Exploring a New Regime for Processing Optical Qubits: Squeezing and Unsqueezing Single Photons

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We implement the squeezing operation as a genuine quantum gate, deterministically and reversibly acting "online" upon an input state no longer restricted to the set of Gaussian states. More specifically, by applying an efficient and robust squeezing operation for the first time to non-Gaussian states, we demonstrate a two-way conversion between a particlelike single-photon state and a wavelike superposition of coherent states. Our squeezing gate is reliable enough to preserve the negativities of the corresponding Wigner functions. This demonstration represents an important and necessary step towards hybridizing discrete and continuous quantum protocols.

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From a fundamental point of view, quantum states of light can behave in a complementary fashion, showing both particlelike and wavelike behavior. With regards to an application such as quantum computing, an important proposal for universally processing photonic qubits [1] makes use of quantum particle detections (i.e., photon counting) and quantum wave evolutions (i.e., quantum interferences through passive, energy-preserving linear optical circuits). In this scheme, however, the required ancilla states consist of many highly entangled photons and thus are out of reach of current experimental capabilities. It is therefore reasonable to extend the toolbox of optical quantum operations in order to reduce the cost of the necessary quantum resources. For instance, apart from discrete "click by click" measurements that rely on the particlelike nature of light [2], quantum light fields may be detected more naturally via continuous phase-space measurements exploiting their wavelike features [3]. In fact, two recent continuous-variable teleportation experiments on non-Gaussian input states, using Gaussian entanglement and Gaussian homodyne measurements, demonstrate that not only a wavelike coherent-state superposition (CSS) [4], but also a particlelike photonic qubit [5] can be transferred efficiently and reliably, preserving the negativity of the Wigner function and exceeding the classical fidelity limits, respectively.

In order to further investigate the potential of such *hybrid* schemes [6], which simultaneously exploit discrete and continuous techniques for encoding, measuring, and processing quantum states of light, it is desirable, besides Gaussian measurements and resource states, to also add Gaussian gate operations to the set of possible optical elements for processing photonic qubits. Indeed, one feasible regime of single-photon operations has still remained unexplored: Gaussian operations including *active squeezers*, still linearly transforming the mode operators, but no longer preserving energy.

The squeezing operation has been traditionally associated with continuous-variable quantum optics and information [7–9]. In fact, it can be considered the essential, elementary operation of this area, as it is a necessary component of all Gaussian gates [10] and even some non-Gaussian gates require it for their implementation [11]. The construction of a genuine squeezing *gate* is fundamentally different from simply preparing a particular squeezed *state*. This basic difference was previously addressed in an experiment employing a measurement-based protocol [12]. Later, this scheme was extended to more advanced Gaussian gates by using the squeezers [12] as their fundamental building blocks: a quantum nondemolition sum gate [13], which may be understood as a continuous-variable version of the controlled-NOT gate for qubits, and a reversible phase-insensitive amplification (two-mode squeezing) gate [14], which also functions as an approximate cloner for coherent-state inputs. However, in all these previous demonstrations, only Gaussian states have been used for the inputs. One reason for this is of a technical nature: the bandwidth of the squeezing gate is typically very narrow and there has been no way so far to generate highly nonclassical, non-Gaussian states in such a narrow frequency band. Moreover, these non-Gaussian states tend to be extremely sensitive to losses, and thus, coupling them directly into an optical parametric oscillator will easily erase any signature of their strong nonclassicality such as the negativity of the Wigner function. Our demonstration here was made possible by introducing a recent technique for bandwidth broadening as well as a mechanism for increased loss robustness to the squeezing gate [4].

We experimentally demonstrate for the first time a deterministic squeezing gate that operates on non-Gaussian input states. In particular, in what we believe to be a nice illustration, we use a particlelike single-photon state as the input state of the squeezing gate. The resulting output state then is a wavelike CSS. Since single-mode squeezing corresponds to a unitary, noiseless amplification process along a certain phase-space direction, our single-photon squeezer can be also interpreted as a phase-sensitive amplifier acting on an optical field mode in its first excited state (for a more detailed discussion of this interpretation, see the Supplemental Material [15]).

