

SELECTIVE FREQUENCY SHIFTING OF QUBITS

TECHNICAL FIELD

[0001] The present disclosure relates to a quantum
5 electronic device, and more particularly to a quantum
computing system and an arrangement for selectively
shifting qubit resonance frequencies.

BACKGROUND

10 [0002] The ability to selectively shift resonance fre-
quencies of qubits in a quantum computing system is
desirable for large scale quantum computing. By shifting
the resonance frequency of a qubit, the qubit can be
brought into resonance with another qubit in the system.
15 The ability to bring to resonance may be important for
performing quantum logic gate operations using the
qubits.

SUMMARY

20 [0003] This summary is provided to introduce a selec-
tion of concepts in a simplified form that are further
described below in the detailed description. This sum-
mary is not intended to identify key features or essen-
tial features of the claimed subject matter, nor is it
25 intended to be used to limit the scope of the claimed
subject matter.

[0004] It is an objective to provide a quantum compu-
ting system and an arrangement for selectively shifting

qubit resonance frequencies. The foregoing and other objectives are achieved by the features of the independent claims. Further implementation forms are apparent from the dependent claims, the description and the
5 figures.

[0005] According to a first aspect, an arrangement for selectively shifting qubit resonance frequencies comprises a plurality of qubits comprising at least a first qubit and a second qubit, each of the first qubit and
10 the second qubit having a respective resonance frequency; a first coupling control resonator and a second coupling control resonator each having a respective resonance frequency band; and a coupling control signal line for feeding a coupling control signal to at least
15 the first coupling control resonator and the second coupling control resonator; wherein the first coupling control resonator is configured to shift the resonance frequency of the first qubit when the coupling control signal comprises a frequency component in the resonance
20 frequency band of the first coupling control resonator and the second coupling control resonator is configured to shift the resonance frequency of the second qubit when the coupling control signal comprises a frequency component in the resonance frequency band of the second
25 coupling control resonator. The arrangement may be able to, for example, selectively shift the resonance frequency of the first qubit and/or of the second qubit.

[0006] In an implementation form of the first aspect, the plurality of qubits further comprises a third qubit

and a fourth qubit, each of the third and the fourth qubit having a respective resonance frequency, wherein the first qubit is capacitively coupled to the third qubit and the second qubit is capacitively coupled to
5 the fourth qubit. The arrangement may be able to, for example, selectively bring the first qubit into resonance with the third qubit and/or selectively bring the second qubit into resonance with the fourth qubit.

[0007] In a further implementation form of the first
10 aspect, each qubit in the plurality of qubits comprises at least one Josephson junction. The arrangement may be implemented using, for example, superconductive qubits.

[0008] In a further implementation form of the first
15 aspect, each qubit in the plurality of qubits comprises a superconducting quantum interference device (SQUID).

[0009] In a further implementation form of the first
aspect, the resonance frequency band of the coupling control resonator is located in a frequency range less than the resonance frequency of the first qubit and the
20 resonance frequency of the second qubit. The arrangement may be able to, for example, shift the resonance frequencies of the qubits while the coupling control signal may not significantly interfere with the operation of the qubits.

[0010] In a further implementation form of the first
25 aspect, the shift of the resonance frequency of the first qubit is proportional to an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator and/or the shift of the

resonance frequency of the second qubit is proportional to an amplitude of the frequency component in the resonance frequency band of the second coupling control resonator. Thus, the resonance frequency of the first
5 qubit and/or of the second qubit may be controlled using the amplitude of the corresponding frequency component.

[0011] In a further implementation form of the first aspect, the first qubit and the second qubit are capacitively coupled to each other and, when the first qubit
10 and the second qubit are set in resonance, quantum gate operations are performed on the first qubit and the second qubit. Thus, the first qubit and the second qubit may be brought into resonance with each other to be used for quantum computing.

[0012] In a further implementation form of the first aspect, the first coupling control resonator is configured to shift the resonance frequency of the first qubit by tuning a Josephson inductance of the first qubit. The arrangement may be able to, for example, efficiently
20 shift the resonance frequency of the first qubit.

[0013] In a further implementation form of the first aspect, the first coupling control resonator is configured to shift the resonance frequency of the first qubit by tuning a Josephson inductance of the first qubit by
25 inducing a magnetic flux through the first qubit or by causing a current flow through the first qubit. The arrangement may be able to, for example, tune the Jo-

sephson inductance via a magnetic coupling or via electrical coupling between the coupling control resonator and the qubit.

[0014] In a further implementation form of the first aspect, the arrangement further comprises: a plurality of coupling control signal lines including the coupling signal line; and a plurality of coupling control resonators, including the first coupling control resonator and the second coupling control resonator; wherein the plurality of qubits is arranged into a matrix, each qubit in the plurality of qubits having a respective resonance frequency, each coupling control signal line in the plurality of coupling control signal lines corresponding to a column/row of the matrix; wherein each coupling control resonator in the plurality of coupling control resonators is configured to shift the resonance frequency of a corresponding qubit in the plurality of qubits when a coupling control signal in a corresponding coupling control signal line comprises a frequency component in the resonance frequency band of that coupling control resonator. The arrangement may be able to, for example, shift the resonance frequency of a selected qubit in the plurality of qubits.

[0015] It is to be understood that the implementation forms of the first aspect described above may be used in combination with each other. Several of the implementation forms may be combined together to form a further implementation form.

[0016] According to a second aspect, a quantum computing system comprises: the arrangement according to the first aspect; and a control unit electrically coupled to the coupling control signal line of the arrangement, wherein the control unit is configured: set an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator according to a frequency difference between the resonance frequency of the first qubit and a resonance frequency of another qubit in the plurality of qubits; and transmit the coupling control signal to the coupling control signal line. The control unit may be able to, for example, bring the first qubit into resonance with the another qubit.

[0017] In an implementation form of the second aspect, the control unit is further configured to set a temporal duration of a pulse comprising the frequency component in the resonance frequency band of the first coupling control resonator according to a pre-configured coupling parameter, wherein the preconfigured coupling parameter indicates an intended coupling strength between the first qubit and the another qubit. The control unit may be able to, for example, control the coupling between the qubits according to the preconfigured coupling parameter.

