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(54) **SUPERINDUCTOR-BASED REMOTE ENTANGLEMENT COUPLER**

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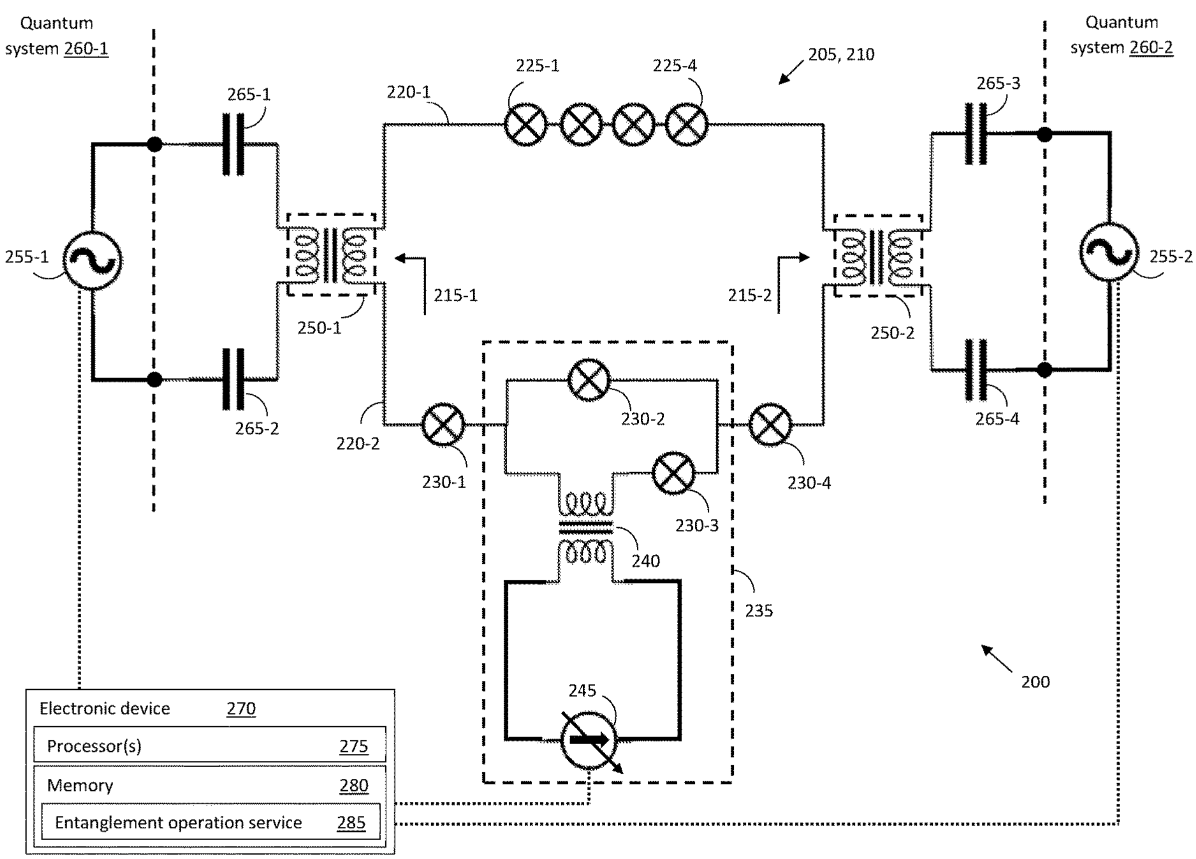
(57) **ABSTRACT**

The present disclosure provides a method of remote entanglement of alternating current (AC) dipoles in one aspect, the method including: supplying a bias current to a tunable superinductor, inductively coupling a current from a first AC dipole into the tunable superinductor, and inductively coupling an induced current from the tunable superinductor into a second AC dipole.



