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Deterministic and cascadable conditional phase gate for photonic qubits

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Previous analyses of conditional ϕNL-phase gates for photonic qubits that treat cross-phase modulation (XPM) in a causal, multimode, quantum field setting suggest that a large (∼π rad) nonlinear phase shift is always accompanied by fidelity-degrading noise [J. H. Shapiro, Phys. Rev. A 73, 062305 (2006); J. Gea-Banacloche, ibid. 81, 043823 (2010)]. Using an atomic ∨ system to model an XPM medium, we present a conditional phase gate that, for sufficiently small nonzero ϕNL, has high fidelity. The gate is made cascadable by using a special measurement, i.e., principal-mode projection, to exploit the quantum Zeno effect and preclude the accumulation of fidelity-degrading departures from the principal-mode Hilbert space when both control and target photons illuminate the gate. The nonlinearity of the ∨ system we study is too weak for this particular implementation to be practical. Nevertheless, the idea of cascading through principal-mode projection is of potential use to overcome fidelity-degrading noise for a wide variety of nonlinear optical primitive gates.

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I. INTRODUCTION

In optical quantum logic, qubit states are usually encoded using the presence or absence of a single photon in one of the many modes of the quantum electromagnetic field. We refer to this special information-carrying mode as the principal mode. Logic gates can be high-fidelity only if they map input principal modes to output principal modes. Gates can be cascaded successfully if the input and output principal modes are the same. In either the dual-rail [1] or polarization [2] architectures, high-fidelity, cascadable single-qubit gates can be readily implemented using linear optics (beam splitters and phase shifters). A significant challenge to implementing optical quantum information processing is the faithful realization of a deterministic and cascadable universal two-qubit photonic logic gate.

Cross-phase modulation (XPM)—a nonlinear process in which one electric field affects the refractive index seen by another—has often been proposed [1,3–5] as a nonlinear optical process that might be used to construct such a universal gate, i.e., the conditional π-phase gate. (Other fundamentally different photonic two-qubit gates have been designed, e.g., [6,7], which involve only single-photon+atom interactions; such gates will not be discussed here.) While a single-mode analysis of XPM-based gates is encouraging, in recent years multimode efforts [8–10] that treat photons as excitations of a quantum field with continuously many degrees of freedom have been somewhat more foreboding.

In [8,9], the problem was studied using a quantized version of the solution to the classical coupled-mode equations for XPM. The XPM material was required to have a noninstantaneous response, as an instantaneous response in the quantum theory does not reproduce classical behavior for coherent-state mean fields. It was then shown that if the material response is noninstantaneous and causal, then noise terms necessary to preserve commutation relations cause the error probability (infidelity) |ε|2 of conditional ϕNL-phase gates to be prohibitively large when ϕNL ∼ π. (See [10] for a comparative model study and [11] for experimental observation of this noise in optical fiber.)

A second difficulty with XPM is obtaining a cross-phase shift uniformly distributed over the control and target pulse profiles. Several authors have proposed conditional phase gate designs that avoid this trouble by allowing one pulse to propagate through the other [12–18]. As some point out [12], however, it is not clear that realizations of these proposals would be free from the causality-induced phase noise discussed above.

In the present paper, we offer a different approach to solving problems associated with quantum XPM. Rather than trying to achieve a high-fidelity π-phase shift all at once, we show that a high-fidelity conditional ϕNL-phase gate can be constructed for small ϕNL, and that these gates can be cascaded to yield a significant nonlinear phase shift with high fidelity. Indeed, showing that a conditional phase gate can be constructed with small nonlinear phase much larger than its error probability, |ε|2 ≪ ϕNL ≪ 1, is relatively easy. Cascading these gates, however, is nontrivial. The error, which results from a slight deformation of the principal modes, can be coherently amplified as the gate is cascaded, preventing the straightforward construction of a conditional π-phase gate. This difficulty can be avoided by performing a measurement after each primitive conditional ϕNL-phase gate that projects onto the principal-mode subspace, exploiting the quantum Zeno effect as an error-preventing mechanism [19–21]. For a particular choice of principal modes, we suggest one way that such a measurement could be realized.

We derive these results using a single ∨-type atom placed within a one-sided cavity as a microscopic model for XPM. While the nonlinearities present in a ∨ atom are not as strong as those in, for example, the giant Kerr effect [22,23], the ∨ system is simple enough that it yields readily to an analysis in terms of quantum fields. After solving for the evolution of our system in the one- and two-photon subspaces, we investigate fidelity and cascadability. It turns out that while cascading small phase shifts with projective measurements interleaved can produce a high-fidelity gate in principle, the number of cascades needed is impractically large when the ∨ system’s weak nonlinearity is used to provide XPM. Nevertheless, the
idea of cascading through principal-mode projection is of potential use to overcome fidelity-degrading noise for a wide variety of nonlinear optical primitive gates.

II. THE FIELDS AND THEIR INTERACTION

In this section, we describe our encoding of qubit states in one-dimensional quantum fields, then consider how these fields evolve when interacting with an optical cavity containing an atomic $\lor$ system. Following the approach used in [7,24,25], this is described by a Hamiltonian $H_{\text{NL}}$ for the fields $+\lor$ cavity $+\lor$ atom system. The Hamiltonian-based approach we use is essentially the basis for an alternative description in terms of the input-output formalism [26].

