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Schuster et al.

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(45) **Date of Patent: Mar. 30, 2021**

(54) **TECHNOLOGIES FOR LONG-LIVED 3D MULTIMODE MICROWAVE CAVITIES**

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Related U.S. Application Data

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(51) **Int. Cl.**

H01P 7/06	(2006.01)
H01P 1/30	(2006.01)
H01P 1/16	(2006.01)
G06N 10/00	(2019.01)

(52) **U.S. Cl.**
CPC ***H01P 7/06*** (2013.01); ***G06N 10/00*** (2019.01); ***H01P 1/16*** (2013.01); ***H01P 1/30*** (2013.01)

(58) **Field of Classification Search**
CPC H01P 7/06; H01P 1/16; H01P 1/30
USPC 333/208, 219, 222
See application file for complete search history.

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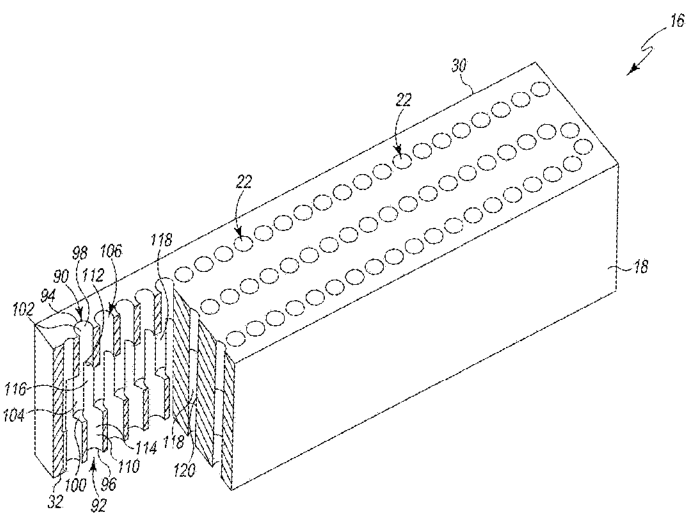
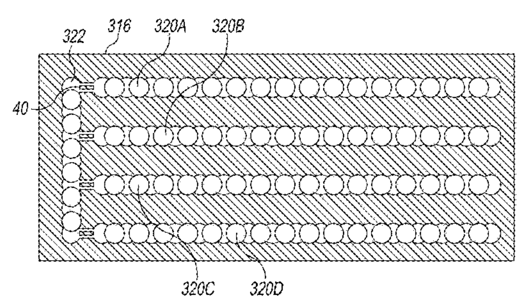
(57) **ABSTRACT**

Technologies for a long-lived 3D multimode microwave cavity are disclosed. In the illustrative embodiment, a series of overlapping holes are drilled into a monolithic block of aluminum forming a cavity. The dimensions of the cavity formed by the overlapping holes can be made long by drilling a long series of holes in a row and can be made high by drilling holes a certain depth into the cavity. If two dimensions of the cavity are bigger than the diameter of the holes used to create the cavity, then the cavity can support electromagnetic waves that cannot propagate through the holes, leading to a long lifetime in the cavity. A superconducting qubit or other non-linear element can be inserted into the cavity, which can controllably interact with each of several modes of the cavity. In this way, the modes of the cavity can act as components in a quantum memory.

