High-fidelity, high-scalability two-qubit gate scheme for superconducting qubits

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High-quality two-qubit gate operations are crucial for scalable quantum information processing. Often, the gate fidelity is compromised when the system becomes more integrated. Therefore, a low-error-rate, easy-to-scale two-qubit gate scheme is highly desirable. Here, we experimentally demonstrate a new two-qubit gate scheme that exploits fixed-frequency qubits and a tunable coupler in a superconducting quantum circuit. The scheme requires less control lines, reduces crosstalk effect, simplifies calibration procedures, yet produces a controlled-Z gate in 30 ns with a high fidelity of 99.5%. Error analysis shows that gate errors are mostly coherence-limited. Our demonstration paves the way for large-scale implementation of high-fidelity quantum operations.

Quantum information processor architectures are scaling up at a fast pace, entering the Noisy Intermediate-Scale Quantum (NISQ) era [1–6]. The prospect of demonstrating quantum advantages with NISQ devices relies critically on continuing extending the system size without compromising the quality of quantum operations. Currently, two-qubit gate operation is the performance bottleneck in various modalities [7–10], and it generally deteriorates as more qubits, and hence more control lines, are integrated together. Obviously, more control lines introduce additional decohering channels, exacerbates crosstalk, adds to the complexity of calibration procedures. Therefore, a high-fidelity yet easy-to-scale two-qubit gate scheme is the key to scalable quantum information processing.

For high-scalability two-qubit gates, two ingredients are highly desirable. First, the use of a tunable coupler between qubits has been proven effective in resolving the problem of frequency crowding, suppressing residual coupling, and enabling fast and high-fidelity two-qubit gates [2, 11–15]. However, homogenous calibration efforts are required for precise control, especially when both qubits and couplers are tunable and sensitive to crosstalk [2]. The iterative and exquisite system tuning-up adds instability to processor performance, hindering further scaling up. Second, fixed-frequency qubits can drastically simplify the system, require less control lines and have better coherence in general. Previous experiments have demonstrated these advantages with non-tunable superconducting qubits made with single Josephson junction [16–20]. However, two-qubit interactions in these schemes are activated by parametrically driving the system, an inherently slow process that is prone to decohering errors. An ideal solution is a two-qubit gate scheme which takes advantage of both fixed-frequency qubits and tunable coupler, while maintaining high fidelity.

In this work, we experimentally demonstrate a new two-qubit gate scheme, compatible with fixed-frequency qubits, in a superconducting quantum circuit. Effective longitudinal qubit-qubit coupling can be adjusted by a single control parameter of a tunable coupler. With proper choice of the idling point, the system has a residual coupling strength as small as 20 kHz. Taking advantage of enhanced adiabaticity due to strong qubit-coupler coupling (> 100 MHz), we realize a fast (30 ns) and high-fidelity (99.5%) adiabatic controlled-Z (CZ) gate. Error analysis from separate measurements shows that the fidelity is limited mostly by decoherence. Moreover, our scheme is intrinsically robust against crosstalk and requires only a simple calibration sequence, promising better scalability in practice.

Our experiment is performed on a superconducting quantum circuit which consists of two Xmon qubits (Q1, Q2) [21] and a transmon-type [22] tunable coupler (C) in between, as shown in Fig. 1(a). Note that the first qubit is made tunable for other experimental purpose [23]. Throughout this work, it is biased at its maximum frequency, and can be treated as an equivalent of a fixed-frequency qubit. The system Hamiltonian can be expressed as

\[
H/h = \sum_{i=1,2,c} \omega_i a_i^+ a_i + \frac{\alpha_i}{2} a_i^+ a_i^+ a_i a_i + \sum_{i \neq j} g_{ij} (a_i^+ a_j + a_i a_j^+),
\]

