Two-photon emission spectrum of a two-level atom in an ideal cavity

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The time-dependent two-photon emission spectra of a two-level atom interacting with a single-mode radiation field in an ideal cavity have been studied. The expressions of the system operators as a function of time have been derived based on the two-photon Jaynes-Cummings model and Heisenberg equation. As a result, the theoretical curves of the time-dependent two-photon emission spectra have been given. The features of two-photon emission spectra depend not only on the photon statistical distribution of the initial field, such as the thermal field, the squeezed vacuum field, and the coherent field, but also on the passband width of the filter detector Γ. The two-photon emission spectra exhibit multipeaked structures when $\Gamma < \lambda$ (two-photon coupling constant).

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I. INTRODUCTION

Generally, the Jaynes-Cummings model (JCM) [1] can be used to describe the interaction between a quantized single mode of the radiation field in a cavity and a two-level atom. Some investigators have applied the model to reveal and explain many pure quantum-mechanical phenomena, such as atomic Rabi oscillations [2], collapses and revivals of atomic inversion [3–5], sub-Poissonian photon statistics [6], and squeezing of the cavity field [7,8]. The two-photon Jaynes-Cummings model (TPJCM) is a generalized form of the JCM and has been used to investigate strong squeezing of the field in a cavity [9] and to discuss the collapses and revivals in the Rabi oscillations of the atomic inversion and of the photon statistics of the field [10].

Recently, advances in experimental technology in the optical cavity, in which only one atom is contained, have opened an avenue where it is possible to study the interaction of the atom with the single mode of the radiation field in the cavity. In particular, the cavity-induced enhancement of the decay rate of an excited atomic state [11], and the one- and two-photon Rabi oscillations [12] as well as the collapse and revival of Rabi oscillations of the Rydberg atom [13] have been observed. It has been demonstrated that the JCM and its various forms can be better used to deal with the interaction between the atom and the single mode of the radiation field in the cavity.

The investigations of atomic emission spectra have been published in many papers [14–17]. However, in most of the early papers, only the emission spectra of the atom in a steady state have been discussed. Since Eberly and Wodkiewicz suggested the counting-rate definition of spectrum [18], many authors have studied the atomic non-steady-state emission spectrum [15,16]. Sanchez-Mdragon, Narozhny, and Eberly showed that the spontaneous emission spectrum of the atom in a cavity is different from the prediction of "every day" QED [16]. Gea-Banacloche, Schlicher, and Zubairy discussed the one-photon emission spectrum of the two-level atom in the single mode of a squeezed-state field. It is found that the one-photon emission spectrum is rather similar to one of the atoms in a thermal field [17]. However, the investigation of the two-photon emission spectrum for the two-level atom in the single mode of a squeezed vacuum field, to the best of our knowledge, has not been found up to now.

As a consequence, in this paper we have investigated the two-photon emission spectra of a two-level atom in an ideal cavity and the effects of the statistical properties in various fields on the two-photon emission spectra. The results show that when the two-photon coupling constant λ is less than the passband width of filter detector Γ, the emission spectra exhibit a single peak or three peaks, depending on the statistics of the initial field, and that when λ is larger than Γ, the emission spectra appears as many-peaked structures. This is a reflection of the atomic multiple quantum Rabi oscillations in emission spectra. Some of the features in the emission spectra might show up in microcavity experiments in the future.

The paper is organized as follows: In Sec. II we shall describe the two-photon interaction of a two-level atom with a single-mode quantized field using a two-photon Jaynes-Cummings model and derive the Heisenberg equations of the system operators. In order to solve the Heisenberg equations and obtain the exact expressions of the system operators as a function of time, a special technique has been developed, in Sec. III we reform properly

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Ebery-Wodkiewicz's formula of the time-dependent physical spectrum [18] for correctly expressing the two-photon emission spectrum. The calculated results and the discussion on the two-photon emission spectra are given in Sec. IV. Finally we summarize the principal results in this paper.

