DUAL-RAIL ENTANGLING GATES VIA BEAMSPLITTER-ACTIVATED CROSS KERR INTERACTIONS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to and the benefit under 35 U.S.C. § 119(e) of U.S. Provisional Patent Application No. 63/560,312, filed on March 1, 2024, under Attorney Docket No. Y0087.70174US00, and titled "DUAL-RAIL ENTANGLING GATES VIA BEAMSPLITTER-ACTIVATED CROSS KERR INTERACTIONS," the entire contents of which are hereby incorporated by reference herein.

FEDERALLY SPONSORED RESEARCH

This invention was made with government support under W911NF-23-1-0051 awarded by U.S. Army Research Office. The government has certain rights in the invention.

BACKGROUND

Quantum information processing techniques perform computation by manipulating one or more quantum objects. These techniques are sometimes referred to as "quantum computing." In order to perform computations, a quantum information processor utilizes quantum objects to reliably store and retrieve information. According to some quantum information processing approaches, a quantum analogue to the classical computing "bit" (being equal to 1 or 0) has been developed, which is referred to as a quantum bit, or "qubit." A qubit can be composed of any quantum system that has two distinct states (which may be thought of as 1 and 0 states) but also has the special property that the system can be placed into quantum superpositions and thereby potentially exist in both of those states at once.

SUMMARY

Some aspects described herein are directed to a quantum information processing system. The quantum information processing system may comprise: a first dual-rail qubit device; a second dual-rail qubit device; a first coupling element coupled between the first dual-rail qubit device and the second dual-rail qubit device; at least one energy source; and at least one controller configured to operate the at least one energy source to perform an entangling gate between the first dual-rail qubit device and the second dual-rail qubit device by: causing, by applying a first drive waveform to the first coupling element, a first exchange of a state of a quantum oscillator of the first dual-

rail qubit device with a state of a quantum oscillator of the second dual-rail qubit device; and after waiting a pre-determined period of time after causing the first exchange, causing, by applying a second drive waveform to the first coupling element, a second exchange of a state of the quantum oscillator of the first dual-rail qubit device with a state of the quantum oscillator of the second dual-rail qubit device.

In some embodiments, the first dual-rail qubit device and the second dual-rail qubit device each comprise a first quantum oscillator, a second quantum oscillator, and a second coupling element coupling the first quantum oscillator to the second quantum oscillator; and the first coupling element is coupled between the first quantum oscillators of the first and second dual-rail qubit devices.

In some embodiments, the first coupling element is dispersively coupled between the first quantum oscillators of the first and second dual-rail qubit devices. In some embodiments, the first coupling element comprises a flux-driven SQUID coupler. In some embodiments, the first coupling element is a transmon qubit device or a superconducting asymmetric inductive element (SNAIL).

In some embodiments, the quantum information processing system further comprises: a first ancilla qubit device coupled to the first dual-rail qubit device; and a second ancilla qubit device coupled to the second dual-rail qubit device. In some embodiments, the first ancilla qubit device is coupled to the second quantum oscillator of the first dual-rail qubit device, and the second ancilla qubit device is coupled to the first quantum oscillator of the second dual-rail qubit device. In some embodiments, the first ancilla qubit device and/or the second ancilla qubit device is a transmon qubit device. In some embodiments, the first and second quantum oscillators comprise microwave cavities. In some embodiments, the at least one controller is configured to apply the first drive waveform and/or the second drive waveform to the first coupling element for a time, $t = \pi/g_{BS}$. In some embodiments, the at least one controller is configured to apply the second drive waveform after a pre-determined period of time having a length of approximately $t = \frac{-\theta}{|\chi_a + \chi_b - \chi_{a_2 b_1}|}$.

In some embodiments, the at least one controller is further configured to apply a pulse sequence comprising applying drive waveforms to respective coupling elements to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, the pulse sequence comprising: the first drive waveform applied to the first coupling element; the second drive waveform applied to the first coupling element; a third drive waveform applied to the second coupling element of the first dual-rail qubit device, the third drive waveform being applied before the first drive waveform; and a fourth drive waveform applied to the second

coupling element of the first dual-rail qubit device, the fourth drive waveform being applied after the second drive waveform.

In some embodiments, the at least one controller is further configured to apply a pulse sequence comprising applying drive waveforms to respective coupling elements to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, the pulse sequence comprising: the first drive waveform applied to the first coupling element; the second drive waveform applied to the first coupling element; a third drive waveform applied to the second coupling element of the first dual-rail qubit device; a fourth drive waveform applied to the second coupling element of the second dual-rail qubit device; a fifth drive waveform applied to the first coupling element; and after a second pre-determined period of time after the fifth drive waveform, a sixth drive waveform applied to the first coupling element.

In some embodiments, the pulse sequence further comprises: a seventh drive waveform applied to the second coupling element of the first dual-rail qubit device; and an eighth drive waveform applied to the second coupling element of the second dual-rail qubit device.

In some embodiments, the at least one controller is further configured to apply a pulse sequence comprising applying drive waveforms to respective coupling elements to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, the pulse sequence comprising: the first drive waveform applied to the first coupling element; the second drive waveform applied to the first coupling element; a third drive waveform applied to the second coupling element of the first dual-rail qubit device; and a fourth drive waveform applied to the second coupling element of the second dual-rail qubit device, the third and fourth drive waveforms being applied between the first and second drive waveforms.

In some embodiments, the pulse sequence further comprises: a fifth drive waveform applied to the second coupling element of the first dual-rail qubit device; a sixth drive waveform applied to the first coupling element; after a second pre-determined period of time after the sixth drive waveform, a seventh drive waveform applied to the first coupling element; and an eighth drive waveform applied to the second coupling element of the first dual-rail qubit device.

In some embodiments, the first coupling element comprises: a third quantum oscillator, a fourth quantum oscillator, and a third coupling element coupled between the first and second quantum oscillators; a fourth coupling element coupled between the first quantum oscillator of the first dual-rail qubit device and the third quantum oscillator; and a fifth coupling element coupled between the first quantum oscillator of the second dual-rail qubit device and the fourth quantum oscillator; applying the first drive waveform to the first coupling element comprises applying the first drive waveform to the fourth and fifth coupling element; and applying the second drive

waveform to the first coupling element comprises applying the second drive waveform to the fourth and fifth coupling elements.

Some aspects described herein are directed to a method for performing an entangling gate between a first dual-rail qubit device and a second dual-rail qubit device coupled via a first coupling element, the first dual-rail qubit device and the second dual-rail qubit device each comprise a first quantum oscillator, a second quantum oscillator, and a second coupling element coupling the first quantum oscillator to the second quantum oscillator, and the first coupling element is coupled between the first quantum oscillators of the first and second dual-rail qubit devices. The method may comprise: applying a first drive waveform to a first coupling element to cause a first exchange of state of the first quantum oscillator of the first dual-rail qubit device with a state of the first quantum oscillator of the second dual-rail qubit device; and after waiting a pre-determined period of time after causing the first exchange, applying a second drive waveform to the first coupling element to cause a second exchange of a state of the first quantum oscillator of the first dual-rail qubit device with a state of the first quantum oscillator of the second dual-rail qubit device.

In some embodiments, applying the first drive waveform and/or second drive waveform comprises applying the first drive waveform and/or second drive waveform for a time, $t = \pi/g_{BS}$. In some embodiments, applying the second drive waveform comprises applying the second drive waveform after the pre-determined period of time having a length of approximately $t = \frac{-\theta}{|\chi_a+\chi_b-\chi_{a_2b_1}|}$.

In some embodiments, the method further comprises applying a pulse sequence comprising drive waveforms configured to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, applying the pulse sequence comprising: applying a third drive waveform to the second coupling element of the first dual-rail qubit device, the third drive waveform being applied before the first drive waveform; and applying a fourth drive waveform to the second coupling element of the first dual-rail qubit device, the fourth drive waveform being applied after the second drive waveform.

In some embodiments, the method further comprises applying a pulse sequence comprising drive waveforms configured to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, applying the pulse sequence comprising: applying a third drive waveform to the second coupling element of the first dual-rail qubit device; applying a fourth drive waveform to the second coupling element of the second dual-rail qubit device; applying a fifth drive waveform to the fifth drive waveform to the first coupling element;

and after a second pre-determined period of time after applying the fifth drive waveform, applying a sixth drive waveform to the first coupling element.

In some embodiments, applying the pulse sequence further comprises: applying a seventh drive waveform to the second coupling element of the first dual-rail qubit device; and applying an eighth drive waveform to the second coupling element of the second dual-rail qubit device.

In some embodiments, the method further comprises applying a pulse sequence comprising drive waveforms configured to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, applying the pulse sequence comprising: applying a third drive waveform to the second coupling element of the first dual-rail qubit device; applying a fourth drive waveform to the second coupling element of the second dual-rail qubit device, the third and fourth drive waveforms being applied between the first and second drive waveforms.

