Deterministic and Universal Quantum Squeezing Gate with a Teleportation-Like Protocol

Xiaocong Sun, Yajun Wang, Yuhang Tian, Qingwei Wang, Long Tian, Yaohui Zheng,* and Kunchi Peng

Squeezing transformation as an essential component of quantum information processing, gives rise to the possibility to perform various tasks such as distributed quantum computation and the quantum-logic gate. However, the reported squeezing gate with best performance so far is realized with low success probability, while the performance of the deterministic ones is currently circumscribed by the limited squeezing degree of the nonclassical ancilla. To address this issue, a new scheme of deterministic and universal quantum squeezing gate with the property of nonlocal operation owing to the teleportation-like protocol is developed and demonstrated. A high-fidelity squeezing operation, even when the level of target squeezing being up to 10 dB, is demonstrated where a squeezed state with nonclassical noise reduction of 6.5 dB is directly observed. Moreover, a high-fidelity complex operation including a Fourier transformation and a phase squeezing gate are performed, exploring the potential of implementing the complex task of quantum information processing with the presented functional unit. The method can be applied to distributed quantum processor, the creation of exotic nonclassical states, and quantum error correction.

1. Introduction

Gaussian transformation along with Gaussian state preparation and tomography constitutes the continuous variable (CV) quantum information processing (QIP).

15 dB-squeezed vacuum state in optical domain has been generated via optical parametric oscillator (OPO), namely in-line squeezing operation. However, applying the operation on arbitrary input states faces substantial challenges.

Here, we present a scheme to attain an unconditional quantum squeezing gate with high-fidelity. Incorporating the high quality Einstein–Podolsky–Rosen (EPR) entangled resource, we demonstrate the ability to operate the squeezing gate with high fidelity. Even when the target squeezing is set up to 10 dB, the measured fidelity is still above 78%, much better than the record in previous deterministic configurations (target squeezing of 6.0 dB with a fidelity of 78% reported in ref. [13]). Strikingly, in contrast to conventional entanglement ancilla-assisted feedforward configuration, only optical splitting ratio and electronic feedback gain are optimized corresponding to various target squeezing, relaxing the technical challenge in relative phase locking at arbitrary angles. Compared with the protocol with the ancillary squeezed state, the one presented here inherently promises nonlocal operation, offering the opportunities to implement the distributed quantum tasks. Furthermore, we take the complex operation by combining the squeezing gate with a Fourier gate, as an example to illustrate the potential of implementing the complex task of quantum information processing with high fidelity by means of the presented scheme, which overcomes the challenge met by the scheme employing an ancillary squeezed state.
2. Quantum Protocol

The principle of the operation is shown in Figure 1. We use a configuration with EPR entanglement assistance to realize the desired high-fidelity squeezing operation, which can be outlined as follows. Generally, quantum states of light can be described by the electromagnetic field annihilation operator $\hat{a}$. The associated $X$-quadrature and $P$-quadrature are written as $\hat{X} = (\hat{a} + \hat{a}^\dagger)/\sqrt{2}$ and $\hat{P} = (\hat{a} - \hat{a}^\dagger)/\sqrt{2}$ respectively with the canonical commutator $[\hat{X}, \hat{P}] = i(\hbar = 1)$. In this teleportation-like protocol, in-put state denoted as $\hat{a}_\text{in}$ is combined with one half of the EPR beam $\hat{a}_\text{EPR}$ at a beam splitter with a variable reflectivity $R$, where the relative phase is locked to zero. And then the amplitude $\hat{X}$ and phase $\hat{P}$ components are measured by two homodyne detectors (HOMs), respectively. Specific phase locking to $0$ and $\pi/2$ are actively controlled to extract the information of the quadratures, relaxing the technical challenge in relative phase locking at arbitrary angles. The extracted information from homodyne detection ($\hat{X}$ in HOM$_1$ and $\hat{P}$ in HOM$_2$) is encoded in an auxiliary beam via two independent amplitude and phase modulators with the adjustable scaling factors $g_X$ and $g_P$, respectively (see Section S1, Supporting Information$^{[23]}$ for more details). The auxiliary beam is combined with the other half of the EPR beam $\hat{a}_\text{EPR}$, on a 1/99 beam splitter ($R_D = 0.01$) with a relative phase of 0. The information from output state is divided into two parts, one half enters the spectrum analyzer to acquire the frequency domain data, and the other half is used to collect the data in time domain.

