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Engineering of Two Quantum States via Conditional Measurement on Two-Mode Squeezed State *

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We propose a scheme for the simultaneously preparation radiation-field modes of a single photon and a superposition of zero- and one-photon states, based on the coherent quantum state displacement and photon subtraction from two-mode squeezed state. It is shown that the single-photon and the superposition states can be obtained by only choosing the suitable parameter of displacements. The experimental feasibility to accomplish this scheme is also discussed.

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In recent years, the quantum engineering of light states has attracted a great deal of attention because it provides potential ways to control, measure and manipulate the quantum states. Quantum states are the essential resource for quantum information processing and communication, thus the realization of quantum state engineering plays an important role in the field of quantum information.[1−2]

It is desirable to implement a general procedure which allows, at least in principle, one to engineer nonclassical states of generic form. In recent years, the attempts to develop quantum state engineering show that there are two types of approaches in the presentation of quantum states. One approach is based on the time evolution generated by a generic, controlling Hamiltonian which drives an initial state to the final target state. Another approach is realized in two steps: first, the quantum system of interest is correlated with another auxiliary system; second, a measurement is performed on the auxiliary system, reducing the state of the system of interest to the desired target state.

In 1987, Yurke and Stoler introduced a crucial idea for the development of state preparation schemes,[3] which concerned the preparation of the number state based on the process of the parametric down conversion. The photon count measurement on the idler output leads to generation and manipulation of nonclassical states of light in the signal output. It has also been shown that the action of an avalanche photondetector on twin beams may lead to a highly nonclassical reduced state.[4] These methods have recently led to the successfully experimental generation of nonclassical states of light.[5,6] It has also been reported that the non-Gaussian operation using postselection technology with beam splitter and single photon detection provides the relevant methods for nonclassical state engineering, e.g. single-photon-added and single-photon-subtracted states.[7,8] Using the postselection technology of photon additions, the engineering of a running-wave superposition of zero- and one-photon field states has been theoretically and experimentally obtained.[9,5] It has been pointed out that based on this method the preparation of arbitrary single-mode states[10,11] and the quantum superposition of coherent states (or Schrödinger-cat states)[12] can be realized. The alternative way to prepare an arbitrary truncated state and a Schrödinger-cat state is the photon subtraction by conditional photodetections,[13,14] with which the vacuum replaces the single photon as the input state, thus the photon subtraction technology is experimentally much more practicable than that with the photon addition because the generation of single photon state is relatively difficult in experiment. Several proposals for the engineering of quantum state using two-mode squeezed state have been reported. In 2005, conditionally preparing a near optimal quantum state for Bell-inequality violation was presented using a non-Gaussian entangled state, which was generated from a two-mode squeezed vacuum state by subtracting a single photon from each mode.[15,16] The increasing entanglement of two-mode squeezed vacuum state by coherent photon subtraction was discussed.[17,18] In this Letter, we study on the preparation scheme of single photon state as well as the superposition state of zero and single photon for travelling fields by photon subtractions on a two-mode squeezed state. In our scheme, the engineering of two quantum nonclassical states can be accomplished simultaneously by means of two-mode squeezed state. The present protocol would be available for further applications in quantum cryptography, quantum engineering and quantum

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measurements where very weak travelling lights of single photons are required usually.

The state engineering of quantum states is started with two-mode squeezed vacuum state of continues variables, which is expressed as

$$|\eta,0\rangle=\hat{S}_{1,2}(\eta)|0,0\rangle, \tag{1}$$

where $\hat{S}_{1,2}(\eta)=\exp[\eta^*\hat{a}_1\hat{a_2}-\eta\hat{a}_1^+a_2{}^+]$is the squeezing operator, $\hat{a}_{1,2}$ and $\hat{a}_{1,2}^+$ are the annihilation and creation operators of the two modes of the squeezed state, the subscripts 1 and 2 denote the two modes, respectively; $\eta=r_0e^{i\varphi_0}$ is the squeezing parameter with modulus r_0 and argument φ_0, $r_0=0$ indicates no squeezing and $r_0\to\infty$ represents the perfect squeezing.