In some embodiments, applying the pulse sequence further comprises: after applying the second drive waveform: applying a fifth drive waveform to the second coupling element of the first dual-rail qubit device; applying a sixth drive waveform to the first coupling element; after waiting a second pre-determined period of time after the sixth drive waveform, applying a seventh drive waveform to the first coupling element; and applying an eighth drive waveform to the second coupling element of the first dual-rail qubit device.

In some embodiments, the method further comprises the first coupling element comprises: a third quantum oscillator, a fourth quantum oscillator, and a third coupling element coupled between the first and second quantum oscillators; a fourth coupling element coupled between the first quantum oscillator of the first dual-rail qubit device and the third quantum oscillator; and a fifth coupling element coupled between the first quantum oscillator of the second dual-rail qubit device and the fourth quantum oscillator; and the method further comprises: applying the first drive waveform to the first coupling element comprises applying the first drive waveform to the fourth and fifth coupling elements; and applying the second drive waveform to the second coupling elements comprises applying the second drive waveform to the fourth and fifth coupling elements.

The foregoing apparatus and method embodiments may be implemented with any suitable combination of embodiments, features, and acts described above or in further detail below. These and other aspects, embodiments, and features of the present description can be more fully understood from the following description in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Various aspects and embodiments will be described with reference to the following figures. It should be appreciated that the figures are not necessarily drawn to scale. In the drawings, each identical or nearly identical component that is illustrated in various figures is represented by a like numeral. For purposes of clarity, not every component may be labeled in every drawing.

FIG. 1 depicts an example block diagram of a system for implementing a dual-rail qubit, according to some embodiments of the technology described herein;

FIG. 2 depicts an example schematic diagram of a system for implementing coupling between two dual-rail qubits, according to some embodiments of the technology described herein;

FIG. 3 illustrates a simplified schematic of the implementation of the system of FIG. 2 depicting the relative interaction strength between oscillators of the system, according to some embodiments of the technology described herein;

FIG. 4 is a flowchart describing a process for performing an entangling gate between two coupled dual-rail qubits, according to some embodiments of the technology described herein;

FIGS. 5A-1 through 5A-3 illustrate example operations for implementing the process of FIG. 4 for performing an entangling gate between two coupled dual-rail qubits, according to some embodiments of the technology described herein;

FIG. 5B illustrates a pulse sequence for implementing the process of FIG. 4, according to some embodiments of the technology described herein;

FIG. 5C illustrates examples of locations of quantum states during the process of FIG. 4, according to some embodiments of the technology described herein;

FIG. 6A illustrates an alternative example of a "wait" operation for the process of FIG. 4, the alternative operation being configured for minimizing coherent leakage caused by non-linear interactions, according to some embodiments of the technology described herein;

FIG. 6B illustrates another example of a system for implementing coupling between two dual-rail qubits, the system including a buffer cavity coupled between the two dual-rail qubits to minimize coherent leakage, according to some embodiments of the technology described herein;

FIG. 7 depicts an example arrangement of five dual-rail qubits for performing entangling gates between pairs of dual-rail qubits in the arrangement, according to some embodiments of the technology described herein;

FIG. 8A depicts another example arrangement of four dual-rail qubits for performing entangling gates between pairs of dual-rail qubits in the arrangement, according to some embodiments of the technology described herein;

FIG. 8B depicts a pulse sequence for performing an entangling gate between dual-rail qubits of the arrangement of FIG. 8A, according to some embodiments of the technology described herein;

FIG. 9 illustrates a schematic for performing long range entangling dual-rail gates, according to some embodiments of the technology described herein;

FIG. 10 is a flowchart describing an alternative process for performing an entangling gate between two coupled dual-rail qubits, the alternative process using an inverted CPHASE angle, according to some embodiments of the technology described herein;

FIG. 11 illustrates an example pulse sequence for implementing the process of FIG. 10, according to some embodiments of the technology described herein;

FIG. 12A illustrates a schematic representation of a process for applying a series of drive waveforms for performing an entangling gate configured to echo out low frequency dephasing noise, according to some embodiments of the technology described herein;

FIG. 12B illustrates another schematic representation of a process for applying a series of drive waveforms for performing a SWAP operation between two coupled dual-rail qubits, the SWAP operation configured to cancel accumulated CPHASE entanglement, according to some embodiments of the technology described herein;

FIG. 13 depicts an illustrative implementation of a computer system 1300 that may be used in connection with any of the embodiments of the technology described herein.

DETAILED DESCRIPTION

Quantum multi-level systems such as superconducting qubits exhibit quantum states that, based on current experimental practices, decohere in around ~100μs. While experimental techniques will undoubtedly improve on this and produce qubits with longer decoherence times, it may nonetheless be beneficial to couple a multi-level system to another system that exhibits much longer decoherence times. A system configured with bosonic modes may be particularly desirable for coupling to a multi-level system. Through this coupling, the multi-level system's state may be represented by the bosonic mode(s) instead, thereby maintaining the same information yet in a longer-lived state than would otherwise exist in the multi-level system alone. When used in this manner, the bosonic system is sometimes referred to as a "logical" qubit, where a "logical" qubit is a collection of physical qubits (e.g., one or more devices supporting the bosonic mode(s)) that work together to represent a quantum state (e.g., the state of the multi-level system).

Quantum information stored in bosonic modes may nonetheless still have a limited lifetime, such that errors will still occur within the bosonic system. It may therefore be desirable to manipulate a bosonic system when errors in its state occur to effectively correct those errors

and thereby regain the prior state of the system. If a broad class of errors can be corrected for, it may be possible to maintain the state of the bosonic system indefinitely (or at least for long periods of time) by correcting for any type of error that might occur, thereby enabling longer periods of computation (e.g., such that a larger number of quantum operations can be performed on the quantum state thereby permitting the performance more complex or lengthy computations).

It is therefore desirable to manipulate a bosonic system when errors in its state occur to effectively correct those errors and thereby regain the prior state of the system. In some cases, it may be sufficient to simply detect that an error occurred during an operation. The desire to detect and/or correct errors in a quantum system requires that a number of requirements are simultaneously addressed, including the number of physical qubits used to encode logical information, a suitable scheme for performing gates and measurements on the quantum system, and the precision of the physical components of the system.

The inventors have recognized and appreciated that not all types of errors in a given quantum error correction architecture are equally likely to occur, nor are they equally harmful to the logical information stored in a quantum system. Some types of errors, for instance, require that a particular error syndrome is measured to pinpoint an error and to gain the required information to properly fix the error. This does not always lead to successful error correction, however, as sometimes there is not enough information to unambiguously determine the error. On the other hand, erasure errors - errors in which the information in a qubit is erased but in a way that allows the qubit to be identified – can be much more easily addressed.

The inventors have further recognized and appreciated techniques for error correction that utilize a dual-rail encoding of a single excitation in a pair of coupled quantum oscillators (e.g., linear quantum oscillators or quantum harmonic oscillators). In particular, the dual-rail qubit may be implemented in a circuit quantum electrodynamics (cQED) system comprising a pair of coupled resonators. In this dual-rail encoding, an excitation is stored in one of the two resonators. An excitation of the first resonator is treated as a logical 0, whereas an excitation of the other resonator is treated as a logical 1. Thus, together the two resonators form a single logical dual-rail qubit in which the logical states are $|0\rangle_L = |01\rangle$ and $|1\rangle_L = |10\rangle$. This type of logical qubit has several benefits, which include the following. First, photon loss appears as an erasure error, which is among the easier types of errors to correct, as described above. Second, the single photon state is the lowest energy state of the oscillator and thereby has the lowest error rate of any state of the oscillator. As, such the dual-rail encoding minimizes the rate of loss errors. Third, photon gains or losses are readily detectable by measuring the joint parity of the cavities.

A dual-rail qubit may be implemented as a cQED system comprising two quantum oscillators (e.g., acoustic and/or optical microwave cavity resonators) coupled together via a suitable non-linear coupling element, including but not limited to a transmon qubit, a superconducting nonlinear asymmetric inductive element (SNAIL), or a superconducting quantum interference device (SQUID). One of the quantum oscillators may be coupled to an ancilla qubit (e.g., a transmon qubit, a fluxonium qubit, or other suitable qubit). Although the ancilla qubit only couples to one of the bosonic modes of the system, due to a beamsplitter interaction provided by the coupling element, both bosonic modes interact with the ancilla qubit, enabling various dual-rail operations. For instance, a dual-rail state may be prepared, and gates may be performed upon a dual-rail state, through application of energy (e.g., microwave pulses) to the ancilla qubit and/or to the coupling element, as described further below.