where \(a_i^+\) and \(a_i\) are corresponding creation and annihilation operators. \(\omega_i/2\pi = 5.27 \text{ GHz}\) and \(\omega_2/2\pi = 4.62 \text{ GHz}\) are the qubit frequencies. The coupler frequency \(\omega_c\) is flux-dependent, and is biased at 6.74 GHz during idling periods and single-qubit gate periods. The corresponding anharmonicities are \(\alpha_1/2\pi = -210 \text{ MHz}\), \(\alpha_2/2\pi = -240 \text{ MHz}\), and \(\alpha_c/2\pi = -370 \text{ MHz}\). To speed up the two-qubit
gate while minimizing unwanted transitions, our design features enhanced coupling parameters. That is, $g_{12}/2\pi = 12$ MHz (between qubits), $g_{1z}/2\pi = 122$ MHz and $g_{2z}/2\pi = 105$ MHz (between qubit and coupler), much stronger than the conventional Xmon design [21]. Each qubit has a local XY control line for single-qubit operations, and is coupled to a $\lambda/4$ resonator for readout. A local Z control line is used to adjust the flux threading the coupler loop, controlling two-qubit interactions. More details about the device and experimental setup can be found in Ref. [24].

To illustrate how the adiabatic CZ gate is implemented, we may rewrite the system Hamiltonian in Eq. (1) using a generic form in its energy-eigenbases ($|Q_1, C, Q_2\rangle$), labelled by the approximate bare states when the coupler is far-detuned):

$$H'/\hbar = \hat{\omega}_1 |100\rangle \langle 100| + \hat{\omega}_2 |001\rangle \langle 001| + (\hat{\omega}_1 + \hat{\omega}_2 + \chi_{12}) |101\rangle \langle 101|,$$

after truncation to the computational subspace. The eigen-energies $\hat{\omega}_1$, $\hat{\omega}_2$, $\chi_{12}$ are all $\omega_c$-dependent. $\chi_{12}$ represents the effective longitudinal coupling between qubits, and is responsible for generating the entangling phase. Finite $\chi_{12}$ is a consequence of interactions among higher levels, which can be relatively strong in transmon-type qubits due to their weak anharmonicity. The energy levels adjacent to $|101\rangle$ are plotted in Fig. 1(b) as a function of $\omega_c$. In our two-qubit gate scheme, we adiabatically adjust the coupler from an idling bias ($\omega_c=6.74$ GHz) to a region where the bare state $|101\rangle$ interacts more strongly with other levels and then back to the original bias. Non-zero $\chi_{12}$ during this process leads to a controlled-phase operation or a CZ gate if the total accumulated phase is $\pi$.

Here, we emphasize that the strong coupling between $|101\rangle$ and $|011\rangle$ is not the sole cause of $\chi_{12}$, because $|011\rangle$ alone would have exactly the same level-pushing effect to $|101\rangle$ as $|010\rangle$ would do to $|100\rangle$, leading to a trivial single-qubit frequency shift. In fact, the non-trivial interaction mainly arises from the coupling between $|101\rangle$ and $|200\rangle$. This coupling may become much stronger when their interaction-mediating state $|110\rangle$ is tuned close to them. Our scheme may further benefit from this effect with an optimized set of device parameters [25].

The adiabatic process is supposed to be slow enough to avoid unwanted transitions, e.g., leakage to non-computational states [26]. In the conventional fixed-coupling architecture, the limit on the adiabatic CZ gate speed is set by the qubit-qubit coupling strength. With the introduction of a tunable coupler and its strong couplings to qubits, non-adiabatic effect can be effectively suppressed in the relevant region for two-qubit interactions. In our device, the minimum gap between $|101\rangle$ and other states, a key factor in determining adiabaticity, is about 190 MHz, much greater than that in the conventional scheme. Also, we find that our scheme adds robustness in adiabaticity against parameter instability and pulse distortion. Detailed explanations can be found in the supplement [24]. Other non-adiabatic approaches that take advantage of the interference effect can also facilitate the gate speed [27–29], but may become sensitive to pulse distortion, adding instability to gate performance.

