The high squeezing and entanglement in regular loss modulated optical parametric amplifier*

Zhao Chao-Ying(赵超樱)[a)b)†] and Tan Wei-Han(谭维翰)[c)]

[a)] College of Science, Hangzhou Dianzi University, Hangzhou 310018, China
[b)] State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, China
[c)] Department of Physics, Shanghai University, Shanghai 200444, China

(Received 7 April 2010; revised manuscript received 18 May 2010)

We investigate the quantum fluctuation characteristic for time dependent regular loss modulated optical parametric amplifier for below and above threshold regions. It is found that a high squeezing and entanglement can be achieved.

Keywords: regular loss modulated, squeezing, entanglement
PACC: 0367, 4250, 4265K

1. Introduction

Up to now, the interest in continuous variable (CV) entanglement is being excited by successful experiments on quantum teleportation[1,2] as well as most applications in the field of quantum information. Numerous theoretical and experimental researches have been published.[3−6] Up to now, bright light beams with high CV entanglement, due to uncontrolled dissipation and de-coherence, cavity induced feedback and phase diffusion, still difficult to achieve. Most important is that we cannot expect to maintain a high squeezing for a long time with constant pump. This squeezing required necessary for these types of applications still poses a challenge. Recently, a systematic perturbation theorem has been developed to study the quantum property of the time-modulated non-degenerate optical parametric amplifier (NOPA) for below and above threshold regions.[5−9] In previous paper,[10−15] we have solved the time-dependent Fokker–Planck equation for degenerate optical parametric amplifier (DOPA), and a transient high squeezing can be achieved. In this study, we show that a transient high squeezing and entanglement can be achieved by regular loss modulation.

2. The time-dependent regular loss modulated NOPA

The total Hamiltonian for NOPA is given by[16,17]

$$\begin{aligned} H &= H_0 + V + W, \\ H_0 &= \hbar\omega_0 a_0^\dagger a_0 + \hbar\omega_1 a_1^\dagger a_1 + \hbar\omega_2 a_2^\dagger a_2 \\ &\quad + \mathrm{i}\hbar(E\mathrm{e}^{-\mathrm{i}\omega_L t}a_0^\dagger - E^*\mathrm{e}^{\mathrm{i}\omega_L t}a_0) \\ &\quad + \sum_{j,i=1,2} \hbar\omega_j B_{ji}^\dagger B_{ji}, \\ V &= \hbar\sum k_j(B_{j1}a_1^\dagger + B_{j2}a_2^\dagger) \\ &\quad + \hbar\sum k_j^*(B_{j1}^\dagger a_1 + B_{j2}^\dagger a_2), \\ W &= \frac{\mathrm{i}\hbar}{2}(2\varepsilon a_1^\dagger a_2^\dagger - 2\varepsilon^* a_1 a_2). \end{aligned} \tag{1}$$

Applying the acousto–optic interactions in the deflection of optical beams,[18] the regular loss is introduced by Bragg diffraction of a portion of the laser intensity by a standing acoustic wave. The schematic diagram of an optical parametric oscillator with the regular loss acousto–optic element is shown in Fig. 1.

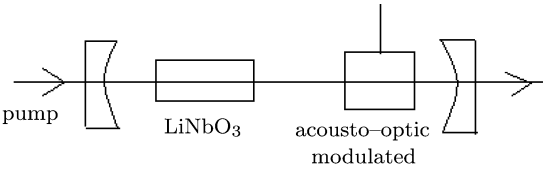


Fig. 1. Sketch of regular loss modulated optical parametric oscillator.

*Project supported by the State Key Laboratory of Quantum Optics and Quantum Optics Devices, Shanxi University, Shanxi, China (Grant No. 200904).
†Corresponding author. E-mail: zchy49@sohu.com
© 2010 Chinese Physical Society and IOP Publishing Ltd

Due to the parametric interaction in the nonlinear medium, these operators are coupled and obey the following equations[10]

$$\begin{aligned}
\frac{\mathrm{d}\alpha_1}{\mathrm{d}\tau} &= -(1+b\sin[\omega\tau])\alpha_1 + \frac{\chi}{\gamma_1}\alpha_0\alpha_1^*, \\
\frac{\mathrm{d}\alpha_2}{\mathrm{d}\tau} &= -(1+b\sin[\omega\tau])\alpha_2 - \frac{\chi}{\gamma_1}\alpha_0\alpha_2^*, \\
\frac{\mathrm{d}\alpha_0}{\mathrm{d}\tau} &= -(1+b\sin[\omega\tau])\gamma_r\alpha_0 \\
&\quad + \frac{\bar{\varepsilon}}{\gamma_1} - \frac{\chi}{2\gamma_1}(\alpha_1^2 - \alpha_2^2),
\end{aligned} \tag{2}$$