20 Claims, 17 Drawing Sheets





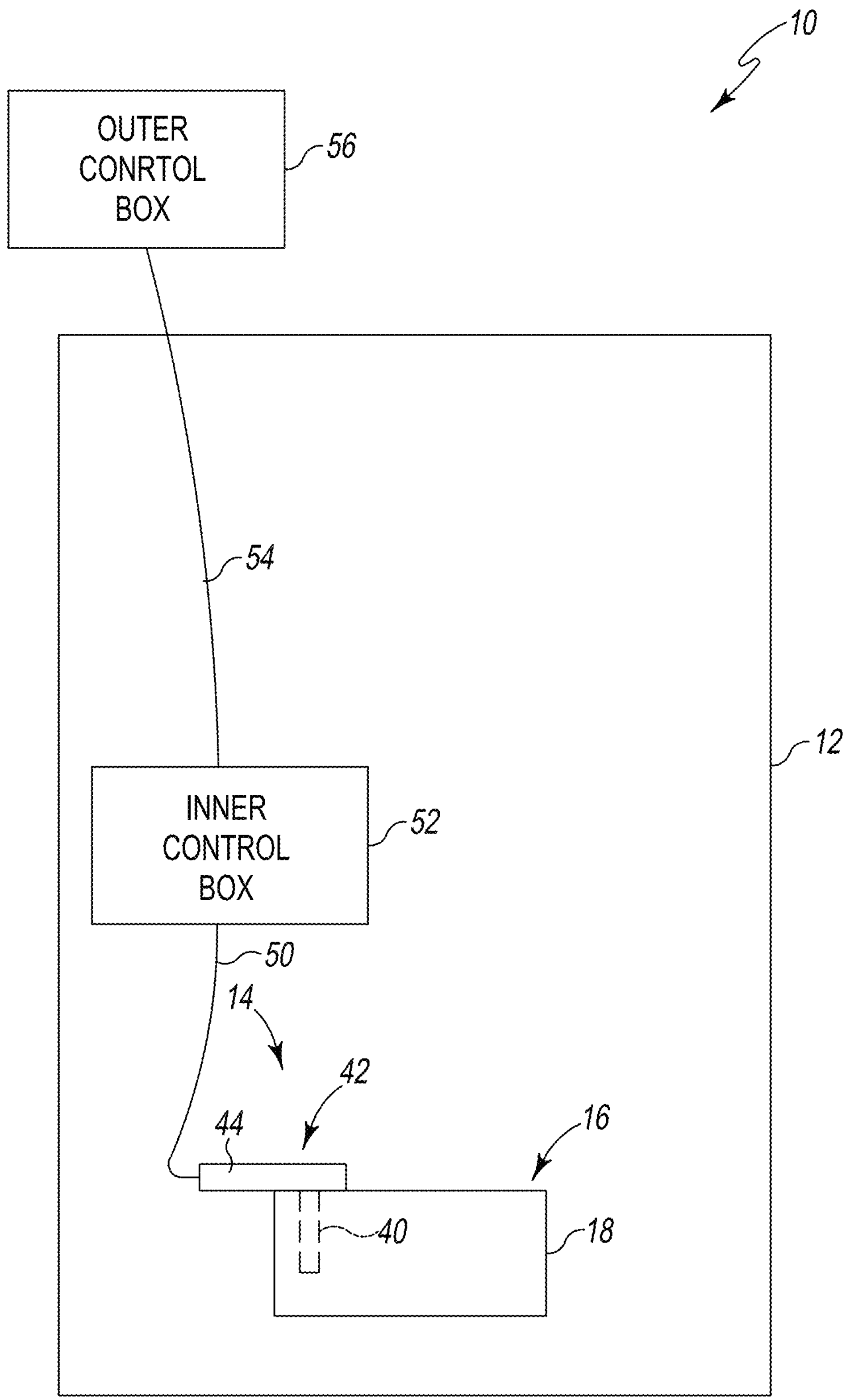

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Fig. 1

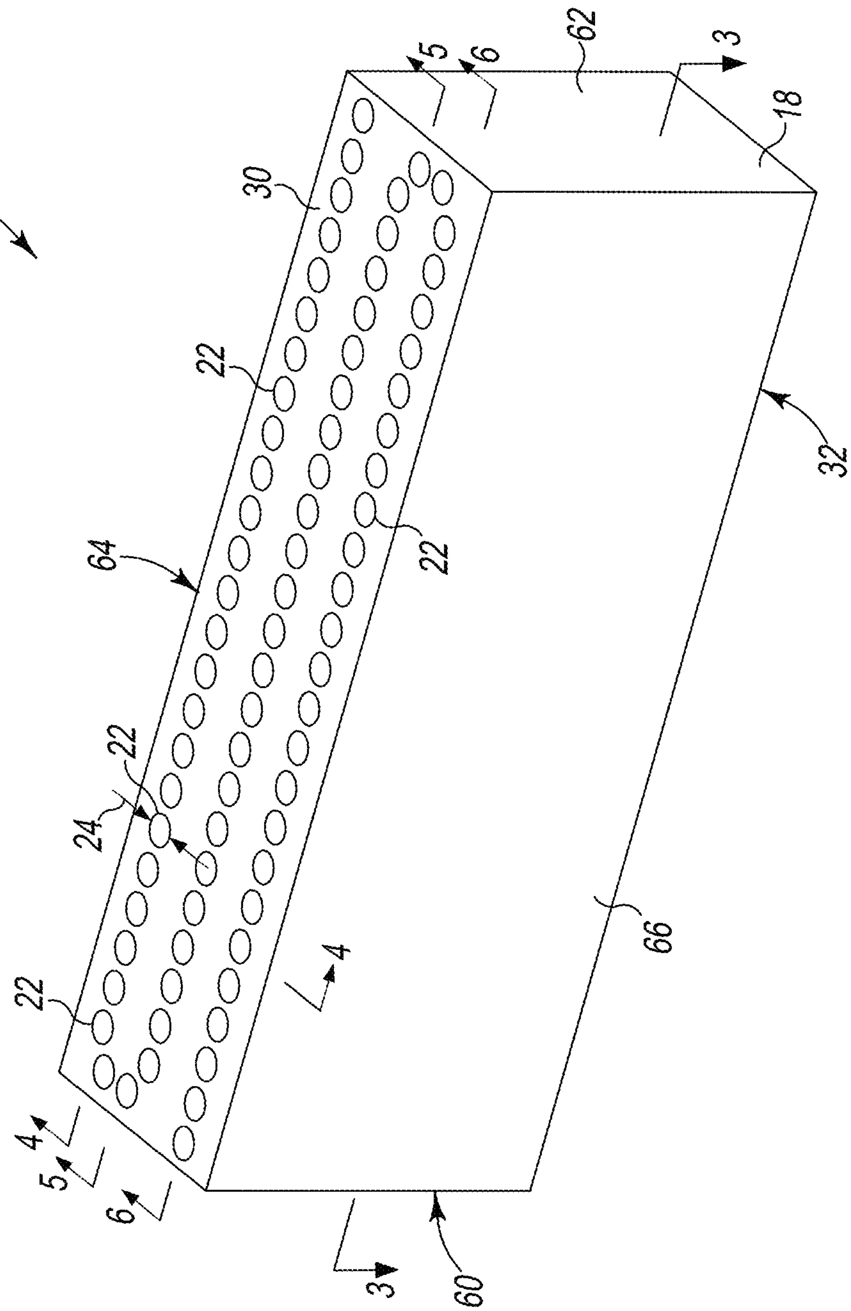

Fig. 2

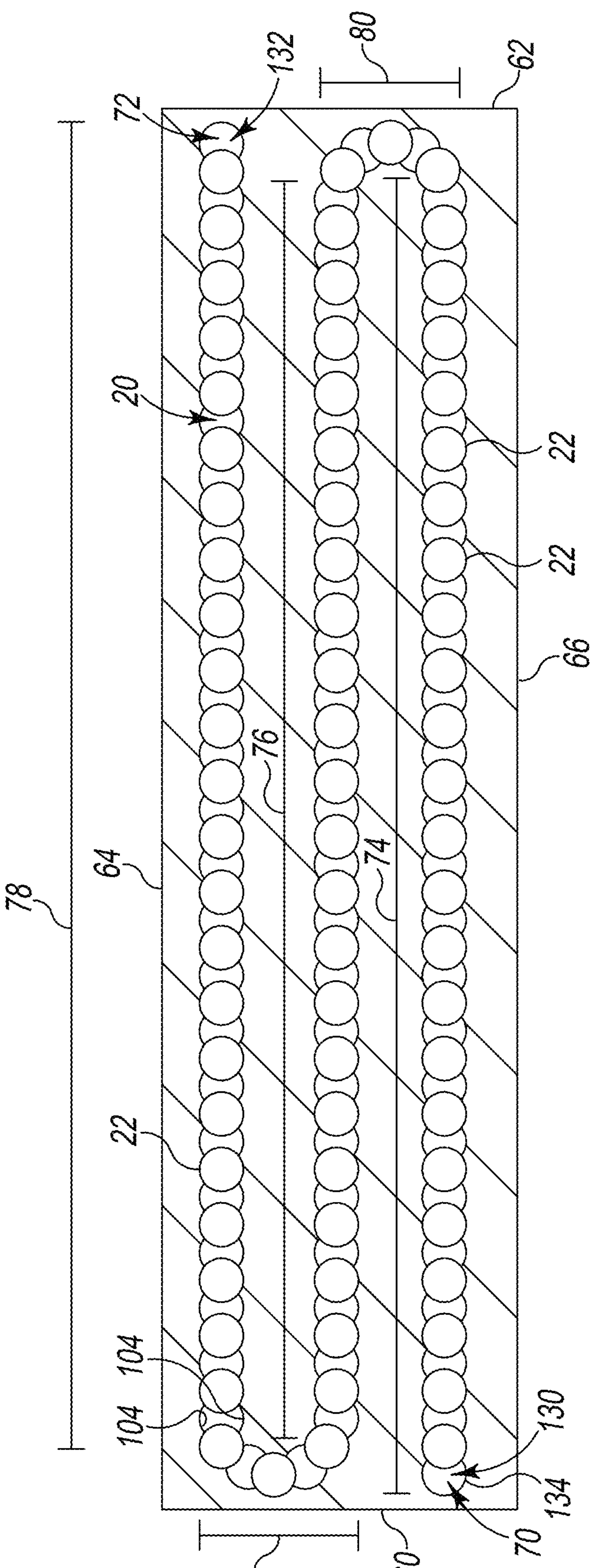

Fig. 3

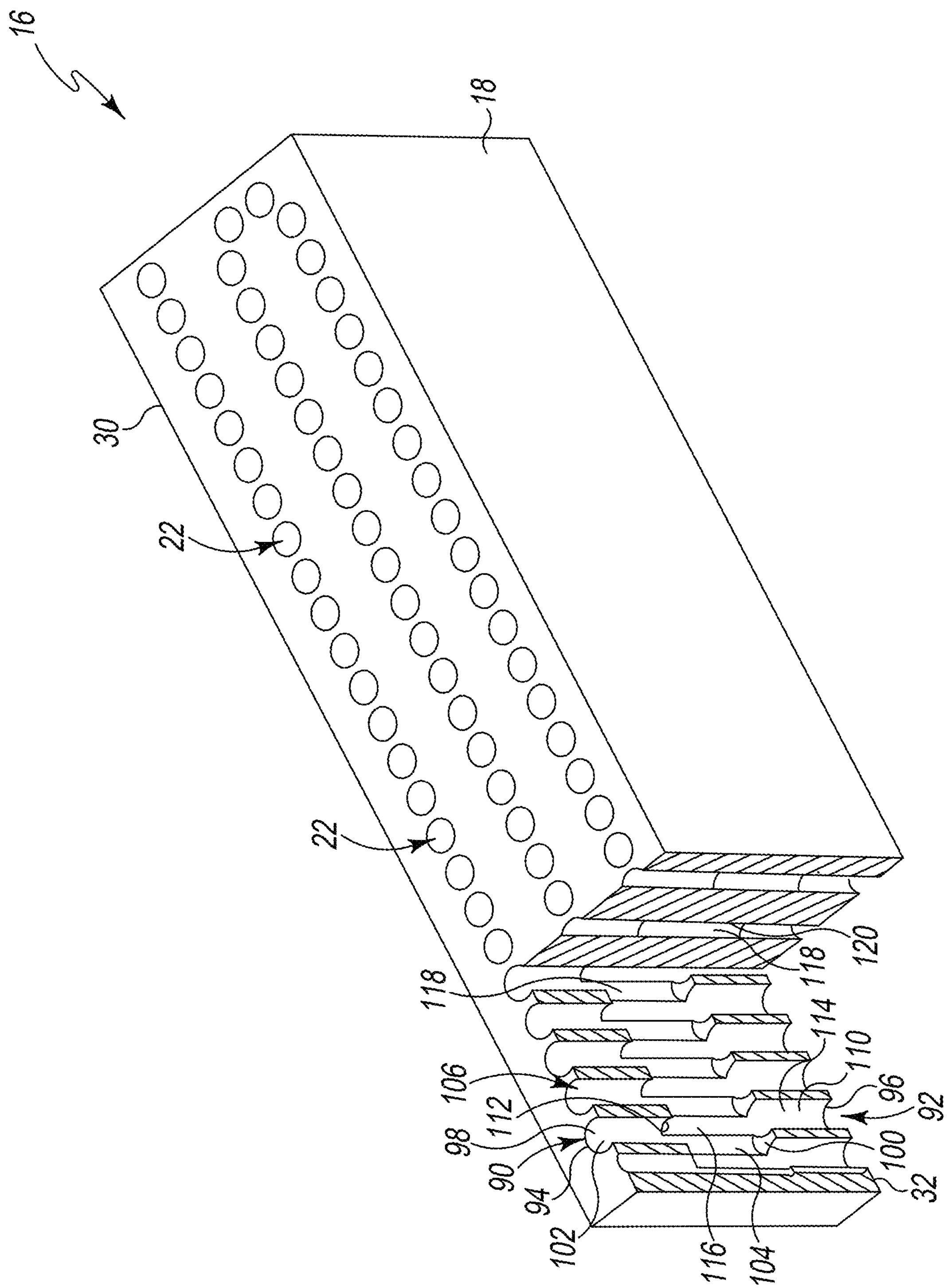
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Fig. 4

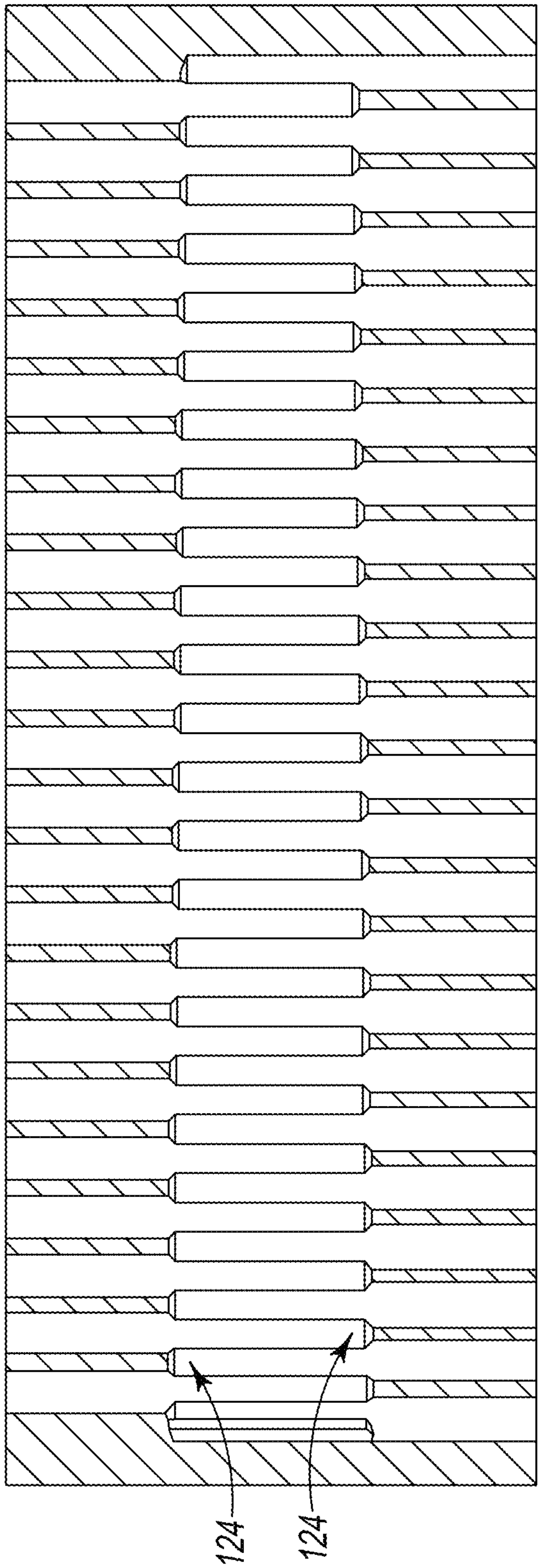


Fig. 5

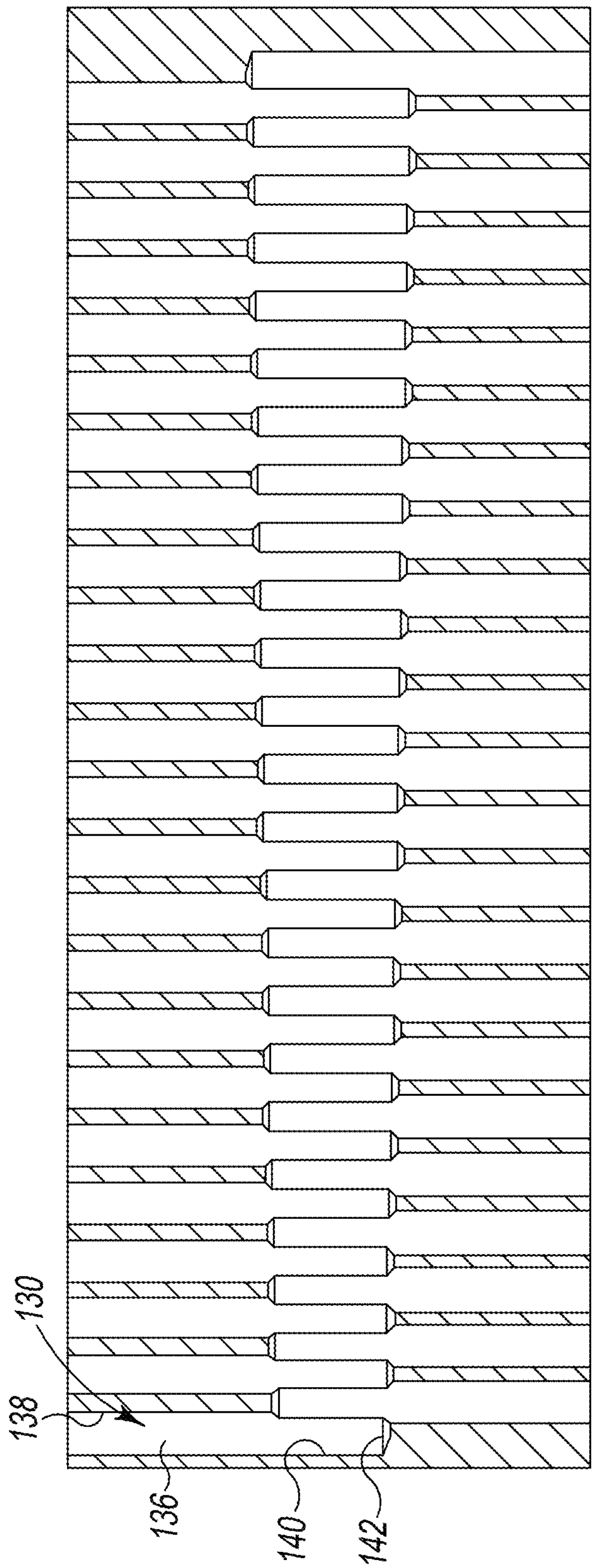


Fig. 6

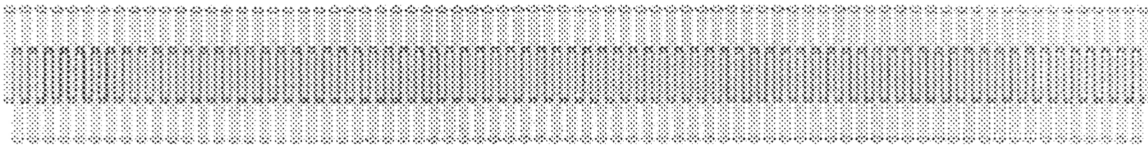


Fig. 7A

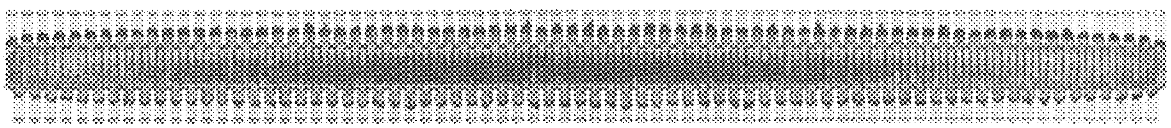


Fig. 7B

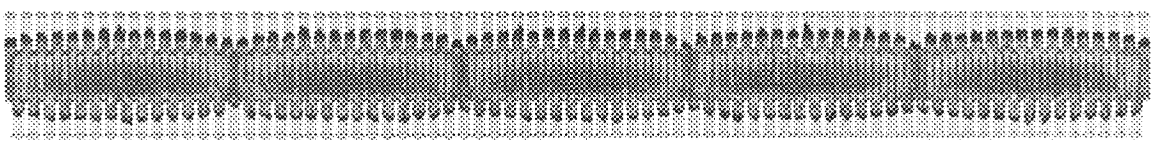


Fig. 7C

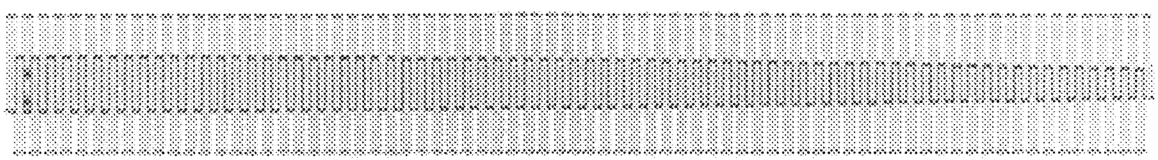


Fig. 7D

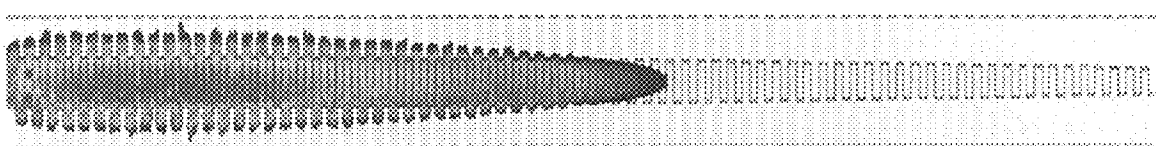


Fig. 7E

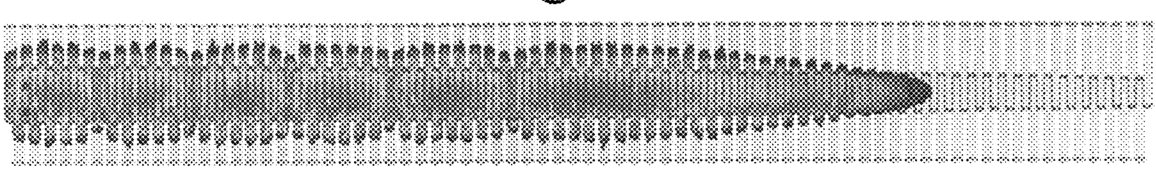
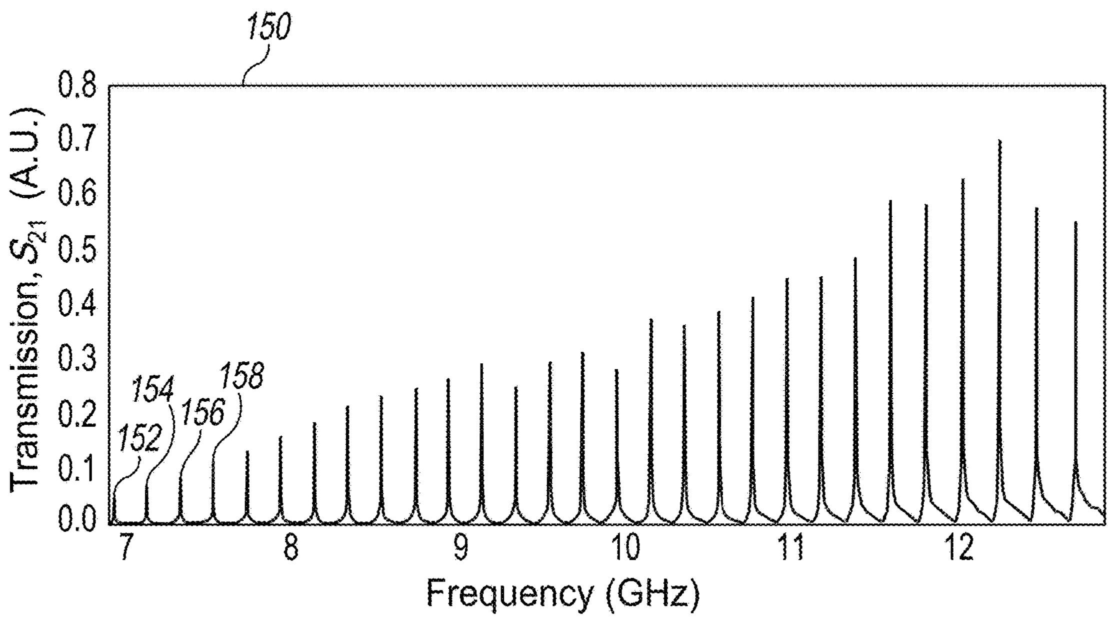


