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PAPER

Quantum manipulation and enhancement of deterministic entanglement between atomic ensemble and light via coherent feedback control

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Abstract

A quantum mechanical model of the non-measurement based coherent feedback control (CFC) is applied to deterministic atom-light entanglement with imperfect retrieval efficiency, which is generated based on Raman process. We investigate the influence of different experimental parameters on entanglement property of CFC Raman system. By tailoring the transmissivity of coherent feedback controller, it is possible to manipulate the atom-light entanglement. Particularly, we show that CFC allows atom-light entanglement enhancement under appropriate operating conditions. Our work can provide entanglement source between atomic ensemble and light of high quality for high-fidelity quantum networks and quantum computation based on atomic ensemble.

1. Introduction

A wide variety of nonclassical optical states, which are the kernel resources of quantum information, have been produced by employing the optical nonlinearities of optical parametric down conversion [1–3]. Quantum networks, composed of quantum nodes and quantum channels, have attracted more and more attention [4–8]. An atomic ensemble is one of the ideal candidates of quantum node for quantum information processing and memory. For near-resonant light, the nonlinearity of atomic ensemble is large, meanwhile the extra noise is small; thus, it is suitable for the generation of nonclassical states. Quantum entanglement between atomic ensemble and light, which enable to convey quantum state across quantum networks, can be constructed by combining quantum memory with entangled photon pairs [9]. Besides, Raman process is another effective approach to produce atom-light entanglement. The experimental generation of discreet variable atom-light entanglement has also been demonstrated based on Raman process [10–12], as well as schemes of continuous variable (CV) quantum entanglement between atomic ensemble and light via atom-light entanglement swapping have been proposed [13], which can be directly applied in atom based quantum networks.

The manipulation of nonclassical states is a building block to achieve quantum information processing and transmission. Quantum manipulation can provide the entangled level of desirable value, and particularly enhance a limited entangled degree limited by imperfect optical components, which is important for high performance quantum information. Usually, there are two types of approaches to manipulate of nonclassical states. On one hand, the theoretical and experimental investigations of phase-sensitive manipulation of degenerate optical parametric amplifier (DOPA) [14, 15] and non-degenerate optical parametric amplifier (NOPA) [16, 17] have been demonstrated. On the other hand, the feedback mechanism has been used to control noise not only from electrical to optical engineering, but also from classical to quantum domain, which can be applied in atomic ensembles [18, 19], trapped ions [20], opto-mechanical oscillators [21], superconductors [22, 23], diamond [24] and so on. The feedback control network can connect the input and output components of open quantum optical systems to stabilise, manipulate or enhance the quantum performance. The traditional

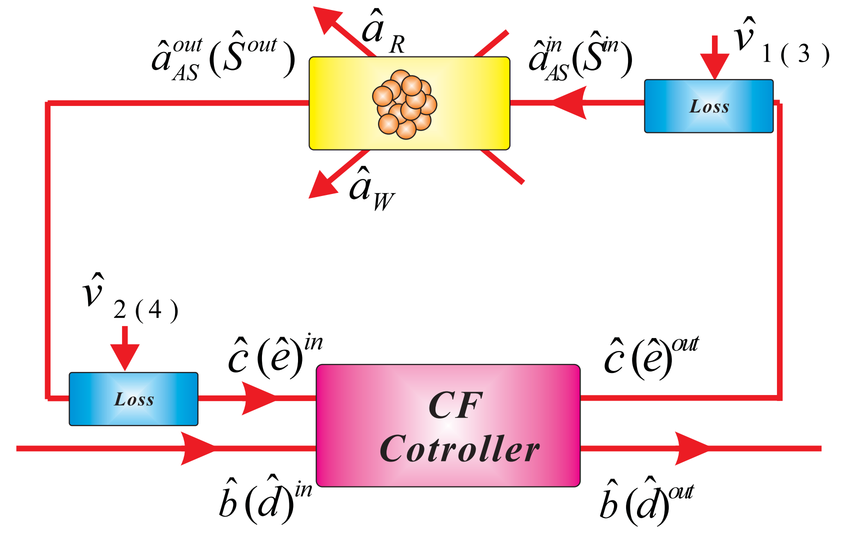

Figure 1. Schematic of CFC Raman system.

