Experimental demonstration of CNOT gate for frequency-encoded qubits

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Abstract: We demonstrate the first two-photon gate for frequency-bin qubits, using optical pulse shaping and electro-optic phase modulation. Our coincidence-basis CNOT has a fidelity of 0.9947 ± 0.0008 and shows controlled qubit flips in the computational basis.

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Photonic qubits encoded in the frequency domain show strong potential for advancing future quantum networks, with single-photon frequency-bin gates demonstrated in both nonlinear [1, 2] and electro-optical [3, 4] approaches. However, two-photon entangling gates, required for universal quantum computing, have yet to be realized on any frequency-bin platform—a consequence not only of the generally weak coupling between two photons, but also the fact that coherent interactions between multiple frequency modes are nontrivial. In this work, we develop and implement the first two-photon frequency-bin gate—a coincidence-basis CNOT—retrieve an ultrahigh gate fidelity inferred from coherent-state measurements, and probe it with two-photon states in the logical basis.

One flexible scheme toward universal quantum information processing (QIP) with frequency-bin qubits is spectral linear-optical quantum computation, which uses electro-optic phase modulators (EOMs) and Fourier-transform pulse shapers (PSs) for coherent frequency operations [5]. This paradigm has been utilized to demonstrate single-photon quantum gates on frequency-bin states with high fidelities [3, 4]. A necessary component toward universal photonic QIP, however, is a two-photon *entangling* gate, which operates on one qubit conditioned on the state of another. Inherently probabilistic with linear optics, such gates can be heralded with ancilla photons [6]; we previously discovered a 4EOM/4PS configuration capable of realizing a controlled-Z (CZ) gate with the best-known success probability of $\mathscr{P} = 2/27$ [5]. Yet if one postselects on the presence of photons in the desired output qubit modes—either with a quantum nondemolition measurement or by detecting these photons directly—it is possible to realize a gate with no ancillas and $\mathscr{P} = 1/9$ [7].

To explore the coincidence-basis CNOT gate in our paradigm, we follow the optimization approach in [3, 5], numerically finding sets of phase patterns for an EOM/PS sequence which maximize success $\mathscr{P}$ constrained to fidelity $\mathscr{F} \geq 0.9999$. If we restrict to a circuit of size 2EOM/1PS with sinewave-only temporal modulation, we obtain a solution with $\mathscr{P} = 0.0445$ which, while falling short of the theoretical optimum, can be realized with our previously developed quantum frequency processor [3, 4] . We thus concentrate on this solution in the following experiment. Figure 1(a) provides a schematic of the setup. The gate itself comprises the central EOM/PS/EOM sequence, and the frequency bins for encoding are spaced by 25 GHz. The specific bins chosen for encoding follow in Fig. 1(b), where $\{C_0, C_1\}$ and $\{T_0, T_1\}$ denote logical $|0\rangle$ and $|1\rangle$ for the control and target, respectively. This mode placement makes sense intuitively: mode C_0 is spectrally isolated from the target's logical bins ensuring a photon in mode C_0 leaves the target unchanged; on the other hand, bin C_1 is close to both target bins, coupled to T_0 and T_1 with equal strength.

Since this gate is based on a linear-optical network, we can predict its performance using coherent-state-based characterization with an electro-optic frequency comb [3, 8]. The experimentally obtained mode transformation matrix V allows us to numerically compute the equivalent two-photon state transformation matrix W [5], from which we obtain the inferred fidelity $\mathscr{F}_{\text{inf}} = 0.9947 \pm 0.0008$ and success probability $\mathscr{P}_{\text{inf}} = 0.045 \pm 0.001$ with respect to the ideal CNOT. We emphasize that, unlike single-qubit gates which act on photons independently and therefore show the same

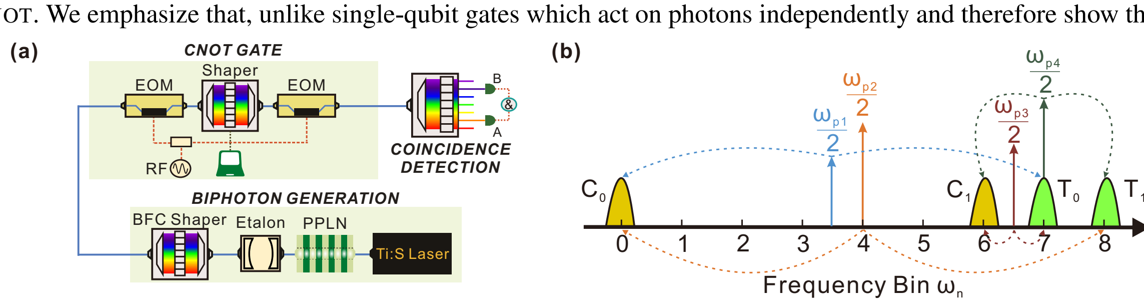

Fig. 1. (a) Experimental setup. (b) Preparation of all four computational-basis inputs.