where time $\tau = kt = \gamma_1 t$, the switching function $(1+b\sin(\omega\tau))$ describes the regular loss modulation. χ is the coupling constant, γ_0, γ_1 are the damping rates, and decay ratio $\gamma_r = \gamma_0/\gamma_1$, $\bar{\varepsilon}$ is the amplitude of external coherent field. $\bar{\varepsilon}/\gamma_1 = \mu\sqrt{\gamma_r/2\eta}$, μ is pump parameter, and $\eta = \chi^2/2\gamma_1\gamma_0$.

In the following, the quantum fluctuation characters are shown numerically in Figs. 2 and 3. We take $\eta = 1/1000$, $\gamma_r = 0.5$, $b = 1$, $\omega = \pi/4$, $\tau_0 = 9$. $\mu = 0.5$ for below threshold (a), $\mu = 1$ for at threshold (b), $\mu = 2$ for above threshold (c), $\mu = 4$ for far above threshold (d).

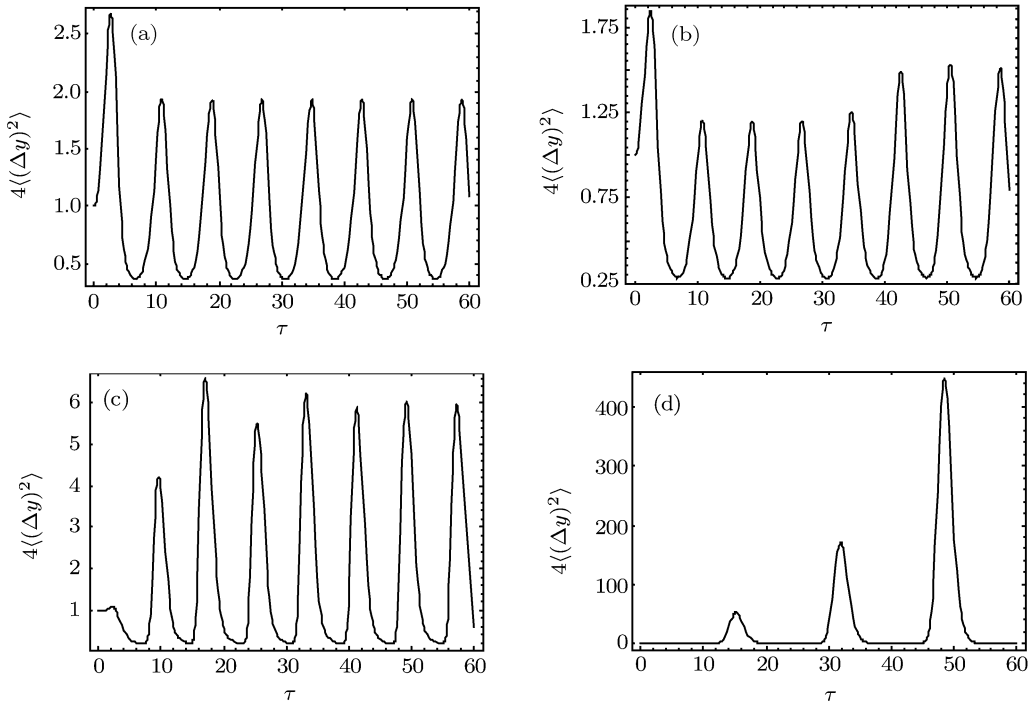
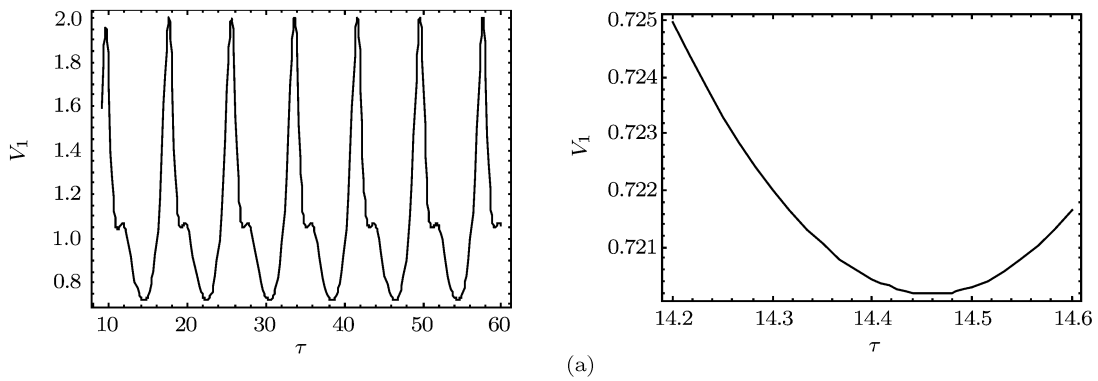


Fig. 2. Squeezing $4\langle(\Delta y)^2\rangle$ versus interaction time τ. (a) $\mu = 0.5$, (b) $\mu = 1$, (c) $\mu = 2$, (d) $\mu = 4$.