[0018] In a further implementation form of the second aspect, the control unit is further configured to frequency-division multiplex the frequency component in the resonance frequency band of the first coupling control

resonator and the frequency component in the resonance frequency band of the second coupling control resonator into the coupling control signal. The control unit may be able to, for example, shift the resonance frequency
5 of the first qubit and of the second qubit with reduced delay or substantially simultaneously.

[0019] It is to be understood that the implementation forms of the second aspect described above may be used in combination with each other. Several of the imple-
10 mentation forms may be combined together to form a further implementation form.

[0020] According to third aspect, a method for selectively shifting qubit resonance frequencies in a quantum computing system comprising the arrangement according
15 to the first aspect is provided. The method comprises: setting an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator according to a frequency difference between the resonance frequency of the first qubit and a reso-
20 nance frequency of another qubit in the plurality of qubits; and transmitting the coupling control signal to the coupling control signal line.

[0021] According to a fourth aspect, a computer program product is provided, comprising program code con-
25 figured to perform a method according to the third aspect when the computer program is executed on a computing device.

[0022] Many of the attendant features will be more readily appreciated as they become better understood by

reference to the following detailed description considered in connection with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

- 5 **[0023]** In the following, example embodiments are described in more detail with reference to the attached figures and drawings, in which:
- [0024]** Fig. 1 illustrates a schematic representation of an arrangement for selectively shifting qubit resonance frequencies according to an embodiment;
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- [0025]** Fig. 2 illustrates a schematic representation of an arrangement for selectively shifting qubit resonance frequencies according to another embodiment;
- [0026]** Fig. 3 illustrates a schematic representation of simulation results according to an embodiment;
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- [0027]** Fig. 4 illustrates a schematic representation of an arrangement for selectively shifting qubit resonance frequencies according to a further embodiment;
- [0028]** Fig. 5 illustrates a plot representation of qubit resonance frequency as a function of magnetic flux according to an embodiment;
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- [0029]** Fig. 6 illustrates a schematic representation of an arrangement for selectively shifting qubit resonance frequencies according to a further embodiment;
- 25 **[0030]** Fig. 7 illustrates a schematic representation of an arrangement for selectively shifting qubit resonance frequencies according to a further embodiment;

[0031] Fig. 8 illustrates a schematic representation of a quantum computing system according to an embodiment;

5 [0032] Fig. 9 illustrates a schematic representation of a control unit according to an embodiment; and

[0033] Fig. 10 illustrates a flow chart representation of a method according to an embodiment.

[0034] In the following, like reference numerals are used to designate like parts in the accompanying drawings.
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DETAILED DESCRIPTION

[0035] In the following description, reference is made to the accompanying drawings, which form part of the disclosure, and in which are shown, by way of illustration, specific aspects in which the present disclosure may be placed. It is understood that other aspects may be utilised, and structural or logical changes may be made without departing from the scope of the present disclosure. The following detailed description, therefore, is not to be taken in a limiting sense, as the scope of the present disclosure is defined by the appended claims.
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[0036] For instance, it is understood that a disclosure in connection with a described method may also hold true for a corresponding device or system configured to perform the method and vice versa. For example, if a specific method step is described, a corresponding device may include a unit to perform the described method
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step, even if such unit is not explicitly described or illustrated in the figures. On the other hand, for example, if a specific apparatus is described based on functional units, a corresponding method may include a step performing the described functionality, even if such step is not explicitly described or illustrated in the figures. Further, it is understood that the features of the various example aspects described herein may be combined with each other, unless specifically noted otherwise.

[0037] Fig. 1 illustrates a schematic representation of an arrangement 100 for selectively shifting qubit resonance frequencies according to an embodiment.

[0038] According to an embodiment, an arrangement 100 for selectively shifting qubit resonance frequencies comprises a plurality of qubits comprising at least a first qubit 101_1 and a second qubit 101_2, each of the first qubit 101_1 and the second qubit 101_2 having a respective resonance frequency.

[0039] The resonance frequency of the first qubit 101_1 may be not equal to the resonance frequency of the second qubit 101_2.

[0040] The resonance frequency of each qubit in the plurality of qubits may be in the range 1 - 100 gigahertz (GHz) or in any subrange of this, such as 4 - 12 GHz, 4 - 10 GHz, or 4 - 8 GHz.

[0041] The frequency difference between the resonance frequency of the first qubit 101_1 and of the second

qubit 101_1 may be, for example, greater than 10 megahertz (MHz) and/or less than 1 GHz. For example, the frequency difference may be in the range 10 - 300 MHz.

[0042] The arrangement 100 may further comprise a
 5 first coupling control resonator 102_1 and a second coupling control resonator 102_2 each having a respective resonance frequency band.

[0043] The resonance frequency band of a coupling control resonator 102 may refer to a frequency band comprising frequencies that cause the coupling control resonator 102 to resonate. The resonance frequency band may be determined by the physical and/or electrical properties of the coupling control resonator 102.
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[0044] For example, in the embodiment of Fig. 1, the
 15 coupling control resonators 102 are implemented using LC resonators each comprising a capacitor and an inductor. Thus, in the idealised case, the resonance frequency f_0 of such a resonator is

$$f_0 = \frac{1}{2\pi\sqrt{LC}},$$

20 where L is the inductance of the inductor and C is the capacitance of the capacitor. However, due to imperfections, such as losses, an LC resonator may not resonate only at a single resonance frequency but in a resonance frequency band. Thus, a coupling control resonator 102
 25 may function as a bandpass filter.

[0045] The width of the resonance frequency band of a coupling control resonator 102 may be defined, using,

for example, full width at half maximum (FWHM) bandwidth of the coupling control resonator 102.

[0046] The resonance frequency band of a coupling control resonator may be, for example, in the range 1 - 10
5 GHz, or in any subrange of this, such as 1 - 8 GHz, 2 - 7 GHz, or 1 - 5 GHz.

[0047] A coupling control resonator 102 may also be referred to as a bandpass filter, a coupling bandpass filter, or similar.