The atomic system mediates an XPM-like interaction that is a central component in the conditional phase gates discussed later. Determining the nonlinear phase shift and error induced by the atomic interaction will be of the utmost importance in evaluating these gates. To this end, one- and two-photon propagators for this system [24] are introduced.

A. Qubit encoding

In our gate, qubit states are encoded using two quasi-monochromatic, positive-frequency, photon units optical fields $h_z(\tau)$ and $v_z(\tau)$ [27] (for convenience, $\tau \equiv ct$ is used to measure time). We take $+z$ as the propagation direction and ignore the transverse character of these fields throughout. The horizontally polarized field $h_z(\tau)$ and the vertically polarized field $v_z(\tau)$ are independent and have a nontrivial commutator, $[h_z(\tau),v_z(\tau)] = \delta(z-z')$.

Logical qubit states are encoded as excitations of two principal modes $h$ and $v$, defined by

$$h^\dagger = \int dz \psi(z)h_z^\dagger, \quad v^\dagger = \int dz \psi(z)v_z^\dagger, \quad (1)$$

where operators without explicit time dependence are in the Schrödinger picture. With the normalization $\int dz|\psi(z)|^2 = 1$, $h^\dagger$ and $v^\dagger$ are interpreted, respectively, as creating horizontally and vertically polarized photons with wave function $\psi(z)$. We refer to all modes orthogonal to $h$ and $v$ as auxiliary, or $bath$, modes and assume that the auxiliary modes are initially unexcited. In this context, the correspondence between logical qubit states and field states reads

$$|00\rangle_L \leftrightarrow \text{vac}, \quad (2a)$$

$$|01\rangle_L \leftrightarrow |H\rangle \equiv h^\dagger \text{vac}, \quad (2b)$$

$$|10\rangle_L \leftrightarrow |V\rangle \equiv v^\dagger \text{vac}, \quad (2c)$$

$$|11\rangle_L \leftrightarrow |HV\rangle \equiv v^\dagger h^\dagger \text{vac}, \quad (2d)$$

where $\text{vac}$ is the multimode vacuum. Equation (2) could describe either a dual-rail or polarization encoding, where fields not participating in our gate have been dropped for convenience.

B. Qubit evolution and interaction Hamiltonian

At the input to our gate, the fields are prepared in some superposition $|\psi_m\rangle$ of the basis states in Eq. (2). This state is localized in a noninteracting input region [Fig. 1(a)]. It then propagates in the $+z$ direction toward a region where both fields interact, evolving under a nonlinear total Hamiltonian $H_{\text{tot}}$ which couples these fields to a three-level atomic $\lor$ system. (Here “nonlinear” means that the total Hamiltonian $H_{\text{tot}}$ generates nonlinear Heisenberg equations of motion, which is a necessary condition for $H_{\text{NL}}$ to effect a two-qubit gate that does not factorize into a product of one-qubit gates.) Much later, the atom has returned to its ground state and the photonic qubits are in a state $|\psi_1\rangle$, which is localized in a noninteracting output region. Working in an interaction picture with respect to the free-field Hamiltonian $H_{\text{fields}}$, the scattering matrix connects the states $|\psi_m\rangle$ and $|\psi_1\rangle$:

$$|\psi_1\rangle = S_{\text{tot}}|\psi_m\rangle, \quad S_{\text{tot}} \equiv \lim_{\tau \to \infty} e^{-i H_{\text{tot}}\tau/\hbar} e^{i H_{\text{tot}}\tau/\hbar}. \quad (3)$$

In interacting with the atom, a single horizontally polarized (vertically polarized) photon acquires a phase shift $\varphi_H (\varphi_V)$, and may undergo some amount of pulse deformation. When both a horizontal and a vertical photon are incident upon the atom at the same time, however, the presence of the horizontal photon frustrates the interaction of the vertical photon with the atom, and vice versa, i.e., the atom cannot absorb both photons simultaneously. As a result, the pair of photons picks up an extra phase shift $\varphi_{\text{NL}}$. In this way, the $\lor$ system models a Kerr medium and can be used to construct conditional phase gates.

To describe this interaction, we use the same Hamiltonian $H_{\text{tot}}$, as in [24]: both fields $h$ and $v$ couple to a one-sided...
cavity containing an atomic ∨ system. For $z < 0$, these fields are interpreted as propagating toward the cavity, while for $z > 0$, they are interpreted as propagating away from the cavity [Fig. 1(a)]. As shown in Fig. 1(b), an optical circulator could be used in practice to achieve this separation of input and output fields. Figure 1(c) shows the ∨ system’s level structure. All cavity modes are ignored, except a horizontally polarized field. The dynamics of the atom+external field system are determined exclusively from the effective Hamiltonian $H_{\text{eff}}$, wherein the effective coupling is $\Gamma_{H,V}^*/\hbar$. For $|z| > r/\theta$, e.g., the field at $z$ is interpreted as propagating toward the cavity, while for $|z| < r/\theta$, e.g., the field at $z$ is interpreted as propagating away from the cavity.