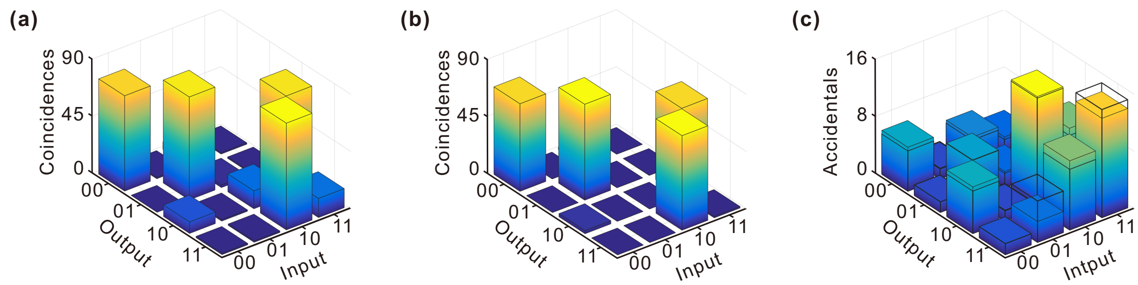

Fig. 2. Measurements of frequency-bin CNOT in the logical basis. (a) Raw data. (b) After accidentals subtraction. (c) Accidental counts (bars, experiment; wireframes, theory).

basic features for quantum as well as classical optical fields, two-qubit entangling gates rely on quantum interference effects that are absent with high-flux coherent states. Accordingly, this inferred fidelity is highly provisional, but it still provides evidence for the phase coherence and proper operation of our gate.

To test our gate with quantum states directly, we prepare a biphoton frequency comb (BFC) by pumping a periodically poled lithium niobate (PPLN) waveguide with a continuous-wave Ti:sapphire laser, followed by filtering with a Fabry-Perot etalon with 25 GHz mode spacing. The BFC shaper subsequently selects specific modes as the input to the gate. By translating the pump frequency to four different values [as shown in Fig. 1(b)], we can prepare all inputs from the computational basis, i.e.: $|00\rangle = |1_{\omega_0} 1_{\omega_7}\rangle$, $|01\rangle = |1_{\omega_0} 1_{\omega_8}\rangle$, $|10\rangle = |1_{\omega_6} 1_{\omega_7}\rangle$, and $|11\rangle = |1_{\omega_6} 1_{\omega_8}\rangle$. To ensure the photon flux remains constant across these four inputs, we tune the temperature in the PPLN waveguide to align the peak of the phase-matching spectrum with the pump laser frequency. After the gate, the output photons are frequency-demultiplexed and sent to detectors for coincidence measurement. Ideally, a coincidence registered (with probability 4.45%) signals the CNOT is successful.

Figures 2(a) and (b) plot the measured coincidences for all 16 input/output mode combinations (for 600 s), before and after accidentals subtraction, respectively. Our results indicate the gate works largely as expected, with a measured computational-basis fidelity [9] of $\mathscr{F}_C = 0.84 \pm 0.04$ and 0.94 ± 0.03 before and after accidentals subtraction (computed via Bayesian mean estimation). Interestingly, the inhomogenous distribution of the experimental accidentals shown in Fig. 2(c) indeed matches well with our theoretical prediction. Since by design a coincidence-basis gate ignores cases when one of the qubit spaces is empty or doubly occupied, the singles counts—which contribute to accidentals in experiment—actually vary significantly across input states. The wireframes in Fig. 2(c) confirm this, showing the accidentals level predicted by the numerically designed transformation matrix and scaled by the measured singles counts.

In conclusion, we have realized a two-photon entangling gate for frequency-bin qubits. We obtain an ultrahigh fidelity of 0.9947 ± 0.0008 using classical coherent-state characterization, and demonstrate qubit flips mediated by the state of a control photon. This coincidence-basis CNOT significantly expands the generality of frequency-based QIP.

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