

Coupler microwave-activated controlled phase gate on fluxonium qubits

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Tunable couplers have recently become one of the most powerful tools for implementing two-qubit gates between superconducting qubits. A tunable coupler typically includes a nonlinear element, such as a SQUID, which is used to tune the resonance frequency of an LC circuit connecting two qubits. Here we propose a complimentary approach where instead of tuning the resonance frequency of the tunable coupler by applying a quasistatic control signal, we excite by microwave the degree of freedom associated with the coupler itself. Due to strong effective longitudinal coupling between the coupler and the qubits, the frequency of this transition strongly depends on the computational state, leading to different phase accumulations in different states. Using this method, we experimentally demonstrate a CZ gate of 44 ns duration on a fluxonium-based quantum processor, obtaining a fidelity of $97.6 \pm 0.4\%$ characterized by cross-entropy benchmarking.

I. INTRODUCTION

During the last decade, there has been a tremendous progress in implementing fluxonium qubits [1–4] as the building blocks of a superconducting quantum processor. Since their proposal [1] fluxonions have become a perspective experimental platform for creating superconducting quantum circuits with a wide range of control parameters due to their richer energy level structure compared to widely used transmons [5, 6]. Due to its large anharmonicity, the fluxonium qubit has significant advantages over the transmon qubit in terms of coherence times, single-qubit gate fidelities, and leakage rates. Fluxonium circuits implemented in a 2D architecture [3] showed qubit coherence of times $T_1, T_{2e} \approx 300\mu s$, while fluxonium qubits installed in 3D cavities demonstrated coherence times higher than 1 ms and average single-qubit gate fidelities above 0.9999 [7].

The implementation of two-qubit gates on the fluxonium platform has moved from directly coupled qubits [8, 9] to a more scalable approach with tunable interaction via a coupler element [10]. Similar to transmons, two-qubit gates on fluxonions can be implemented using the flux tunability of qubits. The obvious disadvantage of tuning the flux is that the coherence time of the qubit is only large when operated at the flux sweet spot. Another disadvantage of flux-activated gates is that sweeping the frequency of the qubits may lead to a Landau-Zener-type interaction with strongly coupled two-level defects that would normally be off-resonant with the qubit [11].

An alternative way of implementing two-qubit gates is by inducing transition interactions between the qubits with microwaves. Microwave-activated gates include transitions via higher-excited energy levels [8] or cross-resonance gates [12, 13]. These gates rely on direct capacitive coupling between the qubits, which has a drawback of large residual ZZ interactions between the qubits when no gate is applied.

In this paper, we propose a CZ gate scheme between two low-frequency fluxonions coupled via an extra coupler fluxonium. Instead of applying a magnetic flux to the coupler element to change the coupling strength between the qubits, we activate microwave transitions in the coupler element. Due to strong interaction between this element and the computational qubits, the spectrum of these transitions is state-dependent. As a result, the detuning of the microwave drive depends on computational states, which results in different acquired phases in these states. This gate principle is closely related to the iToffoli gate proposal [14], with the main difference that here we apply the microwave pulse not to one of the computational qubits, but to the coupler qubit. We experimentally demonstrate this approach by tuning up a 44 ns-long CZ gate with a cross-entropy benchmarking fidelity of $97.6 \pm 0.4\%$.

II. DEVICE AND THEORETICAL BACKGROUND

We investigate a quantum device consisting of three capacitively coupled fluxonium qubits, two of which are the computational qubits and the remaining one plays the role of a tunable coupler, see Fig. 1. Each fluxonium has an additional harmonic mode with a frequency close to 2 GHz. The mutual capacitances between the qubits lead

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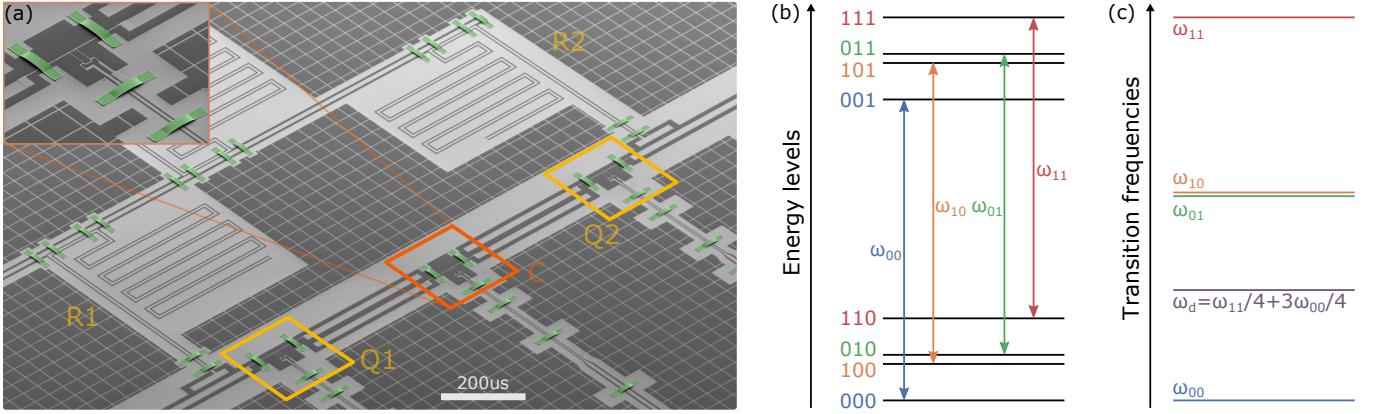


FIG. 1. The device and gate concept. (a) The SEM image of the fluxonium quantum processor. The computational qubits Q1 and Q2 are capacitively coupled to the individual readout resonators R1 and R2, those in turn are connected to the readout transmission line. Both qubits are also capacitively coupled to the middle fluxonium C, which enlarged image is shown in the upper left corner. Each fluxonium has its own excitation line. (b) The energy level structure of the coupled system and the transition frequencies between the pairs of states $|000\rangle - |001\rangle$, $|100\rangle - |101\rangle$, $|010\rangle - |011\rangle$ and $|110\rangle - |111\rangle$.

to large transversal couplings between the bare fluxonium and harmonic modes. The details of the circuit layout and parameters are discussed in detail in [10, 15].