Furthermore, we also demonstrate the inverse operation of the squeezer, where a wavelike CSS is converted into a particlelike single-photon state. From a more fundamental point of view, what we demonstrate here can be considered an unconditional and reversible two-way conversion between a single quantum particle and a nonclassical, continuous wave. Unlike the previous probabilistic conversion from a photon number state to a CSS [16], the squeezing gate deterministically and reversibly transforms a single photon into a CSS. The CSS, $|\alpha\rangle - |-\alpha\rangle$, where $|\alpha\rangle$ is a coherent state [3], is a highly nonclassical quantum state sufficient for universal quantum computation [17]. It is worth noting that an all-optical, high-purity, almost-on-demand single-photon source was reported recently [18], while no such source has ever been demonstrated for a CSS state. Therefore, our unconditional conversion between these two types of states means that, in principle, all such quantum resources, including CSS states, are now available nearly on demand.

We believe that this experiment paves the way for quantum applications that combine discrete-particle and continuous-wave protocols in a so-called hybrid fashion. The squeezing-gate operation when acting on non-Gaussian states has also a number of direct applications, such as quantum state discrimination of optical coherent-state qubits [19], Gaussian optimization in non-Gaussian state preparation [20], improved quantum state transmission through a lossy channel [21], and preprocessing before a light-matter coupling for an efficient quantum memory interface [22]. Recently, it has been also realized that squeezing is an extremely useful tool for manipulating and measuring individual photons, for instance, in squeezing-enhanced Bell measurements of optical qubits [23] or in squeezing-enhanced entanglement distillation protocols where optical Gaussian states are locally transformed into qubit Bell pairs [24,25].

The schematic of our experimental setup is shown in Fig. 1. It consists of two parts: a source of nonclassical states and an unconditional squeezer. For the former, via a small variation of the setup, we can choose the nonclassical

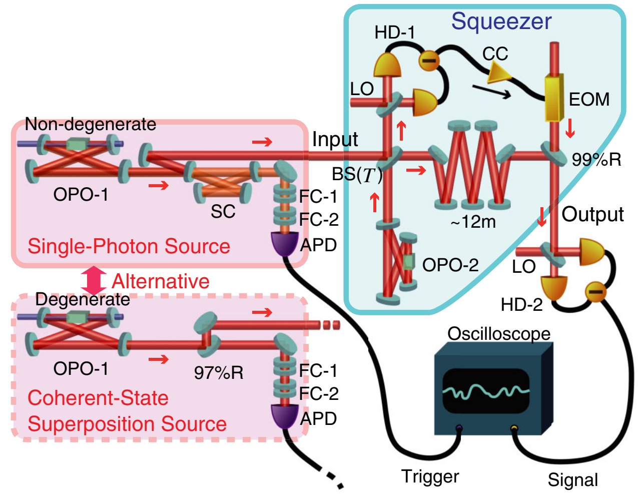

FIG. 1 (color online). Experimental setup. BS(T), beam splitter with transmittance T determining the degree of squeezing; OPO, optical parametric oscillator; SC, separating cavity; FC, filter cavity; APD, avalanche photo diode; HD, homodyne detector; LO, optical local oscillator; EOM, electro-optic modulator; CC, classical channel; R, reflectivity. An optical delay line of about 12 m, traveling in free space, is used to match the propagation times of the two signals, one of which gets converted to an electrical signal and back, while the other one remains optical throughout.

states to be either a single photon [26] or a CSS [27]. The states will always emerge randomly in time; however, from a photon "click" at the avalanche photodiode (APD), we know whenever a state arrives. These "heralded" nonclassical states are localized in time around the detections of correlated photons [26,27]. Therefore, our unconditional squeezer must have enough bandwidth to be applicable in the corresponding short time slots [4]. We extended our previous measurement-based squeezer [12] to meet this requirement. This squeezer avoids direct coupling of fragile input states to nonlinear optical media, which typically involves large optical losses. Instead, an ancillary squeezed state is utilized as a resource of nonlinearity [28] (see the Supplemental Material [15]). In this scheme, the higher the squeezing level of the ancilla state becomes, the more closely the squeezing operation resembles a unitary, completely reversible squeezing gate. Although our squeezer is assisted by homodyne detection on the ancilla beam, the nonclassical signal state is never directly measured (see the quantum eraser [29]) when the squeezer is applied.