feedback technique requires a measurement step, which inevitably introduces extra noises into the feedback process [25–27]. Alternatively, coherent feedback control (CFC) is measurement free, which is suitable for quantum manipulation of nonclassical states [28–33]. The noise-reducing capabilities of CFC in quantum optical generation systems, such as DOPA [34–37] and NOPA [38, 39], have been theoretically and experimentally explored. The application of CFC can be extended to a quantum node. For quantum entanglement between atom ensemble-based quantum node and quantum channel, CFC loop feeds a portion of output field back to control the quantum node as to steer the output state of the controlled system towards a target quantum state. This CFC of atom ensemble-based quantum node plays a key role in the applications of quantum networks because it could allow one to tailor the entangled level for desirable value. Particularly, an entangled state with a high entangled level can be obtained for high-fidelity quantum networks. Therefore, CFC is an effective approach to obtain high quality entangled state between atomic ensemble and light, and can manipulate their correlation variances.

In this paper, we design a CFC Raman system for the manipulation of CV atom-light entangled state with imperfect retrieval efficiency, which incorporates a nonclassical source based on the Raman process in atomic vapour and a CFC loop containing a tunable beam splitter (TBS). We investigate the influence of different experimental parameters on entanglement property, including original atom-light entangled level, retrieval efficiency and optical losses in the CFC loop. The quantum feature of an output-entangled state of the CFC Raman system can be controlled by tailoring the transmissivity of TBS. The physical conditions to manipulate the entanglement are obtained, and CFC can significantly improve entangled level under certain operating conditions. Our approach provides a manipulation and enhancement approach of atomic ensemble and light entanglement without extra measurement losses for quantum networks.

The structure of this paper is as follows. In section 2, we propose the scheme of CFC of entangled state between atomic ensemble and light from Raman process. Quantum mechanical model is deployed to study the entanglement feature from Raman process, which is demonstrated in section 3. Section 4 focuses on quantum manipulation and enhancement performance of CFC Raman system. The influences of the experimental parameters on quantum correlation variances of output fields are studied. In section 5, a brief conclusion is presented.

2. Schematic of CFC on entanglement between quantum node and quantum channel

Our schematic of CFC Raman structure is depicted in figure 1 and consists of quantum node and CFC loop. An atomic vapour-based quantum node, pumped by strong beam of write field $\hat{a}_W$ with small incident angle, can output an entangled state between anti-Stokes field and atomic ensemble by means of Raman process. The CFC loop contains coherent feedback (CF) controller with tunable transmissivity, which can be implemented by the Mach-Zehnder interferometer. The transmissivity of interferometer is able to be controlled by adjusting the phase difference between two arms in the interferometer. A part of the original output anti-Stokes field from quantum node is fed back as its input field of atomic ensemble with the help of the CFC loop. The CFC network can manipulate the entangled level by tuning the transmissibly of CF controller and, in proper conditions, the

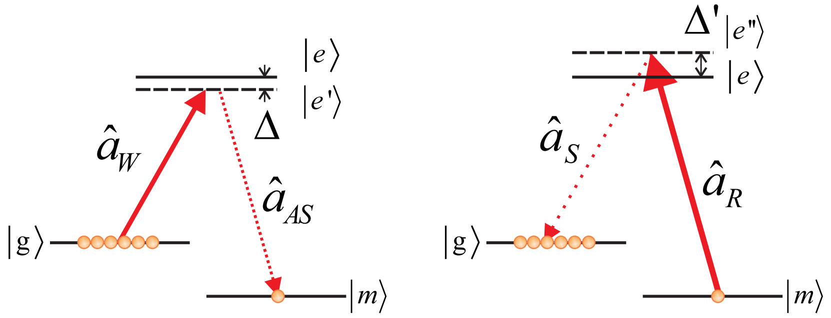

Figure 2. Level structure of atomic transition for Raman process.

entanglement enhancement can be achieved. By applying another strong read field $\hat{a}_R$, the entanglement between atomic ensemble and anti-Stokes field is converted into entanglement between Stokes and anti-Stokes fields, which is used for verifying atom-light entanglement.