II. TWO-PHOTON JAYNES-CUMMINGS MODEL AND THE EXPRESSIONS OF SYSTEM OPERATORS

We consider the two-photon interaction of a two-level atom with a single mode of the radiation field in an ideal optical microcavity without loss. The cavity subtends a large solid angle at the atom and its wall is short. Further, the two-photon emission is weak. So both the reservoir of the cavity mode and the reservoir of the atom are not considered. Having the same parity, the two levels of the atom are assumed to be nondegenerate. Hence the two-photon transition is allowed and the single-photon transition is inhibited between the two levels. In this case, under the rotating-wave approximation, the effective Hamiltonian of the total system, which consists of the atom and the cavity field, is

$$H=\tfrac{1}{2}\Omega\sigma_z+\omega_0(a^\dagger a+\tfrac{1}{2})+\lambda(a^{\dagger 2}\sigma+\sigma^\dagger a^2)\ , \tag{1}$$

where Ω is the atomic natural transition frequency, ω_0 the frequency of the cavity mode, σ ($\sigma^\dagger$) and σ_z are the atomic Pauli operators, a ($a^\dagger$) the photon annihilation (creation) operator, and λ the two-photon coupling constant. This model is called the TPJCM [9,10]. If we were to derive directly the motion equations of the operators σ ($\sigma^\dagger$) and a ($a^\dagger$), the corresponding equations would be very complex entangled equations, so that we would not be able to obtain the exact solutions. Here, generalizing the method in [5] and [19] used to solve the expression of system operators in the single-photon Jaynes-Cummings model, we obtain the exact solutions of the various operators appearing in Eq. (1) with time evolving. To this end, we change Eq. (1) to

$$H=\omega_0 N+C\ , \tag{2}$$

where

$$N a^\dagger a+\sigma_z,\quad C=\lambda(a^{\dagger 2}\sigma+\sigma^\dagger a^2)-\Delta\sigma_z\ ,\quad \Delta=\omega_0-\frac{\Omega}{2}\ . \tag{3}$$

Δ is the detuning between the atomic and the cavity field. It can be immediately proved that there are the following commutation relations between above operators:

$$[H,N]=0,\quad [H,C]=0,\quad [C,N]=0\ .$$

So the operators N and C are constants of the motion. If we look upon whole a^2 ($a^{\dagger 2}$) as a special operator, the equations of operators σ and a^2 can be easily obtained.

$$\left[i\frac{d}{dt}-2\omega_0+2C\right]\sigma(t)=\lambda a^2(t)\ , \tag{4}$$

$$\left[i\frac{d}{dt}-2\omega_0\right]a^2(t)=2\lambda(2N+3)\sigma(t)\ . \tag{5}$$

Owing to the two motion constants N and C, Eqs. (4) and (5) can be treated as differential equations with constant coefficients. Hence Eqs. (4) and (5) can be reduced to

$$\left[i\frac{d}{dt}-2\omega_0+2C\right]\left[i\frac{d}{dt}-2\omega_0\right]\begin{bmatrix}\sigma(t)\\ a^2(t)\end{bmatrix}=2\lambda^2(2N+3)\begin{bmatrix}\sigma(t)\\ a^2(t)\end{bmatrix}\ . \tag{6}$$

With the help of the initial condition we get exact and concise expressions for $\sigma(t)$ and $a^2(t)$.

$$\sigma(t)=\exp(-2i\omega_0 t)\exp(iCt)\times\left\{\left[\cos\theta t+i\frac{\sin\theta t}{\theta}C\right]\sigma(0)-i\lambda\frac{\sin\theta}{\theta}a^2(0)\right\}\ , \tag{7}$$

$$a^2(t)=\exp(-2i\omega_0 t)\exp(iCt)\times\left\{\left[\cos\theta t-i\frac{\sin\theta t}{\theta}C\right]a^2(0)-2i\lambda\frac{\sin\theta t}{\theta}(2N+3)\sigma(0)\right\}\ . \tag{8}$$

Here

$$\theta=[\lambda^2(N^2+5N+6)+\Delta^2]^{1/2}\ ,$$

where θ can be called the operator corresponding to the quantum Rabi frequency of the total system. This method, to the best of our knowledge, has not been previously published. And the form of operator solution is not only elegant, but also specially suitable to calculate the two-time correlation function $\langle\sigma^\dagger(t)\sigma(t')\rangle$, etc.

