

A scheme to identify experimentally the photons with different coherent superposition states

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Abstract: In this paper, we propose a scheme to identify photons with different coherent superposition states through studying 2D, third-order, non-linear rephasing spectra acquired from a special photon echo experiment. The procedures of the experiment can be arranged as follows: Photons (laser) are first input into a fiber, letting them pass through the fiber. Next, the output laser is taken from the fiber as the light source to conduct the photon echo experiment. Finally, the 2D, third-order, non-linear rephasing spectra can be obtained from the photon echo signals. Based on the pattern of the spectra, the quantum states of the input photons can thus be determined.

Key words: coherent superposition state; 2D, third-order, non-linear rephasing spectra; photon echo experiment

CLC number: O433.4

Document code: A

Article ID: 1001-5132 (2019) 02-0100-08

1 Introduction

Quantum superposition principle is fundamental in quantum mechanics. It states that, the linear superposition of two or more quantum states is also a state of the quantum system. Physically, when the system is in a state superposed with two or more distinct states, it must be in all the component states at the same time. This opinion is quite strange from the point of view of classical physics. Mathematically, the degree of the coherence can be described with the non-diagonal elements of the density matrix of a certain state.

A photon has two possible polarization states, one of which is the horizontal polarization state $|H\rangle$ and the other is the vertical polarization state $|V\rangle$. In this sense, it is a qubit. According to the quantum superposition principle, $|\varphi\rangle=c_1|c_1H\rangle+c_2|V\rangle$ is also a state of this qubit, for any complex numbers c_1 and c_2

with $(|c_1|^2+|c_2|^2=1)$. Here, $|c_1|^2$ and $|c_2|^2$ are the probabilities of collapsing to $|H\rangle$ and $|V\rangle$ states when measuring the polarization of the photons. Successful experiments of generating and showing quantum coherent superposition states have been performed in past years. The double slit experiments (photons, electrons, and so on) are the fact of creating coherent superposition states, and the effects shown from interference pattern are observable in the screen. In reverse, the interference pattern is also the evidence of the quantum system in a coherent superposition state. However, in order to obtain the interference pattern we must make the component states of the superposition state be separated spatially. For example, the two component states in double slit experiment must have different propagation pathways.

However, it is not convenient to check whether photons are in the coherent superposition state or not,

收稿日期: 2018-10-14.

宁波大学学报(理工版)网址: <http://journallg.nbu.edu.cn/>

基金项目: 国家自然科学基金(21773131); 宁波大学王宽诚幸福基金.

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when the component states are not separated spatially. In this case, we cannot obtain the interference pattern even the system is in some coherent superposition state, so we cannot distinguish the photons with different coherent degree through this experiment. In this paper, we suggest a novel scheme to identify different coherent superposition states by using the 2D, third order, non-linear spectroscopy developed in recent years. It will be shown that the 2D, third order, non-linear spectra has significant difference when the photons of input light resource are in different coherent superposition states. Here, the component states of coherent superposition states do not require space separability. This method is totally different from the method of measuring interference pattern.

2 Experimental scenario, model, and theoretical strategy

2.1 Experiment scenario

Recently, a non-linear spectroscopy techniques, based on the three-pulse photon echo experiment^[1] has been developed^[2-4], and been extensively applied^[5-10]. This method can be used to study energy transfer of some samples. In three-pulse photon echo experiment, the system to be studied is probed by three incident laser pulses^[6-7,11-12]. The first pulse creates a superposition state between the ground state and excited states, which evolves for time delays t_1 until the second pulse interacts with the sample. The second pulse creates a population in the exciton system, and the corresponding dynamics is recorded by the population time t_2 . The third pulse interacts with the system to generate a photon echo signal, and stands for the signal time. By carefully matching the phases and directions of the input laser pulses, one can obtain the output of the echo signals correlated with the first and third pulses. Normally, the rephasing and nonrephasing signals from the photon echo are summed, and the sum is phased to acquire corrected rephasing and nonrephasing spectra. However, by employing the Gradient Assisted Photon Echo

Spectroscopy (GAPES) technique^[12], the rephasing and nonrephasing signals from pump-probe data can be phased independently. Thus, the experimental rephasing and nonrephasing spectra can be compared with the calculated ones. Then, we can infer the energy level structure of the system and the paths of energy transfer from these two-dimensional spectra.

