16 August 1999

ELSEVIER

Physics Letters A 259 (1999) 171–177

PHYSICS LETTERS A

www.elsevier.nl/locate/physleta

Quantum variances and squeezing of output field from NOPA

Yun Zhang, Hong Su, Changde Xie, Kunchi Peng [1]

Institute of Opto-electronics Shanxi University, Taiyuan 030006, PR China

Received 22 January 1999; received in revised form 14 May 1999; accepted 28 June 1999

Abstract

The quadrature phase squeezing of coupled-mode and intensity difference squeezing between signal and idler mode of output field from continuous nondegenerate optical parametric amplifier (NOPA) are theoretically analyzed and compared. The calculation results provide design references for nonclassical light generation system.

PACS: 42.50; 42.65

1. Introduction

Over the past twenty years the properties of nonclassical states of light with squeezed quantum fluctuations have been extensively studied, both theoretically and experimentally [1]. The continuous optical parametric oscillator (OPO) without injected subharmonic signal and amplifier (OPA) with injected signal are important schemes to generate squeezed states of light. The degenerate optical parametric oscillator (DOPO) and optical parametric amplifier (DOPA) have been successfully used to produce quadrature squeezed light of single-mode [2–4]. The two-mode quadrature squeezed vacuum state of light and the quantum correlated twin beams with squeezed intensity difference fluctuation have been generated from continuous Nondegenerate optical parametric oscillators (NOPO) respectively operated below and above the oscillation threshold [5–7,10]. Recently, the interests of study on the nonclassical states of light concentrate on improving optical measurement sensitivity to beat the the vacuum fluctuation of the electromagnetic field. The quadrature squeezed vacuum state of light has been employed for improvements in measurement precision beyond SQL in Mach–Zehnder [11] and polarization interferometery [12], the detection of directly encoded amplitude modulation [13], spectroscopic measurements of atomic cesium [14]. The intensity difference squeezed twin beams have been used in sub-shot-noise optical measurements such as small signal recovery [15], measurements of transmissivity [16], amplitude modulated signal [17] and weak absorption [18] and two-photon absorption spectroscopy [19]. To practical applications the stability and reliability of nonclassical light generation systems are of great importance. By injecting a seed wave into a type I DOPA, Mlynek's group in Konstanz [3] obtained continuous-wave bright quadrature squeezed state of light with excellent long-term stability over several hours. Later, a series of advanced quantum measurement experiments were accomplished on this DOPA sys-

[1] E-mail: kcpeng@mail.sxu.edu.cn

0375-9601/99/$ - see front matter
PII: S0375-9601(99)00430-2

tem [4,20,21]. It has been well demonstrated that long-term stability of OPA is much better than OPO. On the other hand, the frequency of output wave from OPA can been locked on the frequency of injected signal, so that the investigation on OPA can provide useful information to develop the tunable OPA, that is one of the most hopeful tunable coherent light sources. Therefore, it is necessary to study the quantum optical properties of output fields from OPA.

So far, to our knowledge there is no publication to discuss the quantum variances and squeezing of output fields from NOPA with type II crystal in detail. In this paper, the quantum variances and squeezing of output field from type-II continuous NOPA will be theoretically analyzed. The dependences of quadrature phase squeezing of output coupled mode and intensity difference squeezing between output twin beams on the amplitude of pump field and injected signal field will be numerically calculated. The generation condition of quadrature phase and amplitude squeezed state light from NOPA will been discussed. The decay rates due to the input-output coupler and extra cavity losses have been included in the motion equations. The calculated results provide the useful references for design of practical NOPA.

2. The model

The NOPA device, which is pumped by harmonic wave of frequency 2ω and injected by two subharmonic waves with degenerate frequency ($\omega_1 = \omega_2 = \omega$) but orthogonal polarization is shown in Fig. 1.

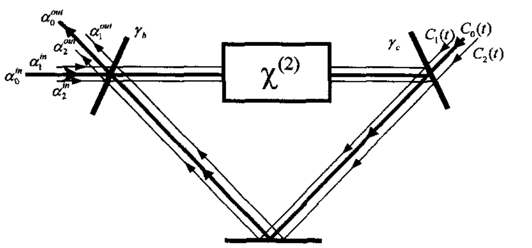

Fig. 1. Scheme of an Optical Parametric Amplifier. α_0^{in}, α_1^{in} and α_2^{in} are the incoming pump, signal and idler fields. γ_b and γ_c are the contributions to cavity damping from the input-output coupling and losses, respectively.