In order to verify the conversions, we perform quantum homodyne tomography on input and output states [30,31]. Recall that wave and particle properties in quantum optics are formally connected via a pair of annihilation and creation operators for photons, $\hat{a}$ and $\hat{a}^\dagger$, respectively. These non-Hermitian operators are the quantized versions of the complex and complex conjugate amplitudes of an optical field mode, satisfying the bosonic commutation

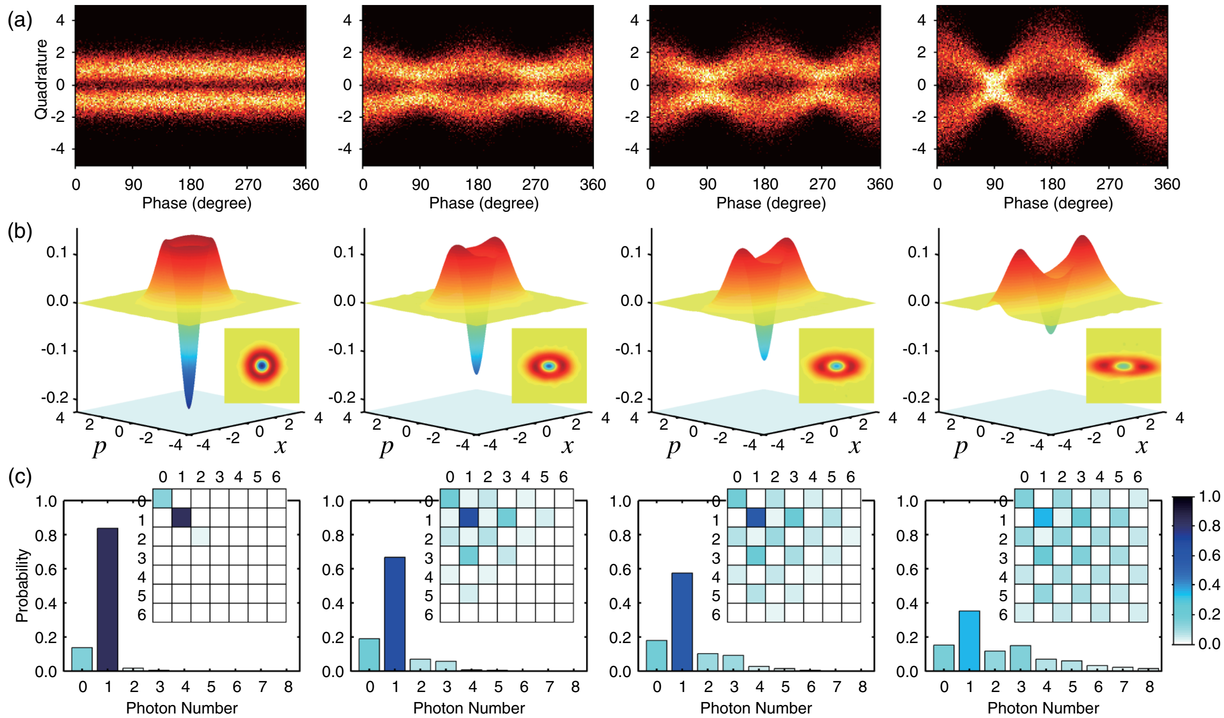

FIG. 2 (color online). Experimental quantum states for the conversion from particle to wave. The leftmost column shows the input single-photon state, while the other three columns show the output states for a squeezing parameter γ of 0.26, 0.37, and 0.67, from left to right. (a) Quadrature distributions over a period. (b) Wigner functions. (c) Photon number distributions and photon number representation of density matrices. The minimum value of -0.22 for the input Wigner function becomes, respectively, -0.15, -0.12, and -0.06, after the conversion.