However, in the scenario of this work, conversely we suppose the energy-level structure of the selected sample is known. Without loss of generality, here, we simply assume the sample is a two-level system which can be excited by the photons. It is interesting that this experiment can be applied to identify the photons with different coherent superposition states. The schematic diagram of our scheme is shown in Fig. 1, where τ is the coherence time after pulses 1 and 2, T is the population time, and t is the coherence time after the third pulse 3; k_1 , k_2 , k_3 , and $k_{4(LO)}$, denote the directions of three pulses and local oscillator field; EMCCD denotes an electron multiplying charge coupled device, BS's denote splitters, SM's denote spherical mirrors, ST's denote step stages, ND is the neutral density filter, BG is the time-delayed beam grass.

The experiment of our scheme is arranged as follows. A beam of laser made up of photons with state $\rho(0)$ is split by a pair of splitter (BS1, and BS2) (see lower left in Fig. 1). Then the split beams are input in their respective light paths of fiber, and this process can be mathematically described with the quantum noise channel models. Next, the split beams are focused by a spherical mirror SM1 onto a grating. Thus, three excitation pulses (1, 2, and 3) and the local oscillator (4) are provided. All of these beams are collimated with a spherical mirror SM2 and are focused by SM3 into the sample. Here, we choose a two-level system as the sample which must be able to be excited by the input photons. Time delays are provided by step stages (SFT, ST1, and ST2). An automated beam shutter and an optical chopper are used to remove the scattering signal and local oscillator from the heterodyne spectrum. When the delay stage ST2 is moved, with the pulse 2

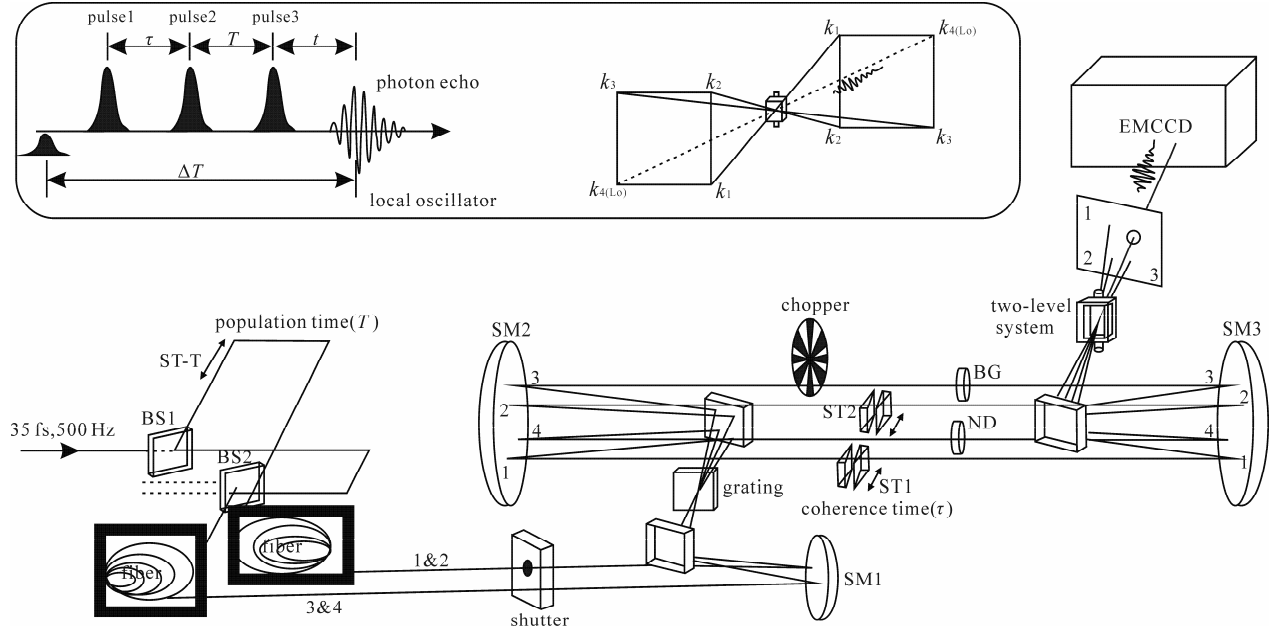


Fig. 1 Schematic diagram of experimentally identifying photons with different coherent superposition states by using the photon echo experiment^[2]

preceding to pulse 1, then the rephasing signals will be generated in the same direction of the Lo pulse. The nonrephasing signals can be generated simply by reversing the timing sequence of the pulses 1 and 2 through moving the delay stage ST1 instead of ST2. The ND is a neutral density filter through which the density of Lo can be attenuated to about three orders in magnitude. In order to compensate the optical path difference between pulses 3 and 4 a clear glass (CG) is added in the optical path 3. The details of obtaining the experimental photon echo signals can be referred to many references^[2-5,7,13-14]. The set-up of the photon echo experiment follows the traditional version of the diffractive optics^[2,15-16].