The harmonic and two subharmonic modes in the cavity are described by α_0, α_1 and α_2. We suppose that there are completely identical losses for α_1 and α_2 in the system and denote γ_b the decay rate of amplitude subharmonic modes due to transmission of the input-output coupler and γ_c due to all other cavity losses, respectively. The total loss rate for each of these modes is thus $\gamma = \gamma_b + \gamma_c$. The transmission of input-output coupler and extra losses for the pump mode α_0 are taken to be γ_{0b} and γ_{0c}, so that the total loss rate for the pump mode is $\gamma_0 = \gamma_{0b} + \gamma_{0c}$. Assuming zero detuning of the cavity, the equations of motion for the intracavity modes with the rotating wave approximation are as follows [7]:

$$\dot{\alpha}_0 = -\gamma_0 \alpha_0 - \kappa \alpha_1 \alpha_2 + \varepsilon + \sqrt{2\gamma_{0c}}\, c_0(t), \tag{1a}$$

$$\dot{\alpha}_1 = -(\gamma_b + \gamma_c)\alpha_1 + \kappa \alpha_0 \alpha_2^* + \sqrt{2\gamma_b}\, \alpha_1^{\text{in}} + \sqrt{2\gamma_c}\, c_1(t), \tag{1b}$$

$$\dot{\alpha}_2 = -(\gamma_b + \gamma_c)\alpha_2 + \kappa \alpha_0 \alpha_1^* + \sqrt{2\gamma_b}\, \alpha_2^{\text{in}} + \sqrt{2\gamma_c}\, c_2(t), \tag{1c}$$

where, κ is the nonlinear coupling parameter, $\varepsilon = \sqrt{2\gamma_{0b}}\, \alpha_0^{\text{in}}$ is the coherent field driving pump mode, α_i^{in} and $c_i(t)$ are the incoming fields, associated with the coupling mirror and with the extra loss respectively. In Eqs. (1), we have assumed that the pump and both signal and idler beams triply resonate in a cavity. At first, by choosing a proper phase we made α_0, α_1, α_2 to be real and taking $d\alpha_i/dt = 0$, the steady state equations are obtained:

$$0 = -\gamma_0 \alpha_0 - \kappa \alpha_1 \alpha_2 + \varepsilon, \tag{2a}$$

$$0 = -\gamma \alpha_1 + \kappa \alpha_0 \alpha_2^* + \sqrt{2\gamma_b}\, \beta, \tag{2b}$$

$$0 = -\gamma \alpha_2 + \kappa \alpha_0 \alpha_1^* + \sqrt{2\gamma_b}\, \beta. \tag{2c}$$

Here we have assumed that $\alpha_1^{\text{in}} = \beta + b_1(t)$, and $\alpha_2^{\text{in}} = \beta + b_2(t)$ have the same non-zero mean value β, but different fluctuations ($b_1(t) \neq b_2(t)$) and $c_i(t)$ have zero mean value, i.e. the vacuum fluctuation.

Let $r = \alpha_1 = \alpha_2$, the solution of Eqs. (2) is given:

$$\alpha_0 = \frac{\varepsilon - \kappa r^2}{\gamma_0} = \frac{\gamma}{\kappa} - \frac{\sqrt{2\gamma_b}\,\beta}{\kappa r},$$

$$0 = r^3 - \frac{\kappa\varepsilon - \gamma\gamma_0}{\kappa^2} r - \frac{\gamma_0\sqrt{2\gamma_b}\,\beta}{\kappa^2}. \quad (3)$$

In the case of $\beta = 0$, we get the parametric oscillation threshold of the cavity $\varepsilon^{\text{th}} = \gamma_0\gamma/\kappa$ from Eq. (3) and the equations go back to the expressions of NOPO.

In the case of non-zero subharmonic input ($\beta \neq 0$), Eq. (3) is a cubic equation. Its solution and the classical behavior of the system given from the solution have been discussed by Harrison et al. [8] and Schiller et al. [9] in detail. The addition of a non-zero coherent input β destroys the symmetry of the standard parametric oscillator, in which the steady-state solution is undergoes a pitchfork bifurcation when the pumping reaches the threshold. There are two boundary values of pump power in this system, corresponding to positive and negative pumping respectively, if pump power beyond the boundaries the bistability appears (see Refs. [8,9])

When pump field and injected wave are not in phase the equations (1) of motion can be solved numerically. Fig. 2 gives the intracavity amplitude r as functions of the relative phase. It is clearly that the intracavity amplitude has the maximum value when $\varphi = 2n\pi$, ($n = 0,1,2,\dots$), (the down-conversion phase match condition is satisfied) and reaches the minimum value when $\varphi = (2n+1)\pi$, ($n = 0,1,2,\dots$) (the phase matching condition is broken).

