\right) \qquad (1)$$

where Ω is the constant, proportional to the amplitude of the external field; f(t) is the sequence of pulses; τ is the interval between two pulses in the sequence; T is the duration of the pulses. a^+ and a in the Hamiltonian are the creation and annihilation operators, respectively. Δ is the detuning between the mean frequency of the driving field and the frequency of the oscillator, and χ is the nonlinearity strength. However, in contrast to [14] in the time dependent part of the Hamiltonian the phase deviation between the two successive pulses should be considered under the φ angle.

$$\mathrm{f}(t)=\sum e^{-(t-t_0-n\tau)^2/T^2}e^{i\varphi} \tag{2}$$

This Hamiltonian describes different physical systems such as optical resonators, nanomechanical oscillators or solid-state devices based on Josephson transition. Since in all of these cases decoherence and dissipative effects are presented, they represent an open physical system the evolution of which can be provided by the Nakjima Zwanzig equation.

$$\frac{\partial\rho}{\partial t}=\frac{i}{h}[H,\rho]+\int_0^t K_{r,S}\left(\rho(t)\right)ds \tag{3}$$

where p is the static operator of the open system, $K_{r,S}$ is the core of the integral operator (until the t moment of the evolution memory) which is $K_{r,S}\left(\rho(t)\right)\approx K\delta(t-s)\rho(s)$ by the Born-Markov approximation. In this case we obtain the Niemann-Lindblad equation.

$$\frac{d\rho}{dt}=-[H,\rho]+\sum_{i=1,2}\left(L_i\rho L_i^\dagger-\frac{1}{2}L_i^\dagger L_i\rho-\frac{1}{2}\rho L_i^\dagger L_i\right) \tag{4}$$

where $L_1=\sqrt{(N+1)\gamma a}$ and $L_2=\sqrt{N\gamma a^+}$ are referred to as Lindblad operators, γ is a dissipation rate and N denotes the mean number of quanta of a thermostat which is quite low, since in all the systems realized the temperature is very low. We solve this equation by numerical methods, particularly by the method of the diffusion of quantum states. Let us suppose that the thermostat temperature satisfies the condition $T\gg T_{cr}=\gamma\hbar/k_B$, which in the given case is satisfied also for not high temperatures. In the absence of the driving field $f(t)$, the $E_n=E_0+\hbar\omega_0 n+\hbar\chi(n-1)$, $n=0,1,\ldots$ energy $|n\rangle$ n photon Fock states are described by the Hamiltonian conducting multi-photon blockade. The energy levels of the non-harmonic oscillator increase gradually by $E_{21}-E_{10}=2\hbar\chi(n-1)$.

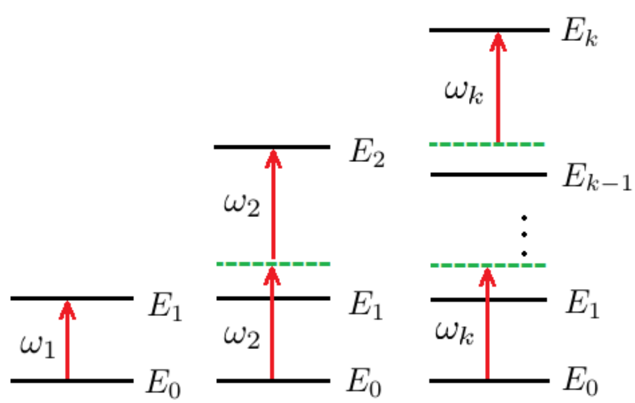

FIG. 1: (Color online) Schematic energy-level diagram with one-photon, two-photon and k -photon resonant transitions between states of Kerr nonlinear resonator. Selective excitations leading to multiphoton blockades are realized for the main frequencies of driving field: $k\omega_k=E_{k0}$ that are calculated as $\omega_k=\omega_0+\chi(k-1)$.

3. Numerical calculation

In our system, the Fock states are considered as oscillator levels. In contrast to the harmonic oscillator choosing accurate values of the external field and non-linearity, we can choose the transitions which we prefer. To obtain the working regimes of the photon blockade it is necessary to choose the parameters, which make $|0\rangle \rightarrow |n\rangle$ transition. In other words, if we need to observe k photon blockade it is necessary to conduct $|0\rangle \rightarrow |k\rangle$ transition, where according to $k = 0,1,2,3,\ldots$ $E_n = E_0 + h\omega_0 n + h\chi(n-1)$ the resonance frequency is $k\omega_k = E_{k0}$ and we can obtain $\omega_k = \omega_0 + \chi(k-1)$ (Fig. 1). For one photon transition $k = 1$ and the resonance frequency is $\omega_1 = \omega_0$. For the double-photon transition $k = 2$ and, $E_{20} = 2\hbar\omega_0 + 2\chi$, $\omega_2 = \omega_0 + \chi$, and to receive the triple-photon blockade we need $k = 3$, $E_{30} = 3\omega_0 + 6\chi$, $\omega_3 = \omega_0 + 2\chi$.