Here, the computational qubits are biased at their flux degeneracy points, and the coupler is at zero flux. At the operating point the frequencies of the computational qubits are 669.64 MHz and 694.35 MHz, while the coupler frequency is about 3.4 GHz. At these flux biases, when the coupler is deexcited, the residual effective coupling between the computational qubits is weak.

We consider the ground and excited states of each fluxonium mode, and a microwave signal applied to the coupler close to its resonance frequency. With all fluxoniums being detuned from each other, the transversal couplings result in state dressing and dispersive frequency shifts. Because of the very large frequency difference between the coupler and the qubits we neglect driving of the dressed computational qubit modes. Thus the effective Hamiltonian of the coupled multi-fluxonium system can be expressed as

$$\frac{\mathcal{H}}{\hbar} = - \sum_{i=1,2,c} \frac{\omega_i}{2} \sigma_{zi} - \sum_{i=1,2} \frac{\zeta_{ic}}{4} \sigma_{zi} \sigma_{zc} + \Omega \sigma_{xc} \cos \omega_d t, \quad (1)$$

where $\omega_i/2\pi$ is the renormalized frequency of the i -th qubit, ζ_{ic} is the dispersive coupling strength between the computational qubits and the coupler, and σ_{xi} and σ_{zi} are Pauli operators acting on the lowest two levels of the i -th fluxonium, and Ω is the drive strength. Here we also neglect the direct interaction between the computational qubits since $\zeta_{12} \ll \zeta_{1c}, \zeta_{2c}$.

The Hilbert space of the system can be separated into four non-interacting subspaces corresponding to different states of the computational qubits. We focus on the transitions between the ground and excited states of the coupler in these subsystems. Within a rotating wave ap-

proximation in the frame of the drive signal their Hamiltonians can be written as

$$\frac{\mathcal{H}}{\hbar} = - \frac{\Delta_{mn}}{2} \sigma_{zc} + \frac{\Omega}{2} \sigma_{xc}, \quad (2)$$

where $\Delta_{mn} = \omega_d - \omega_{mn}$ are the detunings between the drive tone and the effective coupler frequency corresponding to the computational state $mn \in \{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$,

$$\omega_{mn} = \omega_c + \frac{(-1)^m}{2} \zeta_{1c} + \frac{(-1)^n}{2} \zeta_{2c}. \quad (3)$$

The energy spectrum and frequencies are schematically shown in Fig. 1b.

The solution of the Schrödinger equation in case of a rectangular microwave pulse with the initial condition on the wave function $\psi(0) = |0\rangle$ is

$$\psi(t) = \begin{pmatrix} \frac{i\Delta_{mn}}{\Omega_R} \sin\left(\frac{\Omega_R t}{2}\right) + \cos\left(\frac{\Omega_R t}{2}\right) \\ -\frac{i\Omega}{\Omega_R} \sin\left(\frac{\Omega_R t}{2}\right) \end{pmatrix}, \quad (4)$$

where $\Omega_R = \sqrt{\Delta_{mn}^2 + \Omega^2}$ is the generalized Rabi frequency. Apart from the population transfer, these oscillations also result in a phase accumulation of the computational state. Note that, for an integer number of Rabi oscillations this phase is either π or 2π .

Thereby, each subspace has its own common phase, which depends on the signal detuning from the frequency of the corresponding transition. The idea is to find such parameters of the drive pulse that the coupler returns to the ground state for all computational states and the common phases φ_{mn} acquired by the Rabi oscillations of the corresponding transition satisfy the following condition:

$$\theta = \varphi_{00} - \varphi_{10} - \varphi_{01} + \varphi_{11} = \pi + 2\pi k, \quad k \in \mathbb{Z}. \quad (5)$$