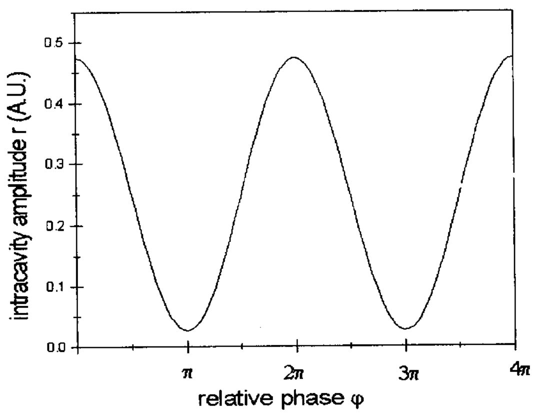

Fig. 2. Steady-state solution of the intracavity amplitude r as function of the relative phase of pump and injected signal wave. $\gamma_0\gamma/\kappa^2 = 1, \varepsilon/\varepsilon^{\text{th}} = 0.9, \sqrt{2\gamma_b}\,\beta/\varepsilon^{\text{th}} = 0.1$.

In order to calculate the variances and squeezing of the quantum fluctuations of the system, we use a semiclassical input-output formalism. More obviously, defining fluctuation operators $a_i = \alpha_i + \delta\alpha_i$, and linearizing Eqs. (1), we obtain the fluctuation dynamic equations [7]

$$\delta\dot{\alpha}_0(t) = -\gamma_0\delta\alpha_0(t) - \kappa r[\delta\alpha_1(t) + \delta\alpha_2(t)] + \sqrt{2\gamma_{0b}}\,b_0(t) + \sqrt{2\gamma_{0c}}\,c_0(t), \quad (4a)$$

$$\delta\dot{\alpha}_1(t) = -\gamma\delta\alpha_1(t) + \kappa[\alpha_0\delta\alpha_2^*(t) + r\delta\alpha_0(t)] + \sqrt{2\gamma_b}\,b_1(t) + \sqrt{2\gamma_c}\,c_1(t), \quad (4b)$$

$$\delta\dot{\alpha}_2(t) = -\gamma\delta\alpha_2(t) + \kappa[\alpha_0\delta\alpha_1^*(t) + r\delta\alpha_0(t)] + \sqrt{2\gamma_b}\,b_2(t) + \sqrt{2\gamma_c}\,c_2(t). \quad (4c)$$

3. The variances of output field from NOPA

3.1. Variances of quadrature components of output coupled-mode

The coupled mode is defined as

$$d_1 = \frac{1}{\sqrt{2}}(a_1 + a_2), \quad d_1^+ = \frac{1}{\sqrt{2}}(a_1^+ + a_2^+), \quad (5)$$

and its two quadrature components are

$$X_+ = \frac{1}{2\sqrt{2}}(a_1 + a_2 + a_1^+ + a_2^+),$$

$$X_- = \frac{1}{2\sqrt{2}\,i}(a_1 + a_2 - a_1^+ - a_2^+). \quad (6)$$

Assuming that the mean fields are real, we can interpret X_+ and X_- quantities as amplitude and phase components, respectively. The fluctuations of the two components are

$$\delta X_+(t) = \frac{1}{2\sqrt{2}}[\delta a_1(t) + \delta a_2(t) + \delta a_1^+(t) + \delta a_2^+(t)], \quad (7a)$$

$$\delta X_-(t) = \frac{1}{2\sqrt{2}\,i}[\delta a_1(t) + \delta a_2(t) - \delta a_1^+(t) - \delta a_2^+(t)], \quad (7b)$$

and the fluctuation equation of motion become

$$\delta \dot{X}_{\pm}(t) = -(\gamma \mp \kappa\alpha_0)\delta X_{\pm}(t) + \sqrt{2}\,\kappa r \delta X^0_{\pm}(t) + \sqrt{2\gamma_b}\,\delta X^b_{\pm}(t) + \sqrt{2\gamma_c}\,\delta X^c_{\pm}(t), \quad (8)$$

where $\delta X^0_+ = \frac{1}{2}(\delta\alpha_0 + \delta\alpha_0^+)$ and $\delta X^0_- = \frac{1}{2i}(\delta\alpha_0 - \delta\alpha_0^+)$ denote the two quadrature fluctuations resulting from pump noise, $\delta X^b_{\pm}$ and $\delta X^c_{\pm}$ are connected to the fluctuation of input subharmonic and extra losses of the cavity respectively.

