Autonomous Stabilization of Fock States in an Oscillator against Multiphoton Losses

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Fock states with a well-defined number of photons in an oscillator have shown a wide range of applications in quantum information science. Nonetheless, their usefulness has been marred by single and multiphoton losses due to unavoidable environment-induced dissipation. Though several dissipation engineering methods have been developed to counteract the leading single-photon-loss error, averting multiple-photon losses remains elusive. Here, we experimentally demonstrate a dissipation engineering method that autonomously stabilizes multiphoton Fock states against losses of multiple photons using a cascaded selective photon-addition operation in a superconducting quantum circuit. Through measuring the photon-number populations and Wigner tomography of the oscillator states, we observe a prolonged preservation of nonclassical Wigner negativities for the stabilized Fock states $|N\rangle$ with $N = 1, 2, 3$ for a duration of about 10 ms. Furthermore, the dissipation engineering method demonstrated here also facilitates the implementation of a nonunitary operation for resetting a binomially encoded logical qubit. These results highlight potential applications in error-correctable quantum information processing against multiple-photon-loss errors.

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Bosonic modes, such as harmonic oscillators, have garnered significant attention in various fields including quantum optics, quantum metrology, quantum simulation, and quantum computation [1–6]. These applications require precise and robust generation of nonclassical bosonic states in the oscillators, of which number states or Fock states are the most fundamental. Fock states are energy eigenstates with a fixed number of excitations or bosons, which possess a pivotal role in quantum optics, quantum metrology, and quantum information science [7]. Over the past few decades, significant efforts have been made to create and manipulate Fock states in various physical platforms, including motional modes of trapped ions [8], mechanical oscillators [9,10], microwave cavities with Rydberg atoms [11], acoustic wave resonators [12–14], and superconducting circuits [15–22]. However, all these methods still manifest significant challenges, largely stemming from multiple energy quanta losses (such as multiphoton losses) in the oscillator arising from non-negligible coupling to the uncontrolled dissipative environment.

Dissipation, on the other hand, can be well controlled and is an essential resource for quantum information processing [23]. Subtly engineered dissipation has found wide-ranging applications in preparing and stabilizing quantum states [24–29], resetting quantum system [30–34], generating entanglement [35–39], implementing quantum simulation [40], and performing quantum error correction [41–44]. In these examples, dissipation generally serves as a one-way valve to remove the system entropy to a reservoir bath and irreversibly transfers the system into a dark state or dissipation-free manifold. In the context of superconducting circuit quantum electrodynamics (QED) systems [45], a quantum reservoir engineering method has been employed to implement autonomous stabilization of a single-photon Fock state in a microwave cavity [26]. Nevertheless, extending this method to stabilize higher photon-number states against multiphoton losses remains a formidable experimental challenge. Recently, engineered dissipation has been applied to autonomous quantum error correction through a parity recovery operation for stabilizing photon-number parity against single-photon-loss error [42]. However, dissipation-induced multiphoton losses continue to persist as a major source of error that jeopardizes the integrity of quantum states in the oscillator and has yet to be fully resolved.

In this Letter, we experimentally demonstrate a dissipation engineering method for autonomously stabilizing multiphoton Fock states against multiphoton-loss errors in a superconducting microwave cavity. The robust generation of these nonclassical bosonic states is realized by developing a cascaded selective photon-addition (CSPA) operation assisted by an ancillary superconducting qubit and a reservoir bath resonator. The nonunitary CSPA operation is implemented by applying a continuous-wave multicomponent microwave drive to engineer the coupling to the dissipative environment. The experimental results indicate that the nonclassical Wigner negativities of the Fock states are preserved for a duration of about 10 ms, which can potentially be extended indefinitely. By controlling the selective photon-addition operations on individual photonic energy levels, we have confirmed that multiphoton-loss errors have been corrected to stabilize multiphoton Fock states. Furthermore, we showcase the potential of our dissipation engineering method in implementing a nonunitary quantum operation that resets a binomially-encoded logical qubit.