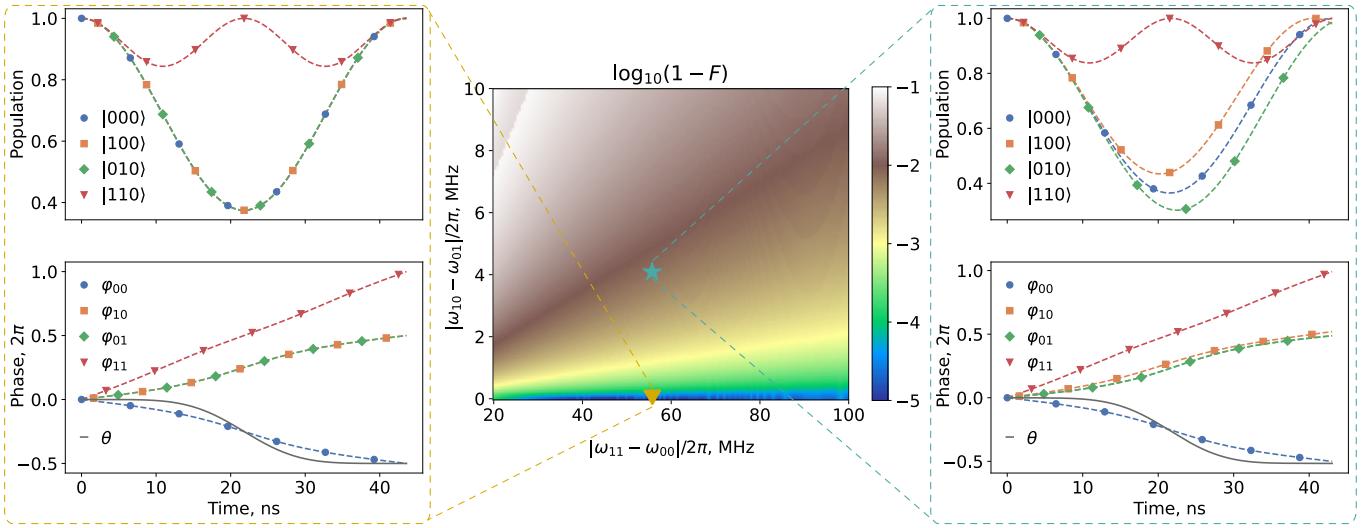


FIG. 2. Gate simulation. The fidelity of a CZ gate $\log_{10}(1 - F)$ as a function of the differences between the design-dependent transition frequencies ω_{10} , ω_{01} and ω_{11} , ω_{00} . The orange triangular correspond to the ideal point when $\omega_{10} = \omega_{01}$ and the left inset plot shows the time evolution of the population and common phase of the four computational states. The dashed gray line shows the acquired phase $\theta = \varphi_{00} - \varphi_{10} - \varphi_{01} + \varphi_{11}$. The fidelity of the such gate is exactly 1. The turquoise star corresponded to the frequencies, observed in the experiment (see Table I). The time dynamics of the computational states associated with the ground state of the coupler and the common phases is shown in the right inset figure. The obtained CZ gate fidelity is 0.992.

Let us make an assumption that the transitional frequencies ω_{10} , ω_{01} are equal: $\omega_{10} = \omega_{01} = (\omega_{11} + \omega_{00})/2$. In this case both conditions mentioned above can be exactly satisfied, and a CZ gate can be implemented if we choose the drive frequency ω_d at the half sum of the transition ω_{00} and ω_{10} : $\omega_d = (\omega_{10} + \omega_{00})/2$, the amplitude $\Omega = \sqrt{\frac{5}{12}}(\omega_{10} - \omega_{00})$, and the duration $\tau = \frac{\sqrt{6}\pi}{\omega_{10} - \omega_{00}}$. Such a signal results in a single Rabi oscillation for the $|00\rangle$, $|01\rangle$ and $|10\rangle$ computational states, and two oscillations for the $|11\rangle$ state. The time dynamics of these four populations and the corresponding common phases under the described external signal is shown in left inset figure in Fig. 2. We calculate the evolution in the rotating wave approximation assuming that the oscillations are independent and isolated from the rest system.

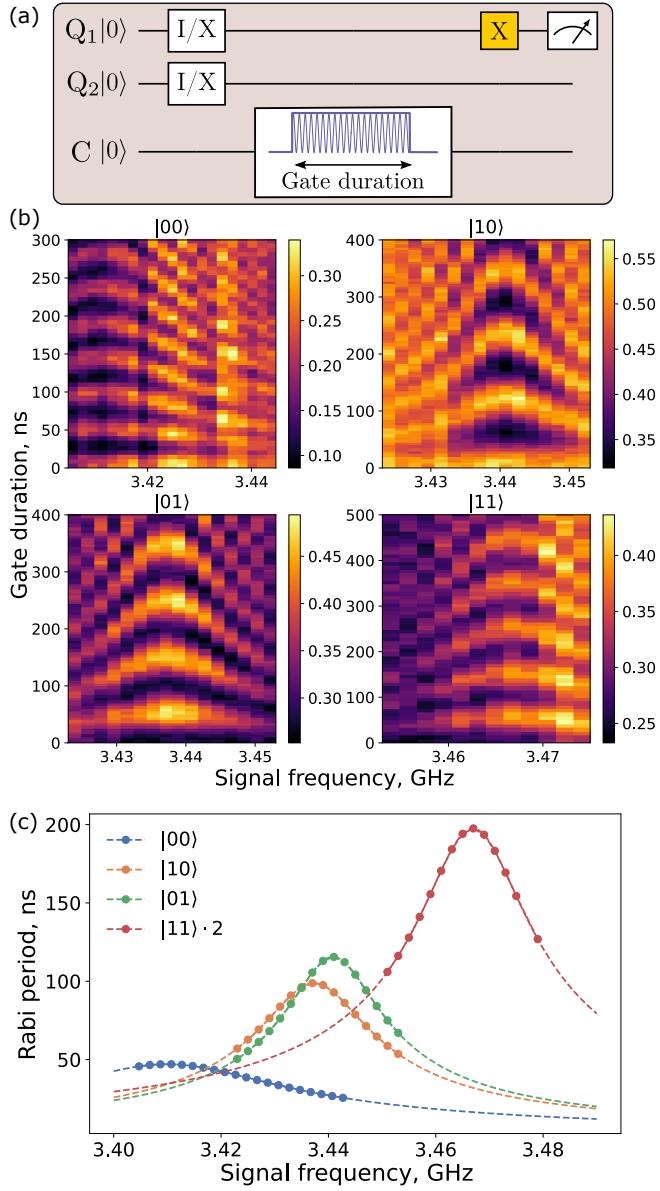
Though the qubits are designed to be identical, the critical currents of the phase slip junctions turn out slightly different, thus, the transition frequencies ω_{10} and ω_{01} are not equal. We simulate the evolution of the system for the different $|\omega_{11} - \omega_{00}|$ and $|\omega_{10} - \omega_{01}|$ under the drive with frequency $\omega_d = \frac{\omega_{11}+3\omega_{00}}{4}$. The optimal drive amplitude and gate duration and fidelity of the CZ gate fidelity calculated on the computational states $|000\rangle$, $|100\rangle$, $|010\rangle$, $|110\rangle$ are shown in Fig 2. The turquoise star on the plot indicates the point corresponding to the obtained experimental data (see Table I), the time dynamics of the four populations and the acquired phase for these frequencies is also shown in the right inset plot in Fig 2. The fidelity of the simulated gate for the experimental frequencies is 0.992 and the duration is 43 ns.