relation $[\hat{a}, \hat{a}^\dagger] = 1$. Similarly, the quadrature operators, $\hat{x} = (\hat{a} + \hat{a}^\dagger)/\sqrt{2}$ and $\hat{p} = (\hat{a} - \hat{a}^\dagger)/i\sqrt{2}$, correspond to the quantized real and imaginary parts of the optical complex amplitudes (up to a factor of $\sqrt{2}$), where $[\hat{x}, \hat{p}] = i$. Through homodyne detection, the quadrature $\hat{x}(\theta)$ can be measured, which gives a Hermitian part of the operator $\hat{a}e^{-i\theta}$; $\theta = 0$ and $\theta = \pi/2$ then correspond to $\hat{x}$ and $\hat{p}$, respectively.

The experimental results for converting single-photon states into several CSSs are shown in Fig. 2, and those for the reciprocal conversion are given in Fig. 3. The top panels show the phase dependence of quadrature distributions obtained by a series of homodyne measurements. From these, Wigner functions and photon-number density matrices are calculated, as shown in the lower panels. In Fig. 2, the leftmost column shows the input single-photon state, while the three right columns show the output CSSs for three different squeezing levels. Similarly, in Fig. 3, the left column shows the input CSS, and the right column shows the output single-photon state.

We shall first discuss the quadrature distributions (top panels). The Fock state $|1\rangle$ of a single photon, which is a typical carrier of discrete-variable quantum information, is a highly nonclassical energy eigenstate of a quantized oscillator with a totally undetermined phase. The phase insensitivity of the quadrature distribution is a characteristic of a single-photon state, as can be seen in the leftmost panel of Fig. 2(a) and in the right panel of Fig. 3(a). On the other hand, any coherent state is an eigenstate of the annihilation operator, $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$. This corresponds to a sinusoidal wave with mean complex amplitude α and minimal quantum noise [3]. By superimposing two coherent states, $|\alpha\rangle - |-\alpha\rangle$, the quadrature distribution corresponds to two sinusoidal waveforms with quantum interference at each intersection, like in the three right panels of Fig. 2(a) and the left panel of Fig. 3(a). This quantum interference is a witness for a genuine quantum superposition of $|\alpha\rangle$ and $|-\alpha\rangle$ and it would never occur for a stochastic mixture of coherent states.

The conversion is achieved by means of a squeezing operation, $\hat{S}(\gamma) = e^{\gamma(\hat{a}^{\dagger 2} - \hat{a}^2)/2}$, where $\gamma \in \mathbb{R}$ quantifies the amount of squeezing. In Fig. 2(a), the phase-dependent oscillations increase with larger squeezing. Three different squeezing levels, $\gamma = 0.26$, 0.37, and 0.67, are demonstrated, resulting in three different amplitudes of CSSs, $\alpha = 0.91$, 1.10, and 1.64, respectively. The gap at the intersection of the waves becomes less pronounced for larger γ because of the finite squeezing of the ancilla mode (about 7 dB relative to shot noise). In an opposite manner, in Fig. 3(a), a phase-dependent oscillation is canceled by squeezing, resulting in a phase-independent distribution with a gap, like for a single-photon state. The input CSS with $\alpha = 0.97$ is converted by squeezing with $\gamma = -0.26$.