The total Hamiltonian $H_{\text{tot}} = H_0 + H_{\text{fields-cav}} + H_{\text{cav-atom}}$ is the sum of a noninteracting Hamiltonian $H_0$ and two interaction pieces. In terms of $k$-space field operators $\tilde{h}_k \equiv \int dz \hat{e}^{-ikz}$ and $\tilde{h}_k \equiv \int dz \hat{e}^{-ikz}$, which annihilate photons with definite frequency, the noninteracting Hamiltonian $H_0$ is

$$H_0 = H_{\text{fields}} + H_{\text{cav}} + H_{\text{atom}},$$

$$H_{\text{fields}} = \int \frac{dk}{2\pi} \omega_h \tilde{h}_k^\dagger \tilde{h}_k + \frac{i}{\hbar} \tilde{h}_k^\dagger \frac{\partial}{\partial \omega_h} \tilde{h}_k,$$

$$H_{\text{cav}} = \hbar \Omega_1, c_{\delta m}^\dagger a_{\delta m} + a_{\delta m}^\dagger c_{\delta m},$$

$$H_{\text{atom}} = \hbar \Omega_1 (c_{\delta 1}^\dagger c_{\delta 2} + c_{\delta 2}^\dagger c_{\delta 1}).$$

We have taken $z = 0$ as the cavity’s position.

As in [24], we consider the lossy-cavity regime in which the cavity decay rates $\kappa$, cavity-atom couplings $g$, and rate $\gamma_{2D}$ of spontaneous emission into free space satisfy $\kappa \gg g \gg \gamma_{2D}$. In this regime, cavity decay dominates spontaneous emission, and cavity operators can be adiabatically eliminated in favor of the external field [24,29], i.e., in the lossy-cavity regime, the cavity couples directly to the one-dimensional input and output fields. The dynamics of the atom-external field system are then identical (up to an inconsequential phase shift resulting from reflection off the one-sided cavity’s perfect mirror) to those generated by an effective Hamiltonian $H_{\text{eff}}$, in which the fields are directly coupled to the atom,

$$H_{\text{eff}} = H_0 + i\hbar \Gamma_{H}^{1/2} (\sigma_{10} + \sigma_{20}) + i\hbar \Gamma_{V}^{1/2} (\sigma_{10} - \sigma_{20}) + i\hbar \Gamma_{V}^{1/2} (\sigma_{10} + \sigma_{20}),$$

where the effective coupling is $\Gamma_{H,V} = 4g^2 R_{H,V}/\kappa_{H,V}$. In this paper, dynamics are derived exclusively from the effective Hamiltonian $H_{\text{eff}}$. To ensure that the gate treats both qubits symmetrically, we will later set $\Gamma_{H} = \Gamma_{V}$, but temporarily retain subscripts for pedagogical clarity.

C. Evolution of one- and two-photon states

To determine how the one- and two-photon states in Eq. (2) that encode the computational basis evolve under the scattering matrix $S_{\text{eff}}$, it suffices to know the one- and two-photon propagators (the vacuum state evolves trivially). Labeling states $|\text{atom}; \text{field}\rangle$, these are

$$G_H(x,y) = \langle 0; \text{vac} | h_x S_{\text{eff}} h_x^\dagger | 0; \text{vac} \rangle, \quad G_V(x,y) = \langle 0; \text{vac} | v_x S_{\text{eff}} v_x^\dagger | 0; \text{vac} \rangle,$$

$$G_{HV}(x_H,x_V,y_H,y_V) = \langle 0; \text{vac} | h_{x_H} v_x S_{\text{eff}} h_{y_H} v_{y}^\dagger | 0; \text{vac} \rangle.$$

The time-dependent propagators—matrix elements of $e^{-iH_{\text{eff}} \tau/\hbar}$ instead of $S_{\text{eff}}$—are given in [24].

The single-photon propagator $G_H(x,y)$ gives the long-time, interaction-picture amplitude for a photon initially at position $y$ to propagate to position $x$. We will always assume that $y < 0$ so that every photon can interact with the atom, located at the origin. In this case,

$$G_H(x,y) = \delta(x-y) - \Gamma_H^{1/2} R_H(y-x),$$

where

$$\Gamma_H^{1/2} R_H(\tau) = \theta(\tau) |1; \text{vac} \rangle \langle 0; \text{vac} | e^{-\Gamma_{H} \tau/\hbar} | 1; \text{vac} \rangle = \theta(\tau) e^{-\Gamma_H \tau/\hbar},$$

is the amplitude for the atom, excited by a horizontally polarized impulse at time zero, to still be excited at a time $\tau$ later. Here $\theta(\tau)$ is the Heaviside step function, equal to 1 for $\tau > 0$ and 0 for $\tau < 0$. The Fourier-space propagator $\tilde{G}_H(k,q) = \langle 0; \text{vac} | h_x S_{\text{eff}} h_{y}^\dagger | 0; \text{vac} \rangle$ is also useful. Using Eq. (8), it is

$$\tilde{G}_H(k,q) = \int dxdy G_H(x,y) e^{iqy - ikx},$$

$$= 2\pi \delta(k - \Omega_1 - i\Gamma_H/2),$$

Analogous results hold for $G_V(x,y)$.