10 [0048] Although some examples of coupling control resonators, such as LC resonators, 102 are disclosed in the embodiments herein, a coupling control resonator 102 may also be implemented in various other ways and using various other components. In any embodiment disclosed
15 herein, a coupling control resonator 102 may be implemented using, for example, any type of bandpass filter. For example, a coupling control resonator 102 may be implemented using a more complex geometry corresponding to a higher order bandpass filter. Such a higher order
20 bandpass filter may approximate a rectangular frequency response of an ideal bandpass filter.

[0049] According to an embodiment, the resonance frequency band of the first coupling control resonator 102_1 and the resonance frequency band of the second
25 coupling control resonator 102_2 do not overlap or overlap only partially.

[0050] The arrangement 100 may further comprise coupling control signal line 103 for feeding a coupling control signal to at least the first coupling control

resonator 102_1 and the second coupling control resonator 102_2.

[0051] The coupling control signal line 103 may also be referred to as a gate bus or similar. The coupling control signal line 103 may be implemented, for example, as a trace on a printed circuit board (PCB), as a cable, as a transmission line, as a waveguide, or similar.

[0052] The first coupling control resonator 102_1 and/or the second coupling control resonator 102_2 may be electrically coupled to the coupling control signal line 103.

[0053] The first coupling control resonator 102_1 is configured to shift the resonance frequency of the first qubit 101_1 when the coupling control signal comprises a frequency component in the resonance frequency band of the first coupling control resonator 102_1 and the second coupling control resonator 102_2 is configured to shift the resonance frequency of the second qubit 101_2 when the coupling control signal comprises a frequency component in the resonance frequency band of the second coupling control resonator 102_2.

[0054] The first coupling control resonator 102_1 may be configured to shift the resonance frequency of the first qubit 101_1 in response to the coupling control signal comprising a frequency component in the resonance frequency band of the first coupling control resonator 102_1.

[0055] The second coupling control resonator 102_2 may be configured to shift the resonance frequency of the

second qubit 101_2 in response to the coupling control signal comprising a frequency component in the resonance frequency band of the second coupling control resonator 102_2.

5 **[0056]** The coupling control signal may comprise, for example, an alternating current (AC) signal, such as a radio frequency (RF) signal or a microwave signal.

10 **[0057]** A coupling control resonator 102 may shift the resonance frequency of a corresponding qubit 101 by tuning the Josephson inductance of the qubit 101. A coupling control resonator may, for example, utilise the nonlinearity of the qubit 101 and AC magnetic flux pulses to tune the Josephson inductance of the qubit 101. For example, in the embodiment of Fig. 1, the mag-
15 netic flux generated by each coupling control resonator 102 may couple with the corresponding qubit 101. The magnetic flux can then shift the resonance frequency of the qubit 101 when the coupling control signal comprises a frequency component in the resonance frequency band
20 of the coupling control resonator.

25 **[0058]** The frequency component in the resonance frequency band of a coupling control resonator 102_1, 102_2 results in an AC magnetic flux through the corresponding qubit 101_1, 101_2. The AC magnetic flux on average results in a lower effective critical current for the qubit 101_1, 101_2, thus increasing the effective Josephson inductance ($L_J \sim 1/I_C$, where I_C is critical current that is proportional to the flux according to the

Josephson effect) and thus lowering the effective resonance frequency of the qubit 101_1, 101_2.

[0059] The shifting may bring two qubits 101 initially at different frequencies to resonance via, for example, capacitively coupling between the qubits. When the two qubits 101 are in resonance, quantum logic gate operations may be performed on the qubits. The qubits in resonance may become entangled. Entanglement between qubits 101 may be required in order to implementing various quantum logic gate operations using the qubits 101.

[0060] Since each coupling control resonator 102 can have a different resonance frequency band, one can frequency-division multiplex multiple frequency components into the coupling control signal. The coupling control resonators 102 may demultiplex the frequency components from the coupling control signal. Thus, each frequency component can be used to shift the resonance frequency of a single qubit. This way, multiple qubits can be addressed substantially simultaneously using a single coupling control signal line 103. This can simplify chip designs and eliminate direct current (DC) as a source of drift.

[0061] A frequency component in the resonance frequency band of a coupling control resonator 102 may result in shifting of the qubit resonance frequency of a corresponding qubit 101. The frequency shift may be proportional to an amplitude of the frequency component. The qubit 101 may remain insensitive to the frequency

components outside the resonance frequency band of the corresponding coupling control resonator 102.

[0062] Parameters of the qubits may be determined during calibration. Amplitude of the frequency component
5 in the resonance frequency band of the coupling control resonator can be configured according to the parameters, since the shift in the resonance frequency of the corresponding qubit is proportional to the amplitude. The value of the coupling capacitance can also be determined
10 during the calibration stage. The coupling capacitance relates to the rate at which the qubits exchange energy when on resonance, thus determining duration of the coupling control pulse in order for the qubits to exchange the desired amount of energy.

15 **[0063]** A coupling control resonator 102 may lower or raise the resonance frequency of a corresponding qubit 101. Depending on the implementation of the coupling control resonator 102 and/or of the qubit 101, only raising or lowering of the resonance frequency of the
20 qubit 101 may be possible/practical.

[0064] In some embodiments, two qubits 101 may be brought into resonance by lowering the resonance frequency of one qubit and raising the resonance frequency of another qubit.

25 **[0065]** According to an embodiment, the shift of the resonance frequency of the first qubit is proportional to an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator and/or the shift of the resonance frequency of

the second qubit is proportional to an amplitude of the frequency component in the resonance frequency band of the second coupling control resonator.

[0066] The frequency shifting may make it possible to, for example, bring the first/second qubit into resonance with another qubit in the arrangement 100. The first/second qubit and the another qubit may be capacitively coupled. The another qubit may comprise, for example, a nearest neighbour qubit of the first/second qubit. The frequency components can also be so far below the qubit resonance frequencies that the coupling control signal does not interfere with the operation of the qubits 101.

[0067] According to an embodiment, the resonance frequency band of the coupling control resonator is located in a frequency range less than the resonance frequency of the first qubit and the resonance frequency of the second qubit. This may reduce interference between the coupling control signal and the qubits in the plurality of qubits as described above.

[0068] According to an embodiment, each qubit 101 in the plurality of qubits comprises at least one Josephson junction 104.