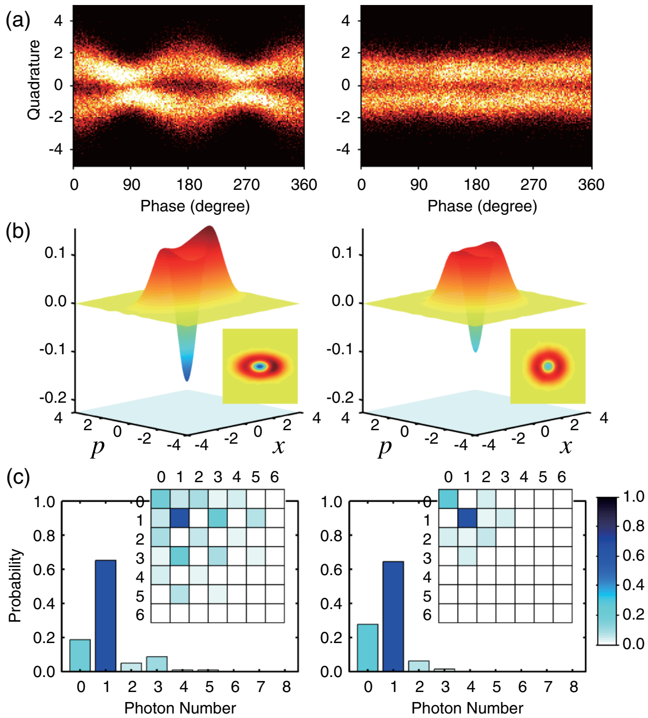

FIG. 3 (color online). Experimental quantum states for the conversion from wave to particle. The left column shows the input coherent-state superposition, while the right column shows the output state for a squeezing parameter γ of -0.26. (a) Quadrature distributions over a period. (b) Wigner functions. (c) Photon number distributions and photon number representation of density matrices. The minimum value of -0.16 for the input Wigner function becomes -0.10 after the conversion.

In the corresponding Wigner functions (middle panels), where detector inefficiencies and losses are not corrected, the nonclassicality of the input and output states becomes manifest in negative values. These Wigner functions are converted from rotationally symmetric to asymmetric [Fig. 2(b)] and from asymmetric to symmetric [Fig. 3(b)], while preserving their large negative values at the phase-space origin. In Fig. 2(b), the minimum value of -0.22 at the input becomes, respectively, -0.15, -0.12, and -0.06, at the output. In Fig. 3(b), -0.16 at the input becomes -0.10 at the output.

The density matrices (bottom panels) represent the particle picture. In the particle picture, the effect of the squeezing is an infinite superposition of photons added and subtracted in multiples of two. As a result, squeezing leads to a superposition of even photon number states when applied to the vacuum and to a superposition of odd photon number states when applied to the single-photon state. Being in such an odd-number superposition is also a distinct feature of the target CSS,

$$|\alpha\rangle - |-\alpha\rangle \propto |1\rangle + \frac{\alpha^2}{\sqrt{6}}|3\rangle + \cdots, \tag{1}$$

and this is exactly the reason why squeezing achieves the desired conversion [32].

The diagonal elements of the density matrices represent photon number distributions, while the off-diagonal elements correspond to superpositions of $|1\rangle$ and $|3\rangle$. The input single-photon state in Fig. 2(c) has a dominant single-photon component of 84% (without any corrections), while the input CSS in Fig. 3(c) has dominating one- and three-photon components compared to the zero-, two-, and four-photon terms. This also holds for the off-diagonal interference terms such as $|1\rangle\langle 3|$. Two-photon creations and annihilations are revealed by an increase [Fig. 2(c)] and a decrease [Fig. 3(c)] of the three-photon components, respectively.

In order to quantitatively assess the experimental conversion processes, besides reconstructing the Wigner functions and density matrices of the input and output states, we used two additional figures of merit. These are specifically designed to reveal either the most distinct features of the particle-to-wave transition or that of the converse, wave-to-particle transition [33] (for details, see the Supplemental Material [15]).

From an experimental point of view, it has been considered notoriously hard to apply a quantum optical squeezing operation upon more exotic, non-Gaussian quantum states such as discrete-variable single-photon states. In our experiment we have succeeded in this difficult task. By demonstrating the efficient and deterministic squeezing and unsqueezing of a single photon, we have opened an entirely new optical toolbox for future quantum-information applications. In principle, such a unitary, phase-sensitive amplifier (and attenuator) will allow for making use of the entire Fock space when processing single photons, which may help to construct quantum gates and error correction codes for logical qubits. Using our universal and reversible low-loss broadband squeezer, we have for the first time access to a complete set of deterministic Gaussian operations applicable to nonclassical, non-Gaussian states. These expand the toolbox for hybrid quantum-information processing [6], and therefore our result will directly lead to applications in this area. At the same time, besides providing a completely new class of optical quantum processors, our experiment bridges two quantum mechanically distinct regimes: that of particlelike quantum states such as single photons with that of more wavelike states such as coherent-state superpositions.

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