Suppression of static $ZZ$ interaction in an all-transmon quantum processor

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The superconducting transmon qubit is currently a leading qubit modality for quantum computing, but gate performance in quantum processor with transmons is often insufficient to support running complex algorithms for practical applications. It is thus highly desirable to further improve gate performance. Due to the weak anharmonicity of transmon, a static $ZZ$ interaction between coupled transmons commonly exists, undermining the gate performance, and in long term, it can become performance limiting. Here we theoretically explore a promising parameter region in an all-transmon system to address this issue. We show that an feasible parameter region, where the $ZZ$ interaction is heavily suppressed while leaving $XY$ interaction with an adequate strength to implement two-qubit gates, can be found for all-transmon systems. Thus, two-qubit gates, such as cross-resonance gate or iSWAP gate, can be realized without the detrimental effect from static $ZZ$ interaction. To illustrate this, we demonstrate that an iSWAP gate with fast gate speed and dramatically lower conditional phase error can be achieved. Scaling up to large-scale transmon quantum processor, especially the cases with fixed coupling, addressing error, idling error, and crosstalk that arises from static $ZZ$ interaction could also be strongly suppressed.

I. INTRODUCTION

The transmon qubit has been demonstrated as a leading superconducting qubit modality for quantum computing since it has been largely responsible for the recent impressive achievements in superconducting quantum information processing [1–3]. These achievements crucially rely on the improvement of the gate performance through increasing the transmon coherence time [4] and mitigating coherent error from non-ideal parasitic interaction [5–8]. Nonetheless, state-of-the-art gate performance in transmon quantum processor so far is probably insufficient to demonstrate quantum advantage for practical applications [9] and to achieve the long-term goals of fault-tolerant quantum computing [10]. This indicates that considerable effort devoted to improving gate performance is still required.

Despite the benefit of the reproducibly long coherence times, the weak anharmonicity of transmons currently poses a significant challenge to further improve gate performance. For single qubit gates, due to the weak anharmonicity, higher-energy levels of transmon can be easily populated during microwave driven gate operation, causing leakage error. By using the Derivative Removal by Adiabatic Gate (DRAG) scheme [11, 12], this issue can be substantially mitigated without sacrificing the gate speed, and single qubit gate with fidelity above 99.9% can be achieved [1, 4]. However, various pending challenges for pursuing two-qubit gates with fast speed and high fidelity still exist due to non-ideal parasitic interactions that arise from the weak anharmonicity of transmons [13, 14]. One of the leading non-ideal parasitic interaction is the static $ZZ$ coupling [15, 16], that has been shown to undermine the performance of $XY$ interaction based two-qubit gates, such as cross-resonance gate or iSWAP gate [2, 7, 8]. Meanwhile, its residual can cause idling error, and produce quantum crosstalk related to neighboring spectator qubits [17–20]. More recently, it has been demonstrated, both experimentally [24–26] and theoretically [27–29], that this static $ZZ$ can also be suppressed heavily by coupling superconducting qubits with opposite-sign of anharmonicity. However, mitigating static $ZZ$ coupling for $XY$-based two-qubit gate operations or qubit architecture with fixed inter-qubit coupling is still an outstanding challenge for all-transmon quantum processors [28].

In this work, we show that suppressing static $ZZ$ coupling for two-qubit gate operations can be achieved by engineering quantum interference in an all-transmon quantum processor. Contrary to the commonly accepted view that for all-transmon quantum processors, static $ZZ$ interaction can vanish only by turning off inter-qubit coupling [14, 28]. We find that an experimentally accessible parameter region, where the static $ZZ$ coupling is heavily suppressed while leaving $XY$ interaction with an adequate strength to implement two-qubit gates can be found in an all-transmon system.

II. SYSTEM HAMILTONIAN

Since a superconducting qubit is naturally a multi-level system, especially for qubits with weak anharmonicity such as the transmon, its higher-energy levels have a non-negligible effect on qubit dynamics. For coupled transmons system shown in Fig. 1(a), truncation to the qubit (computational) subspace gives rise an effective two-qubit Hamiltonian with not only an inter-qubit $XY$ coupling $J$ but also a static $ZZ$ coupling $\zeta$ that mainly arises from interactions between qubit states and higher-energy states [16, 27]. To suppress this $ZZ$
coupling for $XY$-based two qubit gates, here we consider the all-transmon system schematically depicted in Fig. 1(b), where transmons $Q_{1(2)}$ are coupled through a coupling circuit combing a ancilla transmon $Q_a$ and a capacitor. The full system can be modeled by three coupled weakly anharmonic oscillators \[30\], and described by (hereafter $\hbar = 1$)

$$
H = \sum_j \left( \tilde{\omega}_j q_j^\dagger q_j + \frac{\alpha_j}{2} q_j^\dagger q_j q_j^\dagger q_j \right) + \sum_{j \neq k} g_{jk} (q_j + q_j^\dagger) (q_k + q_k^\dagger),
$$

where subscript $j(k) = \{1, 2, c\}$ labels transmon $Q_j$ with anharmonicity $\alpha_j$ and bare qubit frequency $\tilde{\omega}_j$, $q_j$ ($q_j^\dagger$) is the associated annihilation (creation) operator, and $g_{jk}$ denotes strength of the coupling between $Q_j$ and $Q_k$.

