Physica A 498 (2018) 1–9

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Evolution of the squeezing-enhanced vacuum state in the amplitude dissipative channel

Gang Ren *, Jian-ming Du, Wen-hai Zhang

Department of Physics, Huainan Normal University, Huainan 232001, China

HIGHLIGHTS

- The evolution of the squeezing-enhanced vacuum state (SEVS) in the amplitude dissipative channel is given.
- We discuss the sub-Poissonian behavior for the output state.
- The effect of the dissipation factor on the SEVS are reported.
- Exact numerical solutions for the nonclassical feature of the output state for the SEVS are investigated.

ARTICLE INFO

Article history:
Received 30 September 2017
Received in revised form 2 December 2017

Keywords:
Amplitude dissipative channel
Squeezing-enhanced vacuum state
Kraus operator

ABSTRACT

We study the evolution of the squeezing-enhanced vacuum state (SEVS) in the amplitude dissipative channel by using the two-mode entangled state in the Fock space and Kraus operator. The explicit formulation of the output state is also given. It is found that the output state does not exhibit sub-Poissonian behavior for the nonnegative value of the Mandel's Q-parameters in a wide range of values of squeezing parameter and dissipation factor. It is interesting to see that second-order correlation function is independent of the dissipation factor. However, the photon-number distribution of the output quantum state shows remarkable oscillations with respect to the dissipation factor. The shape of Wigner function and the degree of squeezing show that the initial SEVS is dissipated by the amplitude dissipative channel.

1. Introduction

Squeezed states have become a primary topic of the nonclassical state in quantum optics and quantum information [1–3]. It was Kennard who presented the first squeezed states in 1927 [4]. Recently, many theoretical and experimental studies were devoted to the generation of the squeezed states, such as the resonance fluorescence [5], the harmonic generation [6] and parametric amplification [7], etc. Stoler proved that the minimum uncertainty states can be obtained by operating the squeezing operator $S(\zeta)$ on the vacuum state $|0\rangle$, and $S(\zeta)$ was defined as

$$S(\zeta) = \exp\left(\frac{\zeta}{2}a^{\dagger 2} - \frac{\xi^*}{2}a^2\right), \tag{1}$$

where ζ is a complex squeezing parameter and $a\left(a^\dagger\right)$ is the annihilation (creation) operator, satisfying the commutation relation $\left[a, a^\dagger\right] = 1$ [8]. The degenerate parametric amplifier has been used to generate such squeezed states [9].

* Corresponding author.
E-mail address: renfeiyu@mail.ustc.edu.cn (G. Ren).

https://doi.org/10.1016/j.physa.2018.01.027
0378-4371/

Due to the widespread applications of squeezed light in high-precision interferometry and optical communication, the study of squeezed states with strong squeezing becomes very popular. Mandel and Wolf have shown a more general squeezing operator, which is generated by

$$\exp\left[i\left(ka^{\dagger 2}+fa^{\dagger}a+k^{*}a^{2}\right)\right], \tag{2}$$

where f and k are two parameters [10]. Its squeezing-enhanced properties were studied in the special case

$$V(\lambda,r)\equiv\exp\left[-\frac{i}{2}\lambda\left(e^{r}Q^{2}-e^{-r}P^{2}\right)\right], \tag{3}$$

where $Q=\left(a+a^{\dagger}\right)/\sqrt{2}$, $P=\left(a-a^{\dagger}\right)/\sqrt{2}i$, λ and r are two real parameters. When $r=0$, $V(\lambda,r)$ in Eq. (3) reduces to a normal squeezing operator in Eq. (1). $V(\lambda,r)$ exhibits squeezing enhancement when the two parameters satisfy the inequality $\tanh\lambda<1/(1+\cosh r)$. It may be experimentally implemented by a nonlinear parametric amplifier process and a self-interaction via the Kerr effect [11]. Acting the operator $V(\lambda,r)$ on the vacuum state, one can get the squeezing-enhanced vacuum state (SEVS).