In our experiment, we first measure the longitudinal coupling strength at different coupler frequencies, i.e., $\chi_{12}(\omega_c)$, from a conditional Ramsey-like experiment, as detailed in Fig. 2. The dynamic range of the longitudinal coupling strength spans more than three orders of magnitude, from 20 kHz to 100 MHz, enabling fast two-qubit gate operations as well as small residual coupling. The results are in good agreement with numerical simulation using our device parameters. Notably, since the two qubits have relatively large detuning ($|\omega_1 - \omega_2| > |\alpha_1|$), there is no working bias such that
the coupling can be turned off completely. This is different from the case when the two qubits are prepared to be near-resonance [2, 12]. However, we can still find a minimum coupling that is small enough (20 kHz) for practical applications.

Next, we calibrate the adiabatic CZ gate. As shown in Fig. 1(b), the 30-ns flux pulse assumes a half-period cosine shape, with rising and falling edges smooth enough for adiabatic evolution at this time scale. A conditional Ramsey experiment similar to the one shown in Fig. 2(a) is used for calibrating the amplitude of the flux pulse, the only free parameter at this step. We obtain a CZ gate when the conditional phase shift satisfies $\Delta \phi = \pi$, and also find out the free phase of the single-qubit phases, later to be compensated by virtual-Z gates [30]. For subsequent randomized benchmarking (RB) experiments, these parameters are further optimized using the RB results as the cost function [31].

We assess our gate performance by the conventional Clifford-based RB method [32–34]. A reference RB experiment is performed by applying multiple random sequences composed of two-qubit Clifford gates $C_2$, followed by a recovery gate $C_{1r}$ to invert the overall operation. The results are finally averaged over 100 random samples. An CZ-interleaved RB experiment is the same except for additional CZ gates inserted to the reference RB sequence. Figure 3(a) shows the measured system ground-state probability or sequence fidelity as a function of the number of two-qubit Clifford gates $m$ for both the reference and CZ-interleaved cases. With exponential fit, we obtain the average error per Clifford $r_{\text{ref}} = 0.0278(3)$ and $r_{\text{int}} = 0.0328(3)$. By comparing the two traces, we can also extract the CZ gate error $r_{CZ} = 0.0052(4)$ and fidelity $F_{CZ} = 0.9948(4)$. As a consistency check, we may re-evaluate the reference RB result by $r_{\text{ref}} = 1.5 r_{CZ} + 8.25 r_{1q} = 0.0185$ (given single-qubit gate error $r_{1q} = 0.0013(1)$ [24]), which is about 70% of the measured result shown in Figure 3(a).
suspect that the remaining difference results from distortion of the flux pulse that degrades the single-qubit gate quality.

To estimate the decoherence error, we first obtain the effective energy relaxation time $T_1$ and pure dephasing time $T_\phi$ during the CZ gate [Fig. 3(b)]. Obviously, the effective $T_1$ and $T_\phi$ times are lower than those during idling periods, a consequence of the stronger interaction between the qubits and the less coherent coupler during the CZ pulse. In particular, $Q_1$, the qubit of higher frequency, has stronger interaction with the coupler than $Q_2$, leading to a much shorter effective $T_\phi \approx 0.5 \mu$s. The RB sequence, however, is insensitive to pure dephasing caused by low-frequency noise, because the relatively slow phase excursion is randomly disrupted or, in many occasions, even well-refocused by the single-qubit gates in the RB sequence. The (Gaussian) pure dephasing from $Q_1$ contributes $\frac{1}{2}(\tau_{\text{gate}}/T_\phi)^2 = 0.12\%$ to gate errors [35], where $\tau_{\text{gate}} = 30$ ns is the pulse duration. The contribution from $Q_2$ (≪ 0.01%) is negligible. The $T_1$ contribution to gate errors can be estimated by an empirical relation, $\frac{2}{3}(\tau_{\text{gate}}/T_1^{\text{eff}} + \tau_{\text{spacing}}/T_1^{\text{idle}})$, where $T_1^{\text{eff}}$ ($T_1^{\text{idle}}$) is the average effective (idling) $T_1$ of the two qubits, and $\tau_{\text{spacing}} = 4$ ns is the inter-pulse spacing. Thus the $T_1$ process leads to a gate error of 0.28%. Therefore, decoherence, including both $T_1$ and $T_\phi$ processes, accounts for about 77% of the total gate error, while leakage and other control errors make up no more than 23%.

