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Realization of stimulated emission-based detector and its application to antinormally ordered photodetection*

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Using a stimulated parametric down-conversion process combined with a conventional detector, we theoretically propose a scheme to realize the stimulated emission-based detector, and investigate the antinormally ordered correlation function and Fano factor for the coherent field based on it. Such a detection has advantages over the normally ordered one especially when the intensity of the field is weak.

Keywords: stimulated emission-based detector, antinormally ordered photodetection

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The conventional detection is a normally ordered photodetection process based on Einstein's photoelectric theory,[1] which means that the electromagnetic field is detected by an absorption-based detector, such a detection process is insensitive to zero-point fluctuations due to the fact that the vacuum components of the fields are lost during the detection,[2] therefore the initial density matrix of the field cannot be logically reversible. While the antinormally ordered photodetection, which is a stimulated emission-based detection process with $<0|\hat{a}\hat{a}^{+}|0>\neq 0$, has the advantages over the normally ordered one since it responds not only to actual photons but also to zero-point fluctuations, so all the information of the field can in principle be retained during the detection process.[2,3] From the point of view of photocounting statistics, the absorption-based and the stimulated emission-based photocounting statistics are different from each other, especially in small photocounting number regions.[4]

The antinormally ordered photodetection process can be observed by a stimulated emission-based detector. There are many theoretical models[4–8] to discuss it based on the stimulated emission process in atoms[9,10] since it was originally proposed as a quantum counter[11] in 1959. But until 2004, Usami *et al.* experimentally measured the antinormally ordered Hanbury Brown–Twiss (HBT) correlations for a coherent field.[12] In the present paper, we propose a scheme to realize the stimulated emission-based detector, which can be used to measure the antinormally ordered values of the quantum fields. As an application to such a detector, we investigate the antinormally ordered correlation function and Fano factor for a coherent field, which shows the different properties with the normally ordered ones. Finally, the experimental possibility of our theoretical scheme is examined.

Here, we consider a Type-II collinear stimulated parametric down-conversion process[13] depicted in Fig. 1, $\hat{a}_{\rm in}$ acts as the operator of input field to be investigated and $\hat{b}_{\rm in}$ as an auxiliary field. $\hat{a}_{\rm in}$ and $\hat{b}_{\rm in}$ are coupled along the idler and signal propagation directions of the parametric down-conversion process respectively, and the polarizations of these two input fields are adjusted to be parallel to the one of idler and signal directions respectively. After the interaction of $\hat{a}_{\rm in}$ and $\hat{b}_{\rm in}$ with the pump field in the nonlinear crystal under a perfect phase matching condition, these two operators are evolved into

$$\hat{a}_{\rm out}=\hat{a}_{\rm in}\cosh(\gamma)-\hat{b}_{\rm in}^{+}{\rm e}^{{\rm i}\,\vartheta}\sinh(\gamma), \quad (1)$$

$$\hat{b}_{\rm out}=\hat{b}_{\rm in}\cosh(\gamma)-\hat{a}_{\rm in}^{+}{\rm e}^{{\rm i}\,\vartheta}\sinh(\gamma), \quad (2)$$

where γ and ϑ represent all the interaction parameters in the parametric down-conversion process such as second-order nonlinear susceptibility, length of crystal, and intensity of pump.[1]

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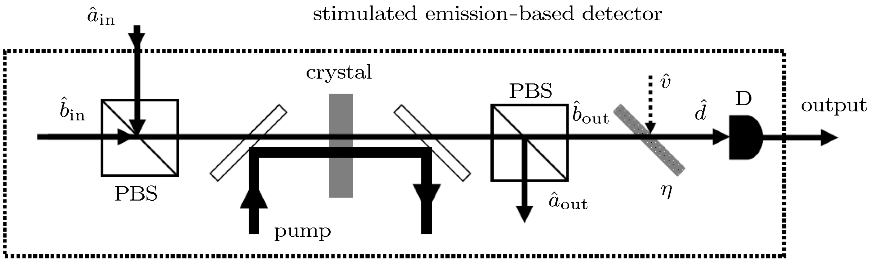

Fig. 1. Theoretical model of a stimulated emission-based detector to realize the antinormally ordered photodetection of input field $\hat{a}_{\rm in}$. PBS: polarized beam splitter, D: conventional detector.