III. EXPRESSION OF TWO-PHOTON EMISSION SPECTRUM

Generally, Eberly-Wodkiewicz's formula of time-dependent physical spectrum, in which the two-time correlation function of the field is simply substituted by the two-time correlation function of the atom, is only suitable to the single-photon emission spectrum. If we use it directly, in this way, to the two-photon emission, then the resulting spectrum is the incorrect single-photon spectrum, which is, in fact, the second harmonic of the light frequency of the radiation field. Because in this case the central frequency of the spectrum ω equals the atomic-level interval Ω. However, the central frequency of the two-photon emission spectrum should be equal to $\Omega/2$. Therefore the formula must be corrected appropriately as

$$S(\omega)=2\Gamma\int_0^T dt\int_0^T dt'\exp[-(\Gamma-i2\omega)(T-t)-(\Gamma+i2\omega)(T-t')]\times\langle\xi,\psi|\sigma^\dagger(t)\sigma(t')|\xi,\psi\rangle\ , \quad (9)$$

where T is the measured time and Γ is the passband width of the filter detector. Assume that the initial state of the system is the general state, which can be represented to

$$|\xi,\psi\rangle=|\xi\rangle|\psi\rangle=\sum_n\langle n|\xi\rangle(\alpha|n,-\rangle+\beta|n,+\rangle)\ , \quad (10)$$

where $|\psi\rangle$ represents the atomic state, $|+\rangle$ the atomic upper state, $|-\rangle$ the atomic lower state, α and β are the probability amplitudes of atom in the lower state and in the upper state, respectively, and $|\xi\rangle$ represents the field state. $|n\rangle$ is the Fock state. Using some techniques, we obtain the two-time correlation function $\langle\xi,\psi|\sigma^\dagger(t)\sigma(t')|\xi,\psi\rangle$.

$$\langle\xi,\psi|\sigma^\dagger(t)\sigma(t')|\xi,\psi\rangle=\tfrac{1}{8}\sum_n[B(\mu_n,\nu_n,t)B^*(\mu_n,\nu_n,t')+B(\mu_n,-\nu_n,t)B^*(\mu_n-\nu_n,t')]\ , \quad (11)$$

where

$$B(\mu_n,\nu_n,t)=\alpha^*\langle\xi|n+2\rangle[f_1(\mu_n,\nu_n,t)+f_1(-\mu_n,\nu_n,t)]+\beta^*\langle\xi|n\rangle[f_2(\mu_n,\nu_n,t)+f_2(-\mu_n,\nu_n,t)]\ , \quad (12)$$

and

$$f_1(\mu_n,\nu_n,t)=\left[1+\frac{\Delta}{\nu_n}\right]^{1/2}\frac{\lambda[(n+1)(n+2)]^{1/2}}{\mu_n}\times\exp[i(2\omega_0+\mu_n-\nu_n)t]\ , \quad (13)$$

$$f_2(\mu_n,\nu_n,t)=\left[1+\frac{\Delta}{\nu_n}\right]^{1/2}\left[1+\frac{\Delta}{\mu_n}\right]\times\exp[i(2\omega_0+\mu_n-\nu_n)t]\ , \quad (14)$$

$$\mu_n=[\lambda^2(n+1)(n+2)+\Delta^2]^{1/2}\ ,$$
$$\nu_n=[\lambda^2 n(n-1)+\Delta^2]^{1/2},\quad \mu_n=\nu_{n+2}\ . \quad (15)$$

When the atom is initially in the upper state $|+\rangle(\alpha=0,\beta=1)$ and the detuning Δ is zero, the functions in Eq. (11) will be reduced as

$$B(\mu_n,\nu_n,t)=\langle\xi|n\rangle[f(\mu_n,\nu_n,t)+(-\mu_n,\nu_n,t)]\ ,$$
$$f(\mu_n,\nu_n,t)=f_2(\mu_n,\nu_n,t)=\exp[i(2\omega_0+\mu_n-\nu_n)t]\ , \quad (16)$$
$$\mu_n=\nu_{n|2}=\lambda[(n+1)(n+2)]^{1/2}\ .$$

From Eqs. (9) and (11) we get the expression of two-photon emission spectrum

$$S(\omega)=\sum_{n=0}^{\infty}P_nS_n(\omega)\ , \quad (17)$$

here P_n is the photon-number distribution of initial fields and S_n is the atomic two-photon emission spectrum when the initial field is in the number state $|n\rangle$.

$$S_n(\omega)=\frac{\Gamma}{4}[|F(\mu_n,\nu_n)+F(-\mu_n,\nu_n)|^2+|F(\mu_n,-\nu_n)+F(-\mu_n,-\nu_n)|^2]\ , \quad (18)$$

where

$$F(\mu_n,\nu_n)=\frac{\exp[i(\Omega-2\omega+\mu_n-\nu_n)T]-\exp(-\Gamma T)}{\Gamma+i(\Omega-2\omega+\mu_n-\nu_n)}\ . \quad (19)$$

Equation (17) shows that the atomic two-photon emission spectrum is due to addition of the atomic two-photon emission spectra in the photon-number state field with the weight P_n. Hence emission spectra in fields with different statistical properties may have characteristics distinct from those in the number state field.