Firstly we perform the unitary displacement transformations on one mode of the two-mode squeezed vacuum state, the state is transformed into

$$|\psi\rangle_1=\hat{D}_1(\alpha_1)\hat{S}_{1,2}(\eta)|0,0\rangle_{1,2}, \tag{2}$$

where $\hat{D}_1(\alpha_1)=\exp(\alpha_1\hat{a}_1^+-\alpha_1^*a_1)$ is the displacement operator.

The conditional single photon subtractions are then interacted on both the modes of squeezed state, which can be realized by highly unbalanced beam splitters and single photon detectors. When the conditional single photon subtraction is applied, the further displacement on the one mode of squeezed state is performed again. After this process, the squeezed state is collapsed into

$$|\psi\rangle_2=\hat{D}_2(\alpha_2)\hat{X}_2\hat{X}_1\hat{D}_1(\alpha_1)\hat{S}_{1,2}(\eta)|0,0\rangle_{1,2}, \tag{3}$$

where $\hat{X}_1$ and $\hat{X}_2$ indicate the process of conditional single-photon subtraction, they take the form $\hat{X}_{1,2}=\hat{a}_{1,2}t^{\hat{n}_{1,2}}$; $\hat{n}_{1,2}=\hat{a}_{1,2}^+\hat{a}_{1,2}$ is the photon-number operator; t is the amplitude transmittance of beamsplitter, for this conditional single photon subtraction, t is selected to be $t-\to 1$.

Finally, an anti-squeezing transformation is performed on both the modes, the final state after experiencing all of the process is transformed into

$$|\psi\rangle_t=\hat{S}_{1,2}^+(\xi)\hat{D}_2(\alpha_2)\hat{X}_2\hat{X}_1\hat{D}_1(\alpha_1)\hat{S}_{1,2}(\eta)|0,0\rangle_{1,2}. \tag{4}$$

Using the decomposition formula of the displacement operator, $\hat{D}(\alpha)=e^{-\frac{1}{2}|\alpha|^2}e^{\alpha\hat{a}^+}e^{-\alpha^*\hat{a}}$, and taking the commutation relations $[\hat{a}_2,\hat{a}_1]=0$, and the other relations $t^{\hat{n}_{1,2}}e^{\alpha\hat{a}_{1,2}^+}=e^{t\alpha\hat{a}_{1,2}^+}t^{\hat{n}_{1,2}}$, $t^{\hat{n}_{1,2}}e^{\alpha^*\hat{a}_{1,2}}=e^{\frac{\alpha^*}{t}\hat{a}_{1,2}}t^{\hat{n}_{1,2}}$, $e^{\alpha_2\hat{a_1}^+}\hat{a}_1=(\hat{a}_1-\alpha_2)e^{\alpha_2\hat{a}_1^+}$, we have

$$|\psi\rangle_t\propto\hat{S}_{1,2}^+(\xi)(\hat{a}_1-\alpha_2)\hat{a}_2e^{(\alpha_2+t\alpha_1)\hat{a}_1^+}e^{-(\alpha_2^*+\alpha_1/t)\hat{a_1}}\cdot t^{\hat{n}_1}t^{\hat{n}_2}\hat{S}_{1,2}(\eta)|0,0\rangle_{1,2}. \tag{5}$$

The operator $t^{\hat{n}_1}t^{\hat{n}_2}$ acting on the input two-mode squeezed vacuum state corresponds to an action reducing the squeezing degree of squeezed state, that is,

$$t^{\hat{n}_1}t^{\hat{n}_2}\hat{S}_{1,2}(\eta)|0,0\rangle_{1,2}\propto\hat{S}_{1,2}(\zeta)|0,0\rangle_{1,2}, \tag{6}$$

when the squeezing parameter satisfies the condition $\zeta<\eta$.