We consider one-photon, double-photon and triple-photon blockade phenomena. Apart from choosing the resonance frequencies and the nonlinearity parameters it is necessary to choose the correct duration of the driving field pulse, amplitude and the interval between two successive pulses. It is necessary to consider duration of the non-linear effect pulse quite quickly so that the dissipative effects are little affected and for the non-linearity to fulfill its function, i.e. $1/\gamma > T > 1/\chi$.

In order to obtain one-photon blockade it is necessary to make $|0\rangle \rightarrow |1\rangle$ transition, i.e. we should choose the resonance frequency of the driving field corresponding to this transition. If $k = 1$ at the difference of energy levels of $k\hbar\omega_k = E_{k0}$ at the $|0\rangle \rightarrow |k\rangle$ transition we have $E_{10} = \hbar\omega_0$, consequently $\omega_1 = \omega_0$. The results of the numerical calculations are presented in Fig. 2, Fi.3, Fig. 4 and 5 where the dotted lines demonstrate the probable distribution with the phase deviation between the pulses and hence $\pi/2, \pi/4, \pi/8$. The solid (A) line shows the probable distribution of the state without the phase deviation. The maximum value of the Fock state $|1\rangle$ in this system is $P_1 = 0.82$, at the phase deviation it decreases to 0.4.

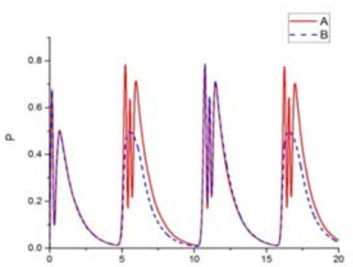

Fig. 2

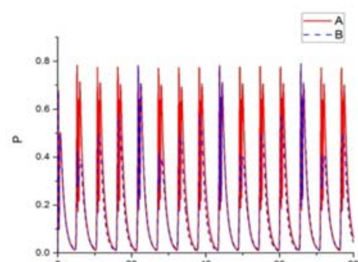

Fig. 3

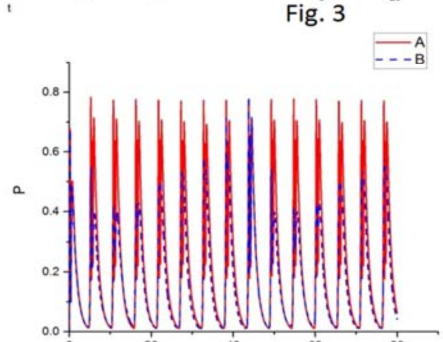

Fig. 4

One-photon blockade regime. The solid lines (A) show the obtained probability in the absence of the phase deviation. The dotted (B) lines show the probability of one-photon state when the pulse deviation is given as $\pi/2$ (Fig. 2), $\pi/4$ (Fig. 3), $\pi/8$ (Fig. 4), respectively. For comparison the parameters of the numerical calculation are chosen to be $\chi/\gamma = 15$ according to [14], the amplitude of the driving field is $\Omega/\gamma = 6$, $\tau = 5.5\gamma^{-1}$, $T = 0.4\gamma^{-1}$.

In the same way the $|0\rangle \to |2\rangle$ transition is needed for the double-photon Fock blockade, i.e. we should choose the resonance frequency of the driving field corresponding to this transition. In case of k=2, we have $E_{20} = 2\hbar\omega_0 + 2\chi$, consequently $\omega_2 = \omega_0 + \chi$.