We further consider that our system operates in the dispersive regime, i.e., the transmon-coupler detuning $|\Delta_{1(2)}| = |\tilde{\omega}_{1(2)} - \tilde{\omega}_c| \gg g_{1(2)c}$, and the two transmons are in the straddling regime, i.e., transmon-tranmson detuning $|\Delta_{12}| = |\tilde{\omega}_1 - \tilde{\omega}_2| < |\alpha_{1(2)}|$ \[23, 31\]. Hence, truncation to two-qubit subpace, the Hamiltonian in Eq. (1) can be approximated by an effective two-qubit Hamiltonian

$$
H = \frac{\omega_1 Z I}{2} + \frac{\omega_2 Z J}{2} + J_{XX} + YY + \frac{\zeta ZZ}{4},
$$

where $(X, Y, Z, I)$ denote the Pauli operators and identity operator, and the order indexes the qubit number, and $\omega_1(2)$ represents the dressed qubit frequency of $Q_{1(2)}$. The last two terms corresponds to the $XY$ coupling with strength $J$ and $ZZ$ coupling with strength $\zeta$, respectively. As shown in Fig. 2(a), the $XY$ coupling results from the direct coupling $g_{12}$ and the coupler-mediated indirect coupling, and its strength can be approximated as $J = g_{12} + g_{1c}g_{2c}/\Delta$ with $1/\Delta = (1/\Delta_1 + 1/\Delta_2)/2$ \[6, 22\]. The $ZZ$ coupling comes from the interaction between qubit states and non-qubit states (including higher-energy states of transmons and coupler states), and its strength is defined as $\zeta = (E_{101} - E_{100}) - (E_{011} - E_{000})$, where $E_{mnl}$ denotes the energy of system eigenstate $|mnl\rangle$ ($m, n, l = \{0, 1, 2\}$), and can be perturbatively obtained \[32–34\]. Making the rotating-wave approximation (RWA), and deriving up to the fourth-order perturbation gives an approximated expression $\zeta \approx \tilde{\zeta}_{020} + \tilde{\zeta}_{200} + \tilde{\zeta}_{002} + \tilde{\zeta}_{101} + \tilde{\zeta}_{112}$ (perturbation theory, making RWA) as a function of coupler frequency $\omega_c$ and direct coupling strength $g_{12}$ with qubit frequency $\tilde{\omega}_{1(2)}/2\pi = 5.114$ (4.914) GHz, qubit/coupler anharmonicity $\alpha_{1(2)}/2\pi = -330$ MHz, $\alpha_c/2\pi = 0$ MHz (linear coupler), and qubit-coupler interaction strength $g_{1c2}/2\pi = 98$ (83) MHz \[7, 35\]. The dashed curves in (c) and (d) correspond to contours of $J = 0$ and $\zeta = 0$, respectively. The open circle (square) in (c,d) mark the set of parameters chosen to suppress $XY$ ($ZZ$) coupling.

\[\zeta_1\] (see Appendix A for details) with

$$
\begin{align*}
\tilde{\zeta}_{020} &= \frac{J_{202}^2}{\Delta_1 + \Delta_2 - \alpha_c}, \\
\tilde{\zeta}_{200} &= \frac{J_{200}^2}{\Delta_1 - \alpha_1}, \\
\tilde{\zeta}_{002} &= -\frac{J_{020}^2}{\Delta_2 + \alpha_1}, \\
\tilde{\zeta}_{000} &= \frac{J_{101}^2}{\Delta_1 \Delta_2}.
\end{align*}
$$

where terms $\zeta_{020}$ and $\zeta_{002}$ result from the effective coupling between qubit state $|10\rangle$ and higher-energy states of coupler $|020\rangle$ and transmons $|002\rangle$, respectively, and $J_{020}, J_{200(002)}$ denote the associated effective coupling strength, as shown in Fig. 2(b).

**III. SUPPRESSION OF STATIC ZZ INTERACTION FOR OFF-RESONANTLY COUPLED TRANSMONS**

First, we consider that transmons are off-resonantly coupled together. According to perturbation analysis \[32–34\], Figures 2(c) and 2(d) show $J$ and $\zeta$ as a function of coupler frequency $\omega_c$ and direct coupling strength $g_{12}$ with $\tilde{\omega}_{1(2)}/2\pi = 5.114$ (4.914) GHz, $\alpha_{1(2)}/2\pi = -330$ MHz, $\alpha_c/2\pi = 0$ MHz (linear coupler), and $g_{1c2}/2\pi = 98$ (83) MHz \[7, 35\]. One can find that in the parameter space of $(\omega_c, g_{12})$, zero-point for $XY$ coupling forms a single branch (dashed line in Fig. 2(c)), and when the coupler has larger transition frequency, the zero-$ZZ$ regime almost overlap with the zero-$XY$ branch, conforming the commonly accepted view, i.e., static ZZ interaction can be suppressed
by turning off inter-qubit coupling. However, interestingly and unexpectedly, with decreasing the coupler frequency, the zero-ZZ regime gradually diverging and eventually splitting into two separate branches (dashed lines in Fig. 2(d)), and the presence of the lower branch shows that ZZ coupling can be heavily suppressed without the need for suppressing XY coupling, thus one can mitigate static ZZ coupling for implementing XY-based two-qubit gates.

