High-fidelity and robust two-qubit controlled-Z gates for direct-coupling superconducting transmon qubits

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Quantum supremacy has been demonstrated experimentally by using the frequency-tunable superconducting qubits. To achieve the ultimate goal of fault-tolerant quantum computation or to increase the reliable circuit depth (the number of gates that can be successively and reliably performed in a quantum circuit) on noisy intermediate-scale quantum (NISQ) machines, keeping pursuing high-fidelity and robust quantum universal gates is an important and timely issue. Here we construct single-shot smooth flux pulses to achieve the high-fidelity and robust two-qubit controlled-Z (CZ) gates for the direct-coupling superconducting qubits by our robust control method. For superconducting qubits, shrinking the gate time can reduce the decoherence error, but will enhance the leakage error. The gate time of our optimized CZ gate constructed by controlling only the external fluxes can be reduced to 12 ns, and the leakage error can still be kept to be $\sim 2.5 \times 10^{-5}$, demonstrated by simulations using the experimental system parameters and also considering the finite bandwidths of the commercial arbitrary waveform generators. We characterize the slow and fast dephasing noises from the experimental data, and use the characterized noises to setup the noise models in our robust control method. The optimized 12 ns CZ gate can reduced the total dephasing error to $\sim 4.1 \times 10^{-5}$, and the CZ gate infidelity is limited by the energy relaxation process with error $\sim 4.0 \times 10^{-4}$ for $T_1 = 30\ \mu s$. Finally, we take the dephasing and relaxation noises and system parameter uncertainties into the robust control method to provide the optimal control solutions for the high-fidelity and robust CZ gates.

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