Fig. 7F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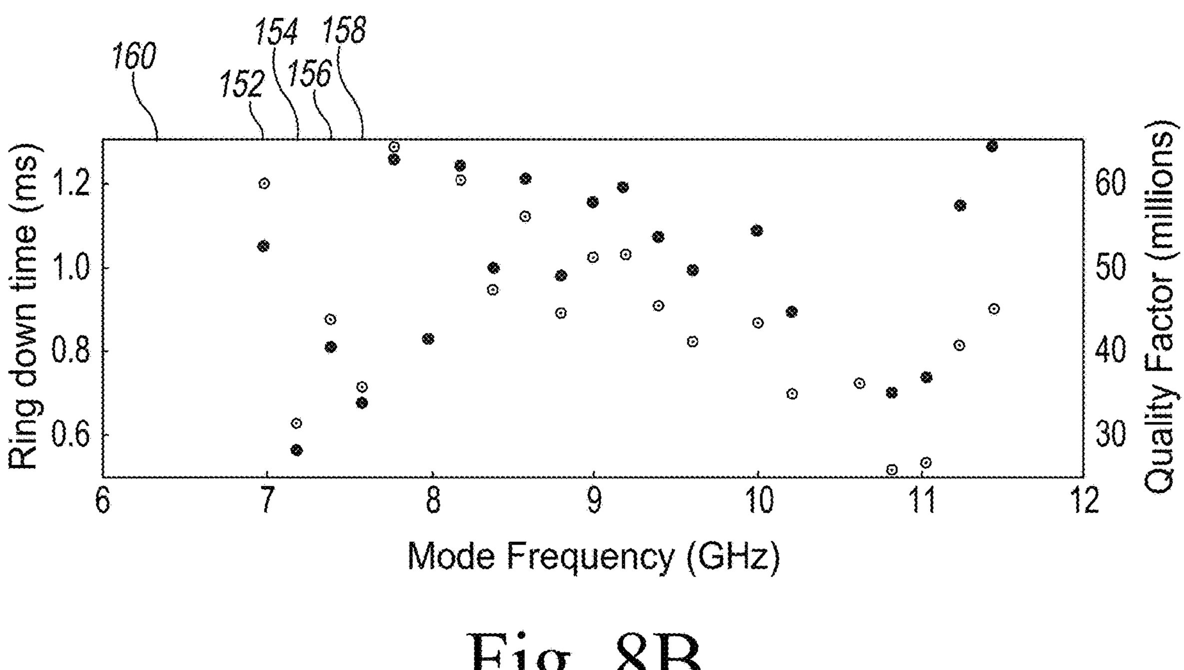
152
154
156
158
Transmission, S_{21} (A.U.)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
7
8
9
10
11
12
Frequency (GHz)

Fig. 8A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156
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Ring down time (ms)
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Quality Factor (millions)
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60
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7
8
9
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11
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Mode Frequency (GHz)