The physics behind the above interesting features are: (i) As shown in Eq. (3), when coupler has larger transition frequency, the energy of coupler state $|020\rangle$ is far larger than that of the states $|101\rangle$ and $|200\rangle(002)$, i.e., $E_{020} \gg \{E_{101}, E_{200}, E_{002}\}$, and $\Delta_{12} \gg \{\Delta_{12}, \alpha_{12}(2)\}$, the terms $\zeta_{020}$ and $\zeta_1$ can be omitted. Thus, the dominated contribution to the total ZZ coupling results from the effective interaction between qubit state $|101\rangle$ and higher-energy states $|200\rangle (002)$, whose strength can be approximated as $J^{000\langle 002 \rangle} \sim \sqrt{2} J$ (see Appendix A for details). When the inter-qubit XY coupling $J$ is tuned off, the interactions between $|101\rangle$ and $|200\rangle (002)$ are also turned off effectively, causing suppression of ZZ coupling.

(ii) However, when decreasing the coupler frequency, thus $E_{020} \gg \{E_{101}, E_{200}, E_{002}\}$ and $\Delta_{12} \gg \{\Delta_{12}, \alpha_{12}(2)\}$, the terms $\zeta_{020}$ and $\zeta_1$ can no longer be neglected. Since $E_{020} > E_{101} > E_{200}$, the interaction $|101\rangle \leftrightarrow |200\rangle (002)$ gives rise an ZZ coupling term with a positive sign, while the interaction $|101\rangle \leftrightarrow |020\rangle$ contributes a term with a negative sign. Therefore, the conditions for suppressing ZZ coupling cannot be achieved by just turning off the XY coupling. To the opposite, the XY coupling should be tuned on, thus the positive contribution and the negative contribution can interfere destructively, giving rise the suppression of net ZZ coupling. Moreover, since $\zeta_{200\langle 002 \rangle} \propto (\sqrt{2} J)^2$ (see Appendix A for details), for a fixed coupler frequency, there should be two different values of $g_{12}$ (giving rise a total XY coupling of same magnitude but opposite signs) for suppressing ZZ coupling. Up to now, the discussion above suggests that the zero-ZZ regime should be split into two separate branches which are approximately symmetrical with respect to the zero-XY branch. Thus for a given coupler frequency, the strength of the maintained XY coupling in the lower and upper branch of the zero-ZZ region should be approximately equal. However, as shown in Eq. (3), along with the terms associated with higher-energy state of transmons and coupler, there is an addition terms $\zeta_1$ associated with lower-energy states giving rise a positive contribution with strength $\zeta_1 \propto g_{12}$ (see Eq. (3)). Thus, taking all these terms in Eq. (3) into consideration, the strength of the maintained XY coupling in the lower branch should be larger than that in the upper branch, as shown in Fig. 2(d).

To numerically verify the above results, we consider two sets of parameters, i.e., $(6.0, 6.5)$ and $(6.0, 8.8)$, which are chosen to suppress XY and ZZ coupling, respectively. The ZZ coupling strength can be exactly obtained by numerical diagonalization of the system Hamiltonian in Eq. (1), giving rise $\zeta/2\pi = 3.9 (3.3)$ KHz for the two parameter.
sets. While for $XY$ coupling, we note that the effective $XY$ coupling is not perfectly well-defined for present system with off-resonantly coupled transmons. Here the $XY$ coupling strength is estimated from the period $T$ of the simulated cross-resonance oscillation with the controlled qubit $Q_1$ in its ground state (see Appendix B for details). In the weak-drive limit, the period $T$ can be well approximated by $2\pi/T = J\Omega_d/\Delta_{12}$ [35], where $\Omega_d$ denotes strength of the driving applied on $Q_1$. As such, the estimated $XY$ coupling strength are $J/2\pi = 1.75 \pm (0.63)$ MHz.

