

CO-PLANAR WAVEGUIDE FLUX QUBITS

BACKGROUND

[0001] Quantum computing is a relatively new computing method that takes advantage of quantum effects, such as superposition of basis states and entanglement to perform certain computations more efficiently than a classical digital computer. In contrast to a digital computer, which stores and manipulates information in the form of bits (e.g., a “1” or “0”), quantum computing systems can manipulate information using qubits. A qubit can refer to a quantum device that enables the superposition of multiple states (e.g., data in both the “0” and “1” state) and/or to the superposition of data, itself, in the multiple states. In accordance with conventional terminology, the superposition of a “0” and “1” state in a quantum system may be represented, e.g., as $\alpha |0\rangle + \beta |1\rangle$. The “0” and “1” states of a digital computer are analogous to the $|0\rangle$ and $|1\rangle$ basis states, respectively of a qubit. The value $|\alpha|^2$ represents the probability that a qubit is in $|0\rangle$ state, whereas the value $|\beta|^2$ represents the probability that a qubit is in the $|1\rangle$ basis state.

SUMMARY

[0002] The present disclosure relates to co-planar waveguide flux qubits. In general, in a first aspect, the subject matter of the present disclosure may be embodied in a qubit device that includes an elongated thin film uninterrupted by Josephson junctions, a quantum device (e.g., a superconducting quantum interference device (SQUID)) in electrical contact with a proximal end of the elongated thin film, and a ground plane that is co-planar with the elongated thin film and is in electrical contact with a distal end of the elongated thin film, in which the thin film, the quantum device, and the ground plane comprise a superconductor material, and wherein the elongated thin film forms a single-branched co-planar waveguide extending from the SQUID.

[0003] Implementations of the device can optionally include one or more of the following features, alone or in combination. For example, in some implementations, the elongated thin film includes a first side and a second opposite side and each of the first side and the second side is separated from the superconducting ground plane by a

respective gap. A width of each respective gap may be constant along the length of the elongated thin film.

[0004] In some implementations, each of the elongated thin film, the superconducting loop, and the ground-plane includes aluminum or niobium.

5 [0005] In some implementations, the quantum device includes a superconducting loop interrupted by at least one Josephson junction. The quantum device may include only two Josephson junctions interrupting the superconducting loop.

[0006] In some implementations, the qubit further includes a substrate, in which the elongated thin film, the ground plane and the quantum device are on a surface of the substrate.

10 The substrate may include sapphire.

[0007] In some implementations, the elongated thin film includes a first section extending along a first direction and a second section extending along a second different direction.

[0008] In general, in another aspect, the subject matter of the present application can be
15 embodied in a qubit device that includes an elongated thin film uninterrupted by Josephson junctions and includes a first section extending along a first direction and a second section extending along a second direction to form a double-branched co-planar waveguide, a superconducting quantum interference device (e.g., SQUID) in electrical contact with the elongated thin film at a position between the first and second section, wherein the SQUID comprises less
20 than three Josephson junctions, and a ground plane that is co-planar with the elongated thin film and is in electrical contact with the elongated thin film, in which the thin film, the SQUID, and the ground plane include a superconductor material.

[0009] In general, in another aspect, the subject matter of the present application can be embodied in a qubit control system that includes a qubit device having (a) an elongated thin film
25 uninterrupted by Josephson junctions, (b) a quantum device (e.g., a SQUID) in electrical contact with a proximal end of the elongated thin film, and (c) a ground plane that is co-planar with the elongated thin film and is in electrical contact with a distal end of the elongated thin film, in which the thin film, the quantum device, and the ground plane including a superconductor material, and wherein the elongated thin film forms a single-branched co-planar waveguide
30 extending from the SQUID. The qubit control system further includes a qubit bias control device adjacent to the elongated thin film such that the qubit bias control device is

inductively coupled to the elongated thin film during operation, and a quantum device bias control device adjacent to the quantum device of the qubit device such that the quantum device bias control device is inductively coupled to the quantum device during operation.

[0010] Implementations of the device can optionally include one or more of the following
5 features, alone or in combination. For example, in some implementations, the qubit bias control device is in electrical contact with the elongated superconducting thin film.

[0011] In some implementations, the qubit bias control device includes a current divider. The current divider may include multiple inductors. The current divider may include a center thin film trace, and an outer thin film trace forming an open loop that circumscribes the center
10 thin film trace and that is in electrical contact with the elongated thin film, in which an end of the center thin film trace is in electrical contact with the outer thin film trace at a plurality of different locations along the open loop.

[0012] In some implementations, the quantum device bias control device can include an inner thin film loop and an outer thin film loop that at least partially circumscribes the inner thin
15 film loop and that is in electrical contact with the quantum device.

[0013] In some implementations, the qubit bias control device has a mutual inductance with the elongated thin film of between about 0.1 pH and 0.2 pH.

[0014] In some implementations, the quantum device bias control device has a mutual inductance with the quantum device of about 0 pH.

[0015] In general, in another aspect, the subject matter of the present disclosure relates to
20 a quantum processor that includes multiple co-planar waveguide flux qubit devices, each co-planar waveguide flux qubit device having (a) an elongated thin film waveguide uninterrupted by Josephson junctions, (b) a quantum device (e.g., a SQUID) in electrical contact with a first end of the elongated thin film waveguide wherein the quantum device comprises less than three
25 Josephson junctions, and wherein the elongated thin film forms a single-branched co-planar waveguide extending from the quantum device, and (c) a ground plane that is co-planar with the elongated thin film waveguide and is in electrical contact with the elongated thin film, in which each co-planar waveguide flux qubit device is operatively coupled to each other co-planar waveguide flux qubit device in the quantum processor.