3. Generation of entanglement between atomic ensemble and anti-Stokes by means of Raman process

In quantum optics, a quantum optical field is denoted with a annihilation operator $\hat{a}$, and the amplitude and phase quadratures $\hat{X}_L$ and $\hat{Y}_L$ correspond to real and imaginary parts of annihilation operator $\hat{a}$, respectively, that is $\hat{X}_L = (\hat{a} + \hat{a}^+)/\sqrt{2}$, and $\hat{Y}_L = (\hat{a} - \hat{a}^+)/\sqrt{2}\,i$. Atomic spin wave is presented by collective atomic spin $\hat{S} = \sum_i |g\rangle\langle m|$, and y, z-components of the collective atomic angular momentum play the role of amplitude and phase quadratures $\hat{X}_A = (\hat{S} + \hat{S}^+)\big/\sqrt{2} = \hat{S}_y\big/\sqrt{\langle\hat{S}_x\rangle}$, $\hat{P}_A = (\hat{S} - \hat{S}^+)\big/\sqrt{2}\,i = \hat{S}_z\big/\sqrt{\langle\hat{S}_x\rangle}$. The three energy-level structure in our scheme should has a ground state $|g\rangle$, a meta-stable state $|m\rangle$ and an excited state $|e\rangle$; an alkali atom, such as Rubidium and Caesium, can provide this kind of atomic energy-level structure, which is shown in figure 2. The write (read) field $\hat{a}_W$ ($\hat{a}_R$) of red (blue) detuning Δ (Δ') with the transition between a ground (meta)state $|g\rangle$ ($|e\rangle$) and a excited state $|e\rangle$, is employed in Raman process.

The Raman process is an effective method for generating quantum entanglement between atomic ensemble and anti-Stokes field. When the nonlinear interaction among write field $\hat{a}_W$, anti-Stokes field $\hat{a}_{AS}$ and atomic spin wave $\hat{S}$ via Raman process happens, the atom-light quantum entanglement will be generated. The undepleted write field is treated as a classical light A_w because its power is much stronger than that of anti-Stokes field. The effective interaction Hamiltonian of Raman process is written as [13, 40]

$$\hat{H}_{int} = i\hbar\kappa(\hat{a}_{AS}^+\hat{S}^+ - \hat{a}_{AS}\hat{S}), \tag{1}$$

which is the type of parametric gain, and where nonlinear coupling efficiency κ is the product of nonlinear coupling coefficient k and the strength of write field A_w, as $\kappa = kA_w$.

By solving the Heisenberg equation $\frac{d}{dt}\hat{a} = \frac{1}{ih}[\hat{a},\ \hat{H}_{int}]$ with the above interaction Hamiltonian (equation (1)), the output anti-Stokes field $\hat{a}_{AS}^{out}$ and atomic spin wave $\hat{S}^{out}$ from atomic vapour can be expressed in terms of input anti-Stokes field $\hat{a}_{AS}^{in}$ and original atomic spin wave $\hat{S}^{in}$, which are [13, 40]

$$\begin{aligned}\hat{a}_{AS}^{out} &= \hat{a}_{AS}^{in}\cosh r + \hat{S}^{in+}\sinh r,\\ \hat{S}^{out} &= \hat{S}^{in}\cosh r + \hat{a}_{AS}^{in+}\sinh r,\end{aligned} \tag{2}$$

where correlation parameter r is dependent on the product of the nonlinear coupling efficiency κ and the interaction time τ_0, as $r = \kappa\tau_0$.

In the Raman process, entanglement between atomic ensemble and anti-Stokes optical pulse can be converted into entanglement between Stokes and anti-Stokes optical pulses with a retrieval efficiency η by applying read optical pulse. The extra noise $\hat{\upsilon}_0$ is introduced by limited retrieval efficiency η. The output Stokes field from atomic ensemble $\hat{a}_s^{out}$ is given by

$$\hat{a}_s^{out} = \sqrt{\eta}\hat{S}^{out} + \sqrt{1-\eta}\hat{\upsilon}_0. \tag{3}$$