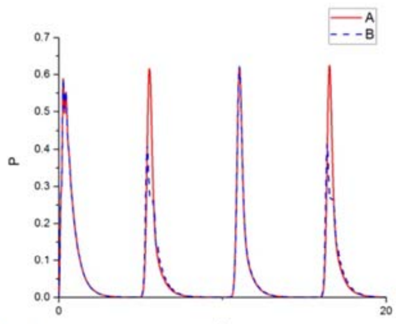

Fig. 5

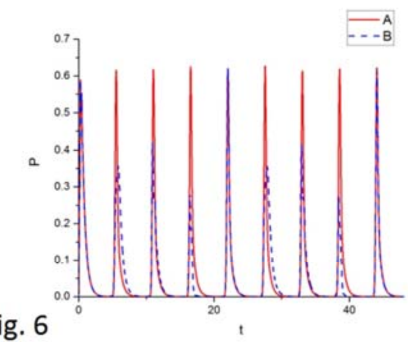

Fig. 6

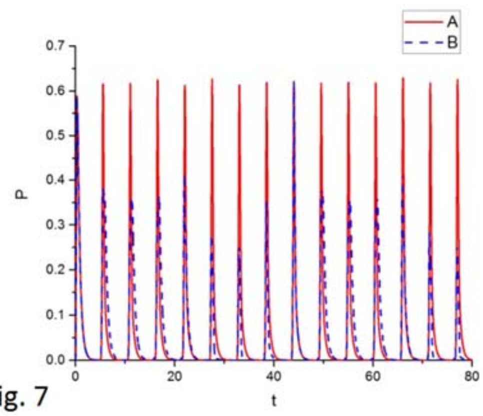

Fig. 7

This regime provides double-photon blockade. The solid (A) lines show the probability obtained in the absence of phase deviation. The dotted (B) lines show the probability of one-photon state when the phase deviation is given as $\pi/2$ (Fig. 5), $\pi/4$ (Fig. 6), $\pi/8$ (Fig. 7) respectively. The parameters are chosen as follows: $\chi/\gamma = 30$, the amplitude of the driving force is $\Omega/\gamma = 12$, $\tau = 5.5\gamma^{-1}$, $T = 0.4\gamma^{-1}$.

In the same way let us discuss the triple-photon Fock states blockade, when $E_{30} = 3\hbar\omega_0 + 6\chi$, $\omega_3 = \omega_0 + 2\chi$. The results of the calculation are presented in Fig. 8, Fig.9 and Fig 10 for the phase deviations $\pi/2$, $\pi/4$ and $\pi/8$, respectively.

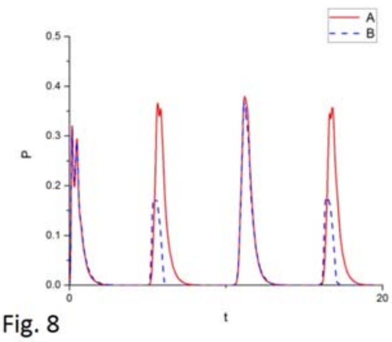

Fig. 8

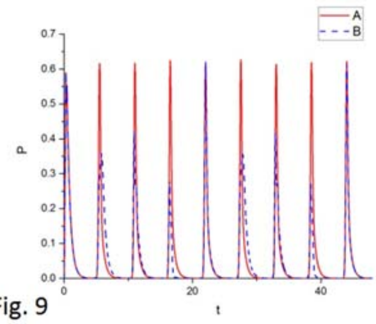

Fig. 9

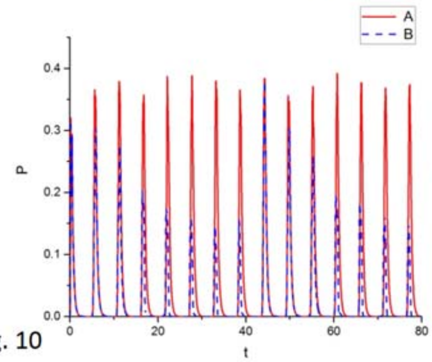

Fig. 10

Triple-photon blockade regime. The solid (A) lines show the obtained probability in the absence of phase deviation, and the dotted (B) lines show the probability of one-photon state with the phase deviation given as $\pi/2$ (Fig. 8), $\pi/4$ (Fig. 9), $\pi/8$ (Fig. 10), respectively. The parameters are chosen as follows: $\chi/\gamma = -22$, the amplitude of the driving field $\Omega/\gamma = 12$, $\tau = 5.5\gamma^{-1}$, $T = 0.4\gamma^{-1}$.

Conclusion

Thus, in the sequence of the control signal pulses the impact of the relative deviation of phases on the Fock states is enough for the phase deviation to be considered in Quantum Informatics and as a means of computer control. It can change the vector of the superposition state of the Kerr qubit. It can be applied particularly in the installation and information input process, as well as for unary operations.

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