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Noguchi et al.

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(54) **QUANTUM GATE DEVICE**

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PCT Pub. Date: **Nov. 25, 2021**

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H10N 69/00 (2023.01)

(52) **U.S. Cl.**
CPC ***H10N 69/00*** (2023.02); ***G06N 10/20*** (2022.01)

(58) **Field of Classification Search**
CPC H10N 69/00; H10N 60/12; G06N 10/20; G06N 10/00; H03K 17/92; H03K 19/195
See application file for complete search history.

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Noguchi et al., "Single-photon quantum regime of artificial radiation pressure on a surface acoustic wave resonator," Aug. 8, 2018, <URL: https://arxiv.org/pdf/1808.03372.pdf>.

(Continued)

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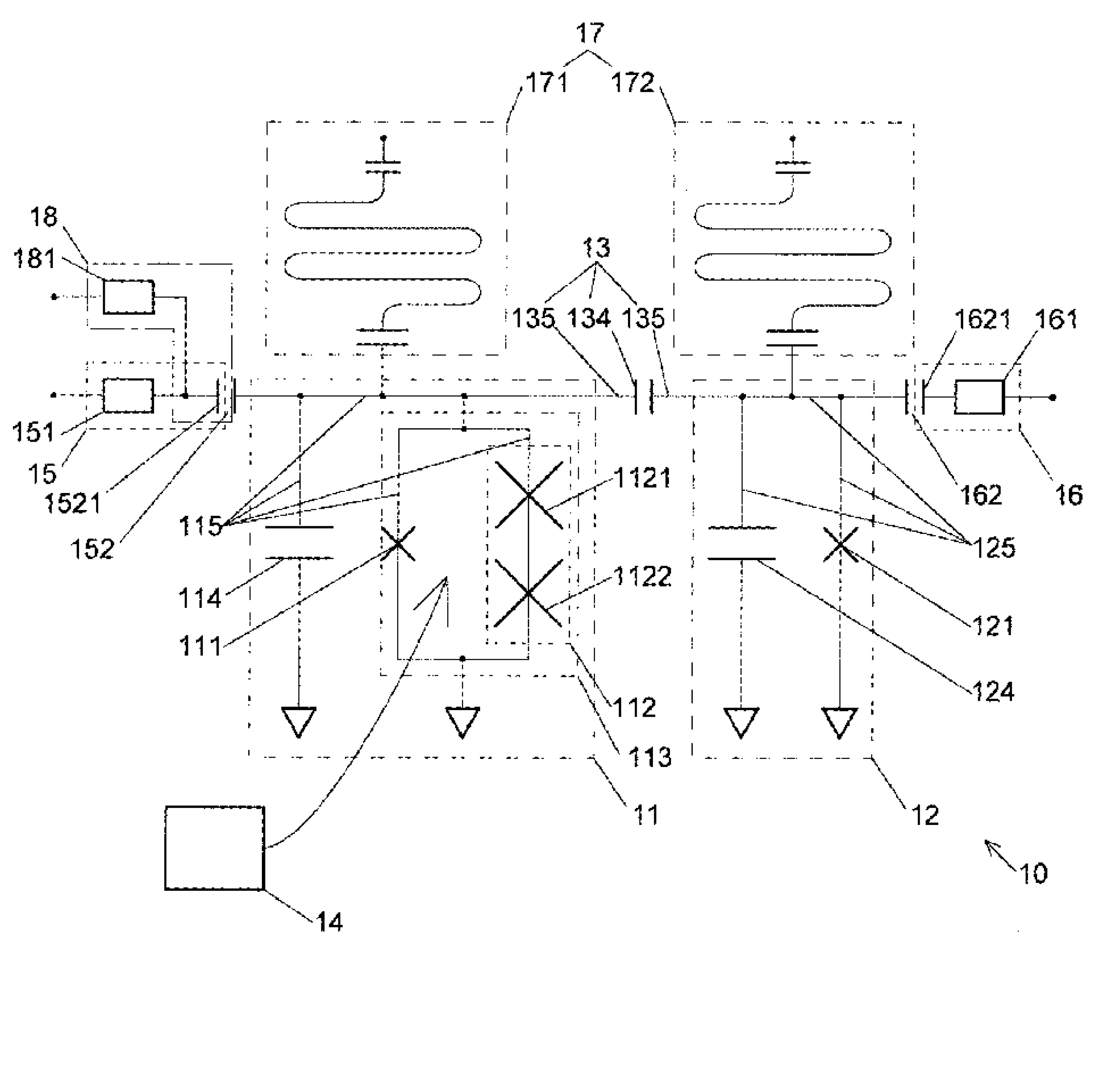
(57) **ABSTRACT**

A quantum gate device includes a first superconducting circuit which includes at least one of Josephson devices in an annular circuit including a superconducting wire and resonates at a first resonance frequency, a second superconducting circuit which includes at least one of Josephson devices in an annular circuit including a superconducting wire and resonates at a second resonance frequency, a connection unit which includes a capacitor and a superconducting wire provided at each electrode of the capacitor and connects the first and second circuits, a magnetic field application means applying a magnetic field to one or both of the first and second circuits, a quantum gate control electromagnetic wave irradiation unit irradiating one of the first and second circuits with a control electromagnetic wave, and an unnecessary transition suppression electromagnetic wave irradiation unit irradiating one of the first and second circuits with an unnecessary interaction suppression electromagnetic wave.

8 Claims, 6 Drawing Sheets



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Mundada et al., “Suppression of Qubit Crosstalk in a Tunable Coupling Superconducting Circuit,” Physical Review Applied, 2019, vol. 12, pp. 054023-1-054023-10.
Ware et al., “Cross-resonance interactions between superconducting qubits with variable detuning,” May 27, 2019, <URL: https://arxiv.org/pdf/1905.11480.pdf>.
Jun. 29, 2021 Written Opinion of the International Searching Authority issued in International Patent Application No. PCT/JP2021/014961.