The above numerical results confirm that for systems operating on the lower branch of zero-$ZZ$ region, the $ZZ$ coupling can indeed be strongly suppressed without the need for suppressing the $XY$ coupling heavily. However, the maintained $XY$ coupling (here is 1.75 MHz) is too weak to support implementing a successful two-qubit gate, such as the cross-resonance gate [36]. To achieve a larger maintained $XY$ coupling for a given coupler frequency, according to the above analysis, one can reduce the energy of $|020\rangle$ by replacing the linear coupler ($\alpha_c = 0$) with a nonlinear coupler with $\alpha_c < 0$, such as a transmon. Then the negative $ZZ$ contribution ($\zeta_{20}$) from interaction $|101\rangle \leftrightarrow |020\rangle$ gets larger, and a larger $XY$ coupling $J$ is thus needed to suppress $ZZ$ coupling. Figure 3 show the numerical calculated $ZZ$ coupling strength and the $XY$ coupling strength as a function of $\omega_c$ and $g_{12}$ with coupler anharmonicity $\alpha_c/2\pi = \{0, -200, -400, -600\}$ MHz. The other parameters are same to those used in Fig. 2. In order to easily identify the desired parameter region for suppressing $ZZ$ coupling, for each coupler anharmonicity, the associated two landscapes ($XY$ and $ZZ$ where date point with $ZZ$ coupling strength below 20 kHz is removed) are superposed in a single panel. One can find that the lower branch of zero-$ZZ$ region is shifted downward along with the increased coupler anharmonicity. Thus, the maintained $XY$ coupling is also increased, as shown in the inset of Fig. 3. Thus, by using the transmon coupler, the static $ZZ$ coupling below 20 kHz and the maintained $XY$ coupling strength above 2 MHz should be assessed experimentally for implementing cross-resonance gate with current fabrication technology [37, 38]. We note that the maintained $XY$ coupling may further increase by optimizing the full system parameters (see Appendix C for details).

IV. SUPPRESSION OF STATIC ZZ INTERACTION FOR ON-RESONANTLY COUPLED TRANSMONS

Having shown the suppression of $ZZ$ coupling for the off-resonantly coupled case, we now turn to consider the on-resonance case. Fig. 4(a) shows the numerically calculated $ZZ$ coupling strength $\zeta$ and $XY$ coupling strength $J$ (extracted as half the energy difference between the eigenstate $|100\rangle$ and $|001\rangle$) as a function of $\omega_c$ and $g_{12}$ for resonantly coupled transmons. Similar to that of the off-resonantly coupled case, here, the zero-$ZZ$ points also form two branches in the parameter space ($\omega_c$, $g_{12}$) (see Appendix D for details), where the lower branches allow us to mitigate $ZZ$ coupling for on-resonance $XY$ coupling based two-qubit gates.

To illustrate this, we consider the implementation of an iSWAP gate with diabatic scheme [15, 39], and in order to mitigate leakage, here the direct coupling strength $g_{12}$ are chosen to achieve the full synchronization between the swap and leakage error channels [39]. During the gate operations, the frequency of the transmon $Q_1$ stays fixed at 6.50 GHz, while the frequencies of coupler $Q_c$ and transmon $Q_2$ vary from their idle point ($\omega_c/2\pi = 8.70$ (6.45) GHz, where both $XY$ and $ZZ$ coupling are strongly suppressed) to their interaction point and then come back according to the Gaussian flat-top pulse with a fixed rise/fall time of 5.66 ns [40]. We firstly consider that the system operates in the dispersive regime, and coupler interaction frequency takes $\omega_c/2\pi \approx 7.79$ GHz, marked by the open square in Fig. 4(a), and the associated control pulse is shown as the dashed line in Fig. 4(b). Fig. 4(c) shows the swap error $\varepsilon_{\text{swap}} = 1 - P_{001}$ ($P_{001}$ denotes the population in $|001\rangle$ after the time evolution for system initialized in $|100\rangle$) and the leakage $L_I$ [41, 42] as function of the hold time that is defined as the time-interval between the midpoints of the ramps [39]. One can find that an iSWAP gate with an
We note that for qubit architectures with bus-mediated couplings, the static ZZ coupling is heavily suppressed while leaving XY interaction with an adequate strength to implement two-qubit gates, such as cross-resonance gate or iSWAP gate, can be found in an all-transmon system. We further show that an iSWAP gate with fast gate speed and dramatically low conditional phase error can indeed be achieved in this parameter region. Without the detrimental effect from the static ZZ coupling, for transmon quantum processor with fixed coupling, single-qubit addressing error, idling error, and crosstalk that arise from static ZZ coupling should also be heavily suppressed. From the point view of perturbation theory, the main physics behind these benefits is that in the proposed system, XY and ZZ coupling are enabled by different virtual transitions and different intermediate states, thus providing the possibility to engineer quantum interference for mitigating ZZ coupling while retaining XY coupling. One thus reasonably estimate that it is also possible to achieve the mitigation of static ZZ coupling for XY-based two-qubit gates with other types of coupler circuits [23] (see Appendix E for details).