Fig. 8B

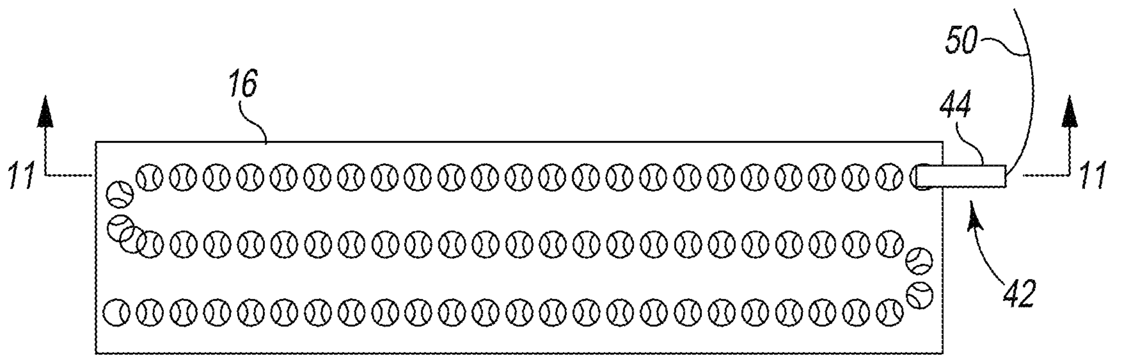


Fig. 9

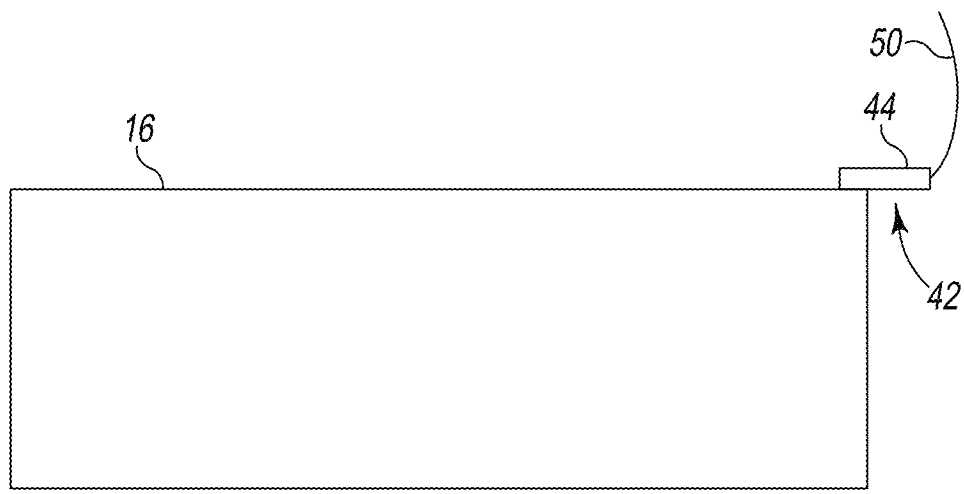


Fig. 10

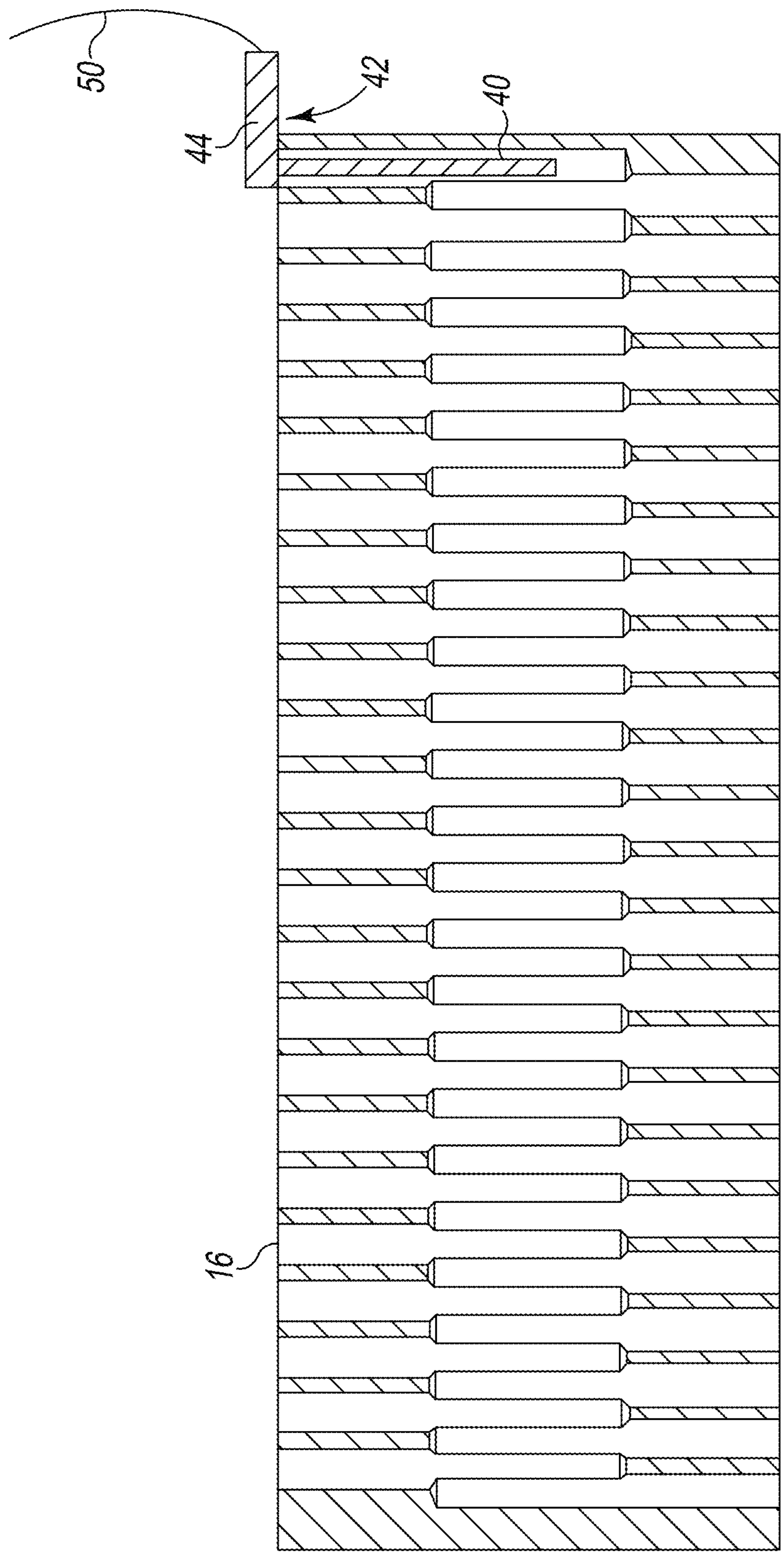


Fig. 11

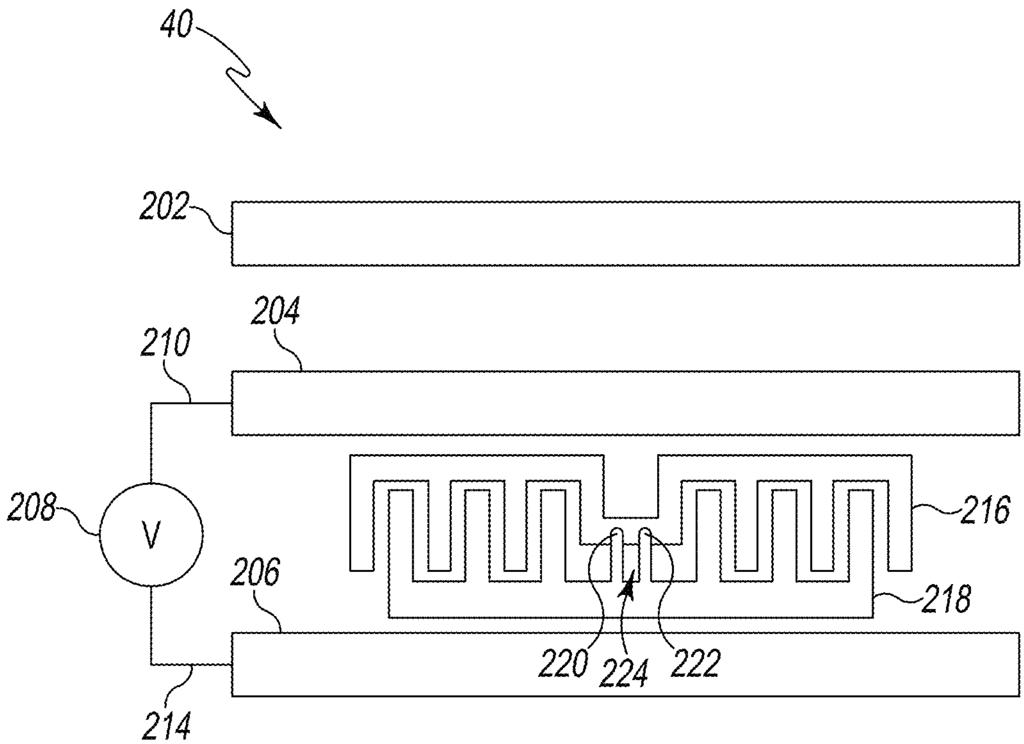


Fig. 12A

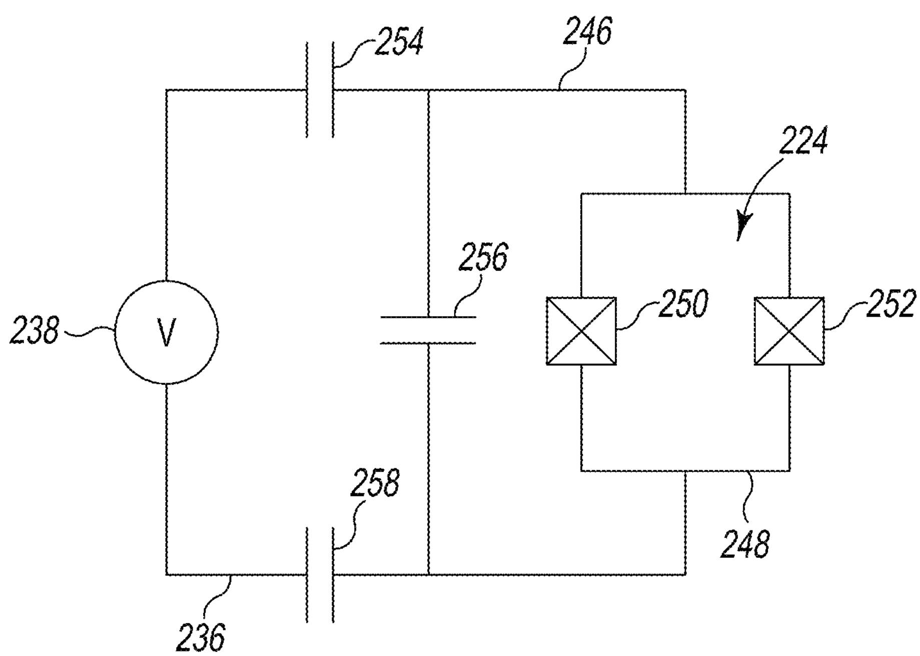


Fig. 12B

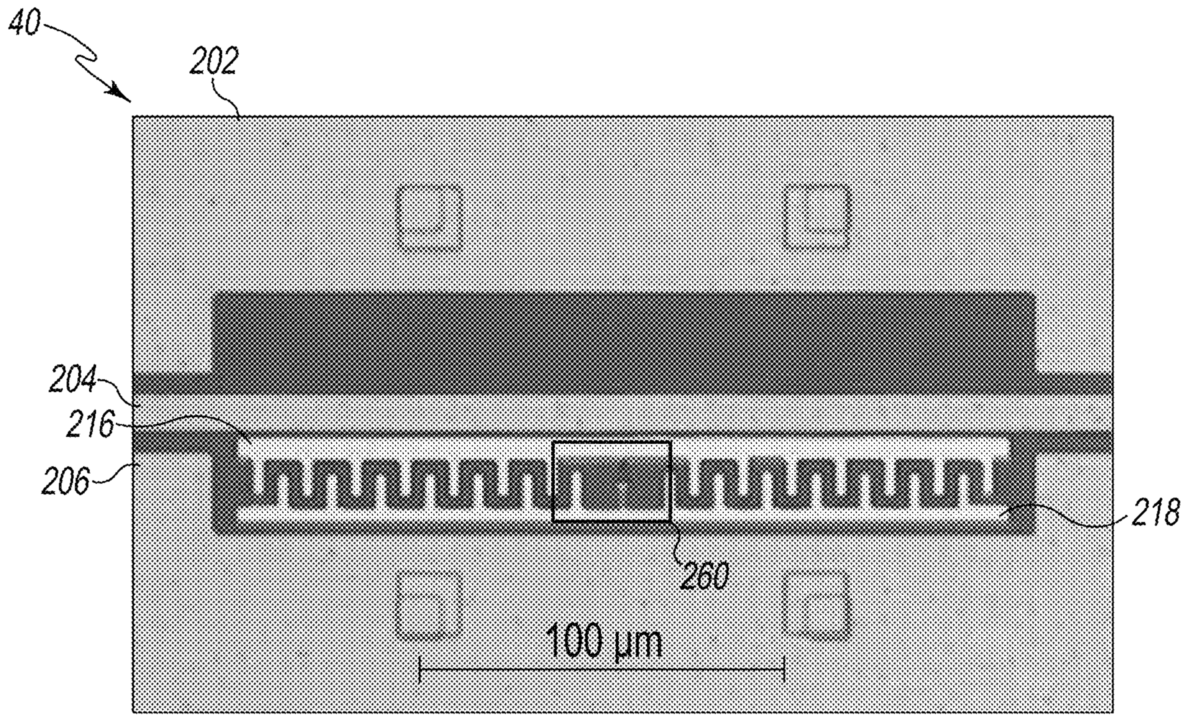


Fig. 13A

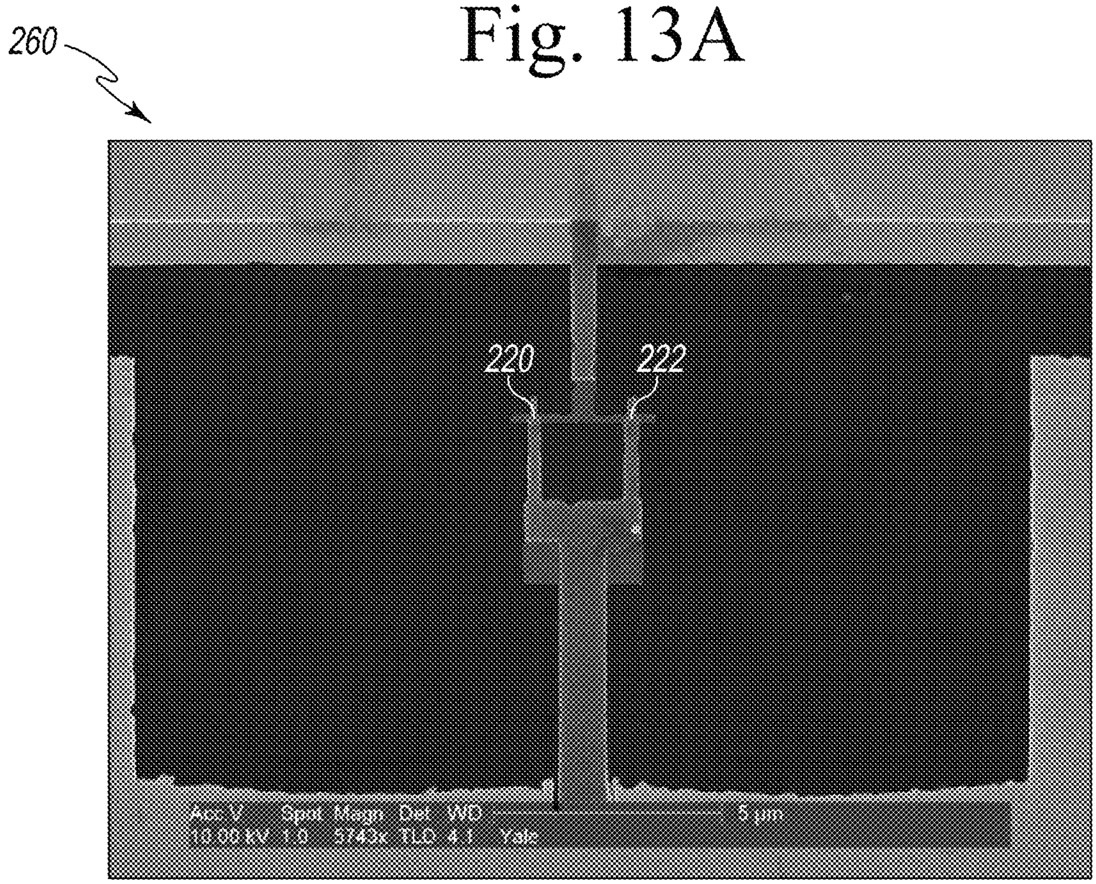
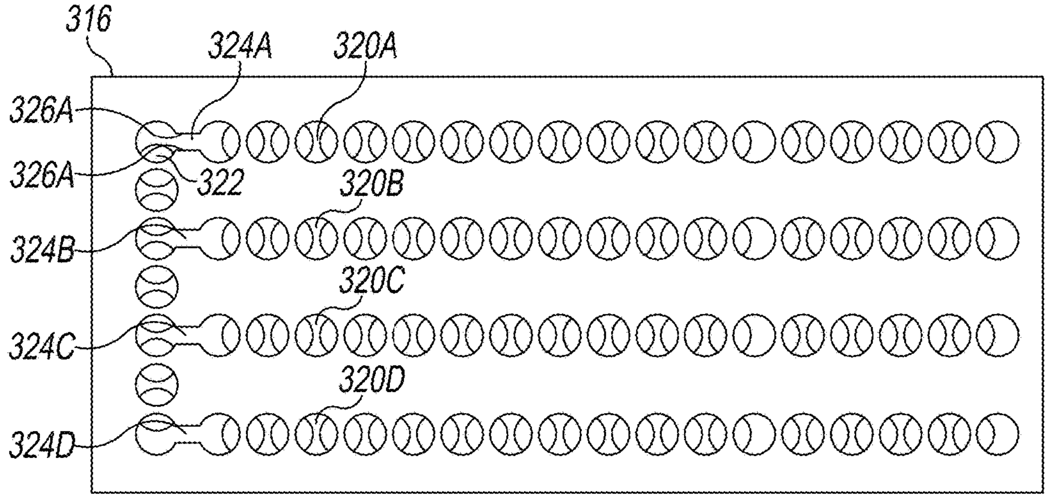


Fig. 13B



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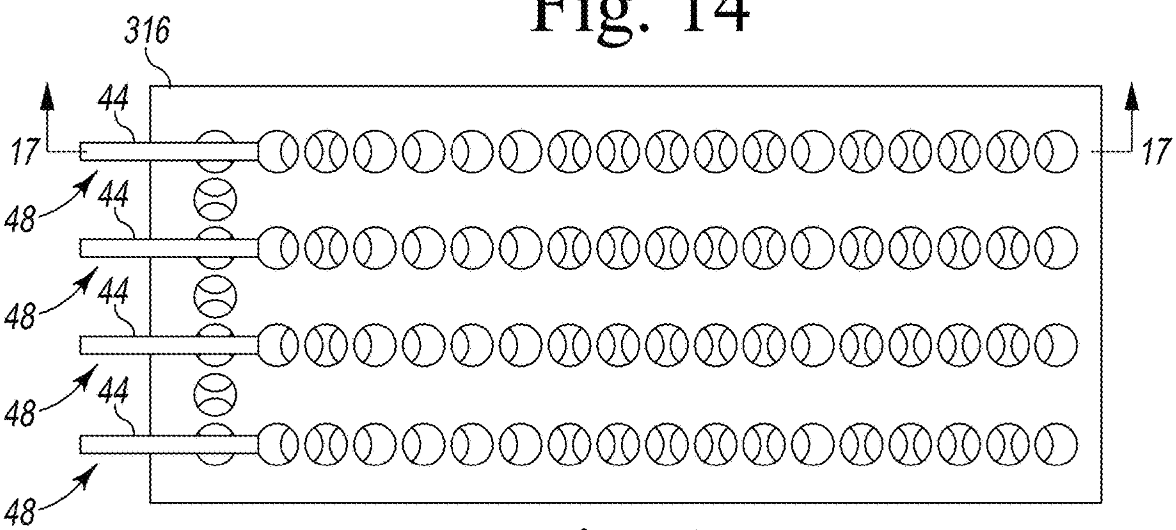

