Superactivation of Multipartite Unlockable Bound Entanglement

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The superactivation of multipartite bound entanglement (BE) is a special protocol proposed by Shor *et al.* in 2003, which can distill Einstein-Podolsky-Rosen (EPR) entanglement states between two subsystems of two multipartite BE states. Here we present the first experimental realization of the superactivation of the BE state, in which two copies of the four-partite unlockable BE state in a continuous-variable regime are used. Coupling two thermal states with Gaussian noises into two submodes of an EPR entangled state on two 50-50 beam splitters respectively, the four output optical modes form a four-partite unlocklable BE state. Using two EPR entangled states, we experimentally produce two BE states first. Then through a superactivation operation involving measurements and feedback on the two BE states, an EPR entangled state is distilled out between two designated parties of the two four-partite BE states. The experiment demonstrates the superadditivity of quantum entanglement as the individual BE state cannot be distilled, only two BE states together can be distilled.

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Entangled states are very fragile resources, which are easily destroyed by the decoherence processes to become mixed states owing to unwanted coupling with the environment. Therefore, it is important to know which mixed states can be distilled to maximally entangled states from many identical copies by means of local operation and classical communication (LOCC). There are some mixed entangled states from which no pure entanglement can be distilled. The specific states are called bound entangled states [1]. For the bipartite case, the bound entanglement (BE) has been clearly defined, where only two spatially separated parties are involved. The necessary and sufficient condition for distillability of bipartite quantum states is well known [1]. It has been pointed out that the bipartite BE may be used to activate some entanglement, in which a finite number of free-entangled (distillable) mixed states can be distilled with the help of a large number of BE states [2]. This is not a true distillation of the BE in that no more pure entanglement is produced than the distillable entanglement of the free-entangled mixed states. For the multipartite case, the distillability is much more complicated than that of bipartite entangled states due to the existence of several distinct spatially separated configurations. A multipartite entangled state is bound entangled if no pure entanglement can be distilled between any two parties by LOCC when all the parties remain spatially separated from each other. However, a multipartite BE state may be unlocked or activated sometimes. If one organizes all the parties of a multipartite BE state into several groups, and then performs collective quantum operations among these groups, the pure entanglement may be distilled out between the two different designated groups [3–7]. This type of bound state is called the unlocked or activable BE state. Further, the multipartite BE can be truly activated without the need of meeting with each other group, which is named the superactivation of BE [5]. The superactivation of BE means that two multipartite unlockable BE state tensors together produce distillable entanglement between two parties. Especially, the novel entangled states can be distilled from two copies of a multipartite BE state distributed to different stations [5]. The Smolin state is a typical four-qubit unlockable BE state [4], which has been experimentally demonstrated with polarization photons [8,9] and ions [10], respectively. Successively, the Smolin state is generalized to larger numbers of qubits [11,12], and the applications of the BE state in quantum information are proposed [13,14]. Then, the properties of the multipartite unlockable BE state are obviously explained by the stabilizer formalism [7].

For a continuous-variable (CV) quantum system, the bipartite BE states have been considered and their nontrivial examples have been constructed [15–17]. Recently, the CV multipartite unlockable BE state (also named CV Smolin state) has been proposed and it has been pointed out that the CV Smolin state has different properties compared with its qubit counterpart [18]. Since quantum variables with a continuous spectrum yield very promising perspectives concerning both experimental realizations and general theoretical insights [19–21], due to relative simplicity and high efficiency in the generation, manipulation, and detection of CV states, the experimental investigation on the CV Smolin state is significant. In this Letter we present the experimental demonstrations on the preparation of the CV Smolin state and its superactivation. The basic quantum resources used in the experiments are the Einstein-Podolsky-Rosen (EPR) entangled states of optical fields. The optical EPR state is a bipartite entangled state, in which two entangled submodes with quantum correlations of both amplitude and phase quadratures are involved [22,23]. It has been theoretically proved that if the two submodes of an EPR state are coupled with two independent Gaussian noisy thermal states respectively, the resultant four modes form a real CV four-mode unlockable BE state. In this process, the quantum correlations among the resultant four modes have been partially destroyed by the mixed noises and thus no EPR entanglement can be distilled out between any two output modes, which means that a four-partite BE state is obtained (see Supplemental Material [24] and Ref. [18]). According to the theoretical protocol, we modulate the coherent states of light with Gaussian noises to produce the optical thermal states in the experiment first, then couple two Gaussian noisy thermal states and two submodes of an EPR state on two 50-50 beam splitters, respectively, to generate the BE state. The experimental results and the theoretical calculations show that no EPR entanglement can be distilled between any two modes of the obtained four optical modes with LOCC when the four modes are spatially separated, although at the same time the quantum correlations among all four modes exist always. This means that a real BE state has been demonstrated [4,7]. We realize the superactivation of the CV Smolin state under the aid of another CV Smolin state (a copy of the first one) by means of the measurements and the feedback of the measured results among the submodes of the two CV Smolin states.

