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Y. B. Yu, J. T. Sheng, and M. Xiao

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The Generation of Bright Quadricolor Continuous-variable Entanglement by Four-wave Mixing Process

Y. B. Yu,[1,2,*] J. T. Sheng,[1] and M. Xiao[1,3,†]

[1] *Department of Physics, University of Arkansas, Fayetteville, Arkansas 72701, USA*

[2] *School of Science, Ningbo University of Technology, Ningbo 315211, China*

[3] *National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China*

Abstract

We propose an experimentally feasible scheme to produce bright quadricolor continuous-variable (CV) entanglement by a four-wave mixing process (FWM) with four-level atoms inside the optical ring cavities operating above the threshold. The Stokes and anti-Stokes beams are generated via the pump beam (tuned close to one atomic transition) and the coupling beam (tuned to the resonance of another atomic transition), respectively. The quadruply resonant and narrowed linewidth of the cavity fields with different frequencies are achieved and quadricolor CV entanglement among the four cavity fields is demonstrated according to the criterion proposed by van Loock and Furusawa (Phys. Rev. A 67, 052315 (2003)). This scheme provides a new way to generate bright quadricolor CV entanglement and will be significant for the applications in quantum information processing and quantum networks.

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* Email: ybyu@163.com

† Email: mxiao@uark.edu

The studies of quantum entanglement attract many interests in recent years since it is the central resource in the applications such as quantum communication and computation. Multipartite CV entangled beams with different frequencies are necessary to connect different physical systems at the nodes of quantum networks [1] since they can be separated easily in the applications [2]. It was predicted that two-color CV entanglement can be produced by nondegenerate optical parametric oscillator (OPO) [3], which has been experimentally demonstrated below [4] and above [5] the oscillation threshold. Then, Villar *et al* predicated that three-color CV entanglement can be generated using an OPO operating above the threshold [6], which has been verified by the recent experiment [2]. When one pump photon is annihilated, exactly two photons are created, i. e., when N pump photons are annihilated, 2N longer-wavelength photons are created. So the intensities of the three beams, i. e. pump, signal and idler, will be strongly correlated when the losses and uncertainties are minimized [7]. There are also many proposed schemes to produce multicolor CV entanglements, such as with cascaded nonlinearities inside an optical cavity [8–11] and vector FWM in a fiber [12] and so on.

Alternatively, entanglement can also be produced in coherent atomic systems which has attracted much attention since the entangled beams from atomic systems have narrowed linewidth and longer coherent time. Moreover, the wavelengths of the beams at about 800 nm allow them to be used directly in the quantum memory [13] and free-space (from a low-earth-orbit satellite to a ground station) quantum teleportation [14]. Balić *et al* reported that strong biphoton correlation can be produced by FWM process in a cold atomic assemble [15] which is similar to the entangled biphoton obtained by the process of spontaneous parametric down-conversion in nonlinear crystals. Duan *et al* proposed a scheme to use bipartite CV entanglement generated in atomic ensembles for long-distance quantum communication [16] which has been experimentally demonstrated by Kuzmich *et al* [17]. In addition, van der Wal *et al* experimentally demonstrated emission of two quantum-mechanically correlated light pulses produced by an ensemble of rubidium atoms [18] and Josse *et al* also experimentally verified that the bipartite CV entanglement can be generated by cold atoms in a high finesse optical cavity [19]. These bipartite CV entanglement are similar to the bipartite CV entanglement generated from an OPO below the threshold [4]. Wu and Xiao obtained bright nonclassical correlated anti-Stokes and Stokes beams with Doppler-broadened four-level atoms inside an above-threshold optical ring cavity[20], which is similar to the bright two-color CV entanglement produced by nondegenerate OPO operating above the threshold as in Ref. [5]. The Stokes and anti-Stokes beams are generated by the interaction among the pump/coupling beams and the multi-level atomic medium. When two photons (a pump photon and a coupling photon) are absorbed, two new photons (i.e., an anti-Stokes photon and a Stokes photon) are generated simultaneously. Therefore, the intensities of the pump, coupling, anti-Stokes, and Stokes beams will also be quantum correlated for energy conservation ($\omega_p + \omega_c = \omega_s + \omega_{as}$) [15], which likes the case in an OPO operating above threshold as in Ref. [2] and [6].