IV. RESULTS AND DISCUSSION

In order to understand profoundly details of time-dependent two-photon emission spectrum, we discuss first the atomic two-photon emission spectrum in the case of the number state field. It is known from Eq. (19) that the linewidths of all $S_n(\omega)$ are the same, Γ, the passband width of the filter detector, and the shape of peak is approximately Lorentzian, which is only slightly corrected by the two exponential terms in Eq. (19). If Γ is very small, i.e., $\Gamma\ll\lambda$, then the peak of the spectrum may be very narrow. It is to be emphasized what we consider to be the atomic two-photon emission spectrum in an ideal cavity. The width of the emission spectrum itself γ can tend to zero, as the width of the one-photon emission spectrum shown in [18]. But in a cavity with loss, $\gamma\neq 0$, the emission spectrum would be affected. (The effect will be discussed in another paper.) The information in the structures and the height and position of the peaks for the emission spectra $S_n(\omega)$ are given in Table I.

You can see from Table I that the intervals between

TABLE I. The structure and position of peaks in the case of the number state field ($\Gamma<\lambda$).

Spectrum	Position of peaks ($\omega-\Omega/2$)	Height	Spectrum structure
$S_0(\omega)$	$\pm\lambda/2^{1/2}$	$\frac{1}{2\Gamma}(1-e^{-\Gamma T})^2$	two-peak structure
$S_1(\omega)$	$\pm\lambda/(3/2)^{1/2}$	$\frac{1}{2\Gamma}(1-e^{-\Gamma T})^2$	two-peak structure
$S_n(\omega)$	$\pm\lambda\{[(n+1)(n+2)]^{1/2}-[n(n-1)]^{1/2}\}/2$ (inner)	$\frac{1}{4\Gamma}(1-e^{-\Gamma T})^2$	four-peak structure
$n\geq 2$	$\pm\lambda\{[(n+1)(n+2)]^{1/2}+[n(n-1)]^{1/2}\}/2$ (side)		

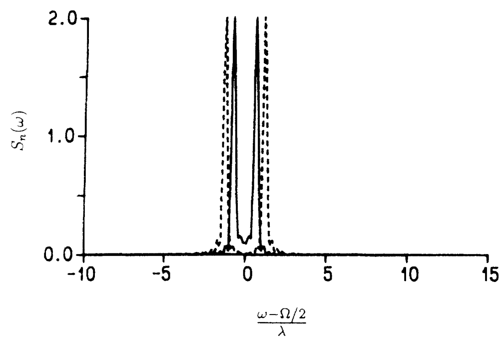

FIG. 1. Two-photon emission spectrum for the number state, $S_n(\omega)$ vs ω. $\Gamma/\lambda=0.1$, $\lambda T=10.0$. Solid line: $n=0$; dashed line: $n=1$.

peaks are proportional to the two-photon coupling constant λ, both $S_0(\omega)$ and $S_1(\omega)$ have two peaks, respectively, and $S_n(\omega)$ $(n\geq 2)$ has four peaks. The peak height of $S_n(\omega)$ $(n\geq 2)$ is half of the peak heights of $S_0(\omega)$ or $S_1(\omega)$, shown in Figs. 1, 3 and 4. For $S_n(\omega)$ $(n\geq 2)$, the positions of the two inner peaks change very little with increasing n. As $n\rightarrow\infty$ the interval between two inner peaks tends to a certain value, 2λ, but the two side peaks depart far away from the center. These peaks are due to the Rabi split. The split of $S_0(\omega)$ is also called the vacuum Rabi split. The split of $S_1(\omega)$ is a special phenomenon in a two-photon process. The inner peaks of $S_n(\omega)$ $(n\geq 2)$ result from the difference frequencies between the quantum Rabi oscillations. The side peaks originate from the sum frequencies between the quantum Rabi oscillations. Here the sign $(\pm)$ represent Rabi splits. If Γ is larger than the interval between peaks, those peaks will be overlapped together and then it can change the structure of the emission spectrum. In this case, obviously, the width of each peak will be larger than Γ.