Before describing the experiments we briefly introduce the principle of generating and superactivating CV Smolin state. The EPR entangled state with two quantum correlated submodes EPR1 and EPR2, the wave function of which is expressed by $|\psi(r)\rangle = \sum_n \lambda^n \sqrt{1-\lambda^2}|n, n\rangle$ with $\lambda = \tanh r$, where r is the squeezing factor [22], is used to generate the CV Smolin state. Here, the quantum states are described by the electromagnetic field annihilation operator $\hat{a} = (\hat{x} + i\hat{p})/2$, which is expressed in terms of the amplitude $\hat{x}$ and phase $\hat{p}$ quadrature with the canonical commutation relation $[\hat{x}, \hat{p}] = 2i$. The EPR entangled state has a very strong correlation property, that is both their sum-amplitude quadrature variance $\langle \delta^2(\hat{x}_{a_{\mathrm{EPR1}}} + \hat{x}_{a_{\mathrm{EPR2}}})\rangle = 2e^{-2r}$ and difference-phase quadrature variance $\langle \delta^2(\hat{p}_{a_{\mathrm{EPR1}}} - \hat{p}_{a_{\mathrm{EPR2}}})\rangle = 2e^{-2r}$ are less than the quantum noise limit (QNL). For experimentally realizing the decoherence process, each submode of the EPR entangled state is mixed with a Gaussian noisy thermal state on a 50-50 beam splitter, respectively, as shown in Fig. 1(a). The output four-mode state is expressed by $\{\hat{b}_1 = (\hat{a}_{\mathrm{EPR1}} + \hat{\nu}_1^T)/\sqrt{2}, \hat{b}_2 = (\hat{a}_{\mathrm{EPR1}} - \hat{\nu}_1^T)/\sqrt{2}, \hat{b}_3 = (\hat{a}_{\mathrm{EPR2}} + \hat{\nu}_2^T)/\sqrt{2}, \hat{b}_4 = (\hat{a}_{\mathrm{EPR2}} - \hat{\nu}_2^T)/\sqrt{2}\}$, where $\hat{\nu}_1^T$ and $\hat{\nu}_2^T$ are the thermal state and $\langle \delta^2 \hat{x}_{\nu_1^T}\rangle = \langle \delta^2 \hat{x}_{\nu_2^T}\rangle = \langle \delta^2 \hat{p}_{\nu_1^T}\rangle = \langle \delta^2 \hat{p}_{\nu_2^T}\rangle \gg 1$. Thus the output four-mode state is a mixed state and only presents two independent quantum correlations

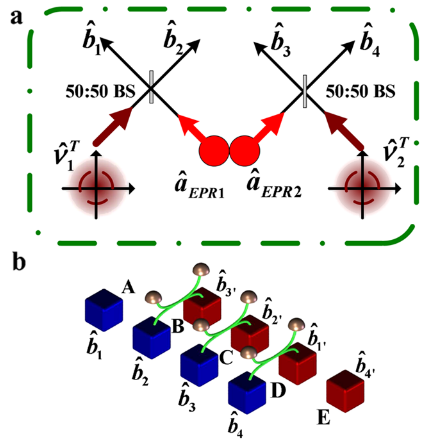

FIG. 1 (color online). (a) Schematic diagram of generating a CV four-mode unlockable BE state. (b) The superactivation of bound entanglement.