As shown in Fig. 1(a), a quantum harmonic oscillator with a quadratic potential well has infinite evenly spaced energy levels. Each energy level corresponds to an energy eigenstate $|n\rangle$, commonly known as the photon-number state or Fock state, containing n photons in the oscillator. However, these Fock states are susceptible to environment-induced decoherence, resulting in photon loss described by the annihilation operator $\hat{a} = \sum_n \sqrt{n}|n-1\rangle\langle n|$. To stabilize the Fock state against decoherence-induced photon loss errors, we introduce a CSPA operation, capable of adding photons in a tailored photon-number subspace. This operation is similar to the conjugate operator of $\hat{a}$ and can be described by

$$\mathrm{CSPA}_{m\to n} = \sum_{i=m}^{n-1} |i+1\rangle\langle i| \tag{1}$$

in a truncated photon-number subspace. Continuously implementing CSPA operations adds $n-m$ photons to an initial Fock state $|m\rangle$, resulting in the target Fock state $|n\rangle$. This nonunitary operation is implemented through simultaneously applying selective photon-addition operators $\hat{\Lambda}_{i\to i+1} = |i+1\rangle\langle i|$ between adjacent energy levels, adding a single photon to Fock state $|i\rangle$. These cascaded operations finally stabilize the Fock state $|n\rangle$ against losses of $n-m$ photons.

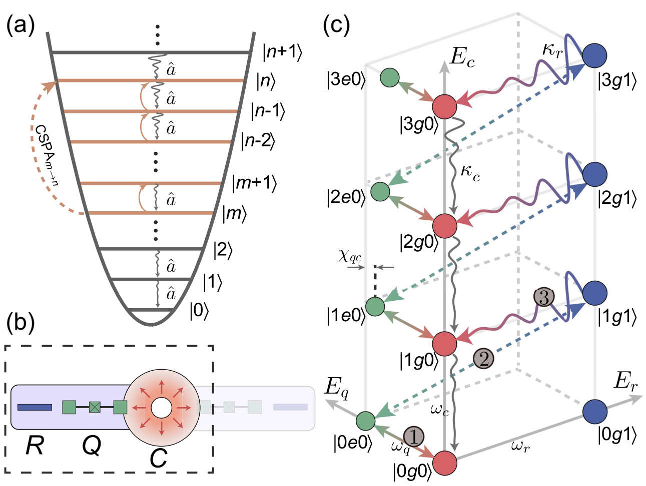

FIG. 1. Schematic of the multiphoton Fock state stabilization. (a) Fock state $|n\rangle$ in a harmonic oscillator is stabilized against losses of $n-m$ photons by continuously implementing the nonunitary operation $\mathrm{CSPA}_{m\to n}$ in a truncated photon-number subspace. The CSPA operation comprises a series of selective photon-addition operations between adjacent energy levels. (b) Experimental device schematic consisting of a 3D microwave cavity C as the oscillator, which is dispersively coupled to two superconducting qubits Q and associated readout resonators R. Note that only the left qubit and its readout resonator (inside dashed box) are used in the experiment. (c) Energy level diagram of the C-Q-R system. The CSPA operation is realized by combining two sets of continuous-wave frequency combs and the fast spontaneous decay of the readout resonator. The first set of comb selectively drives the qubit transitions ① and the second set swaps the excitation of the qubit to the storage cavity and readout resonator ②. The fast spontaneous decay dissipates the excitation of R to the environment ③, thus stabilizing the Fock states in cavity C.

In our experiment, the nonunitary CSPA operation is implemented in a superconducting quantum circuit system, similar to that in Ref. [46], with the schematic shown in Fig. 1(b). The system comprises a three-dimensional microwave cavity (C), acting as the oscillator, and two superconducting transmon qubits (Q) and their associated readout resonators (R). Note that only one qubit and its associated readout resonator are utilized to implement the quantum reservoir control for stabilizing multiphoton Fock states in cavity C. The relevant leading-order interactions of the C-Q-R system can be described by the dispersive Hamiltonian

$$\begin{aligned} H_0/\hbar = {} & \omega_c \hat{a}^\dagger \hat{a} + \omega_q |e\rangle\langle e| + \omega_r \hat{r}^\dagger \hat{r} \\ & - \chi_{qc} \hat{a}^\dagger \hat{a} |e\rangle\langle e| - \chi_{qr} \hat{r}^\dagger \hat{r} |e\rangle\langle e|, \end{aligned} \tag{2}$$

