

Single-Shot Conditional Displacement Gate between a Trapped Atom and Traveling Light

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We propose a single-shot conditional displacement gate between a trapped atom as the control qubit and a traveling light pulse as the target oscillator, mediated by an optical cavity. Classical driving of the atom synchronized with the light reflection off the cavity realizes the single-shot implementation of the crucial gate for the universal control of hybrid systems. We further derive a concise gate model incorporating cavity loss and atomic decay, facilitating the evaluation and optimization of the gate performance. This proposal establishes a key practical tool for coherently linking stationary atoms with itinerant light, a capability essential for realizing hybrid quantum information processing.

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Introduction—Traveling light offers a promising platform for quantum information processing, owing to its unique features such as high scalability and long-distance transmission capability [1,2]. Light is also a natural host of continuous-variable (CV) encoding methods, enabling efficient quantum error-correcting codes—as exemplified by Gottesman-Kitaev-Preskill (GKP) code [3]—by harnessing the inherent redundancy of the Hilbert space. However, due to the inherently weak nonlinearity, the controllability of bosonic systems is generally more limited than that of discrete-variable (DV) qubits encoded into atomic systems.

To overcome this limitation, hybrid systems consisting of oscillators and atomic qubits have been explored, where nonlinearity is cultivated with the help of qubits. In such systems, conditional displacement (CD)—oscillator displacement conditioned by a qubit—is one of the key building blocks; this indeed enables universal control of hybrid systems with single-qubit gates and beam-splitter operations [4]. Several stationary oscillator platforms, such as the motional states of trapped-ion systems [5–7] and circuit quantum electrodynamics (QED) [8–10] have successfully demonstrated operations of GKP states via CD gates. Furthermore, CD gates have broad applications, including mitigation of optical loss [11], certification of

non-Gaussian entanglement [12], and efficient entanglement distributions [13–15], highlighting their versatility.

Nevertheless, the implementation of CD gates for traveling light fields remains largely unexplored, potentially due to the lack of efficient implementation protocols. While a CD gate can be synthesized from conditional rotation gates, implementable by passive reflection off an atom-cavity system [16–18], and displacement operations, this requires multiple reflections of light off the (lossy) atom-cavity system, limiting fidelity with near-term system performance [19,20]. Thus, to fully exploit the intrinsic capability of CV light by supplementing it with mature qubit control, theoretical development of efficient optical CD gates is indispensable.

In this work, we propose a single-shot CD gate between a trapped atomic qubit and a traveling light pulse. The interaction between them is mediated by an optical cavity, where the atom couples to the cavity mode that interfaces with the propagating field through a partially transmitting mirror. By driving the atom simultaneously with the incidence of the target pulse, we realize an atom-conditional displacement gate on the reflected light. Our single-shot implementation eliminates the need for multiple optical operations, which would otherwise incur additional temporal overhead and optical loss, thereby providing a fast and robust hybrid gate. Thus, our proposal fills a missing component for hardware-efficient universal control, accelerating the development of light-atom CV-DV hybrid systems.

Reflection-based conditional displacement gate—We first present the target operation that our proposed gate aims to realize, as shown in Fig. 1. The optical mode $\hat{a}$ represents a light pulse with a temporal envelope function

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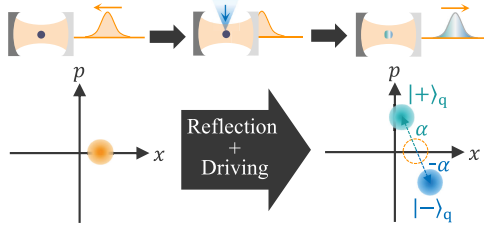


FIG. 1. Schematic of the RCD gate, along with the conceptual representation in the phase space.