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WHAT IS CLAIMED IS:

1. A qubit device comprising:
 - an elongated thin film uninterrupted by Josephson junctions;
 - a superconducting quantum interference device (SQUID) in electrical contact with a proximal end of the elongated thin film, wherein the SQUID comprises less than three Josephson junctions; and
 - a ground plane that is co-planar with the elongated thin film and is in direct electrical contact with a distal end of the elongated thin film;
 - wherein the thin film, the SQUID, and the ground plane comprise a superconductor material, and wherein the elongated thin film forms a single-branched co-planar waveguide extending from the SQUID.
2. The qubit device of claim 1, wherein the elongated thin film comprises a first side and a second opposite side and wherein each of the first side and the second side is separated from the superconducting ground plane by a respective gap.
3. The qubit device of claim 2, wherein a width of each respective gap is constant along the length of the elongated thin film.
4. The qubit device of claim 1, wherein the SQUID comprises a superconducting loop interrupted by at least one Josephson junction.
5. The qubit device of claim 4, wherein the SQUID comprises two Josephson junctions interrupting the superconducting loop.
6. The qubit device of claim 4, wherein each of the elongated thin film, the superconducting loop, and the ground-plane comprises aluminum or niobium.
7. The qubit device of claim 1, further comprising a substrate, wherein the elongated thin film, the ground plane and the SQUID are on a surface of the substrate.

8. The qubit device of claim 7, wherein the substrate is sapphire.
9. A qubit device comprising:
an elongated thin film uninterrupted by Josephson junctions and comprising a first section extending along a first direction and a second section extending along a second direction to form a double-branched co-planar waveguide;
a superconducting quantum interference device (SQUID) in electrical contact with the elongated thin film at a position between the first and second section, wherein the SQUID comprises less than three Josephson junctions; and
a ground plane that is co-planar with the elongated thin film and is in direct electrical contact with the elongated thin film;
wherein the thin film, the SQUID, and the ground plane comprise a superconductor material,.
10. A qubit control system comprising:
a qubit device comprising (a) an elongated thin film uninterrupted by Josephson junctions, (b) a superconducting quantum interference device (SQUID) in electrical contact with a proximal end of the elongated thin film, wherein the SQUID comprises less than three Josephson junctions, and (c) a ground plane that is co-planar with the elongated thin film and is in direct electrical contact with a distal end of the elongated thin film,
wherein the thin film, the SQUID, and the ground plane comprise a superconductor material, and wherein the elongated thin film forms a single-branched co-planar waveguide extending from the SQUID;
a qubit bias control device adjacent to the elongated thin film such that the qubit bias control device is inductively coupled to the elongated thin film during operation; and
a SQUID bias control device adjacent to the SQUID of the qubit device such that the SQUID bias control device is inductively coupled to the SQUID during operation.

11. The qubit control system of claim 10, wherein the qubit bias control device is in electrical contact with the elongated superconducting thin film.
12. The qubit control system of claim 10, wherein the qubit bias control device comprises a current divider.
13. The qubit control system of claim 12, wherein the current divider comprises a plurality of inductors.
14. The qubit control system of claim 12, wherein the current divider comprises:
 - a center thin film trace; and
 - an outer thin film trace forming an open loop that circumscribes the center thin film trace and that is in electrical contact with the elongated thin film, wherein an end of the center thin film trace is in electrical contact with the outer thin film trace at a plurality of different locations along the open loop.
15. The qubit control system of claim 10, wherein the SQUID bias control device comprises:
 - an inner thin film loop; and
 - an outer thin film loop that at least partially circumscribes the inner thin film loop and that is in electrical contact with the SQUID.
16. The qubit control system of claim 10, wherein the qubit bias control device has a mutual inductance with the elongated thin film of between about 0.1 pH and 0.2 pH.
17. A quantum processor comprising a plurality of co-planar waveguide flux qubit devices, each co-planar waveguide flux qubit device comprising:
 - an elongated thin film waveguide uninterrupted by Josephson junctions;
 - a superconducting quantum interference device (SQUID) in electrical contact with a first end of the elongated thin film waveguide, wherein the quantum device comprises less than three Josephson junctions, and wherein the elongated thin film forms a single-branched co-planar waveguide extending from the SQUID; and

a ground plane that is co-planar with the elongated thin film waveguide and is in direct electrical contact with the elongated thin film, wherein each co-planar waveguide flux qubit device of the plurality of co-planar waveguide flux qubit devices is operatively coupled to at least one other co-planar waveguide flux qubit device of the plurality of co-planar waveguide flux qubit devices in the quantum processor.

18. The quantum processor of claim 17 wherein the elongated thin film waveguide of each co-planar waveguide flux qubit crosses a plurality of elongated thin film waveguides associated with other co-planar waveguide flux qubits in the processor.

19. The quantum processor of claim 18, further comprising a plurality of inductive couplers, wherein each inductive coupler is arranged adjacent to a crossing between two elongated thin film waveguides associated with different co-planar waveguide flux qubits.