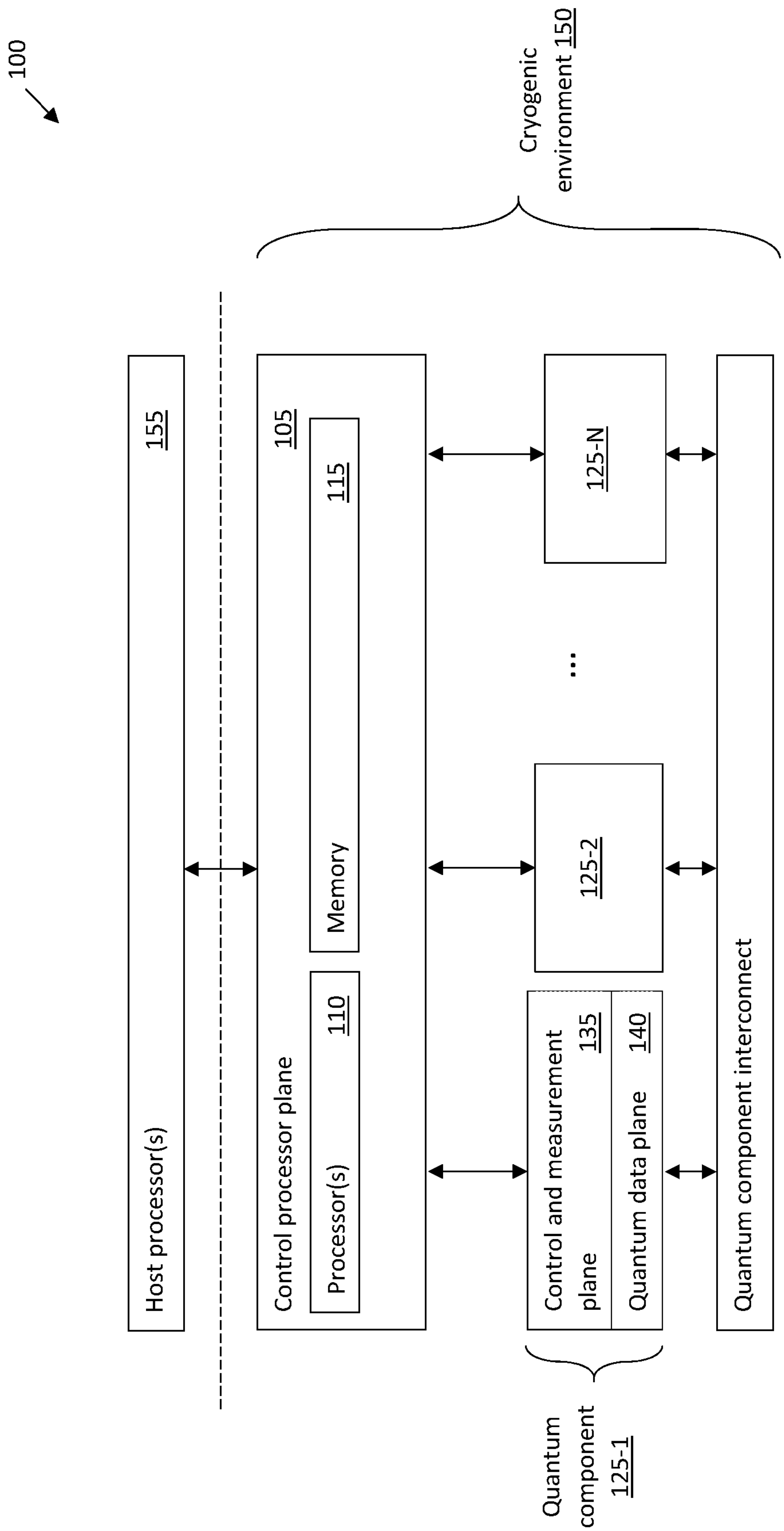

100
Cryogenic environment 150
Host processor(s)
155
Control processor plane
105
Processor(s)
110
Memory
115
Control and measurement plane
135
Quantum data plane
140
Quantum component 125-1
125-2
125-N
...
Quantum component interconnect

FIG. 1

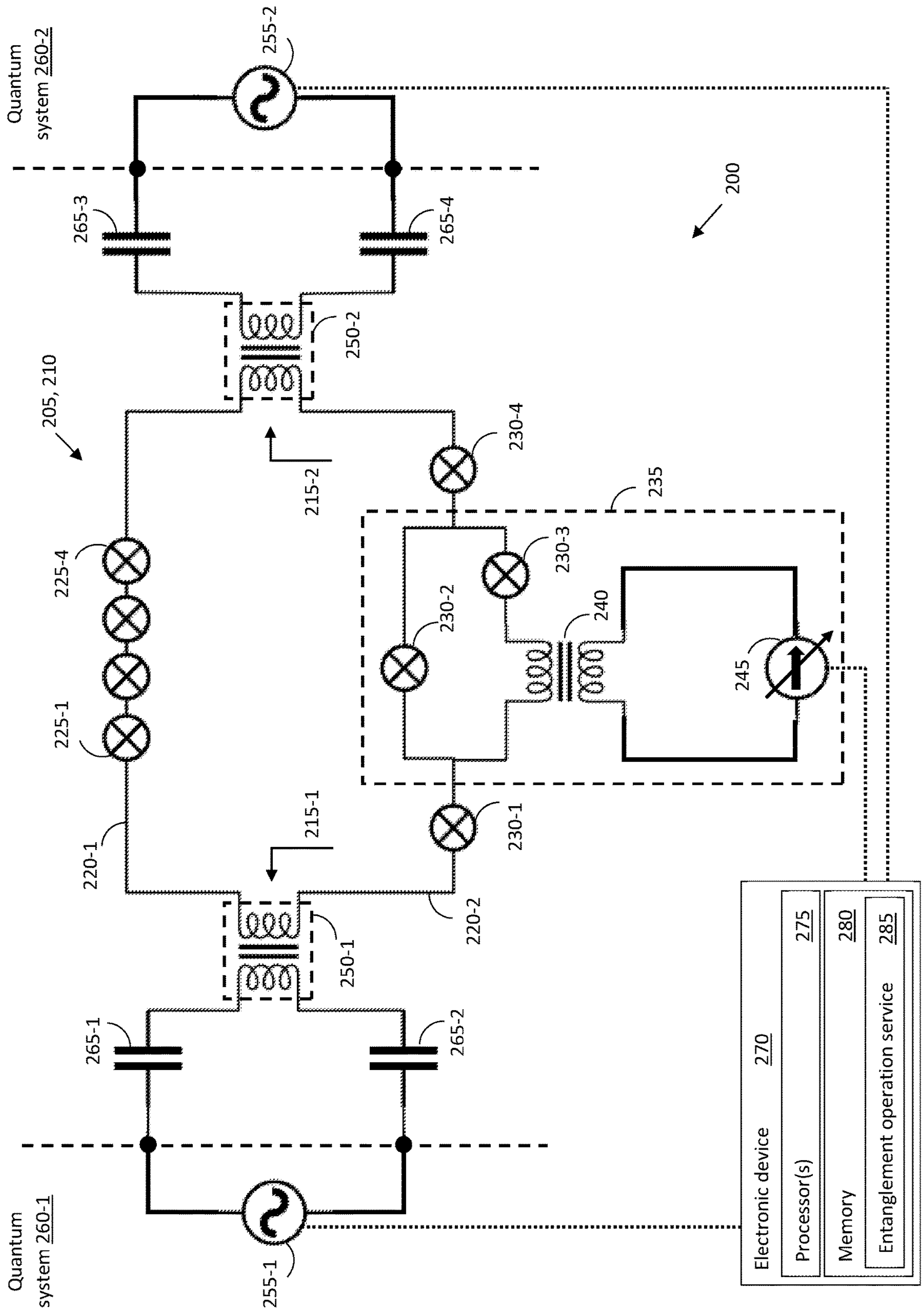

Quantum system 260-2
255-2
265-3
265-4
250-2
200
205, 210
215-2
230-4
235
225-4
230-3
230-2
240
245
225-1
215-1
220-1
230-1
220-2
250-1
265-1
265-2
Quantum system 260-1
255-1
Electronic device 270
Processor(s) 275
Memory 280
Entanglement operation service 285