If the displacement parameters α_1 and α_2 satisfy the relations, then

$$(\alpha_2+t\alpha_1)\cosh(\zeta)=(\alpha_2^*+\alpha_1^*/t)\sinh(\zeta),\ \xi=\zeta. \tag{7}$$

After some algebras, Eq. (5) becomes

$$|\psi\rangle_t\propto[\hat{a}_1\cosh(\zeta)+\hat{a}_1^+\sinh(\zeta)-\alpha_2]\cdot[\hat{a}_2\cosh(\zeta)+\hat{a}_2^+\sinh(\zeta)]|0,0\rangle_{1,2}, \tag{8}$$

Finally we obtain

$$|\psi\rangle_t\propto[\sinh(\zeta)|1\rangle_1-\alpha_2|0\rangle_1]\otimes|1\rangle_2. \tag{9}$$

Thus one beam of the two-mode squeezed state will be prepared into the superposition of zero and single photon state, and the other beam will be changed into the single photon state. In order to reach an arbitrary superposition state, the parameter α_2 can be chosen to satisfy the condition of coefficients for the target state, and the other parameter α_1 will be required to satisfy the condition of Eq. (7).

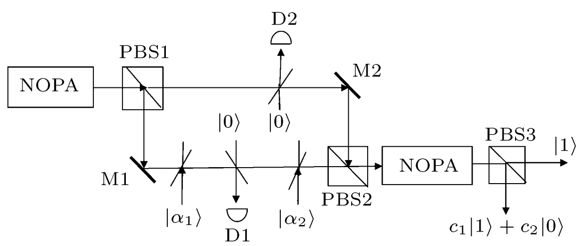

Fig. 1. Scheme of the quantum state preparation. NOPA: nondegenerate optical parametric amplifier, PBS1(2): polarization beam splitter; M1(2): reflected mirror, D1(2): single photon detector, $|\alpha_{1,2}\rangle$: coherent state, $|0\rangle$: vacuum state, $|1\rangle$: single photon state, $c_1|1\rangle+c_2|0\rangle$: arbitrary zero- and single photon superposition state.

We have discussed the theoretical implementation of nonclassical state of single photon as well as the zero and single photon superposition state for travelling field by conditional measurement on two-mode squeezed vacuum state. It provides not only the resources of single photon state, but also the nonclassical state of truncated superposition of Fock states. The mature technique to produce the two-mode squeezed state light and the simplification of photon subtraction detection make the proposed scheme easier to be realized experimentally. The schematic diagram to accomplish this proposal is outlined in Fig. 1. The two-mode squeezed vacuum state can be generated from nondegenerate optical parametric amplifier

(NOPA),[19] the two polarization perpendicular beams which are the output of the NOPA are separated by polarization beam splitter (PBS), one of the beams propagates through three beam splitters to realize the coherent displacement of $\hat{D}_1(\alpha_1)$, single photon subtraction of $\hat{X}_1$ and displacement of $\hat{D}_2(\alpha_2)$, and the other beam is guided through one beam splitter only for the single photon subtraction $\hat{X}_2$. After the sequence process, the two beams are overlapped again on a polarization beam splitter, then injected into the other NOPA for the antisqueezing operation $\hat{S}^{+}_{1,2}(\xi)$, which can be manipulated by controlling the relative phase between the pump field and injected two beams of the NOPA.[20] The target state is the output of this NOPA, it generates a two-mode nonclassical state, one of the modes is prepared in a single photon state, and the other is reduced to the zero and one-photon superposition state, which can be separated by a PBS for their own applications. This scheme may be developed for the complex application in the future quantum information process since it simultaneously provides two nonclassical states of travelling field at the level of single photon. The well-known optical parametric and the photon subtraction techniques provide great convenience for its experimental demonstration and applications.

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