$v(t)$, while qubit states $\{|0\rangle_q, |1\rangle_q\}$ are encoded in the internal states of an atom. The atomic qubit is coupled to a one-sided cavity that interfaces with the external optical mode through a partially transmitting mirror. To realize the desired atom-light gate, the light pulse is incident on the cavity with synchronized driving of the atom, resulting in a reflection-based conditional displacement (RCD) gate,

$$\text{CD}(\alpha) = \hat{D}(\alpha \hat{\sigma}_x) = e^{\hat{\sigma}_x(\alpha \hat{a}^\dagger - \alpha^* \hat{a})}, \quad (1)$$

where $\hat{\sigma}_x$ is the Pauli X operator on the qubit, and $\hat{D}(\alpha) = e^{\alpha \hat{a}^\dagger - \alpha^* \hat{a}}$ is the displacement operator. In the phase space, this gate allows the qubit in $|\pm\rangle_q = (|0\rangle_q \pm |1\rangle_q)/\sqrt{2}$ to displace the light state by $\pm\alpha$, as conceptually shown in Fig. 1.

Hereafter, we present the details of the implementation in the cavity-QED system. We consider a four-level system (FLS) with two stable and excited states, where the stable states act as the qubit states $\{|0\rangle_q, |1\rangle_q\}$. The two optical transitions couple with a single cavity mode at strength g , and the other diagonal transitions are driven by laser fields of Rabi frequency $\Omega(t)$ at the cavity frequency ω_c [see Fig. 2(a)]. Here, we assume that the excited states can be adiabatically eliminated, by sufficiently large detunings $\Delta = \omega_e - \omega_c$ between the optical transitions and the cavity and sufficiently slow driving, leading to an effective Hamiltonian in the qubit space (its validity is discussed later). In the rotating frame at the transition frequency ω_e and an effective cavity frequency $\omega_c - \chi$, where $\chi = g^2/\Delta$ is the dispersive shift, the simplified Hamiltonian is given by [21]

$$\hat{H}_{\text{sys}}^{\text{eff}}(t) = \hat{\sigma}_x[\lambda(t)\hat{c}^\dagger + \lambda^*(t)\hat{c}], \quad (2)$$

where $\hat{c}$ is the annihilation operator of the cavity field and

$$\lambda(t) = -\frac{g\Omega(t)}{\Delta} e^{-i\chi t}. \quad (3)$$

Since the cavity mode couples to the output field mode at rate κ_{ex} , the total Hamiltonian is given by

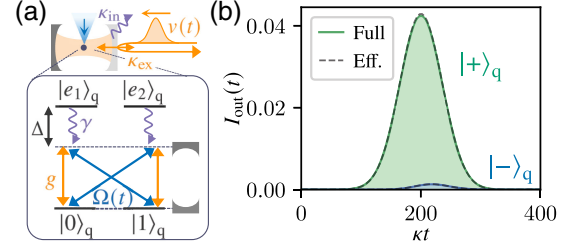


FIG. 2. System and proof of concept for the RCD gate. (a) Detail of the cavity-QED system. The two optical transitions couple with a single cavity mode $\hat{c}$ at strength g , and the other diagonal transitions are driven by laser fields of Rabi frequency $\Omega(t)$ at the cavity frequency ω_c . The detuning $\Delta = \omega_e - \omega_c$ of the atomic transition frequency ω_e is sufficiently large to suppress the atomic excitation. The one-sided optical cavity is coupled to the external optical field at rate κ_{ex} while this also has a nonzero internal loss at rate $\kappa_{\text{in}} (< \kappa_{\text{ex}})$; the total cavity decay rate is $\kappa = \kappa_{\text{ex}} + \kappa_{\text{in}}$. The atom can decay spontaneously from excited states at rate γ . (b) State-dependent output-field intensity $I_{\text{out}}(t)$ via numerical simulation of the full model shown in panel (a) (solid lines) and the effective model (dashed lines). For the input coherent state $|\beta = 1\rangle$ in a Gaussian pulse (11), centered at $t = 4\tau$, applying the RCD gate $\text{CD}(\alpha = 1)$ ideally yields the coherent state $|\beta = 2\rangle$ ($|\beta = 0\rangle$, the vacuum state) if the initial qubit state is in $|+\rangle_q$ ($|-\rangle_q$). The system parameters are $(\Delta, \kappa, \kappa_{\text{in}}, \gamma) = (20, 1, 0.01, 0.1)g$ and $\kappa\tau = 50$, resulting in $\epsilon_{\text{pulse}} = 8 \times 10^{-4}$ and the atomic decay probability $p_{\text{sp}} \simeq 0.1$ [see Eqs. (12), (16)].