It is well known from Figs. 2, 5, and 6 that $S_n(\omega)$ becomes a single peak when $n=0$ or $n=1$, and $S_n(\omega)$ $(n\geq 2)$ is the single peak as well for the case of smaller n, but $S_n(\omega)$ becomes a three-peak structure for the case of larger n. The fluctuations in both sides of each peak are caused by the modulation of the first exponential term in

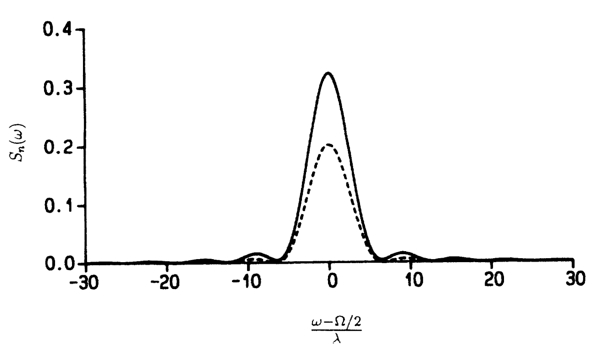

FIG. 2. Two-photon emission spectrum for the number state, $S_n(\omega)$ vs ω. $\Gamma/\lambda=2.0$, $\lambda T=0.5$. Solid line: $n=0$; dashed line: $n=1$.

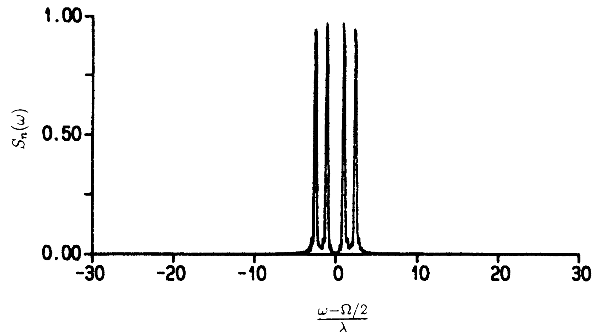

FIG. 3. Two-photon emission spectrum for the number state, $S_n(\omega)$ vs ω. $n=2$; $\Gamma/\lambda=0.1$; $\lambda T=10.0$.

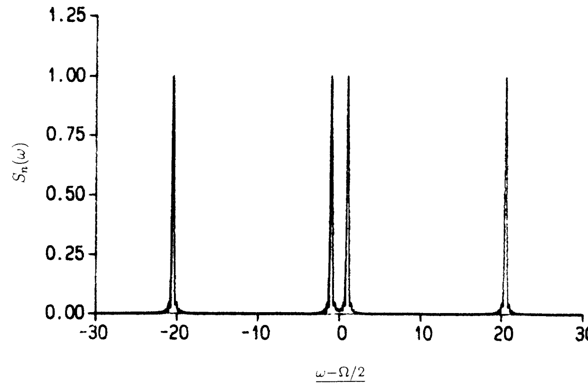

FIG. 4. Two-photon emission spectrum for the number state, $S_n(\omega)$ vs ω. $n=20, \Gamma/\lambda=0.1$; $\lambda T=10.0$.

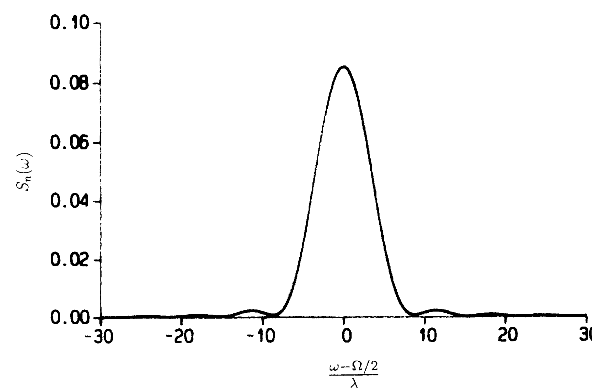

FIG. 5. Two-photon emission spectrum for the number state, $S_n(\omega)$ vs ω. $n=2$; $\Gamma/\lambda=2.0$; $\lambda T=0.5$.