Since an EPR entangled beam used here is identified by satisfying the condition $V(\hat{X}_\text{EPR1} + \hat{X}_\text{EPR2}) = V(\hat{P}_\text{EPR1} - \hat{P}_\text{EPR2}) = e^{-2r}$, the squeezing transformation of $X$-quadrature (Equation (1) for $R < 1/2$) and $P$-quadrature (Equation (1) for $R > 1/2$) can be realized by manipulating the variable reflectivity $R$ and optimizing the values of $g_X$ and $g_P$, respectively, given as (see Section S2, Supporting Information$^{[23]}$ for more details)

$$
\begin{pmatrix}
\hat{X}_\text{out} \\ \hat{P}_\text{out}
\end{pmatrix} =
\begin{pmatrix}
\sqrt{\frac{1 - R}{1 - R}} & 0 \\
0 & \sqrt{\frac{1 + R}{1 - R}}
\end{pmatrix}
\begin{pmatrix}
\hat{X}_\text{in} \\ \hat{P}_\text{in}
\end{pmatrix}
+ \begin{pmatrix}
\hat{X}_\text{EPR} \\ -\hat{P}_\text{EPR}
\end{pmatrix}
$$  (1)

More explicitly, in contrast with the standard quantum teleportation$^{[34-38]}$ the value of $R$ is varied to manipulate the level of target squeezing, rather than being fixed at 1/2. It is much easier to be implemented than the conventional schemes$^{[14,15]}$ where the tunability is promised by the relative phase to be locked. Ideally, unit fidelity can be achieved at arbitrary target squeezing.

Figure 1. Schematic illustration of the deterministic squeezing gate. a) Mechanism of squeezing gate $\mathcal{S}$. b) Experimental setup of off-line scheme with an entangled state. OPO: optical parametric oscillator; BS: beam splitter; HWP: half wave plate; PBS: polarization beam splitter; VBS: variable beam splitter; HR: high reflectivity mirror; AM: amplitude modulator; PM: phase modulator; OPS: optical phase shifter; HOM: homodyne detection; Aux: auxiliary beam; PS: power splitter; SA: spectrum analyzer; LP: low-pass filter; PA: preamplifier; OSC: oscilloscope.
level by exploiting the EPR source with infinite degree of entanglement.

As stated above, a prerequisite for such an universal and unconditional squeezing gate is the generation of high quality optical EPR entangled state. Here, 12 dB-entangled EPR beams are experimentally produced by combining two independent squeezed beams at a 50/50 beam splitter, with the relative phase $\pi/2$ actively servo-controlled (see Section S3, Supporting Information for more details). 13.8 dB squeezed vacuum states with 20.2 dB anti-squeezing are produced by OPOs, where the semi-monolithic single-resonant standing wave cavity is formed by a piezo-actuated concave mirror and the back surface of a periodically poled KTiOPO4 (PPKTP) crystal with a dimension of 1 mm $\times$ 2 mm $\times$ 10 mm. In addition, to verify the universality of the squeezing gate reported here, one has to create the input states located at arbitrary location of the phase space, and this is realized by modulating the fundamental beam at 3 MHz sideband frequency using electro-optical phase and amplitude modulators. Notice that all the relative phases, including those in the beam interference and homodyne detection, are actively stabilized during the measurement cycle in order to suppress the noise coupling of anti-squeezing as much as possible.

### 3. Experimental Results

We proceed to evaluate the performance of our scheme. Typically, it is characterized by the fidelity, determined by the overlap between the ideal state $|\psi\rangle$ and output state $|\psi_{\text{out}}\rangle$, that is, $F = \langle \psi | \hat{\rho}_{\text{out}} | \psi \rangle$ with the density matrix $\hat{\rho}_{\text{out}} = |\psi_{\text{out}}\rangle \langle \psi_{\text{out}} |$. Experimentally, the output states are evaluated via the measurements of the noise variances of the quadrature components and also the reconstructions of Wigner functions distributions of the quantum states in phase space. Figure 2a illustrates the fidelity as a function of the level of target squeezing for three values of EPR ancilla with vacuum input. Compared with the results of the numerical simulation with 4 and 6 dB EPR ancilla (yellow and green curves, respectively), our work (red points and curve) shows a remarkable advantage, exhibiting the optimal fidelity better than 95%. As the target squeezing increases, the fidelity has a slower decrease. Even when the target squeezing is set up to 10 dB, the measured fidelity is still above 78%, much better than previous deterministic configurations. In fact, we expect to realize a higher fidelity and simultaneously keep the high success probability by applying an extra probability filter (see Section S5, Supporting Information for more details). Figure 2b shows the fidelity as a function of the squeezing level of EPR source while fixing the target squeezing at 10 dB, indicating the significant improvement attributed to the better initial EPR source. As for high level of target squeezing, the high quality EPR ancilla is a key building block of quantum squeezing gate. In addition, the experimental observations are in good agreement with the theoretical predictions (red solid line in Figure 2a, blue dashed line in Figure 2b, demonstrating the feasibility of the presented scheme. Figure 2c shows the (anti-)squeezing level of output state as a function of target squeezing level.