Based on the above analysis and the previous experimental demonstration of two-color quantum correlation [20], we propose a scheme in this paper to generate bright quadricolor CV entangled beams by adjusting the pump and coupling beams, as well as the generated anti-Stokes and Stokes beams, simultaneously on resonance in the optical cavities. We theoretically demonstrate entanglements among the four beams according to the inseparability criterion for multipartite CV entanglement proposed by van Loock and Furusawa [21]. Recently, triply-resonant OPO by FWM with rubidium vapor inside an optical cavity has been experimentally achieved [22]. So it is experimentally feasible to achieve a quadruply-resonant OPO and obtain quadricolor CV entangled beams by appropriately adjusting the previous experimental system used in Ref. [20].

The proposed experimental setup for this scheme is shown in Fig. 1(a). An ensemble of four-level ^{87}Rb atoms contained in a vapor cell is placed inside a three-mirror optical ring cavity (formed by mirrors M1, M2, and M3). The relevant energy level diagram for the ^{87}Rb atomic system is shown in Fig. 1(b). The pump beam P_p with frequency ω_p is tuned close to the atomic transition from $|1\rangle$ to $|4\rangle$, which generates the Stokes light a_s with frequency ω_s. The coupling beam P_c with frequency ω_c is tuned to the resonant atomic transition from $|2\rangle$ to $|3\rangle$, which generates the anti-Stokes light a_{as} with frequency ω_{as}. By adjusting the alignments and dispersions of the pump and coupling beams and the mirrors, one can achieve simultaneous resonances for the pump, coupling, anti-Stokes, and Stokes beams in the two ring cavities and obtain outputs from the mirrors M5 and M1, respectively. Initially, the pump and coupling beams have orthogonal polarizations with vertical and horizontal directions, respectively, which is different from the previous experiment [20]. The anti-Stokes and coupling beams have the same horizontal polarization in order to create efficient parallel channels for electromagnetically induced transparency

(EIT) [23]. The Stokes beam also has the horizontal polarization which is the same as in the previous experiment [20]. The beams of a_s, a_{as}, and a_c can directly pass through the PBSs (polarization beam splitter) and resonate in the ring cavity (formed by Mirrors M1, M2, and M3). Their output fields from M1 can be spatially separated due to the phase-matching angle in the nonlinear FWM process [15, 23]. The injecting pump beam a_p has vertical polarization and is reflected by the two PBSs, which can resonate in another ring cavity (formed by two PBSs and two mirrors M4 and M5) and the output is from the mirror M5. Then the bright quadricolor CV entanglement beams which spatially separate from each other can be produced in this simple setup. In order to measure the entanglement one can set four analysis cavities for the four output fields, which are the same as in the case of Ref. [5]. To produce anti-Stokes and stokes photons, a pump photon and a coupling photon must be annihilated. The sum of annihilated photon numbers in the pump and coupling beams must be equal to the sum of generated photon numbers in the anti-Stokes and Stokes beams due to the energy conservation $\omega_p + \omega_c = \omega_s + \omega_{as}$ when the losses and uncertainties are minimized. Therefore, the intensity anti-correlation is expected between the pump (or coupling) beam and the anti-Stokes (or Stokes) beam. From the frequency constraint translated into a constraint for the phase fluctuations of the four fields, one can see that the phase fluctuations between the anti-Stokes (or Stokes) beam and the pump (or coupling) beam should be correlated. Contrarily, the phase fluctuations between the anti-Stokes and Stokes beams or the pump and coupling beams should be anti-correlated. Then, from the multipartite CV entanglement criteria reported in Ref. [21], the satisfactions of these three inequalities