$\langle \delta^2(\hat{x}_{b_1} + \hat{x}_{b_2} + \hat{x}_{b_3} + \hat{x}_{b_4})\rangle \to 0$ and $\langle \delta^2(\hat{p}_{b_1} + \hat{p}_{b_2} - \hat{p}_{b_3} - \hat{p}_{b_4})\rangle \to 0$ when $r \to \infty$. We have theoretically proved that when the added noise of the thermal state $\langle \delta^2 \hat{x}_{\nu_i^T}\rangle = \langle \delta^2 \hat{p}_{\nu_i^T}\rangle$ is larger than $(2 - 3e^{-2r} + 2\sqrt{1 - 2e^{-2r} + 2e^{-4r}})$, the four-mode state generated by mixing EPR1 (2) and the thermal state is an unlockable BE state (see "Nondistillabity" in the Supplemental Material [24]). In this experiment $r = 0.63$, thus for preparing BE state the added noise $\langle \delta^2 \hat{x}_{\nu_i^T}\rangle = \langle \delta^2 \hat{p}_{\nu_i^T}\rangle$ should be larger than 2.69.

Generally, when the four parties sharing four-mode unlockable BE state are located in four spatially separated stations (thus they cannot perform joint quantum operation), they cannot be distilled by LOCC. However, an EPR entangled state can be distilled by the superactivation protocol, in which the tensor product of two identical CV four-mode unlockable BE states has to be employed [5]. Based on the superactivation protocol proposed originally by Shor *et al.* [5], two copies of CV four-mode unlockable BE states, $\rho^{(S)}_{1,2,3,4}$ and $\rho^{(S)}_{1',2',3',4'}$, are assigned to five remote stations A, B, C, D, and E as shown in Fig. 1(b). The four modes of state $\rho^{(S)}_{1,2,3,4}$ ($\rho^{(S)}_{1',2',3',4'}$), $\hat{b}_1$, $\hat{b}_2$, $\hat{b}_3$ and $\hat{b}_4$ ($\hat{b}_{1'}$, $\hat{b}_{2'}$, $\hat{b}_{3'}$ and $\hat{b}_{4'}$), are distributed to stations A, B, C and D (D, C, B and E), respectively. The joint Bell-state measurement on each pair of modes is performed in stations B, C, and D, respectively, and then all measured results are sent to A. The station A transfers the measurement results into the mode $\hat{b}_1$, which is expressed by

$$\begin{aligned}
\hat{x}_1' &= \hat{x}_1 + (\hat{x}_{3'} + \hat{x}_2) + (\hat{x}_{2'} + \hat{x}_3) + (\hat{x}_{1'} + \hat{x}_4) \\
&= \hat{x}_{1'} + \hat{x}_{2'} + \hat{x}_{3'} + (\hat{x}_1 + \hat{x}_2 + \hat{x}_3 + \hat{x}_4), \\
\hat{p}_1' &= \hat{p}_1 - (\hat{p}_{3'} - \hat{p}_2) + (\hat{p}_{2'} - \hat{p}_3) + (\hat{p}_{1'} - \hat{p}_4) \\
&= \hat{p}_{1'} + \hat{p}_{2'} - \hat{p}_{3'} + (\hat{p}_1 + \hat{p}_2 - \hat{p}_3 - \hat{p}_4). \qquad (1)
\end{aligned}$$

In this case, an EPR pair between A and E is distilled with $\langle \delta^2(\hat{x}_1' + \hat{x}_{4'})\rangle \to 0$ and $\langle \delta^2(\hat{p}_1' - \hat{p}_{4'})\rangle \to 0$ when $r \to \infty$, which means that the superactivation of a CV Smolin state can be achieved with the help of another CV Smolin state. From another point of view, the superactivation process can be systematically similar to perform the unconditional CV entanglement swapping [25,26], in which entanglement can be swapped onto two parties originating from two different sources which were completely independent before. In the experiment, two independent four-mode unlockable BE states are employed as the two different sources instead of two entangle pairs [25,26]. Since the CV four-mode unlockable BE state is asymmetric, which is different from the four-qubit unlockable BE state with the invariance under arbitrary permutation, only two cases of $(\hat{b}_{3'}, \hat{b}_{2'}, \hat{b}_{1'})$ and $(\hat{b}_{3'}, \hat{b}_{1'}, \hat{b}_{2'})$ [all other cases $(\hat{b}_{2'}, \hat{b}_{3'}, \hat{b}_{1'})$, $(\hat{b}_{2'}, \hat{b}_{1'}, \hat{b}_{3'})$, $(\hat{b}_{1'}, \hat{b}_{2'}, \hat{b}_{3'})$, and $(\hat{b}_{1'}, \hat{b}_{3'}, \hat{b}_{2'})$ cannot] corresponding to the stations (B, C, D) may distill the EPR pair between A and E by holding $\hat{b}_1$ and $\hat{b}_{4'}$ with $(\hat{b}_2, \hat{b}_3, \hat{b}_4)$ distributed to the stations (B, C, D), respectively. Thus the superactivation process also exhibits the asymmetric characteristics in the CV regime.