Recently, two independent experimental works on suppression of ZZ interactions for all-transmon qubit systems have also been published [46, 47]. In the qubit architecture with tunable coupling, Sung et al. [46] have demonstrated experimentally that for qubit systems operated in the quasi-dispersive regime (the qubit-coupler detuning should have a magnitude compared with that of qubit anharmonicity), there is a working point (similar to the working point marked by a yellow reversed triangle shown in Fig. 4(a)), where the static ZZ coupling is eliminated while XY coupling is preserved, and based on the presence of this zero-ZZ point, an ZZ-free iSWAP gate is implemented with high gate fidelity. In this working point, the static ZZ coupling is mainly resulted from the interaction between qubit state $|101\rangle$ and its higher-energy state $|200(002)\rangle$ (giving a positive contribution) and coupler higher-energy state $|020\rangle$ (giving a negative contribution), thus when the positive and negative contribution destructive interference, the static ZZ interaction is eliminated. We note that for qubit architectures with bus-mediated couplings operated in the quasi-dispersive straddling regime, there also exists a zero-ZZ point [44, 45]. However, as shown in Fig. 4, in the qubit architecture with tunable coupling, by choosing a suitable system parameters, there are three zero-ZZ points, two of them can be used to realize an ZZ-free iSWAP gate. For system comprising two off-resonantly coupled transmons shown in Fig. 1(b) (in [47], the coupler is a linear bus), Kandala et al. [47] have shown experimentally that when the qubit system operates in the dispersive regime, there exists a parameter region (similar to the parameter region shown in Fig. 2(d)), where one can suppress the residual static ZZ coupling while retain XY coupling with an adequate strength for implementing a successful CR gate. According to the analysis and numerical results given in Sec. II and Sec. III, we further show that by using a coupler with larger anharmonicity, i.e., replacing the linear bus with an ancillary transmon, the retained XY coupling should have a more larger strength. The physics behind how this works is that when using a transmon coupler, the energy of $|020\rangle$ is reduced, and thus the negative ZZ contribution $(g_{020})$ from interaction $|011\rangle \leftrightarrow |020\rangle$ gets larger. Therefore, in this case, a larger retained XY coupling $J$ is needed to eliminate ZZ coupling.

V. CONCLUSION

In summary, we have demonstrated that a feasible parameter region, where static ZZ coupling is heavily suppressed while leaving XY interaction with an adequate strength to implement two-qubit gates, such as cross-resonance gate or iSWAP gate, can be found in an all-transmon system. We further show that an iSWAP gate with fast gate speed and dramatically low conditional phase error can indeed be achieved in this parameter region. Without the detrimental effect from the static ZZ coupling, for transmon quantum processor with fixed coupling, single-qubit addressing error, idling error, and crosstalk that arise from static ZZ coupling should also be heavily suppressed. From the point view of perturbation theory, the main physics behind these benefits is that in the proposed system, XY and ZZ coupling are enabled by different virtual transitions and different intermediate states, thus providing the possibility to engineer quantum interference for mitigating ZZ coupling while retaining XY coupling. One thus reasonably estimate that it is also possible to achieve the mitigation of static ZZ coupling for XY-based two-qubit gates with other types of coupler circuits [23] (see Appendix E for details).

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Appendix A: strength of static ZZ coupling

In this section, according to perturbation theory [32], we present the details deviation of the static ZZ coupling strength ζ for our two-transmon system. In order to give a clear explanation of how to mitigating ZZ coupling for XY-based gate operations, in the following discussion, we have made two approximations: (i) Making the rotating-wave approximation (RWA) by neglecting the counter-rotating terms in Eq. (1) of the main text, the system Hamiltonian now reads

\[ H_0 = \sum_j \left[ \omega_j q_j^\dagger q_j + \frac{\alpha_j}{2} q_j^\dagger q_j^\dagger q_j q_j \right], \]

\[ V = \sum_{j,k} g_{jk}(q_j^\dagger q_k + q_j q_k^\dagger), \]  

(A1)

and its level diagram is shown in Fig. 5. (ii) Since \( g_{12} \ll \{g_{1c}, g_{2c}\} \) and \( \Delta_{12}(2) \gg \{\Delta_{12}, \alpha_{1,2,c}\} \), one can neglect small terms in the calculation of ZZ coupling strength ζ.

The perturbed result for ZZ coupling strength can be defined as ζ ≡ ζ(2) + ζ(3) + ζ(4), where ζ(n) denotes nth-order perturbational result, defined as ζ(n) ≡ \( (E_{101} - E_{000}) - (E_{101}^{(n)} - E_{000}^{(n)}) \) with

\[ E_{y}^{(2)} = \sum_{j \neq s} |V_{sj}|^2/|E_s|, \]

\[ E_{y}^{(3)} = \sum_{j,k \neq s} V_{sj}V_{jk}V_{ks}/|E_s|, \]

\[ E_{y}^{(4)} = \sum_{j,k,l \neq s} V_{sj}V_{jk}V_{kl}V_{ls}/|E_s|^2 - \sum_{j,k \neq s} |V_{sj}|^2|V_{sk}|^2/|E_s|^2, \]

(A2)

where \( V_{sj} = \langle s|V|j \rangle \) and \( E_{sj} = E_{101} - E_{000} \). Thus, after making the above mentioned two approximations, and according to the expression in Eq. (A2), one has [32–34]

\[ \zeta^{(2)} = 2g_{12}^2 \left[ \frac{1}{\Delta_{12} - \alpha_2} - \frac{1}{\Delta_{12} + \alpha_1} \right], \]  