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Fig. 1

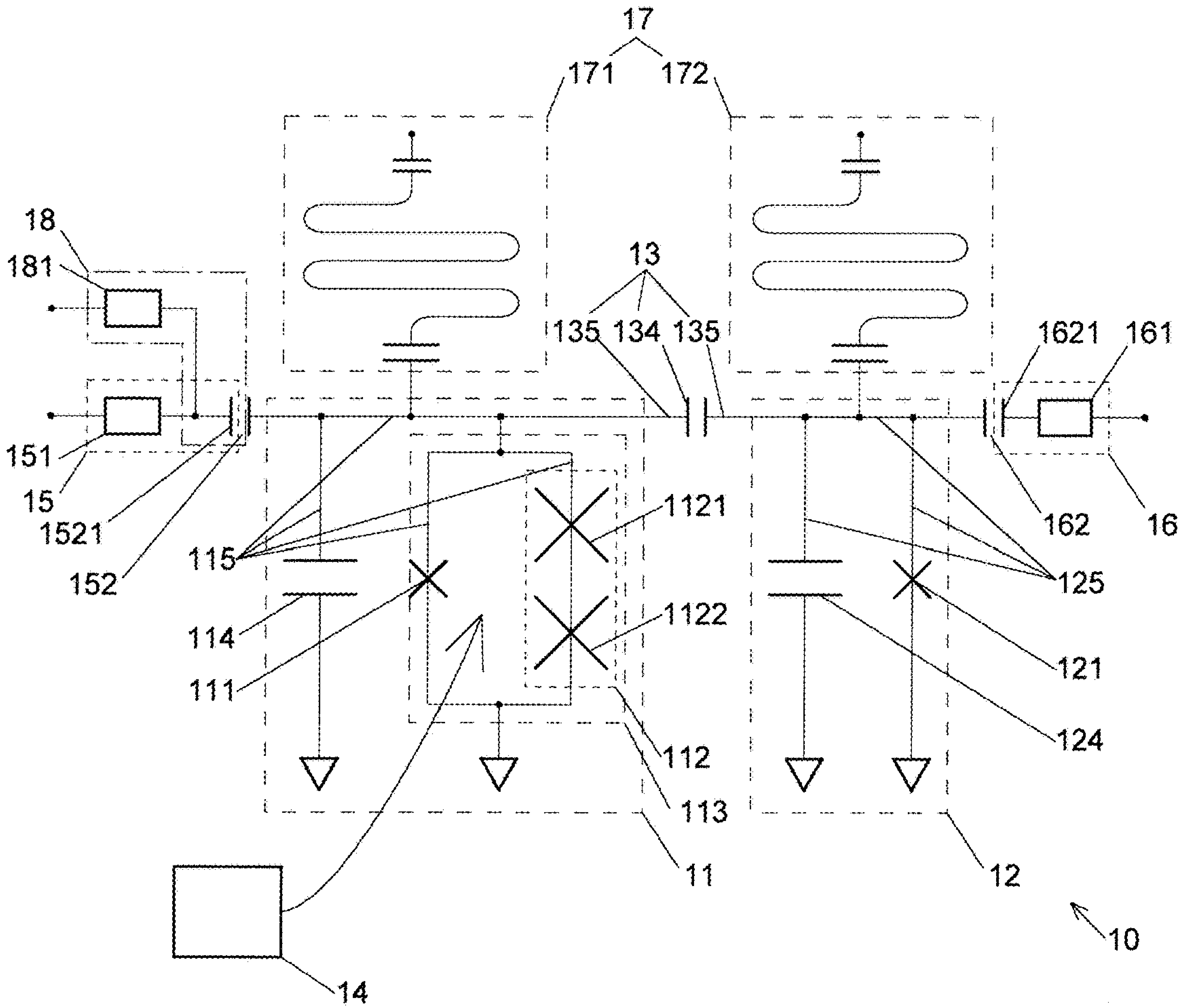


Fig. 2A

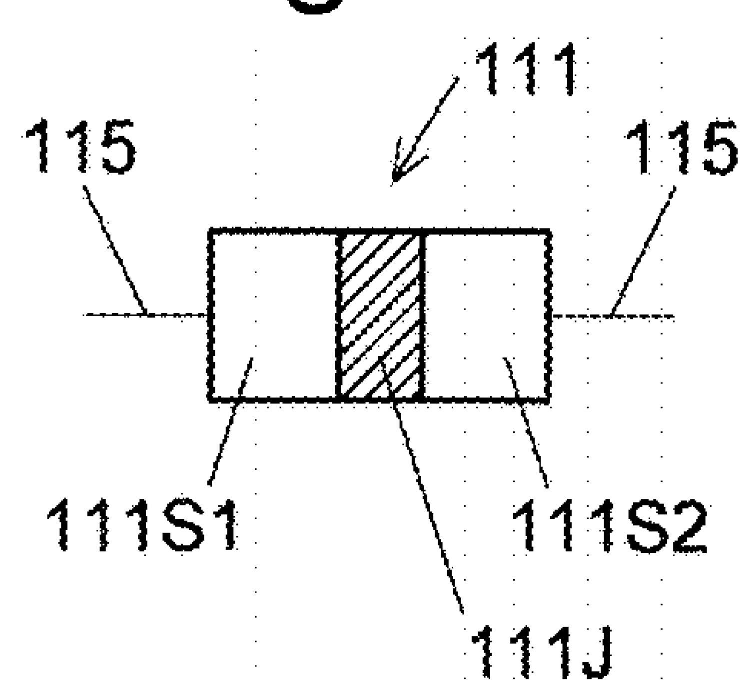


Fig. 2B

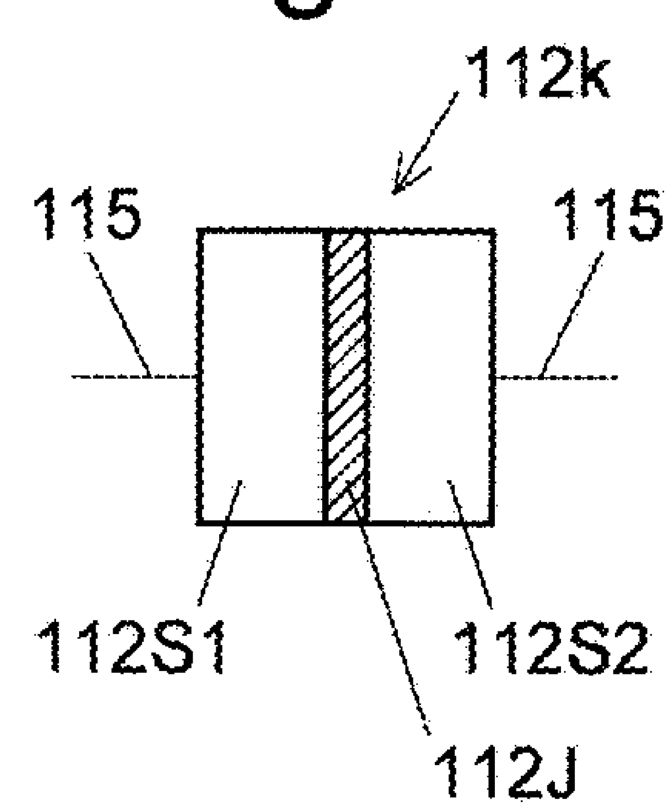
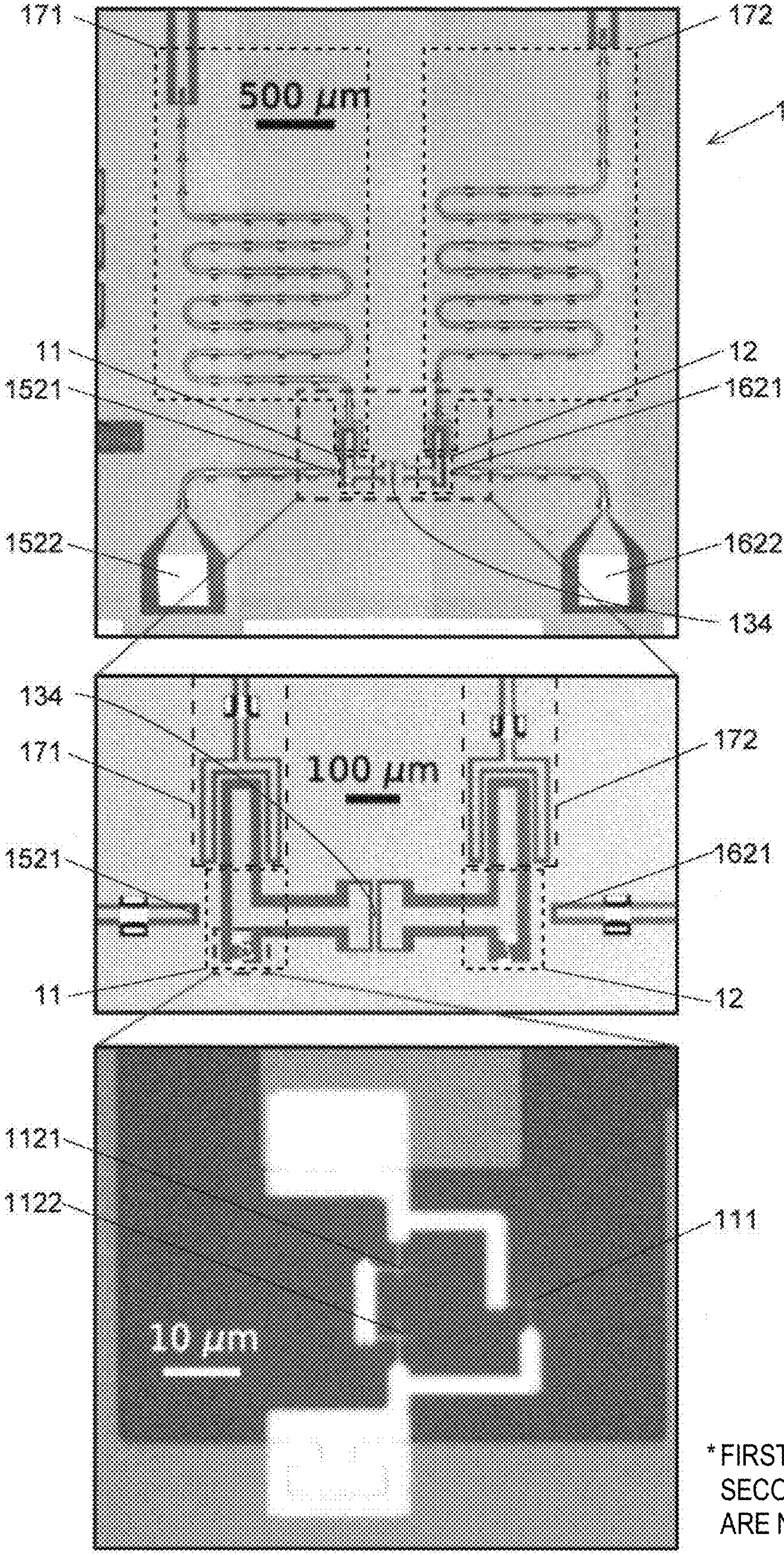
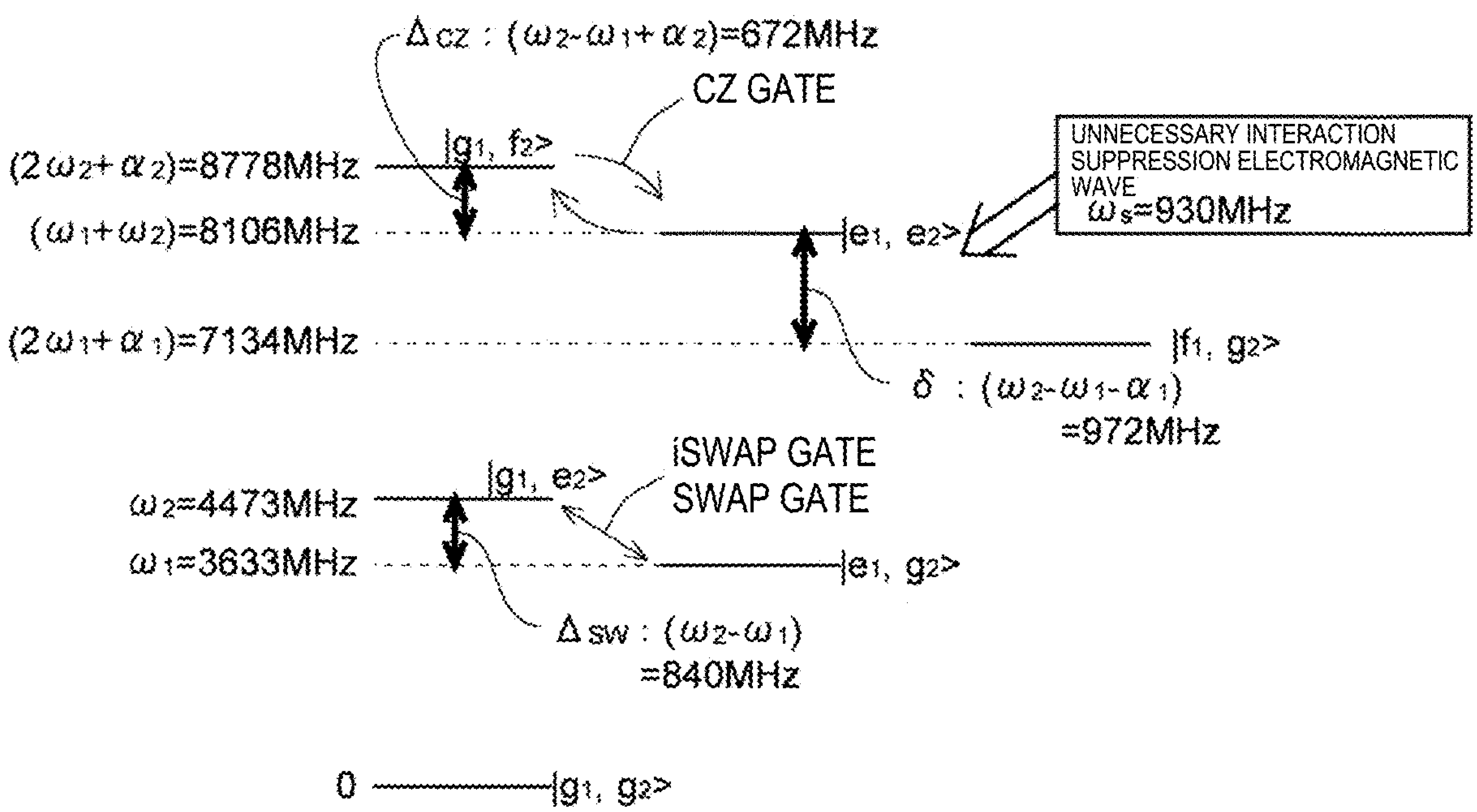