Fig. 15

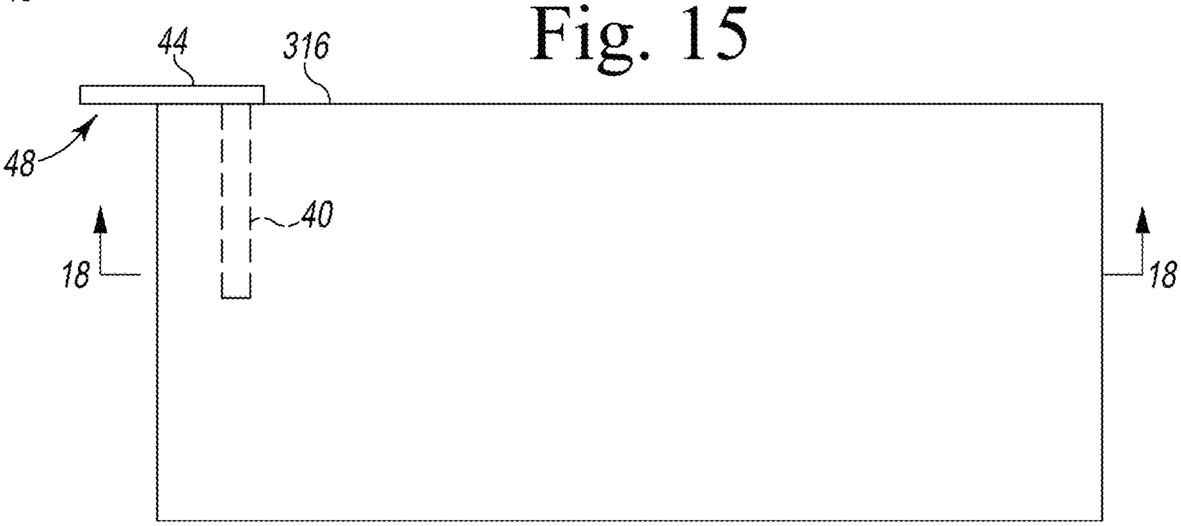

Fig. 16

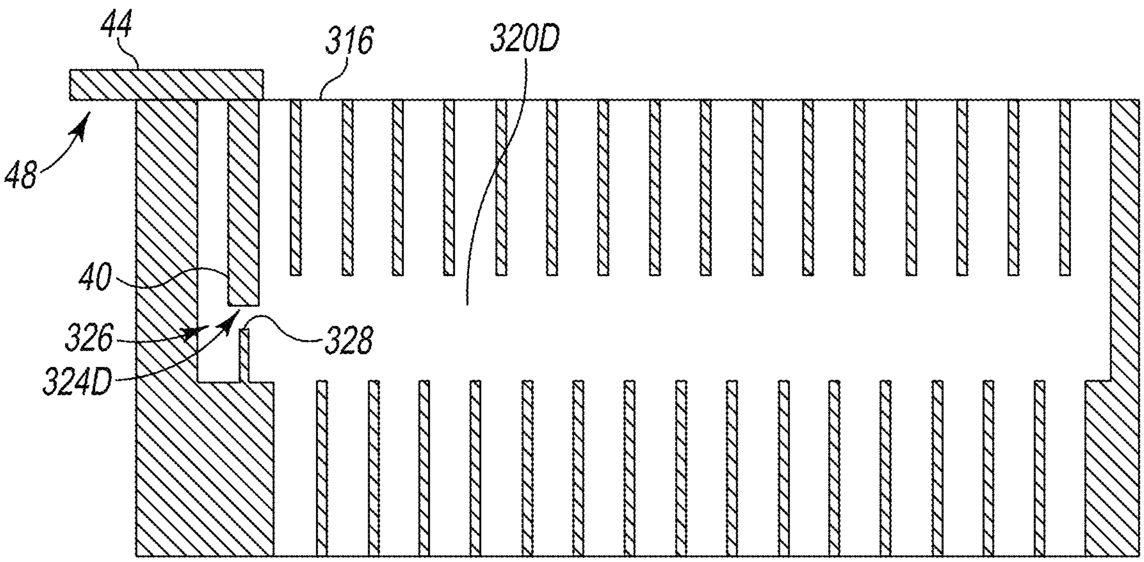

Fig. 17

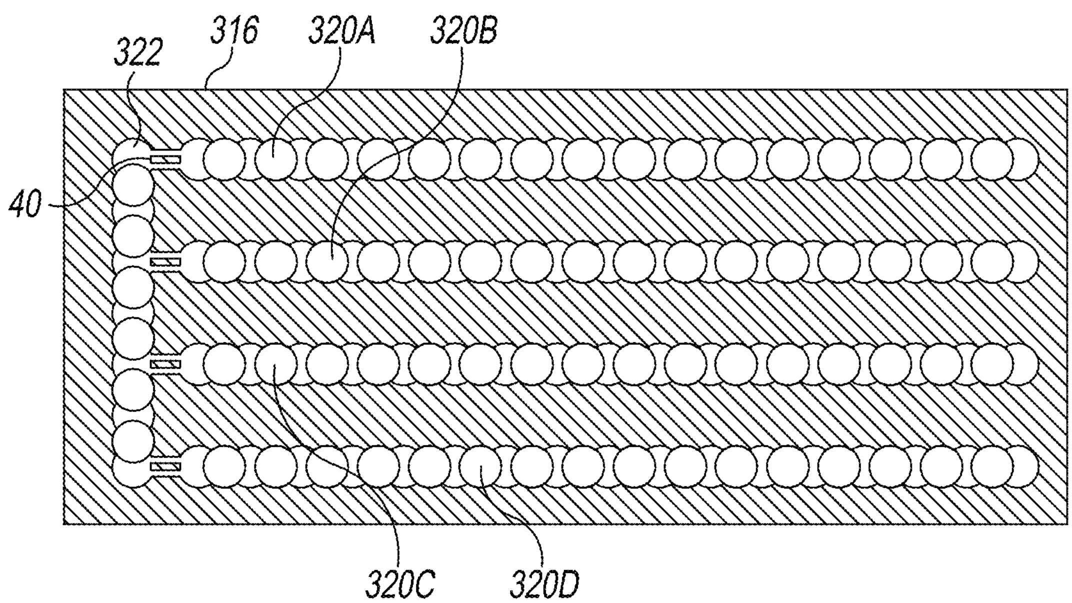

Fig. 18

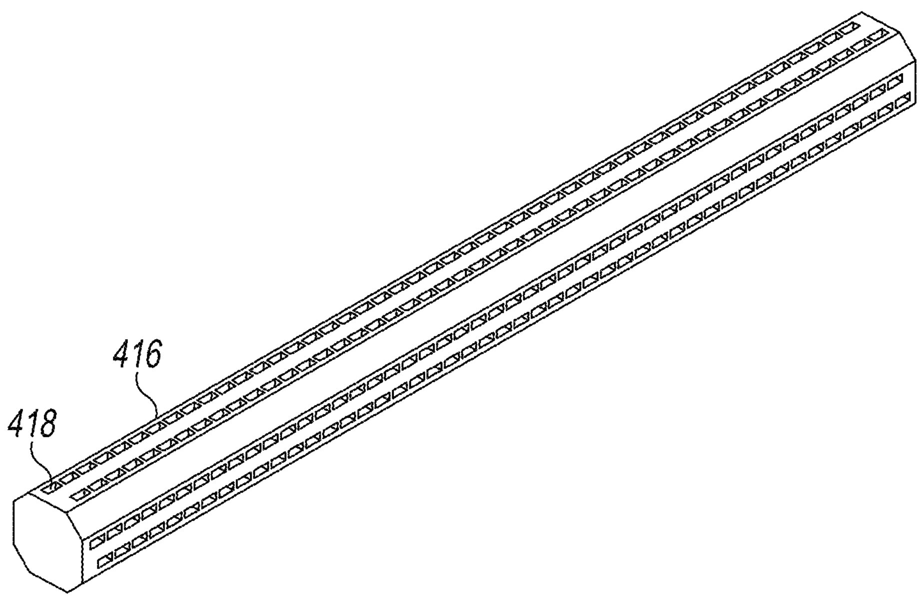

Fig. 19

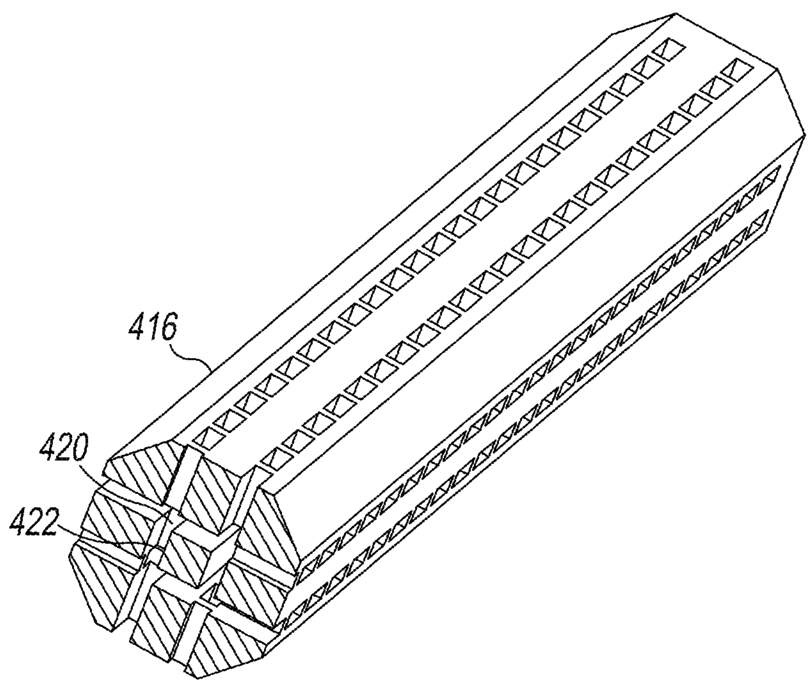

Fig. 20

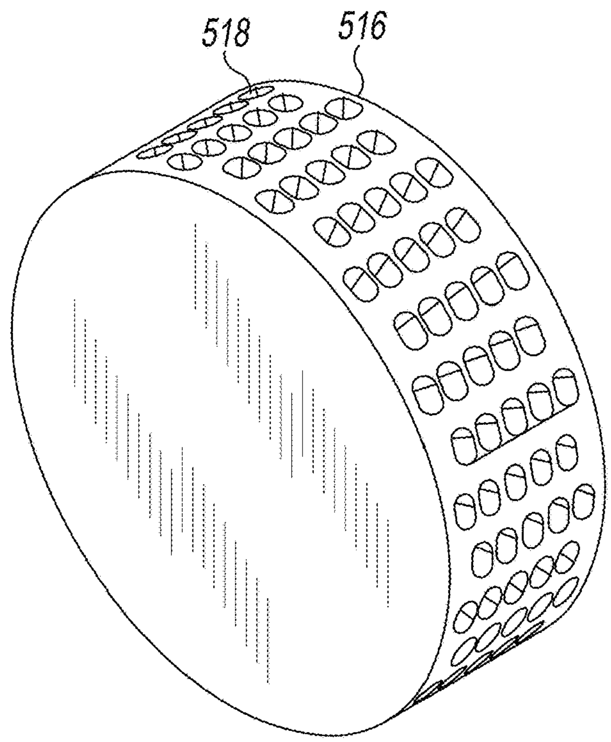

Fig. 21

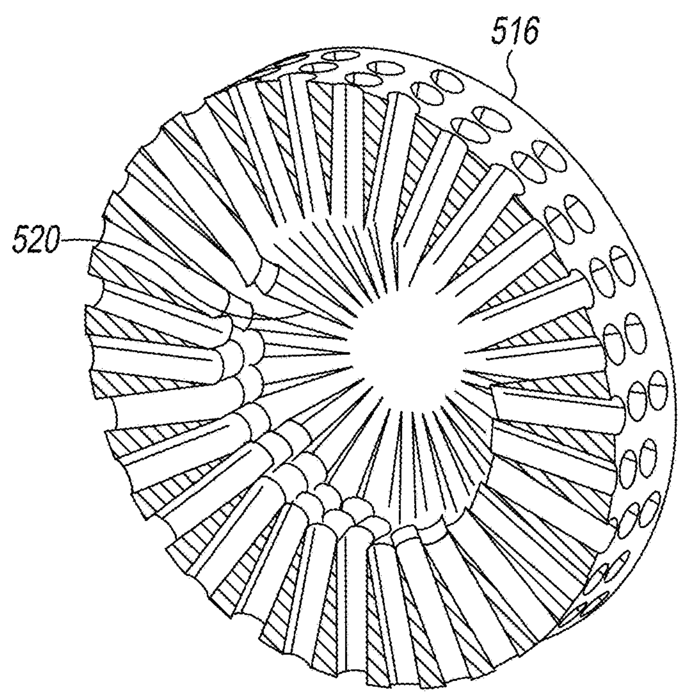

Fig. 22

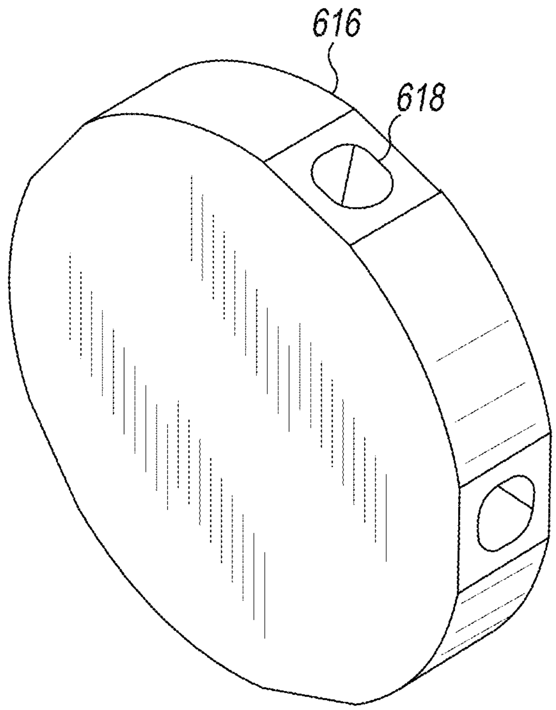

Fig. 23

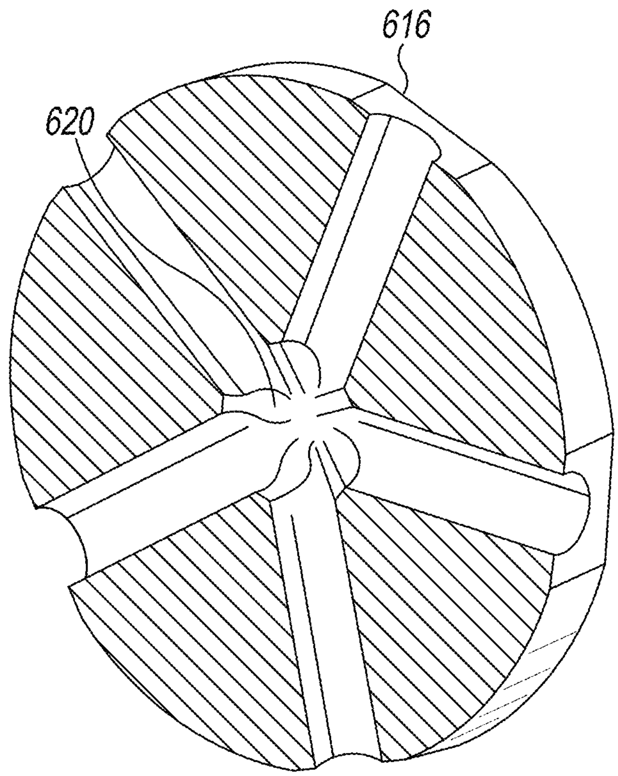

Fig. 24

TECHNOLOGIES FOR LONG-LIVED 3D MULTIMODE MICROWAVE CAVITIES

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the benefit of U.S. provisional patent application No. 62/642,514, filed Mar. 13, 2019, by David Schuster, Ravi Naik, and, Srivatsan Chakram, entitled "TECHNOLOGIES FOR LONG-LIVED 3D MULTIMODE MICROWAVE CAVITIES."

BACKGROUND

Quantum computing promises advances in solving problems that cannot be addressed with a classical computer, such as performing specific algorithms to efficiently solve certain problems, including, for example, factoring large numbers and performing simulations of large quantum systems. Superconducting quantum computing is a promising candidate, having demonstrated high-fidelity one- and two-qubit gates.

Like all quantum computing systems, a superconducting quantum computing system requires storage of qubits with low loss and small amounts of noise. Many proposals have been made, but the loss and noise present in superconducting quantum memories remains a limiting factor in superconducting quantum computing systems.

SUMMARY

According to one aspect of the disclosure, a device for supporting electromagnetic modes is disclosed. The device comprises a resonator comprising a monolithic block, a cavity that is defined in the monolithic block, and a port that opens into the cavity. The port is configured to receive a coupling element that is able to be coupled to a plurality of electromagnetic modes supported by the cavity. The cavity is defined between a number of seamless sidewalls.

In some embodiments, the device may further comprise the coupling element. The coupling element may be a non-linear element inserted into the port.

In some embodiments, the non-linear element may be a superconducting qubit.

In some embodiments, the non-linear element may be a tunable resonator.

In some embodiments, a first hole extending transverse to the cavity may be defined in the monolithic block, and a second hole extending transverse to the cavity may be defined in the monolithic block. The second hole may include an inner end that overlaps with an inner end of the first hole.

In some embodiments, a first plurality of holes extending transverse to the cavity in a first direction may be defined in the monolithic block, and a second plurality of holes extending transverse to the cavity in a second direction different from the first direction may be defined in the monolithic block. Each hole of the second plurality of holes may include an inner end that overlaps with an inner end of an adjacent hole of the first plurality of holes.

In some embodiments, the cavity may extend from a first end to a second end, and a first dimension of the cavity may be defined between the first end and the second end. A depth of the first and second plurality of holes into the cavity may decrease from the first end to the second end.

In some embodiments, the cavity may extend from a first end to a second end and a first dimension of the cavity may be defined between the first end and the second end. The cavity may have a second dimension that is defined at the first end orthogonal to the first dimension, and each of the first dimension and the second dimension may be bigger than the diameter of any of the first plurality of holes or second plurality of holes.

In some embodiments, a quality factor of at least one of the plurality of electromagnetic modes may be at least ten million.

In some embodiments, the monolithic block may be at a temperature less than a superconducting temperature of the monolithic block.

In some embodiments, the monolithic block may be at a temperature such that there is an average of less than one thermal photon in the lowest-frequency mode supported by the cavity.

In some embodiments, the monolithic block may be aluminum.

In some embodiments, the monolithic block may be at least 99.99% pure aluminum.

In some embodiments, the monolithic block may be one of niobium, copper, titanium nitride, niobium-titanium alloy, niobium titanium nitride, indium, lead, tin, lead-tin alloy, and rhenium.

In some embodiments, the resonator may further comprise a plurality of additional cavities, a bus cavity, and a plurality of superconducting qubits. Each superconducting qubit of the plurality of superconducting qubits may be positioned such that it is able to be coupled to both (i) one or more electromagnetic modes of a corresponding additional cavity of the plurality of additional cavities and (ii) one or modes of the bus cavity.

In some embodiments, the device may further comprise a film of material on the monolithic block.

In some embodiments, the monolithic block may not be superconducting at any temperature and the film of material may be superconducting when below a superconducting temperature.

In some embodiments, the monolithic block may be oxygen-free high thermal conductivity copper and the film of material may be one of titanium nitride, niobium titanium nitride, indium, lead, lead-tin allow, rhenium or rhenium, gold, and copper multilayers.

According to another aspect, a method of manufacturing a resonator is disclosed. The method comprises creating, in a monolithic block, one or more first holes from a first surface of the monolithic block such that each of the one or more first holes extends from the first surface to an end of the corresponding hole and creating, in the monolithic block, one or more second holes from a second surface of the monolithic block such that each of the one or more second holes overlaps with at least one hole of the one or more first holes to create a cavity in the monolithic block. The cavity extends from a first end to a second end and a first dimension of the cavity is defined between the first end and the second end, and the cavity has a second dimension that is defined at the first end orthogonal to the first dimension. Each of the first dimension and the second dimension is bigger than the diameter of any of the first plurality of holes or second plurality of holes.