If the atomic system were linear, it could absorb multiple photons before emitting any. In this case, the two-photon propagator $G_{HV}(x_H,x_{V},y_{H},y_{V})$ would just be a product of single-photon propagators. Instead, it is

$$G_{HV}(x_H,x_V,y_H,y_V) = G_H(x_H,y_H) G_V(x_V,y_V) - \Gamma_H^{1/2}\Gamma_V^{1/2} \times R_H(y_H - x_H) R_V(y_V - x_V) \times \theta(\min[y_H,y_V] - \max[x_H,x_V]).$$

Here the second piece removes from $G_{HV}(x_H,y_H) G_V(x_V,y_V)$ exactly those terms that correspond to two absorptions before any emissions. This causes two-photon output states to be antibunched.

The corresponding two-photon Fourier-space propagator is

$$\tilde{G}_{HV}(k_H,k_V,q_H,q_V) = \tilde{G}_H(k_H,q_H) \tilde{G}_V(k_V,q_V) + i\Gamma_H \Gamma_V (2\pi) \delta(k_H + k_V - q_H - q_V) \times \frac{1}{\delta_{k_H}} \frac{1}{\delta_{k_V}} \left( \frac{1}{\delta_{q_H}} + \frac{1}{\delta_{q_V}} \right),$$
where \( S_k^{H/V} \equiv k - \Omega_0 + i \Gamma_{H/V}/2 \). The Fourier-space propagators \( \tilde{G}_H, \tilde{G}_V \), and \( \tilde{G}_{H/V} \) enable the gate fidelity calculations reported in Sec. III C.

### III. A PRIMITIVE CONDITIONAL PHASE GATE

In this section, we describe a conditional phase gate based on the interaction \( S_{\text{int}} \) described above. We first discuss how the unnecessary and undesirable linear evolution can be removed. We then consider the fidelity of this primitive (noncascaded) gate with an ideal conditional phase gate.

#### A. Removing linear evolution

In interacting with the atomic \( \vee \) system, both the one- and two-photon states that encode the computational basis [Eq. (2)] evolve nontrivially:

\[
\begin{align*}
|H\rangle & \rightarrow S_{\text{NL}} \left( 1 - |\epsilon_H|^2/2 e^{i\Omega_1} |H\rangle + |\epsilon_H|e_H \right), \\
|V\rangle & \rightarrow S_{\text{NL}} \left( 1 - |\epsilon_V|^2/2 e^{i\Omega_2} |V\rangle + |\epsilon_V|e_V \right), \\
|HV\rangle & \rightarrow S_{\text{NL}} \left( 1 - |\epsilon_{HV}|^2/2 e^{i(\Omega_1 + \Omega_2)} |HV\rangle + |\epsilon_{HV}|e_{HV} \right).
\end{align*}
\]

(13c)

Here all kets are normalized, \( \{\psi_H, \psi_V\} \) are the single-photon (linear) phase shifts, and the various \( \epsilon \) terms represent errors that occur because of photons evolving out of the principal modes.

The linear phase shifts \( \{\psi_H, \psi_V\} \) are not only irrelevant to the construction of conditional logic gates, but come also with some amount of fidelity-degrading evolution out of the principal-mode subspace. In order to build high-fidelity gates, it would be useful to remove completely the linear evolution that causes these effects. Removing linear evolution is also theoretically appealing because it allows one to study the fundamental limitations of the \( \vee \) system’s capacity for quantum XPM.

Formally, linear evolution is removed by evolving backward in time under a linearized Hamiltonian \( H_L(\Omega_1) \) in which the atomic lowering operators \( \sigma_{01} \) and \( \sigma_{02} \) are replaced by independent harmonic-oscillator annihilation operators \( b_V \) and \( b_H \) [cf. Eq. (6)]:

\[
H_L(\Omega_1) = H_{\text{fields}} + h c \Omega_1 (b_V^\dagger b_V + b_H^\dagger b_H) + \text{disp. terms}.
\]

This Hamiltonian, which we have explicitly parametrized by the cavity frequency \( \Omega_1 \) for later convenience, is linear in the sense that the equations of motion which it generates for the field operators \( h_L(\tau) \) and \( v_L(\tau) \) are linear differential equations. Application of the corresponding inverse scattering matrix \( S_{\text{NL}}(\Omega_1) \equiv \lim_{\tau \to -\infty} e^{-iH_{\text{fields}}(\Omega_1)\tau}/h c e^{iH_L(\Omega_1)\tau}/h c \) then removes linear evolution from \( S_{\text{NL}} \).

This useful form of error correction can, in principle, be implemented using linear optics. Figure 2(a) shows an optical circuit that removes linear evolution from input photons with center wave number \( k_0 \) by simulating time-reversed evolution under Eq. (14). The idea is to run the photons through \( H_L \) backwards: first, the baseband modulation of the input photon pulses is inverted (\( I \)); the pulses then interact with empty one-sided cavities; finally, the baseband modulation is reinverted.

Real-space inversion of an optical pulse’s baseband modulation corresponds to inversion about its center wave number \( k_0 \) in Fourier space. This transformation,

\[
I^\dagger \tilde{h}_I I = \tilde{h}_{2k_0 - k},
\]

(15)

can be achieved using temporal imaging [30–33]. Temporal imaging is the longitudinal analog of traditional spatial imaging: in spatial imaging, a beam’s transverse profile is manipulated using free-space diffraction and thin lenses; in temporal imaging, the longitudinal (temporal) profile is manipulated using dispersive delay lines and quadratic phase modulation. Figure 2(b) shows a temporal imaging system for baseband modulation inversion, while Fig. 2(c) shows its spatial analog.