As the hallmark of the unitary squeezing gate, the universality and robustness should be held. A universal squeezing gate operates on arbitrary inputs regardless of the original location in phase space. Figure 3 shows the reconstructed Wigner function of six input states (marked with states A–F) at different location in phase space after processing the data collected by the oscilloscope, where squeezing in X-quadrature is operated on states A–C and squeezing in P-quadrature is realized in states D–F. Here, the squeezing axis is set by adjusting the value of $R$, larger or smaller than 1/2, as stated above. The target squeezing for all states are 4.1, 7.2, and 10.0 dB, respectively. We find fidelity of 0.912 $\pm$ 0.024 for state A marked in orange and state D denoted in red (4.1 dB squeezing), 0.848 $\pm$ 0.014 for state B marked in pink and state E denoted in blue (7.2 dB squeezing), and 0.780 $\pm$ 0.016 for state C marked in purple and state F denoted in green (10.0 dB squeezing).

To confirm the reversibility of the presented configuration, we further explore the complex operation with Fourier transformation followed by a phase squeezing gate with 10.0 dB-target squeezing as indicated in Figure 4. Fourier operation is a special case ($\theta = \pi/2$) of rotation operation $R(\theta) = e^{iR(\pi/2)P}$, describing the state rotated counter-clockwise in phase space with an angle $\theta$. Such a complex operation is experimentally realized by exchanging the information encoded on amplitude and phase modulators, that is, feeding forward the measurement outcomes of HOM to PM, and that of HOM to AM. As shown in Figure 4b, the input is a coherent state with the displacement $|\psi\rangle = 0.78|0\rangle + 0.66|\pm\rangle$. The phase noise $\Delta \varphi = 0.005$ set by the key building block of quantum squeezing gate.
Figure 3. Phase-space diagram for the operation of squeezing gate on six different input states. Left panel: The dashed and solid ellipse represent the theoretical predictions and measured results of reconstructed Wigner functions, respectively. The target squeezing are 4.1 dB for state A and state D, 7.2 dB for state B and state E, and 10.0 dB for state C and state F, respectively. States A, B, and C are squeezed in the X-quadrature with the variable reflectivity \( R < 1/2 \), while states D, E, and F are squeezed in the P-quadrature with \( R > 1/2 \). Right panel: Reconstructed Wigner functions of states A–F.

Figure 4. A complex operation with a Fourier transformation followed by a phase squeezing gate. The level of the target squeezing is 10.0 dB. a) Schematic of the mechanism of Fourier transformation \( F \) and squeezing gate \( S \). Panels b,c) present the noise contours of the reconstructed Wigner function distribution from data collected by the oscilloscope. As shown in Figure 4b, the input is a coherent state with a displacement in P-quadrature. It is realized by applying a 10.0 \( \pm \) 0.20 dB phase modulation relative to shot noise limit at 3 MHz. Following the Fourier transformation, amplitude and phase components exchange the information with each other. It means that the transformed state owns the displacement of 10.0 \( \pm \) 0.20 dB in X-quadrature but no displacement in P-quadrature. Finally, the squeezing operation in P-quadrature is implemented with 10 dB target squeezing, accompanying with 10.2 \( \pm \) 0.27 dB anti-squeezing in X-quadrature, as interpreted in Figure 4c.
in P-quadrature. It is realized by applying a 10.0 ± 0.20 dB phase modulation relative to shot noise limit at 3 MHz. The output state is presented in Figure 4c with 10.2 ± 0.27 dB anti-squeezing in X-quadrature and 9.5 dB squeezing in P-quadrature. We therefore achieve a fidelity of $F = 0.779 ± 0.017$. As a universal case, a rotation operation with arbitrary angle $\theta$ can be achieved by manipulating the measured quadrature angles of HOMs ($\theta$ for HOM$_X$, $-\theta$ for HOM$_P$). In this regard, by combining with a rotation operation, we can implement a universal high-fidelity squeezing gate, no matter where the location of the input state is in phase space (see Section S4, Supporting Information[23] for more details).

4. Conclusion

Here we report the realization of a deterministic and universal quantum squeezing gate with high-fidelity. Intriguingly, by utilizing the high quality EPR source, high fidelity is always ensured even when the level of target squeezing increased up to 10 dB, while the maximum squeezing level of 6.5 dB is directly obtained. By manipulating the optical splitting ratio, the associated target squeezing is achieved, relaxing the technical challenge of locking the relative phase to arbitrary angles. Its nonlocal property ensures the potential application in distributed quantum processor, which aims to realize the large scale quantum computer. Moreover, a complex gate sequence is operated with a high fidelity, demonstrating the feasibility of implementing multi-step quantum operation with only one processing unit. This work offers the opportunities to explore the hybrid quantum information,[41–47] revealing the potential for the generation of unconventional non-classical states and even the universal quantum computation. For instance, the efficiency of Bell measurement can be boosted by inserting a CV squeezing operation before discrete variable photon counting measurement.[48,49] Further, by applying an extra probability filter,[50,51] our scheme expects to achieve higher fidelity with high success probability[52] (see Section S5, Supporting Information[23] for more details).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

quantum information, quantum gates, quantum protocol

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