$$\begin{aligned} V_{p-c} &= \Delta^2\left(\frac{\hat{X}_p - \hat{X}_c}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{Y}_p + \hat{Y}_c}{\sqrt{2}} + g_s\hat{Y}_s + g_{as}\hat{Y}_{as}\right) < 1, \\ V_{c-s} &= \Delta^2\left(\frac{\hat{X}_c + \hat{X}_s}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{Y}_c - \hat{Y}_s}{\sqrt{2}} + g_p\hat{Y}_p + g_{as}\hat{Y}_{as}\right) < 1, \\ V_{s-as} &= \Delta^2\left(\frac{\hat{X}_a - \hat{X}_{as}}{\sqrt{2}}\right) + \Delta^2\left(\frac{\hat{Y}_s + \hat{Y}_{as}}{\sqrt{2}} + g_p\hat{Y}_p + g_c\hat{Y}_c\right) < 1, \end{aligned} \tag{1}$$

should be sufficient to verify the quadripartite entanglement. $\hat{X}_i = (\hat{a}_i^{out} + \hat{a}_i^{\dagger out})/2$ ($i = p, c, s, as$) represent the amplitude quadratures of the fields; $\hat{Y}_i = (\hat{a}_i^{out} - \hat{a}_i^{\dagger out})/2$ stand for their phase quadratures, $\hat{a}_i^{out}$ and $\hat{a}_i^{\dagger out}$ are the output fields for the four modes in cavities; g_i are the adjustable parameters chosen to minimize the left of the inequalities.

Here, the energy levels of ^{87}Rb atoms serve as the medium to produce nonlinear FWM process. In present study, we only focus on the entanglement characteristics among the four optical fields rather than that between atoms and optical fields. So the interaction Hamiltonian in this nondegenerate FWM process can be simply written by optical field operators as [16, 24]:

$$H_{int} = i\hbar\kappa\hat{a}_p\hat{a}_c\hat{a}_s^\dagger\hat{a}_{as}^\dagger + H.c. \ , \tag{2}$$

where κ is the dimensionless nonlinear coupling coefficient and is commonly taken to be a real number [4, 9]. Considering the driving fields in the cavity, the Hamiltonian for pump and coupling beams is given by

$$H_{ext} = i\hbar\epsilon_p\hat{a}_p^\dagger + i\hbar\epsilon_c\hat{a}_c^\dagger + H.c. \ , \tag{3}$$

where ϵ_i are the classical pump/coupling laser amplitudes. The loss of the ith mode in the cavity can be written as [25]:

$$L_i\hat{\rho} = \gamma_i(2\hat{a}_i\hat{\rho}\hat{a}_i^\dagger - \hat{a}_i^\dagger\hat{a}\hat{\rho} - \hat{\rho}\hat{a}_i^\dagger\hat{a}_i). \tag{4}$$

where γ_i stand for the damping rates for the corresponding cavity modes which are related to the amplitude transmission coefficients [9]. The master equation for the four cavity modes is

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[H_{int} + H_{ext}, \hat{\rho}] + \sum_i L_i\hat{\rho} \quad . \tag{5}$$

The equations of motion for the four cavity modes can be obtained by solving the Fokker-Planck equation in the P representation as [26]

$$\begin{aligned}
\frac{\partial\alpha_p}{\partial t} &= \epsilon_p - \gamma_p\alpha_p - \kappa\alpha_c^\dagger\alpha_s\alpha_{as} - \sqrt{2\kappa\alpha_s\alpha_{as}}\eta_1(t), \\
\frac{\partial\alpha_c}{\partial t} &= \epsilon_c - \gamma_c\alpha_c - \kappa\alpha_p^\dagger\alpha_s\alpha_{as} - \sqrt{2\kappa\alpha_s\alpha_{as}}\eta_2(t), \\
\frac{\partial\alpha_s}{\partial t} &= \kappa\alpha_p\alpha_c\alpha_{as}^\dagger - \gamma_s\alpha_s + \sqrt{2\kappa\alpha_p\alpha_c}\eta_3(t), \\
\frac{\partial\alpha_{as}}{\partial t} &= \kappa\alpha_p\alpha_c\alpha_s^\dagger - \gamma_{as}\alpha_{as} + \sqrt{2\kappa\alpha_p\alpha_c}\eta_4(t),
\end{aligned} \tag{6}$$

where η_i are real noise terms and have $\langle\eta_i(t)\rangle = 0$ and $\langle\eta_i(t)\eta_j(t')\rangle = \delta_{ij}\delta(t-t')$. In this nonlinear FWM process, the pump and coupling beams are both coherent driving fields and they have similar quantum characteristics. In order to simplify the calculation we assume they have the same damping rate in the cavity and the same classical pumping laser amplitudes, i.e. $\gamma_p = \gamma_c = \gamma_a$ and $\epsilon_p = \epsilon_c = \epsilon$. Likewise, we assume the anti-Stokes and