$$\begin{aligned} \hat{H}(t) &= \hat{H}_{\text{sys}}^{\text{eff}}(t) + \hat{H}_B + \hat{H}_{\text{int}}, \\ \hat{H}_B &= \int \omega \hat{a}^\dagger(\omega) \hat{a}(\omega) d\omega, \\ \hat{H}_{\text{int}} &= i\sqrt{\frac{\kappa_{\text{ex}}}{\pi}} \int [\hat{a}^\dagger(\omega) \hat{c} - \hat{a}(\omega) \hat{c}^\dagger] d\omega, \end{aligned} \quad (4)$$

where ω is the detuning of the field frequency from the effective cavity frequency $\omega_c - \chi$, and $\hat{a}(\omega)$ is a monochromatic annihilation operator in a propagating mode. At a sufficiently large time $t = T$ to ensure the complete reflection, the unitary propagator of $\hat{H}(t)$ reduces to [21]

$$\hat{U}(T) = \text{CD}(\alpha) e^{-i(\hat{H}_B + \hat{H}_{\text{int}})T}, \quad (5)$$

where we have set the time-dependent coupling as

$$\lambda(t) = \frac{i\alpha}{\sqrt{2\kappa_{\text{ex}}}} [\dot{v}(t) + \kappa v(t)], \quad (6)$$

by tuning the Rabi frequency $\Omega(t)$. Here, $\kappa = \kappa_{\text{ex}} + \kappa_{\text{in}}$ represents the total cavity decay rate that includes the cavity internal loss rate κ_{in} [31]; $\kappa_{\text{in}} = 0$ is assumed in the above analysis, and the effects of $\kappa_{\text{in}} > 0$ are discussed later. A byproduct unitary operator $e^{-i(\hat{H}_B + \hat{H}_{\text{int}})T}$, which represents an empty-cavity response, is translated into a π -phase shift for a sufficiently long pulse $v(t)$; this can be canceled by

offsetting the phase origin by π after the reflection. Thus, the Rabi-type Hamiltonian (2) can realize the RCD gate.

We now incorporate the cavity internal loss at rate κ_{in} , which can be modeled as the coupling of the cavity mode to a loss mode $\hat{a}_{\text{loss}}$ initially occupying the vacuum state $|0\rangle_{\text{loss}}$ [18,32]. The system dynamics is obtained by tracing out the loss mode at the final step. For a long pulse $v(t)$, the internal-loss effect is represented by an additional unitary operator

$$\hat{U}_{\text{loss}}(\alpha, \eta_{\text{ex}}) = \text{CD}_{\text{loss}}\left(\sqrt{\eta_{\text{ex}}^{-1} - 1}\alpha\right)\hat{B}(\phi), \quad (7)$$

with

$$\cos \phi = 2\eta_{\text{ex}} - 1, \quad \sin \phi = 2\sqrt{\eta_{\text{ex}}(1 - \eta_{\text{ex}})}, \quad (8)$$

where $\eta_{\text{ex}} = \kappa_{\text{ex}}/\kappa$ is the coupling efficiency. The first beam-splitter operator $\hat{B}(\phi) = e^{\phi(\hat{a}\hat{a}_{\text{loss}}^\dagger - \hat{a}^\dagger\hat{a}_{\text{loss}})}$ between the desired and loss modes represents the optical loss due to the reflection. The second conditional displacement operator $\text{CD}_{\text{loss}}(\sqrt{\eta_{\text{ex}}^{-1} - 1}\alpha)$ represents the unintentional displacement of the loss mode. The reflected state $\hat{\rho}(T)$, corresponding to the initial state $\hat{\rho}_{\text{ini}}$ of the qubit and the desired-mode oscillator states, is given by sequentially applying the loss unitary operator and the ideal CD gate,