On the other hand, since quantum state is not absolutely isolated, quantum dissipation in a thermal environment has been an issue of widespread interest in many fields of quantum physics. When a pure state propagates in a dissipation channel, it inevitably interacts with the medium and turns into a mixed state [12]. Agarwal revealed that a vortex state of a two-mode system can be generated from a squeezed vacuum by passing through a quantum channel with amplitude damping [13]. In quantum information processing, the time evolution of the density operators are the key to the study of the decoherent properties of quantum states.

Thus an interesting and challenging question naturally arises: What kind of mixed state does the initial SEVS turns into when passing through the amplitude dissipative channel? How squeezing effects and photon statistics distributions varies in this evolution? To answer these questions, the passage is arranged as follows. In Section 2, we derive the evolution of the SEVS in the amplitude dissipative channel in term of the Kraus operators and the explicit formulation of the output state ρ_t is given by using the two-mode entangled state in the Fock space. In Section 3, the statistical properties of ρ_t, such as Mandel's Q-parameter, second-order correlation function, photon-number distribution and Wigner function are discussed in detail. The degree of squeezing for ρ_t is studied in Section 4. We summarize our main results in Section 5.

2. Evolution of the SEVS in the amplitude dissipative channel

The master equation for describing the amplitude decay mode is

$$\frac{d\rho}{dt}=k\left(2a\rho a^{\dagger}-a^{\dagger}a\rho-\rho a^{\dagger}a\right), \tag{4}$$

where k is the real rate of decay.

In order to derive the infinite operator-sum representation of ρ from Eq. (4), we construct the two-mode entangled state in the Fock space as

$$|\eta\rangle=\exp\left(-\frac{1}{2}|\eta|^{2}+\eta a^{\dagger}-\eta^{*}\tilde{a}^{\dagger}+a^{\dagger}\tilde{a}^{\dagger}\right)|00\rangle, \tag{5}$$

where $a^{\dagger}$ mode is the system-mode and $\tilde{a}^{\dagger}$ is a fictitious mode denoting the effect of environment, $a^{\dagger}$ is independent of $\tilde{a}^{\dagger}$, $\left[a^{\dagger},\tilde{a}^{\dagger}\right]=0$. $|\eta\rangle$ is the eigenstate of two commutative operators $\left(a-\tilde{a}^{\dagger}\right)$ and $\left(a^{\dagger}-\tilde{a}\right)$,

$$\left(a-\tilde{a}^{\dagger}\right)|\eta\rangle=\eta|\eta\rangle, \qquad \left(a^{\dagger}-\tilde{a}\right)|\eta\rangle=\eta^{*}|\eta\rangle. \tag{6}$$

From Eq. (6), we can see the operators $\left(a-\tilde{a}^{\dagger}\right)$ and $\left(a^{\dagger}-\tilde{a}\right)$ can be replaced by the complex number η and η^{*}.

When $\eta=0$, the entangled state in Eq. (5) becomes

$$|I\rangle\equiv|\eta=0\rangle=\exp\left(a^{\dagger}\tilde{a}^{\dagger}\right)|00\rangle. \tag{7}$$

It is easy to see that $|I\rangle$ in Eq. (3) has the properties

$$a|I\rangle=\tilde{a}^{\dagger}|I\rangle, \qquad a^{\dagger}|I\rangle=\tilde{a}|I\rangle, \qquad a^{\dagger}a|I\rangle=\tilde{a}^{\dagger}\tilde{a}|I\rangle. \tag{8}$$

Acting both sides of Eq. (4) on the state $|I\rangle$ and using Eq. (8), Eq. (1) is converted into

$$\frac{d}{dt}|\rho\rangle=k\left(2a\tilde{a}-a^{\dagger}a-\tilde{a}^{\dagger}\tilde{a}\right)|\rho\rangle, \tag{9}$$

where $|\rho\rangle\equiv\rho|I\rangle$ and $|\rho\rangle$ satisfies the following relations

$$\langle\eta|\tilde{a}|\rho\rangle=-\left(\frac{\partial}{\partial\eta}+\frac{\eta^{*}}{2}\right)\langle\eta|\rho\rangle, \qquad \langle\eta|a|\rho\rangle=\left(\frac{\partial}{\partial\eta^{*}}+\frac{\eta}{2}\right)\langle\eta|\rho\rangle,$$