Fig. 3



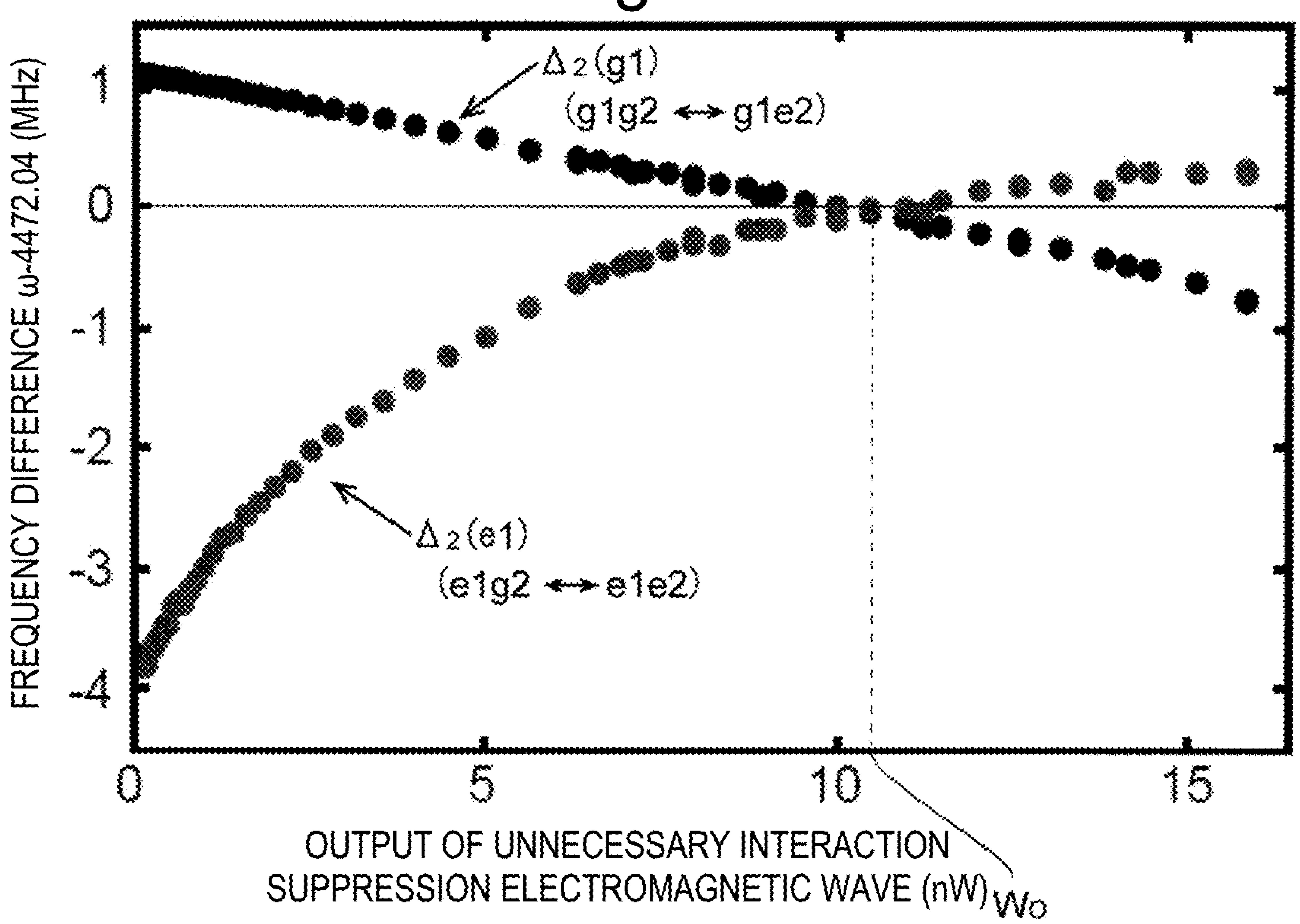
* FIRST CAPACITOR 114 AND SECOND CAPACITOR 214 ARE NOT ILLUSTRATED

Fig. 4



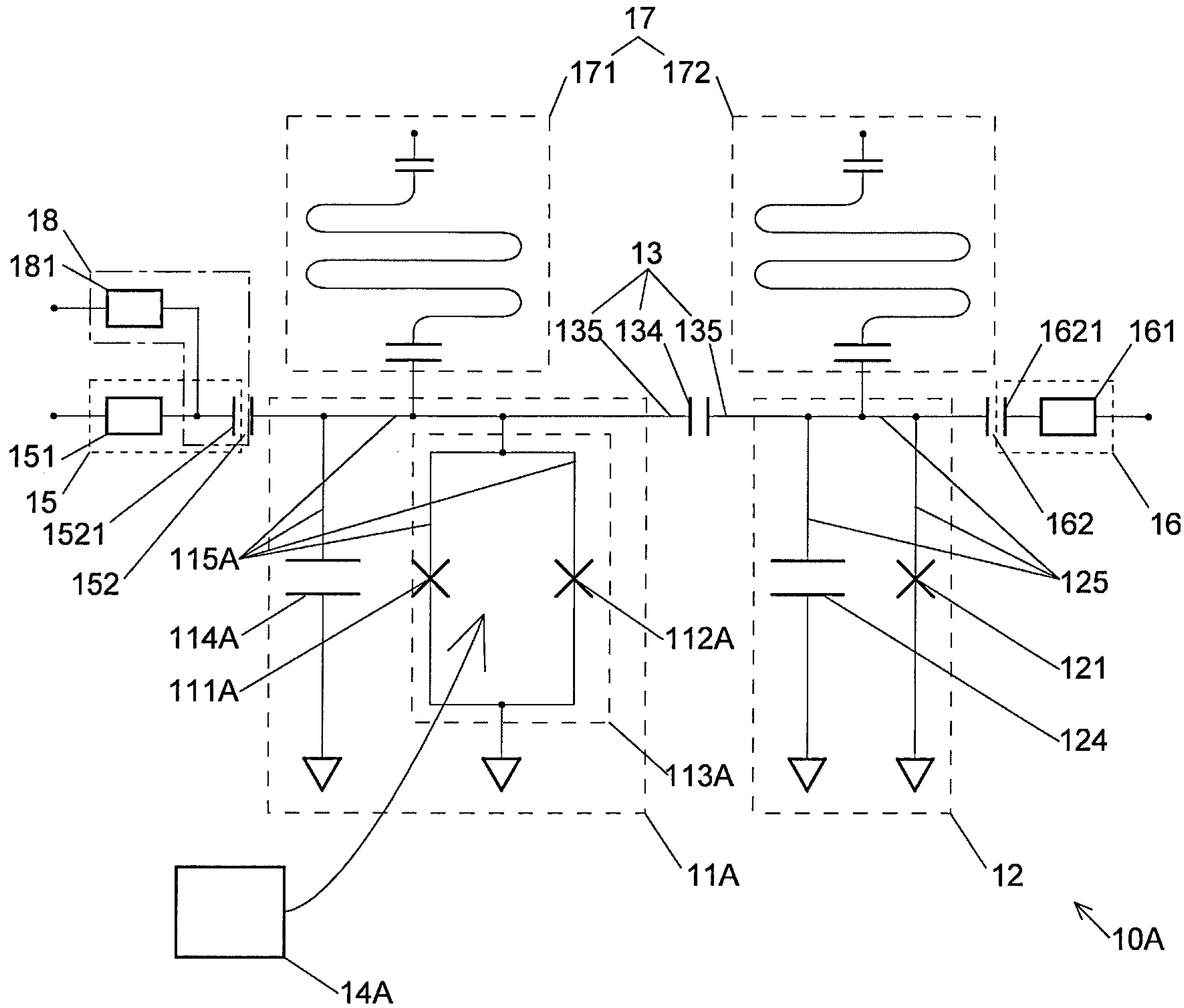
Δcz : (ω2-ω1+α2)=672MHz
CZ GATE
(2ω2+α2)=8778MHz
|g1, f2>
(ω1+ω2)=8106MHz
|e1, e2>
UNNECESSARY INTERACTION SUPPRESSION ELECTROMAGNETIC WAVE
ωs=930MHz
(2ω1+α1)=7134MHz
|f1, g2>
δ : (ω2-ω1-α1) =972MHz
iSWAP GATE
SWAP GATE
ω2=4473MHz
|g1, e2>
ω1=3633MHz
|e1, g2>
Δsw : (ω2-ω1) =840MHz
0
|g1, g2>

Fig. 5



FREQUENCY DIFFERENCE ω-4472.04 (MHz)
1
0
-1
-2
-3
-4
Δ2(g1)
(g1g2 ↔ g1e2)
Δ2(e1)
(e1g2 ↔ e1e2)
0
5
10
15
OUTPUT OF UNNECESSARY INTERACTION SUPPRESSION ELECTROMAGNETIC WAVE (nW)
Wo

Fig. 6



17
171
172
18
181
13
135
134
135
1621
161
151
15
1521
152
115A
114A
111A
112A
113A
125
121
124
162
16
11A
12
10A
14A

Fig. 7

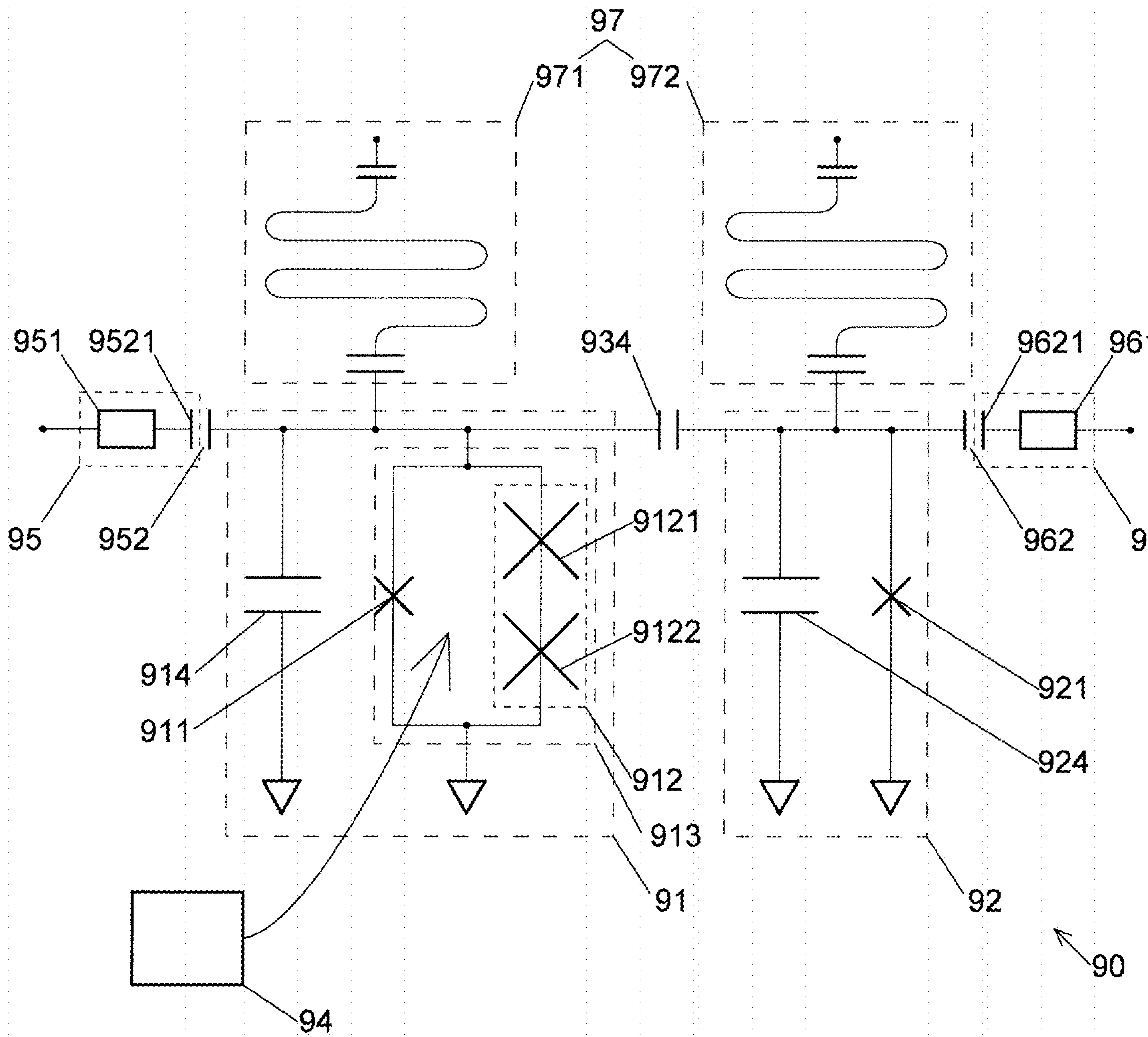

97
971
972
951
9521
934
9621
961
95
952
9121
962
96
914
911
9122
921
924
912
913
91
92
90
94