4. Quantum manipulation and enhancement of entangled state between atomic ensemble and anti-Stokes field based on CFC

By employing a quantum mechanical model, we study the nonclassical feature of CFC Raman system. Mach-Zehnder interferometer can be treated as a TBS of CFC loop with the transmissivity T and used not only as a CF controller, but also as an input-output port of CFC loop. The coherent input field is sent to one input port of the TBS, and then the transmitted entangled optical field $\hat{c}^{in}$ $(\hat{e}^{in})$ from the quantum node together with the reflected coherent field $\hat{b}^{in}$ $(\hat{d}^{in})$ become the final output field $\hat{b}^{out}$ $(\hat{d}^{out})$ from CFC Raman system. Meanwhile, the transmitted field $\hat{b}^{in}$ $(\hat{d}^{in})$ of coherent state and the reflected field $\hat{c}^{in}$ $(\hat{e}^{in})$ of entangled state serve as output field $\hat{c}^{out}$ $(\hat{e}^{out})$ of CF controller, which is used as input field $\hat{a}^{in}$ $(\hat{S}^{in})$ of quantum node. In the entanglement establishment, the input-output relations at TBS in CFC loop can be obtained as [38]

$$\begin{aligned} \hat{b}^{out} &= \sqrt{T}\hat{c}^{in} - \sqrt{1-T}\hat{b}^{in}, \\ \hat{c}^{out} &= \sqrt{T}\hat{b}^{in} + \sqrt{1-T}\hat{c}^{in}. \end{aligned} \tag{4}$$

In entanglement verification, the input-output relations at TBS in CFC loop can be expressed by [38]

$$\begin{aligned} \hat{d}^{out} &= \sqrt{T}\hat{e}^{in} - \sqrt{1-T}\hat{d}^{in}, \\ \hat{e}^{out} &= \sqrt{T}\hat{d}^{in} + \sqrt{1-T}\hat{e}^{in}. \end{aligned} \tag{5}$$

In our model, the extra vacuum noises are introduced by the losses of the CFC loop. In entanglement generation, the extra noise $\hat{\upsilon}_1$ $(\hat{\upsilon}_2)$ from (to) TBS to (from) quantum node is coupled to field in the CFC loop with a loss L_1 (L_2), and in entanglement verification, the extra noise $\hat{\upsilon}_3$ $(\hat{\upsilon}_4)$ from (to) TBS to (from) quantum node is coupled to field in the CFC loop with a loss L_1 (L_2). We then have the expressions of input field $\hat{a}^{in}$ $(\hat{S}^{in})$ of quantum node and input field $\hat{c}^{in}$ $(\hat{e}^{in})$ of TBS in quantum entanglement generation (verification) as follows:

$$\begin{aligned} \hat{a}_{AS}^{in} &= \sqrt{1-L_1}\,e^{i\varpi_0\tau_1}\hat{c}^{out} + \sqrt{L_1}\,\hat{\upsilon}_1, \\ \hat{a}_{S}^{in} &= \sqrt{1-L_1}\,e^{i\varpi_0\tau_1}\hat{e}^{out} + \sqrt{L_1}\,\hat{\upsilon}_3, \\ \hat{c}^{in} &= \sqrt{1-L_2}\,e^{i\varpi_0\tau_2}\hat{a}_{AS}^{out} + \sqrt{L_2}\,\hat{\upsilon}_2, \\ \hat{e}^{in} &= \sqrt{1-L_2}\,e^{i\varpi_0\tau_2}\hat{a}_{S}^{out} + \sqrt{L_2}\,\hat{\upsilon}_4, \end{aligned} \tag{6}$$

where τ_1 (τ_2) is time delay in optical path length of the CFC loop from (to) TBS to (from) quantum node, and ϖ_0 is optical frequency. The CFC loop operates on resonance with both Stokes and anti-Stokes fields, i.e. $e^{i\varpi_0\tau_1} = e^{i\varpi_0\tau_2} = 1$.

According to equations (2)–(6), the performance of CFC of quantum node can be studied by means of numerical evaluation. We investigate the output quantum correlation variances of CFC Raman system as a function of different experimental parameters such as the original entangled level between atomic ensemble and anti-Stokes field, retrieval efficiency and the losses of CFC loop. All the values of parameters are taken according to practical experimental condition and our scheme can provide a direct reference for experimental implementation of CFC Raman system.