[0069] For example, in the embodiment of Fig. 1, each qubit 101 comprises two Josephson junctions 104. In other embodiments, each qubit in the plurality of qubits may comprise any number of Josephson junctions 104 depending on the type of qubit.

[0070] According to an embodiment, each qubit 101 in the plurality of qubits comprises a superconductive qubit.

5 [0071] According to an embodiment, each qubit 101 in the plurality of qubits comprises a superconducting quantum interference device (SQUID). A SQUID may comprise two Josephson junctions connected in a loop. Such a loop may also be referred to as a SQUID loop.

10 [0072] Although some embodiments may be disclosed herein with reference to a certain type of qubit, these qubit types are only exemplarily. In any embodiment disclosed herein, the qubits may be implemented in various ways and using various technologies.

15 [0073] The plurality of qubits may comprise, for example, flux qubits, phase qubits, and/or transmons. Different types of qubits can be made to possess the Josephson inductance tuning functionality with simple circuit modifications.

20 [0074] In some embodiments, the shifting of the qubit resonance frequency may be achieved using an AC, such as RF or microwave, current through a SQUID or a Josephson junction. A similar functionality follows from the fact that in a SQUID or in a Josephson junction the Josephson inductance can be also controlled by current
25 in a qualitatively similar manner as by magnetic flux.

[0075] According to an embodiment, the first coupling control resonator 102_1 is configured to shift the resonance frequency of the first qubit 101_1 by tuning a

Josephson inductance of the first qubit 101_1. Additionally or alternatively, the second coupling control resonator 102_2 may be configured to shift the resonance frequency of the second qubit 101_2 by tuning a Josephson inductance of the second qubit 101_2.

[0076] According to an embodiment, the first coupling control resonator 102_1 is configured to shift the resonance frequency of the first qubit 101_1 by tuning a Josephson inductance of the first qubit 101_1 by inducing a magnetic flux through the first qubit 101_1 or by causing a current flow through the first qubit 101_1. Additionally or alternatively, the second coupling control resonator 102_2 may be configured to shift the resonance frequency of the second qubit 101_2 by tuning a Josephson inductance of the second qubit 101_2 by inducing a magnetic flux through the second qubit 101_2 or by causing a current flow through the second qubit 101_2.

[0077] Fig. 2 illustrates a schematic representation of an arrangement 100 for selectively shifting qubit resonance frequencies according to a further embodiment.

[0078] In the embodiment of Fig. 2, the plurality of qubits further comprises a third qubit 101_3 in addition to the first qubit 101_1 and the second qubit 101_2.

[0079] According to an embodiment, the first qubit 101_1 and the second qubit 101_2 are capacitively coupled to each other. For example, in the embodiment of Fig. 2, the first qubit 101_1 and the second qubit 101_2 are capacitively coupled to each other via a capacitor.

[0080] The first qubit 101_1 and/or the second qubit 101_2 may be capacitively coupled to any other qubits in the plurality of qubits. In the embodiment of Fig. 2, for example, the second qubit 101_2 is capacitively
5 coupled to the first qubits 101_1 and to the third qubit 101_3.

[0081] In the embodiment of Fig. 2, the resonance frequencies of the first 101_1, second 101_2, and third qubit 101_3 are 6.8 GHz, 6.7 GHz, and 6.6 GHz, respectively. Further, the resonance frequency band of the first coupling control resonator 102_1 comprises the frequency 1.6 GHz and the resonance frequency band of the second coupling control resonator 102_2 comprises the frequency 1.8 GHz. Thus, a coupling control signal
15 comprising a frequency component at 1.6 GHz may shift the resonance frequency of the first qubit 102_1, since the 1.6 GHz component is demultiplexed by the first resonator 102_1 which in turn tunes the Josephson inductance of the first qubit 101_1. Similarly, a coupling
20 control signal comprising a frequency component at 1.8 GHz may shift the resonance frequency of the second qubit 102_2.

[0082] The arrangement 100 may further comprise a third coupling control resonator 102_3 for shifting the
25 resonance frequency of the third qubit 101_3.

[0083] Fig. 3 illustrates a plot representation of simulation results for the arrangement illustrated in the embodiment of Fig. 2.

[0084] The embodiment of Fig. 3 illustrates simulated envelopes 201_1, 201_2, 201_3 of voltages across each qubit 101_1, 101_2, 101_3, respectively. The embodiment of Fig. 3 further illustrates a coupling control signal
5 202 comprising two pulses 203_1, 203_2.

[0085] The embodiment of Fig. 3 illustrates only a principle of operation and the parameters used for the simulation have not been optimized. Moreover, no DC is present in any of the waveforms. Rather, the waveforms
10 have been shifted for clarity of visualization. The coupling control signal 202 has been scaled down to fit the figure.

[0086] At the start of the simulation, the first qubit 101_1 is in an excited state and both the second qubit
15 101_2 and the third qubit 101_3 are initially in ground states. This can be observed in the voltages over the qubits, 201_1, 201_2, 201_3.

[0087] The first qubit 101_1 is brought to resonance with the second qubit 101_2 by a 30 nanosecond (ns) AC
20 signal pulse 203_1 at frequency 1.6 GHz at a time instant $t = 65$ ns. Since the resonance frequency band of the first coupling control resonator 102_1 comprises the frequency 1.6 GHz of the pulse 203_1, the first coupling control resonator 102_1 shifts the resonance frequency
25 of the first qubit 101_1 down to substantially match the resonance frequency of the second qubit 101_2.

[0088] Thus, the coupling control signal 202 from the coupling control signal line 103 is demultiplexed and routed to the first qubit 101_1, i.e. the target qubit,

via the first coupling control resonator 102_1. The first qubit 101_1 and the second qubit 101_2 exchange energy through a capacitive coupling while in resonance. Thus, energy is transferred from the first qubit 101_1
5 to the second qubit 101_2, which can be observed from the voltages over the qubits, 201_1, 201_2.

[0089] At time instant $t = 315$ ns, a second coupling control signal pulse 203_2 at frequency 1.8 GHz brings the second qubit 101_2 into resonance with the third
10 qubit 101_3. Thus, energy is transferred from the second qubit 101_2 to the third qubit 101_3 in a similar fashion as described above for the first 101_1 and second qubit 101_2.