To validate our analysis, we perform a separate experiment, measuring the pulse-induced transitional errors on each of the four joint eigen-states, as detailed in Fig. 3(c) and Ref. [24]. The extracted transition rates per gate are the additional errors caused by the CZ pulse, compared to the identity operation. Therefore, this pulse-induced transitional errors include additional energy relaxation during gate and other unwanted transitions such as leakage. For most of the joint states, the results are in good agreement with the additional $T_1$ contribution calculated from Fig. 3(b), except for the $|001\rangle$ state. The averaged error difference is $(0.016 \pm 0.046)\%$, suggesting small leakage error.

Finally, we discuss the scalability of our scheme from the perspective of crosstalk and calibration. Consider a 2D qubit array for implementing surface code [36], as shown in Fig. 4(a). With the problem of frequency crowding addressed by tunable couplers, we may pattern the qubit array with an interleaved frequency setup. Such an arrangement provides robustness against the XY-line crosstalk between neighboring qubits, because of the ineffectiveness of driving a qubit with a frequency-detuned signal. More importantly, our scheme is also intrinsically robust against the Z-line crosstalk. Given that the maximum frequency of the coupler can be designed to be at the idling point (minimal residual coupling), the longitudinal coupling becomes doubly insensitive to flux variations, since both $\chi_{12}(\omega_c)$ and $\omega_c(\Phi_C)$ are at first-order insensitive points. With our device parameters, a 10% flux crosstalk from neighboring Z drive only incurs an additional coupling less than 1 kHz.

In our gate scheme, the calibration procedures for finding the optimized system and control parameters are also drastically simplified. A typical routine calibration flow in our experiment is drawn in Fig. 4(b), after the coupler’s idling point was chosen. Since the qubits are fixed-frequency and the couplers are insensitive to crosstalk, the calibration process does not require iterative (cross) tuning-ups or complicated check procedures. Single-qubit and two-qubit control parameters are calibrated separately in turn. The graph of the

![Diagram of a 2D qubit array and calibration flow.](image)
To conclude, we experimentally demonstrate a new type of adiabatic CZ gate with fixed-frequency qubits and a tunable coupler in a superconducting quantum circuit. With a large ON/OFF ratio (> 1000) of the effective coupling which is adjusted by the coupler frequency (flux), we achieve small residual coupling (20 kHz) and fast CZ gate (30 ns). A high gate fidelity of 99.5% is obtained from interleaved randomized benchmarking, with error analysis showing mostly coherence-limited gate error. The gate performance may further benefit from optimized pulse shape for faster adiabatic process [38] and from coherence improvement with new material platform [39]. Also, our scheme is easy-to-scale due to its intrinsic robustness against crosstalk and a simple calibration flow. This high-fidelity, high-scalability two-qubit gate scheme promises reproducibly high-quality quantum operations in future large-scale quantum information processors.

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Note added.– We notice concurrent development of a similar work to implement conditional-phase gates with a tunable coupler [40].