A beam splitter with transmission rate η in front of the conventional detector D is equivalent to the optical loss and the imperfection efficiency of the detector,[14] thus the signal in front of the detector can be described as

$$\hat{d} = \sqrt{\eta}\hat{b}_{\rm out} + {\rm i}\sqrt{1-\eta}\hat{\nu}, \tag{3}$$

where $\hat{\nu}$ represents the vacuum component introduced by the beam splitter. The conventional detector then gives out the measured mean photon number and the variance of field $\hat{d}$. When the auxiliary field $\hat{b}_{\rm in}$ is also considered as a vacuum field, we can calculate out the first and second moments measured from D as

$$\begin{aligned}\langle n_d\rangle &= \langle \hat{d}^+\hat{d}\rangle \\ &= \eta\langle \hat{b}^+_{\rm out}\hat{b}_{\rm out}\rangle = \eta\sinh^2(\gamma)\langle \hat{a}_{\rm in}\hat{a}^+_{\rm in}\rangle, \qquad (4)\\ \langle n^2_d\rangle &= \langle \hat{d}^+\hat{d}\hat{d}^+\hat{d}\rangle = \eta^2\langle \hat{b}^+_{\rm out}\hat{b}_{\rm out}\hat{b}^+_{\rm out}\hat{b}_{\rm out}\rangle \\ &\quad + (\eta-\eta^2)\langle \hat{b}^+_{\rm out}\hat{b}_{\rm out}\rangle \\ &= \eta^2\sinh^4(\gamma)\langle \hat{a}_{\rm in}\hat{a}^+_{\rm in}\hat{a}_{\rm in}\hat{a}^+_{\rm in}\rangle + [\eta^2\sinh^4(\gamma) \\ &\quad + \eta\sinh^2(\gamma)]\langle \hat{a}_{\rm in}\hat{a}^+_{\rm in}\rangle, \qquad (5)\end{aligned}$$

so the variance can be obtained to be

$$\begin{aligned}\varDelta^2(n_d) &= \langle \hat{d}^+\hat{d}\hat{d}^+\hat{d}\rangle - \langle \hat{d}^+\hat{d}\rangle^2 \\ &= \eta^2\sinh^4(\gamma)[\langle \hat{a}_{\rm in}\hat{a}_{\rm in}\hat{a}^+_{\rm in}\hat{a}^+_{\rm in}\rangle - \langle \hat{a}_{\rm in}\hat{a}^+_{\rm in}\rangle^2] \\ &\quad + \eta\sinh^2(\gamma)\langle \hat{a}_{\rm in}\hat{a}^+_{\rm in}\rangle. \qquad (6)\end{aligned}$$

We can see from Eqs. (4) to (6) that such a scheme can give out the antinormally ordered photodetection of input field $\hat{a}_{\rm in}$. Parameter $\eta\sinh^2(\gamma)$ in the above equation is determined by the gain of parametric down-conversion and the optical loss of detection process, and can be obtained from Eq. (4) directly when the input field is a vacuum field. For the vacuum input field, $\langle 0|\hat{a}_{\rm in}\hat{a}^+_{\rm in}|0\rangle = 1$, the mean photon number obtained from Eq. (4) is $\langle n_d\rangle_0 = \eta\sinh^2(\gamma)$. It corresponds to the measured mean photon number of the spontaneous parametric down conversion. From Eqs. (4) and (5), the antinormally ordered first and second moments of the input field can be expressed as

$$\bar{n}^{(A)} \equiv \langle \hat{a}_{\rm in}\hat{a}^+_{\rm in}\rangle = \frac{\langle n_d\rangle}{\langle n_d\rangle_0}, \tag{7}$$

and

$$\begin{aligned}\overline{n^{2(A)}} &\equiv \langle \hat{a}_{\rm in}\hat{a}^+_{\rm in}\hat{a}_{\rm in}\hat{a}^+_{\rm in}\rangle \\ &= \frac{\langle n^2_d\rangle}{\langle n_d\rangle^2_0} - \frac{\langle n_d\rangle}{\langle n_d\rangle_0}\left[1+\frac{1}{\langle n_d\rangle_0}\right]. \qquad (8)\end{aligned}$$

And therefore, the dot box in Fig. 1 can be considered as a stimulated emission-based detector.

We can investigate some useful values of antinormally ordered operators for the input field by using this stimulated emission-based detector. Here we examine the antinormally ordered HBT correlation function $g^{(2{\rm A})}$ and the antinormally ordered Fano factor $F^{({\rm A})}$ for the input field $\hat{a}_{\rm in}$.

The antinormally ordered HBT correlation function and the Fano factor are defined as

$$g^{(2{\rm A})}(0) \equiv \frac{\langle \hat{a}\hat{a}\hat{a}^+\hat{a}^+\rangle}{\langle \hat{a}\hat{a}^+\rangle^2}, \tag{9}$$

and

$$F^{({\rm A})} \equiv \frac{\varDelta^{2({\rm A})}}{\bar{n}^{({\rm A})}}, \tag{10}$$

where $\varDelta^{2({\rm A})} = \overline{n^{2({\rm A})}} - \langle \hat{a}\hat{a}^+\rangle^2$ is the antinormally ordered variance of the field. Applying Eq. (4) to Eq. (8), we can easily write the antinormally ordered correlation function (9) as

$$g^{(2{\rm A})}(0) = \frac{\varDelta^2(n_d) - \langle n_d\rangle}{\langle n_d\rangle^2} + 1. \tag{11}$$

Equation (11) shows that the measurement of antinormally ordered correlation function for the input field may be realized by the stimulated emission-based detector, regardless of measurement efficiency η.