Stokes beams have the same damping rate with $\gamma_s = \gamma_{as} = \gamma_b$. To obtain the output spectra one have to know the classical steady-state solutions [11, 25]. By letting $\partial\alpha_i/\partial t = 0$, it is easy to find the solutions when the noise terms are ignored [11, 25]. We find the pump threshold at $\epsilon_{th} = \gamma_a\sqrt{\gamma_b/\kappa}$. When $\epsilon < \epsilon_{th}$, the steady-state outputs can be obtained as $A_i = A_a = \epsilon/\gamma_a$ $(i = p, c)$ and $A_i = A_b = 0$ $(i = s, as)$. When $\epsilon > \epsilon_{th}$, the steady-state outputs can be obtained as $A_i = A_a = \pm\sqrt{\gamma_b/\kappa}$ $(i = p, c)$ and $A_i = A_b = \pm\sqrt{\gamma_a(\epsilon - \epsilon_{th})/\epsilon_{th}\kappa}$ $(i = s, as)$, where A_a is the mean value of the pump or coupling field in the steady state, and A_b is the value of the anti-Stokes or Stokes field in the steady state. In the present scheme we only consider the situation for the field modes to oscillate above the threshold.

In the following, one can decompose the system variables into their steady-state values and small fluctuations around the steady-state values as $\alpha_i = A_i + \delta\alpha_i$. Then one can use this linearized analysis as a method to calculate the spectra for the output cavity modes [11, 25]. Equation (6) can be linearized as [26]

$$\frac{d}{dt}\delta\tilde{\alpha} = -\mathrm{M}\delta\tilde{\alpha} + \mathrm{B}\eta, \tag{7}$$

where $\delta\tilde{\alpha} = [\delta\alpha_p, \delta\alpha_P^*, \delta\alpha_c, \delta\alpha_c^*, \delta\alpha_s, \delta\alpha_s^*, \delta\alpha_{as}, \delta\alpha_{as}^*]^{\mathrm{T}}$, B contains the coefficients of the noise terms, $\tilde{\eta}$ is the noise matrix, and M is the drift matrix with the steady-state values inserted and given by

$$\mathrm{M} = \begin{pmatrix} \gamma_a & 0 & 0 & \kappa A_b^2 & \kappa A_a^* A_b & 0 & \kappa A_a^* A_b & 0 \\ 0 & \gamma_a & \kappa A_b^{*2} & 0 & 0 & \kappa A_a A_b^* & 0 & \kappa A_a A_b^* \\ 0 & \kappa A_b^2 & \gamma_a & 0 & \kappa A_a^* A_b & 0 & \kappa A_a^* A_b & 0 \\ \kappa A_b^{*2} & 0 & 0 & \gamma_a & 0 & \kappa A_a A_b^* & 0 & \kappa A_a A_b^* \\ -\kappa A_a A_b^* & 0 & -\kappa A_a A_b^* & 0 & \gamma_b & 0 & 0 & -\kappa A_a^2 \\ 0 & -\kappa A_a^* A_b & 0 & -\kappa A_a^* A_b & 0 & \gamma_b & -\kappa A_a^{*2} & 0 \\ -\kappa A_a A_b^* & 0 & -\kappa A_a A_b^* & 0 & 0 & -\kappa A_a^2 & \gamma_b & 0 \\ 0 & -\kappa A_a^* A_b & 0 & -\kappa A_a^* A_b & -\kappa A_a^{*2} & 0 & 0 & \gamma_b \end{pmatrix}. \tag{8}$$

The Eq. (7) can be solved in the frequency domain as $\delta\tilde{\alpha}(\omega) = (\mathrm{M} + i\omega\mathrm{I})^{-1}\mathrm{B}\eta$, where I is the identity matrix and ω is the analysis frequency. The output fields can be obtained along with the well-known input-output relations [26, 27].