(A3)

\[ \zeta^{(3)} = 2g_{12}^2g_{1c}g_{2c} \left[ \frac{2}{\Delta_{12} - \alpha_2} - \frac{2}{\Delta_{12} + \alpha_1} \right] \left[ \frac{2}{\Delta_1 \Delta_2} \right], \]

\[ + \frac{2}{\Delta_1 \Delta_2}, \]  

(A4)

\[ \zeta^{(4)} = 2g_{12}^2g_{2c}^2 \left[ \frac{1}{\Delta_1 \Delta_2(\Delta_{12} - \alpha_2)} - \frac{1}{\Delta_1 \Delta_2(\Delta_{12} + \alpha_1)} \right] \]

\[ + \frac{1}{\Delta_1 + \Delta_2 - \alpha_c(\frac{1}{\Delta_1} + \frac{1}{\Delta_2})^2}. \]  

(A5)

To identify the physical mechanism behind these terms (\( \zeta^{(2)}, \zeta^{(3)}, \zeta^{(4)} \)), and also to give a clear analysis of the relation between ZZ coupling strength ζ and XY coupling strength J, after writing out all these terms and rearranging them, ζ can be approximated as (here we recover the Eq. (3) of the main text)

\[ \zeta \simeq \zeta_{020} + \zeta_{002} + \zeta_{001} + \zeta_1, \]

\[ \zeta_{020} = \frac{J_0^2}{\Delta_1 + \Delta_2 - \alpha_c}, \]

\[ \zeta_{002} = \frac{J_0^2}{\Delta_1 + \Delta_2 + \alpha_c}, \]

\[ \zeta_{001} = \frac{g_{12}g_{1c}g_{2c}}{\Delta_1 \Delta_2}, \]

\[ \zeta_1 = \frac{4g_{12}g_{1c}g_{2c}}{\Delta_1 \Delta_2}. \]

where terms \( \zeta_{002(001)} \) can be considered as the ZZ contributions resulting from the effective coupling between qubit state |101⟩ and higher-energy states of coupler |020⟩ and transmons |002(200)⟩), respectively, and \( J_{020}, J_{200(020)} \) denote the associated effective coupling strength, given as

\[ J_{020} \simeq \sqrt{2}g_{1c}g_{2c}\left(\frac{1}{\Delta_1} + \frac{1}{\Delta_2}\right) \simeq \frac{2 \sqrt{2} g_{1c} g_{2c}}{\Delta}, \]

\[ J_{200} \simeq \sqrt{2}(g_{12} + g_{1c}g_{2c}) \Delta_1 \simeq \sqrt{2}J, \]

\[ J_{002} \simeq \sqrt{2}(g_{12} + g_{1c}g_{2c}) \Delta_2 \simeq \sqrt{2}J, \]

while term \( \zeta_1 \) results from the interaction among lower-energy states of qubits and coupler.

Appendix B: Estimated XY coupling strength from cross-resonance oscillation

For two on-resonantly coupled qubits, the inter-qubit XY coupling strength can be extracted as half the energy difference between the eigenstate \( |100⟩ \) and \( |001⟩ \). However, for two off-resonant qubits coupled via a coupler circuit shown in Fig. 1(b) of the main text, the effective XY coupling is not perfectly well-defined in this case. In present work, the XY coupling strength is estimated from the period T of the cross-resonance oscillation with the controlled qubit \( Q_1 \) in its ground state, as shown in Fig. 6. In the weak-drive limit,
the period $T$ of the oscillations can be well approximated by $2\pi/T = J\Omega_d/\Delta_{12}$ [36], where $\Omega_d$ denotes strength of the driving applied on $Q_1$. In present work, $\Omega/2\pi = 10$ MHz is used to infer the $XY$ coupling strength.

**Appendix C: off-resonantly coupled qubits with varying qubit detuning**

As we have mentioned in the main text, the strength of the maintained $XY$ coupling may further increase by optimizing the full system parameters. In Figs. 7 and 8, we have shown the landscapes of $XY$ coupling $J$ and $ZZ$ coupling $\zeta$ as a function of coupler frequency $\omega_c$ and direct coupling strength $g_{12}$ for off-resonantly coupled qubits system with different qubit detuning, i.e., $\Delta_{12}/2\pi = 100$ MHz, and $\Delta_{12}/2\pi = 50$ MHz, respectively.

**Appendix D: on-resonantly coupled qubits with varying coupler anharmonicity**

Similar to the off-resonantly coupled case, when we reduce the energy of $|020\rangle$, i.e., increasing the coupler anharmonicity for on-resonantly coupled transmon system, the negative $ZZ$ contribution $|G_{020}\rangle$ from interaction $|101\rangle \leftrightarrow |020\rangle$ gets larger, thus a larger maintained $XY$ coupling $J$ is needed to suppress $ZZ$ coupling. Figure 9 show the numerical calculated $ZZ$ coupling strength and the $XY$ coupling strength as a function of $\omega_c$ and $g_{12}$ with coupler anharmonicity $\alpha_c/2\pi = \{0, -200, -400, -600\}$ MHz. The other parameters are same to those used in Fig. 4(a) of the main text. One can indeed find that the lower branch of zero-$ZZ$ region is shifted downward along with the increased coupler anharmonicity, suggesting a larger maintained $XY$ coupling.