The antinormally ordered Fano factor for the input field can also be obtained by combining Eq. (10) with Eqs. (4) and (6) to be

$$F^{(\mathrm{A})}=\frac{\Delta^2(n_d)-\langle n_d\rangle}{\langle n_d\rangle_0\langle n_d\rangle}-1. \tag{12}$$

Equation (12) shows that the measured antinormally ordered Fano factor is dependent on the optical parametric process and optical loss, which is included in $\langle n_d\rangle_0$.

The coherent field is one of the most important fields in quantum optics,[15] and it is usually used as a boundary one to discriminate the nonclassical states from classical ones in normally ordered photodetection process.[16] We can obtain the antinormally ordered HBT correlation function and Fano factor scaled by the mean photon number for a coherent field from Eq. (4) to Eq. (12). They are plotted in Fig. 2 together with the normally ordered ones.

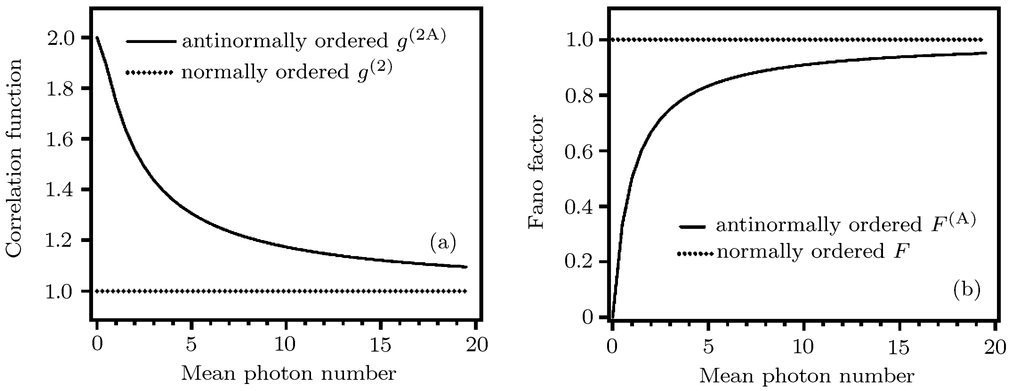

Fig. 2. Correlation function and Fano factor versus mean photon number for antinormally and normally ordered correlation function (a) and Fano factor (b) for a coherent field.

It is shown obviously in Fig. 2 that the antinormally ordered photon detection process is very different from the normally ordered one. Both the correlation function and Fano factor for a coherent field with antinormal order are not constant but dependent on mean photon number, which may provide more information about the field than the normally ordered one. In condition of antinormal order, the correlation function shows strong 'bunching' effect for the coherent fields, especially in small photon number regions; while the Fano factor shows strong 'anti-bunching' effect in small photon number regions. All of these phenomena are different from the normally ordered ones. Figure 2 also shows that the difference between the antinormally ordered values and the normally ordered ones is trivial when the mean photon number of the coherent field is large enough, which means that the stimulated emission-based detector is more powerful when the intensity of the field is weak.

For the experimental studying of the antinormally ordered $g^{(2\mathrm{A})}$ and $F^{(\mathrm{A})}$, the following aspects must be considered. Firstly, in order to measure the mean photon number and the variance of the fields, we can use the conventional detector to measure the photocounting statistical distribution of the input field in the case where the detection time for the photocounting statistics is smaller than the coherence time of the field, because the photocounting statistical distribution is the same as the photon number statistical distribution for a field in such a circumstance.[17] So it is required that the coherence time of the fields in front of the conventional detector should be as long as possible compared with the counting interval for the photocounting statistics. Secondly, a single photon detector usually acts as this conventional detector to measure the photocounting statistics distribution, since the most commonly used single photon detector now can only verify the existence of photon and cannot discriminate the multi-photon cases, so it is required that the intensity of the field in front of the detector must be weak enough to make the multi-photon events at the same time negligible in the counting interval for the photocounting statistics.[18] In fact, under the situation of parametric deamplification, the optical parametric amplifier operating in continuous wave (for example, load the nonlinear crystal in Fig. 1 into a cavity) can satisfy both conditions above, we will examine the theoretical results in the future experiments.

In conclusion, we propose a scheme to realize a stimulated emission-based detector by using a stimulated parametric down-conversion process and a conventional detector. Such a detector can be used to examine the antinormally ordered properties of the fields, such as the antinormally order HBT correlation function and Fano factor. Furthermore, we also theoretically investigate the antinormally ordered HBT correlation function and Fano factor for a coherent field. The results show that the antinormally ordered values of these two parameters are different from the normally ordered ones, since they are not constant but dependent on the intensity of the coherent field, especially in small photon number regions. Finally, the experimental possibility of our theoretical scheme is examined. Since the antinormally ordered values for a field can be measured according to this scheme, our results provide a convenient way to investigate the quantum systems where zero-point fluctuations are important.

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