III. EXPERIMENTAL RESULTS

The setup used in this experiment is based on an earlier work [10], with a number of modifications, described in Appendix A. Here we just briefly summarize the techniques used for single-qubit gates, readout and initialization, and then focus on the coupler microwave-activated CZ gate implementation.

The reset procedure is realized via capacitively coupled microwave antennas as dissipation channels. We tune the qubit to the zero flux point, where the longitudinal relaxation rate is an order of magnitude higher, and then return the qubit to the operating point just before the scheduled pulse sequence. The readout is implemented using adjacent resonators with fidelities 0.67 and 0.62 for the first and second computational qubits for simultaneous qubit measurement. We explain such a poor readout fidelity by weak coupling strength between the qubit and corresponding resonator, which is an innate feature of the chip layout. The single qubit gates are generated from $\pi/2$ rotations around axes in the equatorial plane of the Bloch sphere, realized by gaussian pulses with 13.3 ns duration. The excitation pulses are applied through to flux line of the qubit. Due to the large amplitude of these pulses we apply a phase error compensation with a virtual rotation about the Z axis after every $\pi/2$ pulse. We construct each of the 24 elements of the single-qubit Clifford group from two $\pi/2$ gates and virtual Z rotations. The average fidelity of single-qubit Clifford group gates $F = 0.9928 \pm 0.0003$ has been measured with the cross entropy benchmarking method (Fig. 6).

Going back to the CZ gate realization, first, we should



note that our device contains no resonator intended for the readout of the coupling fluxonium, and therefore we cannot measure the coupler directly. To deal with this problem we use the coupler state-dependent frequency shift of the computational qubits. Before reading out one

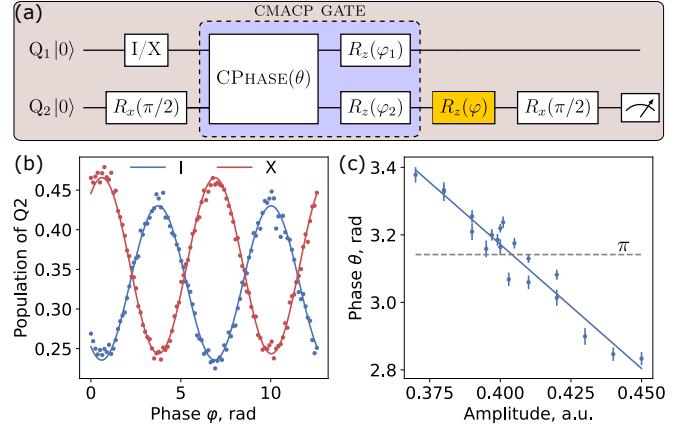


FIG. 4. Calibration of the CZ gate. (a) Excitation pulse sequence. The first qubit is prepared in one of the two states $|0\rangle$ (I gate) or $|1\rangle$ (X gate). Then we apply the coupler microwave-activated controlled-phase gate, make a single-qubit phase rotation on the second qubit and finally measure the second qubit in the X-basis. (b) Populations p_1 and p_2 of the second qubit as a function of the phase φ of the highlighted gate. The solid line is the fit of the experimental dots with the function 6. (c) Conditional phase θ as a function of the excitation pulse amplitude.

	$\omega_{00}/2\pi$	$\omega_{10}/2\pi$	$\omega_{01}/2\pi$	$\omega_{11}/2\pi$	
value	GHz	3.4098	3.44009	3.43605	3.4660
σ	MHz	0.1	0.07	0.08	0.2

TABLE I. Measured transition frequencies between the ground and excited state of the coupler for the four logical states of the computational qubits $|00\rangle$, $|01\rangle$, $|10\rangle$, and $|11\rangle$ with corresponding frequencies ω_{00} , ω_{01} , ω_{10} , and ω_{11} . The errors are calculated as a standard deviation of the least squares method.

of the computational qubits, we apply a low-amplitude, 120 ns-long π -pulse. The frequency of this pulse corresponds to the qubit frequency when the coupler is unexcited. If the coupler is excited, such an excitation pulse will be out of resonance with the qubit, only weakly affecting the qubit state.

The calibration procedure of the CZ gate starts with determining the transition frequencies of the coupler for the four different states of the computational qubits. For this we perform the pulse sequence shown in Fig. 3a. We prepare the computational qubits in one of the four initial states $|00\rangle$, $|10\rangle$, $|01\rangle$, $|11\rangle$ and then apply a microwave pulse on the coupler, varying the frequency and duration. After that the coupler state measurement protocol consisting of a low-amplitude X-gate applied to one of the qubits followed by the measurement of that qubit is performed. In this manner, we observe Rabi chevron patterns, from which we extract Rabi frequencies for each detuning of the drive signal. We approximate the data by the formula $\sqrt{\Omega^2 + \Delta_{mn}^2}$, where the drive amplitude Ω and the resonance Rabi frequency ω_{mn} are the fitting pa-

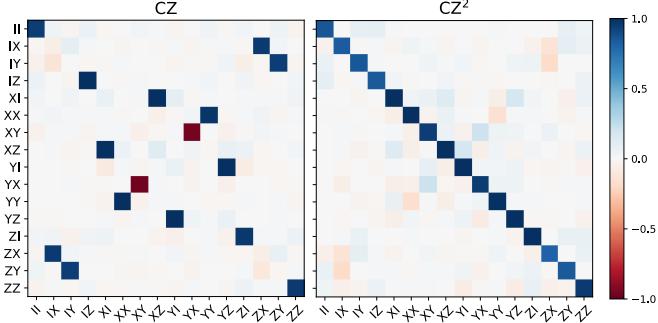


FIG. 5. Experimental reconstruction of the Pauli process matrices for the obtained coupler microwave-activated CZ gate $F = 0.9892$ and two CZ gates implemented in a row $F = 0.9637$. For comparison the fidelity of the identity matrix is $F = 0.9824$.

rameters. We collect the results in Table I and plot the drive dependence of the Rabi frequency in Fig 3.