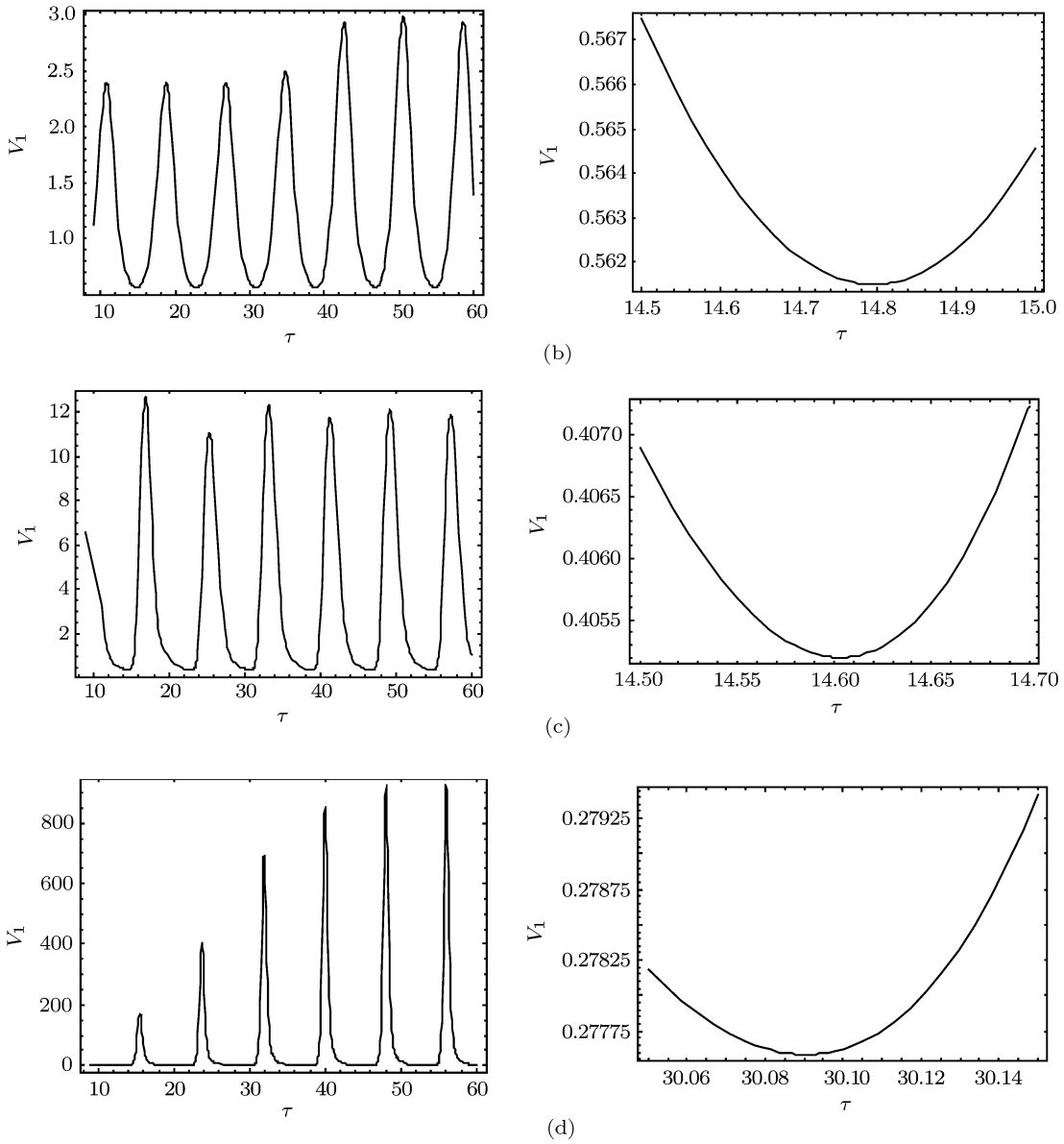


Fig. 3. Minimum variance V_1 as a function of time τ. (a) $\mu = 0.5$, (b) $\mu = 1$, (c) $\mu = 2$, (d) $\mu = 4$.