Taking the Fourier transform of Eq. (8), we get

$$\delta X_+(\omega) = \frac{1}{(\gamma - \kappa\alpha_0) + i\omega}\left[\sqrt{2}\,\kappa r \delta X^0_+(\omega) + \sqrt{2\gamma_b}\,\delta X^b_+(\omega) + \sqrt{2\gamma_c}\,\delta X^c_+(\omega)\right], \quad (9a)$$

$$\delta X_-(\omega) = \frac{1}{(\gamma + \kappa\alpha_0) + i\omega}\left[\sqrt{2}\,\kappa r \delta X^0_-(\omega) + \sqrt{2\gamma_b}\,\delta X^b_-(\omega) + \sqrt{2\gamma_c}\,\delta X^c_-(\omega)\right]. \quad (9b)$$

Using the boundary condition at the output coupling mirror $\alpha^{\text{out}}(\omega) = \sqrt{2\gamma_b}\,\alpha(\omega) - \alpha^{\text{in}}(\omega)$, we obtain the output fluctuation in term of the input fluctuation. The quadrature components of output fluctuations are:

$$\delta X^{\text{out}}_+(\omega) = \frac{\sqrt{2\gamma_b}}{(\gamma - \kappa\alpha_0) + i\omega}\left[\sqrt{2}\,\kappa r \delta X^0_+(\omega) + \sqrt{2\gamma_c}\,\delta X^c_+(\omega)\right] + \frac{(\gamma_b - \gamma_c + \kappa\alpha_0) - i\omega}{(\gamma - \kappa\alpha_0) + i\omega}\delta X^b_+(\omega), \quad (10a)$$

$$\delta X^{\text{out}}_-(\omega) = \frac{\sqrt{2\gamma_b}}{(\gamma + \kappa\alpha_0) + i\omega}\left[\sqrt{2}\,\kappa r \delta X^0_-(\omega) + \sqrt{2\gamma_c}\,\delta X^c_-(\omega)\right] + \frac{(\gamma_b - \gamma_c - \kappa\alpha_0) - i\omega}{(\gamma + \kappa\alpha_0) - i\omega}\delta X^b_-(\omega). \quad (10b)$$

Assuming that the fluctuation of input waves and noise of extra losses are uncorrelated, we have

$$\text{Var}(\delta X^0_{\pm},\omega) = \text{Var}(\delta X^b_{\pm},\omega) = \text{Var}(\delta X^c_{\pm},\omega) = 1. \quad (11)$$

From Eqs. (10), we calculate the output variances:

$$\text{Var}(\delta X^{\text{out}}_+,\omega) = \frac{4\gamma_b\gamma_c}{(\gamma - \kappa\alpha_0)^2 + \omega^2} + \frac{4\gamma_b\kappa^2 r^2}{(\gamma - \kappa\alpha_0)^2 + \omega^2} + \frac{(\gamma_b - \gamma_c + \kappa\alpha_0)^2 + \omega^2}{(\gamma - \kappa\alpha_0)^2 + \omega^2}, \quad (12a)$$

$$\text{Var}(\delta X^{\text{out}}_-,\omega) = \frac{4\gamma_b\gamma_c}{(\gamma + \kappa\alpha_0)^2 + \omega^2} + \frac{4\gamma_b\kappa^2 r^2}{(\gamma + \kappa\alpha_0)^2 + \omega^2} + \frac{(\gamma_b - \gamma_c - \kappa\alpha_0)^2 + \omega^2}{(\gamma + \kappa\alpha_0)^2 + \omega^2}. \quad (12b)$$

If the output variance is less than 1, we say that it is squeezed.

For the other coupled mode $d_2 = 1/\sqrt{2}(a_1 - a_2)$ in the perpendicular polarization with respect to d_1 the same analyses and similar conclusions can be performed and obtained. While the system can be regarded as a NOPA with injected vacuum in orthogonal polarization with above mentioned injected signal. The fluctuation properties of output field are identical with d_1, the only difference is that it has zero mean intensity, i.e., it is a squeezed vacuum. Therefore, we can conclude that the system can generate bright and vacuum squeezing on two different polarisations.