First, we study the influence of original entangled level between atomic ensemble and anti-Stokes field on the output quantum correlation feature of the CFC Raman system in an ideal retrieval efficiency case, and in an imperfect retrieval efficiency case, when the losses of CFC loop $(L = 0.02)$ are taken into account. Figure 3 depicts the output quantum correlation variances of CFC Raman system in ideal retrieval efficiency $(\eta = 1)$ versus the transmissivity of TBS with various original entangled levels, (a): 3.0 dB ; (b): 5.0 dB; (c): 7.0 dB. Trace i is quantum noise limit (QNL); Trace ii is the output quantum correlation variances of uncontrolled quantum entangled state; Trace iii is the output quantum correlation variances of CFC controlled entanglement. In CFC Raman system, the entangled state between atomic ensemble and anti-Stokes field plays the positive role for the entanglement enhancement, and the extra noises resulting from the losses in CFC loop has the negative influence. From each subplot of figure 3, it can be seen that the quantum correlation noises of the entangled state from CFC Raman system can be manipulated only by tuning the transmissivity of TBS. The entangled level of the CFC Raman system (Trace iii) is higher or lower than that without CFC loop (Trace ii), when the transmissivity values of TBS is varied. When $T = 1$, the CFC Raman system is operated at the situation without the feedback and thus quantum correlation noises of CFC Raman system (Trace iii) are close to original quantum noises (Trace ii). In the ranges of $0.14 < T < 1$ at original entanglement of 3.0 dB, $0.32 < T < 1$ at original entanglement of 5.0 dB, and $0.53 < T < 1$ at original entanglement of 7.0 dB, the positive roles are dominant compared to the negative influences. For other transmissivity range of TBS, the negative influences of the input coherent light, the extra noises in CFC loop are larger than the positive roles for entanglement enhancement, thus the quantum noises with CFC (Trace iii) are higher than those without CFC loop (Trace ii). In figure 3(a) the output entanglement is improved from 3 dB to 11 dB at optimal transmissivity $T = 0.53$ of

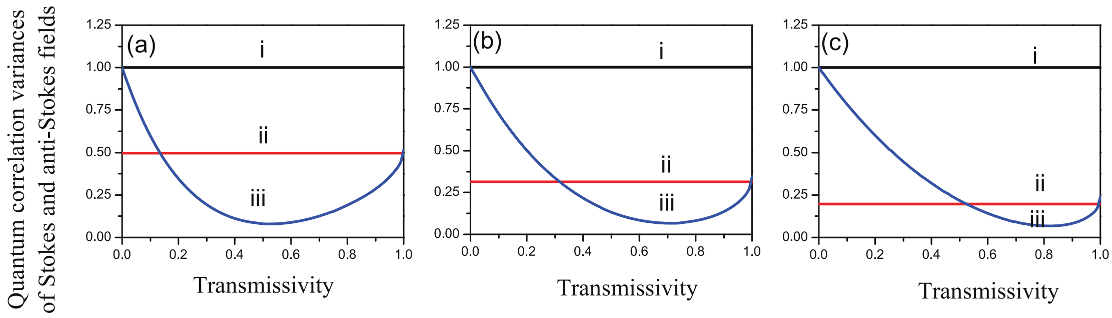

Figure 3. Output quantum correlation variances of CFC Raman system in ideal retrieval efficiency versus the transmissivity of TBS with various original entangled degrees. Trace i: QNL; Trace ii: Raman process without CFC; Trace iii: Raman process with CFC. (a), 3 dB; (b), 5 dB; (c), 7 dB.