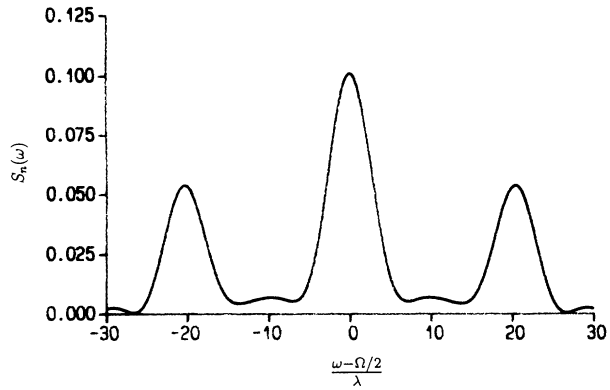

FIG. 6. Two-photon emission spectrum for the number state, $S_n(\omega)$ vs ω. $n=20$; $\Gamma/\lambda=2.0$; $\lambda T=0.5$.

Eq. (19) with the variation of frequency ω.

Second we investigate the influence of the statistical properties of the field on the emission spectrum. For comparison, we consider three kinds of fields: the thermal field and the squeezed vacuum as well as the coherent field.

(a) The photon distribution of the thermal field (THF) is

$$P_n^{\text{th}}=\frac{1}{\bar{n}+1}\left[\frac{\bar{n}}{\bar{n}+1}\right]^n . \tag{20}$$

(b) The photon distribution of the squeezed vacuum field (SVF) is

$$P_{2n}^{\text{SV}}=\frac{1}{(\bar{n}+1)^{1/2}}\frac{(2n)!}{2^{2n}(n!)^2}\left[\frac{\bar{n}}{\bar{n}+1}\right]^n, \quad P_{2n+1}^{\text{SV}}=0 . \tag{21}$$

(c) The photon distribution of the coherent field (COHF) is

$$P_n^{\text{coh}}=\exp(-\bar{n})\frac{\bar{n}^2}{n!} . \tag{22}$$

The numerical results calculated from Eqs. (17)–(22) are shown in Figs. 7–12. From Figs. 7 and 8 you can see

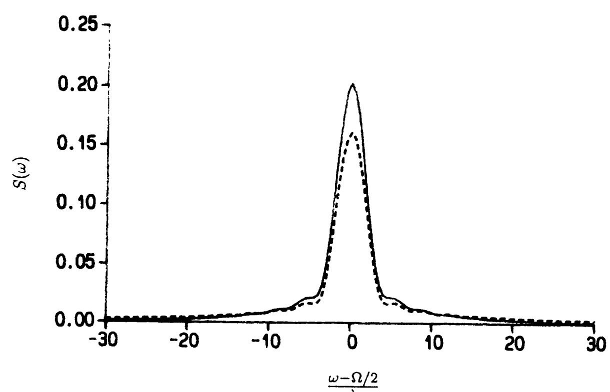

FIG. 7. Two-photon emission spectrum for the squeezed vacuum state, $S(\omega)$ vs ω. $\Gamma/\lambda=1.0$; $\lambda T=1.0$. Solid line: $\bar{n}=5$; dashed line: $\bar{n}=20$.

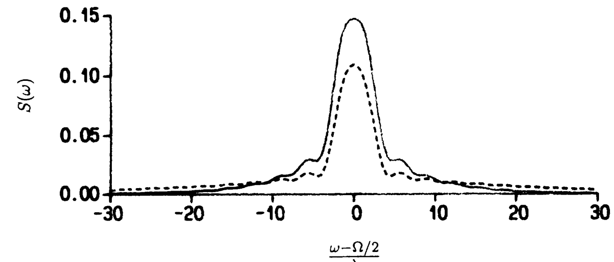

FIG. 8. Two-photon emission spectrum for the thermal field, $S(\omega)$ vs ω. $\Gamma/\lambda=1.0$; $\lambda T=1.0$. Solid line: $\bar{n}=5$; dashed line: $\bar{n}=20$.