In the following, we discuss the experimental generation of the CV Smolin states first, and then perform the superactivation of the produced state. Figure 2 is the schematic of the experimental setup for the superactivation of multipartite unlockable BE state. For the generation of a four-partite unlockable BE state, two pairs of EPR entangled states ($\hat{a}_{\rm EPR1}$, $\hat{a}_{\rm EPR2}$ and $\hat{a}_{\rm EPR3}$, $\hat{a}_{\rm EPR4}$) are generated from two nondegenerate optical parametric amplifiers (NOPA_1 and NOPA_2) respectively, which are pumped by an intracavity frequency-doubled and frequency-stabilized Nd:YAP-LBO (Nd doped YAlO_3 perovskite–$\mathrm{LiB}_3\mathrm{O}_5$) laser with the harmonic wave output of 4.0 W at 540 nm wavelength and the subharmonic wave of 1.2 W at 1080 nm wavelength (Yuguang Co. Ltd., F-VIB). To obtain a pair of symmetric EPR entangled state, the two NOPAs are constructed in identical configuration, both of which consist of an α-cut type-II KTP crystal and a concave mirror. The configuration and system parameters of NOPAs are described in the online Supplemental Material [24] and Ref. [27]. Through a parametric down-conversion process with type-II phase matching, two EPR entangled states with the anticorrelated amplitude quadratures and the correlated phase quadratures are produced by the two independent NOPAs operating at deamplification (i.e., the pump field and the injected signal field are out of phase) [25]. The measured correlation noise levels of the amplitude sum and the phase difference for $\mathrm{EPR}_{1,2}$ ($\mathrm{EPR}_{3,4}$) both are -5.5 ± 0.1 dB [-5.4 ± 0.1 dB] below the QNL (0 dB), which correspond to $\langle\delta^2(\hat{x}_{a_{\rm EPR1}} + \hat{x}_{a_{\rm EPR2}})\rangle = \langle\delta^2(\hat{p}_{a_{\rm EPR1}} - \hat{p}_{a_{\rm EPR2}})\rangle = 0.56 \pm 0.02 < 2(\langle\delta^2(\hat{x}_{a_{\rm EPR3}} + \hat{x}_{a_{\rm EPR4}})\rangle = \langle\delta^2(\hat{p}_{a_{\rm EPR3}} - \hat{p}_{a_{\rm EPR4}})\rangle = 0.58 \pm 0.02 < 2)$, where 2 is the normalized QNL for the optical field involving the two modes. At the same time the antisqueezing quantum noise levels of the amplitude difference and the phase sum are also measured, both of which are 9.7 ± 0.1 dB (9.5 ± 0.1 dB) above the QNL corresponding to $\langle\delta^2(\hat{x}_{a_{\rm EPR1}} - \hat{x}_{a_{\rm EPR2}})\rangle = \langle\delta^2(\hat{p}_{a_{\rm EPR1}} + \hat{p}_{a_{\rm EPR2}})\rangle = 9.33 \pm 0.21 > 2, (\langle\delta^2(\hat{x}_{a_{\rm EPR3}} - \hat{x}_{a_{\rm EPR4}})\rangle = \langle\delta^2(\hat{p}_{a_{\rm EPR3}} + \hat{p}_{a_{\rm EPR4}})\rangle = 8.91 \pm 0.21 > 2)$. The thermal state $(\hat{\nu}_1^T, \hat{\nu}_2^T, \hat{\nu}_3^T, \hat{\nu}_4^T)$ is generated by randomly modulating the amplitude and the phase quadratures of a coherent state at 1080 nm with noisy signals of Gaussian function distribution. The modulations are achieved by means of the amplitude and the phase modulators (AM and PM), respectively, connected to Gaussian random number generators (GRNGs). The entangled optical modes $\hat{a}_{\rm EPR1}$, $\hat{a}_{\rm EPR2}$ and $\hat{a}_{\rm EPR3}$, $\hat{a}_{\rm EPR4}$ coming from NOPA1 and NOPA2 are mixed with the Gaussian noisy thermal state $\hat{\nu}_1^T$, $\hat{\nu}_2^T$ and $\hat{\nu}_3^T$, $\hat{\nu}_4^T$ at a 50-50 beam splitter (BS_{1-4}), respectively. The output four-mode $\hat{b}_1$, $\hat{b}_2$, $\hat{b}_3$, $\hat{b}_4$ ($\hat{b}_{1'}$, $\hat{b}_{2'}$, $\hat{b}_{3'}$, $\hat{b}_{4'}$) are detected by the balanced homodyne detectors (BHDs) in which all needed local oscillation beams originate from the pump laser. The fluctuation variances of the amplitude or phase quadratures of the corresponding modes are measured by controlling the phase of the local oscillators. The measured photocurrents of quadratures of respective modes are combined by the positive (⊕) or negative (⊖) power combiners. The results in Fig. 3 show that only two pairs of the measured correlation variances, $(\hat{x}_{b_1} + \hat{x}_{b_2} + \hat{x}_{b_3} + \hat{x}_{b_4})$, $(\hat{p}_{b_1} + \hat{p}_{b_2} - \hat{p}_{b_3} - \hat{p}_{b_4})$ [$(\hat{x}_{b_{1'}} + \hat{x}_{b_{2'}} + \hat{x}_{b_{3'}} + \hat{x}_{b_{4'}})$, $(\hat{p}_{b_{1'}} + \hat{p}_{b_{2'}} - \hat{p}_{b_{3'}} - \hat{p}_{b_{4'}})$] are -5.2 ± 0.1 dB [-5.0 ± 0.1 dB] below the QNL, respectively, which correspond to $\langle\delta^2(\hat{x}_{b_1} + \hat{x}_{b_2} + \hat{x}_{b_3} + \hat{x}_{b_4})\rangle = \langle\delta^2(\hat{p}_{b_1} + \hat{p}_{b_2} - \hat{p}_{b_3} - \hat{p}_{b_4})\rangle = 1.21 \pm 0.03 < 4[\langle\delta^2(\hat{x}_{b_{1'}} + \hat{x}_{b_{2'}} + \hat{x}_{b_{3'}} + \hat{x}_{b_{4'}})\rangle = \langle\delta^2(\hat{p}_{b_{1'}} + \hat{p}_{b_{2'}} - \hat{p}_{b_{3'}} - \hat{p}_{b_{4'}})\rangle = 1.27 \pm 0.03 < 4]$, where 4 is the normalized QNL for the optical field involving four modes. For generating a real unlockable BE state we have to destroy