FIG. 2

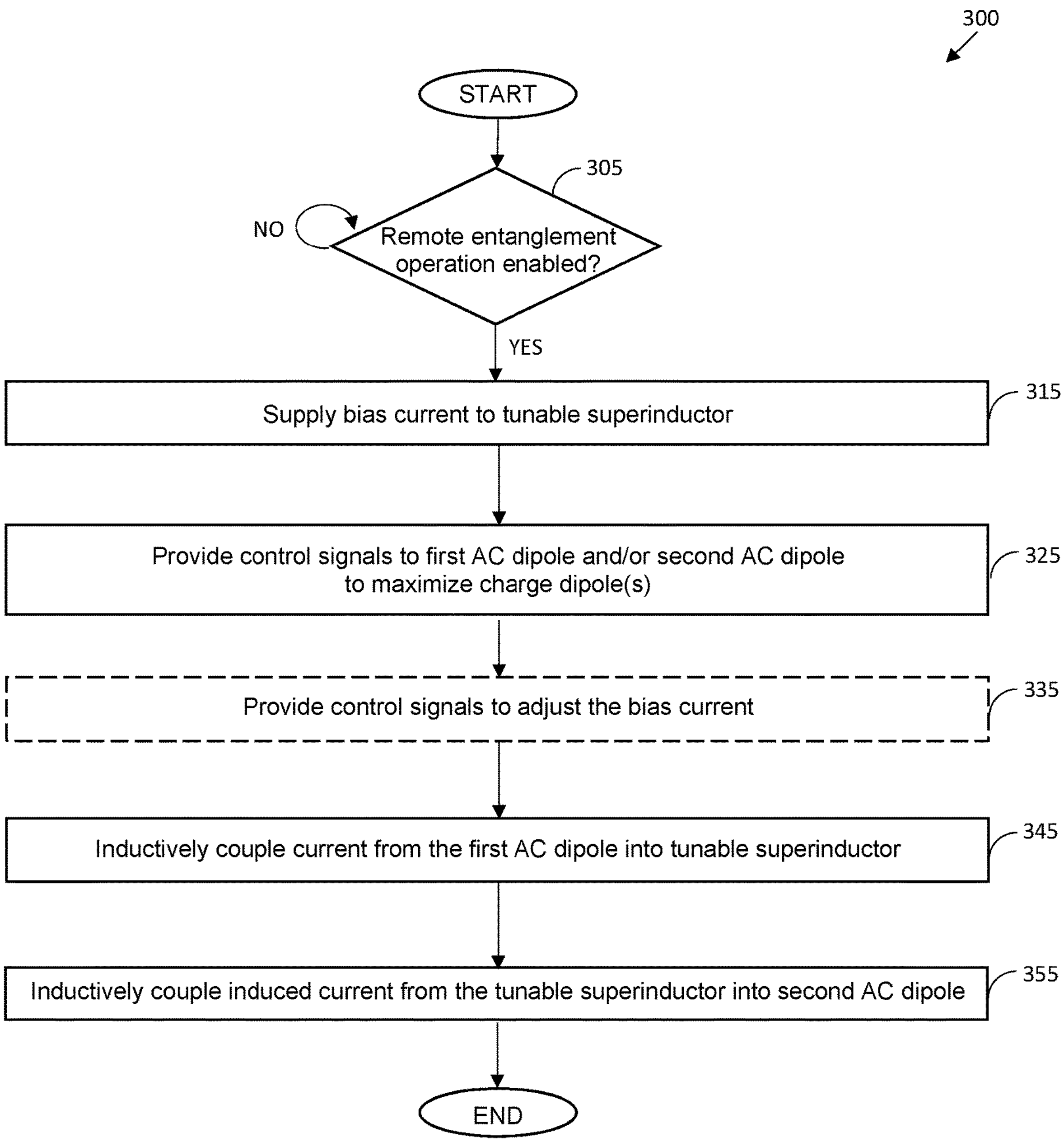

300
START
305
NO
Remote entanglement operation enabled?
YES
Supply bias current to tunable superinductor
315
Provide control signals to first AC dipole and/or second AC dipole to maximize charge dipole(s)
325
Provide control signals to adjust the bias current
335
Inductively couple current from the first AC dipole into tunable superinductor
345
Inductively couple induced current from the tunable superinductor into second AC dipole
355
END

FIG. 3

SUPERINDUCTOR-BASED REMOTE ENTANGLEMENT COUPLER

FIELD

[0001] Aspects of the present disclosure relate to quantum sensing, and more specifically, techniques for remote entanglement between quantum systems using superconducting components.

BACKGROUND

[0002] Various technologies are used to provide alternating current (AC) dipoles, such as quantum dots and superconductors. Such quantum devices are capable of holding single electrons, which may be manipulated to perform a number of quantum computing functions.

[0003] One conventional solution for achieving remote entanglement of quantum devices relies primarily on superconducting cavity resonators. These resonators tend to be challenging to fabricate with a quality factor sufficient to achieve clean entanglement operations. Further, these resonators are unable to accurately tune their resonant frequency and modes. For example, to generate certain standing wave configurations, an electrode at the center is needed to enforce a node in the resonant waveform to maximize entanglement. Further, the operation of the resonators relies on transmission of single photons to carry the energy between the entangled quantum devices. Any external noise that is received from the environment or adjacent electronics is a dominant corrupting mode, which competes with a relatively weak coupling and can render the resonator inoperable, e.g., by decohering the quantum information.

SUMMARY

[0004] The present disclosure provides a method of remote entanglement of alternating current (AC) dipoles in one aspect, the method including: supplying a bias current to a tunable superinductor, inductively coupling a current from a first AC dipole into the tunable superinductor, and inductively coupling an induced current from the tunable superinductor into a second AC dipole.

[0005] In one aspect, in combination with any example method above or below, the method further includes providing control signals to one or both of the first AC dipole and the second AC dipole to maximize a charge dipole thereof.

[0006] In one aspect, in combination with any example method above or below, the tunable superinductor comprises: a superconducting quantum interference device (SQUID), and a direct current (DC) current source that supplies the bias current.

[0007] In one aspect, in combination with any example method above or below, a first mutual inductor couples the first AC dipole with a first port of the tunable superinductor, and a second mutual inductor couples the second AC dipole with a second port of the tunable superinductor.

[0008] In one aspect, in combination with any example method above or below, the tunable superinductor comprises: a first branch coupling the first mutual inductor with the second mutual inductor. The first branch comprises one or more Josephson junctions (JJs) coupled in series. The tunable superinductor further comprises a second branch coupling the first mutual inductor with the second mutual inductor. The second branch comprises the SQUID and the DC current source.

[0009] In one aspect, in combination with any example method above or below, the second branch further comprises a third mutual inductor having an input port coupled with the DC current source, and the SQUID comprises a first JJ coupled in parallel with a series coupling of a second JJ and an output port of the third mutual inductor.

[0010] In one aspect, in combination with any example method above or below, the second branch further comprises one or more JJs coupled in series with the SQUID.

[0011] The present disclosure provides a system in one aspect, the system including: a first alternating current (AC) dipole, a second AC charge dipole, and an entanglement circuit coupled with the first AC charge dipole and with the second AC charge dipole, the entanglement circuit comprising a tunable superinductor.

[0012] In one aspect, in combination with any example system above or below, the tunable superinductor comprises: a superconducting quantum interference device (SQUID), and a direct current (DC) current source.

[0013] In one aspect, in combination with any example system above or below, the system further including: a first mutual inductor coupled with the first AC charge dipole and with a first port of the entanglement circuit, and a second mutual inductor coupled with the second AC charge dipole and with a second port of the entanglement circuit.