where $\hat{a}$ and $\hat{r}$ are the annihilation operators of the cavity and readout resonator modes, respectively. $|e\rangle$ and $|g\rangle$ represent the excited and ground states of the transmon qubit, respectively. The resonance frequencies of the three modes are $\omega_c/2\pi = 6.37$ GHz, $\omega_q/2\pi = 5.68$ GHz, and $\omega_r/2\pi = 8.60$ GHz. The dispersive couplings between the qubit and the other two modes are $\chi_{qc}/2\pi = 7.7$ MHz and $\chi_{qr}/2\pi = 2.4$ MHz. The microwave cavity has a single-photon lifetime of about 50 μs (corresponding to a decay rate $\kappa_c/2\pi = 3.1$ kHz) for storing photons, while the readout resonator is designed with a fast decay rate of $\kappa_r/2\pi = 2.4$ MHz for qubit readout and assisting in dissipation engineering. More details of the device parameters can be found in the Supplemental Material [47].

With the relevant energy levels of the system illustrated in Fig. 1(c), the CSPA operation is achieved by applying two sets of continuous-wave drives, resulting in a drive Hamiltonian,

$$H_d/\hbar = \sum_{i=m}^{n-1} (\Omega_i |i, e, 0\rangle\langle i, g, 0| + J_i |i+1, g, 1\rangle\langle i, e, 0|) + \text{H.c.}, \quad (3)$$

under the rotating wave approximation. Here, the indices in the bras and kets are labeled by the Fock states in the C-Q-R order, and H.c. represents Hermitian conjugate. By exploiting the photon-number-dependent qubit frequency shift in the dispersive Hamiltonian described in Eq. (2), we can achieve selective transitions between individual energy levels.

The drive Hamiltonian described in Eq. (3) comprises two sets of continuous-wave frequency combs, as illustrated with double arrows in the energy level diagram in Fig. 1(c). The first set of drives achieves resonant oscillations between the states $|i, g, 0\rangle$ and $|i, e, 0\rangle$ at a coupling rate of Ω_i. The second set targets the transition $|i, e, 0\rangle \leftrightarrow |i+1, g, 1\rangle$ at a coupling rate of J_i by applying a four-wave mixing pump on the superconducting qubit [47]. Finally, the fast spontaneous decay of the reservoir resonator R effectively removes the entropy by irreversibly transferring the state $|i+1, g, 1\rangle$ to $|i+1, g, 0\rangle$ with a loss rate of κ_r. As a result, combined with the two sets of drives, a photon-addition operator $\hat{\Lambda}_{i\to i+1}$ is constructed for adding a single photon to the Fock state $|i\rangle$ in C, given that $\kappa_c < \Omega_i < J_i < \kappa_r < \chi_{qc}$. By selectively applying a series of these drives, we can achieve the nonunitary operation $\text{CSPA}_{m\to n}$ to autonomously stabilize the Fock state $|n\rangle$ against the loss of $n-m$ photons in the cavity.

In our experiment, we first demonstrate the nonunitary CSPA operations to autonomously generate Fock states $|N\rangle$ in the storage cavity. The experimental sequence is depicted in Fig. 2(a), where we first apply a $\text{CSPA}_{0\to N}$ operation on an initial vacuum state in the cavity for a variable duration, and then perform a transmon spectroscopy measurement to extract the photon-number populations in the cavity after the CSPA operation.

Figures 2(b)–2(d) show the measured photon-number populations as a function of the total evolution duration of the CSPA operation for generating Fock states $|N\rangle$ with $N = 1, 2, 3$. The insets show the measured Wigner functions for the stabilized Fock states at a duration of approximately 50 μs, giving a state fidelity of 0.93, 0.86, and 0.77 for Fock states $|1\rangle$, $|2\rangle$, and $|3\rangle$, respectively. These measured fidelities are comparable with the estimated ones (0.96, 0.91, and 0.87) from analytical calculations in Supplemental Material [47]. The generated Fock states are preserved for up to approximately 10 ms, which is mainly limited by the classical control electronics used in the experiment and can potentially be extended indefinitely, indicating the successful and robust generation of the target