Using the obtained transition frequencies we calculate the gate duration for an optimal rectangular pulse and experimentally find the corresponding amplitude. Thus we roughly define the frequency, amplitude and duration of the drive pulse. For the precise calibration we execute the gate sequence shown in Fig. 4, which is commonly used for the phase estimation of a CPhase gate [16]. In this experiment we measure the population of the second qubit as a function of the phase φ of the highlighted gate when the first qubit is initially in the $|0\rangle$ and $|1\rangle$ states. These populations are fitted with the functions

$$\begin{aligned} p_1(\varphi) &= \frac{1}{2} (1 - \cos(\varphi + \varphi_2)) \\ p_x(\varphi) &= \frac{1}{2} (1 - \cos(\varphi + \varphi_2 + \theta)) \end{aligned} \quad (6)$$

and the phase difference θ is the parameter of the CPhase gate. We measure this angle for different signal amplitudes, fit the obtained points with a line and find an amplitude corresponding to the π phase, see Fig. 4. Then we measure the period of the Rabi oscillations of the coupler at this amplitude for the computational qubit states $|00\rangle$, $|10\rangle$, and $|01\rangle$ (the oscillations associated to the state $|11\rangle$ are indistinct under the current experimental conditions), find the best drive frequency, when these states have close Rabi frequencies and update the gate duration. After that we again refine the amplitude with the previous method. We repeat the procedure in total for three times, until the amplitude converges.

Finally, after we determine the parameters of the drive signal, we test the CZ gate. First, we perform a tomography experiment of the two-qubit identity gate I with zero duration, and of the CMACP-generated CZ gate, repeated once and twice. The obtained fidelities are 0.9824, 0.9892 and 0.9637 for the I, CZ and CZ² gates, correspondingly, and the Pauli process matrices are shown in Fig. 5. The disadvantage of the tomography method is that the result is strongly affected by state preparation

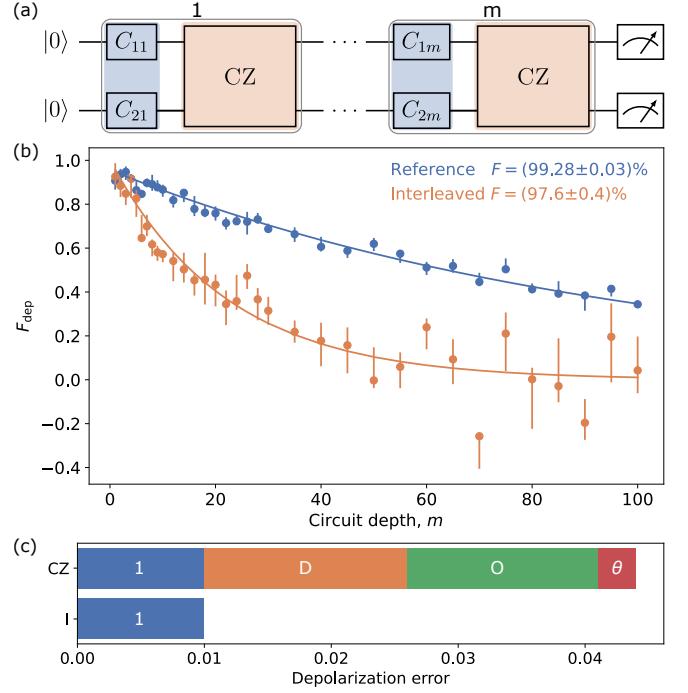


FIG. 6. Cross entropy benchmarking. (a) Quantum circuit for the XEB experiment. (b) Depolarization fidelity for the XEB sequences without (reference) and with interleaved target CZ gate. (c) Error rate estimates for the implemented gate: ε_θ relates to the non-exact π phase of CZ gate; ε_1 and ε_D correspond to decoherence on the computational qubits during single-qubit and two-qubit gates, respectively; ε_O is the residual error rate which includes effects of residual population and decoherence of the coupling element.

and measurement (SPAM) errors. Thus, in consideration of the poor readout, the fidelity of the CZ gate turned out to be higher than that of the identity gate. The large difference between the fidelities of the CZ and CZ² gates indicates significant residual population of the coupler after the first CMACP gate, expected for the current system parameters. Indeed, if the coupler does not completely return to the ground state after the gate execution, it does not decrease fidelity of the current gate, but has a strong effect on subsequent gates.

Second, we test the CZ gate using the cross entropy benchmarking technique (XEB) [17, 18]. This method accommodates SPAM errors, and is highly sensitive to the residual population of the non-computational states. For the experiment we test quantum circuits with depth m up to 100, for each depth we generate 150 sets of two random sequences $\{C_{11}, \dots, C_{1m}\}$, $\{C_{21}, \dots, C_{2m}\}$ of the single-qubit Clifford gates and average the readout results over 10000 repetitions of each of these sets with and without (reference) the interleaved target CZ gate. We approximate the average depolarization fidelity F_{dep} by the function ap^m , where p is the depolarization probability and a is a fitting parameter. The conventional gate

fidelity can be calculated with the formula

$$F = p + (1 - p)/D, \quad (7)$$

where $D = 2^n$ is the dimension of the Hilbert space ($n = 2$). If a target gate is inserted after each single-qubit operation, then the average fidelity of the gate is determined by the eq. 7 with $p = p_2/p_1$, where p_2 and p_1 are the depolarizing parameters corresponding to the interleaved and reference sequences.