$$\hat{\rho}(T) = \text{CD}(\alpha)\mathcal{E}(\hat{\rho}_{\text{ini}})\text{CD}^\dagger(\alpha), \quad (9)$$

with

$$\mathcal{E}(\hat{\rho}) = \text{Tr}_{\text{loss}}[\hat{U}_{\text{loss}}(\alpha, \eta_{\text{ex}})(\hat{\rho} \otimes |0\rangle_{\text{loss}}\langle 0|)\hat{U}_{\text{loss}}^\dagger(\alpha, \eta_{\text{ex}})]. \quad (10)$$

So far, we have considered a sufficiently long pulse $v(t)$; we now analyze a finite-length-pulse effect. For simplicity, we consider a Gaussian pulse

$$v(t) = \frac{1}{(\pi\tau^2)^{1/4}} e^{-t^2/(2\tau^2)}, \quad (11)$$

where τ characterizes the pulse length. First of all, the empty-cavity response, which is denoted by $\hat{B}(\phi)$ in a long pulse, indeed depends on the light frequency spectrum, disturbing the reflected pulse shape for large bandwidth (small τ) light. For a coherent state with average photon number $\bar{n}_{\text{in}}$, the deviation from $\hat{B}(\phi)$ can be calculated as [21]

$$\begin{aligned} \epsilon_{\text{pulse}} &= 1 - e^{-4\eta_{\text{ex}}\bar{n}_{\text{in}}[1 - \sqrt{\pi\kappa\tau}e^{(\kappa\tau)^2}\text{erfc}(\kappa\tau)]} \\ &= \frac{2\eta_{\text{ex}}\bar{n}_{\text{in}}}{(\kappa\tau)^2} + \mathcal{O}\left(\frac{1}{(\kappa\tau)^4}\right), \end{aligned} \quad (12)$$

where $\text{erfc}(x) = (2/\sqrt{\pi}) \int_x^\infty dt e^{-t^2}$ is the complementary error function. Furthermore, a fast pulse induces a fast driving $\Omega(t)$, which will break down the adiabatic elimination assumed to derive the effective Hamiltonian (2). The elimination requires $|\Delta| \gg g\sqrt{\langle \hat{c}^\dagger(t)\hat{c}(t) \rangle}$ and $|\Delta| \gg |\Omega(t)|$. The former condition is satisfied with a sufficiently large Δ for any τ ; for example, it reduces to $|g\alpha/\Delta|^2 \ll \kappa\tau$ for $\bar{n}_{\text{in}} = 0$ [33]. The latter, however, does not depend on Δ because $|\Omega(t)/\Delta| = |\lambda(t)/g|$ from Eq. (3), yielding the requirement of the pulse width [33]

$$\frac{g^2}{\kappa}\tau\left(1 + \frac{1}{\kappa\tau}\right)^{-2} \gg |\alpha|^2. \quad (13)$$

A fast driving further increases the probability of the atomic spontaneous decay from excited states at rate γ . The decay probability through an RCD gate is approximately given by [21]

$$p_{\text{sp}} \simeq 1 - e^{\int dt 2\gamma_{\text{eff}}(t)}, \quad (14)$$

where the instantaneous effective decay rate is given by

$$\gamma_{\text{eff}}(t) = \gamma \left| \frac{\Omega(t)}{\Delta} \right|^2 = \gamma \left| \frac{\lambda(t)}{g} \right|^2. \quad (15)$$