According to some embodiments, the logical quantum state of a dual-rail qubit is prepared by preparing a single excitation of one of the two quantum oscillators of the dual-rail qubit. For instance, to prepare the $|0\rangle_L$ state (the logical 0 state), both oscillators may be prepared in their respective ground state $|0\rangle$, and the first oscillator excited to its $|1\rangle$ state while the second oscillator remains in its $|0\rangle$ state. Similarly, to prepare the $|1\rangle_L$ state (the logical 1 state), both oscillators may be prepared in their respective ground state $|0\rangle$, and the second oscillator excited to its $|1\rangle$ state while the first oscillator remains in its $|0\rangle$ state. In the case of a cQED dual-rail qubit comprising two quantum resonators, for example, one of the resonators may be prepared in a $|1\rangle$ state by loading a single photon into the resonator.

The inventors have recognized and appreciated that quantum information processing systems including two or more dual-rail qubits have static sources of non-linearity (e.g., cross Kerr interactions or ZZ crosstalk). The inventors have further recognized and appreciated that these static interactions between quantum oscillators may effectively be "turned on" and "turned off" by swapping the positions of photons between quantum oscillators of neighboring dual-rail qubits. By swapping the positions of photons between quantum oscillators, and "turning on" a non-linear interaction between two quantum oscillators, two neighboring dual-rail qubits may be entangled (e.g., an entangling gate may be implemented). Accordingly, the inventors have developed quantum information processing systems configured to implement entangling gates between dual-rail qubits, the entangling gates being equivalent to CPHASE gates up to local Z rotations.

In some embodiments, the entangling gates may be performed by implementing a first beam-splitter interaction between a first quantum oscillator of a first dual-rail qubit and a first quantum oscillator of a second dual-rail qubit by applying a first drive waveform to a coupling

element coupling the first quantum oscillators. In this manner, the photons may be swapped between the first quantum oscillators of the first and second dual-rail qubits. The controller may be configured to wait a pre-determined period of time such that the static cross Kerr interaction causes a phase accumulation during the pre-determined period of time. After waiting, the controller may then implement another beam-splitter interaction between the first quantum oscillators of the first and second dual-rail qubits to swap the photons back between the first quantum oscillators. The beam-splitter interaction may be implemented by applying a second drive waveform to the coupling element coupling the first quantum oscillators.

FIG. 1 depicts an example block diagram of a system 100 for implementing a dual-rail qubit, according to some embodiments of the technology described herein. In system 100, oscillators 101 and 102 are coupled to one another via coupling element 103. The oscillator 101 is also coupled to an ancilla qubit 104. Energy source 105 may be operated by controller 106 to direct energy to the ancilla qubit 104, the coupling element 103, and/or the readout resonator 107.

According to some embodiments, the oscillator 101 and the oscillator 102 each includes a cavity that supports quantum states of microwave photons (e.g., microwave cavities). For example, in some embodiments, the first oscillator 101 and the second oscillator 102 may each comprise a resonator, such as a transmission line resonator or three-dimensional cavity formed from a superconducting material, such as aluminum.

Coupling element 103 may comprise a non-linear element that is coupled to the oscillators 101 and 102. The coupling element 103 mediates coupling between the quantum states of the two oscillators, allowing for interactions between the first oscillator 101 and the oscillator 102. In some embodiments, the coupling element 103 may be a superconducting nonlinear asymmetric inductive element (SNAIL), a superconducting quantum interference device (SQUID), a Josephson junction, or some other non-linear element. In some embodiments, the coupling element 103 may comprise a transmon qubit that is dispersively coupled to both the first oscillator 101 and the second oscillator 102.

As shown in the illustrated embodiment, ancilla qubit 104 is coupled (e.g., dispersively coupled) to oscillator 101. However, in some embodiments, ancilla qubit 104 may be coupled to oscillator 102. In other embodiments, system 100 may include two ancilla qubits 104 each coupled to one of oscillators 101 or 102. In some embodiments, the ancilla qubit 104 may be a transmon qubit, a fluxonium qubit, a charge qubit, a SNAIL, a SQUID or some other non-linear element.

In some embodiments, energy source 105 may comprise a microwave source configured to direct microwave pulses or drive waveforms of desired amplitudes, frequencies, and phases to one or more components of the dual-rail qubit, for example, the ancilla qubit 104, coupling

element 103, or any other suitable component. In some embodiments, energy source 105 may be capacitively coupled to each of the ancilla qubit 104, coupling element 103, and/or readout resonator 107. As noted below, in some embodiments, a plurality of instances of the dual-rail qubit shown may arranged coupled with each other. In some embodiments, energy source 105 may be coupled to components of some or all of the plurality of dual-rail qubits, so that energy source 105 may be utilized to direct microwave pulses to each of the dual-rail qubits it may be coupled to. In other embodiments, each dual-rail qubit may be coupled to a different respective energy source 105.

Energy source 105 may be configured to provide the microwave drive waveforms in response to receiving one or more control signals from controller 106. In embodiments employing multiple instances of dual-rail qubits, controller 106 may be configured to control one or more of the energy sources 105 utilized in the system. As such, any suitable number of controllers 106 may be used.

As noted above, the inventors have recognized and appreciated that quantum information processing systems including two or more dual-rail qubits as described above have static sources of non-linearity, which can be leveraged to perform an entangling gate that is equivalent to CPHASE gates up to local Z rotations. FIG. 2 depicts an example schematic of a system 200 for implementing coupling between two dual-rail qubits, according to some embodiments of the technology described herein. In the illustrated embodiment, the system 200 includes two dual-rail qubits 210 and 220, implemented as described above with respect to FIG. 1, and coupling element 230.

First dual-rail qubit 210 includes oscillators 211 and 212 (e.g., microwave cavities), coupling element 213, and ancilla qubit 214. Second dual-rail qubit 220 includes oscillators 221 and 222 (e.g., microwave cavities), coupling element 223, and ancilla qubit 224. Although the illustrated embodiment depicts ancilla qubit 214 being coupled to oscillator 212 and ancilla qubit 224 being coupled to oscillator 222, the technology is not limited in this manner and either or both cavities in each dual-rail qubit may be coupled to an ancilla qubit. In some embodiments, neither or only one dual-rail qubit may include an ancilla qubit.

Coupling element 230 is coupled between oscillator 211 of first dual-rail qubit 210 and oscillator 222 of second dual-rail qubit 220. As with coupling element 103, coupling element 230 coupling the two dual-rail qubits, as well as coupling elements 213 and 223 coupling the cavities of each dual-rail qubit, may be a superconducting nonlinear asymmetric inductive element (SNAIL), a superconducting quantum interference device (SQUID), a Josephson junction, and/or any other suitable non-linear element.

Dual-rail entangling gates as described herein may be performed on the two dual-rail qubits by directing energy (e.g., microwave energy from a microwave source) to coupling element 230 between the dual-rail qubits, rather than (and/or in addition to) coupling elements 213 and 223 coupling the cavities of each respective dual-rail qubit 210 and 220. In previous approaches to two-qubit gates, methods have leveraged different pulse sequences comprising different drive waveforms (e.g., provided by energy source 105) applied to both the inter-qubit coupling element (e.g., coupling element 230) and the ancilla qubit(s) coupled to the central cavities (e.g., ancilla qubit 224). As noted above, the inventors have developed techniques for performing two qubit dual-rail entangling gates by leveraging the static sources of non-linearity (e.g., cross-Kerr interactions) present in the system by applying drive waveforms to the coupling elements (e.g., 230, 213, and/or 223) to turn the interactions between cavities on and off, without applying drive waveforms to the ancilla qubit(s).

FIG. 3 illustrates simplified schematics of the implementation of the system 200 of FIG. 2 depicting the relative interaction strength between oscillators of the system, according to some embodiments of the technology described herein. To leverage the various non-linear interactions between the cavities in the dual-rail entangling gate, the strength of the interactions between various cavities can be engineered to provide a high effective interaction strength between the two qubits, and a high on-off ratio for the non-linear interactions. For clarity, ancilla qubits are not depicted in dual-rail qubit illustrations from FIGs. 3 onwards, but it should be appreciated that ancilla qubits may be present as described above with respect to FIGS. 1 and 2, as aspects of the technology described herein are not limited in this respect.