2.2 Computation models (quantum noise channels)

The reduced dynamics of the quantum system in its environment can be described by many kinds of methods. In this paper, we use the quantum noise channel language to investigate the quantum dissipative dynamics. There are many kinds of forms to describe the quantum noise channels. They are the phase flip channel, the depolarizing channel, the amplitude channel, the phase damping channel, and so on^[17-18]. The evolution of an open quantum system can be

described with the operator-sum expression as

$$\rho(t) = \sum E_i \rho(0) E_i^\dagger, \quad (1)$$

where E_i is an operation element, for all of which there must have

$$\sum_i E_i^\dagger E_i = 1. \quad (2)$$

For a single qubit, there are many kinds of decoherence mechanisms which correspond to different kinds of operation elements. For example, for the generalized amplitude damping channel, they are

$$E_0 = \sqrt{p} \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-\gamma} \end{bmatrix}, E_1 = \sqrt{p} \begin{bmatrix} 0 & \sqrt{\gamma} \\ 0 & 0 \end{bmatrix}. \quad (3)$$

Here, p is the probability of the photon not being depolarized, and γ is the probability of losing for the qubit. In this scheme, some input photons (laser beam) with initial state $\rho(0)$ are let to pass through the generalized amplitude damping channel ("fiber" in Fig. 1). Then, after the photons being output from the channel, a photon echo experiment is executed, which has been described in the above subsection. It will be shown that the input photon with different coherent superposition states can be distinguished by virtue of patterns obtained from the photon echo signals.

2.3 Calculation scheme of photon echo signal pattern

Three laser pulses are projected onto the sample along $\vec{k}_1, \vec{k}_2$ and $\vec{k}_3$, and the detected 2D, third-order, non-linear response signals are propagated along the phase-matched directions $\vec{k}_s$ (see upper-right plot in Fig. 1). In the impulsive limit, the rephasing and nonrephasing spectra are calculated as the real part of the following double Fourier-Laplace transforms of $R_r(t_1, t_2, t_3)$ and $R_{nr}(t_1, t_2, t_3)$ with respect to t_1 and t_3 , respectively:

$$I_{r,nr} = \int_0^\infty dt_1 \int_0^\infty dt_3 e^{i(\mp\omega_{t_1} + \omega_{t_3})} R_{r,nr}(t_1, t_2, t_3), \quad (4)$$

here, R_r and R_{nr} are the rephrasing ($\vec{k}_s = -\vec{k}_1 + \vec{k}_2 + \vec{k}_3$) and nonrephrasing ($\vec{k}_s = \vec{k}_1 - \vec{k}_2 + \vec{k}_3$) signals, which are detected in experiments and can be calculated theoretically through [19-21],

$$R_{r,nr}(t_1, t_2, t_3) = \text{Tr}\{\mu G(t_3) \mu_\pm^* G(t_2) \mu_\pm^* G(t_1) \mu_\mp^* \rho_{\text{tot}}^{\text{eq}}(0)\}. \quad (5)$$

Here, $G(t)$ is the retarded propagator of the total system in Liouville space, $\mu_\pm^* x = [\mu_\pm, x]$, where $\mu_+ \equiv \sum_m \mu_{m0} |m\rangle \langle 0|$ and $\mu_- \equiv \sum_m \mu_{0m} |0\rangle \langle m|$, with the dipole operator being constructed as $\mu = \mu_+ + \mu_-$, and we suppose the total system is in the equilibrium state, initially, represented with $\rho_{\text{tot}}^{\text{eq}}(0)$, $t_1 = \tau_2 - \tau_1$, $t_2 = \tau_3 - \tau_2$, and $t_3 = \tau - \tau_3$, where τ_1, τ_2 and τ_3 are the time points of the laser projecting onto a sample, and τ is the time point of receiving echo signals (see upper-left plot in Fig. 1).