While this method has not, to our knowledge, been used to demonstrate pulse inversion with quantum light, we see no fundamental physical principle preventing its implementation. Because the scheme to implement \( \tilde{I} \) shown in Fig. 2(b) involves only passive linear field transformations (dispersion and phase modulation), it behaves identically with respect to classical fields and few-photon pulses.

After inverting the optical pulses, the fields in Fig. 2(a) evolve forward in time under the linearized Hamiltonian \( H_L(\Omega_2) \) with cavity frequency \( \Omega_2 \). This corresponds to applying \( S_{\text{NL}}(\Omega_2) \) on the field operators. Because the equations of motion generated by \( H_L(\Omega_2) \) are linear, the mapping of the
field operators under $S_i(\Omega_2)$ is analogous to the mapping of single-photon packets under $S_{NL}$ [Eq. (10)],
\[ S_i(\Omega_2) N_k S_i(\Omega_2) = \tilde{N}_k - (\Omega_1 + i\Gamma H/2) \tilde{N}_k - (\Omega_2 - i\Gamma H/2), \] (16)
and similarly for $v_k$. By picking the pulse center wave number $k_0$, atomic resonance $\Omega_1$, and cavity resonance $\Omega_2$, such that photon-atom and photon-cavity detunings are equal and opposite, viz., $k_0 - \Omega_1 = -(k_0 - \Omega_2)$, the combined effect of pulse inversion, followed by evolution under $H_i(\Omega_2)$, followed by pulse inversion, yields time-reversed evolution under $H_i(\Omega_1)$:
\[ \mathcal{I} S_i(\Omega_2) \mathcal{I} = S_i(\Omega_1). \] (17)
In this way, the linear portion of $S_{NL}$ can be undone.

B. The primitive gate

The combined effect of nonlinear interaction with the $\nu$ system and removal of linear evolution is evolution under $S_i S_{NL}$:
\[ |\text{vac}\rangle \xrightarrow{S_i S_{NL}} |\text{vac}\rangle, \] (18a)
\[ |H\rangle \xrightarrow{S_i S_{NL}} |H\rangle, \] (18b)
\[ |V\rangle \xrightarrow{S_i S_{NL}} |V\rangle, \] (18c)
\[ |HV\rangle \xrightarrow{S_i S_{NL}} (1 - |e|^2) e^{i\phi_{NL}} |HV\rangle + |e|e \] (18d)
Here $|e\rangle$ is a two-photon state whose presence reflects errors intrinsic to the nonlinear evolution only. We refer to the Eq. (18) transformation as our primitive conditional $\psi_{NL}$-phase gate; this gate is primitive in the sense that it is not built by cascading simpler logic gates.

It is convenient to describe the primitive gate as transformation on the logical subspace $\{|\text{vac}\rangle, |H\rangle, |V\rangle, |HV\rangle\}$ alone. For nonzero errors $\epsilon$, the mapping given by Eq. (18) between input and output field states is not unitary when restricted to this subspace because of pulse deformation and undesirable entanglement generated between continuous degrees of freedom (e.g., photon momentum). When restricted to the logical subspace, Eq. (18) corresponds to a trace-preserving quantum operation $E_{\text{prim}}$:
\[ E_{\text{prim}}(\rho) = U_{\psi_{NL}}(E_1 \rho E_1^\dagger + E_2 \rho E_2^\dagger) U_{\psi_{NL}}^\dagger. \] (19)
Here $\rho$ is a two-qubit density matrix, $U_{\psi}$ is the ideal conditional $\varphi$-phase gate, and the operation elements $\{E_1, E_2\}$ represent pure amplitude damping of the two-photon state $|HV\rangle$ out of the logical subspace. In the usual basis,
\[ U_{\psi} = \begin{bmatrix} 1 \quad 0 \\ 0 \quad 1 \end{bmatrix}, \] (20a)
\[ E_1 = \begin{bmatrix} 1 \quad 0 \quad 0 \\ 0 \quad 1 \quad 0 \\ 0 \quad 1 \quad 0 \end{bmatrix}, \] (20b)
\[ E_2 = \begin{bmatrix} 0 \quad 0 \quad 0 \quad e \rangle \\ 0 \quad 0 \quad 0 \quad 0 \end{bmatrix}. \] (20c)
This operator-sum representation of the primitive gate is useful in determining its fidelity with an ideal conditional phase gate.

C. Fidelity of a single gate

The fidelity of two states is a measure of how close they are to one another, increasing from 0 (orthogonal states) to 1 (identical states). The fidelity of a pure state $\psi$ with a mixed state $\rho$ may be defined as their overlap, $F(|\psi\rangle, \rho) = |\langle \psi | \rho | \psi \rangle|$. Gate fidelity extends this idea from states to logical operations on qubits. The (minimum) gate fidelity of a quantum operation $E$ with a unitary gate $U$ that $E$ approximates is the fidelity of $E$’s output with the target output, minimized over pure state inputs [34],
\[ F(E, U) = \min_{|\psi\rangle} |\langle \psi | U \rangle|^2. \] (21)
The infidelity $1 - F(E, U)$ is the (maximum) probability that the $E$ fails to effect the desired transformation $U$.