In Fig. 6, blue dots show an exponential decay of the depolarization fidelity of the reference random single-qubit Clifford-gate sequence executed simultaneously on two computational qubits. The orange dots present similar data with the inserted target CZ gate. With a least squares fit we obtain $p_1 = (99.00 \pm 0.05)\%$ and $p_2 = (95.6 \pm 0.4)\%$. The average fidelities of the single-qubit Clifford gates and the CMACP-generated CZ gate are $F = (99.28 \pm 0.03)\%$ and $F = (97.6 \pm 0.4)\%$, correspondingly.

Furthermore, we estimate the contributions of the various error sources to the total error $\varepsilon = 1 - p$ of the CZ gate. The first one is the non-exact conditional phase π . We find that the fidelity of the XEB data is maximized for the phase of the target gate $\theta = 0.963\pi$ and calculate the infidelity $\varepsilon_\theta = 0.003$. The next error source is decoherence of the computational qubits. This contribution can be estimated by the extrapolation of the average single-qubit error $\varepsilon_1 = 1 - p_1 = 0.01$ from the duration of a single-qubit operation 26.6 ns to the CZ gate duration 44 ns, yielding $\varepsilon_D = 0.016$. The rest infidelity $\varepsilon_O = 0.015$ we attribute to other error sources, that include the decoherence processes and residual population on the coupling fluxonium. The estimated error budget is shown with a bar plot in Fig. 6. Note that the errors for the interleaved sequences are significantly larger than for the reference sequences. This is related to the larger spread of fidelities for different random sequences, which indicates a significant fraction of coherent errors in the implemented two-qubit gates.

IV. CONCLUSION AND OUTLOOK

In this work, we propose and demonstrate a CZ gate realized using a microwave drive applied to a coupler qubit. Due to the strong interaction between the coupling and computational qubits, the main transition frequency of the coupler depends on the state of the computational qubits. This allows to choose such exciting pulse that the speed of phase acquisition on the computational states is different, that in turn results in an effective CPhase operation. We experimentally demonstrate the proposed CZ gate of 0.976 fidelity and 44 ns duration on a device consisting of three capacitively coupled fluxoniums.

The obtained gate fidelity can be improved in further experiments. We identify two significant error sources: decoherence processes and the residual population of the coupler. While decoherence is a significant limiting factor

for the performance of many contemporary qubits, the residual population of a degree of freedom mediating the two-qubit interaction is not typical for superconducting qubits. We stress that the latter error has a coherent nature, and can thus be reduced by using advanced control signal shaping [19].

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Appendix A: Experimental setup

The scheme of the experimental setup is presented in Fig. 7. The experiments are performed in a BlueFors LD-250 dilution refrigerator with a base temperature of 10 mK. The chip is connected to the control setup with six lines: the readout line, two excitation and flux control lines (XYZ controls), two lines coupled with 10 mK stage and ended with 50Ω terminators for qubit reset, and the coupler’s excitation and flux control line (XYZ controls).

Pulse generation and flux control are fully performed by a Zurich Instruments HDAWG8 arbitrary waveform generator. One analog output port of the generator is used per fluxonium circuit. IQ microwave mixers are employed to up- and downconvert the intermediate frequency readout pulses to the resonator frequencies and back. After getting reflected from the qubit chip, the readout microwave signal is measured by a vector network analyzer (R&S ZVB20) for spectroscopy and a home-built digitizer setup for single-shot readout. For mixer calibration we use a spectrum analyzer (Agilent N9030A).

Microwave attenuators are used to isolate the qubit chip from thermal and instrumental noise from the signal sources, which are located at room temperature. The readout line is equipped with an impedance matched parametric amplifier (IMPA) followed by a Quinstar CWJ1019KS414 isolator to prevent noise from higher temperature stages entering the IMPA and the qubit device. We pump the IMPA using an Agilent E8257D signal generator. Three Raditec RADC-4.0-8.0-Cryo circulators and a set of low-pass and high-pass filters placed after the sample preserves it from IMPA pumping and reflected signal. At the PT2 stage (3 K) of the cryostat, a LNF-LNC0.3 14A high electron mobility transistor (HEMT) is installed. The output line is further amplified outside the cryostat with two Mini-Circuits ZVA-183-S+ ampli-