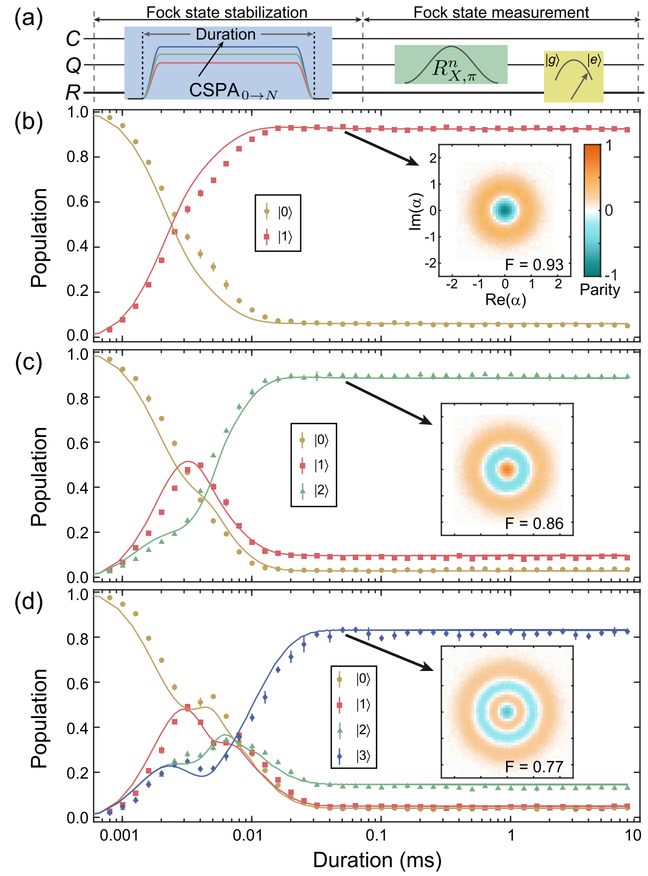

FIG. 2. Autonomous stabilization and characterization of multiphoton Fock states. (a) Experimental sequence for measuring the photon-number populations of the stabilized Fock states. (b)–(d) Measured photon-number populations (symbols) as a function of the evolution duration of the nonunitary CSPA operation, for stabilizing the Fock states $|1\rangle$ (b), $|2\rangle$ (c), and $|3\rangle$ (d), respectively. Error bars are standard deviations from repeated experiments. Solid lines are from numerical simulations. The insets in (b)–(d) show the Wigner snapshots of the stabilized Fock states at a duration of about 50 μs.

multiphoton Fock states in the cavity. The quantum dynamics of the stabilization process can be fully described by a rate equation of the photon-number populations during the evolution [47], confirming the effectiveness of the nonunitary CSPA operations in adding photons to the cavity. The main infidelity of the stabilized Fock states arises from the mismatch of the coupling rates and decay rates (see Supplemental Material [47] for more details of the error analysis).

To further validate the stabilization against multiphoton losses, we conditionally apply different configurations of CSPA operations after generating the initial Fock state $|N\rangle$ with $N = 1, 2, 3$, as shown in Figs. 3(a)–3(c). We then measure the photon-number population P_N of the Fock state $|N\rangle$ as a function of the evolution time, as well as the measured Wigner snapshots at an evolution time of about 200 μs for all cases, with the results shown in