From Eqs. (6) and (11), we find

$$p_{\text{sp}} \simeq 1 - \exp\left\{-\frac{|\alpha|^2}{2\eta_{\text{ex}}(1 - \eta_{\text{ex}})C_{\text{in}}}\left[1 + \frac{1}{2(\kappa\tau)^2}\right]\right\}, \quad (16)$$

where $C_{\text{in}} = g^2/(2\kappa_{\text{in}}\gamma)$ is the internal cooperativity. Thus, to suppress the finite-length-pulse effect, the pulse length should satisfy the requirement

$$\frac{g^2}{\kappa}\tau \gg |\alpha|^2, \kappa\tau \gg \max(1, 2\eta_{\text{ex}}\bar{n}_{\text{in}}), \quad (17)$$

for an RCD gate with amplitude α on the input light with average photon number $\bar{n}_{\text{in}}$.

To confirm that the effective model—characterized by the effective Hamiltonian (2) and decay effect [21]—well captures the full-model dynamics under the pulse-length condition (17), we simulate the RCD gate $\text{CD}(\alpha = 1)$ on the coherent state $|\beta = 1\rangle$, as an interesting example; the qubit $|+\rangle_{\text{q}}$ doubles the input amplitude, while the qubit $|-\rangle_{\text{q}}$ completely absorbs the input light, even though the system is driven by a classical laser. The clear contrast of the output-laser intensity will enable an efficient qubit-state measurement via reflected-light power monitoring. The qubit-dependent output-field intensity is presented in Fig. 2(b), where we numerically simulate the full-level (solid lines) and effective (dashed lines) systems [21]; two results are in good agreement. Note that RCD gates can

handle other wave packet functions by tuning the Rabi frequency $\Omega(t)$ [21].

System optimization—Our comprehensive analysis for gate performance, especially shown in Eqs. (9) and (16), clarifies two key metrics for characterizing system performance: the coupling efficiency η_{ex} and the internal cooperativity C_{in} . The former is readily tunable by changing the (effective) mirror transmittance; the tunability has been achieved in a fabrication process of an asymmetric diamond nanophotonic cavity [34], and even dynamically in several cavity implementations, such as fiber-taper-coupled microsphere resonators [35], nanofiber cavities [36], and macroscopic resonators with one mirror placed outside a vacuum chamber [37], to maximize the performance of their cavity-QED-based operations. Thus, the latter metrics, C_{in} , should characterize intrinsic system performance, as in various protocols such as photon generation [38] and atom-photon gates [39–41].

To efficiently optimize η_{ex} for a fixed C_{in} , we note that an output state $\hat{\rho}_{\text{fin}}$ can be decomposed as $\hat{\rho}_{\text{fin}} \simeq (1 - p_{\text{sp}})\hat{\rho}_0 + p_{\text{sp}}\hat{\rho}_{\text{sp}}$, where $\hat{\rho}_0$ is given by the channel (9) and $\hat{\rho}_{\text{sp}}$ is the output state when the event with one or more atomic decays occur. For an initial pure state $|\psi_{\text{ini}}\rangle$ that leads to the ideal final state $\text{CD}(\alpha)|\psi_{\text{ini}}\rangle$, the state fidelity F satisfies

$$F_{\text{LB}} \lesssim F \lesssim F_{\text{LB}} + p_{\text{sp}}, \quad (18)$$

where the approximated lower bound is given by

$$F_{\text{LB}} = (1 - p_{\text{sp}})\langle\psi_{\text{ini}}|\mathcal{E}(|\psi_{\text{ini}}\rangle\langle\psi_{\text{ini}}|)|\psi_{\text{ini}}\rangle. \quad (19)$$

Thus, with the analytical results for the channel $\mathcal{E}(\cdot)$ and p_{sp} shown in Eqs. (10) and (16), we can easily optimize η_{ex} by using an objective function such as $1 - F_{\text{LB}}$, without resorting to exhaustive numerical simulations.