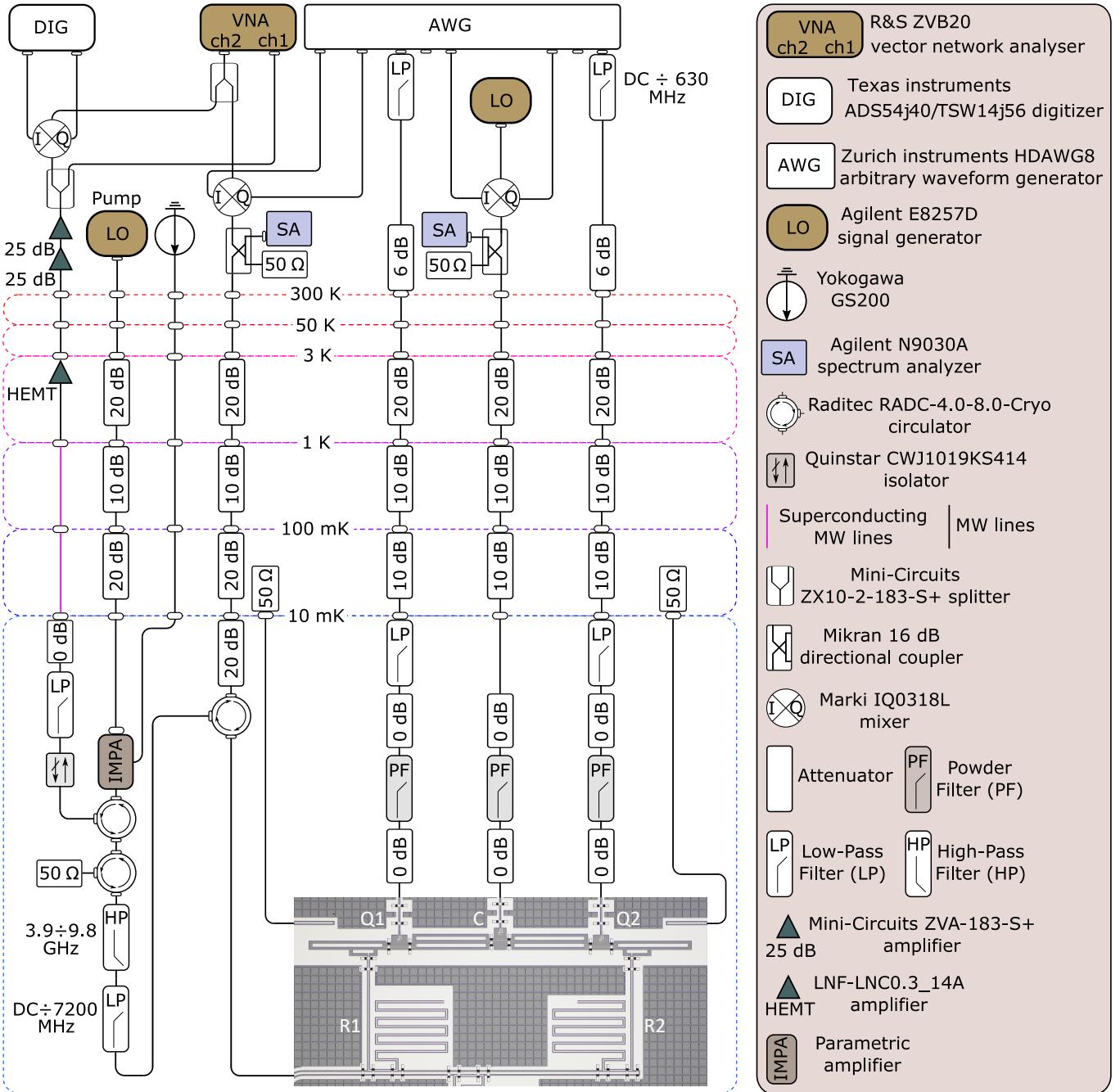


FIG. 7. Experimental setup.

fiers. We use a low-pass filter (Mini Circuits VLF-630+) in combination with a powder filter with 15 dB attenuation close to the qubit frequencies in qubit control lines and only powder filter in coupler control line.

Capacitively coupled qubit control lines are connected to $50\ \Omega$ terminators at the 10 mK stage of the cryostat. These lines are used for the qubit initialization and reset.

REFERENCE

- [1] Vladimir E. Manucharyan, Jens Koch, Leonid I. Glazman, and Michel H. Devoret. Fluxonium: Single cooper-pair circuit free of charge offsets. *Science*, 326(5949): 113–116, oct 2009. doi:10.1126/science.1175552. URL <https://doi.org/10.1126/science.1175552>.
- [2] Long B. Nguyen, Yen-Hsiang Lin, Aaron Somo-roff, Raymond Mencia, Nicholas Grabon, and Vladimir E. Manucharyan. High-coherence fluxonium qubit. *Phys. Rev. X*, 9:041041, Nov 2019.