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Supplementary Material for
“High-fidelity, high-scalability two-qubit gate scheme for superconducting qubits”

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I. THE DEVICE

A. Device parameters and experimental setup

The device is fabricated with aluminum on sapphire substrate. Relevant device parameters are summarized in Table S1. The device is mounted inside a dilution refrigerator at a base temperature of about 10 mK. Fridge wiring and measurement circuitry are shown in Fig. S1. We perform the standard circuit-QED measurements.

| Parameters (MHz) | $Q_1$ | $Q_2$ |
|------------------|-------|-------|
| Resonator frequency ($\omega_{R1}/2\pi, \omega_{R2}/2\pi$) | 6955  | 7002  |
| Qubit frequency ($\omega_1/2\pi, \omega_2/2\pi$) | 5271  | 4615  |
| Qubit anharmonicity ($\alpha_1/2\pi, \alpha_2/2\pi$) | -210  | -240  |
| Coupler frequency (idling) | 6704  |       |
| Coupler anharmonicity ($\alpha_c/2\pi$) | -370  |       |
| Qubit-coupler coupling ($g_{1c}/2\pi, g_{2c}/2\pi$) | 122   | 105   |
| Qubit-qubit direct coupling ($g_{12}/2\pi$) | 12    |       |

FIG. S1: Wiring diagram and circuit components.
B. Z crosstalk

In order to use qubit \( Q_1 \) (tunable) as a fixed-frequency qubit, its flux bias has to be set to zero throughout the experiment. Therefore, we characterize and compensate crosstalk of \( Z \) control lines between qubit \( Q_1 \) and the coupler. The crosstalk coefficients (about 8%) are derived from measuring the frequency response to the control lines. However, when qubit \( Q_1 \) is biased at its maximum frequency as in all subsequent experiments, its frequency becomes insensitive to flux variation, adding extra robustness against crosstalk. Therefore, it is valid to treat qubit \( Q_1 \) as a fixed-frequency qubit in our experiment.

C. Coupler spectrum

Due to strong coupling between \( Q_2 \) and the coupler, there is a frequency shift of \( Q_2 \) depending on the coupler state. We take advantage of this effect to measure the spectrum of the coupler \([1]\). The pulse sequence and the measured results are shown in Fig. S2. The two visible avoided crossings correspond to the couplings between the coupler and the two qubits, from which the coupling strengths \( g_{1c} \) and \( g_{2c} \) can be extracted.

**FIG. S2**: Measured coupler spectrum with corresponding pulse sequence (inset). The coupler is pulse-biased to a varying amplitude \( V_b \) while driven by a microwave pulse applied to the XY control line of qubit \( Q_1 \). Transitions occur when the drive frequency is on resonance with the pulse-biased coupler frequency. Due to strong coupling between the coupler and \( Q_2 \), a coupler-state-dependent frequency shift of \( Q_2 \) can be used to distinguish the coupler state by probing \( R_2 \) after a selective \( \pi \)-pulse on qubit \( Q_2 \). On the greyed color plot, red dashed lines are the measured transitions and the blue solid line is the fitted bare coupler spectrum. The smallest gaps of the two avoided crossings indicate twice the coupling strength.
II. ENHANCED ADIABATICITY

In general, the adiabatic condition in an adiabatic process between any two states, \(|m\rangle\) and \(|n\rangle\), is defined by the relation:

$$\beta_{nm} = \left| \frac{\hbar \langle n | \frac{\partial H}{\partial t} | m \rangle}{(E_n - E_m)^2} \right| \approx \frac{\hbar \langle n | m \rangle}{|E_m - E_n|} \ll 1, n \neq m. \quad (S1)$$

\(\beta_{nm}\) quantifies the unwanted leakage. Here, we compare two protocols of adiabatic CZ gate, which are constructed by modulating the frequency of tunable qubits\(^2, 3\) or the frequency of the tunable coupler as done in our work. Summing over all the possible leakage states, we can rewrite Eq. S1 as

$$\beta_m = \sum_{n \neq m} \left| \frac{\hbar \langle n | \frac{\partial H}{\partial t} | m \rangle}{(E_n - E_m)^2} \right| = \left( \sum_{n \neq m} \left| \frac{\hbar \langle n | \frac{\partial H}{\partial f} | m \rangle}{(E_n - E_m)^2} \right| \right) \left| \frac{\partial f}{\partial t} \right|, \quad (S2)$$

where \(f\) denotes the frequency of the tunable coupler. Note that the ramping speed of frequency \(|df/dt|\) can be modulated with different pulse waveforms. Normally, \(|df/dt| \sim 100 \text{ MHz/1 ns}\) in a rapid gate. The energy structure and the corresponding non-adiabaticity factor,

$$\beta = \sum_{n \neq m} \left| \frac{\hbar \langle n | \frac{\partial H}{\partial f} | m \rangle}{(E_n - E_m)^2} \right|, \quad (S3)$$

are then crucial quantities in our discussion.