[0090] As can be observed from the semiclassical analysis of Fig. 3, a coupling control resonator 102 can
15 tune the Josephson inductance of a corresponding qubit 101 by an external drive at a frequency different from the qubit 101 resonance frequency. This has the effect of shifting the resonance frequency of the qubit 101. The coupling control resonators 102 can demultiplex the
20 different frequency components from the coupling control signal 202 so that the resonance frequency of an appropriate qubit 101 is shifted. A differing circuit schemes may also carry out the same functionality.

[0091] In the embodiment of Fig. 3, the frequency components in the coupling control signal 202 are at lower
25 frequencies compared to the resonance frequencies of the qubits 101. In other embodiments, the frequencies of the frequency components may be higher than the resonance

frequencies of the qubits 101. In such cases, the coupling control signal can cause time-varying frequency control, i.e. the resonance frequency of the corresponding qubit may vary in time. After time averaging, this
5 can lead to, for example, transfer of energy between the two qubits.

[0092] There may be some qualitative differences, however, in how the inductances of the qubits 101 are tuned using high frequency coupling control signals compared
10 to low frequency coupling control signals.

[0093] For high frequency coupling control signal, the Josephson inductance during the tuning may be essentially constant during the coupling control signal pulse whereas, for the lower frequency coupling control signal,
15 the Josephson inductance (and thus the coupling) varies in time.

[0094] Fig. 4 illustrates a schematic representation of an arrangement for selectively shifting qubit resonance frequencies according to a further embodiment.

20 **[0095]** According to an embodiment, the plurality of qubits further comprises a third qubit 101_3 and a fourth qubit 101_4, each of the third and the fourth qubit having a respective resonance frequency.

[0096] The first qubit 101_1 may be capacitively coupled to the third qubit 101_3 and the second qubit 101_2
25 may be capacitively coupled to the fourth qubit 101_4.

[0097] Using the coupling control signal in the coupling control signal line 103, the first qubit 101_1 may be brought into resonance with the third qubit 101_3 by

shifting the resonance frequency of the first qubit 101_1 as disclosed herein.

[0098] Similarly, using the coupling control signal in the coupling control signal line 103, the second
5 qubit 101_2 may be brought into resonance with the fourth qubit 101_4 by shifting the resonance frequency of the second qubit 101_2 as disclosed herein.

[0099] The third qubit 101_3 and/or the fourth qubit 101_4 may also be coupled to the coupling control signal
10 line 103 via respective coupling control resonators. Alternatively, the third qubit 101_3 and/or the fourth qubit 101_4 be coupled to a second coupling control signal line via respective coupling control resonators. The arrangement 100 may comprise any number of coupling
15 control signal lines.

[0100] Fig. 5 illustrates a plot representation of qubit resonance frequency as a function of magnetic flux according to an embodiment.

[0101] In the embodiment of Fig. 5, the resonance frequency f_{SQUID} 500 of a SQUID qubit shifts due to the mag-
20 netic flux Φ applied through the SQUID. Thus, the resonance frequency of the SQUID qubit can be tuned by changing the magnetic flux Φ . Other types of qubits may demonstrate similar behaviour at least when simple cir-
25 cuit modifications are applied to the qubit. Similar tuning of the resonance frequency may also be achieved via an electrical current instead of a magnetic flux as disclosed herein.

[0102] Fig. 6 illustrates a schematic representation of an arrangement 100 for selectively shifting qubit resonance frequencies according to a further embodiment.

[0103] The arrangement 100 may comprise a plurality of coupling control signal lines 103 including the coupling signal line. For example, in the embodiment of Fig. 6, two coupling control signal lines 103 are illustrated.

[0104] The arrangement 100 may further comprise a plurality of coupling control resonators 102, including the first coupling control resonator and the second coupling control resonator. For example, in the embodiment of Fig. 6, four coupling control resonators 102 are illustrated.

[0105] The plurality of qubits may be arranged into a matrix. Each qubit 101 in the plurality of qubits may have a respective resonance frequency. Each coupling control signal line 103 in the plurality of coupling control signal lines may correspond to a column/row of the matrix. For example, in the embodiment of Fig. 6, four qubits 101 arranged into matrix are illustrated. The illustrated qubits 101 may be comprised in a large matrix of qubits.

[0106] Each coupling control resonator 102 in the plurality of coupling control resonators may be configured to shift the resonance frequency of a corresponding qubit 101 in the plurality of qubits when a coupling control signal in a corresponding coupling control signal line 103 comprises a frequency component in the

resonance frequency band of that coupling control resonator 102. For example, in the embodiment of Fig. 6, each qubit 101 in the plurality of qubits has a corresponding coupling control resonator 101.

5 **[0107]** A corresponding coupling control signal line 103 may refer to a coupling control signal line 103 in the same column/row of the matrix as the coupling control resonator 102 in question. For example, in the embodiment of Fig. 6, a corresponding control signal
10 line 103 may refer to a coupling control signal line 103 in the same column of the matrix as the coupling control resonator 102 in question, since each coupling control signal line 103 corresponds to a column of the matrix.

[0108] Each qubit 101 in the plurality of qubits may
15 be capacitively coupled to each nearest neighbour qubit. For example, in the embodiment of Fig. 6, each qubit is capacitively coupled to two other qubits. In a larger matrix of qubits, each qubit 101 may be capacitively coupled to at least three or four nearest neighbour
20 qubits.

[0109] The arrangement may further comprise a plurality of rotation signal lines 501. Each rotation signal line 501 may correspond to a row/column of the matrix. For example, in the embodiment of Fig. 6, each rotation
25 signal line 501 corresponds to a column of the matrix.

[0110] The arrangement 100 may further comprise a plurality of rotation resonators 502. Each rotation resonator 502 may be coupled to a corresponding qubit 101.

Each rotation resonator 502 may be coupled to a corresponding rotation signal line 503. Thus, the quantum state of the qubits 101 may be rotated using the rotation signal lines 501.