In some embodiments, creating the one or more first holes from the first surface may comprise creating a plurality of first holes in a first direction from the first surface, and creating the one or more second holes from the second surface may comprise creating a plurality of second holes in a second direction different from the first from the second surface.

In some embodiments, the method may further comprise creating one or more third holes in a third direction different from the first and second from a third surface.

In some embodiments, creating the plurality of first holes and the plurality of second holes may comprise controlling one or more parameters of each of the plurality of first holes and each of the plurality of second holes to control a spectrum of modes supported in the cavity.

In some embodiments, controlling the one or more parameters of each of the plurality of first holes and each of the plurality of second holes may comprise controlling a depth of each of the plurality of first holes and of each of the plurality of second holes such that a height of the cavity decreases from the first end to the second end.

In some embodiments, controlling the one or more parameters of each of the plurality of first holes and each of the plurality of second holes may comprise controlling a depth of each of the plurality of first holes and of each of the plurality of second holes such that a height of the cavity decreases from the first end to the second end at a rate proportional to the distance from the first end.

In some embodiments, the method may further comprise creating a plurality of holes in the monolithic block. Each of the plurality of holes may comprise an outer end that does not overlap with any other hole of the plurality of holes and an inner end that overlaps with an inner end of one or more of the plurality of holes. The overlapping inner ends of the plurality of holes may form a volume that is approximately cylindrical.

In some embodiments, the method may further comprise creating a plurality of holes in the monolithic block. Each of the plurality of holes may comprise an outer end that does not overlap with any other hole of the plurality of holes and an inner end that overlaps with an inner end of one or more of the plurality of holes. The overlapping inner ends of the plurality of holes may form a volume that extends from the first end to the second end and surrounds a center core. The center core may form an inner conductor of a coaxial cavity.

In some embodiments, the cavity supports a plurality of electromagnetic modes at a plurality of wavelengths, and a quality factor of at least one of the electromagnetic modes may be at least ten million.

In some embodiments, the method may further comprise inserting a non-linear element into the cavity and performing a two-qubit operation on two modes of the cavity by controlling parameters of the non-linear element.

In some embodiments, the non-linear element may be a superconducting qubit.

In some embodiments, the non-linear element may be a tunable resonator.

In some embodiments, the method may further comprise cooling the monolithic block to a temperature less than a superconducting temperature of the monolithic block.

In some embodiments, the method may further comprise cooling the monolithic block to a temperature such that there is an average of less than one thermal photon in the lowest-frequency mode supported by the cavity.

In some embodiments, the monolithic block may be aluminum.

In some embodiments, the monolithic block may be at least 99.99% pure aluminum.

In some embodiments, the method may further comprise creating, in the monolithic block, a plurality of additional cavities in the same manner as the cavity and creating, in the monolithic block, a bus cavity in the same manner as the cavity. The method may further comprise creating, in the monolithic block, a port for each additional cavity of the plurality of additional cavities connecting the corresponding additional cavity to the bus cavity and inserting, in each port corresponding to an additional cavity of the plurality of additional cavities, an additional superconducting qubit such that the additional qubit is coupled to both one or more electromagnetic modes of the corresponding additional cavity of the plurality of additional cavities and one or modes of the bus cavity.

According to another aspect, a device for supporting electromagnetic modes is disclosed. The device comprises a resonator comprising a monolithic block, a cavity that may be defined in the monolithic block, and a port that opens into the cavity. The port is configured to receive a coupling element that is able to be coupled to a plurality of electromagnetic modes supported by the cavity. The cavity is defined between a number of sidewalls. A first plurality of holes extending transverse to the cavity in a first direction is defined in the monolithic block, and a second plurality of holes extending transverse to the cavity in a second direction different from the first direction is defined in the monolithic block. Each hole of the second plurality of holes includes an inner end that overlaps with an inner end of an adjacent hole of the first plurality of holes.

In some embodiments, a quality factor of at least one of the electromagnetic modes of the plurality of electromagnetic waves may be at least ten million.

In some embodiments, the resonator further may comprise a plurality of additional cavities, a bus cavity, and a plurality of additional superconducting qubits. Each additional superconducting qubit of the plurality of superconducting qubits may be positioned such that it is able to be coupled to both one or more electromagnetic modes of a corresponding additional cavity of the plurality of additional cavities and one or modes of the bus cavity.

According to another aspect, a system for supporting electromagnetic modes in a plurality of cavities is disclosed. The system comprises one or more resonators comprising the plurality of cavities defined in the one or more resonator and a bus cavity defined in the one or more resonators. Each of the plurality of cavities and the bus cavity support a corresponding plurality of electromagnetic modes. The system further comprises a plurality of non-linear elements. Each non-linear element of the plurality of non-linear elements is coupled to one of the plurality of cavities and to the bus cavity.

In some embodiments, the one or more resonators may comprise one resonator comprising a monolithic block. Each of the plurality of cavities and the bus cavity may be defined in the monolithic block.

In some embodiments, a frequency of each of the plurality of electromagnetic modes of the bus cavity may not overlap with a frequency of any of the electromagnetic modes of the pluralities of electromagnetic modes of the plurality of cavities.

In some embodiments, each non-linear element of the plurality of non-linear elements may be a superconducting qubit.

In some embodiments, each non-linear element of the plurality of non-linear elements may be a tunable resonator.

BRIEF DESCRIPTION OF THE DRAWINGS

The detailed description particularly refers to the following figures, in which:

FIG. 1 is a simplified block diagram of a system of a superconducting quantum computing device;

FIG. **2** is a perspective view of a resonator of the superconducting quantum computing device of FIG. **1**;

FIG. **3** is a cross-sectional plan view of the resonator of FIG. **2**;

FIG. **4** is a cross-sectional perspective view of the resonator of FIG. **2**;

FIG. **5** is a cross-sectional elevation view of the resonator of FIG. **2**;

FIG. **6** is a cross-sectional elevation view of the resonator of FIG. **2**;

FIGS. **7**A-**7**F illustrate simplified models of two embodiments of cavities formed inside the resonator of FIG. **1**, including field strengths of modes of the cavity;

FIGS. **8**A & **8**B are charts showing frequencies of modes of the cavity and quality factors and ring-down times of the modes of the cavity;

FIG. **9** is a top plan view of a probe inserted into the resonator of the superconducting quantum computing device of FIG. **1**;

FIG. **10** is a side elevation view of the probe and the resonator of FIG. **9**;

FIG. **11** is a cross-sectional side elevation view of the quantum computer element of FIG. **9**;

FIGS. **12**A & **12**B are a simplified block diagram of a superconducting qubit and an equivalent circuit diagram;

FIGS. **13**A & **13**B show pictures of one embodiment of a superconducting qubit;

FIG. **14** is a top plan view of at least one embodiment of the resonator of FIG. **1**, which includes several cavities formed from a monolithic block with slots for inserting superconducting qubits;

FIG. **15** is a top plan view of the resonator of FIG. **14** with a probe including a superconducting qubit inserted between cavities;

FIG. **16** is a side elevation view of the resonator of FIG. **15**;

FIG. **17** is a cross-sectional side elevation view of the resonator of FIG. **15**;

FIG. **18** is a cross-sectional top plan view of the resonator of FIG. **15**;

FIG. **19** is a perspective view of at least one embodiment of the resonator of FIG. **1**;

FIG. **20** is a cross-sectional perspective view of the resonator of FIG. **19**;

FIG. **21** is a perspective view of at least one embodiment of the resonator of FIG. **1**;

FIG. **22** is a cross-sectional perspective view of the resonator of FIG. **21**;

FIG. **23** is a perspective view of at least one embodiment of the resonator of FIG. **1**; and

FIG. **24** is a cross-sectional perspective view of the resonator of FIG. **23**.

DETAILED DESCRIPTION OF THE DRAWINGS

While the concepts of the present disclosure are susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and will be described herein in detail. It should be understood, however, that there is no intent to limit the concepts of the present disclosure to the particular forms disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives consistent with the present disclosure and the appended claims.

In the drawings, some structural or method features may be shown in specific arrangements and/or orderings. However, it should be appreciated that such specific arrangements and/or orderings may not be required. Rather, in some embodiments, such features may be arranged in a different manner and/or order than shown in the illustrative figures. Additionally, the inclusion of a structural or method feature in a particular figure is not meant to imply that such feature is required in all embodiments and, in some embodiments, may not be included or may be combined with other features.

Referring now to FIG. **1**, a system **10** for performing superconducting quantum computing operations includes a refrigerator **12**, which has a quantum computer element **14** positioned inside of it. It should be appreciated that, as used herein, the term "quantum computer element" refers to an element that is able to be used to perform quantum computing operations, such as preparation, manipulation, or measurement of a qubit, but does not necessarily need to be a component in a fully-functional quantum computing and need not include a physical qubit.

The illustrative quantum computer element **14**, as described in more detail below, includes a resonator **16** formed from a monolithic block **18** of material such as aluminum that supports multiple long-lived 3D electromagnetic modes at microwave frequencies. For example, the long-lived modes may have a quality factor of over 10 million. In the illustrative embodiment, the resonator **16** includes a seamless cavity **20** (see FIG. **3**) that is defined in the monolithic block **18**. As used herein, the term "seam" refers to a joint that is formed at the joining of two separate blocks of material, such as by mating the blocks together through application of physical force, welding, soldering, and/or the like. A "seamless" structure should be understood to refer to a single, continuous structure that is devoid of any seams. It should be appreciated that the resonator **16** as described in FIGS. **2-6** is seamless even though it has holes in it because it is created from a monolithic block.

As shown in FIG. **2**, the resonator **16** includes a plurality of transverse holes **22** that open into the cavity **20**. The holes **22** are arranged in a number of parallel rows extending from one end of the block **18** to the other. Each hole **22** in the illustrative embodiment is cylindrical and has a diameter **24**. The cavity **20** is sized such that electromagnetic waves at a wavelength greater than twice the diameter **24** of each hole **22** can exist in the cavity **20** and the electromagnetic waves cannot propagate outward from the holes **22**, thereby permitting the electromagnetic waves to persist in the cavity **20**. As described in greater detail below, the holes **22** are drilled into opposite surfaces **30**, **32** (illustratively top surface **30** and bottom surface **32**) of the block **18** and are spaced apart such that the holes **22** defined in the surface **30** overlap with the holes **22** defined in the opposite surface **32**, thereby forming the cavity **20**.

Returning to FIG. **1**, the quantum computer element **14** includes a superconducting qubit **40**, which is configured to be inserted into any of the holes **22** of the resonator **16**. In that way, each hole **22** acts as a port connecting the superconducting qubit **40** to the cavity **20**. It should be appreciated that, as used herein, the term "superconducting qubit" refers to a physical structure that can support two or more quantum states. In the illustrative embodiment, the superconducting qubit **40** is a type of charge qubit called a transmission-line shunted plasma oscillation qubit, or transmon, as described in more detail below in regard to FIGS. **12** & **13**. In other embodiments, the superconducting qubit **40** may be a different type of superconducting qubit, such as, for example, a charge qubit or a flux qubit. In some embodiments, the quantum computer element **14** may not include a superconducting qubit **40** but may include some other component such as an antenna, a transceiver for converting photons from one frequency to another, or some other component. The superconducting qubit **40** is part of a probe assembly **42** that includes a base **44**. The base **44** is illustratively a metallic plate configured to support or mount the superconducting qubit **40** in place on the resonator **16**. It should be appreciated that in other embodiments the base may be any suitable structure for holding or mounting the superconducting qubit **40** in place. In some embodiments, the base **44** may be incorporated into or otherwise form a part of the resonator **16**, the superconducting qubit **40**, or some other component.

One or more wires **50** extend from the probe assembly **42** to an inner control box **52**. The inner control box **52** may send, receive, amplify, filter, attenuate and otherwise control various signals to and from the superconducting qubit **40**. One or more wires **54** extend from the inner control box **52** to the outer control box **56**. The outer control box **56** may send, receive, amplify, filter, attenuate and otherwise control various signals to and from the superconducting qubit **40** in a similar manner as the inner control box **52**. The wires **50** and **54** may be any suitable wire capable of carrying signals to and from the superconducting qubit **40**, such as copper coaxial wires or twisted-pair wires.

The refrigerator **12** is a dilution refrigerator capable of chilling a sample to a temperature of approximately 20 millikelvin (mK). In other embodiments, the refrigerator **12** may be any other suitable type of refrigerator, such as a magnetic refrigerator, and may be capable of cooling down a sample such as the resonator **16** to a different temperature, such as 77 Kelvin, 4 Kelvin, 1 Kelvin, or 100 mK. The illustrative inner control box **52** is inside the refrigerator **12**, cooled down to a low temperature such as 1 Kelvin. It should be appreciated that, in some embodiments, the system **10** may include more than one inner control box **52** or various other electrical elements not shown, which may be at various temperatures such as 4 Kelvin, 1 Kelvin, 100 mK, or 20 mK. The illustrative outer control box **56** is outside the refrigerator **12** and is at room temperature. It should be appreciated that the system **10** may include additional electronics in some embodiments, such as logic electronics, wave-shaping electronics, etc.

As described above, the resonator **16** includes a monolithic block **18** and a cavity **20** that is defined in the block **18**. As shown in FIG. **2**, the block **18** in the illustrative embodiment is a rectangular prism that extends from a longitudinal end wall **60** to an opposite longitudinal end wall **62**. A pair of planar sidewalls **64**, **66** connect the end walls **60**, **62** and the top surface **30** and the bottom surface **32**. It should be appreciated that the labels "top," "bottom," etc. of the resonator **16** are merely used as a convenient way to describe the device, and do not restrict the orientation of the resonator **16**. It should also be appreciated that in other embodiments the block may take other geometric forms.

As shown in FIG. **3**, the cavity **20** is positioned within the block **18**, inset from the walls **60**, **62**, **64**, **66** and the surfaces **30**, **32**. The cavity **20** extends from a closed end **70** at end transverse hole **132** positioned adjacent to the end wall **60** to another closed end **72** at end transverse hole **130** positioned adjacent to the opposite end wall **62**. The cavity **20** in the illustrative embodiment includes three longitudinal sections **74**, **76**, **78** that are connected by end sections **80**, **82**. The sections **74**, **76**, **78**, **80**, **82** cooperate to define the length of the cavity **20** between its ends **70**, **72**. Each of the sections **74**, **76**, **78** extend parallel to one another and are formed by parallel rows of transverse holes **22**.