In some embodiments, including those depicted in FIG. 3, the strength of the intra-dual-rail qubit interactions (e.g., χ_a between cavity modes of oscillators 211 and 212 of first dual-rail qubit 210 and χ_b between cavity modes of oscillators 221 and 222 of second dual-rail qubit 220) may be made to be greater than the inter-dual-rail-qubit interaction χ_{ab} between cavity modes of the coupled oscillators 211 and 222. By engineering the relative interaction strengths, the effective entangling interaction strength given $\theta \propto \chi_a + \chi_b - \chi_{ab}$ may be made large and the on-off ratio for the entangling interaction given by $\frac{\chi_a+\chi_b-\chi_{ab}}{\chi_{ab}}$ may also be made large. The different interaction strengths may be engineered in any suitable manner. In some embodiments, a first type of coupling element may be used to couple the oscillators of a dual-rail qubit (e.g., oscillators 211 and 212) and a second type of coupling element may be used to couple the oscillator of the first dual-rail qubit and the oscillator of the second dual-rail qubit (e.g., oscillators 211 and 222). For example, the first type of coupling element may be one of a SQUID, SNAIL, or transmon qubit, while the second type of coupling element may be a different one of a SQUID, SNAIL, or transmon qubit.

The first and second types of coupling elements may provide different coupling strengths. Additionally or alternatively, in some embodiments, the interaction strengths may be adjusted by applying one or more drive waveforms (e.g., microwave drive pulses) to the coupling elements to increase the non-linear interaction strengths χ_a, χ_b, and/or χ_{ab}.

In some embodiments, applying a drive waveform to coupling element 230 swaps the photons, and thus the encoded states, of cavities 211 and 222. For example, when dual-rail qubit 210 is initialized in $|0\rangle_L = |01\rangle$ and dual-rail qubit 220 is initialized similarly in $|0\rangle_L = |01\rangle$, applying the drive waveform to coupling element 230 swaps the positions of the photons, and thus the encoded quantum states, of cavities 211 and 222 such that the dual-rail qubit 210 is placed in the state $|00\rangle$ and the dual-rail qubit 220 is placed in the state $|11\rangle$. The interaction between the two photons of dual-rail qubit 210 will then be controlled by χ_a, and the interaction between the two photons of dual-rail qubit 220 will then be controlled by χ_b. By leaving the photons in the new swapped state for a period of time, a time evolution of the quantum states in the dual-rail qubits 210, 220 will occur, causing entanglement between the photons in each of the dual-rail qubits 210, 220. In this manner, by applying a series of drive waveforms to the various coupling elements, the encoded states of the system may be moved between the dual-rail qubits 210 and 220 to turn non-linear interactions between the encoded states on and off as desired, thereby performing various entangling gates between the dual-rail qubits 210 and 220 as described herein.

The components of the dual-rail qubits for use in performing an entangling gate as described herein may be configured to have any suitable parameter values. For example, the ancilla qubit(s) may have values of the parameter T_1 in a range from 100 μs to 400 μs and values of T_{2R} in a range from 20 μs to 400 μs, in some embodiments. For example, in some embodiments, both T_1 and T_{2R} of the ancilla qubit(s) may be approximately 200 μs. In some embodiments, the quantum oscillators may have values of the parameter T_1 in a range from 300 μs to 900 μs and values of the parameter T_{2R} in a range from 350 μs to 1000 μs. For example, in some embodiments, the T_1 value of one or more of the oscillators may be approximately 500 μs and the T_{2R} value of one or more of the oscillators may be approximately 700 μs.

Further, in some embodiments, the beamsplitter drive waveform may have a frequency in a range from 0.5 MHz to 2.5 MHz, and the non-linear interactions strengths χ_a, χ_b, and χ_{ab} may be in a range from 5 kHz to 50 kHz. As noted above, in some embodiments, χ_a and χ_b may be configured to be greater than χ_{ab}. For example, in some embodiments, χ_a and χ_b may be greater by a factor of 5-10. For example, χ_a may be approximately 40 kHz, χ_b may be approximately 40 kHz, and χ_{ab} may be approximately 8 kHz.

FIG. 4 is a flowchart describing a process 400 for performing an entangling gate between two coupled dual-rail qubits, according to some embodiments of the technology described herein. FIG. 5A depicts illustrative operations for implementing the process 400 of FIG. 4 for performing an entangling gate between two coupled dual-rail qubits, according to some embodiments of the technology described herein. FIG. 5B illustrates a pulse sequence of the example process 400 of FIG. 4, according to some embodiments. Process 400 may be implemented using coupled dual-rail qubits (e.g., as depicted in the example of FIG. 2) to perform a two-qubit entangling gate as described herein.

In some embodiments, after each of the two dual-rail qubits are initialized in an initial state (e.g., either $|0\rangle_L$ or $|1\rangle_L$), process 400 may begin at step 402, as illustrated in FIGS. 5A-1 and 5B. At step 402, a first drive waveform 502 is applied (e.g., using an energy source such as, but not limited to, a microwave source) to the coupling element between a quantum oscillator 211 of the first dual-rail qubit 210 and a quantum oscillator 222 of the second dual-rail qubit 220 (e.g., coupling element 230). The drive waveform 502 may be configured to perform a beamsplitter SWAP operation (e.g., as described in connection with the examples of FIGS. 3A-3B herein) to swap the states of the coupled quantum oscillators 211 and 222. In some embodiments, to apply the SWAP operation, the strength of the beamsplitter drive may be determined by:

$$\theta = \int_0^{\tau_1} \frac{g_{BS}(\tau)}{2} dt.$$

where θ is phase of the beamsplitter interaction between oscillators 211 and 222 (which may be indicative of the effective interaction strength of the beamsplitter interaction) and $g_{BS}(\tau)$ describes the beamsplitter drive waveform. When $\theta = \pi$ (which represents a flip from an initial phase $\theta = 0$), the beamsplitter drive $g_{BS}(\tau)$ implements the SWAP operation, causing the swapping of the states of the cavity modes between the quantum oscillators 211 and 222. As such, to implement the SWAP operation, in some embodiments, the drive waveform 502 may be applied to the coupling element for a time $\tau = \pi/g_{BS}$. For example, in embodiments where $g_{BS} = 5$ MHz, the drive waveform may be applied for a time of approximately 0.6 μs. However, the technology is not limited in this manner, and the drive waveform may be applied for any suitable time corresponding to the frequency of the drive waveform (e.g., g_{BS} in the range of 5 MHz to 50 MHz).

After implementing the SWAP operation in step 402, the entangling interaction between the two dual-rail qubits may be turned "on" by the static cross-Kerr interactions, χ_a and χ_b, as illustrated in FIG. 5A-2, thereby causing a phase accumulation in the states of the photons. For example, when dual-rail qubits 210 and 220 are both initialized in the state $|0\rangle_L = |01\rangle$,

performing the first SWAP operation at step 402 may place dual-rail qubit 210 in the state $|00\rangle$, and dual-rail qubit 220 in the state $|11\rangle$. This places both photons in dual-rail qubit 220, allowing the photons to interact via coupling element 223 of dual-rail qubit 220. Thus, the SWAP operation may turn on an interaction controlled by χ_b between the photons in the system.

A period of time (e.g., a "wait time," as illustrated in FIG. 5B) may be allowed to pass to allow a desired phase accumulation to occur. The selected wait time may be used to control the CPHASE angle (e.g., $0 < \theta_3 < 2\pi$) associated with the two-qubit entangling gate being implemented by the process 400. In some embodiments, the CPHASE angle may be defined as $\theta_3 = -(\chi_a + \chi_b - \chi_{ab})t$, such that the predetermined period of time may be given by $t_{wait} = \theta_3/(\chi_a + \chi_b - \chi_{ab})$. In some embodiments, process 400 may be used to implement a controlled Z (CZ) gate having $\theta_3 = \pi$. In such embodiments, $t_{wait} = \frac{\pi}{|\chi_a+\chi_b-\chi_{ab}|}$. In some embodiments, $t_{wait} = \frac{\pi}{|\chi_a+\chi_b-\chi_{ab}|}$ may give an initial estimate of the predetermined wait time. Then the wait time can be fine-tuned to achieve the desired phase accumulation. For example, the resulting t_{wait} may be fine-tuned within 5-15% of the initial estimated value of t_{wait}.

In some embodiments, after waiting the predetermined period of time, t_{wait}, process 400 may continue to step 404, where a second drive waveform 504 is applied to the coupling element (e.g., coupling element 230) to implement a second SWAP operation, causing the exchange of the states between the quantum oscillator 211 of the first dual-rail qubit 210 and the quantum oscillator 222 of the second dual-rail qubit 220. In some embodiments, the second drive waveform 504 may be applied in the same manner as described above with respect to first drive waveform 502. In some embodiments, the phase of second drive waveform 504 may be reversed with respect to first drive waveform 502, as illustrated in FIG. 5B, to reduce effects of calibration errors. In some embodiments, to have the freedom to select the phase of the second drive waveform 504, g_{BS} may be configured to be much greater than $\chi_a, \chi_b,$ and χ_{ab} (e.g., such that $g_{BS} \gg \chi_a, \chi_b, \chi_{ab}$). In some embodiments, g_{BS} may be configured to be in a range of 10 times to 500 times greater than $\chi_a, \chi_b,$ and/or χ_{ab}.