Fig. 8

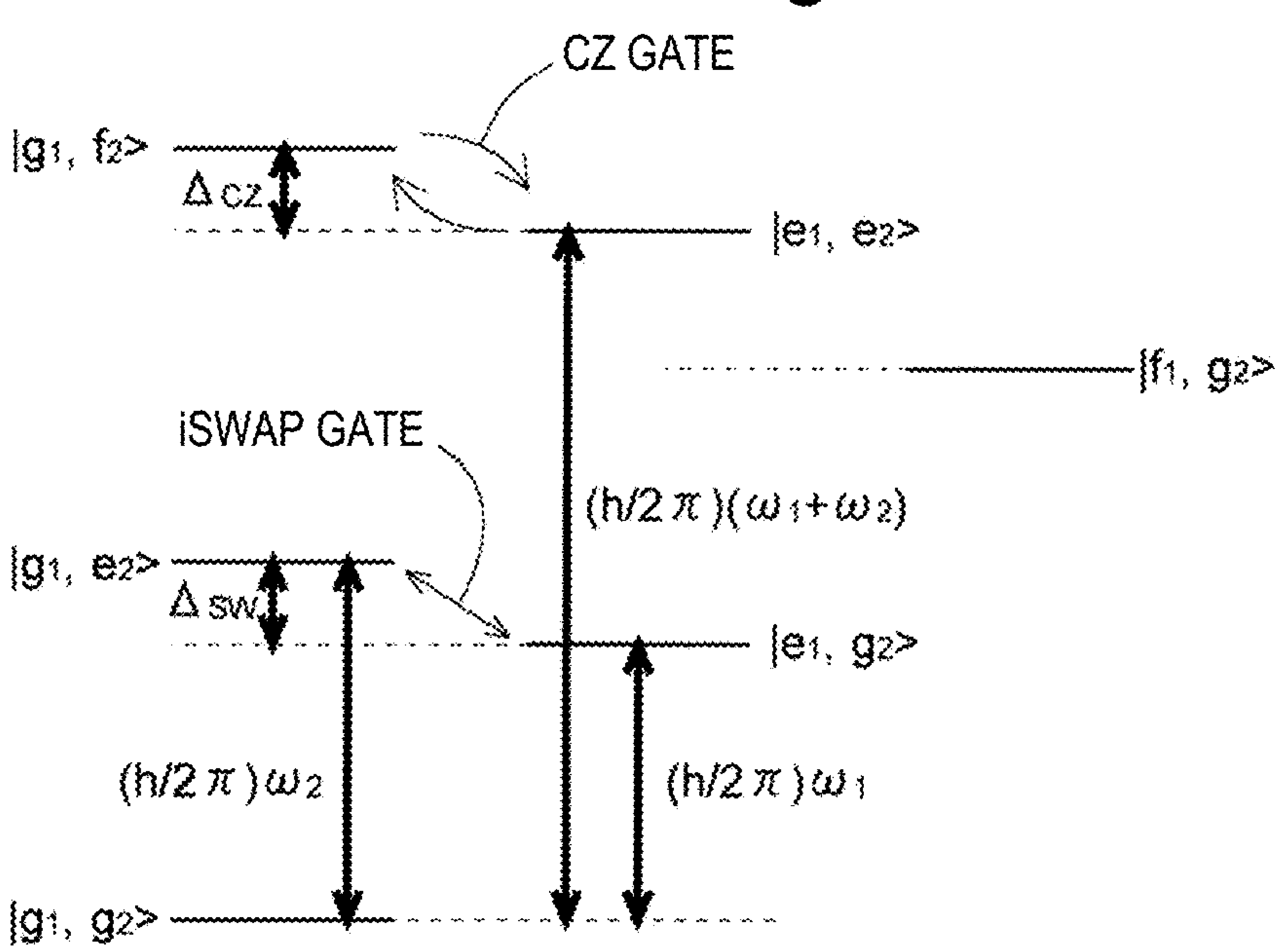
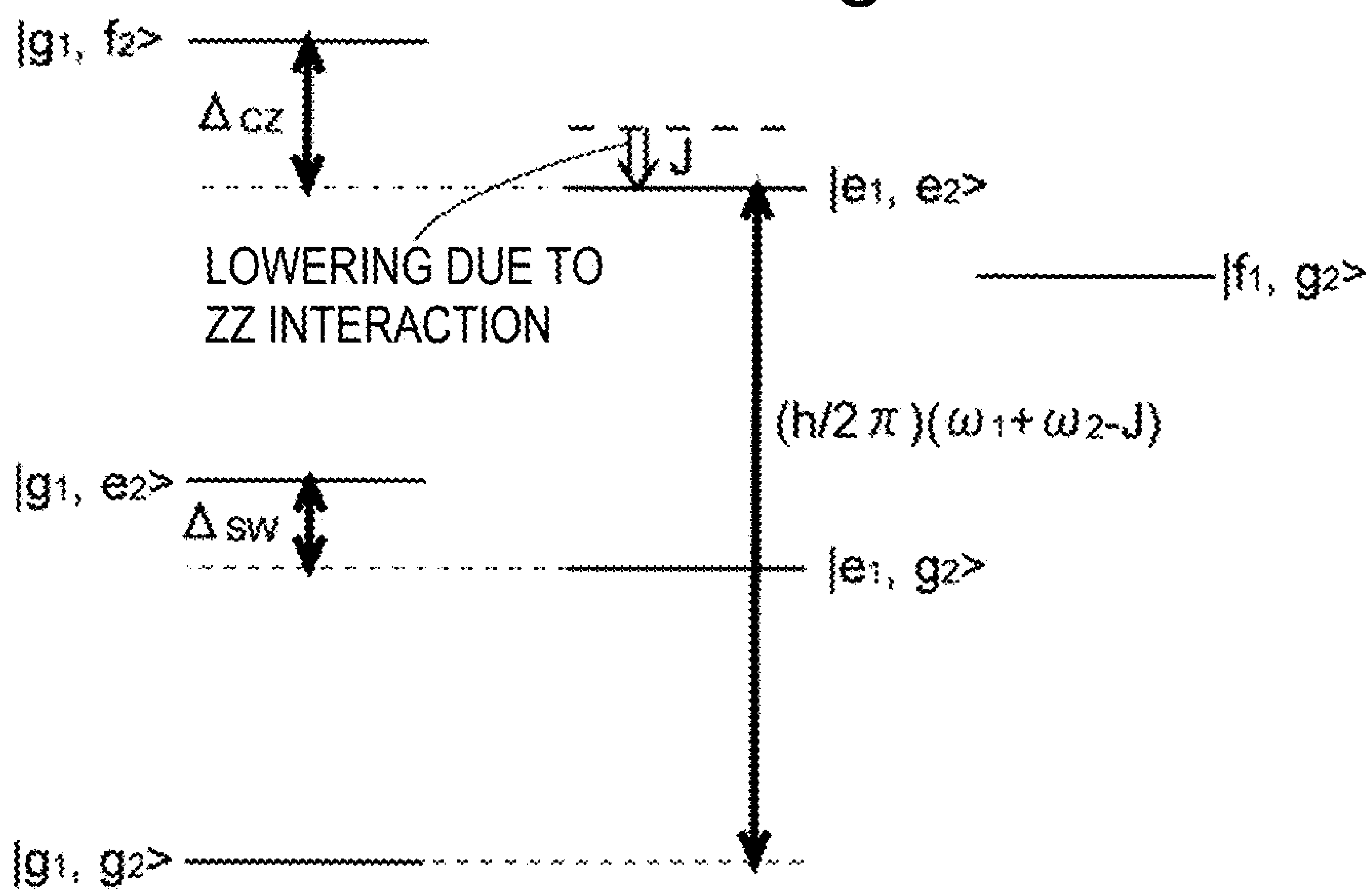

CZ GATE
|g1, f2>
Δcz
|e1, e2>
|f1, g2>
iSWAP GATE
(h/2π)(ω1+ω2)
|g1, e2>
Δsw
|e1, g2>
(h/2π)ω2
(h/2π)ω1
|g1, g2>

Fig. 9


|g1, f2>
ΔCZ
J
|e1, e2>
LOWERING DUE TO
ZZ INTERACTION
|f1, g2>
(h/2π)(ω1+ω2-J)
|g1, e2>
ΔSW
|e1, g2>
|g1, g2>

QUANTUM GATE DEVICE

TECHNICAL FIELD

The present invention relates to a quantum gate device which is a constituent element of a quantum computer.

BACKGROUND ART

Quantum computers are actively researched and developed in recent years. In a conventional computer, calculation is performed using data represented by either one of binary values (generally "0" and "1") as a minimum unit. On the other hand, in a quantum computer, calculation is performed on a superposition state occurring in quantum mechanics, so that calculation capability is expected to be enhanced. When measurement (observation) is performed on the superposition state after calculation, one of discrete eigenstates is obtained as a calculation result. In another expression used in quantum mechanics, calculation is performed in a wave state, and a calculation result is obtained in a particle state.

In a conventional computer, an operation called a logic gate is performed, in which data is input, a logical operation such as logical conjunction (AND), logical disjunction (OR), or negation (NOT) is performed, and the result of the logical operation is output. Similarly, in a quantum computer, an operation called a quantum gate is performed, in which data is input and a predetermined logical operation is performed. A device that performs such an operation is referred to as a quantum gate device.

Non Patent Literature 1 describes a partial superconducting circuit serving as a constituent element of a quantum gate device. The partial superconducting circuit described in Non Patent Literature 1 includes, similarly to a first superconducting circuit (referred to as "first superconducting circuit **91**") illustrated in FIG. **7** of the present application, one first Josephson device **911** and a second Josephson device group **912** in which n (n is an integer of two or more, and FIG. **7** illustrates an example in which n=2) second Josephson devices **9121**, **9122**, . . . are connected in series by a superconducting wire, which is a wire made from a superconductor, are annularly connected by a superconducting wire. The first superconducting circuit **91** illustrated in FIG. **7** of the present application is configured by annularly connecting a partial superconducting circuit **913** and a capacitor (referred to as "first capacitor" in the present description) **914** by a superconducting wire. In each of the first Josephson device **911** and the second Josephson devices **9121**, **9122**, . . . , a thin film made from an insulator is sandwiched between two superconductors. As each of the second Josephson devices **9121**, **9122**, . . . , a device having Josephson energy higher than n times (here, n is the same as the number n of the second Josephson devices **9121**, **9122** . . .) the first Josephson device **911** is used. The first superconducting circuit **91** is a circuit equivalent to an LC resonance circuit including a coil and a capacitor. A resonance frequency of the first superconducting circuit **91** is set to ω_1.

Non Patent Literature 2 describes, as illustrated in FIG. **7** of the present application, that a quantum gate device **90** is configured by combining a superconducting circuit (first superconducting circuit **91**) and another superconducting circuit (second superconducting circuit **92** in FIG. **7**) generally called transmon. The second superconducting circuit **92** is formed by annularly connecting a Josephson device **921** and a capacitor (referred to as a "second capacitor" in the present description) **924** by a superconducting wire. The second superconducting circuit **92** is also a circuit equivalent to an LC resonance circuit. A resonance frequency of the second superconducting circuit **92** is set to ω_2.

The quantum gate device **90** includes a circuit in which the first superconducting circuit **91** and the second superconducting circuit **92** are connected by a superconducting wire provided with a capacitor (referred to as a "connection capacitor" in the present description) **934**. The quantum gate device **90** further includes a magnetic field application unit **94** which applies a static magnetic field to the partial superconducting circuit **913**, a first quantum gate control electromagnetic wave irradiation unit **95** which irradiates the first superconducting circuit **91** with an electromagnetic wave of a first predetermined frequency, and a second quantum gate control electromagnetic wave irradiation unit **96** which irradiates the second superconducting circuit **92** with an electromagnetic wave of a second predetermined frequency. Hereinafter, an electromagnetic wave emitted by the first quantum gate control electromagnetic wave irradiation unit **95** and the second quantum gate control electromagnetic wave irradiation unit **96** is referred to as "control electromagnetic wave". The first quantum gate control electromagnetic wave irradiation unit **95** includes a radio-frequency power supply **951** and an electromagnetic wave irradiation electrode **9521** provided to face the first superconducting circuit **91** and to which radio-frequency voltage is applied between the electromagnetic wave irradiation electrode **9521** and the ground. The second quantum gate control electromagnetic wave irradiation unit **96** includes a radio-frequency power supply **961** and an electromagnetic wave irradiation electrode **9621** similar to the first quantum gate control electromagnetic wave irradiation unit **95**. The electromagnetic wave irradiation electrode **9521** (**9621**) is represented as one electrode of a capacitor **952** (**962**) connected to the first superconducting circuit **91** (second superconducting circuit **92**) in the equivalent circuit illustrated in FIG. **7**. While application of a magnetic field by the magnetic field application unit **94** is always performed during operation of the quantum gate device **90**, irradiation of a control electromagnetic wave from the first quantum gate control electromagnetic wave irradiation unit **95** and the second quantum gate control electromagnetic wave irradiation unit **96** is performed at a predetermined timing as described later. Further, the quantum gate device **90** includes a first measurement unit **971** which measures an energy state and a phase (described later) of the first superconducting circuit **91** and a second measurement unit **972** which measures an energy state and a phase of the second superconducting circuit **92**. The first measurement unit **971** and the second measurement unit **972** are collectively referred to as "measurement unit **97**".