5 **[0111]** The arrangement may further comprise a plurality of readout signal lines 503. Each readout signal lines 503 may correspond to a row/column of the matrix. For example, in the embodiment of Fig. 6, each readout signal line 503 corresponds to a row of the matrix.

10 **[0112]** The arrangement 100 may further comprise a plurality of readout resonators 504. Each readout resonator 504 may be coupled to a corresponding qubit 101. Each readout resonator 504 may be coupled to a corresponding readout signal line 503. Thus, the state of the qubits
15 101 may be measured using the readout signal lines 503.

[0113] Using the arrangement 100, qubit rotations, gates, and/or measuring the state of qubits may be performed. This may be done without blowing up the number of connections needed in the arrangement 100.

20 **[0114]** Each coupling control resonator 103, rotation resonator 502, and/or readout resonator 504 may function as a per qubit bandpass filter. Thus, frequency shifting, rotations, and readout can be performed independently on each qubit 101 without introducing unwanted
25 effects due to the same signal unintentionally operating on several different qubits 101 at once.

[0115] Fig. 7 illustrates a schematic representation of an arrangement 100 for selectively shifting qubit resonance frequencies according to a further embodiment.

[0116] According to an embodiment, the first coupling control resonator 102_1 is configured to shift the resonance frequency of the first qubit 101_1 by tuning a Josephson inductance of the first qubit 101_1 by causing
5 a current flow through the first qubit.

[0117] The embodiment of Fig. 7 illustrates an example of tuning Josephson inductance of a qubit 101 using a current flow through the qubit 101. Similarly to the embodiments disclosed above, each qubit 101 is coupled
10 to a corresponding coupling control resonator 102. Each coupling control resonator 102 may be coupled to the coupling control signal line 103. In the embodiment of Fig. 7, when the coupling control signal comprises a frequency component in the resonance frequency band of
15 the first coupling control resonator 102_1, a current flows through the first coupling control resonator 102_1 to the first qubit 101_1. Thus, the Josephson inductance of the first qubit 101_1 is tuned by the current and the resonance frequency of the first qubit 101_1 is shifted.

[0118] Similarly to the tuning via magnetic flux, when
20 tuning the Josephson inductance via a current flow, the frequency component in the resonance frequency band of the coupling control resonator may be at a lower or at a higher frequency than the resonance frequency of the
25 corresponding qubit. Like with magnetic flux tuning, coupling control signals with a lower frequency than the resonance frequency of the qubit provide a parametric tuning mechanism for a substantially instantaneous controlling the Josephson inductance.

[0119] For coupling control signals with a higher frequency than the resonance frequency of the qubit, there are analytic approximations for the effective Josephson junction critical current $I_{c,eff}$ as a function of the coupling control signal amplitude and frequency. This can be expressed as

$$I_{c,eff} = I_c \left| J_1 \left(\frac{I_1}{2\pi\Phi_0 f^2 C} \right) \right|,$$

where I_c is the critical current of the Josephson junction without the coupling control signal, I_1 is the current amplitude of the coupling control signal, Φ_0 is the flux quantum, f is the coupling control signal frequency, C is the capacitance of the Josephson junction, and J_1 is the Bessel function of the first kind and of order one. This leads to the Josephson inductance L_{eff} as tuneable by an AC coupling control signal (amplitude I_1 , frequency f) as

$$L_{eff} = \frac{\Phi_0}{2\pi I_{c,eff}}.$$

The resonance frequency then shifts according to the resonance condition

$$f_0 = \frac{1}{2\pi\sqrt{L_{eff}C}}.$$

[0120] Using the resonance frequency shift, the first qubit 101_1 may be brought into resonance with the second qubit 101_2.

[0121] In a similar fashion, the resonance frequency of the second qubit 101_2 and/or of the third qubit 101_3 may be shifted. The second qubit 101_2 may be

brought into resonance with the first qubit 101_1 and/or with the third qubit 101_3. Alternatively or additionally, the third qubit 101_3 may be brought into resonance with the second qubit 101_2.

5 **[0122]** Each qubit 101 may further comprise a shunt capacitor. The shunt capacitor may be arranged in parallel with the Josephson junction of each qubit. The shunt capacitors are not illustrated in the embodiment of Fig. 7 for clarity.

10 **[0123]** When the Josephson inductance of a qubit 101 is tuned using an electrical current, the qubit 101 may comprise a single Josephson junction. This may have the advantage of making the arrangement 100 more insensitive to magnetic noise and interference. The need for a galvanic contact for current driving may set some challenges in the circuit design.

15 **[0124]** Fig. 8 illustrates a schematic representation of a quantum computing system 700 according to an embodiment.

20 **[0125]** According to an embodiment, the quantum computing system 700 comprises the arrangement 100 and a control unit 701 electrically coupled 702 to the coupling control signal line 103 of the arrangement 100.

25 **[0126]** When the system 700 is operational, the arrangement 100 may be physically located in a cryostat or similar. The cryostat may cool the plurality of qubits in the arrangement 100 to cryogenic temperatures. This may be required if the qubits in the plurality of

qubits are, for example, superconductive qubits. The control unit 701 may be located outside the cryostat.

[0127] The control unit 701 may be configured to set an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator 102_1 according to a frequency difference between the resonance frequency of the first qubit 101_1 and a resonance frequency of another qubit in the plurality of qubits and transmit the coupling control signal to the coupling control signal line 103.

[0128] Alternatively or additionally, the control unit 701 may be configured to set an amplitude of the frequency component in the resonance frequency band of the second coupling control resonator 102_2 according to a frequency difference between the resonance frequency of the second qubit 101_2 and a resonance frequency of another qubit in the plurality of qubits and transmit the coupling control signal to the coupling control signal line 103.

[0129] An amplitude of the coupling control signal may refer to, for example, the current amplitude, voltage amplitude, or electric field amplitude of the coupling control signal.

[0130] The another qubit may comprise, for example, the second qubit 101_2, the third qubit 101_3, or any other qubit in the plurality of qubits. The another qubit may be capacitively coupled to the first/second qubit.

[0131] The frequency shift of the first/second qubit 101_1, 101_2 may be proportional to the amplitude of the frequency component in the resonance frequency band of the first/second coupling control resonator 102_1, 102_2. Thus, the control unit 701 can set the amplitude in such a way that the first/second qubit 101_1 can be brought into resonance with the another qubit using the coupling control signal.