3 2D, third-order, non-linear spectroscopy of input photons with different coherence

In this section we shall investigate what differences there are of the 2D, third-order, non-linear spectra when the photons with different coherent superposition states are taken as the input laser light. Here, the quantum dissipative dynamics is described with a generalized amplitude damping channel. We consider two classes of

initial states of the photon's polarization states:

$$\rho_i(0) = \begin{bmatrix} |\alpha|^2 & \alpha^* \beta \\ \alpha \beta^* & |\beta|^2 \end{bmatrix} = \begin{bmatrix} p_1 & \alpha^* \beta \\ \alpha \beta^* & p_2 \end{bmatrix}, \quad (6)$$

$$\sigma_i(0) = \begin{bmatrix} p_3 & 0 \\ 0 & p_4 \end{bmatrix}. \quad (7)$$

In the following, we investigate the pattern of the rephasing signals obtained from the following different initial states (see table 1 and table 2).

Table 1 The probabilities of the initial states with different degree of coherence corresponding to Eq. (6)

probability	state						
	$\rho_1(0)$	$\rho_2(0)$	$\rho_3(0)$	$\rho_4(0)$	$\rho_5(0)$	$\rho_6(0)$	$\rho_7(0)$
P_1	0.50	0.45	0.35	0.25	0.15	0	1
P_2	0.50	0.55	0.65	0.75	0.85	1	0

Table 2 The initial states with different degree of mix corresponding to Eq. (7)

probability	state						
	$\sigma_1(0)$	$\sigma_2(0)$	$\sigma_3(0)$	$\sigma_4(0)$	$\sigma_5(0)$	$\sigma_6(0)$	$\sigma_7(0)$
P_3	0.50	0.45	0.35	0.25	0.15	0	1
P_4	0.50	0.55	0.65	0.75	0.85	1	0

Here, $\rho_i(0) (i=1, \dots, 5)$ are pure states, and the input initial states with different superposition coefficients, and from $\rho_1(0)$ to $\rho_5(0)$ the off-diagonal elements of the density matrix are decreased. $\sigma_i(0) (i=1, \dots, 5)$ describes mixed states, and from $\sigma_1(0)$ to $\sigma_5(0)$, the degree of the mix are decreased. $\rho_6(0) = \sigma_6(0)$ and $\rho_7(0) = \sigma_7(0)$ are two single states. These different states are easily recognized in mathematics, it is, however, not easy to identify them in physics. In Fig. 2 we plot the pattern of the rephasing signals obtained from the photon echo experiment. The 2D, third-order, non-linear spectra are shown when the input photons (laser light) are in the maximally coherent superposition state $\rho_1(0)$, see Fig. 2(a), or in the maximally mixed state $\sigma_1(0)$, see Fig. 2(b). It is shown that when the input photons are in the maximally mixed state there is not any peak in the rephasing spectra of the photon echo signals. However, when the input state is the maximally coherent superposition state there is a band of light

which is precisely parallel to the axis of ω_3 . If the input states are in the other mixed states, for example $\sigma_2(0)$, $\sigma_3(0)$, $\sigma_4(0)$, $\sigma_5(0)$, the obtained 2D, third-order, non-linear spectra have their similar pattern but their intensities are increased with the decrease of mix degree, as shown in Figs. 2(d), (f), (h), (j). However, if the input