The first superconducting circuit **91** functions as a quantum bit having one-bit information represented by using two states of a ground state (referred to as "g**1**") and a first excited state (e**1**). The second superconducting circuit **92** functions as a quantum bit having one-bit information represented by using two states of a ground state (g**2**) and a first excited state (e**2**). In the quantum gate device **90** as a whole, there are four energy states "g**1**g**2**", "e**1**g**2**", "g**1**e**2**", and "e**1**e**2**" formed by interaction of these two quantum bits. An energy difference between "g**1**g**2**" and "e**1**g**2**" is $(h/2\pi)\omega_1$, an energy difference between "g**1**g**2**" and "g**1**e**2**" is $(h/2\pi)\omega_2$, and an energy difference between "g**1**g**2**" and "e**1**e**2**" is $(h/2\pi)\times(\omega_1+\omega_2)$ (h is the Planck constant). FIG. **8** illustrates each energy state in a case where $\omega_1<\omega_2$.

The phase refers to a phase φ used when a quantum bit in a superposed state of two states $|g\rangle$ (g**1** of the first superconducting circuit **91** or g**2** of the second superconducting circuit **92** in the quantum gate device **90**) and |e> (e**1** of the first superconducting circuit **91** or e**2** of the second superconducting circuit **92**) is represented as a wave of A|g>+(cos φ+i sin φ)B|e>. Here, A and B are both real numbers, and satisfy a condition of $A^2+B^2=1$. At this time, the probability that |g> is observed is A^2, and a probability that |e> is observed is B^2, and neither of them depends on the phase φ.

Quantum gates that can be operated by the quantum gate device **90** includes a quantum gate called an iSwap gate. In the iSwap gate, first, the first quantum gate control electromagnetic wave irradiation unit **95** irradiates the first superconducting circuit **91** with a control electromagnetic wave having the frequency ω_1 or ω_2 to set the energy state to either "g**1**e**2**" or "e**1**g**2**". This state is referred to as an initial state. Next, when the first quantum gate control electromagnetic wave irradiation unit **95** irradiates the first superconducting circuit **91** with a control electromagnetic wave having a difference frequency $|\omega_2-\omega_1|$ corresponding to the energy difference $\Delta_{SW}=(h/2\pi)|\omega_2-\omega_1|$ between "g**1**e**2**" and "e**1**g**2**", the first superconducting circuit **91** and the second superconducting circuit **92** resonate and interact with each other. By the above, operation is repeated in such a manner that, in a case where the initial state is "g**1**e**2**", the energy state changes to "ie**1**g**2**" (i is the imaginary unit), "−g**1**e**2**", "−ie**1**g**2**", and the like and returns to "g**1**e**2**", and in a case where the initial state is "e**1**g**2**", the energy state changes to "ig**1**e**2**", "−e**1**g**2**", "−ig**1**e**2**", and the like and returns to "e**1**g**2**". Here, "i", "−", and "−i" mean that the phase is changed by 90°, 180°, and 270°, respectively. Then, after predetermined time elapses from start of irradiation of the control electromagnetic wave, the irradiation of the control electromagnetic wave is stopped, and then the measurement is performed by the measurement unit **97**. As a result, the energy state changes from "g**1**e**2**" before irradiation to "ie**1**g**2**", or from "e**1**g**2**" before irradiation to "ig**1**e**2**" (see an arrow indicated by a solid line in FIG. **8**). This operation is referred to as an iSwap gate because it means exchanging (swapping) two pieces of data. Note that the iSwap gate does not affect a phase difference between the first superconducting circuit **91** and the second superconducting circuit **92**. Further, the second quantum gate control electromagnetic wave irradiation unit **96** is not used in the iSwap gate.

Further, as another quantum gate that can be operated by the quantum gate device **90**, there is one called a CZ gate. In the CZ gate, "e**1**e**2**" is set as an initial state, and further, one of energy states in which one of the first superconducting circuit **91** and the second superconducting circuit **92** is in a second excited state (denoted as "f**1**" or "f**2**") and the other is in a ground state is used. Hereinafter, a case where an energy state of "g**1**f**2**" in which the first superconducting circuit **91** is in the ground state and the second superconducting circuit **92** is in the second excited state is used will be described as an example. First, the first superconducting circuit **91** is irradiated with a control electromagnetic wave having the frequency ω_1 from the first quantum gate control electromagnetic wave irradiation unit **95**, and the second superconducting circuit **92** is irradiated with a control electromagnetic wave having the frequency ω_2 from the second quantum gate control electromagnetic wave irradiation unit **96**, so that the energy state is set to the initial state "e**1**e**2**". Next, when the first superconducting circuit **91** is irradiated with a control electromagnetic wave having a frequency corresponding to an energy difference Δ_{CZ} between "g**1**f**2**" and "e**1**e**2**" from the quantum gate control electromagnetic wave irradiation unit **95**, two energy states of "e**1**e**2**" and "g**1**f**2**" are in a state of resonance. During occurrence of this resonance, the phase is inverted, that is, changed by 180°, every time excitation from "e**1**e**2**" to "g**1**f**2**" and returning to "e**1**e**2**" occurs once. Then, when the control electromagnetic wave is stopped after irradiation with the control electromagnetic wave is performed for predetermined time and phase inversion is generated odd number of times, the phase is inverted from "e**1**e**2**" before the irradiation. Such a state in which the phase is inverted is written as "−e**1**e**2**". This inverted state can be measured by the measurement unit **97**.

CITATION LIST

Non Patent Literature

Non Patent Literature 1: Atsushi Noguchi, and three others, "Single-photon quantum regime of artificial radiation pressure on a surface acoustic wave resonator", [online], Aug. 9, 2018, arXiv, [searched on Apr. 28, 2020], Internet

Non Patent Literature 2: Atsushi Noguchi, "Quantum gate with a radiation pressure interaction between superconducting qubits", [online], Apr. 23, 2019, Center for Emergent Matter Science, Institute of Physical and Chemical Research, [searched on Apr. 28, 2020], Internet

Non Patent Literature 3: Pranav Mundada, and three others, "Suppression of Qubit Crosstalk in a Tunable Coupling Superconducting Circuit", PHYSICAL REVIEW APPLIED, (USA), American Physical Society, Nov. 11, 2019, Vol. 12, No. 5, pp. 054023-1 to 054023-10

Non Patent Literature 4: Matthew Ware, and five others, "Cross-resonance interactions between superconducting qubits with variable detuning", [online], May 27, 2019, arXiv, [searched on Apr. 28, 2020], Internet

SUMMARY OF INVENTION

Technical Problem

In the above description, a frequency of the control electromagnetic wave is determined based on the value of energy in each energy state obtained without considering an interaction occurring between the first superconducting circuit **91** and the second superconducting circuit **92**. However, in practice, there is an extra interaction (See Non Patent Literatures 3 and 4) called a ZZ interaction between the first superconducting circuit **91** and the second superconducting circuit **92**. For this reason, the value of energy in each energy state of one superconducting circuit depends on an energy state of the other superconducting circuit. For example, the energy difference between "g**1**g**2**" and "e**1**e**2**" is $(h/2\pi)\times(\omega_1+\omega_2)$ as described above if the interaction between the first superconducting circuit **91** and the second superconducting circuit **92** is not considered, but actually becomes $(h/2\pi)\times(\omega_1+\omega_2-J)$ due to the ZZ interaction of energy J (FIG. **9**). Further, when the second superconducting circuit **92** is in a superposition state of g**2** and e**2**, the energy state of the first superconducting circuit **91** cannot be determined only by g**1** and e**1**, and the first superconducting circuit **91** has two resonance frequencies different from the resonance frequency due to the energy difference between g**1** and e**1** when there is no ZZ interaction. When such two resonance frequencies exist, operation of a quantum bit cannot be correctly controlled by a control electromagnetic wave having a single frequency, and a phase due to a deviation between the two resonance frequencies occurs.

Further, such a problem caused by the ZZ interaction is not limited to the quantum gate device described in Non Patent Literature 2, and may similarly occur in a quantum gate device obtained by combining two (or more) superconducting circuits including at least one Josephson device in an annular circuit including a superconductor. Examples of such a superconducting circuit include a superconducting circuit having a partial superconducting circuit (corresponding to a configuration in which the second Josephson device group in the partial superconducting circuit described in Non Patent Literature 1 is replaced with only one Josephson device) in which two Josephson devices are annularly connected by a superconducting wire, in which the partial superconducting circuit and a capacitor are annularly connected by a superconducting wire (see FIG. 1 of Non Patent Literature 4).

An object of the present invention is to provide a quantum gate device in which two or more superconducting circuits having a Josephson device are combined, the quantum gate device being capable of suppressing influence of an extra ZZ interaction.

Solution to Problem

A quantum gate device according to the present invention made to solve the above problems includes:

a) a first superconducting circuit including at least one Josephson device in an annular circuit including a superconducting wire, the first superconducting circuit being configured to resonate at a first resonance frequency;

b) a second superconducting circuit including at least one Josephson device in an annular circuit including a superconducting wire, the second superconducting circuit being configured to resonate at a second resonance frequency different from the first resonance frequency;

c) a connection unit including a capacitor and a superconducting wire provided at each of both electrodes of the capacitor, the connection unit being configured to connect the first superconducting circuit and the second superconducting circuit;

d) a magnetic field application means configured to apply a magnetic field to one or both of the first superconducting circuit and the second superconducting circuit;

e) a quantum gate control electromagnetic wave irradiation unit configured to irradiate one of the first superconducting circuit and the second superconducting circuit with a control electromagnetic wave which is an electromagnetic wave having a control frequency corresponding to an original energy difference between two energy states contributing to operation of a quantum gate among a plurality of quantized energy states formed by the first superconducting circuit and the second superconducting circuit; and

f) an unnecessary interaction suppression electromagnetic wave irradiation unit configured to irradiate one of the first superconducting circuit and the second superconducting circuit with an unnecessary interaction suppression electromagnetic wave which is an electromagnetic wave having an unnecessary interaction suppression frequency, the unnecessary interaction suppression frequency being a frequency between a first frequency and a second frequency, and differing by 10 MHz or more from a frequency corresponding to an original energy difference between arbitrarily selected two energy states among a plurality of the energy states, where the first frequency is a frequency corresponding to an original energy difference between a first energy state that is highest and a second energy state that is second highest in three energy states among a plurality of the energy states, and the second frequency is a frequency corresponding to an original energy difference between the second energy state and a third energy state having lowest energy.

The "original energy difference" refers to the energy difference between two energy states in a state where there is no influence by ZZ interaction between the first superconducting circuit and the second superconducting circuit.

In the quantum gate device according to the present invention, operation of a quantum gate is performed by irradiating one of the first superconducting circuit and the second superconducting circuit with a control electromagnetic wave having a control frequency which is a frequency corresponding to an original energy difference between two energy states contributing to the operation of the quantum gate among a plurality of quantized energy states formed by the first superconducting circuit and the second superconducting circuit for predetermined time by using a quantum gate control electromagnetic wave irradiation unit while applying a magnetic field to one or both of the first superconducting circuit and the second superconducting circuit by the magnetic field application means. For example, in a case where the first superconducting circuit and the second superconducting circuit in the quantum gate device according to the present invention are the first superconducting circuit **91** and the second superconducting circuit **92** described in Non Patent Literature 2 described above, the two energy states correspond to "g**1**e**2**" and "e**1**g**2**", or "e**1**e**2**" and "g**1**f**2**". In a case of "g**1**e**2**" and "e**1**g**2**", the quantum gate operates as an iSwap gate or a swap gate to be described later, and in a case of "e**1**e**2**" and "g**1**f**2**", the quantum gate operates as a CZ gate.