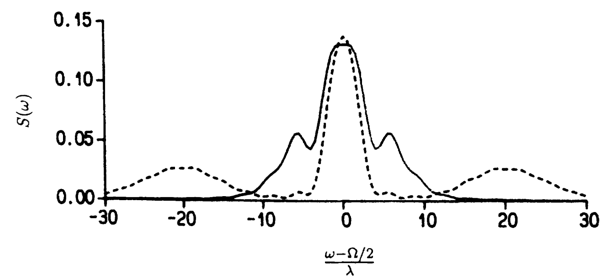

FIG. 9. Two-photon emission spectrum for the coherent field, $S(\omega)$ ω. $\Gamma/\lambda=1.0$; $\lambda T=10.0$. Solid line: $\bar{n}=5$; dashed line: $\bar{n}=20$.

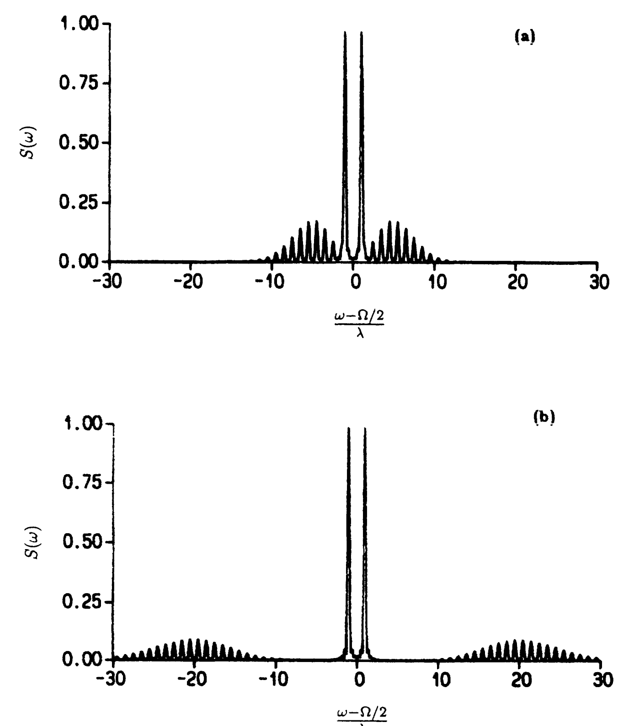

FIG. 10. Two-photon emission spectrum for the coherent field, $S(\omega)$ vs ω. $\Gamma/\lambda=0.1$; $\lambda T=10.0$. (a) $\bar{n}=5$; (b) $\bar{n}=20$.

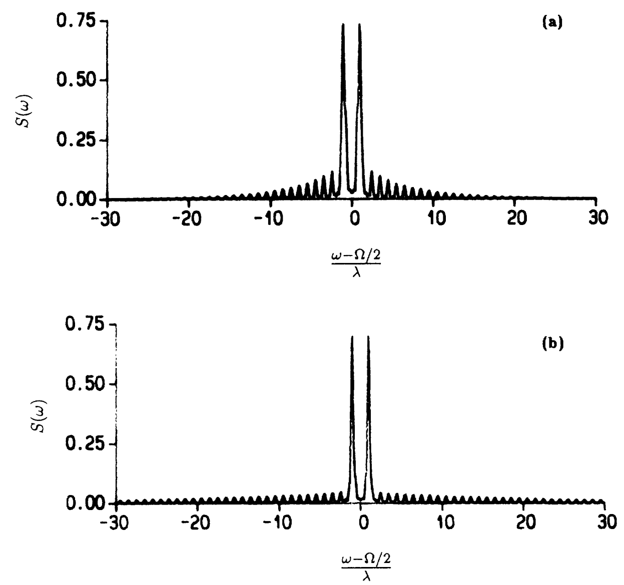

FIG. 11. Two-photon emission spectrum for the thermal field, $S(\omega)$ vs ω. $\Gamma/\lambda=0.1$; $\lambda T=10.0$. (a) $\bar{n}=5$; (b) $\bar{n}=20$.