From now on, we numerically calculate the values of inequalities in Eqs. (1) according to the results obtained above. In Fig. 2 we plot the minimum of the inequalities versus the analysis frequency normalized to γ_a with $\gamma_a = 0.03, \gamma_b = 0.015$, $\epsilon = 1.5\epsilon_{th}$, and $\kappa = 1$.

It is obvious that the minimal values of inequalities are all less than 1 in a wide range of analysis frequency, which is sufficient to demonstrate that the pump, coupling, anti-Stokes, and Stokes beams are CV entangled with each other. In this FWM process, the production of a pair of new photons (i. e. anti-Stokes and Stokes photons) must be accompanied with the annihilation of a pair of pump and coupling photons simultaneously due to the energy conservation. Therefore, the sum of decreasing intensities of the pump and coupling beams is equal to that of the anti-Stokes and Stokes beams, and the four beams are quantum correlated which is similar to the case in OPO operating above the threshold [2]. Smaller the value of the inequality is, higher the degree of entanglement is, therefore, stronger the degree of quantum correlation is. In Fig. 2 one can see that the value of V_{s-as} is the smallest in the three inequalities, which indicates that the degree of entanglement between the anti-Stokes and Stokes beams is the biggest. This is similar to the case of twin beams produced by spontaneous parametric down-conversion.

In Fig. 3, we plot the minima of the inequalities versus the pump power parameter ϵ normalized to the threshold of the pump with $\gamma_a = 0.03, \gamma_b = 0.015$, $\omega = \gamma_a$, and $\kappa = 1$. One can see that the minima of the inequalities are less than 1 when the optical oscillators are operated above the threshold, and it verifies that the four field modes are entangled. Moreover, the value of V_{s-as} is also the smallest in the three inequalities and it demonstrates that the degree of quantum correlation between the anti-Stokes and stokes beams is the strongest. In addition, the best quadricolor CV entanglement can be obtained at about $\epsilon = 1.3\epsilon_{th}$. When $\epsilon < \epsilon_{th}$, the steady-state values of anti-Stokes and Stokes beams are both equal to zero, the powers of the pump and coupling beams are higher than that of the anti-Stokes and Stokes beams. Thus, the quantum characteristics of the pump and coupling beams do not present in such case and they are not entangled with the weak anti-Stokes and Stokes fields. With the increase of the pump above the threshold, the anti-Stokes and Stokes fields will be enhanced, however, the pump and coupling beams become weaker since their energies are transferred to the anti-Stokes and Stokes beams. Then, their quantum characteristics are present and bright quadricolor CV entanglement can be obtained. With further increase of the pump far above the threshold, the gain begins to saturate, the intensities of pump and coupling beams are higher than that of the signal and idler beams and their quantum characteristics vanish when the values of inequalities exceed 1.

In summary, we proposed a new scheme to produce bright quadricolor CV entanglement from an atomic ensemble in the optical cavity operating above threshold, which is experimental feasible based on our previous experiment [20]. We have theoretically demonstrated that quadripartite CV entanglement according to the criterion proposed by van Loock and Furusawa [21]. These bright quadricolor entangled beams with different frequencies and narrow linewidths are spatially separated after generation which can be employed for the needs in quantum networks [2]. Moreover, their wavelengths at about 800nm can be directly used in quantum memory and storage [13] and can be used as important entanglement resources in free-space quantum teleportation [14].