In some embodiments, the wait time may be reduced by applying one or more drive waveforms to the system to increase the non-linear interactions χ_a and/or χ_b during the wait time. By applying one or more drive waveforms to the coupling elements within the dual-rail cavities (e.g., coupling elements 213 and/or 223), the effective interaction strength may be increased such that $\chi_{eff} > \chi_a + \chi_b - \chi_{ab}$. As χ_{eff} increases, t_{wait} decreases. In some embodiments, the pump tone may be an off-resonant pump tone, for example, 50 MHz above the resonant frequency of the intra-dual-rail coupler (e.g., coupling element 213 or 223), which downshifts the resonant

frequency of the coupler. By downshifting the resonant frequency of the coupler, when the resonant frequency of the coupler approaches the resonant frequency of the quantum oscillators that it is coupled between, then the effective coupling strength of the coupler increases (e.g., the effective strengths of χ_a and/or χ_b increases).

When implemented, applying the drive waveforms to perform this SWAP-wait-SWAP entangling gate may provide a high gate fidelity and may enable implementation of two-qubit entangling without any state preparation and measurement (SPAM) correction. For example, in some embodiments, the entangling gates described herein may provide a fidelity of 99.20% with no SPAM correction.

FIG. 5C illustrates examples of locations of quantum states during process 400 of FIG. 4, according to some embodiments of the technology described herein. The example of FIG. 5C depicts the quantum states within a pair of coupled dual-rail qubits during the process 400 for examples of different initialized states. When the dual-rail qubits are initialized in the $|0\rangle_L|0\rangle_L$ states, as shown along the top line of FIG. 5C, performing the first SWAP operation places the first dual-rail qubit 210 into the $|00\rangle$ state and the second dual-rail qubit 220 into the $|11\rangle$ state, causing the photons to interact via the coupling element of the second dual-rail qubit. The interaction may be controlled by the non-linear interaction strength, χ_b, of the coupling element between the cavities of the second dual-rail qubit 220. The phase accumulated during the wait time is therefore $\chi_b t_{wait}$. Performing the second SWAP operation (e.g., as described in connection with step 404 of FIG. 4) places both of the dual-rail qubits back into the $|0\rangle_L|0\rangle_L$ states.

In some embodiments, when dual-rail qubits are initialized in the $|1\rangle_L|1\rangle_L$ states, as shown along the bottom line of FIG. 5C, performing the first SWAP operation places the first dual-rail qubit 210 into the $|11\rangle$ state and places the second dual-rail qubit into the $|00\rangle$ state. In this case, the photons in the first dual-rail qubit 210 interact via the coupling element of the first dual-rail qubit 210 such that the interaction is controlled by the coupling strength, χ_a, of the coupling element of the first dual-rail qubit 210. The phase accumulated during the wait time is therefore $\chi_a t_{wait}$. Performing the second SWAP operation (e.g., as described in connection with step 404 of FIG. 4) places both of the dual-rail qubits back into the $|1\rangle_L|1\rangle_L$ states.

When the dual-rail qubits are initialized in $|0\rangle_L|1\rangle_L$, as shown in the second line of FIG. 5C, performing the first SWAP operations swaps the photons in each qubit. The resulting interaction via the coupling element between the qubits (e.g., coupling element 230) may be controlled by χ_{ab}, causing the total phase accumulated to be $\chi_{ab} t_{wait}$. Performing the second SWAP operation (e.g., as described in connection with step 404 of FIG. 4) places both photons back into their original qubits.

Finally, when the dual-rail qubits are initialized in $|1\rangle_L|0\rangle_L$, as shown in the third line of FIG. 5C, neither photon may swap and there may be no interaction. As no photons occupy the oscillators coupled via the inter-qubit coupling element (e.g., coupling element 230), applying the drive waveform to perform the SWAP operation does not swap any of the photons between the qubits. As such, no interaction may occur.

In some embodiments, the presence of the non-linear interactions caused by coupling elements between the different quantum oscillators may introduce coherent leakage into the quantum processing system, which can cause information encoded in the quantum states to leak into a non-computational energy state. Accordingly, the inventors have recognized and appreciated processes for providing improved resistance to coherent leakage. For example, leakage may be detected when, after the second SWAP operation, the resulting state of the two dual-rail qubit system is $|00\rangle|11\rangle$, $|11\rangle|00\rangle$, $|02\rangle|00\rangle$, or $|00\rangle|20\rangle$. Adjustment of the different coupling strengths between each pair of quantum oscillators may be engineered to reduce coherent leakage as described with reference to FIGS. 6A and/or 6B.

FIG. 6A illustrates an alternative example of a "wait" operation for the process 400 of FIG. 4, the alternative operation being configured for minimizing coherent leakage caused by non-linear interactions, according to some embodiments of the technology described herein. In the example of FIG. 6A, the non-linear interaction of first dual-rail qubit 210 denoted by χ_a is engineered to be larger than the other inter-oscillator interactions (e.g., $\chi_a \gg \chi_b, \chi_{ab}$). When the amplitude of the beamsplitter drive waveform, g_{BS}, is approximately equivalent to the larger non-linear interaction, χ_a, coherent leakage may be reduced by preventing a photon from leaking from the oscillator a_2 to the oscillator b_1. It should be appreciated that while FIG. 6A illustrates the non-linear interaction, χ_a, of the first dual-rail qubit 210 as being the larger non-linear interaction in the system, in some embodiments, χ_b may alternatively be larger than the other non-linear interactions of the system of FIG. 6B (e.g., $\chi_b \gg \chi_a, \chi_{ab}$).

FIG. 6B illustrates another example of a system for implementing coupling between two dual-rail qubits, the system including a buffer cavity coupled between the two dual-rail qubits to minimize coherent leakage, according to some embodiments of the technology described herein. In the example of FIG. 6B, the strength of the non-linear interactions is only large in one location—e.g., between the oscillator of the first dual-rail qubit 210A and the buffer oscillator 250. In that way, the non-linear interactions between the two dual-rail qubits 210A and 220A are only "on" when a SWAP is performed to exchange the state of the other dual-rail qubit 220A and the buffer oscillator 250. Thus, because there are no interactions between the two dual-rail qubits when the buffer oscillator is empty, coherent leakage can be reduced to zero, or near-zero.

It can be appreciated that a quantum information processing system implementing the dual-rail entangling gates described herein may include more than two coupled dual-rail qubits. The entangling gates described herein can thus be performed between different dual-rail qubits depending on the arrangement of the dual-rail qubits in the quantum information processing system.

FIG. 7 depicts an example arrangement of five dual-rail qubits for performing entangling gates between pairs of dual-rail qubits in the arrangement, according to some embodiments of the technology described herein. Each of the dual-rail qubits 710-750 may be configured in the manners described above, and may each include two quantum oscillators, coupling elements, and/or ancilla qubits respectively coupled to either or both of the quantum oscillators of the dual-rail qubits.

In the illustrated embodiment, connection schema 701 depicts the various connections between which the dual-rail entangling gates may be performed in the given arrangement. For example, an entangling gate may be performed between dual-rail qubits 710 and 750, 720 and 750, 730 and 750, and/or 740 and 750 by applying the drive waveform sequences described herein (e.g., as described with respect to FIGS. 4-5B, and 11-12B) to the various coupling elements between the dual-rail qubits. For example, to perform an entangling gate between dual-rail qubits 710 and 750, the first and second drive waveforms to perform the beamsplitter SWAP operations may be applied to coupling element 1, and performing the entangling gate between dual-rail qubits 720 and 750 may be done by applying the drive waveforms to coupling element 2.

FIG. 8A depicts another example arrangement of four dual-rail qubits for performing entangling gates between pairs of dual-rail qubits in the arrangement, according to some embodiments of the technology described herein. In the illustrated embodiment, the connection schema 801 depicts the various connections between which the dual-rail entangling gates may be performed in the given arrangement. Although depicted as a similar arrangement as FIG. 7, FIG. 8 differs in that central dual-rail qubit 750 is replaced by two vacant quantum oscillators 852 and 854 (e.g., buffer cavities). As such, the entangling gates may be performed between next-nearest neighbors. For example, an entangling gate may be performed between dual-rail qubits 810 and 830, 810 and 840, 820 and 830, and 820 and 840.