- doi:10.1103/PhysRevX.9.041041. URL <https://link.aps.org/doi/10.1103/PhysRevX.9.041041>.
- [3] Helin Zhang, Srivatsan Chakram, Tanay Roy, Nathan Ernest, Yao Lu, Ziwen Huang, D. K. Weiss, Jens Koch, and David I. Schuster. Universal fast-flux control of a coherent, low-frequency qubit. *Phys. Rev. X*, 11: 011010, Jan 2021. doi:10.1103/PhysRevX.11.011010. URL <https://link.aps.org/doi/10.1103/PhysRevX.11.011010>.
- [4] Il'ya Nikolaevich Moskalenko, Il'ya Stanislavovich Besedin, Ivan Andreevich Tsitsilin, Grigorii Stefanovich Mazhorin, Nikolai Nikolaevich Abramov, Aleksandr Grigor'ev, Il'ya Anatol'evich Rodionov, Alina Aleksandrovna Dobronosova, Dmitrii Olegovich Moskalev, Anastasiya Aleksandrovna Pishchimova, et al. Planar architecture for studying a fluxonium qubit. *JETP Letters*, 110(8):574–579, 2019.
- [5] Jens Koch, Terri M. Yu, Jay Gambetta, A. A. Houck, D. I. Schuster, J. Majer, Alexandre Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf. Charge-insensitive qubit design derived from the cooper pair box. *Phys. Rev. A*, 76:042319, Oct 2007. doi:10.1103/PhysRevA.76.042319. URL <https://link.aps.org/doi/10.1103/PhysRevA.76.042319>.
- [6] B. Foxen, C. Neill, A. Dunsworth, P. Roushan, B. Chiaro, A. Megrant, J. Kelly, Zijun Chen, K. Satzinger, R. Barends, F. Arute, K. Arya, R. Babbush, D. Bacon, J. C. Bardin, S. Boixo, D. Buell, B. Burkett, Yu Chen, R. Collins, E. Farhi, A. Fowler, C. Gidney, M. Giustina, R. Graff, M. Harrigan, T. Huang, S. V. Isakov, E. Jeffrey, Z. Jiang, D. Kafri, K. Kechedzhi, P. Klimov, A. Korotkov, F. Kostritsa, D. Landhuis, E. Lucero, J. McClean, M. McEwen, X. Mi, M. Mohseni, J. Y. Mutus, O. Naaman, M. Neeley, M. Niu, A. Petukhov, C. Quintana, N. Rubin, D. Sank, V. Smelyanskiy, A. Vainsencher, T. C. White, Z. Yao, P. Yeh, A. Zalcman, H. Neven, and J. M. Martinis. Demonstrating a continuous set of two-qubit gates for near-term quantum algorithms. *Phys. Rev. Lett.*, 125:120504, Sep 2020. doi:10.1103/PhysRevLett.125.120504. URL <https://link.aps.org/doi/10.1103/PhysRevLett.125.120504>.
- [7] Aaron Somoroff, Quentin Ficheux, Raymond A. Menchia, Haonan Xiong, Roman V. Kuzmin, and Vladimir E. Manucharyan. Millisecond coherence in a superconducting qubit, 2021. URL <https://arxiv.org/abs/2103.08578>.
- [8] Quentin Ficheux, Long B Nguyen, Aaron Somoroff, Haonan Xiong, Konstantin N Nesterov, Maxim G Vavilov, and Vladimir E Manucharyan. Fast logic with slow qubits: microwave-activated controlled-z gate on low-frequency fluxoniums. *Physical Review X*, 11(2):021026, 2021.
- [9] Feng Bao, Hao Deng, Dawei Ding, Ran Gao, Xun Gao, Cupjin Huang, Xun Jiang, Hsiang-Sheng Ku, Zhisheng Li, Xizheng Ma, Xiaotong Ni, Jin Qin, Zhijun Song, Han-tao Sun, Chengchun Tang, Tenghui Wang, Feng Wu, Tian Xia, Wenlong Yu, Fang Zhang, Gengyan Zhang, Xiaohang Zhang, Jingwei Zhou, Xing Zhu, Yaoyun Shi, Jianxin Chen, Hui-Hai Zhao, and Chunqing Deng. Fluxonium: An alternative qubit platform for high-fidelity operations. *Phys. Rev. Lett.*, 129:010502, Jun 2022. doi:10.1103/PhysRevLett.129.010502. URL <https://link.aps.org/doi/10.1103/PhysRevLett.129.010502>.
- [10] Ilya N. Moskalenko, Ilya A. Simakov, Nikolay N. Abramov, Alexander A. Grigorev, Dmitry O. Moskalev, Anastasiya A. Pishchimova, Nikita S. Smirnov, Evgeniy V. Zikiy, Ilya A. Rodionov, and Ilya S. Besedin. High fidelity two-qubit gates on fluxoniums using a tunable coupler. *npj Quantum Information*, 8(1), nov 2022. doi:10.1038/s41534-022-00644-x. URL <https://doi.org/10.1038/s41534-022-00644-x>.
- [11] V. Negîrneac, H. Ali, N. Muthusubramanian, F. Battistel, R. Sagastizabal, M. S. Moreira, J. F. Marques, W. J. Vlothuizen, M. Beekman, C. Zachariadis, N. Haider, A. Bruno, and L. DiCarlo. High-fidelity controlled-z gate with maximal intermediate leakage operating at the speed limit in a superconducting quantum processor. *Phys. Rev. Lett.*, 126:220502, Jun 2021. doi:10.1103/PhysRevLett.126.220502. URL <https://link.aps.org/doi/10.1103/PhysRevLett.126.220502>.
- [12] Konstantin N. Nesterov, Chen Wang, Vladimir E. Manucharyan, and Maxim G. Vavilov. Cnot gates for fluxonium qubits via selective darkening of transitions. *Phys. Rev. Applied*, 18:034063, 2022.
- [13] E. Dogan, D. Rosenstock, L. L. Guevel, H. Xiong, R. A. Mencia, A. Somoroff, K. N. Nesterov, M. G. Vavilov, V. E. Manucharyan, and C. Wang. Demonstration of the two-fluxonium cross-resonance gate. *arXiv:2204.11829*, 2022. URL <https://arxiv.org/abs/2204.11829>.
- [14] Aneirin J. Baker, Gerhard B. P. Huber, Niklas J. Glaser, Federico Roy, Ivan Tsitsilin, Stefan Filipp, and Michael J. Hartmann. Single shot i-Toffoli gate in dispersively coupled superconducting qubits. *Appl. Phys. Lett.*, 2022. doi:10.1063/5.0077443.
- [15] I. N. Moskalenko, I. S. Besedin, I. A. Simakov, and A. V. Ustinov. Tunable coupling scheme for implementing two-qubit gates on fluxonium qubits. *Applied Physics Letters*, 119(19):194001, nov 2021. doi:10.1063/5.0064800. URL <https://doi.org/10.1063/5.0064800>.
- [16] M Ganzhorn, G Salis, DJ Egger, A Fuhrer, M Mergenthaler, C Müller, P Müller, S Paredes, M Pechal, M Werninghaus, et al. Benchmarking the noise sensitivity of different parametric two-qubit gates in a single superconducting quantum computing platform. *Physical Review Research*, 2(3):033447, 2020.
- [17] Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando GSL Brandao, David A Buell, et al. Quantum supremacy using a programmable superconducting processor. *Nature*, 574(7779):505–510, 2019.
- [18] Sergio Boixo, Sergei V. Isakov, Vadim N. Smelyanskiy, Ryan Babbush, Nan Ding, Zhang Jiang, Michael J. Bremner, John M. Martinis, and Hartmut Neven. Characterizing quantum supremacy in near-term devices. *Nature Physics*, 2018. doi:10.1038/s41567-018-0124-x.
- [19] Eyob A. Sete, Nicolas Didier, Angela Q. Chen, Shobhan Kulshreshtha, Riccardo Manenti, and Stefano Poletto. Parametric-resonance entangling gates with a tunable coupler. *Phys. Rev. Appl.*, 16:024050, Aug 2021. doi:10.1103/PhysRevApplied.16.024050. URL <https://link.aps.org/doi/10.1103/PhysRevApplied.16.024050>.