3.2. Variance of intensity difference between output quantum correlated twin beams

The fluctuation of the intensity difference of the signal and idler modes is

$$D(t) = \delta(I_1 - I_2) = \delta(a_1^+ a_1 - a_2^+ a_2) = r\left[\delta a_1(t) + \delta a_1^+(t) - \delta a_2(t) - \delta a_2^+(t)\right], \quad (13)$$

and the equation of motion is

$$\dot{D}(t) = -\gamma D(t) - \kappa\alpha_0 D(t) + \sqrt{2\gamma_b}\, D^b(t) + \sqrt{2\gamma_c}\, D^c(t). \qquad (14)$$

The important point to notice is that the pump fluctuations were cancelled in the intensity difference fluctuation. Solving Eq. (14) fluctuation of output intensity difference in frequency domain is obtained:

$$D^{\text{out}}(\omega) = \frac{\sqrt{2\gamma_b}\sqrt{2\gamma_c}}{(\gamma+\kappa\alpha_0)+i\omega} D^c(\omega) + \frac{(\gamma_b-\gamma_c-\kappa\alpha_0)-i\omega}{(\gamma+\kappa\alpha_0)+i\omega} D^b(\omega). \qquad (15)$$

Using the same process as above-mentioned, the output variance is straight-forwardly calculated

$$\operatorname{Var}(D^{\text{out}},\omega) = \frac{4\gamma_b\gamma_c}{(\gamma+\kappa\alpha_0)^2+\omega^2} + \frac{(\gamma_b-\gamma_c-\kappa\alpha_0)^2+\omega^2}{(\gamma+\kappa\alpha_0)^2+\omega^2}. \qquad (16)$$

4. The noise squeezing of output field from NOPA

In Fig. 3 and Fig. 4 the dependences of output variances on the input pump and injected subharmonic amplitudes are presented. The parameters $\xi = \gamma_b/(\gamma_b+\gamma_c)$, $x = \varepsilon/\varepsilon^{\text{th}}$, and $\eta = \beta/\varepsilon^{\text{th}}$ in the figures denote the input-output coupling efficiency, normalized pump power and injected power of signal, respectively. The best squeezing is obtained at the limit $\omega \to 0$. Fig. 3 gives the variances of squeezed quadrature component ($\operatorname{Var}(\delta X_-^{\text{out}},\omega)$) and intensity difference of output field as the functions of pump power, where $\xi = 0.9$, $\eta = 0.1$. Both variances reach the minima at the pump power of a little below the threshold. In the situation of OPO and NOPO the minima is at the oscillation threshold ($\varepsilon = \varepsilon^{\text{th}}$) [7], however with an injected signal the minima moves towards lower power. Above the threshold, the two-mode quadrature variance increases, but the intensity difference variance keeps constant, that is similar to the calculation based on NOPO[7]. Fig. 4 shows the

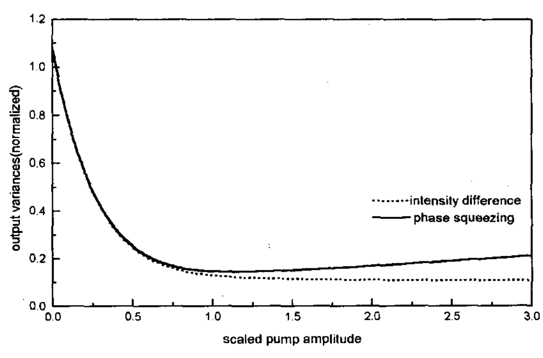

Fig. 3. Variances as functions of the normalized pump amplitude $|\varepsilon|/\varepsilon^{\text{th}}, \beta/\varepsilon^{\text{th}} = 0.1$, $\xi = 0.9$ Solid line: two-mode squeezing. Dotted line: intensity difference.

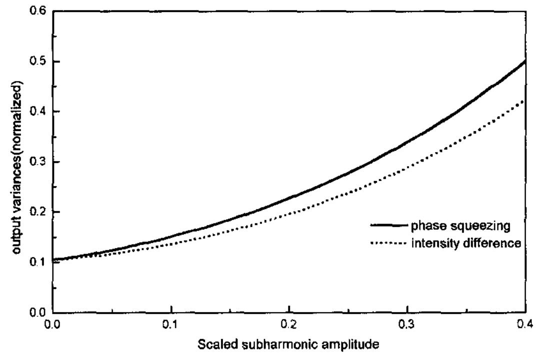

Fig. 4. Variances as functions of the normalized subharmonic amplitude $\beta/\varepsilon^{\text{th}}$, $|\varepsilon|/\varepsilon^{\text{th}} = 0.9$, $\xi = 0.9$. Solid line: two-mode squeezing. Dotted line: intensity difference.