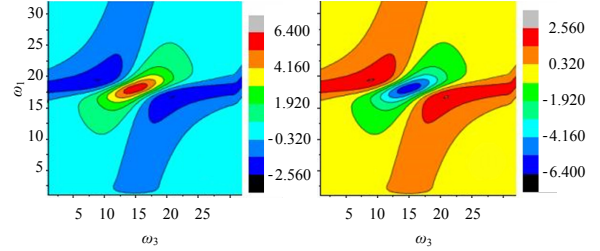
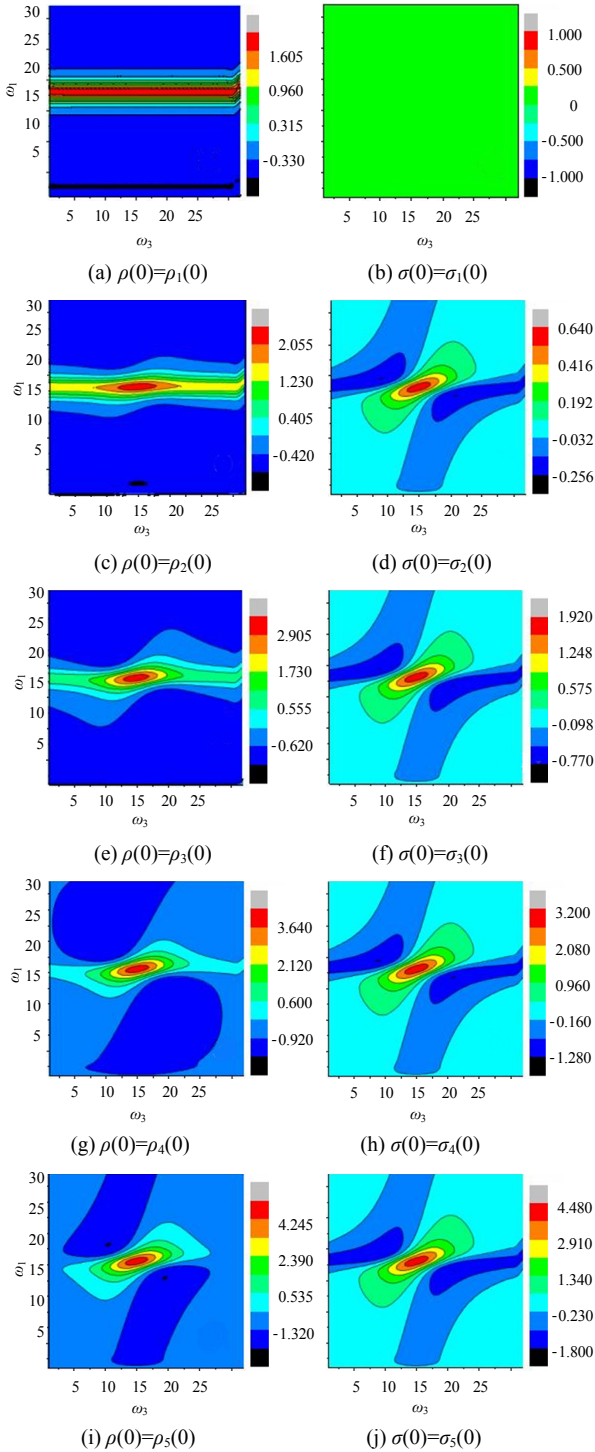


Fig. 2 2D, third order, non-linear rephasing spectra of two-level system in photon echo experiment, when the input laser beams are coherent super-position states and mix states; the environment is described with the generalized amplitude damping channel as Eq. (3), with probability $p=0.5$, $\gamma=0.25$

state are in the other coherent superposition states, not only the forms become more and more slant, but also the intensities become more and more stronger (see Figs. 2(c), (e), (g), (i)) with the decrease of the off-diagonal elements for the states $\rho_2(0)$, $\rho_3(0)$, $\rho_4(0)$, $\rho_5(0)$. When the input states are in the single states $|H\rangle$ and $|V\rangle$, their values of the peaks for the rephrasing spectra are just the reverse, see Fig. 2(k), (l). It is shown that the maximally mixed state, and the maximally coherent superposition state can be clearly identified through the photon echo experiment.

In Fig. 3, we plot the 2D, third order, non-linear rephasing spectra of two-level system in different parameters. Figs. 3(a), (b), (c), and (d) are the spectra corresponding to parameters $\gamma=0.1$, 0.3 , 0.7 , 0.9 , and $p=0.5$, respectively. Figs. 3(e), (f), (g), (h) are the spectra corresponding to parameters $p=0.1$, 0.3 , 0.7 , 0.9 and $\gamma=0.5$, respectively. Here, the initial state is chosen as $|H\rangle$. The results show that the figures are not sensitive to the change of parameter p , but they become more smaller with the decrease of γ . It is also shown that the shapes of the figures were similar to those shown in Fig. 2 in other different initial states, when the γ and p are fixed.

In the above calculations, the generalized amplitude damping channel model has been used. In fact, we do not know which noise channel model can actually describe the dynamics in some experimental environment.