As a demonstration, we optimize η_{ex} in the RCD gate $\text{CD}(\alpha = i)$ acting on $|0\rangle_{\text{q}}|\beta\rangle$ to minimize $1 - F_{\text{LB}}$, as shown in Fig. 3(a). For $\beta = 0$, the optimized η_{ex} is well approximated as $\eta_{\text{ex}} = 1 - 1/(1 + \sqrt{1 + 2C_{\text{in}}})$, consistent with other protocols such as photon generation and atom-photon gates [33,38,39,42]. As β increases, the optimum value becomes larger to mitigate the optical loss induced by the internal cavity loss; even when $\alpha = 0$, the empty cavity acts as a loss channel with transmittance $\cos^2 \phi = (2\eta_{\text{ex}} - 1)^2$ [43]. We further solve the master equation for $\hat{\rho}_{\text{fin}}$ and evaluate the infidelity, as shown in Fig. 3(b) [21]. This shows that the numerical solution satisfies inequality (18), and that F is close to F_{LB} , which indicates that an atomic-decay event results in nearly zero fidelity. We have also compared the infidelity with that of CD gates synthesized via multiple reflections [20], quantitatively showing our advantage [21]. We then plot the Wigner functions with the postselection of the qubit states in $|0\rangle_{\text{q}}$ for $C_{\text{in}} = 100, 1000$, shown in Fig. 3(c). Both output states clearly exhibit Wigner negativity, confirming that the RCD

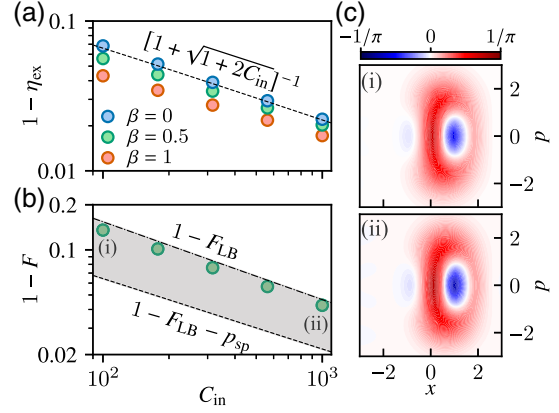


FIG. 3. Optimization of the coupling efficiency η_{ex} to maximize the gate performance. (a) Numerical optimization of η_{ex} based on our analytical results (10), (16), in the RCD gate $\text{CD}(i)$ acting on $|0\rangle_{\text{q}}|\beta\rangle$. The dashed line represents $1 - \eta_{\text{ex}} = 1/(1 + \sqrt{1 + 2C_{\text{in}}})$, which captures well the result for $\beta = 0$. (b) Infidelity $1 - F$ for $\beta = 0.5$ with the optimized η_{ex} [see panel (a)], where we numerically solve the master equation of an effective model [21]. Given C_{in} , the system parameters are $(\kappa_{\text{in}}, \Delta) = (0.01, 30)g$, which gives $\gamma = g^2/(2\kappa_{\text{in}} C_{\text{in}})$, while κ_{ex} is determined by the optimized η_{ex} . The pulse length satisfies $g\tau = 300$. The dashed and dash-dot lines respectively represent $1 - F_{\text{LB}} - p_{\text{sp}}$ and $1 - F_{\text{LB}}$ calculated by the analytical results (10), (16). (c) Wigner functions of the output light with the postselection of the qubit states in $|0\rangle_{\text{q}}$ for (i) $C_{\text{in}} = 100$ and (ii) $C_{\text{in}} = 1000$. Measuring the qubit state in $|0\rangle_{\text{q}}$ projects the light state onto the nonclassical state $\propto [\hat{D}(i) + \hat{D}(-i)]|\beta = 0.5\rangle$ in the ideal case. While the contrast of the Wigner function in $C_{\text{in}} = 1000$ is larger than that in $C_{\text{in}} = 100$, both projected states clearly show the Wigner negativity.

gate preserves qubit-light coherence throughout the gate dynamics despite photon losses induced by atomic decay and cavity internal loss.