The fidelity of our gate $E_{\text{prim}}$ with the ideal conditional phase gate $U_{\psi_{NL}}$ is
\[ F(E_{\text{prim}}, U_{\psi_{NL}}) \equiv \min_{|\psi\rangle} |\langle \psi | U_{\psi_{NL}} \rangle|^2 \equiv \min\{ |\langle \psi | E_1 | \psi \rangle|^2 + |\langle \psi | E_2 | \psi \rangle|^2 \} = 1 - |\epsilon|^2. \] (22)
Here the minimizing state is $|11\rangle_L = |HV\rangle$.

We now consider the relationship between the fidelity $F(E_{\text{prim}}, U_{\psi_{NL}})$ and the nonlinear phase shift when the real-space principal-mode wave function $\psi(z)$ in Eq. (23) is a rising exponential with center wave number $k_0$ and width $\gamma$,
\[ \psi(z) \equiv e^{ik_0z} \Psi(z), \quad \Psi(z) \equiv \theta(-zi) r(z) e^{-r(z)/2}. \] (23)
This particular principal-mode wave function is chosen because, as demonstrated in the next section, it is possible to make a projective measurement that distinguishes excitations of this principal mode from all other modes by exploiting the fact that photons with exponential wave functions are created when excited atoms decay. This fact can also be used to generate such photons and is the basis of several microwave-frequency single-photon sources that use artificial atoms coupled to superconducting resonators [35–37].

Henceforth we specialize to the case in which $\Gamma_H = \Gamma_V = \Gamma$ in order that the qubits are treated symmetrically.

Large phase shifts. If the fidelity $F(E_{\text{prim}}, U_{\psi_{NL}})$ and phase shift $\psi_{NL}$ could both be large simultaneously, then the primitive gate would be an effective conditional phase gate.

It is only when the atomic linewidth $\Gamma$ is comparable in size to the pulse bandwidth $\gamma$ that a large nonlinear phase shift is possible. If $\gamma \gg \Gamma$, then the pulse is too broadband to interact significantly with the atom, while if $\gamma \ll \Gamma$, then one sees from Eq. (11) that the range $\Gamma^{-1}$ of the nonlinear piece of the two-photon propagator is negligible in comparison to the pulse length $\gamma^{-1}$.
and absorption curves,

\[ \varphi_{NL} = \frac{\gamma \Gamma^2}{\delta^2 + (\Gamma/2)^2} \delta, \]  

(25a)

\[ |\epsilon|^2 = \frac{\Gamma}{\delta} \varphi_{NL}, \]  

(25b)

to lowest nonvanishing order in \( \gamma/\Gamma \).

From Eq. (25), it is clear that when \( \gamma \ll \Gamma \ll \delta \), the nonlinear phase shift, while very small, is large in comparison to the error probability: \( |\epsilon|^2 \ll \varphi_{NL} \). Actually, the relation \( |\epsilon|^2 \ll \varphi_{NL} \) can be achieved without requiring that \( \gamma \ll \Gamma \): it is enough for the photons to be far detuned. When \( \Gamma, \gamma \ll \delta \), we have

\[ \varphi_{NL} = \text{Re}[\xi] = \frac{\gamma \Gamma^2}{\delta^2} \left( \frac{1 + 5\gamma}{1 + \gamma/\Gamma} \right), \]  

(26a)

\[ |\epsilon|^2 = 2\text{Im}[\xi] = \frac{\Gamma}{\delta} \left( \frac{1 + 10\gamma^2 + \gamma^2}{1 + 5\gamma/\Gamma} \right) \varphi_{NL}. \]  

(26b)


to lowest order in \( \max(\gamma, \Gamma)/\delta \). Again, the nonlinear phase shift, though small, is much larger than the infidelity \( |\epsilon|^2 \).

In this sense, our primitive conditional phase gate can be considered high fidelity for small phase shifts.

IV. CASCADING SMALL PHASE SHIFTS

The error \( |\epsilon|^2 \) in the primitive conditional phase gate discussed above is the probability that the gate causes the two-photon state \( |HV\rangle \) to leak out of the principal-mode subspace. Because this error probability can be made much smaller than the phase shift in the far-detuned regime, the possibility of cascading \( N = \pi/\varphi_{NL} \) primitive gates to produce a high-fidelity conditional \( \pi \)-phase gate arises.

When the primitive gate \( S_{\text{NL}}^1S_{\text{NL}} \) is cascaded \( N \) times, two sorts of errors can occur. With each application, the probability of photons leaking out of the principal-mode subspace increases; for small \( |\epsilon|^2 \), these leakage errors grow as \( N|\epsilon|^2 \ll \varphi_{NL} \ll 1 \) and are not terribly problematic. However, amplitude that leaked from the principal-mode subspace in earlier applications of \( S_{\text{NL}}^1S_{\text{NL}} \) can return in later applications with corrupted phase; these coherent feedback errors can grow as \( N^2|\epsilon|^2 \), which is not small. Alternatively, this difficulty can be seen by noting that the primitive gate cascaded \( N \) times does not correspond to the quantum operation \( \mathcal{E}_{\text{prim}} \) cascaded \( N \) times. This is because the state of the auxiliary modes changes with each application of the \( S_{\text{NL}}^1S_{\text{NL}} \).