In the illustrative embodiment, the configuration of each traverse hole **22** is identical such that the features used to describe the configuration of one pair of transverse holes provide a description of the configurations of the other transverse holes. Referring now to FIG. **4**, the number of transverse holes **22** include a transverse hole **90**, which extends inwardly from the top surface **30**, and a transverse hole **92**, which overlaps with the transverse hole **90** and extends inwardly from the bottom surface **32**. The transverse hole **90** includes an opening **94** that is defined in the top surface **30**, and the transverse hole **92** includes a similar opening **96** that is defined in the bottom surface **32**.

The transverse hole **90** is defined by a sidewall **98** that extends inwardly from the opening **94** of the hole **90** to a base inner surface **100**. The sidewall **98** includes an outer cylindrical surface **102** that extends from the opening **94** and defines the transverse hole **90**. The sidewall **98** also includes a pair of curved inner surfaces **104** (see FIG. **3**) that extends from the outer cylindrical surface **102** to the base inner surface **100**. The outer cylindrical surface **102** defines an outer end of the hole **90**, and the curved inner surfaces define an inner end of the hole **90**.

The transverse hole **92** is defined by another sidewall **110** extends inwardly from the opening **96** of the hole **92** to a base inner surface **112**. It should be appreciated that the base inner surfaces **100**, **112** may be concave and conical, matching a portion of the shape of the drill bit or reamer used to create the hole. The sidewall **110** includes an outer cylindrical surface **114** that extends from the opening **96** and defines the transverse hole **92**. The sidewall **110** also includes a pair of curved inner surfaces **116** (see FIG. **3**) that extends from the outer cylindrical surface **114** to the base inner surface **112**. The outer cylindrical surface **114** defines an outer end of the hole **92**, and the curved inner surfaces **116** define an inner end of the hole **92**. The overlapping inner ends of the holes **90**, **92**, along with the overlapping inner ends of the other number of transverse holes, define the cavity **20**.

End transverse holes **130**, **132** only overlap with one other hole, leading to a different configuration of the corresponding sidewalls. As shown in FIG. **6**, the sidewall **136** that defines hole **130** includes an outer cylindrical surface **138** that extends from the opening **134** and defines the end transverse hole **130**. The sidewall **136** also includes a curved inner surface **140** that extends from the outer cylindrical surface **138** to the base inner surface **142**.

In the illustrative embodiment, the inner surfaces **104**, **116** of the sidewalls **98**, **110** defining the holes **22** cooperate to define the seamless sidewalls **118**, **120** of the cavity **20**. The base inner surfaces **100**, **112** connected to the sidewalls **98**, **110** cooperate to define the top and bottom walls **124** (see FIG. **5**), respectively, of the cavity **20**.

In the illustrative embodiment, the transverse holes **90**, **92** each have the same diameter and are approximately equally spaced apart. For example, the diameter of the hole **90** may be 7 millimeters (mm) and the spacing between transverse hole **90** and adjacent transverse hole **106** may be 1.5 mm. In other embodiments, the holes may be different diameter and spacing, such as 100 micrometer to 100 millimeter diameter holes and/or 20 micrometer to 20 millimeter spacing between holes. In the regions where series of holes curve and are not collinear, the spacing of the transverse holes may vary in order to maintain the desired cavity **20** structure inside the resonator **16**. The height of the cavity **20** at the location of the holes **90**, **92** is defined by the distance between the top and bottom walls **124**. In some embodiments, the height of the cavity **20** may be approximately constant. In other embodiments, the height of the cavity **20** may vary, such as by varying the depth of the number of holes of the cavity **20**. For example, in the illustrative embodiment and as can be seen in FIGS. **5** & **6**, the distance between base inner surfaces may vary such that the height of the cavity **20** decrease at a rate proportional to the distance from the start of the cavity **20** defined at transverse hole **72**. Such a taper may lead to an equal spacing of the frequencies of the cavity **20**, as discussed in more detail below. In other embodiments, the number of transverse holes in the resonator **16** may have different diameters and spacing in a manner that still create the desired cavity **20** in the resonator **16**.

The illustrative resonator **16** is made from aluminum that is over 99.999% pure. In other embodiments, a different purity may be used such as >99%, >99.9%, >99.99%, or >99.9999%. In some embodiments, different materials may be used, such as niobium, copper, titanium nitride, niobium-titanium alloy, niobium titanium nitride, indium, lead, tin, lead-tin alloy, rhenium, etc. Additionally or alternatively, a coating, electroplating, or other deposition may be applied as a thin or thick film to a material. The film may be any suitable material, such as titanium nitride, niobium titanium nitride, indium, lead, lead-tin allow, rhenium or rhenium, gold, and copper multilayers. The material which is plated may be any suitable material, such as oxygen-free high thermal conductivity (OFHC) copper. In the illustrative embodiment, in use, the resonator **16** is cooled to cryogenic temperatures, such as 20 mK, and the resonator **16** is formed from a material that is superconducting at such temperatures. In other embodiments, the resonator **16** may operate at different temperatures, such as 100 mK, 1 K, 4 K, 77 K, or room temperature, and/or may be made of a material that is not superconducting. Of course, the properties of the material such as whether it is superconducting may affect the performance of the resonator **16**, such as the lifetime of the electromagnetic modes supported by the resonator **16**. The illustrative resonator **16** is formed by drilling or milling each of the transverse holes straight into the resonator **16**. The tool used may be any suitable cutter or drill bit and may be chosen based on the properties of the transverse holes created. For example, an end mill cutter that creates a flat surface at the end of the cutter may be used in some embodiments. In the illustrative embodiment, an end mill cutter is used that creates a round hole, as shown in transverse holes **90**, **92**. Additionally or alternatively, in other embodiments, an end mill cutter or drill bit that creates holes of other shapes may be used, such as square holes. In some embodiments, other machining or manufacturing techniques may be used, such as electrical discharge machining (EDM), sinker EDM, wire EDM, etc. After the holes are drilled into the illustrative resonator **16**, the resonator **16** is etched to remove the outer layer, which may have been damaged during the drilling process. In the illustrative embodiment, the resonator **16** is submerged in an aluminum etchant at 50° C. with a spinner for two hours, then submerged in fresh aluminum etchant 50° C. for two more hours. The resonator **16** is then thoroughly rinsed with water. Of course, the resonator **16** may be formed in other embodiments by any suitable process. For example, in the illustrative embodiment, the resonator **16** may be manufactured using 3D printing or other additive manufacturing processes.

For purposes of rough calculations, the illustrative cavity **20** can be approximated as a box with a height corresponding to the distance between the base inner surfaces **100**, **112**, a width corresponding to the distance between the inner curved walls **104** (which will be equal to the diameter of the hole **90**), and a length corresponding to the distance between the ends **70** and **72** when traversing the cavity **20**. It should be appreciated that the height, width, and length of the cavity **20** are merely convenient labels, and do not imply that the cavity **20** has a uniform width and length or is in the shape of a box. In particular, the length is an effective length of the cavity **20**, and may be larger than any exterior dimension of the resonator **16**. The cavity **20** supports one or more electromagnetic waves. It should be appreciated that the cavity **20** supports electromagnetic modes despite the bends in the cavity **20**. The supported mode frequencies of an ideal box cavity with perfectly conducting walls and with length a, height b, and width d have frequencies

$$\omega_{mnl} = \pi c\sqrt{\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2 + \left(\frac{l}{d}\right)^2},$$

where at least two of mode indices n, m, and l must be non-zero. Approximating the cavity **20** as a box with a length of 1 meter, a height of 22 mm, and a width of 7 mm, the cavity **20** would support a mode with a frequency of about 7 GHz for n=1, m=1, and l=0. The transverse holes, such as transverse hole **90**, can be considered as a waveguide that could potentially support the waves contained in the cavity **20**. If the waves in the cavity **20** can propagate through, e.g., transverse hole **90**, then the quality factor or ring-down time of the cavity **20** would be limited. The cutoff frequency for a waveguide is approximately the frequency corresponding to a wavelength that is half of the diameter of the holes. With a 7 mm diameter for the transverse hole **90**, the cutoff frequency would be approximately 21 GHz. It should be appreciated that the cavity **20** may support multiple modes that are below the cutoff frequency of the transverse, such as several modes with n≥1, m=1, l=0. Of course, in some embodiments, the cavity **20** may also support modes with, e.g., m=2, 3, etc. Which modes are supported depend on the effective length of the cavity and the height of the cavity.

As can be seen from FIGS. **5** & **6**, in the illustrative embodiment, the cavity **20** that has a non-uniform height. The shape of the cavity **20** affects the spectrum of the supported modes. In particular, if we consider the equation for the frequencies of the modes in the cavity,

$$\omega_{mnl} = \pi c\sqrt{\left(\frac{n}{a}\right)^2 + \left(\frac{m}{b}\right)^2 + \left(\frac{l}{d}\right)^2},$$

we can simplify the equation if we assume that a>>b and b>d. Assuming that l=0 and m=1, the equation simplifies to

$$\omega_n \approx \frac{\pi c}{b} + \frac{\pi c b}{2a^2}n^2.$$

Based on this equation, we can see that the frequency of the mode for any given n is proportional to

$$\frac{n^2}{a^2}$$

plus a fixed amount. This fact can be used to manipulate the spacing of the modes. For example, if we can manipulate the effective length of the cavity to be proportional to $\sqrt{n}$, then the modes will be equally spaced. One way to do that would be to taper the cavity **20** by changing the height of the cavity **20** along the length of the cavity **20**. Since longer wavelengths with lower frequencies will be excluded from portions of the cavity **20** that are tapered to the point where the longer-wavelength modes are not supported, the effective length of the cavity depends on the frequency. By reducing the height an amount that is proportional to the square of the distance from the end of the cavity, the desired spacing can be achieved, as shown in FIG. **7**E. Another option for tapering would be to have the height be a maximum at the middle of the cavity **20** and taper both ends of the cavity **20** to be a smaller height.

It should also be appreciated that the modes of the cavity **20** will have non-zero field amplitude in the transverse holes, but if the frequency of the modes of the cavity **20** is below the cutoff frequency of the holes, the amplitude will decay exponentially in the holes. The length of the necks outer sidewalls, such as outer sidewall **102**, determines how much the amplitude decays before reaching the top surface **30** and the bottom surface **32**. In the illustrative embodiment, the lengths of the outer sidewalls such as outer sidewall **102** are chosen such that the field amplitude is small enough at the top surface **30** and bottom surface **32** that the lifetime of the modes in the cavity **20** is not significantly limited by the intensity leaking out through the transverse holes.

Referring now to FIGS. **7**A-**7**E, FIG. **7**A shows a model of a cavity based on overlapping holes that does not have a tapered height. The logarithm of the mode intensity is shown in FIG. **7**B for the fundamental mode, n=1, m=1, l=0 calculated using a finite-element simulation. The logarithm of the mode intensity for a higher-frequency mode, n=5, m=1, l=0 is shown in FIG. **7**C. Note that the intensity near the outer edges of the holes is negligible.

FIG. **7**D shows a model of a cavity based on overlapping holes that has a tapered height. FIG. **7**D corresponds to the snake-like cavity **20** if it were "unfolded" to be straight with an equivalent length. The logarithm of the mode intensity is shown in FIG. **7**E for the fundamental mode, n=1, m=1, l=0 calculated using a finite-element simulation. The logarithm of the mode intensity for a higher-frequency mode, n=6, m=1, l=0 is shown in FIG. **7**F. Note that the high-frequency mode extends further into the tapered region, indicating that the effective length is longer for the higher-frequency mode.

Referring now to FIGS. **8**A & **8**B, the mode frequencies supported by the cavity **20** are shown in a graph **150**. As discussed below in more detail in regard to FIGS. **14**-**16**, the height of the cavity **20** is tapered, varying the effective length of the cavity based on the mode frequency. The tapering causes the frequencies of the modes supported in the cavity **20** to be approximately equal, as can be seen in FIG. **8**A. For example, modes **152**, **154**, **156**, and **158**, which correspond to the lowest-frequency 4 modes, are spaced by approximately 200 MHz. The modes in FIG. **8**A were measured by weakly coupling an input cable and an output cable to the cavity **20**. Since the amplitudes of the peaks depend on the coupling strength of the input and output cables, the height of the peaks does not indicate any performance parameters of the cavity **20** itself.

FIG. **8**B shows a plot **160** of the measured quality factor (Q-factor) and ring down time for some of the modes supported by the cavity **20**. The Q-factor of a mode is defined as the ratio of the energy stored in the mode to the energy dissipated per cycle of the mode. The measured Q-factors were measured to be over 25 million for each mode and the ring-down time was measured to be over 0.5 milliseconds for each mode. Due to measurement errors, the measured Q-factors may not necessarily exactly correspond to the measured ring-down time.

Referring now to FIG. **9**, a top plan view of the quantum computer element **14** includes the probe assembly **42** which supports a superconducting qubit **40** inserted into a port of the cavity **20** through one of the transverse holes. As discussed in more detail below in regard to FIGS. **12** & **13**, the superconducting qubit **40** can interact with the modes of the cavity **20**. FIG. **10** shows a side elevation view of the quantum computer element **14**. FIG. **11** shows a cross-sectional side elevation view of the quantum element **14** with the superconducting qubit **40** inserted into the cavity **20**. In the illustrative embodiment, one superconducting qubit **40** is inserted in the cavity **20**. In some embodiments, two or more superconducting qubits **40** may be inserted in the cavity **20**.

Referring now to FIGS. **12**A & **12**B, FIG. **12**A shows a simplified block diagram of an illustrative embodiment of a superconducting qubit **40**. The illustrative superconducting transmon qubit **40** is formed by a first ground plane **202**, a second ground plane **206**, and a strip **204**. In some embodiments, the first ground plane **202**, the second ground plane **206**, and the strip **204** may form a transmission line cavity. In other embodiments, no transmission line may be present, in which case the ground plane **202** may not be necessary. Between the ground plane **206** and the strip **204**, two superconducting islands **216**, **218** are arranged to have a particular desired capacitance controlled by the geometry of the islands. Two Josephson junctions **220**, **222** are formed by a slight gap between the two superconducting islands **220**, **222** that is filled with an insulator such as aluminum oxide.

The superconducting qubit **40** can be in different quantum states based on the difference between the number of electrons in the superconducting islands **216**, **218**. The spacing between the energy levels is not uniform. The state of the superconducting qubit **40** can be controlled by controlling the voltage levels across the ground plane **206** and the control strip **204**, such as by applying a voltage **208** across wires **210** and **214** connected to the strip **204** and the ground plane **206**, respectively. A magnetic flux can be applied in the loop **224** formed by the superconducting islands **216**, **218** and the Josephson junctions **220**, **222**. The amount of magnetic flux applied can change the Josephson energy and, therefore, change the energy levels of the superconducting qubit **40**. The magnetic flux can be applied by, e.g., an inductor that is not shown.