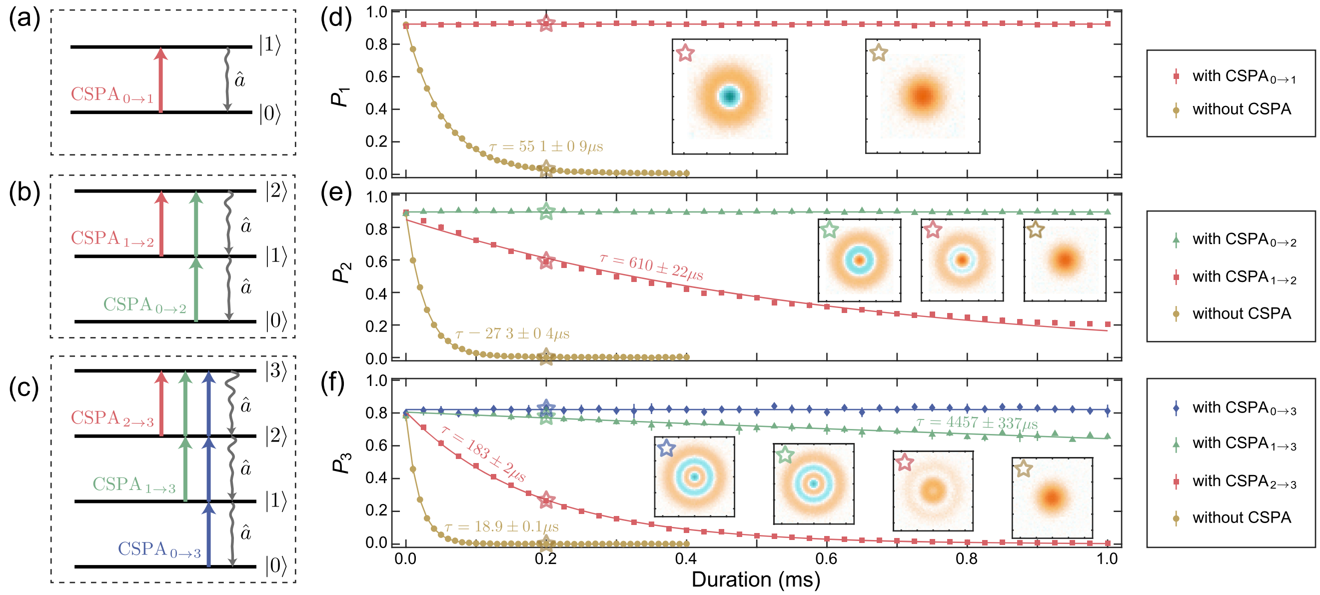

FIG. 3. Fock state stabilization against multiphoton losses. (a)–(c) Energy level diagrams for illustrating the protection of Fock state $|1\rangle$ (a), $|2\rangle$ (b), and $|3\rangle$ (c) against losses of different number of photons. (d)–(f) Measured photon-number populations (symbols) P_1 (d), P_2 (e), and P_3 (f) as a function of the stabilization duration when applying different sets of CSPA operations on corresponding initial Fock states. Error bars are standard deviations from repeated experiments. The decay curves are fitted to an exponential function $y = Ae^{-t/\tau}$ to extract the decay time constant τ. Solid lines for the cases with CSPA$_{0\to N}$ operation represent the average photon-number population for the corresponding stabilized Fock states. The insets in (d)–(f) show the measured Wigner functions (with same axis scales and color bars as that in Fig. 2) at a duration of about 200 μs for each case.

Figs. 3(d)–3(f). For example, in the case of initial Fock state $|3\rangle$, we apply nonunitary operations CSPA$_{0\to3}$, CSPA$_{1\to3}$, and CSPA$_{2\to3}$ to protect the cavity Fock state $|3\rangle$ against as large as three, two, and one-photon losses, respectively. The measured photon-number populations P_3 of the Fock state $|3\rangle$ for these three cases, as well as that without any CSPA operation, are shown in Fig. 3(f) and fitted to an exponential function to extract the decay time constant. The Fock state shows slow decay rates due to the protection against additional photon losses when applying these CSPA operations. As a result, the measured decay time constants 55.1 μs, (27.3, 610) μs, and (18.9, 183, 4457) μs are consistent with the estimated ones 51 μs, (26, 639) μs, and (17, 228, 4862) μs for Fock states $|1\rangle$, $|2\rangle$, and $|3\rangle$, respectively [47]. These results demonstrate that the multiphoton Fock states in the cavity can indeed be preserved and protected from both single and multiphoton-loss errors by the dissipation engineering method, highlighting the significant differences from previous works that only corrected single-photon-loss errors [26,42].

Furthermore, our dissipation engineering method can also be extended to design a cascaded selective photon-subtraction (CSPS) operation, employing the third energy level of the transmon qubit [47]. This nonunitary CSPS operation can be utilized to protect the photonic states against photon-gain errors induced by thermal excitation in the oscillator. By combining the nonunitary CSPS operation with the CSPA operation, we can achieve greater flexibility in realizing arbitrary nonunitary quantum control over the oscillator.