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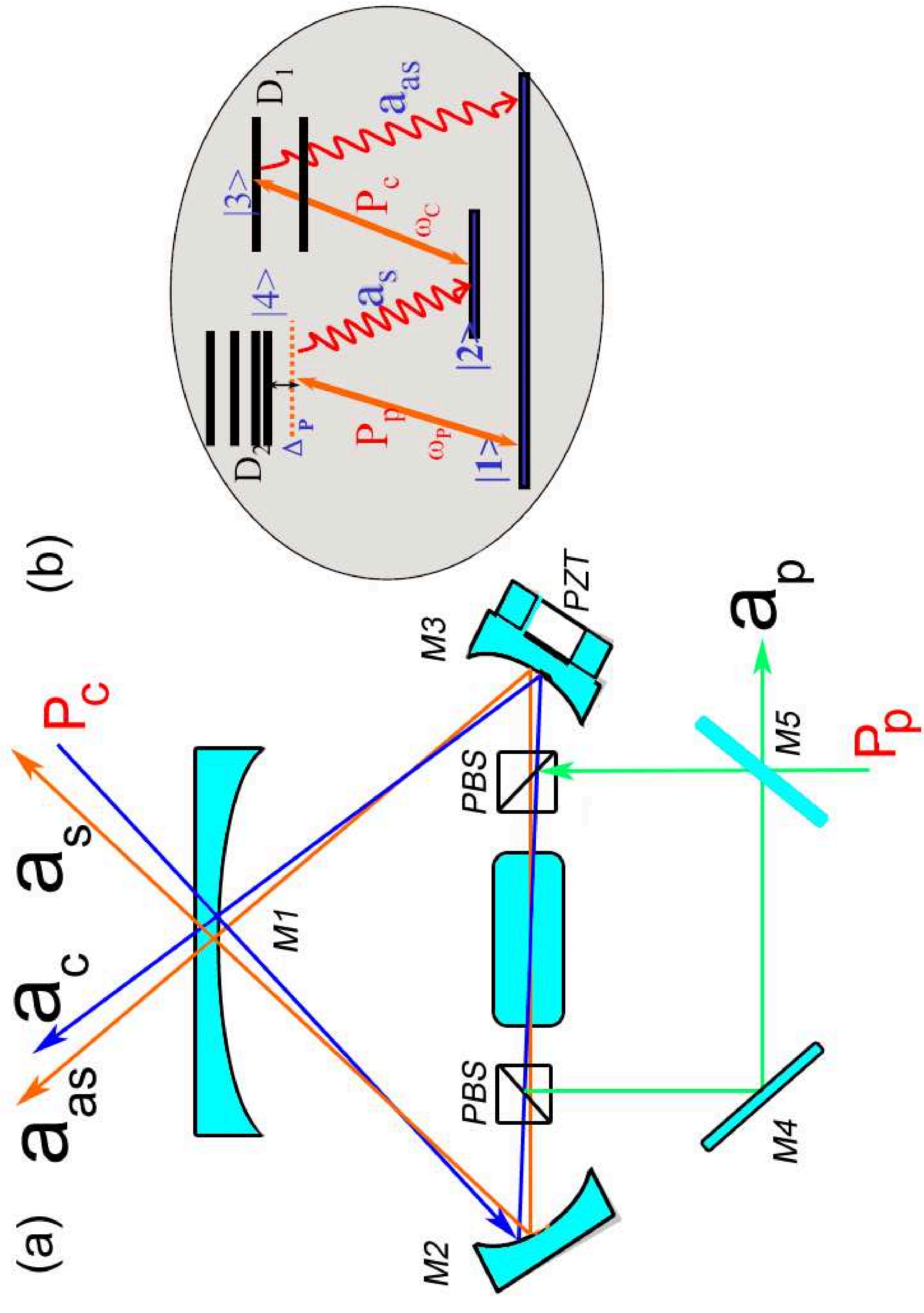
Figure captions

Fig. 1: (a)The experimental setup for the proposed scheme. (b)The relevant energy level diagram of the ^{87}Rb atomic system.

Fig. 2: The minima of the inequalities versus the analysis frequency normalized to γ_a with $\gamma_a = 0.03, \gamma_b = 0.015$, $\epsilon = 1.5\epsilon_{th}$, and $g = 1$.

Fig. 3: The minima of the inequalities versus the pump power parameter ϵ normalized by its threshold value with $\gamma_a = 0.03, \gamma_b = 0.015$, $\omega = \gamma_a$, and $\kappa = 1$.