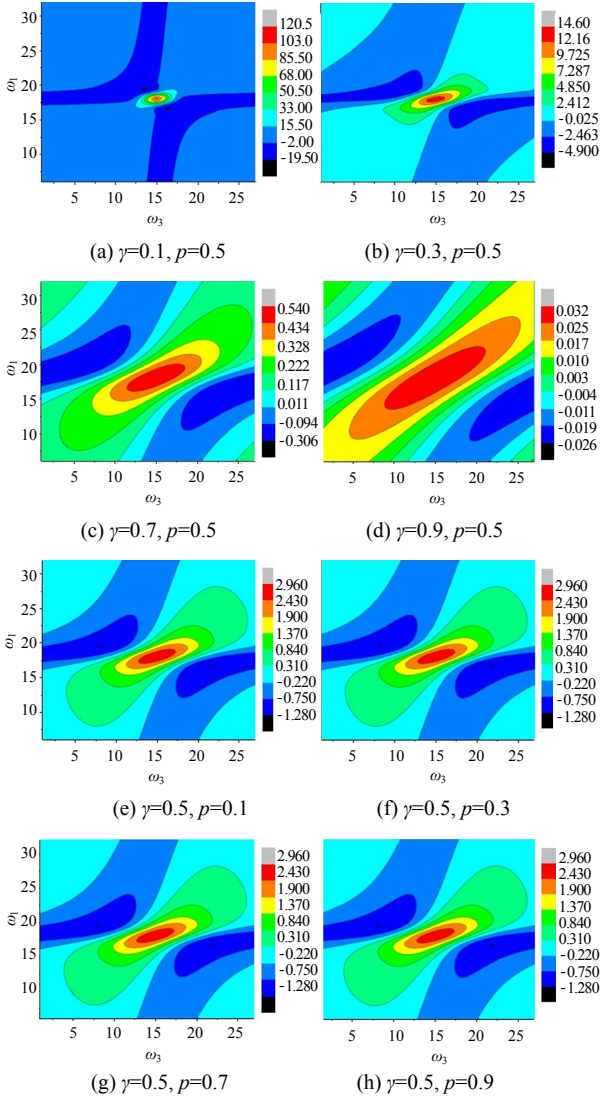


Fig. 3 2D, third order, non-linear rephasing spectra of two-level system in photon echo experiment, when the input laser beams are chosen as $\rho_0(0)$

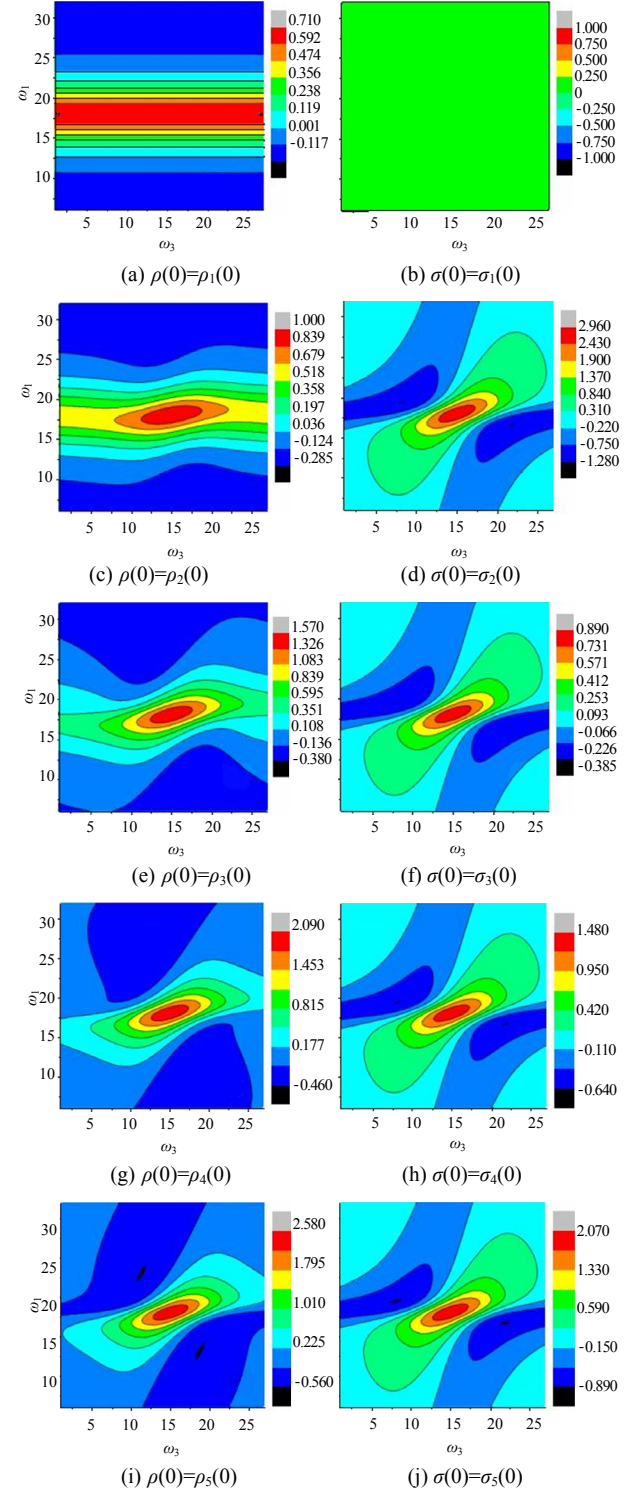
If the channel through which the photons passes is not a generalized amplitude damping channel, can we also identify the photons in different coherent superposition states through this scheme? In Fig. 4 we plot the 2D, third-order, rephasing spectra of these photon echo signals when the input photons pass through the depolarizing channel.