[0014] In one aspect, in combination with any example system above or below, the tunable superinductor comprises: a first branch coupling the first mutual inductor with the second mutual inductor. The first branch comprises one or more Josephson junctions (JJs) coupled in series. The tunable superinductor further comprises a second branch coupling the first mutual inductor with the second mutual inductor. The second branch comprising the SQUID and the DC current source.

[0015] In one aspect, in combination with any example system above or below, the second branch further comprises a third mutual inductor having an input port coupled with the DC current source, and the SQUID comprises a first JJ coupled in parallel with a series coupling of a second JJ and an output port of the third mutual inductor.

[0016] In one aspect, in combination with any example system above or below, the second branch further comprises one or more JJs coupled in series with the SQUID.

[0017] In one aspect, in combination with any example system above or below, the DC current source is configured to supply a bias current to the input port, a value of the bias current selected to maximize a coupling between the first AC charge dipole and the second AC charge dipole.

[0018] The present disclosure provides an apparatus in one aspect, the apparatus including: a first port to couple with a first alternating current (AC) dipole, a second port to couple with a second AC dipole, and a tunable superinductor coupled with the first port and with the second port.

[0019] In one aspect, in combination with any example apparatus above or below, the tunable superinductor circuit comprises: a superconducting quantum interference device (SQUID), and a direct current (DC) current source.

[0020] In one aspect, in combination with any example apparatus above or below, the apparatus further comprises: a first mutual inductor coupled with the first AC charge dipole and with the first port, and a second mutual inductor coupled with the second AC charge dipole and with the second port.

[0021] In one aspect, in combination with any example apparatus above or below, the tunable superinductor comprises a first branch coupling the first mutual inductor with the second mutual inductor. The first branch comprises one or more Josephson junctions (JJs) coupled in series. The tunable superinductor further comprises a second branch coupling the first mutual inductor with the second mutual inductor. The second branch comprises the SQUID and the DC current source.

[0022] In one aspect, in combination with any example apparatus above or below, the second branch further comprises a third mutual inductor having an input port coupled with the DC current source, and the SQUID comprises a first JJ coupled in parallel with a series coupling of a second JJ and an output port of the third mutual inductor.

[0023] In one aspect, in combination with any example apparatus above or below, the second branch further comprises one or more JJs coupled in series with the SQUID.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] So that the manner in which the above recited features can be understood in detail, a more particular description, briefly summarized above, may be had by reference to example aspects, some of which are illustrated in the appended drawings.

[0025] FIG. **1** depicts an exemplary quantum system, according to one or more aspects.

[0026] FIG. **2** depicts a system having an exemplary entanglement circuit, according to one or more aspects.

[0027] FIG. **3** depicts an exemplary method of remote entanglement of alternating current (AC) dipoles, according to one or more aspects.

DETAILED DESCRIPTION

[0028] The present disclosure relates to techniques for high-precision, tunable, electrically-protected remote entanglement of alternating current (AC) dipoles. In some aspects, a method of remote entanglement comprises supplying a bias current to a tunable superinductor, inductively coupling a current from a first AC dipole into the tunable superinductor, and inductively coupling the current from the tunable superinductor into a second AC dipole. In some aspects, the tunable superinductor is based on a series of Josephson junctions that present a large and tunable inductance (and impedance) and strong coupling.

[0029] Use of the tunable superinductor allows for long range entanglement with superior tunability and greater isolation of the entangled quantum state than conventional solutions, such as cavity resonators in combination with current transmission line technologies. Beneficially, these high-precision, tunable, electrically-protected remote entanglement techniques support the further development of robust quantum sensing technologies, cryo-control electronics, and more capable entanglement swapping. The remote entanglement techniques described herein also improve fabrication uniformity.

[0030] In the current disclosure, reference is made to various aspects. However, it should be understood that the present disclosure is not limited to specific described aspects. Instead, any combination of the following features and elements, whether related to different aspects or not, is contemplated to implement and practice the teachings provided herein. Additionally, when elements of the aspects are described in the form of "at least one of A and B," it will be understood that aspects including element A exclusively, including element B exclusively, and including element A and B are each contemplated. Furthermore, although some aspects may achieve advantages over other possible solutions and/or over the prior art, whether or not a particular advantage is achieved by a given aspect is not limiting of the present disclosure. Thus, the aspects, features, aspects and advantages disclosed herein are merely illustrative and are not considered elements or limitations of the appended claims except where explicitly recited in a claim(s). Likewise, reference to "the invention" shall not be construed as a generalization of any inventive subject matter disclosed herein and shall not be considered to be an element or limitation of the appended claims except where explicitly recited in a claim(s).

[0031] FIG. **1** depicts an exemplary quantum system **100**, according to one or more aspects. The features depicted in the quantum system **100** may be used in conjunction with other aspects described herein. For example, the remote entanglement operation (described in greater detail below) may be achieved using one or more quantum systems **100**.

[0032] The quantum system **100** comprises a plurality of quantum components **125-1**, **125-2**, . . . , **125**-N, a quantum component interconnect **145**, a control processor plane **105**, and a host processor **155**. As used herein, the plurality of quantum components **125-1**, **125-2**, . . . , **125**-N refer to any suitable number of units that are physically and/or logically distinct from each other, e.g., a plurality of quantum chips. While the quantum system **100** of FIG. **1** generally represents a large-scale quantum system, other architectures of the quantum system **100** are also contemplated, e.g., a quantum system **100** having only a single "component".

[0033] Each of the quantum components **125-1**, **125-2**, . . . , **125**-N comprises a respective quantum data plane **140** and a control and measurement plane **135**, and is communicatively coupled with the control processor plane **105**. The quantum components **125-1**, **125-2**, . . . , **125**-N are communicatively coupled with each other by the quantum component interconnect **145**. In some aspects, the quantum data plane **140** comprises hardware that physically forms one or more qubits, as well as the structures used to support and/or retain the one or more qubits. In some aspects, the quantum data plane **140** forms one or more AC dipoles. The qubits may have any suitable form, such as quantum dots, superconducting circuits, and so forth. In other aspects, the quantum data plane **140** comprises a quantized quantum device operable as a sensor. In yet other aspects, the quantum data plane **140** comprises a repeater (or quantum information amplifier) that is used in a quantum network. Thus, implementations of the entanglement circuit **205** of FIG. **2**, discussed below, may be used in quantum processing environments, as well as outside of quantum processing environments.

[0034] In some aspects, the quantum data plane **140** comprises further circuitry that operates to measure the states of the one or more qubits, and to manipulate the states of the one or more qubits when carrying out operations. For example, gate operations may be performed using control signals that alter the Hamiltonian (i.e., a description of the state) of the one or more qubits. In some aspects, quantum information in the one or more qubits may be stored, changed, and/or read by transmitting microwave photons at the one or more qubits.