[0132] The frequency difference between the resonance frequency of the first/second qubit and a resonance frequency of the another qubit may be, for example, pre-configured into the control unit 701. The preconfiguring may be performed, for example, during calibration of the system 700.

[0133] According to an embodiment, the control unit 701 is further configured to set a temporal duration of a pulse comprising the frequency component in the resonance frequency band of the first coupling control resonator according to a preconfigured coupling parameter, wherein the preconfigured coupling parameter indicates an intended coupling strength between the first qubit and the another qubit.

[0134] Alternatively or additionally, the control unit 701 may be further configured to set a temporal duration of a pulse comprising the frequency component in the resonance frequency band of the second coupling control resonator according to a preconfigured coupling parameter, wherein the preconfigured coupling parameter

indicates an intended coupling strength between the second qubit and the another qubit.

[0135] The coupling control signal may comprise the pulse comprising the frequency component in the resonance frequency band of the first/second coupling control resonator.

[0136] The temporal duration of the pulse comprising the frequency component in the resonance frequency band of the first/second coupling control resonator may be, for example, in the range 1 - 100 ns or in any subrange of this, such as 10 - 100 ns, 10 - 80 ns, or 5 - 50 ns.

[0137] The strength of the coupling between the first/second qubit 101_1, 101_2 and the another qubit may be proportional to the duration of the pulse. Thus, the control unit 701 may control the strength of coupling between the first/second qubit 101_1, 101_2 and the another qubit by adjusting the duration of the pulse. The relation between the temporal duration of the pulse and the strength of the coupling may depend on the implementation of the coupling control resonator and/or of the qubits.

[0138] The preconfigured coupling parameter may be set by, for example, a user. The intended coupling strength may depend on the type of computing operation to be performed by the qubits. The user may need the first/second qubit and the another qubit to perform, for example, a quantum logic gate operation. Thus, the con-

trol unit 701 may set the preconfigured coupling parameter according to the quantum logic gate operation needed by the user.

[0139] According to an embodiment, the control unit
5 701 is further configured to frequency-division multiplex the frequency component in the resonance frequency band of the first coupling control resonator 102_1 and the frequency component in the resonance frequency band of the second coupling control resonator 102_2 into the
10 coupling control signal.

[0140] The frequency component in the resonance frequency band of the first coupling control resonator 102_1 and the frequency component in the resonance frequency band of the second coupling control resonator
15 102_2 may, for example, temporally overlap. Since the first coupling control resonator 102_1 and the second coupling control resonator 102_2 may demultiplex the frequency components from the coupling control signal, the control unit 701 may shift the frequency of the
20 first 101_1 and second qubit 101_2 with a reduced delay.

[0141] Although the connection 702 between the arrangement 100 and the control unit 701 is schematically illustrated as a single connection in the embodiment of Fig. 8, the control unit 701 may be electrically coupled
25 to a plurality of coupling control signal lines 103 in the arrangement 100. The control unit 701 may also be electrically coupled to the plurality of rotation signal lines 501 and/or to the plurality of readout signal lines 503 in the arrangement 100. Thus, the control unit

701 may be configured to control qubit frequency shifting, rotation, and/or readout in the arrangement 100.

[0142] Any parameter related to the arrangement 100, such as the resonance frequency of any qubit in the plurality of qubits, the resonance frequency band of any coupling control resonator in the plurality of coupling control resonators, an amplitude of any frequency component in the coupling control signal, and/or a temporal duration of any pulse in the coupling control signal may be preconfigured into the control unit 701. The preconfiguring may be performed during, for example, calibration of the system 700.

[0143] Fig. 9 illustrates a schematic representation of a control unit 701 according to an embodiment.

[0144] The control unit 701 may comprise at least one processor 801. The at least one processor 801 may comprise, for example, one or more of various processing devices, such as a co-processor, a microprocessor, a control unit 701, a digital signal processor (DSP), a processing circuitry with or without an accompanying DSP, or various other processing devices including integrated circuits such as, for example, an application specific integrated circuit (ASIC), a field programmable gate array (FPGA), a microprocessor unit (MCU), a hardware accelerator, a special-purpose computer chip, or the like.

[0145] The control unit 701 may further comprise a memory 802. The memory 802 may be configured to store, for example, computer programs and the like. The memory

802 may comprise one or more volatile memory devices, one or more non-volatile memory devices, and/or a combination of one or more volatile memory devices and non-volatile memory devices. For example, the memory 802 may
5 be embodied as magnetic storage devices (such as hard disk drives, floppy disks, magnetic tapes, etc.), optical magnetic storage devices, and semiconductor memories (such as mask ROM, PROM (programmable ROM), EPROM (erasable PROM), flash ROM, RAM (random access memory),
10 etc.).

[0146] The memory 802 may comprise, for example, the preconfigured coupling parameter, the frequency difference between the resonance frequency of the first/second qubit and a resonance frequency of the another qubit,
15 and/or any other parameter related to the arrangement 100.

[0147] The control unit 701 may further comprise other components not illustrated in the embodiment of Fig. 9. The control unit 701 may comprise, for example, an input/output bus for connecting the control unit 701 to
20 the arrangement 100. Further, a user may control the control unit 701 via the input/output bus. The user may, for example, control quantum computation operations performed by the arrangement 100 via the control unit 701
25 and the input/output bus.

[0148] When the control unit 701 is configured to implement some functionality, some component and/or components of the control unit 701, such as the at least

one processor 801 and/or the memory 802, may be configured to implement this functionality. Furthermore, when the at least one processor 801 is configured to implement some functionality, this functionality may be implemented using program code comprised, for example, in the memory.

[0149] The control unit 701 may be implemented using, for example, a computer, some other computing device, or similar.

10 **[0150]** Fig. 10 illustrates a flow chart representation of a method 900 according to an embodiment.

[0151] According to an embodiment, the method 900 comprises setting 901 an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator according to a frequency difference between the resonance frequency of the first qubit and a resonance frequency of another qubit in the plurality of qubits.

15 **[0152]** The method 900 may further comprise transmitting 902 the coupling control signal to the coupling control signal line.