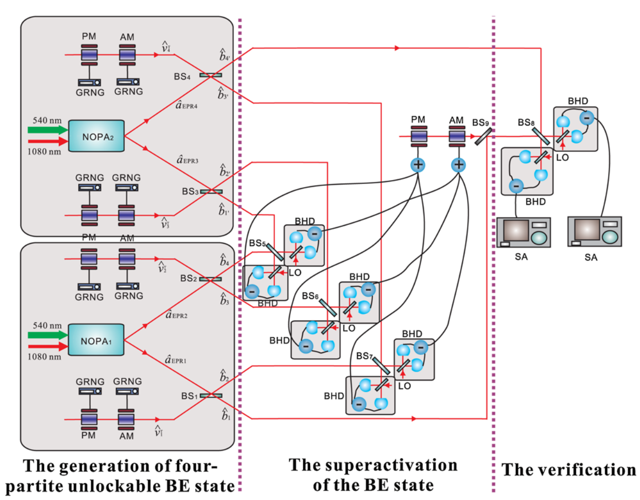

FIG. 2 (color online). Schematic of the experimental setup. NOPA_{1-2}, nondegenerate optical parametric amplifier; PM, phase modulator; AM, amplitude modulator; GRNG, Gaussian random number generator; BS_{1-8}, 50-50 beam splitter; BS_9, 98/2 beam splitter; LO, local oscillator beam; BHD, balanced homodyne detector; SA, spectrum analyzer.