Fig.1


(a)
(b)
a as
a c
a s
P c
M1
M2
M3
PZT
PBS
PBS
M4
M5
P p
a p
D1
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|1>
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|3>
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Δ P
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P c
a s
a as

Fig.2

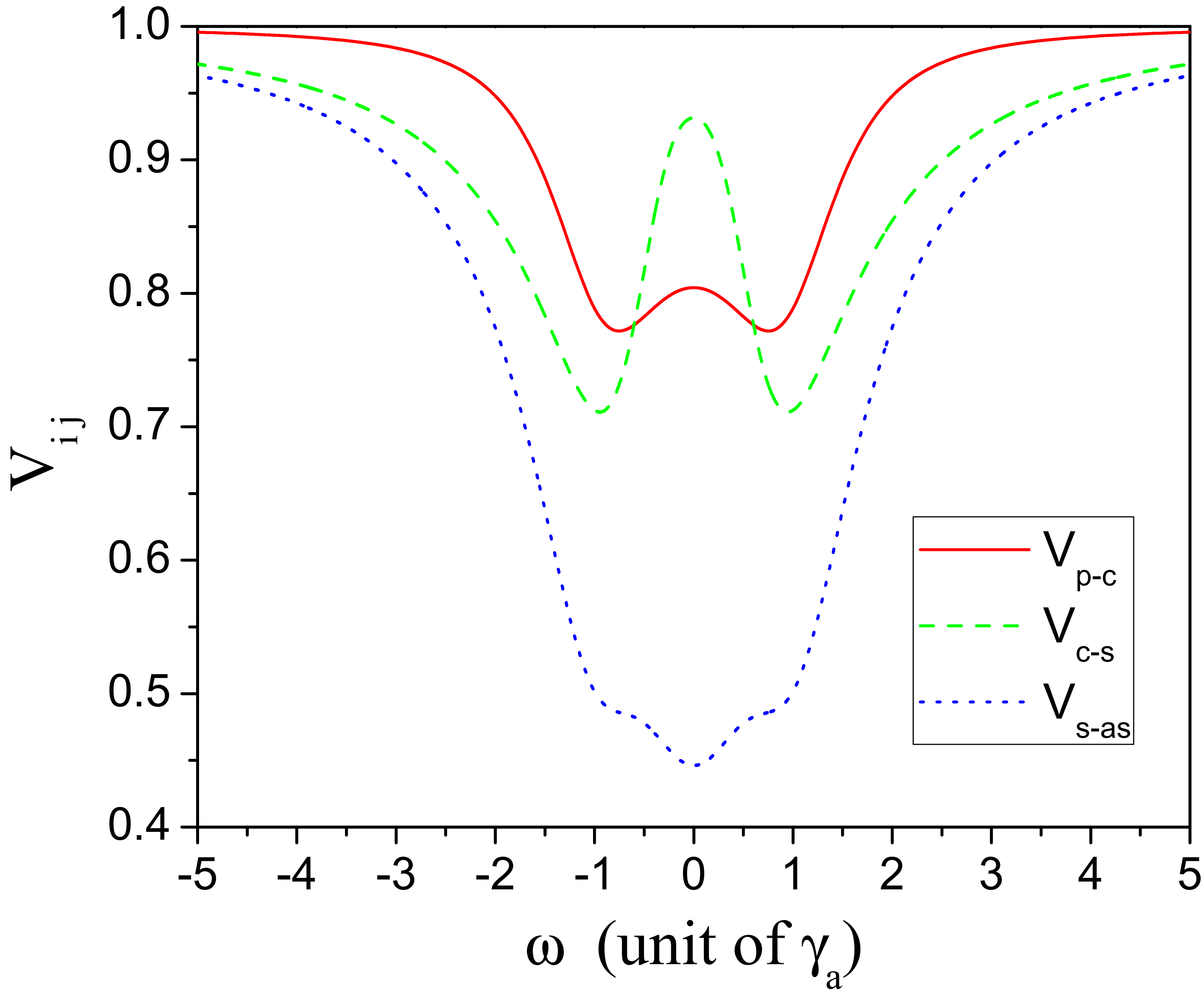

Figure 2 LX12704A 14Dec2010

Figure 3 LX12704A 14Dec2010

Fig. 3