[0035] The control and measurement plane **135** comprises hardware that receives digital control signals from the control processor plane **105**, and translates the digital control signals into analog (or wave) control signals that are read and executed in the quantum data plane **140** to perform quantum operations on the one or more qubits. In some aspects, the control and measurement plane **135** comprises one or more waveguides supporting transmission (and, in some cases, shielding) of signals to and/or from the quantum data plane **140**. For example, in a quantum data plane **140** having the qubits formed in superconducting circuits, the control signals may be transmitted to the qubits through microwave waveguides extending through a dilution refrigerator or other cooling device.

[0036] The control and measurement plane **135** further comprises hardware that receives analog outputs from the quantum data plane **140** (representing measurements of qubits), and converts the analog outputs into digital signals that are transmitted to the control processor plane **105**. The hardware included in the control and measurement plane **135** may include additional shielding to mitigate the effects of environmental noise on the analog outputs received from the quantum data plane **140**.

[0037] The control processor plane **105** implements a quantum algorithm or sequence of quantum operations, and provides corresponding instructions to be implemented in the control and measurement plane **135**. The host processor **155** is communicatively coupled with the control processor plane **105**, and provides digital signal(s) that implement the quantum algorithm in the control processor plane **105** and/or interact with the quantum algorithm.

[0038] In some aspects, the quantum algorithm is implemented using quantum circuits, each of which represents a computing routine having a series of quantum operations on the qubits of the quantum data plane **140**. In some aspects, the quantum algorithm may be implemented using development tools and libraries. In some aspects, the quantum algorithm comprises a sequence of gate operations and measurements that are performed in the control and measurement plane **135**.

[0039] As shown, the control processor plane **105** is implemented as one or more processors **110** and a memory **115**. The one or more processors **110** are any electronic circuitry, including, but not limited to one or a combination of microprocessors, microcontrollers, application-specific integrated circuits (ASIC), application-specific instruction set processors (ASIP), and/or state machines, that is communicatively coupled to the memory **115** and controls the operation of the control processor plane **105**.

[0040] The one or more processors **110** may include other hardware that operates software to control and process information. The one or more processors **110** executes software stored in the memory **115** to perform any of the functions described herein. The one or more processors **110** control the operation and administration of the computing device **105** by processing information (e.g., information received from input devices and/or communicatively coupled electronic devices).

[0041] The memory **115** may store, either permanently or temporarily, data, operational software, or other information for the one or more processors **110**. The memory **115** may include any one or a combination of volatile or non-volatile local or remote devices suitable for storing information. For example, the memory **115** may include random access memory (RAM), read only memory (ROM), magnetic storage devices, optical storage devices, or any other suitable information storage device or a combination of these devices. The software represents any suitable set of instructions, logic, or code embodied in a computer-readable storage medium such as the memory **115**. In particular embodiments, the software may include an application executable by the one or more processors **110** to perform one or more of the functions described herein.

[0042] In some aspects, some or all of the components of the quantum system **100** operates within a cryogenic environment **150**. As shown, the hardware of the control processor plane **105**, the plurality of quantum components **125-1**, **125-2**, . . . , **125**-N, and the quantum component interconnect **145** are disposed within the cryogenic environment **150**, and the one or more host processors **155** are disposed outside the cryogenic environment **150**. In some aspects, the one or more host processors **155** are considered "classical" processors including any electronic circuitry, including, but not limited to one or a combination of microprocessors, microcontrollers, application-specific integrated circuits (ASIC), application-specific instruction set processors (ASIP), and/or state machines.

[0043] In some aspects, a cryogenic cooling system using liquefied gases such as liquid nitrogen, liquid hydrogen, or liquid helium may be in fluid communication with the cryogenic environment **150** to maintain a temperature of about 120 K (−153° C.) or less. In some aspects, the cryogenic environment **150** has a temperature that is very close to absolute zero (0 K; −273.15° C.) as superconductivity and the associated quantum characteristics are most pronounced at these temperatures. However, the cryogenic environment **150** may have any alternate suitable temperature to ensure superconductivity (e.g., based on the critical temperature of the superconductor material(s)).

[0044] FIG. **2** depicts a system **200** having an exemplary entanglement circuit **205**, according to one or more aspects. The entanglement circuit **205** may be alternately described as a superinductor-based resonator. The system **200** may be used in conjunction with other aspects described herein. For example, the various components of the system **200** may be implemented within one or more quantum components **125-1**, **125-2**, . . . , **125**-N of the quantum system **100**.

[0045] The system comprises an entanglement circuit **205** coupled with a first quantum system **260-1** and a second quantum system **260-2**. Each of the quantum systems **260-1**, **260-2** comprises a respective AC dipole **255-1**, **255-2** that may be implemented using any suitable technologies providing oscillating charge representing quantum coherent states, such as quantum dots or superconducting circuits. For example, the oscillating charge may represent quantum fluctuations that are associated with a stationary state of a quantum circuit. In some aspects, the AC dipoles **255-1**, **255-2** are included in a same quantum data plane **140** of a particular quantum component **125-1**, **125-2**, . . . , **125**-N. In other aspects, the AC dipoles **255-1**, **255-2** are included in quantum data planes **140** of different quantum components **125-1**, **125-2**, . . . , **125**-N of the quantum system **100**.

[0046] Thus, in some aspects, the quantum systems **260-1**, **260-1** may represent one or more instances of the quantum system **100**. However, the entanglement circuit **205** enables coherent quantum information transfer between the AC dipoles **255-1**, **255-2** regardless of their implementation. As discussed above, some example implementations of the AC dipoles **255-1**, **255-2** include a set of one or more qubits, a quantized quantum device operable as a sensor, and a repeater (or quantum information amplifier) that is used in a quantum network. For example, when implemented in a quantum network repeater, the AC dipoles **255-1**, **255-2** may represent qudits of N-level states of the quantum systems **260-1**, **260-2**, supporting quantum information swapping and entanglement between chips or other circuitry.

[0047] The entanglement circuit **205** comprises a first port **215-1** that couples with the first quantum system **260-1**, and a second port **215-2** that couples with the second quantum system **260-2**. As shown, the nodes of the AC dipole **255-1** are coupled with a first port of a first mutual inductor **250-1** through respective capacitors **265-1**, **265-2**. The first mutual inductor **250-1** and the capacitors **265-1**, **265-2** may have any suitable implementation. The second port of the first mutual inductor **250-1** is coupled with the first port **215-1** of the entanglement circuit **205**. Each of the first port and the second port of the first mutual inductor **250-1** may be operated as an input port or as an output port depending on the configuration of the system **200**.