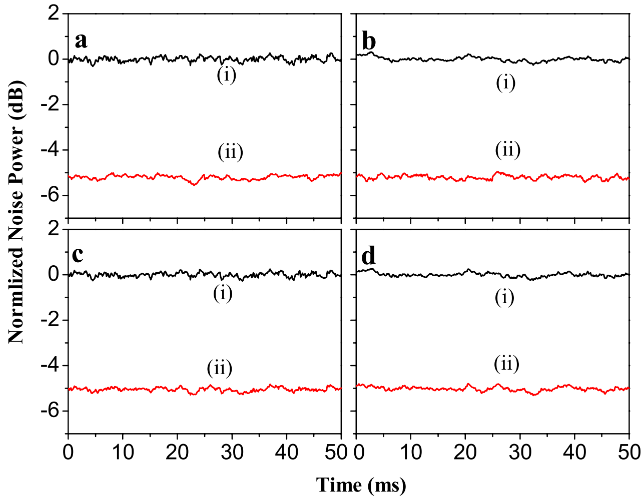

FIG. 3 (color online). The measured correlation variance of four-mode unlockable BE states at 2 MHz. (a) $\langle\delta^2(\hat{x}_{b_1}+\hat{x}_{b_2}+\hat{x}_{b_3}+\hat{x}_{b_4})\rangle$, (b) $\langle\delta^2(\hat{p}_{b_1}+\hat{p}_{b_2}-\hat{p}_{b_3}-\hat{p}_{b_4})\rangle$, (c) $\langle\delta^2(\hat{x}_{b_{1'}}+\hat{x}_{b_{2'}}+\hat{x}_{b_{3'}}+\hat{x}_{b_{4'}})\rangle$, (d) $\langle\delta^2(\hat{p}_{b_{1'}}+\hat{p}_{b_{2'}}-\hat{p}_{b_{3'}}-\hat{p}_{b_{4'}})\rangle$. (i) The QNL; (ii) The correlation noise power. The measurement parameters of the SA: RBW 30 kHz; VBW 100 Hz.

the quantum correlations between modes $\hat{b}_1$ and $\hat{b}_3$ as well as $\hat{b}_2$ and $\hat{b}_4$ by noise environments, totally. If the GRNGs are not applied and thus the quantum fluctuation of the input fields $\hat{\nu}_1^V$ and $\hat{\nu}_2^V$ on the BS1 and BS2 is the vacuum noise $\langle\delta^2\hat{x}_{\nu_i^V}\rangle=\langle\delta^2\hat{p}_{\nu_i^V}\rangle=1.00$, the measured correlation noises of the amplitude sum of $(\hat{x}_{b_1}+\hat{x}_{b_3})$ and $(\hat{x}_{b_2}+\hat{x}_{b_4})$ as well as the phase difference of $(\hat{p}_{b_1}-\hat{p}_{b_3})$ and $(\hat{p}_{b_2}-\hat{p}_{b_4})$ are -1.9 ± 0.1 dB below the QNL, i.e., $\langle\delta^2(\hat{x}_{b_1}+\hat{x}_{b_3})\rangle=\langle\delta^2(\hat{x}_{b_2}+\hat{x}_{b_4})\rangle=\langle\delta^2(\hat{p}_{b_1}-\hat{p}_{b_3})\rangle=\langle\delta^2(\hat{p}_{b_2}-\hat{p}_{b_4})\rangle=1.29\pm0.02<2$. In this case the quantum correlations exist between the modes $\hat{b}_1$ and $\hat{b}_3$ as well as $\hat{b}_2$ and $\hat{b}_4$. The calculated results show that when the added thermal noise increases the superactivated entanglements decrease (see Fig. 1 of the Supplemental Material [24]). To obtain a larger superactivation entanglement, the added noises should be as small as possible and of course it must be larger than 2.69, at least for our system. We take two noise values of 2.70 and 4.70 to implement the experiment. When the GRNGs are turned on and the input fields on BS_1 and BS_2 are changed to the noisy thermal optical field, $\hat{\nu}_1^T$ and $\hat{\nu}_2^T$, with the noise higher than the vacuum noise $\langle\delta^2\hat{x}_{\nu_i^T}\rangle=\langle\delta^2\hat{p}_{\nu_i^T}\rangle=2.70\pm0.01(4.70\pm0.02)$, the measured correlation variances of $(\hat{x}_{b_1}+\hat{x}_{b_3})$ and $(\hat{x}_{b_2}+\hat{x}_{b_4})$ as well as $(\hat{p}_{b_1}-\hat{p}_{b_3})$ and $(\hat{p}_{b_2}-\hat{p}_{b_4})$ are 1.8 ± 0.1 dB (4.0 ± 0.1 dB) above the QNL, i.e., $\langle\delta^2(\hat{x}_{b_1}+\hat{x}_{b_3})\rangle=\langle\delta^2(\hat{x}_{b_2}+\hat{x}_{b_4})\rangle=\langle\delta^2(\hat{p}_{b_1}-\hat{p}_{b_3})\rangle=\langle\delta^2(\hat{p}_{b_2}-\hat{p}_{b_4})\rangle=2.98\pm0.03(4.97\pm0.08)$. Obviously, the noisy thermal optical field has destroyed the unwanted quantum correlations between modes $\hat{b}_1$ and $\hat{b}_3$ as well as $\hat{b}_2$ and $\hat{b}_4$. However, at the same time the four-mode quantum correlations are still retained, since $\langle\delta^2(\hat{x}_{b_1}+\hat{x}_{b_2}+\hat{x}_{b_3}+\hat{x}_{b_4})\rangle=\langle\delta^2(\hat{p}_{b_1}+\hat{p}_{b_2}-\hat{p}_{b_3}-\hat{p}_{b_4})\rangle=1.21\pm0.03(1.21\pm0.03)<4$. According to the definition of the BE states and certification in the Supplemental Material, when the four modes are located in spatially separated stations, if no EPR entanglement can be distilled between any two parties with LOCC, the modes $\hat{b}_1$, $\hat{b}_2$, $\hat{b}_3$, $\hat{b}_4$ (similarly $\hat{b}_{1'}$, $\hat{b}_{2'}$, $\hat{b}_{3'}$, $\hat{b}_{4'}$) form a four-mode multipartite CV unlockable BE state [4,18,24]. Thus the above results show that a real four-mode CV BE state has been experimentally produced.