The operation elements of the depolarizing channel are

$$E_0 = \sqrt{1 - \frac{3p}{4}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, E_1 = \sqrt{\frac{p}{4}} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix},$$

$$E_2 = \sqrt{\frac{p}{4}} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, E_3 = \sqrt{\frac{p}{4}} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \quad (8)$$

Then, when the input laser in the photon echo experiment is made up of the photons which are output from the depolarizing channel, the rephasing spectra are



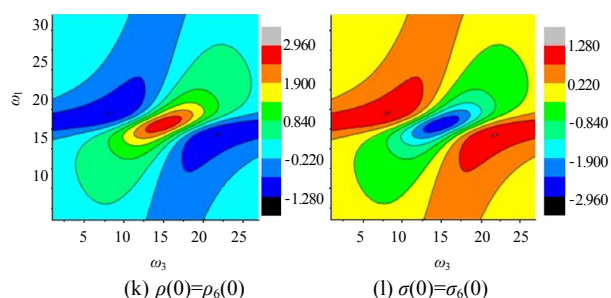


Fig. 4 2D, third order, non-linear rephasing spectra of two-level system in photon echo experiment, when the input laser beams are coherent superposition states and mix states; the environment is described with the depolarizing channel as Eq. (8), with probability $p=0.5$

plotted as Fig. 4. It is shown that the forms of the pattern of photon echo signals are similar in the two cases.

In fact, we have tried many other quantum noise channel models. It is shown that the results obtained from other models are all similar to the ones obtained from the generalized amplitude damping channel and the depolarizing channel. This means that the conclusions obtained in this paper do not depend on specific quantum noise channel models.

4 Summary

We found that the maximally coherent superposition state and maximally mixed state can be clearly identified by using the rephasing spectra of the photon echo signals. The rephasing spectrum is a band of light paralleling to the ω_3 axis when the input laser consists of photons with maximally coherent superposition state. However, when the input laser consists of photons with maximally mixed state, there will not be any peaks in the rephasing spectra. The results can be used to identify the photons with different states and this is perfectly understandable because photons with different coherence excite the sample with different forms. The best advantage of this method is that it is not required for the photons with different component states to have different propagation paths, which is needed to identify photons in the interference pattern experiment. In a word, we find out that if the

parameter γ is not too small we can experimentally identify photons with different coherent superposition states through distinguishing the shapes of the 2D, third-order, rephasing spectra of the photon echo signals.

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一种通过实验识别具有不同相干叠加态光子的方法

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摘要: 通过对一种特殊的光子回波实验得到的二维三阶非线性复相光谱研究, 提出了一种识别不同相干叠加态光子的方法. 实验步骤为: 首先将光子(激光)输入光纤, 让其通过光纤; 然后以光纤输出的激光器为光源, 进行光子回波实验; 最后从光子回波信号中得到二维三阶非线性的复相谱. 根据得到的二维三阶非线性复相谱图形, 确定输入光子处于何种量子态.

关键词: 量子相干叠加态; 二维三阶非线性再定相光谱图; 光子回波实验

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