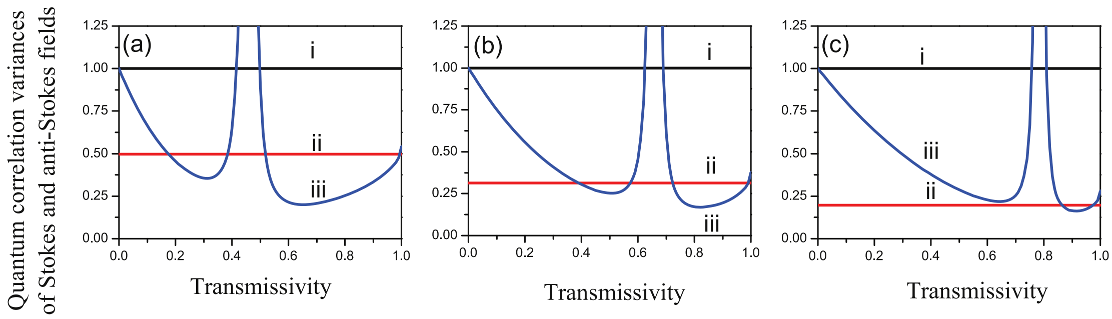

Figure 4. Dependence of output quantum correlation variances of CFC Raman system in limit retrieval efficiency on the transmissivity of TBS with various original entangled degrees. Trace i: QNL; Trace ii: Raman process without CFC; Trace iii: Raman process with CFC. (a), 3 dB; (b), 5 dB; (c), 7 dB.

TBS, in figure 3(b) it improves the entangled degree from 5 dB to 12 dB at optimal transmissivity $T = 0.70$ of TBS, and in figure 3(c) the entangled degree is improved from 7 dB to 12 dB at optimal transmissivity $T = 0.82$ of TBS. The optimal transmissivity of TBS for entanglement enhancement is enlarged with the increase of original entangled level. Although the original entangled degree is low, it can be improved by making use of CFC mechanism, and the original 3 dB entanglement is increased to 11 dB entanglement.

However, CFC in the limit retrieval efficiency is different from that in the ideal case. Figure 4 shows the dependence of output quantum correlation fluctuation from CFC Raman system on the transmissivity of TBS with various original entangled levels in limit retrieval efficiency ($\eta = 0.9$), (a): 3.0 dB; (b): 5.0 dB; (c): 7.0 dB. From each subplot, we can see that the quantum correlation variances of the entangled state from CFC Raman system can still be manipulated only by tuning the transmissivity of TBS, although the imperfect retrieval efficiency will break the balance of CFC on Stokes field and anti-Stokes field, and quantum correlation variances will get worse (much higher than QNL) at optimal transmissivity of TBS. Fortunately, in the ranges of $0.18 < T < 0.38$ and $0.52 < T < 1$ at original entanglement of 3.0 dB, $0.39 < T < 0.57$ and $0.73 < T < 1$ at original entanglement of 5.0 dB, and $0.87 < T < 0.97$ at original entanglement of 7.0 dB, the quantum correlation noises of the output fields from CFC Raman system (Trace iii) become better than those without the use of CFC (Trace ii). There exists the trade-off between the positive effect of the nonlinear effect and the negative effect of CFC Raman system. The blue curves (Trace iii) in figure 4 are in fact continuous with finite value. In order to show the manipulation effect clearly, we have zoomed in the range between 0 and 1.25, which is around QNL. From figures 4(a) to (c), we can see that entangled level can still be improved with the optimal transmissivity of TBS compared to that of the uncontrolled quantum node, and the entanglement enhancement effect is better in the low entangled degree. Therefore the quantum manipulation and enhancement can work for the limited retrieval efficiency case.

The losses in the CFC loop limit the attainable output-entangled level. The dependence of quantum correlation variances of CFC Raman system on the losses in CFC loop is studied in figure 5, when $r = 0.58$, $T = 0.75, \eta = 0.9$. Trace i is QNL, and Trace ii (iii) is the output quantum fluctuation of quantum node without (with) CFC. It demonstrates that the output-entangled level is sensitive to the losses in the CFC loop. In CFC Raman system, the extra noises introduced by the losses in CFC loop have the negative influence for entanglement enhancement, while the input atom-light entangled state of CFC plays the positive role. The

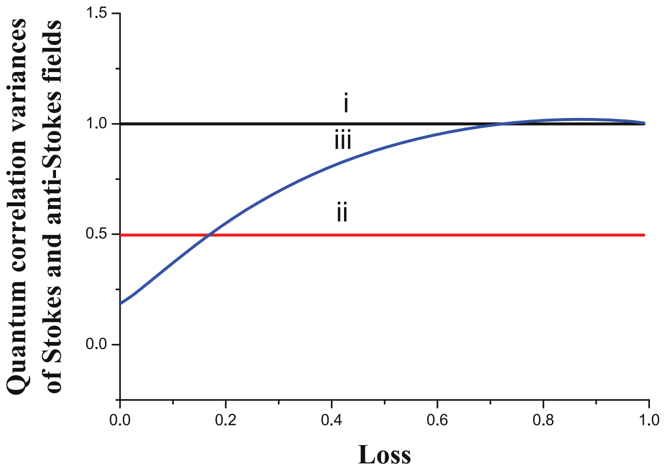

Figure 5. Dependence of quantum correlation variances of CFC Raman system on the loss in CFC loop. Trace i: QNL; Trace ii: Raman process without CFC; Trace iii: Raman process with CFC.