In order to implement superactivation, the submodes $\hat{b}_1$, $\hat{b}_2$, $\hat{b}_3$, $\hat{b}_4$ are sent to four remote stations A, B, C, D and the submodes $\hat{b}_{1'}$, $\hat{b}_{2'}$, $\hat{b}_{3'}$, $\hat{b}_{4'}$ are sent to stations D, C, B, E, respectively. Then the parties B, C as well as D perform joint Bell-state measurements of mode $\hat{b}_2$ and $\hat{b}_{3'}$, $\hat{b}_3$ and $\hat{b}_{2'}$, as well as $\hat{b}_4$ and $\hat{b}_{1'}$ as shown in Fig. 2. In this case, both the variances of the sum of amplitude quadrature $\langle\delta^2(\hat{x}_{b_{3'}}+\hat{x}_{b_2})\rangle$, $\langle\delta^2(\hat{x}_{b_{2'}}+\hat{x}_{b_3})\rangle$, $\langle\delta^2(\hat{x}_{b_{1'}}+\hat{x}_{b_4})\rangle$ and the difference of phase quadrature $\langle\delta^2(\hat{p}_{b_{3'}}-\hat{p}_{b_2})\rangle$, $\langle\delta^2(\hat{p}_{b_{2'}}-\hat{p}_{b_3})\rangle$, $\langle\delta^2(\hat{p}_{b_{1'}}-\hat{p}_{b_4})\rangle$ are simultaneously measured with six sets of BHDs and the measured results are sent to station A. To establish the entanglement of mode $\hat{b}_1$ and $\hat{b}_{4'}$, a coherent light at 1080 nm is modulated by the received photocurrents with AM and PM modulators, and then is combined with mode $\hat{b}_1$ on a beam splitter (BS_9) of reflectivity $R=98\%$ at the station A. In this manner the mode $\hat{b}_1$ is displaced to $\hat{b}_1'$:

$$\begin{aligned}\hat{b}_1' = \hat{b}_1 &+ g_x^B(\hat{x}_{b_{3'}}+\hat{x}_{b_2}) + g_x^C(\hat{x}_{b_{2'}}+\hat{x}_{b_3}) \\ &+ g_x^D(\hat{x}_{b_{1'}}+\hat{x}_{b_4}) + ig_p^B(\hat{p}_{b_{3'}}-\hat{p}_{b_2}) \\ &+ ig_p^C(\hat{p}_{b_{2'}}-\hat{p}_{b_3}) + ig_p^D(\hat{p}_{b_{1'}}-\hat{p}_{b_4}),\end{aligned} \tag{2}$$

where the parameters g_x^B, g_x^C, g_x^D, g_p^B, g_p^C, and g_p^D describe the amplitude and phase classical gains in the process of transforming the modulation photocurrents into the corresponding output light fields.