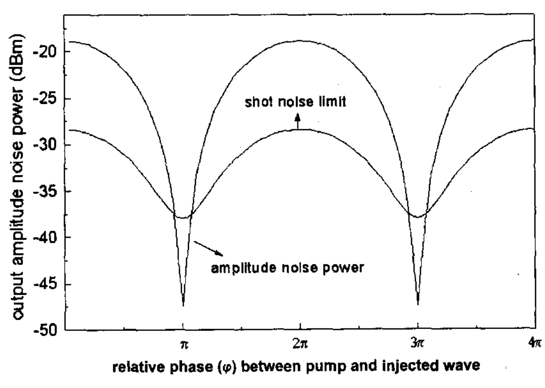

Fig. 5. Output amplitude noise power as functions of the relative phase between pump and injected wave. $\beta/\varepsilon^{\text{th}} = 0.1, |\varepsilon|/\varepsilon^{\text{th}} = 0.9$, $\xi = 0.9$.

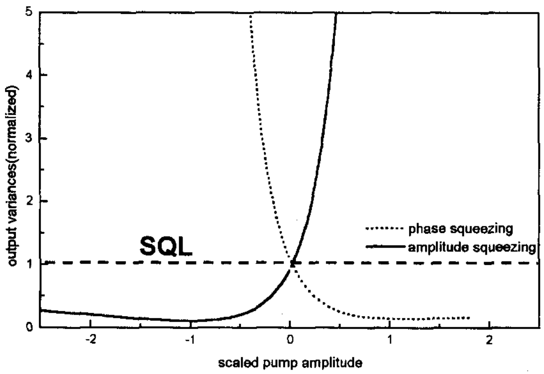

Fig. 6. Output variances as functions of the scaled pump amplitude $\varepsilon/\varepsilon^{th}, \beta/\varepsilon^{th} = 0.1$, $\xi = 0.9$ Solid line: phase component. Dotted line: amplitude component. SQL: normalized standard quantum limit.

variances of output fields as the functions of input subharmonic amplitude. It is clear that the two variances increase along with the input subharmonic amplitude since the more extra noise is brought in the cavity by the injected signal og coherent state. From Fig. 3 and Fig. 4, we can see that the two-mode quadrature variance is always larger than the intensity difference variance. The physical origin of this fact is that the influence of pump noise on the intensity difference fluctuation has been eliminated. Fig. 5 shows the amplitude squeezing as functions of relative phase φ between pump and injected wave. The lowest amplitude noise is obtained at the out-of-phase points that is in agreement with the experimental result present by K.Schneider et al. [3]. Fig. 6 shows the variances of output phase-component and amplitude-component as the function of pump amplitude, here negative power means out of phase. At the case of out-of phase the injected subharmonic mode is deamplified and the variances of output amplitude component is squeezed below the normalized standard quantum limit. It is should be noticed that $\mathrm{Var}(\delta X_+^{out},0) \cdot \mathrm{Var}(\delta X_-^{out},0) > 1$ in the figure since the extra losses have been evaluated in our calculations, so the total noise of output field is higher than the SQL level.

5. Conclusion

In summary, we have investigated in detail the noise properties of the output light field generated by a non-degenerate parametric amplifier. The most important results are as follows:

1. The output fields have both properties of two-mode quadrature squeezing and intensity difference squeezing.
2. The two-mode quadrature squeezing is sensitive not only to the pump noise and pump power, but also the power of injected signal. The intensity difference squeezing is insensitive relative to the pump noise and pump power when the OPA is operating above the threshold. Below threshold the squeezing of the two types decreases along with the reduction of pump amplitude.
3. It is possible to generate the two-mode bright phase or amplitude squeezing using NOPA. The quadrature squeezing and intensity difference squeezing of output field from a NOPA are calculated and compared in both cases of above and below the oscillation threshold. Due to that the pump noise, injected signal and extra noise have been included in the calculation, the calculated results can provide the useful references for design of NOPA which will be employed to produce stable nonclassical lights.
4. The behavior of NOPA system at any relative phase between pump field and injected signal has been also discussed.

Acknowledgements

This work is supported by National Natural Science Foundation of China (No. 69837010), the Natural and Youth Science Foundation of Shanxi province (No. 981003). One of the authors (Y.Z.) wishes to acknowledge Prof. Hai Wang, Qing Pan and Tiancai Zhang for very helpful discussions.

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