Using the energy structure of our device, we calculate the effective ZZ coupling \(\chi_{12}\) and the factor \(\beta\) as a function of the coupler frequency, and compare them to the conventional scheme without a tunable coupler (Fig. S3). We find that, with a tunable coupler, the strongest \(\beta\) experienced during the pulse is near two-orders-of-magnitude smaller than the conventional scheme, enabling faster and lower-leakage adiabatic controlled-phase gate. Also, we notice that there is a flat response region in \(\beta\) after the coupler being tuned across the higher-frequency \(Q_1\) during the process of our pulse. This suggests that our scheme has intrinsic robustness against instability of control parameters and pulse distortion.
III. ERROR ANALYSIS

A. Single-qubit gate randomized benchmarking

We perform standard RB experiment for single-qubit gates on both qubits simultaneously. The results are shown in Fig. S4. The average single-qubit gate infidelity is 0.16% for $Q_1$ and 0.10% for $Q_2$.

B. Frequency-dependence of coherence times

The energy relaxation time $T_1$ and pure dephasing time $T_\phi$ of qubit $Q_1$ and $Q_2$ are measured as a function of coupler frequency, with the experimental results shown in Fig. S5. These measured data are used for generating Fig. 3(b) in the main text. The effective $T_1$ ($T_\phi$) is obtained by integrating the error rates of energy relaxation (pure dephasing) over different coupler frequencies weighted by the actual half-period cosine pulse shape.
FIG. S4: Simultaneous single-qubit gate RB. Plotted are the sequence fidelity decay for the reference case and the interleaved X/2 case.

FIG. S5: Energy relaxation (top) and Gaussian pure dephasing (bottom) times v.s. the coupler frequency. The frequency corresponding to the maximum pulse amplitude is marked with the black dashed line.

C. Pulse-induced error

Figure S6 shows the measured data used for generating Fig. 3(c) in the main text. The experiment is used to characterize the extra errors induced by the CZ gate pulse. Note that these extra errors include both control and decoherence errors. Control errors may include unwanted transitions, e.g. leakage to non-computational states. Decoherence errors are additionally accumulated errors due to the change of energy relaxation time during the CZ pulse, referenced to the idling situation.

Note that the |00⟩ state is supposed to give a flat response, because the adiabatic CZ state should have almost no effect on the |00⟩ state. However, we still observe a slight rising with pulse number in the measured population. One possible explanation is the CZ pulse may facilitate converting residual thermal or non-equilibrium excited-state populations to the ground state. The pulse-induced error of |00⟩ state is extracted from the difference of the slopes of the two linear fits. For the other three cases, the two population decay curves are fitted with an exponential decay function $F = Ap^m + B$, giving two decay constants $p_{Id}$ and $p_{CZ}$. The corresponding error rates are extracted by $r = \frac{3}{4}(1 - p_{CZ}/p_{Id})$.

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FIG. S6: The pulse-induced errors. (a) The pulse sequence for extracting the pulse-induced errors. A number of $m$ repeated CZ (or Identity) gates are applied. Optional $\pi$-pulses before the pulse train are used to prepare the state to $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$. They are inverted back by symmetrically applied $\pi$-pulses after the pulse train before measuring the population of the system ground state. (b-e) The measured decay curves (markers) which are exponentially fitted (solid lines) except for the $|00\rangle$ case (linear fit).