**Appendix E: Tunable coupling superconducting circuit**

In this section, we show that suppressing $ZZ$ coupling while preserving $XY$ coupling can also be realized in the qubit architecture proposed by P. S. Mundada et al. [23], where two transmons are coupled via a coupling circuit comprising two bus couplers. According to Ref. [23], the full system can be modeled as four coupled weakly anharmonic oscillators, and its Hamiltonian reads

\[
H = \sum_{j=1,2,\pm} \left( \tilde{\omega}_j q_j^\dagger q_j + \frac{\alpha_j}{2} q_j^\dagger q_j^\dagger q_j q_j \right) + \sum_{j=1,2} g_{jk} (q_j k^\dagger + q_j^\dagger k) \tag{E1}
\]

where subscript $j(k) = \{1, 2, \pm\}$ labels anharmonic oscillator $Q_j$ with anharmonicity $\alpha_j$ and bare transition frequency $\tilde{\omega}_j$, $q_j$ ($q_j^\dagger$) is the associated annihilation (creation) operator, and $g_{jk}$ denotes strength of the coupling between $Q_j$ and $Q_k$.

From second-order perturbation theory, the $XY$ coupling strength can be obtained as

\[
J = J_+ + J_-,
\]

\[
J_{\pm} = g_{12} \pm \frac{\Omega}{\Delta_{12}} \tag{E2}
\]

with $1/\Delta_{\pm} = (1/\Delta_{12} \pm 1/\Delta_{22})/2$. The $ZZ$ coupling can be defined as $\zeta = (E_{1100} - E_{1000}) - (E_{0100} - E_{0000})$, where $E_{n_1 n_2 n_3 n_4}$ denotes the energy of system eigenstate $|n_1 n_2 n_3 n_4\rangle$ ($n_1, n_2, n_3, n_4 = \{0, 1, 2\}$). According to the fourth order perturbation theory [23, 32], the expression for $\zeta$ is $\zeta = \zeta_{2000} + \zeta_{0200} + \zeta_{0020} + \zeta_{0002} + \zeta_1$ with

\[
\zeta_{2000} = \frac{(g_{1+g_{2+}} + g_{1-g_{2-}})}{\Delta_{2+}} \frac{\Delta_{2-}}{2} \frac{2}{\Delta_{12} - \alpha_1} = \frac{J_{2000}^2}{\Delta_{12} - \alpha_1},
\]

\[
\zeta_{0200} = \frac{(g_{1+g_{2+}} + g_{1-g_{2-}})}{\Delta_{1+}} \frac{\Delta_{2-}}{2} \frac{2}{\Delta_{12} - \alpha_2} = \frac{J_{2000}^2}{\Delta_{12} - \alpha_2},
\]

\[
\zeta_{0020} = \frac{2g_{1+g_{2+}}^2}{\Delta_{1+} + \Delta_{2+} + \alpha_+} \frac{1}{\Delta_{1+}} \frac{1}{\Delta_{2+}} = \frac{J_{0020}^2}{\Delta_{1+} + \Delta_{2+} + \alpha_+},
\]

\[
\zeta_{0002} = \frac{2g_{1+g_{2+}}^2}{\Delta_{1-} + \Delta_{2-} + \alpha_-} \frac{1}{\Delta_{1-}} \frac{1}{\Delta_{2-}} = \frac{J_{0002}^2}{\Delta_{1-} + \Delta_{2-} + \alpha_-},
\]

\[
\zeta_1 = \frac{1}{\Delta_{12}} \left[ \frac{(g_{1+g_{2+}} + g_{1-g_{2-}})}{\Delta_{1+}} \frac{\Delta_{1-}}{2} - \frac{(g_{1+g_{2+}} + g_{1-g_{2-}})}{\Delta_{2+}} \frac{\Delta_{2-}}{2} \right]^2 \frac{1}{\Delta_{1+} + \Delta_{2-}} + \frac{1}{\Delta_{1+} - \Delta_{2-}}
\]

\[
+ \left[ \frac{(g_{1+g_{2-}} + g_{1-g_{2+}})}{\Delta_{1+}} \frac{\Delta_{2-}}{2} + \frac{1}{\Delta_{1+}} \frac{1}{\Delta_{2-}} \right]^2 \frac{1}{\Delta_{1+} - \Delta_{2-}}
\]

\[
- \left( \frac{g_{1+g_{2+}}^2}{\Delta_{1+}^2} \frac{\Delta_{2-}}{2} + \frac{1}{\Delta_{1+}} \frac{1}{\Delta_{2-}} \right) \left( \frac{g_{1+g_{2-}}^2}{\Delta_{1+}^2} \frac{\Delta_{2-}}{2} + \frac{1}{\Delta_{1+}} \frac{1}{\Delta_{2-}} \right) \left( \frac{g_{1+g_{2+}}^2}{\Delta_{1+}^2} \frac{\Delta_{2-}}{2} + \frac{1}{\Delta_{1+}} \frac{1}{\Delta_{2-}} \right),
\]