3. Squeezing character of the time dependent regular loss modulated DOPA

Squeezing of time-dependent regular loss modulated DOPA can be given by[13−15]

$$\left\langle (\Delta y_1)^2 \right\rangle = \frac{1}{4} + (\tilde{A}_1(\tau) - \tilde{A}_{10}\tilde{\alpha}_1^2(\tau)), \tag{3}$$

where

$$\tilde{A}_1(\tau) = \tilde{\alpha}_1^2(\tau)\left(\tilde{A}_{10} + \frac{1}{4}\right) - \frac{1}{4} + \frac{\tilde{\alpha}_1^2(\tau)k}{2} \int_{\tau-\tau_0}^{\tau} \tilde{\alpha}_1^{-2}(t)\mathrm{d}t.$$

The maximum value of $\gamma_1(1+b)$ is obtained when $\sin(\omega\tau) = 1$, which corresponds to a low squeezing, and meanwhile the minimum value of $\gamma_1(1-b)$ is achieved if we choose $\sin(\omega\tau) = -1$, which corresponds to a high squeezing. From below threshold to above threshold, the highest squeezing approaches to the linear theory $1/(1+\mu)$.

4. Entanglement character of the time dependent regular loss modulated NOPA

Entanglement of time dependent regular loss modulated NOPA can be calculated[19]

$$V_1 = \Delta^2 X_1 = \langle X_1^2 \rangle - \frac{\langle X_1 Y_2 \rangle^2}{\langle Y_2^2 \rangle}. \quad (4)$$

We investigate the effect of the pump μ in the system. It is found that the minimum variance V_1 decreases with the increasing of the pump μ, which approaches to the linear theory $1/(1+\mu)$.

5. Conclusions

In this study, we investigate quantum fluctuation characteristics of time dependent regular loss modulated NOPA for below and above threshold regions. The squeezing and entanglement depend on switching function $(1 + b\sin[\omega\tau])$ and pump μ. Both the maximum squeezing and entanglement can be described approximately by the linear theory $1/(1+\mu)$. Entanglement decreases linearly with the increasing of pump μ. It provides a method to achieve a high squeezing and entanglement.

References

[1] Braunstein S L and Kimble H J 1998 *Phys. Rev. Lett.* **80** 869
[2] Bowen W P, Treps N, Schnabel R and Lam P K 2002 *Phys. Rev. Lett.* **89** 253601
[3] Furusawa A, Sorensen J L, Braunstein S L, Fuchs C A, Kimble H J and Polzik E S 1998 *Science* **282** 706
[4] Li X Y, Pan Q, Jing J T, Zhang J, Xie C D and Peng K C 2002 *Phys. Rev. Lett.* **88** 047904
[5] Adamyan H H and Kryuchkyan G Yu 2004 *Phys. Rev.* A **69** 053814
[6] Adamyan H H and Kryuchkyan G Yu 2006 *Phys. Rev.* A **74** 023810
[7] Laurat J, Coudreau T and Fabre C 2005 *Opt. Lett.* **30** 1177
[8] Laurat J, Coudreau T, Keller G, Treps N and Fabre C 2004 *Phys. Rev.* A **70** 042315
[9] Laurat J, Coudreau T, Keller G, Treps N and Fabre C 2005 *Phys. Rev.* A **71** 022313
[10] Zhao C Y and Tan W H 2006 *J.Opt. Soc. Am.* B **23** 2174
[11] Reid M D and Drummond P D 1988 *Phys. Rev. Lett.* **60** 273
[12] Reid M D 1989 *Phys. Rev.* A **40** 913
[13] Zhao C Y, Tan W H and Guo Q Z 2003 *Acta. Phys. Sin.* **52** 2694 (in Chinese)
[14] Zhao C Y and Tan W H 2007 *J. Mod. Opt.* **54** 97
[15] Zhao C Y and Tan W H 2007 *Chin. Phys.* **16** 644
[16] Adamyan N H, Adamyan H H and Kryuchkyyan G Yu 2008 *Phys. Rev.* A **77** 023820
[17] Walls D F and Milburn G J 1994 *Quantum Optics* 2nd ed (New York: Springer)
[18] Yariv A 1989 *Quantum Electronics* 3rd ed (New York: Wiley)
[19] Zhao C Y and Tan W H 2009 *Chin. Phys.* B **18** 4143