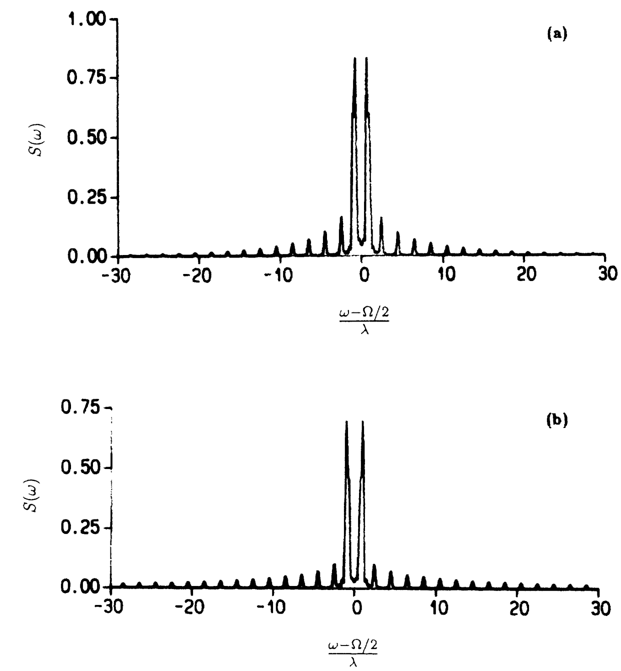

FIG. 12. Two-photon emission spectrum for the squeezed vacuum, $S(\omega)$ vs ω. $\Gamma/\lambda=0.1$, $\lambda T=10.0$. (a) $\bar{n}=5$; (b) $\bar{n}=20$.

that in the case of $\Gamma/\lambda=1.0$ the emission spectrum of the atom in SVF is similar to that in THF. There is only a strong peak at the center. As $\bar{n}$ increases the height of the peak decreases and the width of peak becomes narrower, but the two fringes are raised and extended away. For the same $\bar{n}$, the peak height is higher in the case of SVF than in THF and the peak width is wider in the case of THF than in SVF. Nevertheless, the peak widths in the two cases tend toward equal when $\bar{n}$ is larger. The emission spectrum exhibits a three-peak structure for the COHF. When the average number of photons increases, the central peak is raised and narrowed and the two side peaks are shifted, respectively, far away; the peaks are reduced and widened also (Fig. 9). It is shown from Figs. 10–12 that when $\Gamma \ll \lambda$, the two-photon emission spectrum exhibits the multipeak structure and the central peak is split into two peaks, which are very high because of the overlapping of many small inner peaks in all cases. The height is approximately $(1+P_0+P_1)(1-e^{-\Gamma T})^2/(4\Gamma)$, here P_0 and P_1 are the statistical distribution of photons in the initial field. Many small peaks generate in two sides of the center. The reason is that all contributions, which, respectively, correspond to a distinct number state, do not overlap each other. From comparison of Figs. 9 and 10 it is seen that their envelopes are similar to the spectrum shape as $\Gamma > \lambda$. For the thermal field and the squeezed vacuum, the emission spectra resemble each other as well: the phases of their envelopes are analogous, and as $\bar{n}$ becomes greater, the position of every small peak does not change and only the number of small peaks extending far away increases. Their envelopes are determined by the photon statistics distribution of the initial field.

Based on the above discussion, we can conclude that as $\Gamma \gg \lambda$, for the initial coherent field the three-peaked structure is generated by the Poissonian photon distribution of the coherent field, in which P_n is maximum at the average number of the photons. The three peaks of the spectrum for the coherent field are different from those for the photon-number state field. The width of side peaks for the former, which is enhanced with increasing of $\bar{n}$, depends not only on the passband width of the filter detector, Γ, but also on the width of the statistical distribution in the coherent state P_n. The width of side peaks for the latter, which does not change with the changing of the photon number n, depends only on Γ. The difference between the cases of both THF and SVF is noticed so that for the SVF the small peaks exhibit only in the places where the positions of peaks are "even" numbers. In other words, the small peaks in the case of SVF, relative to THF, appear intermittently. Because $P_{2n+1}=0$ for the SVF.

In summary, using TPJCM we have studied two-photon emission spectrum (TPES) and found that the structures of spectrum depend on the passband width of filter detector Γ, the two-photon coupling constant λ, and the photon statistics distribution of the initial field P_n. We analyzed, in detail, the similarities and differences in two-photon emission spectra as well as the causes generating this difference between the cases of various initial fields. Especially, when $\Gamma \ll \lambda$, TPES exhibits the multipeaked structure. This has enriched the contents of the aspects of quantum character for the interaction of the atom with the field. Hence by the TPES of an atom in microcavity, one can investigate unusual quantum features for the interaction of the field with the atom. The method used in this paper can be generalized to research on m-photon emission spectrum in the arbitrary m-photon Jaynes-Cummings model.

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