Note that simulating the interaction between traveling and local quantum systems typically requires a numerical solution of the master equation in $\mathcal{N} \leq (N + 1) \times d \times (M + 1)$ -dimension Hilbert space, where N and M are the maximum excitation numbers in the incoming and outgoing field, and d is the dimension of the local system [44]. Thus, in particular, a large-photon-number state renders such numerical simulation time-consuming or even infeasible. In the numerical simulations presented in Figs. 2(b) and 3, we consider the initial light state to be a coherent state to make those feasible [21]. However, our analytical results (9) and (16) hold for any initial state, thereby efficiently projecting gate performance, as shown in Fig. 3(b). Our analysis further indicates that achieving high gate performance primarily requires enhancing the internal cooperativity C_{in} .

Implementation—We finally remark on potential physical implementations. The idea of realizing the effective Hamiltonian (2) with the four-level system shown in Fig. 2(a) was originally proposed for simulating the

Dicke model [45] and was employed for spin squeezing [46], along with implementation proposals based on ^{87}Rb atoms [46,47]. Moreover, the Dicke model has been experimentally demonstrated using ^{87}Rb atoms in Refs. [48,49], while more than four levels were involved in the dynamics, leading to additional terms $\propto \hat{\sigma}_z, \hat{c}^\dagger \hat{c} \hat{\sigma}_z$ through ac Stark effects.

Alternative candidates that natively have well-separated four-level systems are diamond silicon-vacancy (SiV) centers and ^{171}Yb atoms. SiV centers in a diamond nanophotonic cavity realized two ground and optically excited states with an appropriate magnetic field, enabling cavity-enhanced photon generation [34,50]; this might straightforwardly realize our four-level system. The other candidate, ^{171}Yb , hosts a nuclear spin $1/2$ and offers a metastable qubit in $^3\text{P}_0, F = 1/2$ states and optically excited states in $^3\text{D}_1, F = 1/2$ states. Cavity-QED systems with $^3\text{P}_0$ - $^3\text{D}_1$ transition have recently been proposed along with concrete cavities such as silicon photonic crystal, twisted ring, and nanofiber cavities [51–53], and a high-finesse nanofiber cavity was fabricated with projected cooperativity of 90 [54]. As an example, a cavity that has $\kappa_{\text{in}}/2\pi = 1.3$ MHz [54] and $g/2\pi = 7.9$ MHz, which gives $C_{\text{in}} = 100$ as the atomic linewidth is $\gamma_{^3\text{D}_1}/2\pi = 0.24$ MHz [55], can implement RCD gates producing nonclassical light with the pulse length $\tau = 6.0$ μs , as shown in Fig. 3. ^{171}Yb atoms further give the capability to mitigate the atomic decay effect by harnessing its versatile level structure; a fraction of the decay from $^3\text{D}_1$ states leaks outside the qubit subspace and eventually ends up in the ground state $^1\text{S}_0$, which can be detectable without disturbing the qubit coherence [56]. This so-called erasure detection or conversion, which is applicable in RCD gates, enhances gate fidelity with postselection [57] and even significantly improves the threshold of fault-tolerant quantum computation [56,58], further enhancing the utility of RCD gates.

Conclusion—We have proposed a single-shot implementation of an atom-conditional displacement gate on a traveling light pulse, where a FLS hosting a qubit is enclosed in an optical cavity. Our proposal presents a hardware-efficient method; the single reflection of the itinerant pulse from the cavity, with the synchronized driving of the FLS, directly realizes a CD gate. We have further analyzed the gate dynamics including the effects of cavity internal loss and atomic decay, and presented concise formulas to predict gate performance; gate fidelity can be effectively captured by only two parameters: the coupling efficiency and the internal cooperativity. This streamlines system optimization to achieve high fidelity, and thus enhances the utility of the single-shot CV-DV hybrid gate. As a result, our gate offers a practical route toward universal and scalable hybrid quantum computation and communication with light. Finally, since the gate is realized with a simple Rabi-type Hamiltonian, our proposal

might be extended to other platforms such as circuit QED with traveling microwave pulses [59–61], offering a versatile approach for hybrid quantum operations across diverse physical systems.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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