The superconducting qubit **40** couples to electromagnetic waves that are at a frequency corresponding to the difference between the current energy level of the superconducting qubit **40** and a different energy level of the superconducting qubit **40**. The electromagnetic waves to which the superconducting qubit **40** couples could be, e.g., a mode in a transmission line cavity formed by the ground planes **202**, **206** and the strip **204** or a mode in the cavity **20**. For example, if the superconducting qubit **40** is in the ground state, and the next highest energy level is 7 GHz, the superconducting qubit **40** will couple to a mode of the cavity **20** that is at 7 GHz. If a 7 GHz photon is in the cavity **20**, it will be absorbed by the superconducting qubit **40**, exciting it to a higher energy level. Since the energy levels of the superconducting qubit **40** can be controlled by changing the amount of flux in the loop **224**, the coupling between the modes of the cavity **20** and the superconducting qubit **40** can be controlled. What the state of the superconducting qubit **40** is (such as whether the superconducting qubit **40** is in the ground state or a first excited state) can be determined by measuring whether the superconducting qubit **40** couples to the first excited state and the second excited state, which are spaced by an energy different from the ground state and the first excited state. This measurement can be done by, e.g., sending a weak signal at or near the frequency corresponding to the difference between the energy of the first and second excited energy levels through a cavity (such as a transmission line or the cavity **20**) and measuring how the signal was shifted. Since the signal will be shifted depending on the state of the superconducting qubit **40**, the state of the superconducting qubit **40** can be determined. It should be appreciated that the various parameters of the superconducting qubit **40**, such as the voltage **208** applied across the superconducting qubit **40** and the flux in the loop **224** may be controlled by one or more external signals that may be carried by the wires **110**. For example, in the illustrative embodiment, the wires **110** may include three cables for carrying three signals: a first connected to a charge port of the superconducting qubit **40** that applies qubit write and readout signals, a second connected to a flux port of the superconducting qubit **40** for shifting the qubit frequency using a DC-flux bias current, and a third connected to an output port for measuring the transmission from the readout signal.

It should be appreciated that the ability to control the superconducting qubit **40** discussed above allows for operation of single-qubit and two-qubit operations on the superconducting qubit **40** and the modes of the cavity **20**. The state of the modes in the cavity **20** may be swapped with the state of the superconducting qubit **40** by virtue of vacuum Rabi oscillations when the energy levels of the superconducting qubit **40** are brought into resonance with a particular mode of the cavity **20**. The state of the superconducting qubit **40** may be manipulated by controlling the applied voltage **208** across the superconducting qubit **40** and by controlling the magnetic flux through the loop **224**. Single-qubit operations can be performed on the modes of the cavity **20** by swapping the state of a mode of the cavity **20** with the state of the superconducting qubit **40**, performing single-qubit operations on the state of the superconducting qubit **40**, and then swapping the state of the superconducting qubit **40** back into the mode of the cavity **20**. Two-qubit operations can be performed between the state of the superconducting qubit **40** and a mode of the cavity by tuning the superconducting qubit **40** so that the energy between the first excitation level and the second excitation level is the same as the energy of a mode of the cavity for a long enough time to swap the states twice. Such a swap will impart a π phase shift on the system only if the state of both the superconducting qubit **40** and the mode of the cavity are both "1" (i.e., the superconducting qubit **40** is in the first excited state and the cavity has a photon in it at that frequency). Such an operation is a controlled-phase gate. Two-qubit operations can be performed between two modes of the cavity **20** by first swapping the state of one of the modes of the cavity **20** with the superconducting qubit **506**. The ability to use the superconducting qubit **506** to swap quantum states in various modes of the cavity in addition to the ability to perform two-qubit operations allows the system to perform universal quantum computation. It should be appreciated that, in some embodiments, different elements may be coupled to modes of the cavity **20** in addition to or as an alternative to the superconducting qubit **506**. Those coupling elements may be linear or non-linear elements that can store and retrieve photons from the cavity, such as a tunable resonator or an antenna.

FIG. **12**B shows a simplified circuit diagram that is approximately the equivalent of the superconducting qubit **40** block diagram shown in FIG. **12**A. One side of both Josephson junctions **250**, **252** is connected to a wire **246** and the other side of the Josephson junctions **250**, **252** is connected to a wire **248**. The Josephson junctions **250**, **252** and wires **246**, **248** form a loop **224** through which a certain magnetic flux can be applied. There is a capacitance **256** between the two sides of the Josephson junctions **250**, **252**. There is also a capacitance **254** between one side of the Josephson junctions **250**, **252** and a wire **234** that is connected to one side of a voltage source **238**. Finally, there is a capacitance **258** between the other side of the Josephson junctions **250**, **252** and a wire **236** that is connected to the other side of the voltage source **238**.

Referring now to FIG. **13**A, an image of the superconducting qubit **40** shows conducting plane **202**, conducting strip **204**, ground plane **206**, and superconducting islands **216** and **218**. Region **260** includes the Josephson junctions **220**, **222**, as shown in FIG. **13**B.

Referring now to FIG. **14**, a top plan view is shown of another embodiment of a resonator **316** which includes several cavities **320**A, **320**B, **320**C, and **320**D (see FIG. **18**). Each cavity **320** is formed in a similar manner as the cavity **20**, which will not be repeated in the interest of clarity. Additionally, the resonator includes a bus cavity **322** (see FIG. **18**), which is formed in a similar manner as the cavity **20**. Each cavity **320** is connected to the bus cavity **322** by a notch **324**. FIG. **15** shows a top plan view of the resonator **316** with probe assemblies **48** which support a qubit **40** (see FIG. **17**) inserted into each notch **324** between the bus cavity **322** and each cavity **320**. The notch **324** acts as a port between the cavities **320**, **322**, allowing the inserted qubits **40** to be simultaneously coupled to each of the two cavities. FIG. **16** shows a side elevation view of the resonator **316**.

Referring now to FIG. **17**, a cross-sectional side elevation view of the resonator **316** shows the cavity **320**D formed by the holes in the resonator **316**. The cross-section also shows a hole **326** of the bus cavity **322** and the notch **324**D. The notch **324**D has a corresponding base inner surface **328**. The superconducting qubit **40** is inserted into the notch **324**D, between the cavity **320**D and the bus cavity **322**.

Referring now to FIG. **18**, a cross-sectional top plan view of the resonator **316** shows the cavities **320** and the bus cavity **322**. Each superconducting qubit **40** is inserted in the corresponding notch **324** and is coupled to each corresponding cavity **320** and the bus cavity **322**. The bus cavity **322** may be configured such that the frequencies of the supported modes of the bus cavity **322** do not overlap with the frequencies of the supported modes of the cavities **320**, so that waves that are present in the cavities **320** will not leak into the bus cavity **322**, and vice versa. Since each of the superconducting qubits **40** can be tuned to be in resonance with the modes of the corresponding cavity **320** and with the modes of the cavity **322** and since the superconducting qubit **40** is in a position where it overlaps with the fields of the modes of the corresponding cavity **320** and the bus cavity **322**, each superconducting qubit **40** is able to interact with both the corresponding cavity **320** and the bus cavity **322**. It should be appreciated that the configuration of the resonator **316** allows each superconducting qubit **40** to perform one- and two-qubit operations on and between the modes of the corresponding cavity **320** as well as "read" and "write" the state of the superconducting qubit **40** to the bus cavity **322**.

With those abilities, two-qubit operations can be performed between any two modes of the cavities **320** with at most two "hops," one hop from, e.g., cavity **320**A into the bus cavity **322** and a second hop from the bus cavity **322** to, e.g., cavity **320**B.

Referring now to FIGS. **19-24**, various possible embodiments of a resonator are shown. Each of the illustrative resonators in FIGS. **19-24** are formed from a monolithic block in a similar manner as the resonator **16**, and each of the cavities in the resonators in FIGS. **19-24** are formed from overlapping holes in a similar manner as the cavity **20**, but the cavities of the resonators in FIGS. **19-24** are formed from holes that are oriented and overlap in different way as the holes in the cavity **20**, as described in more detail below. In FIG. **19**, a perspective view of a resonator **416** is shown. The resonator **416** formed from a number of holes, such as the hole **418**. FIG. **20** shows a cross-sectional perspective view of the resonator **416**, showing the cavity **420** formed in the interior of the resonator **416**. It should be appreciated that, unlike the cavity **20**, the cavity **420** is a coaxial waveguide, which supports modes with a transverse electric and magnetic fields, or "TEM" modes, which may have a wavelength that is not limited by the dimensions of the cross-section (although the allowed wavelengths will still be limited by the length of the cavity).

Referring now to FIG. **21**, a perspective view of an illustrative resonator **516** formed by holes such as hole **518** that extend from a cylindrical surface to a cavity **520**. FIG. **22** shows a cross-sectional perspective view of the resonator **516**, which shows the cavity **520**.

Referring now to FIG. **23**, a perspective view of an illustrative resonator **616** formed by holes such as hole **618** that extend from a cylindrical surface to a cavity **620**. FIG. **24** shows a cross-sectional perspective view of the resonator **616**, which shows the cavity **620**.

It should be appreciated that the embodiments described above are not the only possible embodiments and that the concepts described above could be combined with various other concepts. For example, each cavity **20** and **320** may have more than one superconducting qubit **40** inserted into it. In some embodiments, other degrees of freedom of the resonator **16**, **316** may be used, such as mechanical degrees of freedom including phonons, surface acoustic waves, photonic crystal modes, etc.

The invention claimed is:

1. A device for supporting a plurality of electromagnetic modes, comprising:

a resonator comprising a monolithic block, a cavity that is defined in the monolithic block, and a port that opens into the cavity, the port being configured to receive a coupling element that is able to be coupled to the plurality of electromagnetic modes supported by the cavity, wherein the cavity is defined between a number of seamless sidewalls,

wherein the monolithic block is at a temperature such that there is an average of less than one thermal photon in the lowest-frequency mode supported by the cavity.

2. The device of claim **1**, further comprising the coupling element, wherein the coupling element is a non-linear element inserted into the port.

3. The device of claim **2**, wherein the non-linear element is a superconducting qubit.

4. The device of claim **1**, wherein:

a first hole extending transverse to the cavity is defined in the monolithic block, and

a second hole extending transverse to the cavity is defined in the monolithic block, the second hole including an inner end that overlaps with an inner end of the first hole.

5. The device of claim **1**, wherein:

a first plurality of holes extending transverse to the cavity in a first direction is defined in the monolithic block, and

a second plurality of holes extending transverse to the cavity in a second direction different from the first direction is defined in the monolithic block, each hole of the second plurality of holes including an inner end that overlaps with an inner end of an adjacent hole of the first plurality of holes.

6. The device of claim **5**, wherein the cavity extends from a first end to a second end, and a first dimension of the cavity is defined between the first end and the second end,

wherein a depth of the first and second plurality of holes into the cavity decreases from the first end to the second end.

7. The device of claim **5**, wherein:

the cavity extends from a first end to a second end and a first dimension of the cavity is defined between the first end and the second end;

the cavity has a second dimension that is defined at the first end orthogonal to the first dimension; and

each of the first dimension and the second dimension is bigger than the diameter of any of the first plurality of holes or second plurality of holes.

8. The device of claim **1**, wherein a quality factor of at least one of the plurality of electromagnetic modes is at least ten million.

9. The device of claim **1**, wherein the resonator further comprises:

a plurality of additional cavities;

a bus cavity; and

a plurality of superconducting qubits,

wherein each superconducting qubit of the plurality of superconducting qubits is positioned such that the superconducting qubit is able to be coupled to both (i) one or more electromagnetic modes of a corresponding additional cavity of the plurality of additional cavities and (ii) one or modes of the bus cavity.

10. The device of claim **1**, wherein the monolithic block is aluminum.

11. The device of claim **1**, wherein the monolithic block is one of niobium, copper, titanium nitride, niobium-titanium alloy, niobium titanium nitride, indium, lead, tin, lead-tin alloy, and rhenium.

12. The device of claim **1**, further comprising a film of material on the monolithic block.

13. The device of claim **12**, wherein the monolithic block is oxygen-free high thermal conductivity copper and wherein the film of material is one of titanium nitride, niobium titanium nitride, indium, lead, lead-tin allow, rhenium or rhenium, gold, and copper multilayers.

14. A device for supporting electromagnetic modes comprising:

a resonator comprising a monolithic block, a cavity that is defined in the monolithic block, and a port that opens into the cavity, the port being configured to receive a coupling element that is able to be coupled to a plurality of electromagnetic modes supported by the cavity, wherein the cavity is defined between a number of sidewalls, wherein a first plurality of holes extending transverse to the cavity in a first direction is defined in the monolithic block, and

a second plurality of holes extending transverse to the cavity in a second direction different from the first direction is defined in the monolithic block, each hole of the second plurality of holes including an inner end that overlaps with an inner end of an adjacent hole of the first plurality of holes.

15. The device of claim **14**, wherein the resonator further comprises:

a plurality of additional cavities;

a bus cavity; and

a plurality of additional superconducting qubits,

wherein each additional superconducting qubit of the plurality of superconducting qubits is positioned such that the superconducting qubit is able to be coupled to both (i) one or more electromagnetic modes of a corresponding additional cavity of the plurality of additional cavities and (ii) one or modes of the bus cavity.

16. The device of claim **14**, wherein a quality factor of at least one of the electromagnetic modes of the plurality of electromagnetic waves is at least ten million.

17. A system for supporting electromagnetic modes in a plurality of cavities, the system comprising:

one or more resonators comprising the plurality of cavities defined in the one or more resonators and a bus cavity defined in the one or more resonators, wherein each of the plurality of cavities and the bus cavity support a corresponding plurality of electromagnetic modes;

a plurality of non-linear elements, wherein each non-linear element of the plurality of non-linear elements is coupled to one of the plurality of cavities and to the bus cavity,

wherein a frequency of each of the plurality of electromagnetic modes of the bus cavity does not overlap with a frequency of any of the electromagnetic modes of the pluralities of electromagnetic modes of the plurality of cavities.

18. The system of claim **17**, wherein a quality factor of at least one of the plurality of electromagnetic modes of at least one of the plurality of cavities is at least ten million.

19. The system of claim **17**, wherein the one or more resonators comprises one resonator comprising a monolithic block, wherein each of the plurality of cavities and the bus cavity is defined in the monolithic block.

20. The system of claim **17**, wherein each of the one or more resonators is at a temperature such that there is an average of less than one thermal photon in the lowest-frequency mode supported by the cavity.

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