Furthermore, in the quantum gate device according to the present invention, the unnecessary interaction suppression electromagnetic wave irradiation unit irradiates one of the first superconducting circuit and the second superconducting circuit with an unnecessary interaction suppression electromagnetic wave having an unnecessary interaction suppression frequency which is a frequency (however, for a reason described later, a frequency having a difference of less than 10 MHz from the first frequency and the second frequency is not used) between the first frequency which is a frequency corresponding to an original energy difference between the first energy state that is highest and the second energy state having second highest energy in three energy states among a plurality of the energy states and the second frequency which is a frequency corresponding to an original energy difference between the second energy state and the third energy state having lowest energy. For example, in a case where the first superconducting circuit and the second superconducting circuit in the quantum gate device according to the present invention are the first superconducting circuit **91** and the second superconducting circuit **92** described in Non Patent Literature 2 described above, when the first energy state is "g**1**f**2**", the second energy state is "e**1**e**2**", and the third energy state is "f**1**g**2**", the first frequency is the frequency corresponding to an original energy difference between "g**1**f**2**" and "e**1**e**2**", and the second frequency is the frequency corresponding to an original energy difference between "e**1**e**2**" and "f**1**g**2**". By irradiation of the unnecessary interaction suppression electromagnetic wave, it is possible to suppress remaining of extra ZZ interaction and to suppress deviation of the three energy states from an original energy value.

When irradiation with an electromagnetic wave having a frequency corresponding to arbitrarily selected two energy states among a plurality of the energy states as an unnecessary interaction suppression electromagnetic wave is performed, undesirable interaction occurs between the two energy states. For this reason, an electromagnetic wave having a frequency close to such a frequency is not used as an unnecessary interaction suppression electromagnetic wave. Normally, in a quantum gate, two energy states having an energy difference corresponding to a frequency of about several hundred MHz to several GHz are used. Therefore, if the unnecessary interaction suppression frequency is different from frequencies corresponding to arbitrarily selected two energy states by 10 MHz or more, undesirable interaction can be prevented. Note that, since "plurality of the energy states" mentioned here also include the first to third energy states, "frequencies corresponding to arbitrarily selected two energy states among a plurality of the energy states" also include the first frequency and the second frequency. Therefore, an electromagnetic wave close to the first frequency and the second frequency (differs from them by less than 10 MHz) is also not used as an unnecessary interaction suppression electromagnetic wave.

Preferably, the unnecessary interaction suppression electromagnetic wave irradiation unit continues irradiation of the unnecessary interaction suppression electromagnetic wave not only while irradiation of the control electromagnetic wave by the quantum gate control electromagnetic wave irradiation unit is performed, but also until operation of a quantum gate ends (an energy state and/or a phase of the first superconducting circuit and the second superconducting circuit are measured) from start of irradiation of the control electromagnetic wave. By the above, it is possible to suppress influence of extra ZZ interaction not only during operation of a quantum gate but also during a period from the end of operation of the quantum gate to output of an operation result.

In the quantum gate device according to the present invention, energy of each of a plurality of the energy states changes according to a difference in output of the unnecessary interaction suppression electromagnetic wave. In view of the above, desirably, output of the unnecessary interaction suppression electromagnetic wave is adjusted so that magnitude of a difference between energy differences of two sets having the same original energy difference among sets of energy states including arbitrarily selected two energy states among a plurality of the energy states is close to zero, specifically, falls within a range of −0.1 MHz to 0.1 MHz. For example, in a case where the first superconducting circuit and the second superconducting circuit in the quantum gate device according to the present invention are the first superconducting circuit **91** and the second superconducting circuit **92** described in Non Patent Literature 2 described above, an original energy difference between "g**1**e**2**" and "g**1**g**2**" and an original energy difference between "e**1**e**2**" and "e**1**g**2**" are both ω_2, that is, equal. In view of the above, preferably, by an experiment (in a state where deviation from an original energy difference occurs due to ZZ interaction if there is no irradiation with the unnecessary interaction suppression electromagnetic wave) or calculation in consideration of ZZ interaction, an energy difference between "g**1**e**2**" and "g**1**g**2**" and an energy difference between "e**1**e**2**" and "e**1**g**2**" is obtained while output of the unnecessary interaction suppression electromagnetic wave is changed, and output of the unnecessary interaction suppression electromagnetic wave by which a difference between them is in a range of −0.1 MHz to 0.1 MHz is obtained.

As the quantum gate device according to the present invention, the quantum gate device obtained by adding the unnecessary interaction suppression electromagnetic wave irradiation unit to the quantum gate device described in Non Patent Literature 2 can be suitably used. That is, in the quantum gate device according to the present invention, preferably,

the first superconducting circuit includes a partial superconducting circuit in which a first Josephson device and a second Josephson device group in which n second Josephson devices having Josephson energy higher than n times Josephson energy of the first Josephson device are connected in series by a wire made from a superconductor, in which the partial superconducting circuit and a capacitor are connected annularly by a wire made from a superconductor, and

the second superconducting circuit includes one Josephson device and a capacitor connected annularly by a wire made from a superconductor.

Note, a magnitude relationship between Josephson energy of the Josephson device in the second superconducting circuit and Josephson energy of each of the first and second Josephson devices in the first superconducting circuit does not matter.

As described above, in a case of using the configuration in which the unnecessary interaction suppression electromagnetic wave irradiation unit is added to the quantum gate device described in Non Patent Literature 2, the quantum gate control electromagnetic wave irradiation unit can cause the quantum gate device to operate as an iSwap gate as long as the unnecessary interaction suppression electromagnetic wave irradiation unit irradiates at least the first superconducting circuit with a control electromagnetic wave. On the other hand, in a case where the quantum gate device is operated as a CZ gate and/or a swap gate to be described later, one which irradiates the first superconducting circuit and the second superconducting circuit are with control electromagnetic waves having frequencies different from each other is used as the quantum gate control electromagnetic wave irradiation unit.

Advantageous Effects of Invention

According to the present invention, in a quantum gate device in which two or more superconducting circuits having a Josephson device are combined, influence of extra ZZ interaction can be suppressed.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a schematic diagram illustrating an embodiment of a quantum gate device according to the present invention.

FIG. **2**A is a diagram illustrating a first Josephson device included in the quantum gate device of the present embodiment.

FIG. **2**B is a diagram illustrating a second Josephson device included in the quantum gate device of the present embodiment.

FIG. **3** is a photomicrograph showing an example of manufacturing the quantum gate device of the present embodiment (upper photomicrograph), a photomicrograph obtained by enlarging and photographing a part of a region photographed in the upper photomicrograph (middle photomicrograph), and a photomicrograph obtained by enlarging and photographing a part of a region photographed in the middle photomicrograph (lower photomicrograph).

FIG. **4** is a diagram for explaining an energy state that may be taken by the quantum gate device of the present embodiment, operation of three quantum gates (swap gate, iSwap gate, and CZ gate), and irradiation of an unnecessary interaction suppression electromagnetic wave.

FIG. **5** is a graph illustrating a result of an experiment of measuring an energy difference Δ**2**(g**1**) between "g**1**e**2**" and "g**1**g**2**" and an energy difference Δ**2**(e**1**) between "e**1**e**2**" and "e**1**g**2**" while changing output of an unnecessary interaction suppression electromagnetic wave in the quantum gate device of the present embodiment.

FIG. **6** is a schematic diagram illustrating a variation of the quantum gate device according to the present invention.

FIG. **7** is a schematic diagram illustrating an example of a conventional quantum gate device.

FIG. **8** is a diagram illustrating an example of operation of a swap gate and a CZ gate in a conventional quantum gate device.

FIG. **9** is a diagram illustrating an energy state in consideration of a ZZ interaction in a conventional quantum gate device.

DESCRIPTION OF EMBODIMENTS

An embodiment of a quantum gate device according to the present invention will be described with reference to FIGS. **1** to **6**.

(1) Configuration of Quantum Gate Device of Present Embodiment

FIG. **1** is a diagram illustrating an outline of a configuration of a quantum gate device **10** of the present embodiment by an equivalent circuit. The quantum gate device **10** includes a first superconducting circuit **11**, a second superconducting circuit **12**, a connection unit **13**, a magnetic field application unit **14**, a quantum gate control electromagnetic wave irradiation unit (a first quantum gate control electromagnetic wave irradiation unit **15** and a second quantum gate control electromagnetic wave irradiation unit **16**), a measurement unit **17**, and an unnecessary interaction suppression electromagnetic wave irradiation unit **18**.

The first superconducting circuit **11** includes a first Josephson device **111**, a second Josephson device group **112**, and a first capacitor **114**. The first Josephson device **111** is formed by sandwiching a joint portion having a first thin film **111**J formed of an insulator between two superconductors **111**S**1** and **111**S**2** (FIG. **2**A). In the second Josephson device group **112**, n (n is an integer of two or more) second Josephson devices **1121**, **1122**, . . . , **112**n are connected in series by a wiring **115** including a superconductor. Note that, although a case where n=2 is illustrated as an example in FIG. **1**, n may be an integer of three or more. Each second Josephson device **112**k (k is an integer in a range of 1 to n) is obtained by sandwiching a second thin film **112**J made of the same type of insulator as the first thin film **111**J between two superconductors **112**S**1** and **112**S**2** (FIG. **2**B). Here, thickness and areas of the first thin film **111**J and the second thin film **112**J are set so that a value of tunnel resistance in the first Josephson device **111** is larger than n times a value of tunnel resistance in each of the second Josephson devices **112**k. In this manner, Josephson energy of each of the second Josephson devices **112**k is larger than n times Josephson energy of the first Josephson device **111**.

The first Josephson device **111** and the second Josephson device group **112** are annularly connected by the superconducting wire **115**, by which a partial superconducting circuit **113** is formed. Furthermore, the partial superconducting circuit **113** and the first capacitor **114** are connected in parallel by the superconducting wire **115**.

The first superconducting circuit **11** configured as described above is a circuit equivalent to an LC resonance circuit. A resonance frequency of the first superconducting circuit **11** is set to ω_1.

The second superconducting circuit **12** is a transmon in which one Josephson device **121** and one second capacitor **124** are annularly connected by a superconducting wire **125**. The second superconducting circuit **12** is also a circuit equivalent to an LC resonance circuit. A resonance frequency of the second superconducting circuit **12** is set to ω_2.

The connection unit **13** includes a connection unit capacitor **134** and superconducting wires **135** provided on both electrodes of the connection unit capacitor **134**. The first superconducting circuit **11** and the second superconducting circuit **12** are connected by the connection unit **13**.

The magnetic field application unit **14** applies a static magnetic field to the inside of the partial superconducting circuit **113**. Magnitude of the static magnetic field to be applied is not particularly limited as long as the static magnetic field is smaller than a magnetic field that destroys a superconducting state of the superconductors **111**S**1**, **111**S**2**, **112**S**1**, and **112**S**2** of the first Josephson device **111** and the second Josephson devices **112**k and the superconductor of the superconducting wire **115**, but is preferably smaller. For example, the intensity is desirably one by which a magnetic flux of five times or less a magnetic flux quantum is generated in the partial superconducting circuit **113**, and the intensity is more desirably one by which a magnetic flux of one time or less a magnetic flux quantum is generated in the partial superconducting circuit **113**. A preferable magnitude of a static magnetic field is, for example, about 10 μT.