[0153] The method 900 may be performed by, for example, the control unit 701.

[0154] Any range or device value given herein may be extended or altered without losing the effect sought. Also any embodiment may be combined with another embodiment unless explicitly disallowed.

25 **[0155]** Although the subject matter has been described in language specific to structural features and/or acts,

it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the specific features or acts described above. Rather, the specific features and acts described above are disclosed
5 as examples of implementing the claims and other equivalent features and acts are intended to be within the scope of the claims.

[0156] It will be understood that the benefits and advantages described above may relate to one embodiment
10 or may relate to several embodiments. The embodiments are not limited to those that solve any or all of the stated problems or those that have any or all of the stated benefits and advantages. It will further be understood that reference to 'an' item may refer to one
15 or more of those items.

[0157] The steps of the methods described herein may be carried out in any suitable order, or simultaneously where appropriate. Additionally, individual blocks may be deleted from any of the methods without departing
20 from the spirit and scope of the subject matter described herein. Aspects of any of the embodiments described above may be combined with aspects of any of the other embodiments described to form further embodiments without losing the effect sought.

[0158] The term 'comprising' is used herein to mean including the method, blocks or elements identified, but that such blocks or elements do not comprise an exclusive list and a method or apparatus may contain additional blocks or elements.

[0159] It will be understood that the above description is given by way of example only and that various modifications may be made by those skilled in the art. The above specification, examples and data provide a
5 complete description of the structure and use of exemplary embodiments. Although various embodiments have been described above with a certain degree of particularity, or with reference to one or more individual
10 embodiments, those skilled in the art could make numerous alterations to the disclosed embodiments without departing from the spirit or scope of this specification.

CLAIMS:

1. Arrangement for selectively shifting qubit resonance frequencies, comprising:

5 a plurality of qubits comprising at least a first qubit and a second qubit, each of the first qubit and the second qubit having a respective resonance frequency;

10 a plurality of coupling control resonators comprising at least a first coupling control resonator and a second coupling control resonator each having a respective resonance frequency band; and

15 a coupling control signal line for feeding a coupling control signal to at least the first coupling control resonator and the second coupling control resonator;

20 wherein the first coupling control resonator is configured to shift the resonance frequency of the first qubit when the coupling control signal comprises a frequency component in the resonance frequency band of the first coupling control resonator and the second coupling control resonator is configured to shift the resonance frequency of the second qubit when the coupling control signal comprises a frequency component in the resonance frequency band of the second coupling control resonator.

2. The arrangement according to claim 1, the plurality of qubits further comprising a third qubit and a fourth qubit, each of the third and the fourth qubit

having a respective resonance frequency, wherein the first qubit is capacitively coupled to the third qubit and the second qubit is capacitively coupled to the fourth qubit.

5

3. The arrangement according to claim 1 or claim 2, wherein each qubit in the plurality of qubits comprises at least one Josephson junction.

10 4. The arrangement according to any preceding claim, wherein each qubit in the plurality of qubits comprises a superconducting quantum interference device, SQUID.

15 5. The arrangement according to any preceding claim, wherein the resonance frequency band of the first and/or second coupling control resonator is located in a frequency range less than the resonance frequency of the first qubit and the resonance frequency of the second qubit.

20 6. The arrangement according to any preceding claim, wherein the shift of the resonance frequency of the first qubit is proportional to an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator and/or the shift of the resonance frequency of the second qubit is proportional to an amplitude of the frequency component in the resonance frequency band of the second coupling control resonator.

30

7. The arrangement according to any preceding claim, wherein the first qubit and the second qubit are capacitively coupled to each other, and wherein when the
5 first qubit and the second qubit are set in resonance, quantum gate operations are performed on the first qubit and the second qubit.

8. The arrangement according to any preceding
10 claim, wherein the first coupling control resonator is configured to shift the resonance frequency of the first qubit by tuning a Josephson inductance of the first qubit.

15 9. The arrangement according to claim 8, wherein the first coupling control resonator is configured to shift the resonance frequency of the first qubit by tuning a Josephson inductance of the first qubit by inducing a magnetic flux through the first qubit or by
20 causing a current flow through the first qubit.

10. The arrangement according to any preceding claim, further comprising:

a plurality of coupling control signal lines including the coupling signal line; and
25

wherein the plurality of qubits is arranged into a matrix, each qubit in the plurality of qubits having a respective resonance frequency, each coupling control signal line in the plurality of coupling control signal
30 lines corresponding to a column/row of the matrix;

wherein each coupling control resonator in the plurality of coupling control resonators is configured to shift the resonance frequency of a corresponding qubit in the plurality of qubits when a coupling control signal in a corresponding coupling control signal line comprises a frequency component in the resonance frequency band of that coupling control resonator.

11. A quantum computing system comprising:
the arrangement according to any preceding claim;
and
a control unit electrically coupled to the coupling control signal line of the arrangement, wherein the control unit is configured:
set an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator according to a frequency difference between the resonance frequency of the first qubit and a resonance frequency of another qubit in the plurality of qubits; and
transmit the coupling control signal to the coupling control signal line.

12. The quantum computing system according to claim 11, wherein the control unit is further configured to set a temporal duration of a pulse comprising the frequency component in the resonance frequency band of the first coupling control resonator according to a preconfigured coupling parameter, wherein the preconfigured

coupling parameter indicates an intended coupling strength between the first qubit and the another qubit.

13. The quantum computing system according to claim
5 11 or claim 12, wherein the control unit is further
configured to frequency-division multiplex the frequency component in the resonance frequency band of the first coupling control resonator and the frequency component in the resonance frequency band of the second
10 coupling control resonator into the coupling control signal.

14. A method for selectively shifting qubit resonance frequencies in a quantum computing system comprising the arrangement according to any of claim 1 -
15 10, the method comprising:

setting an amplitude of the frequency component in the resonance frequency band of the first coupling control resonator according to a frequency difference between the resonance frequency of the first
20 qubit and a resonance frequency of another qubit in the plurality of qubits; and

transmitting the coupling control signal to the coupling control signal line.

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15. A computer program product comprising program code configured to perform the method according to claim 14 when the program code is executed on a computer.