A. A cascadable primitive gate

We propose to eliminate coherent feedback errors by measuring the number of photons present in the auxiliary modes after each application of the primitive gate. For the sake of the following analysis, the result of this measurement need not be considered, only that with probability of at least \( 1 - |\epsilon|^2 \) it projects the quantum state back onto the principal-mode subspace. For this reason, we call this measurement process principal-mode projection (PMP). Performing PMP after each application of the primitive gate is a sort of Zeno effect error correction that prevents amplitude from leaking out of the principal-mode subspace too quickly.
most naturally represented by a non-trace-preserving quantum operation [34],

$$\mathcal{E}_{c\text{-prim}}(\rho) = U_{\psi_1} E_i \rho E_i^\dagger U_{\psi_1}^\dagger. \quad (27)$$

where $\text{tr}[\mathcal{E}_{c\text{-prim}}(\rho)]$ is the probability of success, i.e., that the output state has been collapsed into the principal-mode subspace.

### B. Fidelity of the cascaded gate

Because of the PMP, the cascadable primitive gate can be cascaded $N = \pi/\psi_{\text{na}}$ times to produce a high-fidelity conditional $\pi$-phase gate. Without any postselection, the fidelity of this cascaded gate with the ideal conditional $\pi$-phase gate is the probability that PMP success occurs $N$ times:

$$F(\mathcal{E}_{c\text{-prim}}^N, U_\pi) = F(\mathcal{E}_{c\text{-prim}}^N, U_{\psi_{\text{na}}})^N$$

$$= 1 - \frac{\Gamma}{\delta} \left( \frac{1 + 5\Gamma\delta + \pi^2}{1 + 5\Gamma\delta} \right), \quad (28)$$

to lowest nonvanishing order in $\max[\gamma, \Gamma]/\delta$. In the far-detuned regime $\gamma, \Gamma \ll \delta$, this fidelity can become quite large: cascading $\mathcal{E}_{c\text{-prim}}$ can yield a high-fidelity conditional $\pi$-phase gate.

As expected, because the $\gamma$ system’s nonlinearity is so weak, an unrealistic number of cascades $N$ are required to produce a high-fidelity conditional $\pi$-phase gate. That impracticality is the price paid for having chosen a system whose simplicity admits to rigorous analysis.

For fixed $N$, Eq. (28) can be rewritten, after optimizing the ratio $\gamma/\Gamma$, as

$$F(\mathcal{E}_{c\text{-prim}}^N, U_\pi) \approx 1 - 4.82 \times N^{-1/3}. \quad (29)$$

To achieve a fidelity greater than 95%, more than $10^6$ cascades are required. A realization of our primitive gate using the 6.8 GHz microwave photons with exponential decay time $\gamma c^{-1} = 40 \text{ ns generated in [36]}$ and chirped delay-line-based temporal imaging as in [38,39] would take roughly 800 ns. The vast majority of this time is used loading photons into the PMP cavity. The 95%-fidelity conditional $\pi$-phase shift thus takes 0.8 s, which is prohibitively long.

The origin of this $N^{-1/3}$ scaling is the weak cross-phase shift, $\psi_{\text{na}} \propto \delta^{-3}$. If instead the phase shift and error were $\psi_{\text{na}} \propto \delta^{-m}$ and $|\epsilon|^2 \propto \delta^{-n}$, respectively, the fidelity of the cascaded gate would be $F \sim 1 - N^{1-n/m}$. For example, $n = 2$ and $m = 1$ (as in the giant Kerr effect [22,23]) would lead to $F = 1 - 5 \times N^{-3}$ (assuming a prefactor similar to the $\gamma$ system gate). In this case, 100 cascades would suffice for producing a 95%-fidelity conditional $\pi$-phase shift in about 40 $\mu$s.

Our cascadable primitive gate $\mathcal{E}_{c\text{-prim}}$ operates in the far-detuned regime and incorporates two error-correcting steps: the removal of linear evolution ($\mathcal{S}_{\text{nl}}$) and the PMP. Principal-mode projection is absolutely essential in making this gate cascadable. How important is removing the linear evolution? For the mode function used above, the linear errors $[|\epsilon H|^2, |\psi|^2]$ must be removed. It turns out that because the Fourier-space mode function $\tilde{\psi}(k) = i k^{1/2} (k - k_0 + k/2)^{-1}$ falls off only as $k^{-1}$, linear errors are of the same order of magnitude as the nonlinear phase shift. However, for
more well-behaved Fourier-space mode functions (e.g., Gaussians $\tilde{\psi}(k) \sim \exp[-(k-k_0)^2/4\gamma^2]$ and even Lorentzians $\tilde{\psi}(k) \sim [(k-k_0)^2 + \gamma^2]^{-1}$), linear errors are of the same order as nonlinear errors. If PMPs could be constructed for these modes, the removal of linear evolution would not be essential.

V. CONCLUSIONS

Treating light as a multimode quantum field, we have described conditional phase gates in which photonic qubits interact with a three-level $\vee$ system. Although we have used the language of atomic and optical systems in our analysis, other implementations are possible. In the microwave, for example, the one-dimensional field of transmission-line waveguides have been coupled to artificial atoms [40, 41].