To demonstrate the capabilities of these nonunitary operations, we present an example of their use for resetting a binomially encoded logical qubit in cavity C. Here, the logical codewords are expressed as $\{|0\rangle_L = (|0\rangle + |4\rangle)/\sqrt{2}, |1\rangle_L = |2\rangle\}$ [54]. The logical reset operation is achieved by implementing the nonunitary operations CSPA$_{0\to2}$ and CSPS$_{4\to2}$ simultaneously, which will irreversibly transform arbitrary logical states to the logical $|1\rangle_L$ state. The process is characterized by the experimental sequence displayed in Fig. 4(a). Note that due to the large decay rate of the Fock state $|4\rangle$ and the weak stabilization rate to add photons, it is unnecessary to apply the CSPS operation in our experiment. The measured process fidelity of the logical reset operation with the encoding and decoding processes, as a function of the total duration of the reset operation, is shown in Fig. 4(b). As the duration exceeds 50 μs, the process fidelity approaches to a steady value of approximately 0.89, which is close to the process fidelity with only the encoding and decoding processes (0.894), indicating a high fidelity for the logical reset operation. Additionally, the measured process matrix at a duration of about 100 μs is presented in the inset of Fig. 4(b), alongside the ideal matrix. Further verification of the reset operation is provided through measurements of the Wigner functions of the cavity states before and after the reset operation, with results shown in Figs. 4(c) and 4(d).

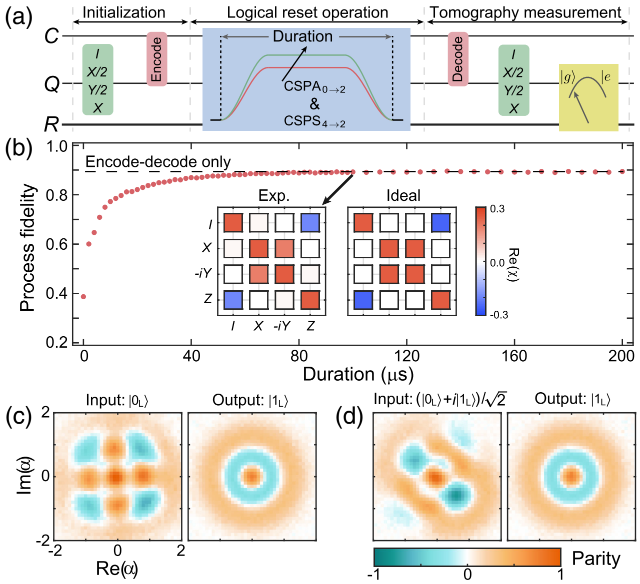

FIG. 4. Logical reset operation of a binomially encoded logical qubit. (a) Experimental sequence to perform quantum process tomography to characterize the logical reset operation. (b) Measured process fidelity defined as $F = (\mathrm{Tr}\sqrt{\sqrt{\chi_{\mathrm{ideal}}}\chi_{\mathrm{meas}}\sqrt{\chi_{\mathrm{ideal}}}})^2$, as a function of the duration of the reset operation. Here, χ_{meas} and χ_{ideal} are the measured and ideal process matrices for the logical reset operation, whose real parts are shown in the inset. Black dashed line represents the process fidelity with only the encoding and decoding processes. (c),(d) Measured Wigner functions of the cavity states before and after the logical reset operation, which irreversibly transform the initial binomially encoded logical states $|0\rangle_{\mathrm{L}}$ (c) and $(|0\rangle_{\mathrm{L}} + i|1\rangle_{\mathrm{L}})/\sqrt{2}$ (d) to a final state of $|1\rangle_{\mathrm{L}}$.

In conclusion, we have demonstrated a dissipation engineering method to stabilize multiphoton Fock states in a superconducting microwave cavity, employing a cascaded selective photon-addition operation. This method represents a crucial development in protecting the cavity states against multiphoton losses beyond single-photon loss, which is critical for robust and high-precision quantum control. The experimental results confirm that the stabilized multiphoton Fock states can be preserved for a time much longer than that without any CSPA operations, opening up the possibility in quantum-enhanced metrology [62] and dark matter search [63]. Additionally, our dissipation engineering method has been successfully employed for implementing a nonunitary operation for resetting a binomially encoded logical qubit, indicating practical implications in error-correctable nonunitary operations of logical qubits. The demonstrated dissipation engineering method can also be directly exploited to stabilize higher-photon-number states with improved device performance [64] and be applicable for optical photons and mechanical and acoustic wave phonons [10,14], promising potential applications in quantum information processing with various bosonic modes.

Note added.—While we were preparing our manuscript, we noticed a similar implementation of selective photon-addition operation, but lacking dissipation engineering [65].

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