\[
\zeta = \zeta_{2000} + \zeta_{0200} + \zeta_{0020} + \zeta_{0002} + \zeta_1
\]
FIG. 7: Landscapes of XY coupling \( J \) and ZZ coupling \( \zeta \) as a function of coupler frequency \( \omega_c \) and direct coupling strength \( g_{12} \) with qubit frequency \( \omega_{1(2)}/2\pi = 5.114 (5.014) \text{ GHz} \). The other system parameters are similar to those used in Fig. 3 of the main text, where the qubit detuning \( \Delta_{12}/2\pi = 200 \text{ MHz} \). Here the two-qubit detuning \( \Delta_{12}/2\pi = 100 \text{ MHz} \).

FIG. 8: Landscapes of XY coupling \( J \) and ZZ coupling \( \zeta \) as a function of coupler frequency \( \omega_c \) and direct coupling strength \( g_{12} \) with qubit frequency \( \omega_{1(2)}/2\pi = 5.114 (5.064) \text{ GHz} \). The other system parameters are similar to those used in Fig. 3 of the main text, where the qubit detuning \( \Delta_{12}/2\pi = 200 \text{ MHz} \). Here the two-qubit detuning \( \Delta_{12}/2\pi = 50 \text{ MHz} \).
where $\Delta_{ij} = \tilde{\omega}_i - \tilde{\omega}_j$. The terms $\zeta_{2000(0200)}$ and $\zeta_{0020(0002)}$ can be considered as the $ZZ$ contributions resulting from the effective coupling between qubit state $|1100\rangle$ and higher-energy states of transmons $|2000(0200)\rangle$ and coupled $|0020(0002)\rangle$, respectively, and the associated effective coupling strength can be approximated as

$$J_{2000} \simeq \sqrt{2}J, \quad J_{0200} \simeq \sqrt{2}J,$$

$$J_{0020} \simeq 2\sqrt{2}J_+, \quad J_{0002} \simeq 2\sqrt{2}J_-, \quad (E4)$$

while term $\zeta_1$ results from the interaction among lower-energy states of qubits and coupler.

From Eqs. (E2), (E3) and (E4), one can find that the conditions for achieving zero-$XY$ coupling and zero-$ZZ$ coupling is not coexist in the same parameter space. This suggests that in this coupler architecture, one may suppress static $ZZ$ coupling while preserve $XY$ interaction. In Figs. 10, 11, and 12, we demonstrate numerically that in this architecture, the static $ZZ$ coupling can indeed be heavily suppressed without the need for suppressing $XY$ coupling. Thus, $XY$-based two-qubit gates could be implemented without the detrimental effect from static $ZZ$ coupling.

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FIG. 10: Off-resonance case. Landscapes of $XY$ coupling $J$ (perturbation theory) and $ZZ$ coupling $\zeta$ (numerical diagonalization) as a function of coupler frequency $\omega_{\pm}$ with qubit frequency $\omega_{\pm}/2\pi = 6.143 (6.421)$ GHz, qubit anharmonicity $\alpha_{-}/2\pi = -330$ MHz, coupler anharmonicity $\alpha_{+}/2\pi = 0$ MHz, transmon-coupler coupling strength $g_{-}(2-)\pi = 85$ MHz, $g_{+}(2+)\pi = 102$ MHz [5] and coupler anharmonicity (a) $\alpha_{-}/2\pi = -100$ MHz, (b) $\alpha_{+}/2\pi = -300$ MHz, (c) $\alpha_{-}/2\pi = -500$ MHz, and (d) $\alpha_{+}/2\pi = -700$ MHz. For each coupler anharmonicity, the two landscapes are superposed in a single panel, where the region corresponding to $ZZ$ coupling with $\zeta$ below 20 KHz is omitted and replaced with the corresponding values of the $XY$ coupling $J$ (the region outlined with black dotted lines).

FIG. 11: Off-resonance case. Landscapes of $XY$ coupling $J$ (perturbation theory) and $ZZ$ coupling $\zeta$ (numerical diagonalization) as a function of coupler frequency $\omega_{\pm}$ with qubit anharmonicity $\alpha_{-}/2\pi = -100$ MHz. (a) $\alpha_{+}/2\pi = 0$, (b) $\alpha_{+}/2\pi = -200$ MHz, (c) $\alpha_{+}/2\pi = -400$ MHz, and (d) $\alpha_{+}/2\pi = -600$ MHz. The other system parameters are similar to those used in Fig. 10.

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FIG. 12: On-resonance case. Landscapes of $XY$ coupling $J$ (numerical diagonalization) and $ZZ$ coupling $\zeta$ (numerical diagonalization) as a function of coupler frequency $\omega_\perp$ with qubit frequency $\omega_{(2)/2\pi} = 6.421$ GHz. The other system parameters are similar to those used in Fig. 11.

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