In the regime of large nonlinear phase shifts, our primitive (noncascaded) gate has unacceptably low fidelity, as has phase shift with very high fidelity (1 vertically polarized fields.

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APPENDIX: PRINCIPAL-MODE PROJECTION WITH CAVITIES

In Sec. IV A, we outlined how principal-mode projection could be achieved for the one-sided exponential mode $\psi(z) = \theta(-z)\gamma^{1/2} e^{i(k_0z+\gamma z^2/2)}$ by exploiting the fact that cavities absorb and emit forward-decaying and backward-decaying exponential pulses. Here we give some mathematical details.

The PMP setup is shown in Fig. 4 and relies on a cavity whose resonant frequency $\omega_0$ and decay rate $\gamma$ are matched to the pulse shape $\psi(z)$. We assume the cavity is placed at position $z = L$. Ignoring the pulse inverter $\mathcal{I}$ for the moment, the interaction between the field $v_z$ and cavity is described by a Hamiltonian

$$\mathcal{H} = \mathcal{H}_{\text{field}} + \hbar \omega_0 b^\dagger b + i\hbar c \gamma^{1/2}(v_L b^\dagger - v_L^\dagger b), \quad (A1a)$$

$$\mathcal{H}_{\text{field}} = \int \frac{dk}{2\pi} \hbar c \gamma \tilde{\psi}_k \tilde{\psi}_k^* = -i\hbar \left[ \int dz v_L^* \partial_z v_L \right], \quad (A1b)$$

where $b$ is the cavity lowering operator and $\tilde{\psi}_k = \int dz v_z e^{-ikz}$, as above. Under this Hamiltonian, the Heisenberg equation of motion for $v_z(\tau)$ can be readily solved. For $\tau > 0$, the solution is $v_z(\tau) = v_z(\tau - \gamma^{-1}\partial(\tau - L)\theta(\tau + L - \gamma)\delta(\tau + L - z))$.

Initially, the cavity in Fig. 4 is empty and the field contains $|\psi(0)\rangle = \int dz \phi(z) v_L^\dagger (0; \text{vac})$.

\begin{equation}
|\phi(0)\rangle = \int dz \phi(z) v_L^\dagger (0; \text{vac}). \quad (A2)
\end{equation}

The amplitude for this photon to have been absorbed by the cavity at a time $\tau$ later is $s_v(\tau) = \langle 1; \text{vac}|e^{-i\pi \tau/\hbar c}\phi(0)\rangle$. By using Eq. (A2) to expand $|\phi(0)\rangle$ and using the Heisenberg equations of motion for $v_z(\tau)$ and $b(\tau)$, one can show that $s_v(\tau)$ obeys

$$\frac{\partial}{\partial \tau} + ik_0 + \gamma/2) s_v(\tau) = -\gamma/2 \phi(L - \tau), \quad (A3)$$

whose solution is

$$s_v(\tau) = \gamma/2 \int_0^\tau \int_{-\infty}^L d\tau' \phi(L - \tau') e^{-(ik_0 \gamma/2)(\tau - \tau')} \quad (A4)$$

At $\tau = L$, this becomes $s_v(L) = \int_{-\infty}^L d\tau \phi(\tau) \psi(-\tau)$; the cavity acts as a filter, preferentially absorbing photons from the inverted mode $\psi^*(\tau)$ and rejecting all others. Note that by making $L$ large enough, essentially all of the photon in the mode $\psi^*(-z)$ can be absorbed: only an exponentially small portion $e^{-\gamma L}$ is missed. This inverted mode $\psi^*(-z)$ is precisely what the principal mode $\psi(z)$ is transformed into by the pulse inverter $\mathcal{I}$. In contrast, absorbed photons are reemitted into the principal mode. Long after absorbing a single photon, the cavity photon decays into the mode

$$\lim_{\tau \to \infty} |0; z\rangle e^{i\hbar \omega_0/\hbar c} - e^{i\pi \tau/\hbar c} |1; \text{vac}\rangle = \psi(z - L). \quad (A5)$$

(Here, $|0; z\rangle = v_L^\dagger (0; \text{vac})$ and free-space translation has been removed by applying $e^{i\hbar \omega_0/\hbar c}$.)

We now summarize the PMP process. Before pulse inversion, the photon’s mode function can be decomposed as $\alpha|\psi(z)\rangle + \beta|\psi^*_L(\tau)\rangle$ and as $\phi(z) = \alpha|\psi^*_L(\tau)\rangle + \beta|\psi^*_L(\tau)\rangle$ after inversion. The pulse propagates into the cavity through iris 1, which is initially open. Next, the cavity absorbs a portion of the pulse and rejects the rest. In order to prevent reflection of the rejected portion, iris 2 is initially closed. At time $\tau = L$,
the amplitude for the cavity to contain a single photon is $\alpha$, i.e., the principal-mode photon has been transferred coherently to the cavity. At this point, iris 2 is opened (pulse timing is known) to allow the cavity photon to decay back into the principal mode, while iris 1 is shut in order to prevent further, unwanted absorption.

[28] Because we consider a one-sided cavity, we should really only integrate over $k > 0$ in Eq. (4b). By using a truly linear dispersion relation, $\omega_k = ck$, we ensure that the unphysical, negative $k$ modes are so far-detuned from the atomic system as to be irrelevant.

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