[0048] The nodes of the AC dipole **255-2** are coupled with a first port of a second mutual inductor **250-2** through respective capacitors **265-3**, **265-4**. The second mutual inductor **250-2** and the capacitors **265-3**, **265-4** may have any suitable implementation. The second port of the second mutual inductor **250-2** is coupled with the second port **215-2** of the entanglement circuit **205**. Each of the first port and the second port of the second mutual inductor **250-1** may be operated as an input port or as an output port depending on the configuration of the system **200**.

[0049] The entanglement circuit **205** further comprises a tunable superinductor **210** disposed between the first port **215-1** and the second port **215-2**. In some aspects, the tunable superinductor **210** comprises a first branch **220-1** coupling the first mutual inductor **250-1** with the second mutual inductor **250-2** (i.e., coupling a first pair of nodes), and a second branch **220-2** coupling the first mutual inductor **250-1** with the second mutual inductor **250-2** (i.e., coupling a second pair of nodes). The first branch **220-1** comprises one or more Josephson junctions (JJs) **225-1**, . . . , **225-4** that are coupled in series with each other. While four (4) JJs **225-1**, . . . , **225-4** are illustrated, other numbers of JJs in the first branch **220-1** are also contemplated.

[0050] In some aspects, the second branch **220-2** comprises a superconducting quantum interference device (SQUID) **235** and a DC current source **245**, which enables tuning of the tunable superinductor **210** by controlling the amount of bias current that is supplied by the DC current source **245**. Stated another way, controlling the amount of the bias current enables the SQUID **235** to modulate the inductance of the loop of the tunable superinductor **210**. In some aspects, and as discussed below, an electronic device **270** comprises an entanglement operation service **285** that provides control signals that are used to select a bias current of the DC current source **245**. Controlling the amount of bias current supplied to the SQUID **235** allows the effective modes of the tunable superinductor **210** to be controlled. For example, the tunable superinductor **210** may be operated in a ring mode for a first value of the bias current, and may be operated in a linear mode for a second value of the bias current (e.g., zero DC current). The DC current source **245** may have any suitable implementation, such as a MOSFET constant-current source.

[0051] In some aspects, the second branch **220-2** (more specifically, the SQUID **235**) further comprises a third mutual inductor **240** having an input port coupled with the DC current source **245**. The SQUID **235** comprises a first JJ **230-2** that is coupled in parallel with a series coupling of a second JJ **230-3** and an output port of the third mutual inductor **240**. The second branch **220-2** further comprises one or more JJs **230-1**, **230-4** that are coupled in series with the SQUID **235**. While four (4) JJs **230-1**, . . . , **230-4** are illustrated, other numbers of JJs in the second branch **220-1** are also contemplated. Further, in some aspects, the number of JJs included in the first branch **220-1** may differ from the number of JJs included in the second branch **220-2**. Thus, in some aspects, the tunable superinductor **210** is formed as a superinductor loop comprising the JJs **225-1**, . . . , **225-4** of the first branch **220-1**, portions of the mutual inductors **250-1**, **250-2**, and the JJs **230-1**, **230-4** and SQUID **235** of the second branch **220-2**.

[0052] Each of the JJs **225-1**, . . . , **225-4**, **230-1**, . . . , **230-4** comprises a first superconductor section that is spaced apart from a second superconductor section by a weak link section. The first superconductor section and the second superconductor section may be formed of any suitable superconducting material(s). In some aspects, the weak link section comprises one of an insulating material, a non-superconducting metal material, and a physical constriction providing areas of reduced superconductivity. The weak link section has suitable dimensioning to support the quantum tunneling of electrons therethrough. Typically, the thickness of the weak link section may be on the order of tens of angstroms (Å), or on the order of several microns, depending on the composition of the weak link section.

[0053] The first superconductor section and the second superconductor section, when cooled to cryogenic temperatures in the cryogenic environment **150**, are able to conduct electricity without providing any electrical resistance. The flow of a supercurrent, conducted through the JJ across the weak link section, is governed by quantum tunneling of Cooper pairs (i.e., pairs of electrons having opposite spins that are bound together at cryogenic temperatures).

[0054] In some aspects, the JJs **225-1**, . . . , **225-4**, **230-1**, . . . , **230-4** may be implemented to have similar parameters (e.g., a same magnitude of dimensioning, critical current values, and so forth). For example, where the SQUID **235** is arranged in parallel, the JJs **225-1**, . . . , **225-4**, **230-1**, . . . , **230-4** should have critical current values as close to each other as possible, as the current tuning ability of the SQUID **235** depends on this. In other cases where the SQUID **235** is arranged in series, it may be possible to trade off capacitance and desired spectral modes. In other aspects, some or all of the JJs **225-1**, **225-4**, **230-1**, . . . , **230-4** may be implemented with differing parameters.

[0055] Collectively, the JJs **225-1**, . . . , **225-4**, **230-1**, . . . , **230-4** of the tunable superinductor **210** effectively operate as a classical inductor having a large inductance (and large impedance), providing a stronger coupling between the quantum systems **260-1**, **260-2**. Thus, the tunable superinductor **210** supports a stronger entanglement between the AC dipoles **255-1**, **255-2**, as the large impedance provides a large coupling and mitigates induced noise during entanglement operations. Further, in some aspects, the various components of the system **205** may be coupled with each other using high quality connections (e.g., superconducting wire segments) that improve the coupling and entanglement between the AC dipoles **255-1**, **255-2**. By integrating the SQUID **235** in the tunable superinductor **210**, the inductance of the tunable superinductor **210** may be precisely tuned, and the impedance and the resonant frequency of the entanglement circuit **205** may be better controlled.

[0056] The system **200** further comprises an electronic device **270**. As used herein, an "electronic device" generally refers to any device having electronic circuitry that provides a processing or computing capability, and that implements logic and/or executes program code to perform various operations that collectively define the functionality of the electronic device. The functionality of the electronic device includes a communicative capability with one or more other electronic devices, e.g., when connected to a same network. An electronic device may be implemented with any suitable form factor, whether relatively static in nature (e.g., mainframe, computer terminal, server, kiosk, workstation) or mobile (e.g., laptop computer, tablet, handheld, smart phone, wearable device). The communicative capability between electronic devices may be achieved using any suitable techniques, such as conductive cabling, wireless transmission, optical transmission, and so forth. In some aspects, the electronic device **270** may be implemented outside of the cryogenic environment **150**. In other aspects, the electronic device **270** may be implemented partly or fully within the cryogenic environment **150**.