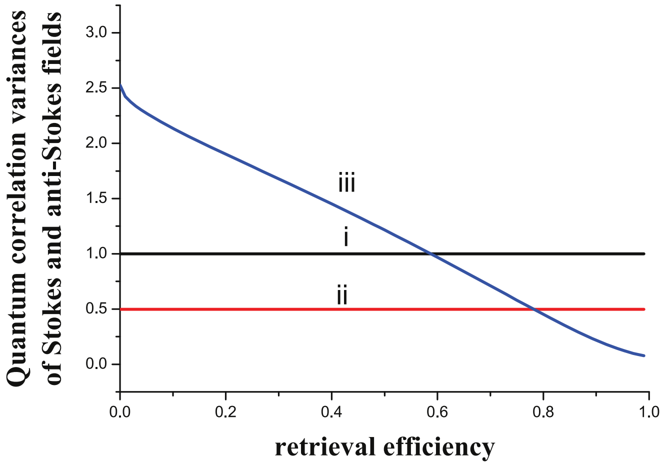

Figure 6. Function of quantum correlation variances of CFC Raman system on the retrieval efficiency from atom to Stokes field. Trace i: QNL; Trace ii: Raman process without CFC; Trace iii: Raman process with CFC.

numerical calculation demonstrates the balance between positive and negative roles. When $L < 0.17$, the entanglement is improved by means of CFC and the positive role is dominant. When $L > 0.17$, the negative influence of the extra noise in CFC loop is larger than the positive role for entanglement enhancement, thus the output entanglement can not be increased with the help of CFC. As $L > 0.72$, the entanglement will disappear. And it will tend to QNL, as the loss L is close to 1. Therefore, the lower loss in the CFC loop is required for the better performance of CFC. The experimental loss in CFC loop can be optimised to reach 0.02 [39].

The retrieval efficiency is also sensitive to the performance of CFC. In figure 6, the function of quantum correlation variances of output Stokes and anti-Stokes fields from CFC Raman system on the retrieval efficiency is investigated, when $r = 0.58, T = 0.75, L = 0.02$. Trace i is QNL and Trace ii (iii) is the output quantum correlation variances of output fields from CFC Raman system without (with) CFC. It can be seen that the the larger retrieval efficiency can provide the better output-entangled level. When $\eta > 0.79$, the output entanglement can be increased with the help of CFC. While $\eta > 0.59$, the entanglement exists. The unbalancing caused by limited retrieval efficiency makes the CFC effect worse when retrieval efficiency gets smaller, and thus the high efficiency is required for the better performance of CFC.

Therefore the transmissivity range for quantum manipulation and optimal transmissivity value for quantum enhancement are dependent on the original entangled level, optical losses in CFC loop and retrieval efficiency, according to the theoretical analysis. For a given system, the maximum amount of entanglement can be attained by choosing the optimal transmissivity of the TBS, reducing optical losses of CFC loop, and increasing the retrieval efficiency.

5. Conclusion

In conclusion, we place deterministic entangled state between atomic ensemble and anti-Stokes field generated via Raman process from an atomic medium in CFC loop with imperfect retrieval efficiency. In CFC, any back-action noise resulting from measurement is not introduced into the control system. The possibility for manipulation of quantum entanglement between quantum node and quantum channel is demonstrated by tailoring the transmissivity of CF controller. We also find appropriate operating conditions enable significantly enhanced entanglement with CFC compared to the case without feedback, which offers one of promising candidates of high quality nonclassical source for high performance quantum information, and is also suitable to manipulate various quantum optical states in different physical systems, such as the superconducting circuits, cavity-optomechanics, nanophotonic devices and so on.

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