To implement the entangling gates in this arrangement, the pulse sequence (e.g., described in FIGS. 4 and 5A) may be modified as depicted in FIG. 8B. Because each dual-rail qubit is separated by the vacant quantum oscillators, to perform the entangling gates, rather than applying the first and second drive waveforms to a single coupling element, the first and second drive waveforms may be applied to two coupling elements simultaneously. FIG. 8B depicts a pulse

sequence for performing an entangling gate between dual-rail qubits 810 and 840. To perform the gate, first and second pulse sequences 802 and 804 are applied to both coupling elements 1 and 4 simultaneously. In that way, the simultaneous pulses swap the state of the quantum oscillator of dual-rail qubit 810 into vacant oscillator 852 and the quantum oscillator of dual-rail qubit 840 into vacant oscillator 854. Thus, the interaction can be turned on and off as with the gates described above but is controlled by the coupling strength χ of the coupling element between vacant oscillators 852 and 854. In some embodiments, the coupling strength χ may be larger than the coupling strengths between the dual-rail qubits and the vacant oscillators (e.g., by a factor of 10-100).

In some embodiments, the techniques described herein may be used to perform entangling gates between distant dual-rail qubits coupled indirectly through a series of other qual-rail qubits. FIG. 9 illustrates a schematic for performing long range entangling dual-rail gates, according to some embodiments. In the illustrated embodiment, system 900 includes four dual-rail qubits 910-940 (although system 900 may include more or less). To perform the entangling gates described herein between first dual-rail qubit 910 and fourth dual-rail qubit 940, a series of SWAPs 902-904 may be performed to exchange the state of the quantum oscillator in the fourth dual-rail qubit 940 until it reaches interaction zone 901. SWAP 905 can then be used to exchange the state of the quantum oscillator in dual-rail qubit 910 into the interaction zone 901 so that the entangling interaction may be performed. To complete the gate (e.g., after t_{wait}), the reverse sequence of SWAPS may be performed to exchange the states back to their original oscillators in first dual-rail qubits 910 and 940.

While the entangling gates described herein can be implemented as described above, the inventors have appreciated that, optionally, applying drive waveforms in addition to those described with respect to FIGS. 4 to the dual-rail qubits may provide additional functionality and improvements to the dual-rail entangling gates described herein.

FIG. 10 is a flowchart describing an alternative process 1000 for performing an entangling gate between two coupled dual-rail qubits, the alternative process 1000 using an inverted CPHASE angle, according to some embodiments of the technology described herein. Process 1000 includes a series of drive waveforms applied to the various coupling elements within the coupled dual-rail entangling gates described herein, including: a first drive waveform (at 1001) applied to the coupling element of the first dual-rail qubit, a second drive waveform (at 1002) applied to the coupling element between the first and second dual-rail qubits, a third drive waveform (at 1004) applied to the coupling element between the first and second dual-rail qubits, and a fourth drive waveform (at 1005) applied to the coupling element of the first dual-rail qubit.

Steps 1002 and 1004 of process 1000 may be performed in the same manner as described above with respect to FIGS. 4-5B. However, process 1000 may additionally bookend the drive waveforms applied to the inter-qubit coupling element (e.g., coupling element 230) with drive waveforms applied to a coupling element of one of the dual-rail qubits (e.g., coupling element 213 or 223). In that way, the wait time between the drive waveforms applied in steps 1002 and 1004 may be shortened.

As the entangling gates may behave in a manner equivalent to a ZZ(θ) gate (up to Z rotations), by taking advantage of the gate identity $ZZ(-\theta) = X_1ZZ(\theta)X_1$, to implement a CPHASE gate with angle $\theta > \pi$, the wait time may be reduced. By applying the bookend SWAP pulses to perform the X_1, instead of having to implement the gate to achieve an angle of θ, the gate may only be implemented to achieve an angle of $\theta_{inverted} = 2\pi - \theta$. For example, to implement a CPHASE gate with angle $\theta = 1.7\pi$, instead of having to wait $t_{wait} = 1.7\pi/(\chi_a + \chi_b - \chi_{ab})$ the bookending pulses applied to the first-dual rail qubit can "invert" the CPHASE angle ($\theta = 2\pi - 1.7\pi = 0.3\pi$) so that only a wait time of $t_{wait} = 0.3\pi/(\chi_a + \chi_b - \chi_{ab})$ may be used. Thus, the maximum wait time used to implement any CPHASE gate may be at most $t_{wait} = \pi/(\chi_a + \chi_b - \chi_{ab})$, with CZ gates ($\theta = \pi$) having the maximum wait time.

FIG. 11 illustrates an example pulse sequence for implementing the process of FIG. 10, according to some embodiments of the technology described herein. Referring to FIGS. 10 and 11, at step 1001 of process 1000, a first drive waveform 1101 is applied to coupling element c_a of first dual-rail qubit 210 (or coupling element c_b of second dual-rail qubit 220). This first drive waveform 1101 may be configured to cause an exchange of states between the quantum oscillators of first dual-rail qubit 210. The SWAP operation may be implemented in the same manner as described above with respect to FIG. 4.

At steps 1002 and 1004 of process 1000, second and third drive waveforms 1102 and 1104 may be applied to coupling element c_{ab} in the same manner as described above with respect to FIG. 4. However, rather than waiting for $t_{wait} = \theta/(\chi_a + \chi_b - \chi_{ab})$, the wait time between waveforms 1102 and 1104 may be $t_{wait} = (2\pi - \theta)/(\chi_a + \chi_b - \chi_{ab})$. As described with respect to FIG. 4, $t_{wait} = (2\pi - \theta)/(\chi_a + \chi_b - \chi_{ab})$, in some embodiments, may provide an initial estimate, and the wait time may be fine-tuned within 5-15% of the initial estimate.

At step 1005, a fourth drive waveform 1105 is applied to coupling element c_a of first dual-rail qubit 210 (or coupling element c_b of second dual-rail qubit 220), in the same manner as waveform 1101. In some embodiments, the phase of the fourth drive waveform 1105 may be inverted with respect to drive waveform 1101.

FIGS. 12A-12B illustrate additional schematic representations of example processes for performing an entangling gate between two coupled dual-rail qubits, according to some embodiments.

FIG. 12A illustrates a schematic representation of a process for applying a series of drive waveforms for performing an entangling gate configured to echo out low frequency dephasing noise, according to some embodiments of the technology described herein. The pulse sequence 1200 may be used to echo out low frequency dephasing noise present on any of the four quantum oscillators of the dual-rail qubits. Taking advantage of the identity $ZZ(\theta) = X_1X_2ZZ(\theta)X_1X_2$, the low frequency dephasing noise can be echoed out without having an effect on the outcome of a circuit operation implemented using the gate. In the given pulse sequence 1200, each "half" of each dual-rail qubit spends the same amount of time in the two quantum oscillators.

The first two pulses, 1201 and 1202, may be implemented in the same manner described above with respect to FIGS. 4-5B, to implement a first half of the entangling gate. As such, the wait time between pulses 1201 and 1202 may be half of that described with respect to FIG. 4. For example, $t_{wait} = \frac{1}{2}\theta/(\chi_a + \chi_b - \chi_{ab})$. After the second SWAP operation by pulse 1202, third and fourth drive waveforms 1203 and 1204 may be applied to coupling elements c_a and c_b (e.g., of dual-rail qubits 1010 and 1020) respectively, to perform a SWAP operation between the quantum oscillators in each respective dual-rail qubit. In some embodiments, third and fourth drive waveforms may be applied simultaneously.

The next two pulses, 1205 and 1206, may be implemented in the same manner as pulses 1201 and 1202 to implement the second half of the entangling gate. The wait time may similarly be half of that described with respect to FIG. 4 such that $t_{wait} = \frac{1}{2}\theta/(\chi_a + \chi_b - \chi_{ab})$. Thus, the total wait time for both halves of the entangling gate implemented via pulses 1201, 1202, 1205, and 1206 is $t_{wait} = \theta/(\chi_a + \chi_b - \chi_{ab})$. As described with respect to FIG. 4, $t_{wait} = \frac{1}{2}\theta/(\chi_a + \chi_b - \chi_{ab})$, in some embodiments, may provide an initial estimate, and the wait time may be fine-tuned within 5-15% of the initial estimate.

After the second SWAP operation by pulse 1206, two more drive waveforms 1207 and 1208 may be applied to coupling elements c_a and c_b (e.g., of dual-rail qubits 1010 and 1020) respectively, to perform a SWAP operation between the quantum oscillators in each respective dual-rail qubit. In that way, states of each quantum oscillator in the system may be returned to their initial state.

In some embodiments, the entangling gates described herein may be used to extend other operations performed on a coupled dual-rail qubit gate, such as a dual-rail SWAP operation. The

dual-rail SWAP operation may exchange the encoded states of both coupled dual-rail qubits. For example, a first pulse may be applied to the inter-qubit coupling element (e.g., coupling element 230, c_{ab}) to swap the states of the coupled quantum oscillators. Then pulses may be applied to each intra-qubit coupling element (e.g., coupling elements 213 and 223, c_a and c_b) SWAP to exchange the states between quantum oscillators within each dual-rail qubit. Finally, and second pulse may be applied to the inter-qubit coupling element to exchange the states between the two qubits. The pulse sequence described above is depicted with respect to pulses 1221-1224 of FIG. 12B.