[0057] The electronic device **270** comprises one or more processors **275** and a memory **280**. The one or more processors **275** are any electronic circuitry, including, but not limited to one or a combination of microprocessors, microcontrollers, application-specific integrated circuits (ASIC), application-specific instruction set processors (ASIP), and/or state machines, that is communicatively coupled to the memory **280** and controls the operation of the electronic device **270**. The one or more processors **275** are not limited to a single processing device and may encompass multiple processing devices.

[0058] The one or more processors **275** may include other hardware that operates software to control and process information. In some aspects, the one or more processors **275** execute software stored in the memory **280** to perform any of the functions described herein. The one or more processors **275** control the operation and administration of the electronic device **270** by processing information (e.g., information received from input devices and/or communicatively coupled electronic devices).

[0059] The memory **280** may store, either permanently or temporarily, data, operational software, or other information for the one or more processors **275**. The memory **280** may include any one or a combination of volatile or non-volatile local or remote devices suitable for storing information. For example, the memory **280** may include random access memory (RAM), read only memory (ROM), magnetic storage devices, optical storage devices, or any other suitable information storage device or a combination of these devices. The software represents any suitable set of instructions, logic, or code embodied in a computer-readable storage medium. For example, the software may be embodied in the memory **280**, a disk, a CD, or a flash drive. In particular embodiments, the software may include an application executable by the one or more processors **275** to perform one or more of the functions described herein.

[0060] In this example, the memory **280** stores an entanglement operation service **285** that controls the remote entanglement of AC dipoles. In some aspects, the entanglement operation service **285** enables and/or disables the remote entanglement operation within the system **200**, and/or controls one or more parameters defining the remote entanglement operation. As shown, the entanglement operation service **285** is coupled with the AC dipoles **255-1**, **255-2** (or with the quantum systems **260-1**, **260-2**) and with the SQUID **235** (or with the tunable superinductor **210**). In some aspects, the entanglement operation service **285** provides signals to control operation of the quantum devices **260-1**, **260-2** to interact with the entanglement circuit **205**. In some aspects, the signals cause the quantum devices **260-1**, **260-2** to adiabatically change their quantum states to maximize the charge dipole for each of the AC dipoles **255-1**, **255-2** (or AC charge dipole), that is, for the left-side plates of the capacitors **265-1**, **265-2** and for the right-side plates of the capacitors **265-3**, **265-4**. In some aspects, the entanglement operation service **285** may further provide signals to control operation of the SQUID **235**, e.g., by selecting or adjusting a bias current of the DC current source **245**.

[0061] In some aspects, the inductance of the tunable superinductor **210** is controlled such that the quantum systems **260-1**, **260-2** may be operated and developed independent of each other. When remote entanglement operation of the system **200** is desired, the quantum systems **260-1**, **260-2** are controlled (e.g., by signals from the entanglement operation service **285**) to have precisely timed (or synchronized) operations. The tunable superinductor **210** typically operates during the entirety of the remote entanglement operation. During the remote entanglement operation, one of the AC dipoles **255-1**, **255-2** creates a current, which is inductively coupled into the tunable superinductor **210**. The induced current in the tunable superinductor **210** is then inductively coupled into the other of the AC dipoles **255-1**, **255-2** to achieve the remote entanglement.

[0062] The inductance presented by the tunable superinductor **210** may be further fine-tuned to maximize the entanglement operation. The fine-tuning operation tends to relax shape and size constraints that allows the system **200** to be more tolerant of any fabrication defects. For example, an AC line may be added to the SQUID **235** to support finer tuning of the tunable superinductor **210**. Such an implementation may also be capable of turning off (or disabling) the tunable superinductor **210**, as the inductance presented by the tunable superinductor **210** may be controlled to minimize or eliminate coupling between the AC dipoles **255-1**, **255-2**.

[0063] The entanglement circuit **205** having the tunable superinductor **210** provides a number of advantages relative to conventional strip-line resonator designs. First, the entanglement circuit **205** suppresses charge fluctuations and supports a greater quality factor The tunable superinductor **210** allows a greater impedance than the resistance quantum

$$\left(\text{e.g., } Z > R_Q = \frac{\hbar}{(2e)^2} = 6.45\ k\Omega\right)$$

to be achieved, while presenting a lower capacitance than the strip-line resonator which increases uniformity of fabrication. Second, the entanglement circuit **205** improves dipole coupling and supports greater coupling between the AC dipoles **255-1**, **255-2**. This advantage is particularly useful for quantum remote sensing (e.g., using interferometry-based devices) using remote entanglement between a probe and a receiver, which enhances the capability to sense a remote target and transfer quantum information therewith. The coupling is often expected to be proportional to a square root of the impedance, which can be controlled by the choice of a critical current for the JJs **225-1**, . . . , **225-4**, **230-1**, . . . , **230-4** and fine-tuned using the SQUID **235**.

[0064] Another advantage provided by the system **200** is that the superconducting components of the system **200** may be fabricated from a different semiconductor fabrication process than the quantum devices. In some aspects, the entanglement circuit **205** may be formed in a first process, a semiconductor chip may be formed in a second process, and the entanglement circuit **205** may be bonded with the semiconductor chip in the final quantum device.

[0065] FIG. **3** depicts an exemplary method **300** of remote entanglement of alternating current (AC) dipoles, according to one or more aspects. The method **300** may be used in conjunction with other aspects described herein. For example, although certain blocks are described as being performed using the entanglement operation service **285**, the method **300** may be performed using various components of the quantum system **100** and/or of the system **200** of FIG. **2**.

[0066] The method **300** begins at block **305**, where the entanglement operation service **285** determines whether remote entanglement operation is enabled in the system **200**. If the remote entanglement operation is not enabled ("NO"), the method **300** repeats block **305**, e.g., after a periodic delay. If the remote entanglement operation is enabled ("YES"), the method **300** proceeds from block **305** to block **315**, a bias current is supplied to the tunable superinductor **210** of the system **200**. In some aspects, the bias current is supplied to the SQUID **235** included in the branch **220-2** of the tunable superinductor **210**. Supplying the bias current causes the entanglement circuit **205** to operate during the remote entanglement operation. In some aspects, block **315** is performed prior to block **305**, such that the entanglement circuit **205** operates with a desired configuration prior to controlling the AC dipoles (connected to the entanglement circuit **205**) to achieve remote entanglement.

[0067] The method **300** proceeds from block **315** to block **325**, where the entanglement operation service **285** provides control signals to a first AC dipole **255-1** and/or to a second AC dipole **255-2** to maximize charge dipole(s) thereof. In some aspects, the signals cause a change to quantum states to maximize the charge dipole for the first AC dipole **255-1** and/or the second AC dipole **255-2**. In an optional block **335**, the entanglement operation service **285** provides control signals to adjust the bias current.