The first quantum gate control electromagnetic wave irradiation unit **15** includes a quantum gate control power supply **151** and an electromagnetic wave irradiation electrode **1521**. The electromagnetic wave irradiation electrode **1521** is represented as one electrode of a capacitor **152** connected to the first superconducting circuit **11** in the equivalent circuit illustrated in FIG. **1**. The quantum gate control power supply **151** applies radio-frequency voltage having a predetermined frequency (control frequency) used for operation as a quantum gate between the electromagnetic wave irradiation electrode **1521** and the ground to irradiate the first superconducting circuit **11** with a control electromagnetic wave having the control frequency.

The second quantum gate control electromagnetic wave irradiation unit **16** includes a quantum gate control power supply **161** and an electromagnetic wave irradiation electrode **1621**, similarly to the first quantum gate control electromagnetic wave irradiation unit **15**. The electromagnetic wave irradiation electrode **1621** is represented as one electrode of a capacitor **162** connected to the second superconducting circuit **12** in the equivalent circuit illustrated in FIG. **1**. The quantum gate control power supply **161** applies radio-frequency voltage having a predetermined control frequency (different from a control frequency in the first quantum gate control electromagnetic wave irradiation unit **15**) between the electromagnetic wave irradiation electrode **1621** and the ground to irradiate the second superconducting circuit **12** with a control electromagnetic wave having the control frequency.

The unnecessary interaction suppression electromagnetic wave irradiation unit **18** includes an unnecessary interaction suppression electromagnetic wave power supply **181** and the electromagnetic wave irradiation electrode **1521**. The electromagnetic wave irradiation electrode **1521** is shared by the first quantum gate control electromagnetic wave irradiation unit **15** and the unnecessary interaction suppression electromagnetic wave irradiation unit **18**. The unnecessary interaction suppression electromagnetic wave power supply **181** applies radio-frequency voltage having a predetermined frequency (unnecessary interaction suppression frequency) different from the control frequency between the electromagnetic wave irradiation electrode **1521** and the ground to irradiate the first superconducting circuit **11** with an unnecessary interaction suppression electromagnetic wave having the unnecessary interaction suppression frequency. Note that the quantum gate control power supply **151** and the unnecessary interaction suppression electromagnetic wave power supply **181** can be shared when mounted by employing a power supply capable of simultaneously generating a plurality of frequencies.

Details of the control frequency and the unnecessary interaction suppression frequency will be described later together with description of operation of the quantum gate device **10**.

The measurement unit **17** includes a first measurement unit **171** which measures an energy state and a phase of the first superconducting circuit **11** and a second measurement unit **172** which measures an energy state and a phase of the second superconducting circuit **12**.

FIG. **3** illustrates a photomicrograph of the quantum gate device **10** which is actually produced. In FIG. **3**, a photomicrograph of the entire quantum gate device **10** is illustrated in the upper part, a photomicrograph of a part of the photomicrograph enlarged and photographed is illustrated in the middle part, and, further, a photomicrograph of a part of the photomicrograph enlarged and photographed is illustrated in the lower part. In FIG. **3**, a portion enclosed by a gray line darker than light gray in the background is a portion where a surface of a substrate made from silicon appears, a light gray portion is made from niobium, and a white portion is made from aluminum. Niobium and aluminum are superconductors. Although not illustrated in this photomicrograph, alumina obtained by oxidizing aluminum is used for a thin film made from an insulator of each of Josephson devices. Note that, in the present invention, the superconductor and the insulator are not limited to these examples, and any material can be used.

FIG. **3** does not illustrate the quantum gate control power supply **151** or the unnecessary interaction suppression electromagnetic wave power supply **181**, but illustrates an electrode **1522** to which the two power supplies are connected in common. Similarly, FIG. **3** does not illustrate the quantum gate control power supply **161**, but illustrates an electrode **1622** to which the power supply is connected. Further, in FIG. **3**, the first capacitor **114** and the second capacitor **124** are not denoted by reference numerals, but the first capacitor **114** is formed between the superconducting wire **115** and the ground, and the second capacitor **124** is formed between the superconducting wire **125** and the ground.

(2) Operation of Quantum Gate Device of Present Embodiment

Hereinafter, operation of the quantum gate device of the present embodiment will be described.

(2-1) Energy State which May be Taken by Quantum Gate Device **10**

The quantum gate device **10** is cooled to the superconducting transition temperature or less by a cooling device, and a static magnetic field is applied from the magnetic field application unit **14** into the partial superconducting circuit **113**. After that, the quantum gate device **10** takes one of a plurality of energy states illustrated in FIG. **4** by irradiation with a control electromagnetic wave having a predetermined control frequency described later from the quantum gate control electromagnetic wave irradiation unit **15** for a predetermined time. FIG. **4** illustrates six energy states of "g**1**g**2**", "e**1**g**2**", "g**1**e**2**", "f**1**g**2**", "e**1**e**2**", and "g**1**f**2**" in which one of a ground state "g**1**", a first excited state "e**1**", and a second excited state "f**1**", which are energy states of the first superconducting circuit **11**, and one of a ground state "g**2**", a first excited state "e**2**", and a second excited state "f**2**", which are energy states of the second superconducting circuit **12**, are combined.

In addition, in FIG. **4**, original energy (in a state in which there is no influence of a ZZ interaction) in each of the six energy states obtained by experiment in the quantum gate device **10** illustrated in FIG. **3** is illustrated in units of frequency with "g**1**g**2**" as a reference (value zero). Values of frequencies below are multiplied by $(h/2\pi)$ to obtain an energy value. Values of these frequencies are 3633 MHz $(=\omega_1)$ for "e**1**g**2**", 4473 MHz $(=\omega_2)$ for "g**1**e**2**", 7134 MHz $(=2\omega_1+\alpha_1$ (α_1 will be described later)) for "f**1**g**2**", 8106 MHz $(=\omega_1+\omega_2)$ for "e**1**e**2**", and 8778 MHz $(=2\omega_2+\alpha_2$ (α_2 will be described later)) for "g**1**f**2**". In the example illustrated in FIG. **4**, since ω_1 is smaller than ω_2, "e**1**g**2**" is smaller than "g**1**e**2**", and "f**1**g**2**" is smaller than "g**1**f**2**". An original difference Δ_{SW} $(=\omega_2-\omega_1)$ between "g**1**e**2**" and "e**1**g**2**" is 840 MHz, an original difference Δ_{CZ} $(=\omega_2-\omega_1+\alpha_2)$ between "g**1**f**2**" and "e**1**e**2**" is 672 MHz, and an original difference δ $(=\omega_2-\omega_1-\alpha_1)$ between "e**1**e**2**" and "f**1**g**2**" is 972 MHz. The value α_1 is defined by a difference between an energy interval between the f**1** state and the e**1** state and an energy interval between the e**1** state and the g**1** state for the energy states g**1**, e**1**, and f**1** in a case where the first superconducting circuit **11** exists alone. Similarly, α_2 is defined by a difference between an energy interval between the f**2** state and the e**2** state and an energy interval between the e**2** state and the g**2** state for the energy states g**2**, e**2**, and f**2** in a case where the second superconducting circuit **12** exists alone. The value α_1 is -132 MHz, and α_2 is -168 MHz.

In the quantum gate device **10** being in such an energy state, suppression of unnecessary interaction in a case where the quantum gate device **10** is operated as one of the three quantum gates, which are an iSwap gate, a CZ gate, and a swap gate, by operation described below will be described. Hereinafter, the initial state is assumed to be "g**1**g**2**".

(2-2) Operation of Each Quantum Gate and Suppression of Unnecessary Interaction

(2-2-1) iSwap Gate

First, the unnecessary interaction suppression electromagnetic wave irradiation unit **18** irradiates the first superconducting circuit **11** with an unnecessary interaction suppression electromagnetic wave having an unnecessary interaction suppression frequency. In the present embodiment, a focus is placed on three energy states of "g**1**f**2**", "e**1**e**2**", and "f**1**g**2**". Then, 930 MHz, which is a frequency between Δ_{CZ}=672 MHz, which is a frequency (the first frequency) corresponding to an original energy difference between "g**1**f**2**" (the first energy state) and "e**1**e**2**" (the second energy state) having highest energy among the three energy states, and δ=972 MHz, which is a frequency (the second frequency) corresponding to an original energy difference between "e**1**e**2**" and "f**1**g**2**" (the third energy state), and is a frequency different by 10 MHz or more from any of original energy differences (for example, Δ_{SW}=840 MHz) between any two energy states including the three energy states, is set as the unnecessary interaction suppression frequency.

Next, the first superconducting circuit **11** is irradiated with a control electromagnetic wave having the frequency ω_1, which is the original control frequency, in a manner superimposed on the unnecessary interaction suppression electromagnetic wave by the first quantum gate control electromagnetic wave irradiation unit **15**, so that the energy state is set to "e**1**g**2**". Subsequently, the first superconducting circuit **11** is irradiated with a control electromagnetic wave having a frequency $((\omega_2-\omega_1)$, 840 MHz in the example of FIG. **4**) corresponding to Δ_{SW}, which is the original control frequency, in a manner superimposed on the unnecessary interaction suppression electromagnetic wave by the first quantum gate control electromagnetic wave irradiation unit **15**. In this manner, the first superconducting circuit **11** and the second superconducting circuit **12** resonate and interact with each other, and operation in which the energy state changes from "g**1**e**2**" to "ie**1**g**2**", "−g**1**e**2**", "−ie**1**g**2**", and returning to "g**1**e**2**" is repeated. Here, "i", "−", and "−i" mean that the phase is changed by 90°, 180°, and 270°, respectively. Then, the irradiation of the control electromagnetic wave is stopped after predetermined time elapses from the start of the irradiation of the control electromagnetic wave. After the above, when measurement is performed by the measurement unit **17**, the energy state changes from "g**1**e**2**" before irradiation to "ie**1**g**2**".

Alternatively, when the first superconducting circuit **11** is irradiated for predetermined time with a control electromagnetic wave having a frequency corresponding to Δ_{SW} which is the original control frequency in a manner superimposed on the unnecessary interaction suppression electromagnetic wave by the first quantum gate control electromagnetic wave irradiation unit **15** from the state where the energy state is "g**1**e**2**", an energy state measured by the measurement unit **17** changes from "e**1**g**2**" before irradiation to "ig**1**e**2**".

As described above, operation in which the energy state changes from "g**1**e**2**" to "ie**1**g**2**" or from "e**1**g**2**" to "ig**1**e**2**", that is, two pieces of data are exchanged (swapped) is performed.

By irradiation of the first superconducting circuit **11** with the unnecessary interaction suppression electromagnetic wave continuously over the entire operation of the iSwap gate, influence of extra ZZ interaction can be suppressed. For this reason, it is possible to prevent an unnecessary phase from being applied when a control electromagnetic wave having the original control frequency is irradiated.

(2-2-2) CZ Gate

First, as in the case of the iSwap gate, the unnecessary interaction suppression electromagnetic wave irradiation unit **18** irradiates the first superconducting circuit **11** with an unnecessary interaction suppression electromagnetic wave having a frequency ω_s. The irradiation of the unnecessary interaction suppression electromagnetic wave is continuously performed over the entire operation of the CZ gate described below.