FIG. 12B illustrates another schematic representation of a process for applying a series of drive waveforms for performing a SWAP operation between two coupled dual-rail qubits, the SWAP operation configured to cancel accumulated CPHASE entanglement, according to some embodiments of the technology described herein. The pulse sequence 1220 may be used to remove any entanglement caused by a dual-rail logical SWAP operation. Because of the non-linear interactions between the quantum oscillator of the first dual-rail qubit coupled to the quantum oscillator of the second dual-rail qubit, a dual-rail logical SWAP operation entangles the two dual-rail qubits and introduces a small accumulation angle (typically smaller than 0.2 rad). As such, an inverted CPHASE gate (e.g. as described above with respect to FIGS. 10-11 may be implemented after the dual-rail logical SWAP to cancel the 0.2 rad accumulated angle. As such, pulses 1221-1224 implement the dual-rail logical SWAP operation as described above. Subsequently, an entangling gate may be implemented via pulses 1225-1228 using the inverted CPHASE angle pulse sequence as described above with respect to FIGS. 10-11.

FIG. 13 depicts an illustrative implementation of a computer system 1300 that may be used in connection with any of the embodiments of the technology described herein (e.g., controller 106 may be implemented as computer system 1300 or may be operatively coupled to a computer system 1300). The computer system 1300 includes one or more processors 1310 and one or more articles of manufacture that comprise non-transitory computer-readable storage media (e.g., memory 1320 and one or more non-volatile storage media 1330). The processor 1310 may control writing data to and reading data from the memory 1020 and the non-volatile storage device 1330 in any suitable manner, as the aspects of the technology described herein are not limited to any particular techniques for writing or reading data. To perform any of the functionality described herein, the processor 1310 may execute one or more processor-executable instructions stored in one or more non-transitory computer-readable storage media (e.g., the memory 1320), which may serve as non-transitory computer-readable storage media storing processor-executable instructions for execution by the processor 1310.

Computer system 1300 may also include a network input/output (I/O) interface 1340 via which the computing device may communicate with other computing devices (e.g., over a network), and may also include one or more user I/O interfaces 1350, via which the computing device may provide output to and receive input from a user. The user I/O interfaces may include devices such as a keyboard, a mouse, a microphone, a display device (e.g., a monitor or touch screen), speakers, a camera, and/or various other types of I/O devices.

The above-described embodiments can be implemented in any of numerous ways. For example, the embodiments may be implemented using hardware, software, or a combination thereof. When implemented in software, the software code can be executed on any suitable processor (e.g., a microprocessor) or collection of processors, whether provided in a single computing device or distributed among multiple computing devices. It should be appreciated that any component or collection of components that perform the functions described above can be generically considered as one or more controllers that control the above-discussed functions. The one or more controllers can be implemented in numerous ways, such as with dedicated hardware, or with general purpose hardware (e.g., one or more processors) that is programmed using microcode or software to perform the functions recited above.

In this respect, it should be appreciated that one implementation of the embodiments described herein comprises at least one computer-readable storage medium (e.g., RAM, ROM, EEPROM, flash memory or other memory technology, CD-ROM, digital versatile disks (DVD) or other optical disk storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or other tangible, non-transitory computer-readable storage medium) encoded with a computer program (i.e., a plurality of executable instructions) that, when executed on one or more processors, performs the above-discussed functions of one or more embodiments. The computer-readable medium may be transportable such that the program stored thereon can be loaded onto any computing device to implement aspects of the techniques discussed herein. In addition, it should be appreciated that the reference to a computer program which, when executed, performs any of the above-discussed functions, is not limited to an application program running on a host computer. Rather, the terms computer program and software are used herein in a generic sense to reference any type of computer code (e.g., application software, firmware, microcode, or any other form of computer instruction) that can be employed to program one or more processors to implement aspects of the techniques discussed herein.

The foregoing description of implementations provides illustration and description but is not intended to be exhaustive or to limit the implementations to the precise form disclosed. Modifications and variations are possible in light of the above teachings or may be acquired from

practice of the implementations. In other implementations the methods depicted in these figures may include fewer operations, different operations, differently ordered operations, and/or additional operations. Further, non-dependent blocks may be performed in parallel.

It will be apparent that example aspects, as described above, may be implemented in many different forms of software, firmware, and hardware in the implementations illustrated in the figures. Further, certain portions of the implementations may be implemented as a "module" that performs one or more functions. This module may include hardware, such as a processor, an application-specific integrated circuit (ASIC), or a field-programmable gate array (FPGA), or a combination of hardware and software.

Having thus described several aspects of at least one embodiment of this invention, it is to be appreciated that various alterations, modifications, and improvements will readily occur to those skilled in the art.

Such alterations, modifications, and improvements are intended to be part of this disclosure, and are intended to be within the spirit and scope of the invention. Further, though advantages of the present invention are indicated, it should be appreciated that not every embodiment of the technology described herein will include every described advantage. Some embodiments may not implement any features described as advantageous herein and in some instances one or more of the described features may be implemented to achieve further embodiments. Accordingly, the foregoing description and drawings are by way of example only.

All definitions, as defined and used herein, should be understood to control over dictionary definitions, definitions in documents incorporated by reference, and/or ordinary meanings of the defined terms.

The indefinite articles "a" and "an," as used herein in the specification and in the claims, unless clearly indicated to the contrary, should be understood to mean "at least one."

The use of "coupled" or "connected" is meant to refer to elements, or signals, that are either directly linked to one another or are linked through intermediate components. Elements that are not "coupled" or "connected" are "decoupled" or "disconnected."

The use of "between" in a coupled signal chain is not meant to require a particular direction of signal flow in the signal chain unless stated otherwise. For instance, where element B is described as coupled between elements A and C in a signal chain, signals may flow from element A to element C through element B and/or from element C to element A through element B unless stated otherwise.

The phrase "and/or," as used herein in the specification and in the claims, should be understood to mean "either or both" of the elements so conjoined, i.e., elements that are

conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with "and/or" should be construed in the same fashion, i.e., "one or more" of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the "and/or" clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to "A and/or B," when used in conjunction with open-ended language such as "comprising" can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

As used herein in the specification and in the claims, the phrase "at least one," in reference to a list of one or more elements, should be understood to mean at least one element selected from any one or more of the elements in the list of elements, but not necessarily including at least one of each and every element specifically listed within the list of elements and not excluding any combinations of elements in the list of elements. This definition also allows that elements may optionally be present other than the elements specifically identified within the list of elements to which the phrase "at least one" refers, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, "at least one of A and B" (or, equivalently, "at least one of A or B," or, equivalently "at least one of A and/or B") can refer, in one embodiment, to at least one, optionally including more than one, A, with no B present (and optionally including elements other than B); in another embodiment, to at least one, optionally including more than one, B, with no A present (and optionally including elements other than A); in yet another embodiment, to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other elements); etc.

In the claims, as well as in the specification above, all transitional phrases such as "comprising," "including," "carrying," "having," "containing," "involving," "holding," "composed of," and the like are to be understood to be open-ended, i.e., to mean including but not limited to. Only the transitional phrases "consisting of" and "consisting essentially of" shall be closed or semi-closed transitional phrases, respectively.

The use of "coupled" or "connected" is meant to refer to circuit elements, or signals, which are either directly linked to one another or through intermediate components. Elements that are not "coupled" or "connected" are "decoupled" or "disconnected."

The terms "approximately" and "about" may be used to mean within ±20% of a target value in some embodiments, within ±10% of a target value in some embodiments, within ±5% of

a target value in some embodiments, within ±2% of a target value in some embodiments. The terms "approximately" and "about" may include the target value.

Use of ordinal terms such as "first," "second," "third," etc., in the claims to modify a claim element does not by itself connote any priority, precedence, or order of one claim element over another or the temporal order in which acts of a process are performed, but are used merely as labels to distinguish one claim element having a certain name from another element having a same name (but for use of the ordinal term) to distinguish the claim elements.

What is claimed is:

CLAIMS

1. A quantum information processing system, comprising:

a first dual-rail qubit device;

a second dual-rail qubit device;

a first coupling element coupled between the first dual-rail qubit device and the second dual-rail qubit device;

at least one energy source; and

at least one controller configured to operate the at least one energy source to perform an entangling gate between the first dual-rail qubit device and the second dual-rail qubit device by:

causing, by applying a first drive waveform to the first coupling element, a first exchange of a state of a quantum oscillator of the first dual-rail qubit device with a state of a quantum oscillator of the second dual-rail qubit device; and

after waiting a pre-determined period of time after causing the first exchange, causing, by applying a second drive waveform to the first coupling element, a second exchange of a state of the quantum oscillator of the first dual-rail qubit device with a state of the quantum oscillator of the second dual-rail qubit device.