[0068] The method **300** proceeds from block **325** or optional block **335** to block **345**, where a current is inductively coupled from the first AC dipole **255-1** into the tunable superinductor **210**. Inductively coupling the current induces a current within the tunable superinductor **210**. The method **300** then proceeds from block **345** to block **355**, where the induced current is inductively coupled from the tunable superinductor into the second AC dipole **255-2**. The method **300** ends following completion of the block **355**.

[0069] As will be appreciated by one skilled in the art, aspects described herein may be embodied as a system, method or computer program product. Accordingly, aspects may take the form of an entirely hardware aspect, an entirely software aspect (including firmware, resident software, micro-code, etc.) or an aspect combining software and hardware aspects that may all generally be referred to herein as a "circuit," "module" or "system." Furthermore, aspects described herein may take the form of a computer program product embodied in one or more computer readable storage medium(s) having computer readable program code embodied thereon.

[0070] Program code embodied on a computer readable storage medium may be transmitted using any appropriate medium, including but not limited to wireless, wireline, optical fiber cable, RF, etc., or any suitable combination of the foregoing.

[0071] Computer program code for carrying out operations for aspects of the present disclosure may be written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++ or the like and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The program code may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

[0072] Aspects of the present disclosure are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatuses (systems), and computer program products according to aspects of the present disclosure. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer program instructions. These computer program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the block(s) of the flowchart illustrations and/or block diagrams.

[0073] These computer program instructions may also be stored in a computer readable medium that can direct a computer, other programmable data processing apparatus, or other device to function in a particular manner, such that the instructions stored in the computer readable medium produce an article of manufacture including instructions which implement the function/act specified in the block(s) of the flowchart illustrations and/or block diagrams.

[0074] The computer program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process such that the instructions which execute on the computer, other programmable data processing apparatus, or other device provide processes for implementing the functions/acts specified in the block(s) of the flowchart illustrations and/or block diagrams.

[0075] The flowchart illustrations and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various aspects of the present disclosure. In this regard, each block in the flowchart illustrations or block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the Figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order or out of order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustrations, and combinations of blocks in the block diagrams and/or flowchart illustrations, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

[0076] While the foregoing is directed to aspects of the present disclosure, other and further aspects of the disclosure may be devised without departing from the basic scope thereof, and the scope thereof is determined by the claims that follow.

What is claimed is:

1. A method of remote entanglement of alternating current (AC) dipoles, the method comprising:
- supplying a bias current to a tunable superinductor;
- inductively coupling a current from a first AC dipole into the tunable superinductor; and
- inductively coupling an induced current from the tunable superinductor into a second AC dipole.

2. The method of claim **1**, further comprising:
- providing control signals to one or both of the first AC dipole and the second AC dipole to maximize a charge dipole thereof.

3. The method of claim **1**, the tunable superinductor comprising:
- a superconducting quantum interference device (SQUID); and
- a direct current (DC) current source that supplies the bias current.

4. The method of claim **3**,
- wherein a first mutual inductor couples the first AC dipole with a first port of the tunable superinductor; and
- wherein a second mutual inductor couples the second AC dipole with a second port of the tunable superinductor.

5. The method of claim **4**, the tunable superinductor comprising:
- a first branch coupling the first mutual inductor with the second mutual inductor, the first branch comprising one or more Josephson junctions (JJs) coupled in series; and
- a second branch coupling the first mutual inductor with the second mutual inductor, the second branch comprising the SQUID and the DC current source.

6. The method of claim **5**,
- the second branch further comprising a third mutual inductor having an input port coupled with the DC current source, and
- the SQUID comprising a first JJ coupled in parallel with a series coupling of a second JJ and an output port of the third mutual inductor.

7. The method of claim **6**,
- the second branch further comprising one or more JJs coupled in series with the SQUID.

8. A system comprising:
- a first alternating current (AC) dipole;
- a second AC charge dipole; and
- an entanglement circuit coupled with the first AC charge dipole and with the second AC charge dipole, the entanglement circuit comprising a tunable superinductor.

9. The system of claim **8**, the tunable superinductor comprising:
- a superconducting quantum interference device (SQUID); and
- a direct current (DC) current source.

10. The system of claim **9**, further comprising:
- a first mutual inductor coupled with the first AC charge dipole and with a first port of the entanglement circuit; and
- a second mutual inductor coupled with the second AC charge dipole and with a second port of the entanglement circuit.

11. The system of claim **10**, the tunable superinductor comprising:
- a first branch coupling the first mutual inductor with the second mutual inductor, the first branch comprising one or more Josephson junctions (JJs) coupled in series; and
- a second branch coupling the first mutual inductor with the second mutual inductor, the second branch comprising the SQUID and the DC current source.

12. The system of claim **11**,
- the second branch further comprising a third mutual inductor having an input port coupled with the DC current source, and
- the SQUID comprising a first JJ coupled in parallel with a series coupling of a second JJ and an output port of the third mutual inductor.

13. The system of claim **12**,
- the second branch further comprising one or more JJs coupled in series with the SQUID.

14. The system of claim **12**, wherein the DC current source is configured to supply a bias current to the input port, a value of the bias current selected to maximize a coupling between the first AC charge dipole and the second AC charge dipole.

15. An apparatus comprising:
- a first port to couple with a first alternating current (AC) dipole;
- a second port to couple with a second AC dipole; and
- a tunable superinductor coupled with the first port and with the second port.

16. The apparatus of claim **15**, the tunable superinductor circuit comprising:
- a superconducting quantum interference device (SQUID); and
- a direct current (DC) current source.

17. The apparatus of claim **16**, further comprising:
- a first mutual inductor coupled with the first AC charge dipole and with the first port; and

a second mutual inductor coupled with the second AC charge dipole and with the second port.

18. The apparatus of claim **17**, the tunable superinductor comprising:

a first branch coupling the first mutual inductor with the second mutual inductor, the first branch comprising one or more Josephson junctions (JJs) coupled in series; and

a second branch coupling the first mutual inductor with the second mutual inductor, the second branch comprising the SQUID and the DC current source.

19. The apparatus of claim **18**,

the second branch further comprising a third mutual inductor having an input port coupled with the DC current source, and

the SQUID comprising a first JJ coupled in parallel with a series coupling of a second JJ and an output port of the third mutual inductor.

20. The apparatus of claim **19**,

the second branch further comprising one or more JJs coupled in series with the SQUID.

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