Next, the first superconducting circuit **11** is irradiated with a control electromagnetic wave having the frequency ω_1 in a manner superimposed on the unnecessary interaction suppression electromagnetic wave by the first quantum gate control electromagnetic wave irradiation unit **15** and the second superconducting circuit **12** is irradiated with a control electromagnetic wave having the frequency ω_2 by the second quantum gate control electromagnetic wave irradiation unit **16**, so that the energy state is set to "e**1**e**2**". Subsequently, the first superconducting circuit **11** is irradiated with a control electromagnetic wave having a frequency $((\omega_2-\omega_1+\alpha_2)$, 672 MHz in the example of FIG. **4**) corresponding to the original energy difference Δ_{CZ} between "g**1**e**2**" and "e**1**g**2**" in a manner superimposed on the unnecessary interaction suppression electromagnetic wave by the first quantum gate control electromagnetic wave irradiation unit **15**. By the above, the first superconducting circuit **11** and the second superconducting circuit **12** resonate and interact with each other, and the energy state alternately takes two states of "e**1**e**2**" and "g**1**f**2**". Further, the phase is inverted, that is, changed by 180° every time excitation from "e**1**e**2**" to "g**1**f**2**" and returning to "e**1**e**2**" occurs once. Then, the irradiation of the control electromagnetic wave is stopped after predetermined time elapses from the start of the irradiation of the control electromagnetic wave. After the above, when measurement is performed by the measurement unit **17**, the states of the first superconducting circuit **11** and the second superconducting circuit **12** measured by the measurement unit **17** change from "e**1**e**2**" before irradiation to "−e**1**e**2**". This means that the energy state does not change before and after the irradiation of the control electromagnetic wave, and the phase is changed by 180°.

Also in the CZ gate, by irradiation of the first superconducting circuit **11** with the unnecessary interaction suppression electromagnetic wave continuously over the entire operation, influence of extra ZZ interaction can be suppressed.

(2-2-3) Swap Gate

A swap gate refers to operation of a quantum gate that changes the energy state from "g**1**e**2**" to "e**1**g**2**" or from "e**1**g**2**" to "g**1**e**2**".

First, as in the case of the iSwap gate and the CZ gate, the unnecessary interaction suppression electromagnetic wave irradiation unit **18** irradiates the first superconducting circuit **11** with an unnecessary interaction suppression electromagnetic wave having the frequency ω_s. The irradiation of the unnecessary interaction suppression electromagnetic wave is continuously performed over the entire operation of the swap gate described below.

Next, the first superconducting circuit **11** is irradiated with a control electromagnetic wave having the frequency ω_1, which is the original control frequency, for predetermined time by the first quantum gate control electromagnetic wave irradiation unit **15**, so that the energy state is set to a quantum superposition state of "g**1**g**2**" and "e**1**g**2**". Alternatively, the second superconducting circuit **12** may be irradiated with a control electromagnetic wave having the frequency ω_2, which is the original control frequency, for predetermined time by the second quantum gate control electromagnetic wave irradiation unit **16**, so that the energy state is set to a quantum superposition state of "e**1**g**2**" and "e**1**e**2**". In such a quantum superposition state, the first superconducting circuit **11** is simultaneously irradiated with an electromagnetic wave of a frequency $(\omega_2-\omega_1)$ and an electromagnetic wave of a frequency $(\omega_2-\omega_1+\alpha_2)$ by the first quantum gate control electromagnetic wave irradiation unit **15**. By the above, the first superconducting circuit **11** and the second superconducting circuit **12** resonate and interact with each other, the energy state changes between "g**1**e**2**" and "e**1**g**2**", and the circuits operate as a swap gate.

Also in the swap gate, by irradiation of the first superconducting circuit **11** with the unnecessary interaction suppression electromagnetic wave continuously over the entire operation, influence of extra ZZ interaction can be suppressed.

(2-3) Output of Unnecessary Interaction Suppression Electromagnetic Wave

As described above, lowering in energy of "e1e2" can be suppressed by irradiation of the unnecessary interaction suppression electromagnetic wave, but degree of the suppression depends on output of the unnecessary interaction suppression electromagnetic wave. In order to check this, an experiment of measuring an energy difference between "g1e2" and "g1g2" (referred to as Δ_2(g1)) and an energy difference between "e1e2" and "e1g2" (referred to as Δ_2(e1)) while changing output of the unnecessary interaction suppression electromagnetic wave was conducted. FIG. 5 shows a measurement result.

When irradiation with the unnecessary interaction suppression electromagnetic wave is not performed, that is, when a value of output of the unnecessary interaction suppression electromagnetic wave on the horizontal axis in FIG. 5 is zero, Δ_2(g1) and Δ_2(e1) are both $(h/2\pi)\omega_2$ if there is no ZZ interaction, but Δ_2(e1) is actually smaller than Δ_2(g1). This is because energy of "e1e2" is lowered due to presence of ZZ interaction. When output of the unnecessary interaction suppression electromagnetic wave is increased from this state, a difference between Δ_2(g1) and Δ_2(e1) decreases. Then, when the output is W_O (see FIG. 5), Δ_2(g1) and Δ_2(e1) are equal. Then, when the output of the unnecessary interaction suppression electromagnetic wave is further increased, Δ_2(e1) becomes larger than Δ_2(g1).

When the quantum gate device 10 is operated, it is desirable to adjust the output of the unnecessary interaction suppression electromagnetic wave so that the difference between Δ_2(g1) and Δ_2(e1) becomes as small as possible. For example, the output of the unnecessary interaction suppression electromagnetic wave is adjusted such that Δ_2(g1)−Δ_2(e1) is −0.1 MHz to +0.1 MHz.

Similarly to the intensity of the unnecessary interaction suppression electromagnetic wave, it is desirable to adjust the frequency ωs of the unnecessary interaction suppression electromagnetic wave so that the difference between Δ_2(g1) and Δ_2(e1) is as small as possible (for example, Δ_2(g1)−Δ_2(e1) is between −0.1 MHz and +0.1 MHz.). Further, it is more desirable to minimize the difference between Δ_2(g1) and Δ_2(e1) while minimizing the intensity of the unnecessary interaction suppression electromagnetic wave by adjusting both the intensity and the frequency ωs of the unnecessary interaction suppression electromagnetic wave.

(3) Variation

The present invention is not limited to the above embodiment, and various variations are possible.

For example, in the above embodiment, irradiation with the control electromagnetic wave for setting the energy state to a predetermined initial state is performed before irradiation with the control electromagnetic wave for operating as the quantum gate (iSwap gate, CZ gate, or swap gate) is performed, but the irradiation of the control electromagnetic wave for setting the energy state to the predetermined initial state is not essential, and irradiation with the control electromagnetic wave for operating as the quantum gate may be performed from an arbitrarily selected initial state. Further, the second quantum gate control electromagnetic wave irradiation unit 16 may be omitted in a case where the irradiation with the control electromagnetic wave for setting the predetermined initial state is not performed, or in a case where the quantum gate device 10 is operated only as the iSwap gate even in a case where such irradiation with the control electromagnetic wave is performed.

The configurations of the first superconducting circuit 11 and the second superconducting circuit 12 are also not limited to those described above. FIG. 6 illustrates a quantum gate device 10A using, instead of the first superconducting circuit 11, a first superconducting circuit 11A in which a partial superconducting circuit 113A in which two Josephson devices (first and second Josephson devices 111A and 112A) are annularly connected by a superconducting wire 115A and a first capacitor 114A are connected in parallel by the superconducting wire 115A. The first and second Josephson devices 111A and 112A may have different and identical Josephson energy. Further, in this variation, a magnetic field application unit 14A applies an AC magnetic field to the inside of the partial superconducting circuit 113A. The quantum gate device 10A corresponds to a configuration obtained by adding the unnecessary interaction suppression electromagnetic wave irradiation unit 18 to the configuration shown in Non Patent Literature 4.

REFERENCE SIGNS LIST

10, **10**A, **90** . . . Quantum Gate Device
11, **91** . . . First Superconducting Circuit
111, **111**A, **911** . . . First Josephson Device
111J . . . First Thin Film
112, **912** . . . Second Josephson Device Group
1121, **1122**, **112**_k_, **112**A, **9121**, **9122** . . . Second Josephson Device
112J . . . Second Thin Film
113, **113**A, **913** . . . Partial Superconducting Circuit
114, **114**A . . . First Capacitor
115, **115**A, **125**, **135** . . . Superconducting Wire
12, **92** . . . Second Superconducting Circuit
121, **921** . . . Josephson Device
124 . . . Second Capacitor
13 . . . Connection Unit
134 . . . Connection Unit Capacitor
14, **94** . . . Magnetic Field Application Unit
15, **95** . . . First Quantum Gate Control Electromagnetic Wave Irradiation Unit
151, **161** . . . Quantum Gate Control Power Supply
152, **162**, **952** . . . Capacitor
1521, **1621**, **9521** . . . Electromagnetic Wave Irradiation Electrode
1522, **1622** . . . Electrode
16, **96** . . . Second Quantum Gate Control Electromagnetic Wave Irradiation Unit
17, **97** . . . Measurement Unit
171, **971** . . . First Measurement Unit
172, **972** . . . Second Measurement Unit
18 . . . Unnecessary Interaction Suppression Electromagnetic Wave Irradiation Unit
181 . . . Unnecessary Interaction Suppression Electromagnetic Wave Irradiation Power Supply
951, **961** . . . Radio-Frequency Power Supply

The invention claimed is:

1. A quantum gate device comprising:

a) a first superconducting circuit including at least one Josephson device in an annular circuit including a superconducting wire, the first superconducting circuit being configured to resonate at a first resonance frequency;

b) a second superconducting circuit including at least one Josephson device in an annular circuit including a superconducting wire, the second superconducting circuit being configured to resonate at a second resonance frequency different from the first resonance frequency;

c) a connection unit including a capacitor and a superconducting wire provided at each of both electrodes of the capacitor, the connection unit being configured to connect the first superconducting circuit and the second superconducting circuit;

d) a magnetic field application means configured to apply a magnetic field to one or both of the first superconducting circuit and the second superconducting circuit;

e) a quantum gate control electromagnetic wave irradiation unit configured to irradiate one of the first superconducting circuit and the second superconducting circuit with a control electromagnetic wave which is an electromagnetic wave having a control frequency corresponding to an original energy difference between two energy states contributing to operation of a quantum gate among a plurality of quantized energy states formed by the first superconducting circuit and the second superconducting circuit; and

f) an unnecessary interaction suppression electromagnetic wave irradiation unit configured to irradiate one of the first superconducting circuit and the second superconducting circuit with an unnecessary interaction suppression electromagnetic wave which is an electromagnetic wave having an unnecessary interaction suppression frequency, the unnecessary interaction suppression frequency being a frequency between a first frequency and a second frequency, and differing by 10 MHz or more from a frequency corresponding to an original energy difference between arbitrarily selected two energy states among a plurality of the energy states, where the first frequency is a frequency corresponding to an original energy difference between a first energy state that is highest and a second energy state that is second highest in three energy states among a plurality of the energy states, and the second frequency is a frequency corresponding to an original energy difference between the second energy state and a third energy state having lowest energy.

2. The quantum gate device according to claim **1**, wherein the unnecessary interaction suppression electromagnetic wave irradiation unit is configured to continue irradiation with the unnecessary interaction suppression electromagnetic wave from start of irradiation with the control electromagnetic wave by the quantum gate control electromagnetic wave irradiation unit to end of operation of a quantum gate.

3. The quantum gate device according to claim **1**, wherein output of the unnecessary interaction suppression electromagnetic wave is adjusted so that magnitude of a difference between energy differences of two sets having a same original energy difference among sets of energy states including arbitrarily selected two energy states among the plurality of energy states falls within a range of −0.1 MHz to 0.1 MHz.

4. The quantum gate device according to claim **1**, wherein the first superconducting circuit includes a partial superconducting circuit in which a first Josephson device and a second Josephson device group in which n second Josephson devices having Josephson energy higher than n times Josephson energy of the first Josephson device are connected in series by a wire made from a superconductor, in which the partial superconducting circuit and a capacitor are connected annularly by a wire made from a superconductor, and

the second superconducting circuit includes one Josephson device and a capacitor connected annularly by a wire made from a superconductor.

5. A quantum computer comprising the quantum gate device according to claim **1**.

6. A quantum computer comprising the quantum gate device according to claim **2**.

7. A quantum computer comprising the quantum gate device according to claim **3**.

8. A quantum computer comprising the quantum gate device according to claim **4**.

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