2. The quantum information processing system of claim 1, wherein:

the first dual-rail qubit device and the second dual-rail qubit device each comprise a first quantum oscillator, a second quantum oscillator, and a second coupling element coupling the first quantum oscillator to the second quantum oscillator; and

the first coupling element is coupled between the first quantum oscillators of the first and second dual-rail qubit devices.

3. The quantum information processing system of claim 2, wherein the first coupling element is dispersively coupled between the first quantum oscillators of the first and second dual-rail qubit devices.

4. The quantum information processing system of any one of claims 1-3, wherein the first coupling element comprises a flux-driven SQUID coupler.

5. The quantum information processing system of any one of claims 1-3, wherein the first coupling element is a transmon qubit device or a superconducting asymmetric inductive element (SNAIL).

6. The quantum information processing system of any one of claims 1-3, further comprising:

a first ancilla qubit device coupled to the first dual-rail qubit device; and

a second ancilla qubit device coupled to the second dual-rail qubit device.

7. The quantum information processing system of claim 6, wherein:

the first ancilla qubit device is coupled to the second quantum oscillator of the first dual-rail qubit device, and

the second ancilla qubit device is coupled to the first quantum oscillator of the second dual-rail qubit device.

8. The quantum information processing system of any one of claims 6, wherein the first ancilla qubit device and/or the second ancilla qubit device is a transmon qubit device.

9. The quantum information processing system of any one of claims 2-3, wherein the first and second quantum oscillators comprise microwave cavities.

10. The quantum information processing system of any one of claims 1-3, wherein the at least one controller is configured to apply the first drive waveform and/or the second drive waveform to the first coupling element for a time, $t = \pi/g_{BS}$.

11. The quantum information processing system of any one of claims 1-3, wherein the at least one controller is configured to apply the second drive waveform after a pre-determined period of time having a length of approximately $t = \frac{-\theta}{|\chi_a+\chi_b-\chi_{a_2b_1}|}$.

12. The quantum information processing system of any one of claims 2-3, wherein the at least one controller is further configured to apply a pulse sequence comprising applying drive waveforms to respective coupling elements to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, the pulse sequence comprising:

the first drive waveform applied to the first coupling element;

the second drive waveform applied to the first coupling element;

a third drive waveform applied to the second coupling element of the first dual-rail qubit device, the third drive waveform being applied before the first drive waveform; and

a fourth drive waveform applied to the second coupling element of the first dual-rail qubit device, the fourth drive waveform being applied after the second drive waveform.

13. The quantum information processing system of any one of claims 2-3, wherein the at least one controller is further configured to apply a pulse sequence comprising applying drive waveforms to respective coupling elements to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, the pulse sequence comprising:

the first drive waveform applied to the first coupling element;

the second drive waveform applied to the first coupling element;

a third drive waveform applied to the second coupling element of the first dual-rail qubit device;

a fourth drive waveform applied to the second coupling element of the second dual-rail qubit device;

a fifth drive waveform applied to the first coupling element; and

after a second pre-determined period of time after the fifth drive waveform, a sixth drive waveform applied to the first coupling element.

14. The quantum information processing system of claim 13, wherein the pulse sequence further comprises:

a seventh drive waveform applied to the second coupling element of the first dual-rail qubit device; and

an eighth drive waveform applied to the second coupling element of the second dual-rail qubit device.

15. The quantum information processing system of any one of claims 2-3, wherein the at least one controller is further configured to apply a pulse sequence comprising applying drive waveforms to respective coupling elements to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, the pulse sequence comprising:

the first drive waveform applied to the first coupling element;

the second drive waveform applied to the first coupling element;

a third drive waveform applied to the second coupling element of the first dual-rail qubit device; and

a fourth drive waveform applied to the second coupling element of the second dual-rail qubit device, the third and fourth drive waveforms being applied between the first and second drive waveforms.

16. The quantum information processing system of claim 15, wherein the pulse sequence further comprises:

a fifth drive waveform applied to the second coupling element of the first dual-rail qubit device;

a sixth drive waveform applied to the first coupling element;

after a second pre-determined period of time after the sixth drive waveform, a seventh drive waveform applied to the first coupling element; and

an eighth drive waveform applied to the second coupling element of the first dual-rail qubit device.

17. The quantum information processing system of any one of claims 2-3, wherein:

the first coupling element comprises:

a third quantum oscillator, a fourth quantum oscillator, and a third coupling element coupled between the first and second quantum oscillators;

a fourth coupling element coupled between the first quantum oscillator of the first dual-rail qubit device and the third quantum oscillator; and

a fifth coupling element coupled between the first quantum oscillator of the second dual-rail qubit device and the fourth quantum oscillator;

applying the first drive waveform to the first coupling element comprises applying the first drive waveform to the fourth and fifth coupling element; and

applying the second drive waveform to the first coupling element comprises applying the second drive waveform to the fourth and fifth coupling elements.

18. A method for performing an entangling gate between a first dual-rail qubit device and a second dual-rail qubit device coupled via a first coupling element, the first dual-rail qubit device and the second dual-rail qubit device each comprise a first quantum oscillator, a second quantum oscillator, and a second coupling element coupling the first quantum oscillator to the second

quantum oscillator, and the first coupling element is coupled between the first quantum oscillators of the first and second dual-rail qubit devices, the method comprising:

applying a first drive waveform to a first coupling element to cause a first exchange of state of the first quantum oscillator of the first dual-rail qubit device with a state of the first quantum oscillator of the second dual-rail qubit device; and

after waiting a pre-determined period of time after causing the first exchange, applying a second drive waveform to the first coupling element to cause a second exchange of a state of the first quantum oscillator of the first dual-rail qubit device with a state of the first quantum oscillator of the second dual-rail qubit device.

19. The method of claim 18, wherein applying the first drive waveform and/or second drive waveform comprises applying the first drive waveform and/or second drive waveform for a time, $t = \pi/g_{BS}$.

20. The method of any one of claims 18-19, wherein applying the second drive waveform comprises applying the second drive waveform after the pre-determined period of time having a length of approximately $t = \frac{-\theta}{|\chi_a + \chi_b - \chi_{a_2 b_1}|}$.

21. The method of any one of claims 18-19, further comprising applying a pulse sequence comprising drive waveforms configured to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, applying the pulse sequence comprising:

applying a third drive waveform to the second coupling element of the first dual-rail qubit device, the third drive waveform being applied before the first drive waveform; and

applying a fourth drive waveform to the second coupling element of the first dual-rail qubit device, the fourth drive waveform being applied after the second drive waveform.

22. The method of any one of claims 18-19, further comprising applying a pulse sequence comprising drive waveforms configured to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, applying the pulse sequence comprising:

applying a third drive waveform to the second coupling element of the first dual-rail qubit device;

applying a fourth drive waveform to the second coupling element of the second dual-rail qubit device;

applying a fifth drive waveform to the fifth drive waveform to the first coupling element; and

after a second pre-determined period of time after applying the fifth drive waveform, applying a sixth drive waveform to the first coupling element.

23. The method of claim 22, applying the pulse sequence further comprising:

applying a seventh drive waveform to the second coupling element of the first dual-rail qubit device; and

applying an eighth drive waveform to the second coupling element of the second dual-rail qubit device.

24. The method of any one of claims 18-19, further comprising applying a pulse sequence comprising drive waveforms configured to cause an exchange of state between the quantum oscillators coupled by the respective coupling element, applying the pulse sequence comprising:

applying a third drive waveform to the second coupling element of the first dual-rail qubit device;

applying a fourth drive waveform to the second coupling element of the second dual-rail qubit device, the third and fourth drive waveforms being applied between the first and second drive waveforms.

25. The method of claim 24, wherein applying the pulse sequence further comprising:

after applying the second drive waveform:

applying a fifth drive waveform to the second coupling element of the first dual-rail qubit device;

applying a sixth drive waveform to the first coupling element;

after waiting a second pre-determined period of time after the sixth drive waveform, applying a seventh drive waveform to the first coupling element; and

applying an eighth drive waveform to the second coupling element of the first dual-rail qubit device.

26. The method of any one of claims 18-19, wherein the first coupling element comprises:

a third quantum oscillator, a fourth quantum oscillator, and a third coupling element coupled between the first and second quantum oscillators;

a fourth coupling element coupled between the first quantum oscillator of the first dual-rail qubit device and the third quantum oscillator; and

a fifth coupling element coupled between the first quantum oscillator of the second dual-rail qubit device and the fourth quantum oscillator; and

the method further comprises:

applying the first drive waveform to the first coupling element comprises applying the first drive waveform to the fourth and fifth coupling elements; and

applying the second drive waveform to the second coupling elements comprises applying the second drive waveform to the fourth and fifth coupling elements.