To verify the superactivation process, the quantum correlation variances of the sum of amplitude quadratures and the difference of phase quadratures between $\hat{b}_1'$ and $\hat{b}_{4'}$ are measured by two sets of BHDs and analyzed by spectrum analyzers (SAs). The dependences of the superactivated EPR entanglement and the gains on the extra noise of antisqueezed quadrature components and the noise of the thermal states are analyzed for a given squeezing degree r in Eq. 12 in the Supplemental Material [24]. When the variance of the thermal states is $\langle\delta^2\hat{x}_{\nu^T}\rangle=\langle\delta^2\hat{p}_{\nu^T}\rangle=2.70\pm0.01(4.70\pm0.02)$, the measured normalized correlation noise powers of the amplitude sum and the phase difference between the superactivated two modes $\hat{b}_1'$ and $\hat{b}_{4'}$ are -0.7 ± 0.1 dB (-0.4 ± 0.1 dB) below the QNL (See trace (ii) and (iv) in Figs. 4(a) and 4(b) which correspond to $\langle\delta^2(\hat{x}_{b_1'}+\hat{x}_{b_{4'}})\rangle=1.70\pm0.01(1.81\pm0.02)$ and $\langle\delta^2(\hat{p}_{b_1'}-\hat{p}_{b_{4'}})\rangle=1.70\pm0.01(1.81\pm0.02)$). Thus the

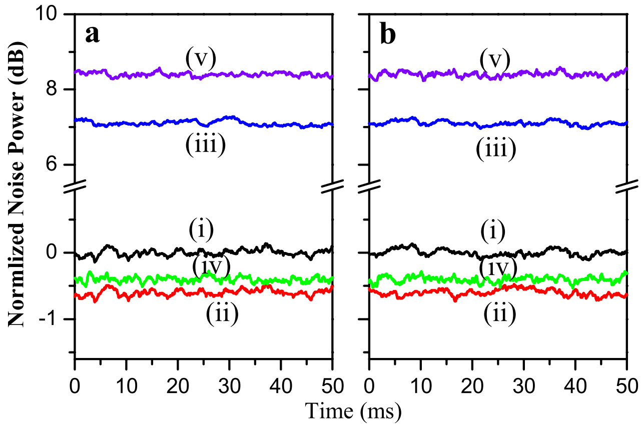

FIG. 4 (color online). The correlation variance of the superactivated EPR entanglement measured at the sideband mode of 2 MHz. (a) $\langle \delta^2(\hat{x}_{b_1'} + \hat{x}_{b_{4'}})\rangle$, (b) $\langle \delta^2(\hat{p}_{b_1'} - \hat{p}_{b_{4'}})\rangle$. (i) The QNL; (ii)[(iv)] The correlation noise power with the help of station B, C and D for $\langle \delta^2 \hat{x}_{\nu_i^T}\rangle = \langle \delta^2 \hat{p}_{\nu_i^T}\rangle = 2.70 \pm 0.01[4.70 \pm 0.02]$; (iii)[(v)] The correlation noise power without the help of stations B, C, and D for $\langle \delta^2 \hat{x}_{\nu_i^T}\rangle = \langle \delta^2 \hat{p}_{\nu_i^T}\rangle = 2.70 \pm 0.01[4.70 \pm 0.02]$.

combination of the correlation variances satisfies the inseparable criteria of EPR entanglement given by Duan *et al.* [28]: i.e., $\langle \delta^2(\hat{x}_{b_1'} + \hat{x}_{b_{4'}})\rangle + \langle \delta^2(\hat{p}_{b_1'} - \hat{p}_{b_{4'}})\rangle = 3.40 \pm 0.02(3.62 \pm 0.04) < 4$. The experimental results demonstrate that the two unlockable BE states generated by mixing the EPR states and two thermal states with noises of 2.70 and 4.70 respectively, both have been superactivated. The trace (iii) and (v) in Figs. 4(a) and 4(b) are the noise power spectra of the amplitude sum and phase difference of mode $\hat{b}_1$ and $\hat{b}_{4'}$ when the photocurrents measured in station B, C, and D are blocked, and are much higher than the QNL [trace (i)].

We have experimentally demonstrated the superactivation of the BE state using two copies of the CV four-mode unlockable BE state. Multipartite unlockable BE states may serve as a useful quantum resource for new multiparty communication schemes, such as remote information concentration [13] and quantum secret sharing [14]. Especially, some interesting quantum information transfers can be achieved only under the aid of the activated BE states [5]. The presented work also provides an experimental platform for the investigation of nonlocality distillation, which is important for quantitatively tackling the problem of nonlocal correlations in quantum mechanics [29]. We believe that this work will contribute to a deep understanding of CV nonlocal entanglement.

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